A Framework for Agile Collaboration in Engineering

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A Framework for Agile Collaboration in Engineering

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“Muchos creen que tener talento es una suerte; nadie que la suerte pueda ser cuestión de talento.”

- Jacinto Benavente (1866-1954)

For Denise and my Parents,
To whom I owe everything.

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Accomplishments tend to be attributed to individuals and in rare cases groups of individuals; few, however, can rightly be ascribed as such. The number of individuals, fortunate enough to be recognized for their achievements, is small and often determined by luck and circumstance.

In my view, there are two key factors to being successful. The first is opportunity and the second persistence, the lack of either of which is likely to stagnate our progress in achieving the goals we have set for ourselves. While it is true that hard work can create opportunity, it is important to acknowledge that the success of any individual is a function of the amalgamated influences, efforts, and contributions of all those surrounding them. My case is no different, as I have been extremely fortunate throughout my life – fortunate to have had a mother who showed me the importance of maintaining both a dream and a vision, fortunate to have had a grandfather who instilled in me the virtue of hard work, fortunate to have a father who encouraged balance and saw successes, not as plateaus for reverie, but as portals to further opportunity, fortunate to have a second mother who had the gift of insight into my character and the ability to provide perspective, and fortunate enough to have enjoyed the continued support and encouragement of a loving family and loyal friends. More recently, I also consider myself extremely fortunate to have found a wife, who has understood me throughout our lifelong friendship - often, she has the faith in me that I do not yet have in myself. I remain grateful for the opportunities with which I have been presented and hopeful that I will be able to continue to make the most of them. It is in this manner that I intend to continue honoring those who have touched my life and influenced my development.

All of this can be summed up quite effectively by the aphorism of the Systems Realization Laboratory - *Happy people are always successful, successful people are not always happy.* In the grander scope of things, the truth is that it is easy to succeed when you are happy and that there is no greater motivator than genuine interest. I truly believe that, at least professionally, there is no greater gift than to do what you love and love what you do, another reason for considering myself to have been quite fortunate.

I am very thankful for the encouragement and support I have received from fellow members (both faculty and students) of the Systems Realization Laboratory. In particular, I thank Carolyn Conner Seepersad for her consistent input, feedback, and support. I have greatly benefited from her mentorship since I first joined the SRL in the fall of 1999. I also thank Jitesh Panchal for being a constant motivator and a good friend. I have learned a lot from our joint ventures over the last four years and look forward to seeing him make his mark on academia. I am very grateful to have found such good friends in Matthew Chamberlain, Scott Duncan, Benay Sager, and Christopher Williams, without whom my graduate experience would have been rather dull. I am also grateful to Farrokh Mistree and Janet K. Allen for their guidance and enthusiasm and appreciate the fact that I have been able to contribute to their vision. I have also gained much from the keen insight and intellectual curiosity of David Rosen, who has played a significant role in channeling my efforts thus far.

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GLOSSARY

Aleatory Uncertainty – irreducible uncertainty or variability

Benevolent Dictator Approach - the chosen method of amalgamating preferences for the resolution of downstream decisions characterized by inherited information content within this thesis, focused on the formulation of multi-attribute utility functions by a chosen emissary, deemed most suitable for making a particular dependent decision, based on the weighted inclusion of normalized and re-scaled utilities pertaining to upstream decision-makers.

Bounded Rationality - a concept attributed to Herbert Simon that focuses on the search for an optimal solution within a sub-range of a problem's solution space, as defined according to the decision-maker's best estimate of the true region of interest in the case of compromise decisions and knowledge regarding the viability of alternatives in the case of selection decisions. A solution determined in this nature is said to be satisficing - superior but not optimal from the system's perspective.

Co-Design – the system conscious designation of shared resources to the same extent or degree.

Collaboration - the synergy inherent in groups working towards the achievement of a common goal.

Communications Protocol - rules of engagement and prescriptions for the content and format of communiqués in decentralized design. Stakeholder tradeoff strategies are often captured in functional form, control relinquished, and solutions determined algorithmically.

Compromise Decision - a decision involving the improvement of a given alternative through modification.

Concurrent - indicating the consideration or resolution of constituent facets of a common whole in a simultaneous manner.

Context - a particular instance, characterized by (1) a distinct point in time, (2) the contribution of a particular decision-maker, (3) a distinct set of information taken into consideration.

Coordination Mechanism – any formalized means of conflict management that shares characteristics of both solution algorithms and communications protocols,

Coupling - a relationship characterized by the dependence or interdependence of constituent facets, where facets can be decisions, attributes, goals, alternatives, etc. Coupling can be characterized further as being either weak or strong.

Data - unorganized, indistinct bits of information that can be stored.

Decision - (1) an action, involving the strategic reduction of design freedom through the deliberate and often irrevocable allocation of resources, (2) a marker, measuring the progress of an artifact's design, (3) the culmination of a design phase.

Decision-Based Design (DBD) – a perspective of design that emphasizes the role of designers as decision-makers and the development of a formalism for making decisions.

Decision-Centric Design (DCD) – an augmentation of DBD that emphasizes the importance of gearing design processes towards improving design decisions, rather than retrospectively accentuating the significance of decisions leading up to finalizing a product. Special attention is paid to both the internal structure of decisions and the manner in which different decisions are linked, in an effort to formalize a modular architecture.

Distributed Collaborative Design and Manufacture - the paradigm in which the effort of systems and product realization is carried out by non-co-located, multi-disciplinary entities, acting as stakeholders in a common process.

Decision-Mapping - the process of representing a given design process in terms of the decisions required for its resolution, the inherent information flows determining the relationships among constituent decisions, required information content, etc.

Decision Point - (1) a specific point in time (i.e., along a design timeline) at which a decision is made, (2) a distinct instance of design freedom reduction.

Decision Support - is defined as the means and mechanics designed to sustain the ability of decision makers to properly account for critical information in the decision-making process. That is to say, that the endeavor behind decision support is to provide a decision-maker with the technology required to properly formulate, structure, and solve problems, requiring decisions.

Decision Templates - a comprehensive, context unspecific Decision Support Problem that is fully developed for a more general class of problems, characterized in terms of required inputs and outputs, and ideally implemented as a software application.

Decision Uncertainty - uncertainty pertaining to the outcome of a particular decision, particular with respect to the achievement of levels of objectives (i.e., either attributes or goals) taken into consideration.

Declarative Information – Product specific information.

Dependence - a relationship among decisions forming constituent facets of a common design process that is characterized by dependent information flows and inherited information content.

Designer - a person characterized by the active role he/she plays in the design process, where possible roles include being a (1) decision-maker, (2) stakeholder in a common design process, (3) creative entity, (4) information manager/knowledge worker.

Design Freedom - (1) the number of options that remain open to a designer for consideration at a particular point along a timeline, characterized by or proportional to the resources at a designer's disposal/discretion, (2) a measure of a designer's independence in making a particular decision.

Design Knowledge – knowledge about the product or artifact being designed as pertaining to the specification of form, function, and performance.

Design Space – (1) the continuous or discrete set of options under consideration by a designer at a particular point in time (2) the region of influence of a designer

Design Timeline - a virtual construct used to indicate progress in a design process where activities are sequenced temporally.

Design Uncertainty - uncertainty pertaining to the final form, function, and performance of a given design.

Design Variable - (1) an independent variable over which a designer has control, (2) a variable that can be adjusted in order to influence the response of a given system in terms of dependent variables.

Digital Interface – boundary separating discrete decision points that have been developed sufficiently in terms of decision templates, so that (1) the communication of critical information along with knowledge, regardless of context, is facilitated, (2) interactions among the stakeholders, assigned responsibility for making the decisions in question, are formalized in terms of decision critical inputs and outputs, and (3) a communications protocol in terms of a common system description/model is established.

Digital Intraface – boundary separating discrete aspects of a given decision, that has been developed sufficiently in terms of a decision template, so that (1) the communication of critical information along with knowledge, regardless of context, is facilitated, (2) interactions among the stakeholders, assigned responsibility for different aspects of the decision in question, are formalized in terms of decision critical inputs and outputs, and (3) a communications protocol in terms of a common system description/model is established.

Distributed Collaborative Design and Manufacture - the paradigm in which the effort of systems and product realization is carried out by non-co-located, multi-disciplinary entities, acting as stakeholders in a common process.

Distribution – (1) complexity with regard to the level of decentralization that characterizes the decisions being made within a design process, (2) indicating non-co-location of entities and resources.

Downstream – (1) indicating the subsequent relative temporal succession of a given decision in a linearized, sequential design process, (2) a decision occurring after a reference point in a design timeline.

Epistemic Uncertainty - reducible uncertainty or imprecision due to ignorance of information

Event - a succinct instance of information transfer that often results in a single decision or a number of closely related decisions although this is not a requirement.

Goal - an objective, used to evaluate the merit of the outcome of a compromise decision

Hysteresis - (1) temporal lag and inefficiency associated with design iteration and poor communication or information transfer between sequential decision points of a design process, (2) loss (in terms of time, money, etc.) associated with iteration in design processes.

Information – processed (i.e., correlated and organized) data that can be stored.

Information Economics – "the study of choice in information collection and management when resources to expend on information collection are scarce" [19].

Information Flow - (1) the propagation of information content along a design timeline (2) the nature of informational dependencies associated with relationships among constituent decisions of a common design process.

Information Support - on the other hand, is defined as the sum of all technologies aimed at providing a decision-maker with decision critical information and relevant insight to a given problem. The inherent means for the 1) attainment, parsing, structuring, interpretation, and perusal of existing knowledge and 2) the synthesis of available information into new knowledge, would then allow for case-based reasoning and knowledge base evolution.

Inherited Information Content – (1) information that is directly altered through consideration with regard to a prior decision point, (2) information that indicates the existence of higher priority preferences and the potential influence thereupon.

Interaction Template – A special type of interface template that encapsulates a coordination mechanism or communications protocol

Interface – (1) juncture of two distinct, sequential decision points (often corresponding to different phases of a design process), (2) the edge separating the stakeholders (either human or computer) having control over the decision points taken into consideration.

Interface Template – a template that encapsulates the underlying mechanics of information flows and serves as a link between two or more information transformation templates.

Inter-Phase - of or pertaining to distinct phases of a common design process.

Intraface - (1) juncture of entities involved concurrently with respect to the same decision point (often constituting the culmination of a phase of a design process), (2) the edge separating the stakeholders (either human or computer) having control over different aspects of the same decision.

Intra-Phase - of or pertaining to the same phase of a design process.

Independence - a relationship among decisions forming constituent facets of a common design process that is characterized by the independent information flows and original or unique information content.

Inter-Dependence - a relationship among decisions forming constituent facets of a common design process that is characterized by the joint information flows and shared information content.

Knowledge – (1) information, enriched through designer insight or experience, (2) context specific understanding that cannot be stored.

***Level of Abstraction* -** the level of detail regarding a problem under consideration, best suited to making a decision from a given perspective.

Objective – a chosen measure of merit, an overarching term, referring to either an attribute (selection) or a goal (compromise), depending on the nature of the decision at hand.

***Phase* -** a distinct temporal grouping of events

***Process Level of Interaction* -** the level of abstraction concerned with interactions within or between decision points of a design process, also referred to as the decision level of interaction.

Procedural Information – Process specific information.

Resource – (1) an available asset (i.e., person, material, process, etc.), (2) a means of accomplishing a desired task, (3) a measure of design freedom.

Scale – complexity with regard to dependence among the decisions pertaining to different phases of a design process.

***Scope* -** internal complexity, with regard to the degree of interdependence of constituent decisions within a design phase.

Selection Decision - an indication of preference for one among a set of feasible alternatives or a decision requiring the choice of one option among a set of feasible alternatives

Sequential - indicating the consideration or resolution of constituent facets of a common whole in a chronological order

Solution algorithms – highly automated and essentially autonomous means of conflict management that once the required inputs have been provided, operate akin to black boxes.

Stakeholder - (1) a primary role of a designer in Distribute Collaborative Design and Manufacture, (2) an entity, responsible in part for the completion of a common effort (i.e., task, process, etc.)

Strong Coupling - an instantiation of interdependent decisions that suggests a two-way flow of information between the constituent DSPs, used to model them, via system descriptors other than the deviation function.

System – "a set of interacting elements exhibiting an overall behavior beyond those of individual parts" [37].

Task - activities that involve the search for, storage of, conversion of, or transfer of information and consequently constitute the means of generating critical information content for decisions. Tasks are used to model activities such as generating concepts, running analysis, and constructing CAD models and can only be instantiated through the use of information. This is also true for tasks that involve the synthesis of information.

Template – (1) a pattern, used as a guide in making something accurately or (2) a document or file, having a preset format, used as a starting point for a particular application so that the format does not have to be recreated each time it is used.

Templatization – the act of (1) modeling and/or designing a design process in terms of information transformation templates and (2) instantiation for a particular context, thereby providing both procedural and declarative information.

Type I Robust Design – centers on achieving insensitivity in performance with regard to noise factors (parameters that designers cannot control in a system) [237]

Type II Robust Design – relates to insensitivity of a design to variability or uncertainty associated with design variables (parameters that a designer can control in a system)

Type III Robust Design – "considers sensitivity to uncertainty embedded within a model (i.e., model parameter/structure uncertainty)" [163].

Type IV Robust Design – "decreasing uncertainty associated with design processes, where design process uncertainty emanates from the "propagation and potential amplification of uncertainty due to the combined effect of analysis tasks performed in series or in parallel" [163].

Uncertainty – see definitions for Aleatory and epistemic uncertainty.

Upstream **–** (1) indicating the prior relative temporal succession of a given decision in a linearized, sequential design process, (2) a decision occurring before a reference point in a design timeline.

Utility-Based Decision Support - referring to (1) the novel implementation of utility theory in supporting the reflection, communication, persistence, and propagation of designer preferences in the design process, (2) the modeling of decisions in terms of utility-based Decision Support Problems, and (3) the consistent structuring of these decisions in terms that facilitate the formalization of designer interactions.

Utility-Based Decision Support Problem - a construct that combines inherent advantages of Decision Support Problems and utility theory, specifically, focusing on the infusion of utility-theory into the prevailing structure of the Decision Support Problem in order to increase preference consistency.

Weak Coupling - an instantiation of interdependent decisions that suggests a typically unidirectional flow of information between the constituent DSPs, used to model them.

NOMENCLATURE

***BRC* –** Best Reply Correspondence

CAD – Computer-Aided Design

CAM – Computer-Aided Manufacturing

CDSFM – Collaborative Design Space Formulation Method

cDSP – Compromise Decision Support Problem

DBD – Decision-Based Design

DCDM – Distributed Collaborative Design and Manufacture

DCSBD – Decision-Centric Simulation-Based Design

DFM – Design for Manufacture

DI – Digital Interface

***DOE* –** Design of Experiments

DSP – Decision Support Problem

DSPT – Decision Support Problem Technique

***FACE* –** Framework for Agile Collaboration in Engineering

FEA – Finite Element Analysis

ICCM – Interaction-Conscious Coordination Mechanism

LCA – Linear Cellular Alloy

MEMS – Micro Electro Mechanical Systems

MNT – Molecular Nano Technology

NEMS – Nano Electro Mechanical Systems

PLM – Product Lifecycle Management

***RMSE* –** Root Mean Squared Error

RRS – Rational Reaction Set

RSM – Response Surface Methodology

sDSP – Selection Decision Support Problem

TDPM – Template-based Design Process Modeling

U-sDSP – Utility-based selection Decision Support Problem

U-cDSP – Utility-based compromise Decision Support Problem

SUMMARY

Often, design problems are strongly coupled and their concurrent resolution by interacting (though decentralized) stakeholders is required. The ensuing interactions are characterized predominantly by degree of interdependence and level of cooperation. Since tradeoffs, made within and among sub-systems, inherently contribute to system level performance, bridging the associated gaps is crucial. With this in mind, effective collaboration, centered on continued communication, concise coordination, and non-biased achievement of system level objectives, is becoming increasingly important.

Thus far, research in distributed and decentralized decision-making has focused primarily on conflict resolution. Game theoretic protocols and negotiation tactics have been used extensively as a means of making the required tradeoffs, often in a manner that emphasizes the maximization of stakeholder payoff over system level performance. More importantly, virtually all of the currently instantiated mechanisms are based upon the *a priori* assumption of the existence of solutions that are acceptable to all interacting parties. No explicit consideration has been given thus far to ensuring the convergence of stakeholder design activities leading up to the coupled decision and the associated determination of values for uncoupled and coupled design parameters. Consequently, unnecessary and costly iteration is almost certain to result from mismatched and potentially irreconcilable objectives.

In this dissertation, an alternative coordination mechanism, centered on sharing key pieces of information throughout the process of determining a solution to a coupled system is presented. Specifically, the focus is on (1) establishing and assessing collaborative design spaces, (2) identifying and exploring regions of acceptable

performance, and (3) preserving stakeholder dominion over design sub-system resolution throughout the duration of a given design process. The principal goal is to establish a consistent **F**ramework for **A**gile **C**ollaboration in **E**ngineering that more accurately represents the mechanics underlying product development on one hand and supports interacting stakeholders in achieving their respective objectives in light of system level priorities on the other. This aim is accomplished via improved utilization of shared resources and avoidance of unnecessary reductions in design freedom.

Comparative performance of the method is established with respect to more traditional game theoretic means of conflict resolution. Three distinct applications of increasing complexity are considered: (1) a transparent tutorial example, involving the resolution of a tradeoff with respect to a system of non-linear equations, (2) a collaborative pressure vessel design example, involving first two and then three designers, and (3) a parametric design example of a structural heat exchanger, requiring reliance on surrogate models for representation of stakeholder considerations.

Implications of this research include improved resource management and design space exploration, augmented awareness of system level implications emanating from sub-system decisions, and increased modularity of decentralized design-processes. Stakeholder synergy in design processes is enhanced via stakeholder focalization, based on the systematic communication of decision-critical information content.

CHAPTER 1 - DESIGNING COMPLEX SYSTEMS

In this chapter, the author gives an overview of the challenges inherent in the design of complex engineering systems. The goal is to illustrate the increasing importance of modeling design processes from a decision-centric perspective. The philosophical tenets, underlying the approach to formalizing agile collaboration, pursued in this dissertation, are also discussed. Special consideration is given to consistently supporting interactions among designers, acting as collaborating stakeholders in a shared endeavor and the importance of judiciously allocating shared resources. In this context, the essential elements of modeling decision-centric design processes are introduced, specifically those most closely related to the reconciliation of system- and subsystem-level objectives. The overarching vision for a comprehensive support framework for decision-centric simulation-based design is also presented. Subsequently, scope and scale of the research are established and research questions, corresponding hypotheses, and a strategy for their validation and verification are presented. Finally the structure of this dissertation is clarified in terms of a roadmap.

1.1 COMPLEXITY IN ENGINEERING SYSTEMS

1.1.1 The Notion of Complexity in Engineering Design

What is a Complex Engineering System, when arguably all engineering systems are complex? What makes one artifact more complex than another? Is complexity determined by scope or scale? Or is it merely function of our level of understanding with regard to the underlying technology and our ability to handle the associated information burden? It is the answers to questions such as these that might explain why a fairly novel means of locomotion such as a hovercraft[1] was considered to be quite complex at the time of its inception, when the underlying working principles are now being applied readily in high school science fairs around the country. Or why Charles H. Duell, U.S. Commissioner of Patents (supposedly, although there remains some contention) stated that "…Everything that can be invented has been invented" in 1899.

Clearly, complexity is related to our level of understanding. It is also related to the capability of technology to "underwrite" the burden associated with implementation and nowadays more importantly computation. The notion of complexity has a significant aspect of relativity. That is to say that what one might consider to be complex is relative to one's level of understanding. Complexity can thus emanate from (1) ignorance (i.e., the novelty or newness of a field), (2) scope (i.e., the number of functional domains, length scales, time scales, etc. considered), (3) scale (i.e., the number of components, models, designers, etc. involved), (4) resource availability (i.e., scarcity, cost, location, etc.), or (5) distribution (i.e., level of co-location or the various resources being drawn

[1] The hovercraft evolved over nearly one and a half centuries from the first recorded design for an air cushioned vehicle by Swedish designer and philosopher Emmanuel Swedenborg in 1716 to the production of the first functioning prototype and the

upon). Engineering design, without a doubt is characterized by all of these and it is because of this very fact that experience and expertise are of such great importance. There is a learning curve associated with every domain, though some are without a doubt much steeper than others, making the effective integration of the associated sources of knowledge, information, and data, whether they be human or computer, so crucial. Since virtually every product produced in this day and age comprises a system, none can be considered in isolation. Interactions (whether intended or potential throughout the lifecycle) must be considered *a priori* and carefully taken into consideration. The difficulty of effectively accomplishing this formidable task of integration increases with complexity. Thus far, much of this challenge has been addressed through *systems engineering*, defined as the "engineering discipline that develops, matches, and trades off requirements, functions, and alternate system resources to achieve a cost-effective, life-cycle-balanced product based upon the needs of the stakeholders" [34]. Clearly, the ability of any single, centralized entity or group, performing this function of domain integration effectively is limited – by computational capability, business or enterprise structure, federation of resources, proprietary nature of data, simulation models, analyses, etc. Decentralized design comprises a more extensible alternative. It is the need for structured methodologies aimed at facilitating the reconciliation of the associated tradeoffs in the absence of a single centralized focal point and the inability to consolidate a sufficient level of understanding, spanning all of the disciplines, domains, and scales involved that is addressed in this dissertation. Adequate motivation in support of this perspective is provided in the remainder of this section.

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associated filing of patents by British Radio Engineer Sir Christopher Cockerell in 1958. The world's first metal hovercraft crossed the Channel between Calais and Dover in 2 hours 3 minutes on July 25th, 1959.

Science and technology have always evolved in tandem. While science pushes the envelope of what is technically feasible in some regards, it has yet to take advantage of new capabilities in others. There are so many fronts to consider that what exactly constitutes the cutting edge of either research or development is mostly relative. New advances in one field open up portals in another and vice versa. The limits of that which is conceivable and that which is practically achievable are thus also determined in large part by creativity and imagination. The resultant "leap frogging" that has fueled the continuous expansion of our collective body of knowledge has taken us from exploring the far reaches of our planet to probing the far corners of the known universe. We have progressed from designing simple parts to designing complex systems, requiring the consideration of individual components as well as any interaction effects. While it was feasible to design relative simple components on a *trial-and-error* basis, doing so for entire systems composed of hundreds of thousands of components was not possible; structured means were required. A good example of designing a complex hierarchical system, requiring a structured approach, is that of aircraft design, pictured in Figure 1-1. Due to improvements in understanding of phenomena occurring at smaller length scales and analogous extensions of observation, handling, modeling and manufacturing technologies it has become possible to consider the realization of systems that are far smaller than those traditionally considered. Several examples follow.

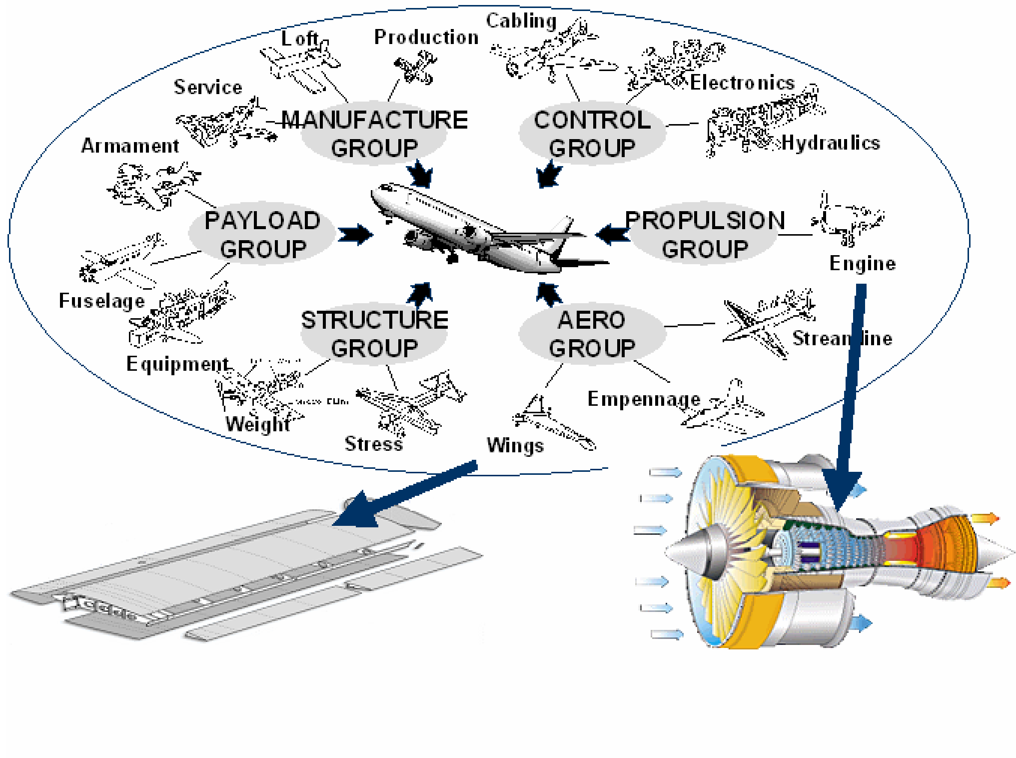

Figure 1-1 - An Aircraft as a Complex, Hierarchical, Multi-Scale System [207]

The design and manufacture of Micro Electro Mechanical Systems (MEMS) takes place on the micrometer level and is accomplished predominantly through various lithographic etching procedures, resulting in 3D features. Typical manufacturing operations include planar processes (similar to those employed for the production of semiconductors) such as bulk and surface micro-machining, resulting in devices ranging in size from several micrometers to a millimeter. Many of the challenges arise from the fact that intuitive aspect of physics often breaks down as a result of surface effects (e.g., electrostatics, wetting, etc.), dominating volume effects (e.g., inertia, thermal mass, etc.). This is a direct result of the relative large surface area to volume ratio, characteristic of MEMS. Representative devices include thermal actuators, optical switches, micro-motors, transmissions with the capability of increasing micro-engine force output by a factor of $3x10^6$, multi-level springs, ratcheting mechanisms, steam engines, clutches, and actuators among others.

Nano Electro Mechanical Systems (NEMS) are similar to MEMS but even smaller. Anticipated applications revolve around the measurement of displacements and forces at the molecular scale. As the name implies, these devices are more closely related to nanotechnology. NEMS also differ from MEMS in the manner in which their manufacture is envisioned. A *top-down* approach emphasizes the creation of tools to make even smaller tools, whereas a bottom-up approach focuses on the composition of atoms and molecules with the intent of achieving a predetermined level of complexity and functionality via the potential application of self-assembly mimicking molecular biological systems.

Nanotechnology is concerned with technological developments on the nanometer scale (i.e., 0.1 to 100 nm) and is complicated further by (1) the quantum-based phenomena and (2) the molecular effects (e.g., Van der Waals forces) that it is susceptible to. These result in often quite counterintuitive effects. The trend of increased surface area to volume ratios is exacerbated further. The primary application for nanotechnology is the envisioned revolution of computer architectures through furnishing a new technological base for storage and processing. Molecular Nanotechnology (MNT), although often used interchangeably with nanotechnology, is an as-of-yet theoretical, advanced form of nanotechnology believed achievable at some point in the future [8]. It is an emerging field that pushes the envelope even further to yet smaller length scales. MNT effectively boils down to nanotechnology via an anticipated technology based on positionally-controlled mechanosynthesis guided by molecular machine systems, namely "molecular manufacturing". The vision is that of combining physical principles emanating from chemistry and other nanotechnologies in concert with "molecular machinery of life" with systems engineering principles found in modern macro-scale factories [60,61].

In the cases of MEMS, NEMS, and nanotechnology many of the challenges have arisen from the inability to scale down principles that govern and predict behavior at the macroscopic level. It follows that manufacturing, assembly, and manipulation have also tested technological capabilities. In each of these cases, however, developments have been limited to or confined within a given length scale. Reconciling domain specific models and simulations across multiple length and time scales by bridging the associated gaps adds an additional element of complexity, marking the genesis of a quest that may one day lead to designing macroscopic products at the sub-atomic scale. A good example of work aspiring towards this ideal interpretation of *bottom-up* design is the emerging realm of complex product-material systems.

Materials *Design* has its origins in the realization that design engineers and materials scientists have traditionally adopted very different approaches to innovation. While "the natural sciences are concerned with how things are … design, on the other hand, is concerned with how things ought to be, with devising artifacts to attain goals" [221]. As pointed out in Refs. [207,208], new materials have primarily been developed using empirical, *trial-and-error* techniques, prominent in the natural sciences. Integration of design engineering and materials science has been limited mostly to the selection of an appropriate material from a finite set of available materials with experimentally determined properties. In contrast, materials *designers* wish to tailor the material structure itself alongside associated processing paths to achieve desirable material properties and performance. The key realization is that the structure and successful performance of a product or system is linked strongly to the properties and performance of its constituent materials; thus, performance objectives for materials and the larger systems they comprise are interdependent for most applications. The subsequent thesis is that innovative, high-performance, product-material systems can be realized by concurrently designing a product and its constituent materials. Moreover, as we increasingly fabricate and utilize multiphase and cellular materials as well as heterogeneous MEMS and NEMS devices, it is nearly impossible to distinguish issues of materials design from those of the larger systems or assemblies. Certainly, it is essential to design materials concurrently with complex products in order to achieve breakthroughs in system performance. Accordingly, in addition to improving our understanding of the intricate interplay of form, function, and behavior throughout the associated hierarchy, *systematic, effective, efficient, and comprehensive methods are needed for supporting the integrated designing of materials and products/systems.*

Recent leaps, associated with this nascent area of research, are the result of technology beginning to catch up with scientific aspirations. While much of the theory has been developed in each of the length scales, shown in Figure 1-2, interpreting the effects of one such scale on the next has previously received little consideration. Even theoretical advances within each length scale have been limited by computational capability. Much of this is due to computational intensity associated with implementing accurate models at increasingly smaller length scales. Innovations in numerical approximations, statistical techniques, surrogate models, and computational infrastructures as well as increased processor and memory capacities, however, have opened the gateway to making the required amalgamation feasible and the required research worthwhile. In fact, it is only because of recent advances in technological capability that consideration of design challenges across multiple length and time scales has become feasible. One effort along these lines is the design of Multifunctional Energetic Structural Materials [2], where the fundamental goal is to design Target Penetrating Missiles (TPM) with superior penetration power and higher payloads by considering form, function, and behavior of product and material simultaneously. Doing so effectively requires integrating models across each of the length and time scales, shown in Figure 1-2. This is a formidable challenge, especially considering that differing length and time scales require consideration of phenomena that do not necessarily relate to one another in a predictable manner, as pointed out previously.

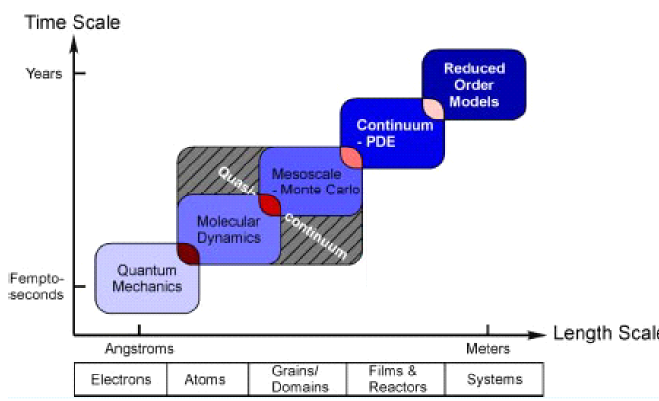

Figure 1-2 - Length and Time Scales Associated with Designing Complex Product-Material Systems

For a more in-depth treatment of the intricacies inherent in the designing complex material product systems, the reader is referred to the research of Seepersad (see, e.g., [100,120,204-209]). Other research aspects of this fascinating field are currently being

[2] This research is being conducted as part of an ongoing MURI project funded by the Air Force Office of Scientific Research.

addressed by Panchal (see, e.g., [161,163-165]) and Choi (see, e.g., [49-51,163]). While Panchal is concerned with information economics in complex design processes and modeling the associated hierarchies effectively, Choi focuses on the characterization and management of uncertainty, stemming from the models used in such heavily simulation-based design effort. Specifically, he is concerned with devising methods for systematic Type III and Type IV Robust Design. Type III Robust Design is focused on reducing design sensitivity to uncertainty embedded within a model. It is important to realize that "model parameter/structure uncertainty is typically different from the uncertainty associated with noise and control factors, because it could exist in the parameters or structure of constraints, meta-models, engineering equations, and associated simulation or analysis models" [163]. Type IV Robust Design is centered on decreasing uncertainty associated with design processes, where design process uncertainty emanates from the "propagation and potential amplification of uncertainty due to the combined effect of analysis tasks performed in series or in parallel" [163]. This stands in marked contrast to the well established aspects of Type I and Type II Robust Design, concerned with achieving insensitivity in performance with regard to noise factors and variability or uncertainty associated with design variables, respectively.

In summary, the leap from materials selection to materials design is profound and challenging. Materials are highly complex systems (nonlinear and time-dependent in general). As stated, desired material characteristics often depend upon phenomena occurring on and traversing multiple length and time scales. Correctly representing the physics, governing relevant behavior at each scale, and linking the corresponding models so that information is shared as appropriate requires the bridging of theoretical, mathematical, and computational gaps. The underlying complexity is likely to limit the integration or explicit linkage of analysis codes on different length and time scales (see Figure 1-2) and consequently diminishes a designer's ability to explore a given material design space unless more efficient, surrogate models and other methods for passing relevant model content are developed. More importantly, many of these simplifications are likely to be context and application specific, representing a tremendous amount of research not only with respect to each discipline, domain, or length/time scale considered, but also with respect to their integration. Additionally, the discrete and heterogeneous nature of material microstructure can often inhibit model simplification. In such cases, the original, complex analysis codes must be relied upon instead. Nevertheless, different perspectives relating to multi-scale and multi-functional considerations must be reconciled and a need for systematic communication and archival of design information arises. Furthermore, the design of the material must be integrated into the overarching design effort, so that requirements are satisfied from a systems perspective, allowing improvements in performance and resource utilization that are not possible through existing independent design and material selection paradigms. Likewise, uncertainty stemming from material process-structure-property relations must manifest itself in systems level concerns. It is important to note that the inherent complexity, associated with each of these aspects, requires a significant level of expertise. Effective integration increases this knowledge burden by a factor proportional to the number of perspectives being interfaced, plus relevant integration savvy. Clearly, centralizing this comprehensive burden is likely to be impractical, if not infeasible, substantiating the promise of adopting a decentralized perspective.

In many ways, the challenges, characterizing the domain of Product-Material Systems, thus surpass those posed by other complex engineering systems, by requiring the integration of multiple functional domains, across the continuum of length and time scales, ranging from the nano- to the macro-scale. Although the promise of new technologies (nano-technology, MEMS, NEMS, Etc.) drive much of technological evolution, economic forces and their effect on business side of engineering enterprise cannot be understated. Many challenges arise from the need to integrate domains that are not easily reconciled on a functional basis (e.g., Biology and Physics in the case of nano-technology). This requires the consistent development of domain independent means of modeling, simulating, and integrating highly specialized expertise (characterized by enormous learning curves) not only across countless domains, but also throughout the different levels of the associated hierarchies. The days of being able to rely on (mythical) systems engineers, able to muster a sufficient level of understanding to effectively tie together information and make crucial tradeoffs among the various tightly coupled levels of systems and sub-systems, while simultaneously disseminating required information among the various stakeholders, all the while managing an overarching design process, closely tied to the whims of consumers in a global market, are long gone. What is required is fundamental paradigm shift that focuses on the modularization of design processes, components, tools, and stakeholders, as well as their contributions so that their independent assessment of decision dependence, effect, and impact becomes possible. It is this goal that the research described in this dissertation addresses. In the sections to follow, many of the underlying assumptions required for the achievement of this aim are provided. Care is taken to clearly delineate the frame of reference from whence this effort originates. Due to the comprehensiveness of the inherent challenges, this contribution comprises only lays the foundation for a single aspect – the system conscious reconciliation of tradeoffs associated with strongly coupled problems among interacting stakeholders. Before proceeding to delineate and scope the contribution, brought forth in this dissertation, specific challenges, exacerbated by the design of complex engineering systems are expounded upon in the next section.

1.1.2 Characteristics of, Approaches to, and Challenges Posed by Designing Complex Engineering Systems

In addition to novelty and technical performance an engineering enterprise's survival is also dictated by its ability to satisfy the dynamic needs of a global consumer base. This business aspect influences (if not guides) a majority of all decisions. Business decisions are most closely associated with the enterprise level of interaction. Emanating at the highest level of the hierarchy, the related requirements (*albeit* somewhat diluted) pervade all other levels in one form or another. This is due to the fact that engineering enterprise is motivated predominantly by economic need, as evidenced in many definitions of engineering that emphasize not only the role of engineering in answering societal needs (either explicit or implicit), but also need for ensuring positive returns in choosing which projects to undertake. For example, Buede defines engineering as "the discipline for transforming scientific concepts into cost-effective products through the use of analysis and judgment" [34]. For many this translates to the pervasive dogma of making (and striving to maximize) economic profit. From an economic perspective many challenges arise from the forecasting and interpretation of consumer tastes on one hand and the reduction of cost associated with meeting these on the other. Consequently, acquisition of raw materials and production locale have always impacted an enterprise's success, leading to outsourcing and the re-focalization of entire economies on core competencies. It is noted, however, that as many of the developing countries, that traditionally served mainly as cheap, mass production centers are requiring such coveted core competencies, traditionally limited to developed nations, the lines are becoming blurred. Consequently, research and development facilities and design centers are also being dispersed in order to level the field and effectively compete with the still significantly lower production costs of the developing third world nations. From the standpoint of complexity, it is virtually impossible to gain sufficient expertise in all required domains and decentralization of design activities is quasi unavoidable. World-wide distribution, and the associated complications, are thus no longer limited to manufacturing and are also taking their toll on design practices, requiring the concurrent design of systems and sub-systems by different vendors, subcontracted based on expertise, capability, cycle time, and cost.

With this in mind, the focus of this research is on enabling engineering enterprise to expedite the dynamic, unpredictable, and highly uncertain requirements originating from global economies as effectively as possible via the focalization of decentralized design activities. Specifically, the aim is to modularize the contributions of distributed stakeholders and ensure the congruity of their activities. Additional support is focused encouraging more judicious resource use by balancing the achievement of system and sub-system level objectives. Considering the enormity of the overarching problem of improving the management of products throughout the entirety of their respective lifecycles, the effort undertaken in this dissertation is quite limited. To better illustrate the cohesiveness of this endeavor with the directions taken by the engineering community as a whole, a brief overview of complementary efforts follows.

A comprehensive view is that of investigating better means of integrating the resulting *value chain* (encompassing all aspects relating to the realization of engineering products, including the *supply* and *design chains*) through Product Lifecycle Management (PLM), defined by as "…a strategic approach to creating and managing a company's product-related intellectual capital, from its initial conception to retirement" [104]. Accordingly, "PLM improves a company's product development processes and its ability to use product-related information to make better business decisions and deliver greater value to customers". JD Edwards [64] defines PLM as "management of a series of business processes, enabled by collaborative applications that manage a portfolio of products … to maximize market share and profitability". CIMData defines PLM as "a strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination, and use of product definition information across the extended enterprise from concept to end of life – integrating people, processes, business systems, and information". Generally, PLM is taken to be a strategic business approach for the effective management and use of corporate intellectual capital [71].

Product Lifecycle Management (PLM) involves activities from the initial conception to retirement of the product and is aimed at improving the product development process. The goal in PLM is to integrate all the product realization activities including market planning, concept development, design, production, sales, marketing, etc. One such effort, and a major thrust in Product Lifecycle Management (PLM), is the integration of the value chain throughout the extended enterprise. Design chains and supply chains form two essential components of this value chain. *Supply chains* are defined as the "network of retailers, distributors, transporters, storage facilities and suppliers that participate in the sale, delivery and production of a particular product" [7]. On the design side, distribution introduces many additional problems into the product realization process including miscommunication, asynchronous sharing of critical information, mismatched priorities, and loss of vital design knowledge, addressed through research in *design chains*. A significant amount of work is currently being undertaken by the Supply Chain Council with regard to describing supply chains. For example, the SCOR model [6] is developed to represent and measure supply chains in a standardized manner to enable improvements in supply chain operations through analysis of current processes and best practice emulation. Along these lines, numerous case studies have been conducted. For example, the SCOR model is currently being extended to the Enterprise Transaction Model by Streamline SCM [5].

Considering the field's extensive scope there are numerous interpretations, each highlighting different facets of import. Examples include *a)* interoperability issues and standardization in CAD/CAM/CAE, *b)* overarching management considerations *c)* collaboration *d)* information management and sharing, and *e)* integration. As pointed out in Ref. [166], a comprehensive perspective, highlighting the diversity of challenges facing the engineering enterprise of today is currently lacking. One of the key components of PLM with regard to this aspect is the integration of the process with the design of the product addressed in the research of Panchal [161]. Although design processes play a crucial role in PLM, integrating the design of "design processes" with the product has received little attention. Systematic methods for designing design processes have not been formalized. Additionally, while it is true that the potential of leveraging components of existing products towards developing new products has been exploited, the possibility of leveraging PLM sub-processes in new product realization scenarios is substantial, as explored further in this dissertation.

All of these heterogeneous aspects (summarized in Figure 1-3), necessitate the development of a means to facilitate collaboration, bridging geographical, disciplinary and linguistic gaps. Although this is a daunting task, modern "…communication tools allow for more than just the sharing of information via e-mail or on the World Wide Web. They make possible real time collaboration, including the remote sharing of data, the operation of equipment, and the carrying out of experiments…such collaborations have the potential of breaking what sociologists refer to as the 'eight-meter rule', which is based on the observation that the most significant interactions take place among people who are in close physical proximity to each other" [190]. To be effective, however, communications must address the issue of reducing the knowledge or information burden on any one individual. Specific information requirements differ widely and there is a need for developing a communications protocol to make interactions efficient and meaningful. In other words, there is a need for information brokering so that decision-makers have ready access to required information without being inundated with irrelevant or partially complete data. It is these PLM needs that are being addressed in this dissertation.

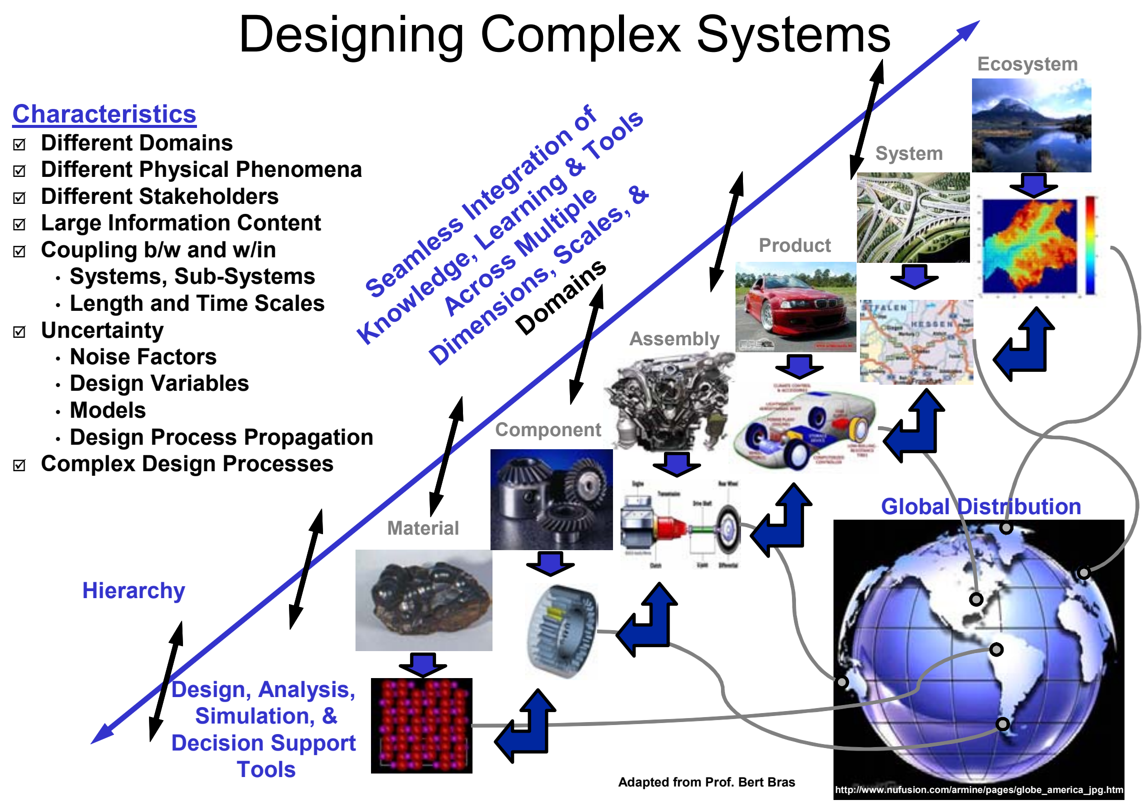

Figure 1-3 - Challenges Inherent in Designing Complex Engineering Systems

Since the strategy for facilitating integration as pertaining to collaborating stakeholders outlined in this dissertation is decision-centric, it is sufficiently generic to allow for adaptation to each any engineering domain and level of interaction therein. The overarching context in the combined research of Panchal and this author (see e.g. [74,75,164-168]) is focused on modeling design chains at various levels of scope and detail, ensuring domain independence and interoperability among the various stake-holders involved in a product realization process, and (re-)use engineering resources in simulation-based design processes as permitted by the underlying design requirements. Consequently, models and methods are being developed to address emerging design process needs on various levels of abstraction, so that the resulting hierarchy effectively supports the design activities of the enterprise and complex systems in general. The aspect of this design approach, explicitly addressed in this dissertation involves modeling and supporting interactions among collaborating stakeholders charged with solving strongly coupled decisions. The resulting research tasks involved in developing flexible interfaces between stakeholders are (1) modeling interactions between the design process elements and associated information flows, (2) modeling stakeholder relationships, commonly encountered throughout the value chain, (3) capturing design process interactions using object oriented templates that can serve as a springboard for knowledge capture, and (4) establishing communications protocols to represent the underlying interactions for enabling the required information transfers. It is important to note that rather than pursuing the integration of stakeholders via knowledge, information, responsibility transfer to a central location, the approach pursued supports decentralized decision-making. Often, decentralization is regarded as a means of decreasing product development times and reducing computational burdens as well as problem complexity [184]. On the whole, a number of methods have been developed to address the solution of coupled sub-systems in the context of decentralized systems. Applications range from control systems [245] and manufacturing systems [115] to computing architectures [214] and product design [16,258]. It also assumed that decentralization of decisions is unavoidable, especially in extensive organizations where the assumptions of having a single (centralized) decision-maker is not realistic [124]. It is more effective to delegate responsibility for making the required decisions to the person, team or supplier most appropriate for the task [39], defined as domain experts in this dissertation.

Consequently, it a fundamental assumption that it such domain experts that are consulted for formulating decisions, interpreting results, and making trade-offs regarding the achievement of the multi-functional objective, characteristic of the design of complex systems. Often these specialists are distributed and forced to make tradeoffs amongst each other in order to reach mutually beneficial design solutions. It is important to note that not only the resulting products but also the underlying design processes can be viewed as systems, where a *system* is defined as “a set of interacting elements exhibiting an overall behavior beyond those of individual parts” [37]. With this in mind, it should be a surprise that the overall behavior of design processes (i.e., achievement of design objectives, satisfaction of constraints, etc.) cannot be predicted by modeling design activities individually. It is thus extremely important to accurately reflect the underlying design interactions as well. The key challenge inherent in the collaborative design of complex artifacts is that associated design spaces are typically vast; concurrent design sub-space exploration by multiple participants tends to be not only expensive and time consuming, but also ineffective. This is due mainly to the extent of interdependencies that invariably lead to conflicts when solutions for subspaces are not consistent with one another [117]. Consequently, there is a constant need for effective information exchange and effective coordination (see, e.g., [56,259]) when making coupled decisions. Since interdependencies between design parameters are generally strong, (1) iterations are both numerous, as well as, frequent and (2) necessitated bandwidth for required information transfers is extensive.

In order to effectively explore and determine viable solutions to such complex engineering problems, significant advances are required in myriad aspects. As previously stated, the focus in this dissertation is on decentralized decision-making and the coordination of the associated stakeholder interactions in terms of structuring required communications, as well as managing the inherent tradeoffs. The conciseness of obligatory information exchanges is a crucial aspect in the underlying effort to balance the achievement of sub-system and system-level objectives. The basic requirements for a comprehensive **F**ramework for **A**gile **C**ollaboration in **E**ngineering are summarized in Table 1-1. These criteria are subsequently used in Table 2-2 of Section 2.2.5.4 to evaluate the suitability of commonly employed interactions protocols to consistently supporting activities in distributed collaborative design.

Table 1-1 - Characteristics of a Comprehensive Coordination Mechanism

Problem Formulation and Interaction Management
1. Modularization and Alignment of Design Process and Domain Expertise
2. Support for Co-Formulation of Coupled Design Problems
3. Support for Establishment and Exploration of Collaborative Design Spaces
4. Stakeholder Retention of Sub-System Control throughout the Duration of Design Processes
5. Decoupled Treatment of Problem Formulation and Solution
Concise Information Exchange
6. Suitability as a Communications Protocol
7. Suitability as a Coordination Mechanism for Structuring Interactions
8. Effectiveness of Iterations
Balanced Achievement of Sub-system and System Level Objectives
9. Support for Systemic Understanding of the Collaborative Design Space and the Determination of Realistic Targets
10. Suitability as a Solution Algorithm
11. Quality of Resultant Solution

To reiterate, the primary focus of this dissertation is that of detailing a methodology for aiding designers in collaborating interactively throughout the course of solving a strongly coupled decision, over the outcome of which they share control. Having elucidated the challenges inherent in the design of complex engineering systems in this section, the foundations upon which this research is built and the overarching vision to which it contributes are clarified in the next.

1.2 A METHODICAL APPROACH TO AGILE COLLABORATION IN THE DESIGN OF COMPLEX ENGINEERING SYSTEMS

1.2.1 A Cohesive, Integrated, Comprehensive, and Methodical Approach to Supporting Collaboration in Systems-Based, Decision-Centric Design

As engineering enterprise becomes increasingly concerned with meeting the dynamic requirements of a global marketplace, closer attention must be paid to the mechanisms underlying product development. Perhaps the most crucial of these mechanisms is the design process. In terms of the engineering enterprise, this translates to the need for a systematic means of development for original, adaptive, variant, and derivative products. Although much attention has been paid to addressing this issue from a product-centric perspective by exploiting the reusability and scalability of products through product platform and product family design, not much attention has been paid to exploiting an engineering enterprise's primary resource commitment – the design process and its *design*.

A fundamental complication in leveraging design processes beyond that product for which they were originally developed, derives from the fact that modern realities have dictated a paradigm shift in design practices towards distributed collaborative efforts. Such efforts at globalized synergy invariably result in information intensive knowledge transfers, requiring not only information management but also deliberate structuring of decisions. This is of special concern in product development, where the interfaces between the distinct phases, decision-makers, and computational resources involved in a design process are not well defined and largely misunderstood. The complexity of related design decisions is substantial. Bandwidth of information in knowledge transfers, high fidelity analyses, and ambiguity associated with interactions among distributed stakeholders engaged in shared, concurrent design tasks further complicate the matter. The result is poor communication, problematic changeovers, and wasteful iteration due to mismatched objectives. Resulting design processes tend to be ineffective and not only increase product development costs and extend time-to-market, but also ultimately impede collaboration.

A fundamental requirement for the effective realization of products by collaborating designers thus consists of the effective modeling of design processes in order to facilitate systems level partitioning and hierarchical administration. Processes can be represented at various levels of detail, depending on the intended use of the resulting models. Most of the traditional process modeling methods like the Program Evaluation and Review Technique (PERT) [152,153], Gantt Charts [152], IDEF 0 [1], etc. capture and (visually) present information at the activity level. As such, these tools are useful for making organizational decisions with regard to processes such as time utilization, resource allocation, task precedence, material flow, etc. Example applications of tools such as these include modeling manufacturing processes to study process characteristics, including time scheduling, material processing, assembly/disassembly and packaging. In a collaborative design scenario, however, modeling activities is insufficient. Instead, models of processes are needed for understanding and coordinating collaborative work, thereby defining conflict management [172].

In order to address the challenges regarding the collaborative design of complex engineering systems, cited in Section 1.1.2, a consistent means of modeling stakeholder activities is required. A fundamental assumption in this research is the notion that the principal role of a designer in the design of an artifact is to make decisions and that decisions serve as markers to identify the progression of a design from initiation to implementation to termination. This concept, described in detail in Section 1.2.3 is often referred to as Decision-Based Design (DBD) [45]. Decisions in all stages of engineering design depend on scientific, factual information as well as empirical, experience-based knowledge. They are influenced strongly by designer preferences regarding the achievement of goals and meeting of targets, subject to constraint satisfaction. Often, conflicts arise, especially when multi-attribute problems are concerned. Furthermore, it is the nature and types of decisions that are being implemented that determine the progression of a design. Also needed is the ability to propagate decision-critical, up-to-date information alongside design knowledge for both sequential and concurrent design tasks. This is particularly important for dependent and interdependent decisions that cannot be made in isolation and are quasi foundational to the design of complex systems.

As indicated in Figure 1-4, design processes, as considered within this dissertation, are composed of series of design decisions, corresponding to the design sub-problems and the sub-systems these constitute. The particular sequence according to which different domain experts interact is determined by the nature of the underlying information flows, as described in Section 2.2.1, and constitutes the design process. Consequently, some decisions are carried out in *series* (e.g., the compromise decision of Design Sub-Problem A and the selection decision of Design Sub-Problem B in Figure 1-4), while others are carried out in *parallel* (e.g., the coupled compromise decision, comprised by Design Sub-Problems C and D in Figure 1-4). Each such design decision is modeled using sub-system specific system descriptors, objectives, and constraints.

Clearly, many such parameters are derived from the overarching system level considerations. In the case of Figure 1-4, these emanate from the customer's product requirements.

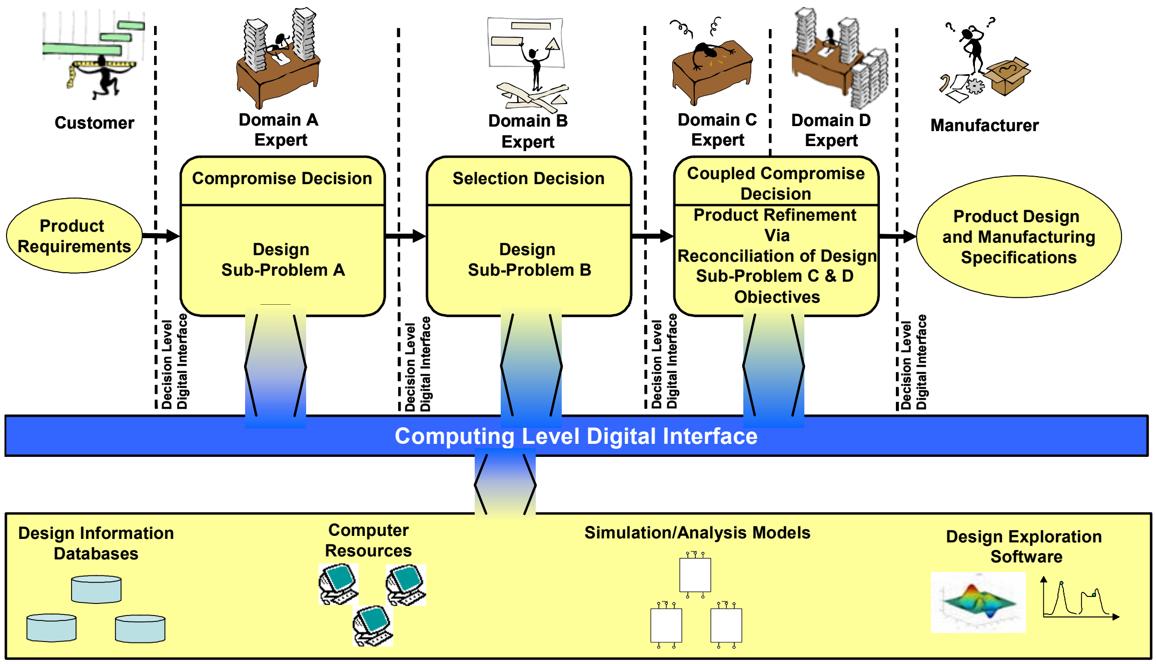

Figure 1-4 - Complex Engineering Design Process

Responsibility for the resolution of design decisions is assigned according to domain expertise. This segmentation of the design process is extremely important (an often economic necessity as pointed out in Section 1.1), considering that the domain specific models (whether they be mathematical, experimental, analytical, computational, etc.) tend to be rather complex, requiring a comprehensive and in-depth understanding of the domain to which they pertain as well as the underlying assumptions and limitations. Consequently, no single individual, regardless of the resources at his or her disposal, can be expected to harness an understanding comprehensive enough for the successful integration of all domains being considered. Alternatively, cooperation is limited by the practical limitations placed on information exchanges, primarily with regard to technological capability to transfer and manipulate all pertinent to successful domain integration, human ability to comprehend and interpret domain relevant results, and business practices. Instead, a comprehensive means of supporting the required exchanges of information for what essentially constitutes a federated or syndicated environment of domain experts, whose design sub-problems are coupled to varying degrees, is required.

Considering that many of the stakeholders share control over the achievement of system level objectives, it follows that they also share some of the information upon which their respective determinations are based. Often this generalization extends to the computational resources at their disposal, especially in the context of computational simulation-based design, where mathematical and virtual models are used as a basis for supporting the decisions making up the design process. This is indicated in Figure 1-4, where various domain experts are called upon for formulating, solving, and interpreting constituent design sub-problems in the process of taking customer requirements and translating these to engineering specifications that can then be passed on for production. As described in Section 2.1, any design process is governed by the underlying information flows and the nature of the associated dependencies. Consequently, certain design tasks can be performed concurrently, while others may be considered sequentially, as indicated by the dependent decisions of Domain Experts A and B and the interdependent coupled decision of Domain Experts C and D. Each of the stakeholders is separated by an interface, across which relevant information must be transmitted. Stakeholders also rely on their expertise in choosing the computational resources best suited for accomplishing their respective tasks and the manner in which to best interface with these. The information, upon which design decisions are based, is bound to change (and hopefully improve) along a design timeline. More than likely, however, these changes are mirrored in all domains being considered. Consequently, the manner in which that information is best interpreted and manipulated also changes. In order to reduce the emergence and propagation of changes originating in one domain, to other domains, and the emergence of undesired effects, the focus in this dissertation is on modularizing design parameters, computational resources, and decision-makers. The desired outcome is to manage change so that undesired effects are contained. This aim is achieved primarily through the development of a template-based means of modeling design decisions and interactions, that is centered on the separation of *declarative* (i.e., problem specific) and *procedural* (i.e., process specific) information, as detailed in Chapter 3. Furthermore, the **F**ramework for **A**gile **C**ollaboration in **E**ngineering presented is based on the fundamental aim of compartmentalizing the contributions and *causata* of individual stakeholders, so that their impact on one another is clarified and their interactions can be formalized in a manner that promotes focalized progression towards individual (i.e., sub-system) as well as common (i.e., system level) goals.

At this point, it is noted that this dissertation builds upon a number of fundamental assumptions. Two of the more relevant instances, crucial to the discussion at hand, being that 1) stakeholders are not engaged in direct competition with another and 2) a "super-savvy" and omniscient systems engineer does not exist. Consequently, 1) it is in every stakeholder's best interest to meet overarching system level objectives, alongside those at the sub-systems level, 2) responsibility for the resolution of design decisions is assigned according to expertise. A less obvious conclusion is that interacting stakeholders must resolve conflicts, barring outside intervention. This requires a means of judging both sensitivity to and impact of objectives to a set of design variables, control over which is shared.

1.2.2 Co-Design: A Step beyond Collaboration in Engineering Design

The two terms most often used to describe the interactions of several stakeholders, engaged in a common effort to produce an artifact are *collaboration* and *cooperation*. *Collaboration* can be defined as working together, especially in a joint intellectual effort [2]. Similarly, *cooperation* denotes (1) working or acting together toward a common end or purpose, (2) to acquiesce willingly; be compliant, or (3) to form an association for common, usually economic, benefit [2]. While all of these definitions stress the aspect of making certain concessions for the achievement of a “greater” good, the manner in which related efforts have been addressed in engineering research emphasize *a posteriori* acquiescence, rather than *ab initio* progression towards a mutually acceptable solution. To clarify, a majority of conflict resolution mechanisms are centered on what is best described as the intersection of independently formulated and managed design problems. Solutions achieved in this manner constitute a compromise among interdependent sub-systems, whose relationships are not modeled outside of their respective objective functions. Since such design problems are formulated in isolation, the chances of their joint solution yielding a mutually desirable result are quite slim. More than likely, one or more of the interacting parties will have to make a serious sacrifice in performance. Often this is due to the nature of the underlying mathematical relationships uniting coupled problems. Due to the postponement of communication until such a time that a compromise can be reached, any modifications or redirection of objectives that might promote the achievement of more balanced solutions is rendered impractical. In fact, the further a stakeholder progresses along the design timeline, the more significant the resources expended on behalf of achieving the goals underlying his or her design sub-problem. Consequently, it becomes increasingly more difficult to refocus a design process underlying the specification of a sub-system, in light of considerations emanating from either the system level or from other inter-related sub-systems. Trial-and-error iterations becomes quasi unavoidable. These facts are expounded upon in Section 2.2.5.4.

Although many advances in engineering science have indeed resulted from trial-and-error, there is significant potential for divergence and poor quality results when implemented as a means of reconciling conflicting objectives as associated with collaborative design. It is unfortunate however, that this recognition has led to a quest for the elimination of repeated interactions among collaborating stakeholders. The elimination of iterative cycles in engineering, presupposes perfect knowledge and rules out the possibility of considering better, more refined, or updated information content in decision-making, thereby essentially negating the notion of change over time. While a significant amount of research in engineering design has been conducted on the improvement of design techniques and much needed mechanisms for the coordination of those involved in the corresponding processes, little attention has been paid to improving the ability of decision-makers to reassess considerations in light of (1) their respective influence on system level objectives via shared design parameters and (2) any changes brought on by the evolving realities of those with whom they interact. The method, detailed in this dissertation, is focused on a continuous exchange of information required for the focalized convergence to a mutually desirable goal that meets not only sub-system level, but also system level considerations in a more balanced fashion. This approach differs philosophically from currently espoused means of conflict management that are aimed at minimizing and potentially excising iteration from engineering design processes.

Taking a step back, engineering is the application of scientific and mathematical principles to practical ends such as the design, construction, and operation of efficient and economical structures, equipment, and systems [2]. The word itself is derived from the Latin root *ingeniator* (contriver) and the Latin word *ingenium*, meaning skill. The term *design* is defined as the invention and disposition of the forms, parts, or details of something according to a plan, the act of *designing*, as conceiving in the mind or inventing, from the Latin word *designare*, to designate [2]. The two fundamental notions, emanating from these definitions are the practical application of formalized principles and the designation of resources. In the case of strongly coupled design problems, all interacting stakeholders are subject to domain specific considerations and share a common set of resources, namely the *collaborative design space*, as defined in Section 4.1. Rather than (1) modeling sub-system coupling as an added constraint that is used as a virtual filter for poor solutions or (2) altering the objective function to cope with the added complexity of sharing control over common design variables, the aspirations of collaborating effectively are better served through strategic interactions aimed at ensuring congruity throughout the duration of stakeholder interactions. Since control for committing a common set of resources is shared, responsibility for doing so in a system conscious manner should be as well.

In an attempt to clarify the underlying paradigm shift, the term *co-design* is chosen to differentiate the **F**ramework for **A**gile **C**ollaboration in **E**ngineering and the associated coordination mechanism from currently instantiated means of conflict resolution. The designation is meant to convey an approach to collaborative design that is not only concerned with making interactions congruent but also increasing the agility of stakeholders to adapt to changing circumstances. The result is a more effective, as well as efficient means of solving strongly coupled problems in engineering design. With this in mind, *co-design* is defined as the system conscious designation of shared resources to the same extent or degree. A detailed description of the underlying assumptions, context, frame of reference, and constituents follows in Section 1.2.3.

1.2.3 Components of a Methodical Approach to Systems-Based, Decision-Centric (Co-) Design

Clearly, not all design processes are characterized by shared responsibility for resource allocation and determination of the final function, form, and behavior of an engineering artifact. As explicated in Section 2.2.1, many relationships are governed by dependent information flows, allowing for sequential, rather than concurrent determination of design sub-system parameters. Others are entirely independent and may be considered in isolation. The interdependent or strongly coupled decisions, for which the proposed decision support method for *co-design* is intended, comprise the most complex form of interaction encountered from the espoused perspective of Decision-Centric Simulation-Based Design. The research described in this dissertation comprises and integral part of a comprehensive vision for effectively supporting human designers in accomplishing the tasks and surmounting the challenges they are likely to be confronted with in the decades to come, as pointed out in Section 1.1. What follows is a concise representation of underlying assumptions, an assertion of key claims, and a presentation of the overarching research vision.

1.2.3.1 Frame of Reference – Decision-Centric Simulation-Based Design and the Decision Support Problem Technique

Decision-Centric Design (DCD), as proposed in Ref. [168] and defined in this dissertation, is an augmentation of a well accepted, but highly controversial perspective on Engineering Design, namely that of Decision-Based Design (DBD). Before proceeding to expound upon the concept of DCD, a description of DBD as the foundational concept follows:

DBD is described by Mistree, Muster, Allen, Shupe, and co-contributors as different perspective of design (as compared to those commonly espoused ca. 1989), that emphasizes the role of designers as decision-makers and the development of a formalism for making decisions [145,148,221,246]. As argued by Marston [133], the realization of the importance of decision-making in the field of engineering was first made by economists and computer scientists and eventually became known as Decision-Based Design. In this paradigm, design can be defined formally as a decision-based process in which the principal role of an engineer, in the design of an artifact, is to make decisions [148]. However, it is important to note that this definition does not rule out reliance on other, scientific, developments in design such as decision theory, utility theory, game theory, etc; it is merely a postulate about the principal role of a designer [133].

Decisions, in an engineering context, usually pertain to the irrevocable allocation of resources [93]. When pondered, this is a statement that makes a lot of sense. In our roles as designers almost every choice we make from determining design parameters to materials and means of production reduce our design freedom in a way that fixes the properties of our final product. Thus, design can be viewed as an intellectual and cognitive activity in which designers convert information that characterizes the needs and requirements for a product or artifact into knowledge about the product or artifact to be designed, as accomplished through successive decision-making [216]. Decision-Based Design then is a process in which these *decisions serve as markers to identify the progression of a design from initiation, to implementation, to termination* [148]. Furthermore, in this paradigm design is viewed as a process in which decisions are made by designers who use computers, rather than as a process that is fully dependent on computers. The ability of a decision-maker to make decisions, however, is greatly enhanced through effective use, synthesis, and analysis of information via the use of computing power. It is in the support of design decision-making, especially when resources and responsibility for their allocation are shared, that the focus of the research presented in this dissertation lies.

It is observed at this point that the application of DBD has taken many forms. For example, Hazelrigg [94] asserts that engineering design is a decision-making process that involves only two steps: 1) determining all possible design options, and 2) selecting the best option using von Neumann-Morgenstern utility as a metric for comparing design alternatives. Other authors from the design community share Hazelrigg's emphasis on implementation of von Neumann-Morgenstern utility as the principal embodiment of decision-based design, and they focus on investigating and implementing multi-attribute utility theory as a means of representing a decision-maker's preferences under risk (see, e.g., [240,243,253,256]). Although decision theory is an important aspect of DBD (see, e.g., [134,135]), the implementation of DBD, augmented in this dissertation, is broader than that espoused by Hazelrigg and others who embrace DBD from the perspective of decision theory alone. It is grounded in the Decision Support Problem (DSP) Technique [155], anchored in the work of Simon [218,221] and described in more detail in Sections 2.3 and 2.4 .

The purpose introducing DCD as a broader interpretation of DBD and making what some might consider to constitute a rather fine distinction from a quasi dogmatic foundation is two-fold. Firstly, it is an attempt to steer clear of the controversy stemming from the practice of equating DBD with decision theory, as purported by some of the more prominent voices within the design community [17,36,93,94,240,242,243,253]. Secondly, the words *decision-centric* better emphasize the importance of gearing design processes towards improving design decisions, rather than retrospectively accentuating the significance of decisions leading up to finalizing a product (as in Decision-*Based*). The importance of decisions in design is thus neither refuted nor subdued in DCD. Instead it is the other elements of design (processes), leading up to the point of resource commitment that are emphasized. Consequently, decisions are viewed to constitute the pinnacles of design processes, which all other activities are aimed at supporting. Focusing on both the internal structure of decisions and the manner in which different decisions are linked, is a prerequisite to formalizing the modular architecture, espoused in this research.

While many researches contend that design is based solely on decisions and emphasize the importance of analysis and simulation, they concede that both analysis and simulation serve the primary purpose of supporting or enabling the making of better decisions. Although, this may seem like petty semantics to an outsider, the fact that exactly this topic has served to fuel endless discussions, is sufficient to warrant clarification. In this dissertation, designing, is viewed as an activity, primarily characterized by the making of decisions, which is influenced by both art and science, but grounded in as much factual *data* as possible. The concert of reconciling form, function, and behavior is thus guided primarily by available *information*, as derived through physical experiment, mathematical model, computer simulation, statistical prediction, etc. There are three other crucial factors (besides information) that are fundamental to the decision-centric perspective subscribed to here, namely *resources*, *uncertainty*, and *time*.

The primary outcome of any design decision is the usually irrevocable commitment of resources. These resources are finite and all designers, whether they are acting in isolation or as stakeholders in a common design process, are governed by their availability or lack thereof. Although many will argue that cost (or profit) is the most important aspect of design, cost is merely a means of quantifying a single resource – money. Although it is true that all other resources can theoretically be reduced (or converted) to this one unifying measure (where depleted resources correspond to infinite cost), doing so not only requires perfect and complete information, but is also impractical. Though ideally suited as a means of evaluation, the granularity afforded by a single driver is insufficient to constructively guide the process of designing. Alternatively, the primary means of considering designer resources in this dissertation is a (collaborative) design space. The fundamental advantage in doing so is that the notion of such a design space furnishes a comprehensive means of visualizing all factors governing to the constraints placed on the evolution of form, function, and behavior.

Another undeniable reality to the practice of engineering design is that of uncertainty. Uncertainty characterizes just about every aspect of engineering design, ranging from the environmental factors and model error to variability and customer whim. The accuracy with which (especially a simulation-based) design process can be modeled is thus highly dependent on the accuracy with which the underlying sources of uncertainty and their interactions are accounted for. This is true whether the uncertainty in question is *epistemic* (i.e., reducible uncertainty or imprecision due to ignorance of information) or *aleatory* (i.e., irreducible uncertainty or variability) in nature. For more information on the treatment of uncertainty in general and in engineering design, the reader is referred to Refs. [19,81,173]. One area of research in engineering design that has recently gained some momentum is that of *Information Economics* (see, e.g., Refs. [19,20,161]), defined as "…the study of choice in information collection and management when resources to expend on information collection are scarce" [19]. The primary concern treated in this vein is thus that of making the cost-benefit trade-off associated with obtaining (additional) information. Costs are incurred through the expenditure of resources (e.g., via experimentation, modeling, etc.). Value is determined with respect to effectiveness in reducing uncertainty. In such cases, where this value cannot be determined precisely, bounds are sought, instead. Since the focus of this dissertation is the creation of enabling technologies for distributed collaboration, the subject of uncertainty is not treated explicitly. It is assumed that domain experts are certain of what they want and, given the required resources, can acquire any needed information. Decisions are based on the status quo of information. Consequently, the purpose is that of aiding stakeholders in making the most suitable decision possible based upon current realities. It is noted, however, reliance on utility functions (assessed in light of attitude towards risk associated with variability) for capturing and mathematically representing designer preferences greatly facilitate the treatment of *aleatory* uncertainty.

The final aspect is that of time. Obviously there are many different ways of representing this element, chronological time being the most intuitive. For the purposes of this dissertation, however, the term time is assumed to refer not to physical time, but *event-based* time. Consequently, it is not the duration or manner in which a change occurs that is considered, but simply the net effect, namely that said change has taken place. With this in mind, the role each of these components play in engineering design are illustrated in Figure 1-5.

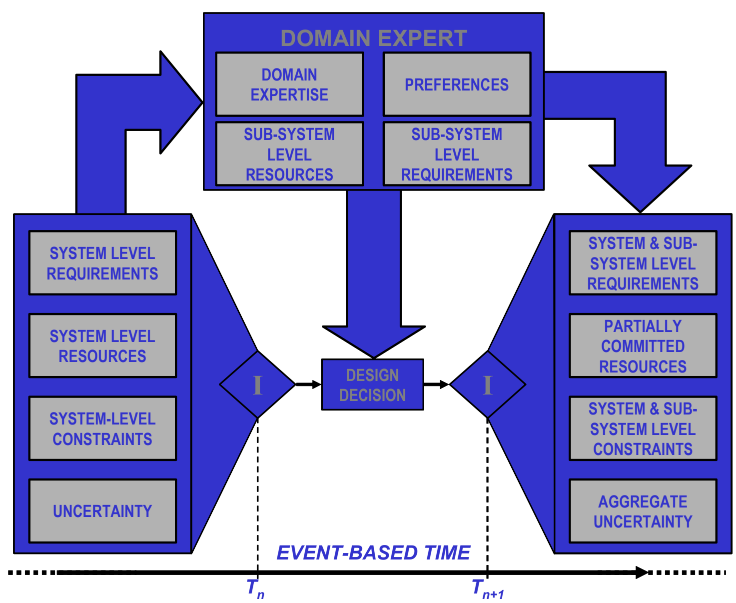

Figure 1-5 - The Role of Information, Knowledge, Uncertainty, Resources, and Time in Decision-Centric Simulation-Based Design

It is important to note the manner in which the various elements elicited in the previous paragraph are interrelated and interpreted in terms of the developments brought forth in this dissertation. A brief discussion, based on Figure 1-5 follows. The fundamental interpretation of the role that the engineering designer plays in product development is that of interpreting system level requirements and constraints for his or her particular context using domain expertise, insight, and knowledge, subject to resources and uncertainty. Although the subject of uncertainty is not explicitly treated here, the foundations for its inclusion/consideration in the decision-making process are provided via reliance on Utility theory for preference assessment, representation, and incorporation into the mathematics for striking the required tradeoffs. Certain allowances are made for practicality and ease of use, as detailed in Section 2.6. As stated previously, the burden of striking required system level tradeoffs in decentralized design is placed on individual domain experts, acting as stakeholders in a common design effort. The reason is that it is these decision-makers that are best qualified for interpreting the effects of system-level considerations such as customer requirements on sub-system objectives, given available design freedom in terms of resources and constraints, placed upon their usage. They are also responsible for formulating the sub-system design problems, simulations, and analyses (not pictured here) to the level of fidelity required for making decisions with the desired level of confidence. Clearly, domain experts are not only subject to system level requirements and resources, but also to those at their own disposal. These will inadvertently have an effect on the manner in which information, emanating from the decision being made is filtered or interpreted with respect to its affect on the overarching system and any dependent, downstream design problems. Clearly, iteration is the only recourse when making the required design decisions is not possible in the scope of the given system level constraints. It is the assurance of feasibility, especially in the context of strongly coupled, concurrent decisions that much of the research documented in this dissertation is aimed at. Another important assumption is that of event-based time, where only information states or resultants of information transformations are considered. This is indicated by the timeline in Figure 1-5, where marks correspond to the information states (T_n and T_{n+1}) prior and subsequent to the design decision being made.

As stated in the beginning of this section, the Decision-Centric Design approach that forms the basis of this research is rooted in the Decision Support Problem (DSP) Technique (see Sections 2.3 and 2.4), developed by Mistree and co-authors [142,145-147,149,155] and extended by Bras and Mistree [32] to model and support design processes. Within the DSP Technique, decisions are modeled as Decision Support Problems (DSPs) [80,143,144,210] which provide a means for modeling a design process. The accompanying domain specific mathematical models are called templates, which although also based upon the premise of facilitating reuse are different from the modular, computational templates, described Sections 1.2.4, and more importantly problem specific. This decision-centric approach contrasts with many other perspectives from which design processes have been modeled, such as the activity based perspective [1,67], the functional evolution perspective [215], the evolution of product states perspective [247], and the manipulation of knowledge perspective [131,132]. Some of these methods are focused on capturing processes to make organizational decisions (e.g., Refs. [1,67]), understanding and capturing designers' intentions (e.g., Refs. [155,247]), or automating the design process via artificial intelligence (e.g., Refs. [131,132]). However, there are significant advantages to modeling a design process from a decision-centric perspective. For example, design processes can be modeled consistently as hierarchical systems, composed of clearly interfaced design process elements, such as the decisions and tasks described in the following section. Since decisions offer a consistent, domain-independent means of modeling processes – regardless of level of abstraction or perspective – it is possible to resolve many of the challenges associated with hierarchical interoperability. Moreover, a decision-centric perspective facilitates modularizing a design process model and makes the development of clear, concise interfaces and interactions between building blocks (both internal and external to the decision at hand) possible. This is an essential feature for facilitating the complete or partial execution, storage, analysis, and subsequent reuse of a decision-centric design process and its components, as illustrated in this dissertation.

It is this decision-centric view of engineering design that the author believes to have the highest inherent potential for continued evolution. Especially taking into consideration the trends considered in Section 1.1, it is in the analysis and further development of design processes both culminating in and described in terms of decisions that the future of engineering design lies. The use of DCD, as defined here, is also paramount to the author's application and reduction to practice of *templates* and the proposed *conflict resolution mechanism* within the overarching context of a **F**ramework for **A**gile **C**ollaboration in **E**ngineering. Finally, the use of decisions to characterize the design process represents the lowest common denominator in linking disciplines and allowing for the representation of design processes form differing perspectives and on different levels of abstraction. Adopting a decision-centric view also facilitates the modularization of the design process and any of the contributions emanating from the associated stakeholders; the continuous development of formalism for addressing the myriad aspects of engineering design is promoted. An overview of the formalism contributed to in this research is provided in the following section.

1.2.3.2 Information, Transformations, and the Design Equation

The overarching theoretical/mathematical construct underlying this research is the design equation, a conceptual-level algebraic relation that maps design operands (i.e., product related design information) and design operators (i.e., information transformations), as indicated in Figure 1-6 and later Figure 1-7. The original design equation, proposed by Bras in his PhD dissertation was of the form **K**=**T**(**I**), indicating that design is a process of converting information into knowledge about the artifact being designed through a series of transformations [31]. Due to its generic formulation this construct can take many different forms, characterized by different types of transformations and information sets, ranging from conceptual design data to detailed facets of engineering drawings, models, and analyses. Several of the possible levels of abstraction at which the design equation can be implemented are indicated in Figure 1-6. The design equation is a hierarchical construct that envisions a mathematical formalism for representing engineering design, comprehensively. Theoretically, it is thus possible to represent the entire design process, regardless of context, domain, discipline, scale, time, or level of abstraction mathematically. Clearly, much work is required to make this vision a reality. Currently, it represents exactly that a vision, an ideal towards which to aspire.

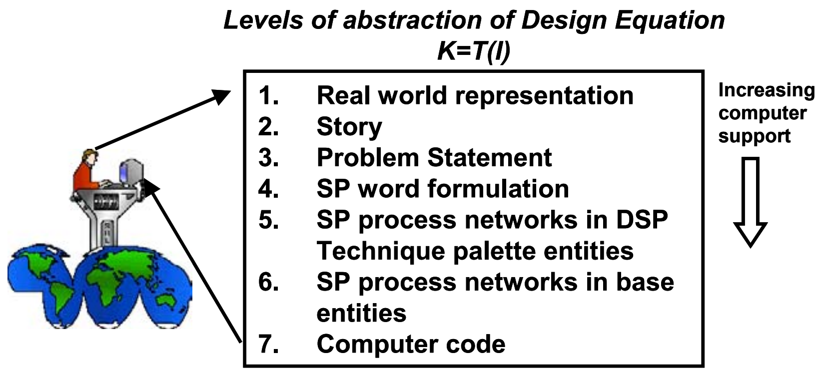

Figure 1-6 - Levels of Abstraction for the Design Equation, Considered within the DSP Technique [31]

The concept of the design equation is currently being transformed from its conceptual roots to more mathematical realizations by Mocko [150] and Panchal [161]. While Mocko is focusing on relating product related design information at different points in time by integrating design and analysis simulations more closely into the design decision-making process, Panchal is focusing on formalizing the design of design processes via concretizing the required information transformations. This dissertation is concerned with formalizing the most fundamental information transformations, namely those of decisions and interactions (i.e., decision level interfaces) among collaborating stakeholders, in a modular fashion so that these can be reused, updated, stored, manipulated, and integrated, akin to a mathematical equation. In terms of Figure 1-6, this translates to facilitating the progression and formalization of (coupled) design decisions ranging from Levels 4 through 7, given design process scenarios that have been defined from Levels 1 through 3. Since the fundamental basis for looking at these information transformations, however, is the nature of the information being transformed, a more detailed discussion of this topic is warranted.

On the whole, decision critical information is often scarce at the onset of design processes when decisions have the most far-reaching impact. Conversely, decisions made in the latter stages of design are convoluted by an overabundance of data and the challenge then becomes one of properly accounting for such information in the decisions to be made. Regardless of temporal considerations, however, decisions tend to be interrelated (see Section 2.1 for a detailed discussion of coupled decisions and their resolution). Decision complexity is overwhelming, downstream dependence is strong, and responsibility for making decisions is usually shared. In order to make design processes more effective, there is a need for supporting designers in making decisions. Due to the nature of this quandary, decision support is necessarily bilateral, focusing on both educating individual designers through the provision of relevant information (i.e., as in commonly available decision support systems) and supporting a group of designers who must model their decisions, structure their design process, and characterize required interactions in terms of inputs/outputs (i.e., as in the proposed research). The development of a **F**ramework for **A**gile **C**ollaboration in **E**ngineering is thus aimed at providing a consistent mechanism for supporting designers in their capacity as interacting decision-makers. The fundamental goals are to manage a design process, coordinate the interactions among stakeholders, and effectively share information in light of dynamic considerations, all with the fundamental goal of working managing collaborative design spaces more effectively what the achievement of system level objectives is concerned. Bearing in mind that information consistently evolves along a design timeline (quality improves, uncertainty decreases, etc.), there is a fundamental need for an effective means of reflecting that updated information content in design decision-making. It is important to note, however, that only event-based time is considered in this dissertation, as indicated in Section 1.2.3.

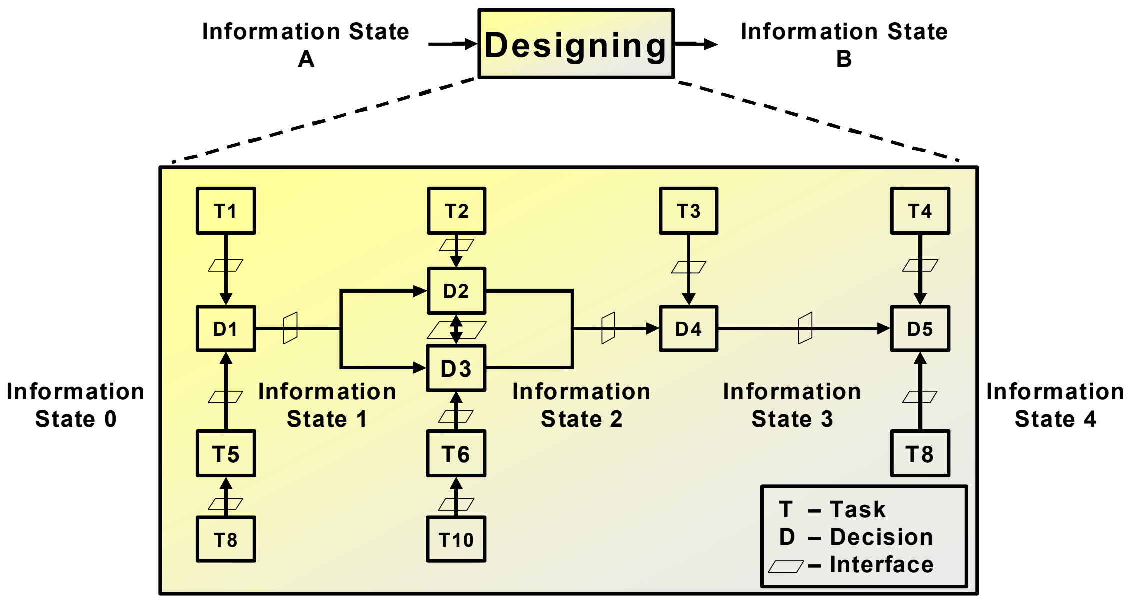

Figure 1-7 - Information Transformations in Design Processes

Although conflicts in engineering design are likely to occur at any of three levels of operation, presented in Table 1-2, the proposed research is centered on supporting interactions among collaborating domain experts situated at the decision or process level. In order for these interchanges to be concise, however, stakeholder design sub-problems must be represented in a consistent fashion, regardless of domain. It is for this reason that a decision-centric perspective of engineering design with three key features – (1) decisions (2) interfaces, and (3) templates – is pursued. Design processes are modeled in terms of decisions and supporting tasks, such as abstraction, concretization, composition, decomposition, mapping, evaluation, etc. [168]. The tasks are needed for synthesizing information content that is essential for proper formulation and solution of decisions. Both decisions and tasks facilitate transformation of information from one state to another, progressively determining the final form, function, and behavior of the product in question. These information transformations constitute the central building blocks of the design process model, espoused here. When combined with the concept of interfaces, decisions and tasks provide a means for modeling design processes as networks of information transformations, as illustrated in Figure 1-7. Templates are instantiated or customized forms of decisions or supporting tasks, such as interfaces, that are modular, archivable, computer interpretable, and reusable.

Table 1-2 - Levels of Operation in Collaborative Engineering Design

Levels of Operation in Collaborative Engineering Design	
Level	**Issues, Challenges, and Activities**
Enterprise	▪ Translate the "Voice of the Customer" ▪ Develop a strategy for attaining market share and determine an effective product portfolio ▪ Design the Design Process ▪ Define, establish, and communicate System Level Objectives ▪ Decompose a system unto design sub-problems ▪ Assign responsibility for design sub-problem resolution to domain experts ▪ Address issues relating to mismatched priorities, asynchronous sharing of critical information, loss of knowledge between organizations, stakeholders, etc.
Decision	▪ Transfer required information between major phases, events, entities, or stakeholders of product development processes ▪ Capture, communicate, and persist decision critical information in an easily interpretable format (e.g., mathematical constructs, computational models, templates, etc.) ▪ Reconcile potentially conflicting design sub-problem objectives
Computing	▪ Generate, archive, and retrieve information at the appropriate level of detail to make it suitable for use by other designers, decision templates, and interfaces ▪ Interpret, and communicate data, information, and knowledge ▪ Integrate resources via distributed computational environments ▪ Reuse analysis and simulation models as appropriate ▪ Furnish a coordination mechanism between distributed software resources and stakeholders

1.2.3.3 <u>Decisions and Interfaces</u>

Decisions

Considering the chosen decision-centric perspective of engineering design, namely the DSP Technique, there are two primary types of decisions: *selection* and *compromise*, described in detail in Section 2.3.1. A *selection* decision involves choosing a preferred alternative among a set of feasible alternatives, whereas a *compromise* decision involves refining a particular alternative. These decisions are structured and modeled mathematically through the selection DSP [80,144] and the compromise DSP [143,210], respectively. Although these two constructs represent conceptually different types of decisions, the selection DSP may be reformulated as a compromise DSP, as shown in Ref. [228]. The author notes that such a reformulation requires the conversion of discrete to continuous variables, prompting careful consideration of any underlying assumptions of the domain in question and mathematical implications of doing so, as well as the invocation of a filter for eliminating any non-existent alternatives generated as a result of the conversion. A more common practice involves the conversion of continuous to discrete variables. Regardless, the compromise DSP is the base construct employed in this research, making it possible to effectively explore and generate families of compromise designs that embody tradeoffs between multiple conflicting goals, often emanating from different functional domains.

Although these constructs form a solid basis for modeling *decisions* within a systems level design process, they constitute a static model of any given design problem. It is important to note that this is true regardless of whether the DSPs are used for modeling products (see Section 2.3) or processes (see Section 2.4). While a foundation for structuring all decision critical information in a consistent format is provided, any changes in the underlying design problem (or series of problems, in effect constituting a process) require the complete reformulation of the instantiated decision model(s). Partial modification is rarely possible, especially in the case of strongly coupled problems. This is due to the fact that *declarative* (i.e., problem specific) and *procedural* (i.e., solution process specific) information are fused; instantiated DSPs are directly tied to their solution mechanisms. Consequently, coordination mechanisms represent a static means of achieving required tradeoffs that is directly tied to the underlying design sub-problem formulations. In order to support the interactions of collaborating decision-makers a fundamental requirement is that design decisions be modeled in a solution neutral, modular, and computer interpretable manner, that facilitates the infusion and reflection of changing information content. The aim in this research is to enable the modular insertion of *declarative* information by designers, while preserving *procedural* elements in a computer interpretable format that lends itself to automation. The means for accomplishing this end are developed in Chapters 3 and 4.

Interfaces

An interface in a design process separates or partitions multiple dependent or interdependent designers and their respective design activities. If there is a boundary between design activities, there must also be an interface in order for information to flow and interactions to take place. The nature of this flow determines the instantiation of said interface. In the context of this dissertation, an interface is envisioned to partition design activities so that only information (e.g., requirements, performance specifications, etc.) flows between them. Although the focus in this research is on supporting activities at the *decision level of interaction*, it is important to note that there are a total of three primary types of interfaces relevant to the design of complex systems

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Although the issue of regulating exchanges among collaborating designers at the *decision level of interaction* has been a subject of design research for a number of years, there are two elements, crucial to interfacing design activities and supporting collaboration along an event-based design timeline, that have thus far not been resolved – evolution of decision-critical information and connectivity. To clarify, interactions, thus far, have been predominantly supported by excising iteration via the one-time transfer of semantically rich information content and any required models. In order to facilitate continued interactions along an event-based design timeline and the achievement of balanced solutions from a systems perspective, it is required that process level interfaces (1) serve as domain-independent communications protocols for regulating the way in which experts (operating in different functional domains) share information for effective collaboration and (2) once instantiated, serve as a means for connecting decision templates to one another in a computer interpretable manner, allowing for design process analysis, exploration, and modification. The aim is to structure and coordinate stakeholder interactions so that collaboration is supported and both decision-makers and the decision constructs, used to model their aspirations (and representing their respective domains in terms of constraints, objectives, resources, etc.), are consistently interfaced. A key consideration in the resolution of the potentially conflicting objectives, associated with stakeholder design sub-problems involved in this process is to prioritize, achieve, and improve upon overarching system level objectives, as well as making more effective use of collaborative design spaces. The challenge lies in conjunctively solving coupled design sub-problems without unnecessarily biasing system level performance based on the satisfaction of design sub-problem aspirations. This challenge is addressed in Chapter 5.

1.2.3.4 Computational Infrastructure

Often, design decisions are supported by domain specific software applications that facilitate the challenges inherent in creating the highly specialized models required for virtual product realization. This is illustrated in Figure 1-4, where domain experts are tapping into myriad computational resources via computational level interfaces. While some of these tools integrate a substantial amount of domain specific knowledge, a detailed understanding of the principles governing product performance is nevertheless required in order to use them correctly; the old adage of garbage in, equaling garbage (or nowadays perhaps pretty pictures) out, still applies.

Using these highly specialized and often proprietary products, however, requires an in-depth understanding of any applicable limitations. That is to say that while it is possible to propagate simulation models downstream in order to reduce (and/or eliminate) iteration, doing so limits design modification to the limits dictated by the underlying model (i.e., those emanating from the assumptions made at the time of its creation). In the absence of the expertise, required for model modification, alteration, or reformulation, consultation by the originator of the model (or someone equally qualified) is unavoidable. Iteration thus ironically becomes the only remedy.

As described in Section 1.1, domain knowledge becomes invaluable, especially when tackling complex systems. Since reliance on multiple experts is unavoidable, modularizing their contributions and thereby isolating their effects simply makes sense. While this is an aim that has been heavily pursued in computational frameworks aimed at integrating various pieces of software [52,59,86,87,162,170,268], the leap of applying the same principles to human agents has thus far not been promoted extensively. One example includes an ongoing Multidisciplinary Research Program of the University Research Initiative (MURI) project for the design of Multifunctional Energetic Structural Materials, the computational infrastructure for which is illustrated in Figure 1-8. Modularizing the design of products, the underlying design processes, and the contributions of stakeholders forms a substantial component of the vision pursued in this dissertation. The chosen means of realizing this idea is through the implementation of templates as described in the next section.

1.2.4 Template-Based Realization of the Proposed Methodical, Systems-Based Design Approach to Agile Collaboration

Templates are commonly defined as patterns or gauges used as guides in making something accurately [2], as in machining or carpentry. In the domain of computer science templates are documents or files having a preset format that are used as starting points for particular applications or uses, the benefit being labor savings emanating from the recreation of format for every use. Finally, templates are also keyboard overlays clearly label functions keys within a particular application [2]. Each of these definitions implies the provision of guidance and the preservation of reusable aspects that are invariant from one application to the next.

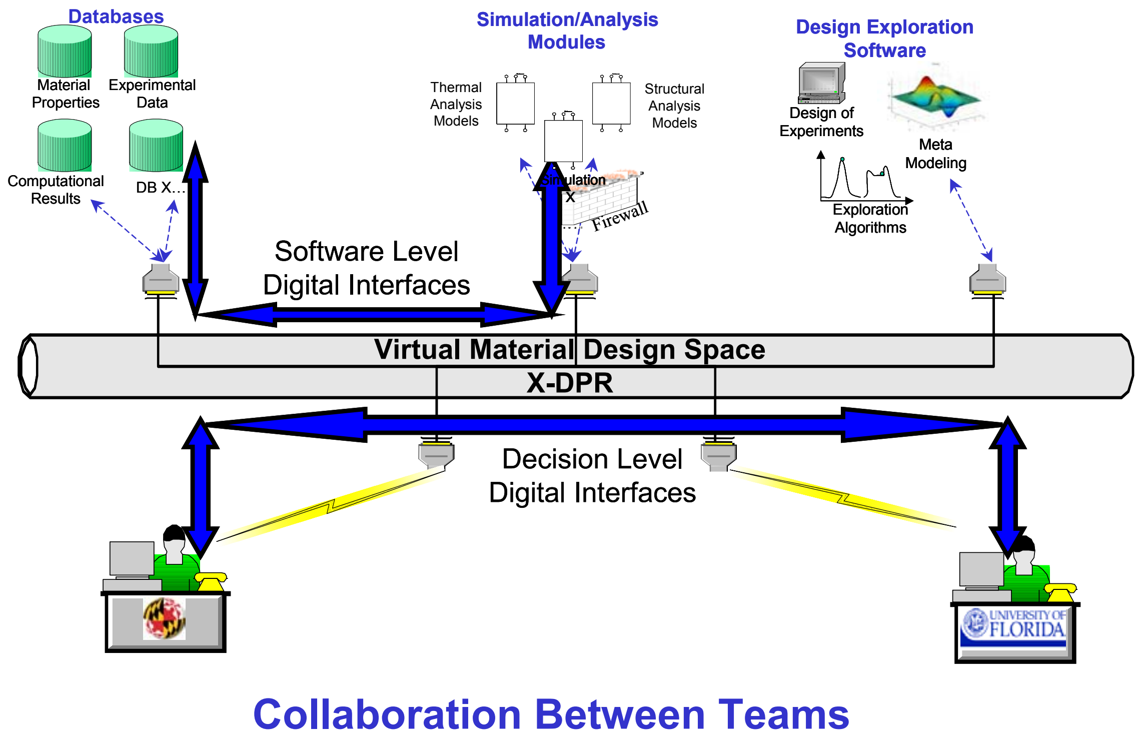

Figure 1-8 - A Distributed Environment for Materials Design [207]

In the context of this dissertation, a template is a decision, task, or interface construct that (1) has been instantiated (i.e., customized via provision of information content into the pre-specified structure) for a specific decision or decision-maker interaction and (2) is computer interpretable. The primary purpose of a template is to facilitate consistent, standardized formulation of models that may include critical information required by other designers. Template formulation at the *decision level of interaction* requires generic models of the corresponding design process building blocks. Such "genericism" requires not only domain independence but also the solution neutral formulation of the underlying model. The resulting decision and interface models should be archivable, computer interpretable (e.g., executable and analyzable), and most importantly reusable. Furthermore, template-based design process building blocks should be completely modular and adaptable, facilitating adaptive or variant redesign of both the product and the underlying design process.

The approach to consistently supporting the interactions of stakeholders throughout the duration of their relationships in the solution of strongly coupled systems is described as being template-based because it emphasizes re-use of recurring elements and requires the uniform formulation of design decisions. Such consistency is only feasible, realistic, and enforceable through the provision of templates that indicate elicit information, implicitly instruct, and ensure the predictability of the manner in which inputs and outputs are formulated.

Considering that the primary components or building blocks of DCD processes developed in this dissertation are decisions and the interfaces connecting them, it is these that templates are developed for. This ensures that decision-maker considerations are represented in a consistent format and greatly facilitates the elicitation, specification, and organization of declarative information for a particular problem at hand. *Representation* is a crucial part of modeling design processes that directly depend on the flows of information and are manipulated by highly visual human designers. *Computational* aspects are also addressed via *templatization*. Specifically, as described previously, it is because computations are primarily procedural in nature that these can be captured in template form. In fact it is around these procedural aspects that the basic architecture of a specific template revolves. Once instantiated for a particular problem, templates are easily stored. As such they capture not only relevant declarative information but also the manner in which such information is used to generate knowledge about the artifact being designed. Since the ability to *store* is independent of the degree of instantiation of the template, decisions can be captured whether they have been formulated completely or only in part. Declarative aspects can then be modified as necessity demands, making previously instantiated design processes (whether composed of a single or a series of design decisions) *adaptable*. Consequently, rework can be avoided and previously expended resources *reused*. Design *exploration* is also facilitated since changes in design considerations are treated as being declarative and do not produce procedural changes. Instantiated templates can also serve as a semantically rich means of *communication*, since they convey not only problem specific domain knowledge, but also the manner in which this knowledge can be extended via the underlying models or simulations. In essence, templates thus serve as a flexible means of capturing information, insight, and knowledge as relating to the various domains being interfaced and at least in this author's opinion comprise the foundation for composable simulations of decision-centric design processes.

1.3 RESEARCH FOCUS, QUESTIONS, AND HYPOTHESES

Having established the overarching context in Section 1.1 as well as a frame of reference in Section 1.2, the main contribution presented in this dissertation – a framework for establishing and managing collaborative design spaces, complemented by a coordination mechanism that represents a viable alternative to existing instantiations of communications protocols and solution algorithms (primarily those originating in game theory) is detailed in this section. The proposed **F**ramework for **A**gile **C**ollaboration in **E**ngineering combines elements of cooperative and non-cooperative behavior, as well as strategic and extensive form games, with utility theory in a modular fashion, promoting win/win situations. The fundamental goal is to address the concerns, raised in establishing the frame of reference of Section 1.2, and formalize a consistent means of support for focalized collaboration that ensures (1) the existence of mutually acceptable solutions and (2) congruent interactions, as well as, (3) stakeholder guidance in achieving their respective objectives in light of system level priorities.

1.3.1 Framing the Research Effort

Although one of the main foci of this research is the promotion of co-design, this concept constitutes an ideal (or extreme) form of collaboration, based on an assumption of stakeholder willingness to compromise sub-system level objectives in order to achieve more balanced system-level performance. The required circumstances for such a scenario clearly comprise only a small (though important and thus far neglected) subset of the myriad forms of collaboration possible or necessitated by enterprise level concerns, structures, and realities. The intent, pursued here, is to provide a consistent basis for decentralized decision-makers to ensure the feasibility and efficient attainment of mutually acceptable solutions, regardless of the manner in which the final tradeoffs are struck. Rather than excising iteration, the goal is to make iteration effective by providing a consistent structure, emphasizing communication that is strategic with respect to timing, information content, and mechanics. It is for this reason that the letter "C" in the acronym FACE for the proposed **F**ramework for **A**gile **C**ollaboration in **E**ngineering stands for *collaboration* and not *co-design*. With this in mind, the most substantial challenges are summarized and mapped to critical requirements for collaborative design in Table 1-3.

Table 1-3 - Challenges and Requirements for Collaborative Design

Challenges in and Requirements for Collaborative Design			
Facet	**Collaborative Design Challenges**	**Requirements**	
Decisions	▪ Consistent design sub-problem formulation ▪ Multiple domains ▪ Evolution of design considerations ▪ Design sub-problem interdependence	▪ Provide a consistent, domain independent platform representing design considerations and aspirations ▪ Develop constructs of modeling design decisions that are solution neutral, modular, and computer interpretable manner ▪ Ensure that the infusion and reflection of changing information content is supported	**I**
Interfaces	▪ Interdependence of design sub-problems, subject to shared design parameters ▪ Communication of relevant information content ▪ Reconcile potentially conflicting stakeholder objectives ▪ Ensure achievement of system level objectives, while satisfying design sub-problem constraints ▪ Continuous autonomy of domain experts over assigned design sub-problems	▪ Structure and coordinate stakeholder interactions ▪ Support collaboration along an event-based design timeline among interacting decision-makers ▪ Link instantiated decision constructs, used to model stakeholder aspirations, so that they are interfaced consistently as informational content considered evolves.	**II**
Templates	▪ Capture, storage, analysis, exploration, and execution of design process constituents ▪ Separation of declarative and procedural information flows ▪ Reuse and extension of existing design process constituents in developing derivative, adaptive, and variant designs	▪ Prioritization, achievement, and improvement of system level objectives while satisfying constraints associated with coupled design sub-problems ▪ Preserve stakeholder autonomy in conflict resolution ▪ Make more effective use of collaborative design spaces.	**III**

The research outlined in this proposal is based on two key assumptions: (1) design is a decision-centric activity that is becoming increasingly reliant on simulation (see Section 1.2.3) and (2) design processes themselves are hierarchical systems (see Section 1.2.1). From a decision-centric standpoint, designing then is a process of converting information that characterizes the needs and requirements for a product into knowledge about the product [110,145], as indicated in Section 1.2.3.2 . From the elicitation of customer requirements to the production of a final product, design processes are carried out through a number of phases. For example, the phases associated with the Pahl and Beitz [160] design process are (1) Planning and Clarification of Task, (2) Conceptual Design, (3) Embodiment Design and (4) Detail Design. Each phase is associated with *stages* of product information. Within each phase, there is a network of transformations that operate on product information. These transformations can be carried out in a sequential or concurrent fashion. The transformations operate on product related information and convert this information from one *state* to another. The state of information refers to the *amount* and *form* of that information that is available for design decision-making. This is indicated in Figure 1-9, where the concept of the design equation is illustrated with respect to modeling design processes as networks of information transformations (i.e., *decisions* and *interactions* in the context of this dissertation). It is important to note that these transformations remain the same during different phases of the product realization process such as those described by Pahl and Beitz (see also Figure 2-3). Although there are many information transformations associated with a decision-centric design process, the focus in this research, as stated, is on the *decisions* and the *interfaces* among them (see Figure 1-7). Specifically, the aim is to support stakeholders in a collaborative design process in negotiating solutions to their respective design sub-problems, while considering the requirements and limitations of those with whom they interact. The role that these domain experts play in the process of making decisions is emphasized in Section 1.2.3.1 and Figure 1-5.

As detailed in Section 1.2 and suggested in Figure 1-4, a systems level engineering design process involves multiple experts who make decisions supported by computational resources such as databases, simulation models, and design exploration software. To facilitate such a systems level design process (and effectively integrate Levels 4 through 7 in Figure 1-6), it is necessary to model the decisions and tasks of each designer *as well as* to facilitate collaboration among multiple interacting designers. Three of the most critical challenges are:

1. *modeling* of individual designer domains in a uniform (i.e., modular, consistent, and generic) manner

2. *facilitation* of designer interactions, required for collaboration, reflecting underlying hierarchical dependencies and information flows

3. *expression* of those elements of a design process that may safely be automated in an executable, computer interpretable manner

Each of these challenges corresponds to an equally numbered facet of the espoused decision-centric approach – (1) *decisions*, (2) *interfaces*, and (3) *templates* – as first indicated in Sections 1.2.3 and 1.2.4 and subsequently mapped to secondary research questions in Section 1.3.3.

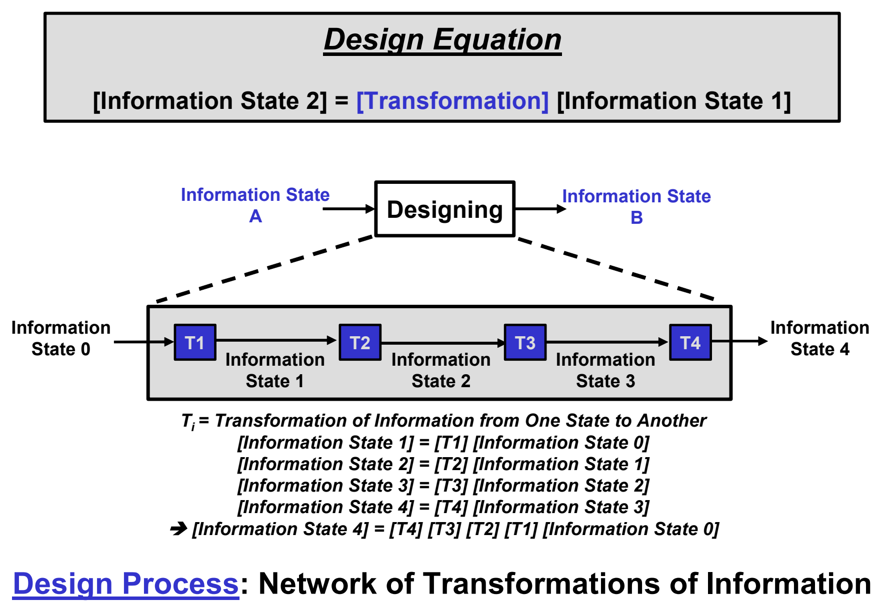

Figure 1-9 - Modeling Design Processes and Design Process Components Using the Design Equation [161]

1.3.2 Research Goal and Primary Research Question

Having framed the overarching research effort in the preceding sections, the objective pursued in this section is to distill the fundamental challenges addressed in this dissertation. These are summarized and mapped to key requirements in Table 1-3. As indicated, the primary aim is that of structuring and ensuring the congruency of interactions among collaborating decision-makers along an event-based design timeline. The principal research question is:

> ***Primary Research Question:*** *How can collaboration in engineering design be modeled so as to facilitate the reflection of evolving stakeholder aspirations, while ensuring the existence of acceptable solutions and promoting the unbiased achievement of system level objectives?*

There are several secondary research questions associated with this primary research question. These are presented alongside their corresponding hypotheses and associated tasks in Table 1-4. They are subsequently elaborated upon in Section 1.3.3. It is in response to these research questions that the proposed **F**ramework for **A**gile **C**ollaboration in **E**ngineering is developed in the remainder of this dissertation with the intent of supporting the activities of interacting designers, acting as stakeholders in a shared endeavor, throughout the duration of their relationship.

1.3.3 Research Questions and Hypotheses

The desired outcome of this research is to facilitate interactions among distributed stakeholders, engaged in a common product realization process, by providing a consistent, modifiable means of structuring decisions and interactions in light of system level objectives. With this goal in mind, the requirements, introduced in Section 1.3.1 and summarized in Table 1-3, are mapped to a set of research questions, hypotheses, and tasks in Table 1-4. Each of the three secondary research questions is explored further in Sections 1.3.3.1 through 1.3.3.3 with respect to their respective relevance to the overarching objective pursued and accompanied by a brief summary of the current state of research. An in-depth literature review follows in Chapter 2.

1.3.3.1 Consistent Modeling of Stakeholder Considerations and Decision Support in Engineering Design

One of the main challenges in modeling any design effort, regardless of scale or scope, is formalizing the manner in which information flows and dependencies are represented. Another challenge lies in representing design processes in a domain neutral form that supports designers in providing and structuring required information content. In order to promote collaboration along a design timeline, it is thus important to develop reusable computational constructs for design decisions that capture all relevant information in a modular fashion. Such decision models can then be combined using appropriate interfaces to represent interactions associated with a design process and capture relationships among coupled design problems, interacting stakeholders, and the overarching system.

Thus far, there has is a lack of formal computational models for representing evolving designer aspirations. Current design process models are either narrative or symbolic in nature [139] and interactions are guided mostly by experience and descriptive/pictorial representations. A detailed overview of past and current efforts in product modeling is provided in Section 2.3, whereas a discussion on modeling processes follows in Section

2.4. An alternative perspective, first proposed as the 3-P Information Model in Ref. [164], promoting the integrated consideration of both products and design processes, is reviewed in Section 2.5. The inherent emphasis on product/process duality in engineering design is crucial to the research undertaken here. Every information transformation considered (i.e., *decisions* and *interfaces*) is an operation on the product. By the same token, each decision or set of interrelated decisions constitutes a design process or component thereof. While it is not true (in general) that all information transformations are strictly about the product, and many are, in fact, concerned only with process specific aspects (e.g., model choice, responsibility assignment, etc.), these are treated as *a priori* organizational or enterprise constraints (i.e., "*Givens"*) in this dissertation.

With the exception of this last perspective (developed in tandem by Panchal [161]), a majority of available models constitute static representations. Consequently, they are incapable of effectively considering evolving information content, while preserving the underlying manner in which decisions are structured. Considering that responsibility for design sub-problems is often transferred during the course of a design process (in order to facilitate conflict resolution in some game theoretic approaches, focused on the achievement of Stackelberg equilibria as in Refs. [267,269,270]) this is a fundamental shortcoming. The static nature of the underlying models limits this transfer to the communication of a design space "snapshot", particular to the current state of information. It is for this reason that *loss of stakeholder dominion is highly undesirable*. It is asserted that an in-depth understanding of the domain models and any underlying assumptions and limitations is required to make cogent inferences beyond the communicated nugget of expertise. A change, deviating beyond the bounds within which the model is valid, requires decision model reformulation by the originating domain expert, resulting in often costly iteration. The same inadequacies hold true for those game theoretic instantiation, not characterized by a loss of stakeholder dominion, that nevertheless require the communication of preference prior to segregated problem resolution as in Refs [39,40,98-100,133,136].

On the whole, design decisions are based on information content that, in turn, is heavily influenced by level of understanding, degree of uncertainty, analysis or simulation results, resource availability, etc. A fundamental requirement for effectively interfacing decision-makers along an event-based design timeline thus is a domain independent means of modeling design problems that can be amended indefinitely. This motivates the following research question:

> ***Research Question 1:*** *How can design problems be modeled so that the reflection of changing information content and evolving stakeholder aspirations can be accommodated while maintaining structural consistency?*

In response to this question, a domain independent means of capturing design decisions in an *archivable*, *executable*, and *extensible* manner is proposed. These decisions comprise the fundamental building blocks for the design processes, considered in this dissertation - involving *strongly coupled* design problems, control over which is shared by a number of decision-makers. These decision-makers are assigned responsibility for the design sub-problems into which the overarching design problem is decomposed. Since both system and sub-system level design problems are modeled in terms of the associated decisions, these constitute key elements of the design processes being considered. Specifically, the focus is on developing a template-based approach to modeling collaboration in engineering design. A *template* is commonly defined to be (1) a pattern, used as a guide in making something accurately (2) a document or file having a preset format, used as a starting point for a particular application so that the format does not have to be recreated each time it is used.[3] Clearly, the word *template* is appropriate in the context of this research because it implies reusability, achievability, and support/guidance.

It is hypothesized that individual decision-maker considerations can be modeled using domain independent, modular, reusable decision templates, based on Decision Support Problem constructs [80,143,144,210], that can be *captured*, *archived*, *analyzed* and *manipulated* on a computer.

Developing the appropriate models will focus on synthesizing elements of object-oriented programming, port-based modeling [171], systems engineering [34], product architecture design [140], utility theory [114,130,196], and open systems [223]. As templates, the resultant constructs are generic, facilitating their instantiation, regardless of context, domain, or level within the systems hierarchy. The required "genericism" of the underlying models is achievable via a separation of the *declarative* from the *procedural* flows of information, as detailed in Ref. [169]. This architecture greatly enhances the ability to update (1) decision constructs to reflect changes emanating from updated information and evolving designer aspirations and (2) interfaces to reflect changes in the manner in which this information is shared and communicated, making the exploration of different design process architectures possible.

[3] Compiled from *www.dictionary.com*

The resulting *generic* constructs effectively maximize external adaptability while minimizing internal variety [248]. Specifically, they are instantiated solely through the provision of required information content, resulting in templates for the corresponding elements of the particular design process under consideration. In fact, it is domain-specific information that serves as the only differentiator among constructs (i.e., templates), instantiated for specific design problems, while the underlying structure remains consistent. This facilitates modular insertion of *declarative* information by the designers, while preserving *procedural* elements in a computer interpretable format that lends itself to automation. While similar models may be developed for supporting (and alleviating the computational burden associated with) other *task* design process building blocks (e.g., abstraction, concretization, composition, decomposition, mapping, and evaluation [161,166,168]) these are not focused upon here. Sole consideration is given to design *decisions* and associated *interactions* (i.e., decision level interfaces).

1.3.3.2 Agile Coordination and Structuring of Stakeholder Interactions in Distributed Collaborative Design and Manufacture

A majority of coordination mechanisms in engineering design have thus far focused on one time interactions and the communication of richer information content to reduce the chances of irreconcilable objectives and improve the overall quality of the results obtained. This at least in part due to the fundamental limitation of current decision models, reviewed in the previous section, namely the fusion of *procedural* (i.e., process specific) and *declarative* (i.e., problem specific) information streams. Consequently, even minor changes in declarative information, emanating from refinements in the understanding, formulation, and analysis of the underlying design problem, require decision model reformulation. This makes iteration a very costly and time consuming activity. Nevertheless, on a more fundamental level, a majority of communication protocols take the existence of a solution for granted. Since irreconcilable mismatches are treated only in an *ad hoc* manner, such mismatches can only be resolved through iteration. The later in the design process that such mismatches are identified, the greater the cost associated with this hysteresis. This is due to a higher quantity of resources having been expended on behalf of sub-systems without regard for limitations emanating from their coupled counterparts.

Overall, current decision coordination mechanisms in engineering design are often focused on streamlining the design process by excising iteration emanating from *trial-and-error* without considering its most fundamental source – prolonged lack of decision-critical information brought on by deliberate procrastination of exchanges in order to minimize interactions. The predominant means for reducing such iteration is via the specification of ranged sets of solutions and the communication of semantically rich information content. While this is an effective *modus operandi* for changeovers associated with sequential, clearly distinct phases of a product realization process (e.g., Design and Manufacture), the existence of a solution that is acceptable to all interacting parties is also presupposed. By the same token this approach is not (in general) suited for facilitating open collaboration among decision-makers, who are required to make congruent progress along an event-based design timeline.

Stakeholder interactions must be both effective and efficient in satisfying the constraints defining their respective design sub-problems (some of which originate from other design sub-problems, and vice versa) while achieving system level objectives in an unbiased manner (as addressed in Section 1.3.3.3). With this in mind a greater level of stakeholder awareness is required. The strategies, upon which system level tradeoffs are based, are most often formulated prior to the first communication, rooted in a very limited understanding of interaction effects. Furthermore, the information upon which any of the payoff strategies are based is assumed to remain fixed. In reality, however, considerations of interacting designers continuously evolve due to changes in understanding, model fidelity, and technology, to name a few. In fact, stakeholders continuously continue to learn about their respective systems, which in turn has a direct effect on the manner in which they interpret data and the values of objectives they pursue. Such a dynamic poses a fundamental challenge. Current decision models and coordination mechanisms are quasi static and thus render the reflection of changes in information content virtually impossible without complete reformulation of both designer aspirations and interaction details. As a partial consequence, forms of collaboration based on more frequent interactions have hitherto not been considered other than via *ad hoc* resolution of conflict or extensive negotiation. This prompts the following research question:

> ***Research Question 2***: *How can the communication of information, required for the resolution of strongly coupled design problems, among collaborating stakeholders be structured so that their efforts are focalized and their subsequent interactions are rendered both effective and concise?*

In response, the development of a methodology for the systematic establishment of a collaborative design space, improving both the efficiency and effectiveness of stakeholder interactions in engineering design, is pursued. The embodied efforts are based on the assertion that iteration is beneficial as long as each resulting interaction constitutes progress towards the achievement of a common objective. Such convergence requires compromise driven by the balanced satisfaction of system level tradeoffs and stands in marked contrast to the often ineffective, stagnant, and potentially divergent negotiation associated with trial-and-error. It is hypothesized that a communications protocol for *co-design*, based on the *co-construction*, *co-exploration*, and *co-management* of collaborative design spaces by all interacting parties, can be developed to structure the interactions of stakeholders, contributing to and pursuing a common set of overarching systems level objectives. The fundamental goal in this effort is to systematically ensure the existence of feasible solutions, where *feasible* is defined as mutually acceptable by all interacting parties, from the onset of the constituent design process. It is important to realize that this proposed means of focalization is independent of the manner in which the final tradeoffs are struck, an aspect addressed with respect to Research Question 3. That is to say that any mathematically sound protocol (e.g., Nash, Pareto, and Stackelberg games, as well as negotiations and mathematical optimization) may be chosen and organizational as well as structural needs accommodated. The aspect that is both crucial and novel is the ability to gain and retain confidence in the existence of a mutually acceptable solution and avoidance of irreconcilable differences throughout the course of the stakeholder relationship.

1.3.3.3 Interaction-Effect-Conscious Reconciliation of System Level Trade-offs

Once the existence of a feasible solution has been ensured, the next step consists of identifying that solution. It is in this regard that the myriad tradeoff strategies reviewed in Section 2.1 are employed. In this dissertation, the focus is on supporting *co-design*.

Consequently, the need to reconcile system level with sub-system level performance arises. This fundamental challenge in not unique to the design of complex systems but common to all problems that are hierarchic in nature. Making judicious tradeoffs, however, requires a good understanding of the problem at hand – a problem likely to constitute the nexus of a number of different disciplines. Reconciling the objectives of all interacting parties constitutes a new challenge in its own right, the responsibility for which must be carefully considered. Often, this issue is addressed by transferring responsibility for making the required tradeoffs to a single stakeholder (e.g., the manufacturer via a *clean digital interface* between design and manufacture as proposed in Refs. [192,193]). The underlying assumption here is that activities can be separated successfully. Xiao asserts that this effective separation of (coupled) design activities requires careful verification that design specifications and intentions will not be violated. Specifically, he addresses the problem of evaluating team preferences so as to ensure the superiority of final decisions under conditions of risk and uncertainty, incurred by the early separation of design and manufacture [267]. This effectively translates to conflict resolution via complete transfer of responsibility during a one time interaction. Such a transmission, in turn, requires a good understanding of all contexts being integrated in order to be successful. This is also the case where coupled design sub-problems are completely reformulated as a single problem, as in cooperative game theoretic formulations of coupled decisions, where additional intricacy stems from inherent computational complexity that often makes obtaining good solutions difficult. The reader may also recognize this problem as the crux of many systems engineering approaches, where it is often assumed that a single "system" engineer is capable of making cogent tradeoffs. This assumption, though ideal, is considered to be unrealistic in this dissertation. In fact, this supposition thwarts the premise of assigning responsibility for sub-problem resolution based upon domain expertise, emphasized in the decentralized design of complex systems.

In many cases, game theoretic formulations are implemented, not only as a coordination mechanism, but also as a means of conflict resolution. Typically, these protocols correspond to Non-Cooperative, Cooperative, or Leader/Follower Stackelberg formulations. In general, these instantiations require each of the constituent problems to be formulated in their entirety, before non-cooperative game theoretic protocols are employed to determine a mutually acceptable solution. As emphasized in Section 1.3.3.2, the very existence of a solution is also presupposed. There are a number additional shortcomings in such approaches – (1) updating information content requires reformulation of the constituent problems, (2) targets are generally myopic, (3) solutions are often Pareto optimal at best (for a "compromised" design space), based on mutual consideration of respective BRCs. More importantly, perhaps, no allowance is made for the evolution of information content over time, making it difficult to design for robustness and changing targets. Recent extensions, aimed at addressing these shortcomings focus on making solitary interactions more effective and preserving design freedom (defined as the number of options that remain open to a designer for consideration at a particular point along a timeline, characterized by or proportional to the resources at a designer's disposal/discretion) in the handoff that occurs between the n and $n+1$ decision-makers in a sequential series. Such alternative techniques thus address the issue of allowing for adjustments in system-level tradeoffs by building in variability via communication of ranged and/or robust sets of specifications, rather than point solutions, as in Refs. [91,109,270].

A fundamental limitation associated with implementing game theoretic protocols for design conflict resolution in general is that the required RRSs/BRCs constitute static representations of a designer's response to a given set of circumstances that are likely voided by any significant changes in decision critical information. Each iteration thus requires the reassessment of individual decision-makers' responses to one another's predicted actions. Game theoretic protocols as implemented in engineering design thus far, merely facilitate *ex post facto* reconciliation of potentially conflicting objectives pertaining to and formulated *a priori* by interacting decision-makers. As such, results obtained tend to represent Nash equilibria and are at best Pareto efficient for the resultant "compromised" and quasi-combined design spaces considered, depending on which protocol (e.g., Cooperative, Non-cooperative, or Stackelberg) is used. No allowance is made for collaboration in formulating the shared design space based on realistic sub-problem performance and effect on the achievement of system level objectives. Coupled design problems, solved using game theoretic protocols, also often suffer from the so called "curse of dimensionality" what generation of the required RRSs/BRCs is concerned.

Efforts associated with linearizing design processes and reducing the number of iterations usually entail a hand-off of design space and an implied loss of stakeholder dominion over design sub-problems assigned them. Considering the multidisciplinary nature of complex systems design, targeted in this research, maintaining decision autonomy with domain experts is paramount. A transfer of responsibility for problem resolution, even when accompanied by design freedom, in effect still amounts to throwing something over the proverbial wall. Though far more effective and efficient than traditional approaches centered on *trial-and-error* reconciliation of mismatched objectives emanating from pursuing point solutions. While such approaches are well suited for those interactions involving the termination of one phase and the start of another, where an actual transfer of authority occurs, they are not supportive of the continuous interactions required by various decision-makers engaged in *co-design* and consequently collaborating with one another along an even-based design timeline. The high likelihood of changing realities associated with the resolution of each of the coupled design sub-problems can often render existing decision models obsolete. Since such models thus far have been limited to static representation, costly iteration, focused on reformulating (1) design sub-problems and (2) the manner in which these are interfaced is the only alternative.

On the whole, coordination mechanisms rooted in both MDO and game theory presuppose and require centralized management (responsible for information exchange and decision-making). As stressed by Xiao in Ref. [267], however, such centralized management no longer exists in distributed product realization outside of the *enterprise level of interaction*. Specifically, (1) there typically is no single engineering team capable of gathering a sufficient amount of information to form the general picture of the entire process that is required and (2) the ability to understand the information available regarding the required, inter-disciplinary decisions is quite limited. More importantly, however, a decentralized view of management reduces the bottleneck in information exchanges and increases flexibility. What is required in order to consistently support the interactions of collaborating decision-makers along an event-based design timeline is a systematic means of resolving system level tradeoffs that preserves stakeholder autonomy over their respective design sub-problems and guides collaborative design space reductions associated with resolving coupled design sub-problems. This prompts the following research question:

> ***Research Question 3:*** *How can stakeholder interactions be guided so that design freedom is not reduced unnecessarily and system level performance is enhanced?*

In response, a strategy for sequencing decision-makers and reducing collaborative design spaces is proposed. Specifically, the goal is to devise a means of enabling interacting decision-makers to efficiently and effectively evaluate the relative responsiveness of their objectives in light of factors both within and outside of their control as well as their effect on the achievement of overarching system level objectives. It is hypothesized that various measures of sensitivity may be employed in conjunction with performance potential in order to gauge individual stakeholder impact on the region of the collaborative design space, constructed and refined in response to Research Question 2. The goal is to reduce the effect of implicit biases on numerical misrepresentations of design performance. Specifically, an effort is made to reduce (1) stakeholder bias, inherent in and resulting from the chosen order of precedence, (2) system bias due to the manner in which coupled sub-systems are mathematically related, and (3) bias due to unrealistic expectations (as resulting from ill constructed normalization), thereby improving utilization of the collaborative design space shared by all stakeholders. Currently, the order in which interacting stakeholders successively fix design variables is often chosen based on design process configuration or natural progression as in DFM. While establishing a set order of precedence is desirable when the goal is to make one-time interactions as effective as possible, it is not advisable when repeated interactions are required and continued stakeholder autonomy over design sub-problems is to be maintained. Considering that protocols for single interactions have been proliferated in the literature and are not suited for the type of stakeholder relation, associated with the decentralized design of complex systems, a viable alternative is offered. Additionally, in order to better explore the potential of collaborative design spaces at each interaction point along a design timeline, it is important to establish realistic targets for designer objectives, thereby utilizing resources more effectively. Much of the computational burden associated with this increased level of design space exploration is alleviated via the use of space filling experiments, employed to efficiently evaluate feasible achievement.

Table 1-4 - Mapping Research Questions to Hypotheses and Tasks

<table>
<tr><th colspan="4">Research Questions, Hypotheses, and Tasks</th></tr>
<tr><td>Problem</td><td colspan="3">Current coordination mechanisms in engineering design are often focused on streamlining the design process by excising iteration via single interactions focused on the communication of pertinent, semantically rich information content. While this is an effective modus operandi for changeovers associated with sequential, clearly distinct phases of a product realization process (e.g., Design and Manufacture), it is not in general suited for decentralized co-design. Continued interactions among decision-makers throughout the course of a collaborative design process are thus not supported. Stakeholder interactions must be both effective and efficient in satisfying the constraints defining their respective design sub-problems while achieving system level objectives. A fundamental challenge lies in that considerations of interacting designers continuously evolve due to changes in understanding, model fidelity, and technology, to name a few. Current decision models and coordination mechanisms are quasi static and thus render the reflection of changes in information content virtually impossible without complete reformulation. Furthermore, the existence of feasible solutions is often assumed a priori and balanced outcomes among sub-systems (by means other than reformulation of constituents as a single problem) are unlikely. A systematic means of focalizing the otherwise independent efforts of stakeholder, charged with the resolution of coupled design sub-systems, ensuring their congruency in decentralized design is required.</td></tr>
<tr><td rowspan="2">Primary</td><td>Research Question:</td><td colspan="2">How can collaboration in engineering design be modeled so as to facilitate the reflection of evolving stakeholder aspirations, while ensuring the existence of acceptable solutions and promoting the unbiased achievement of system level objectives?</td></tr>
<tr><td>Research Hypothesis:</td><td colspan="2">Changes in information content and the evolving aspirations of individual stakeholders can be captured using modular, computer interpretable constructs, designed to effectively separate declarative from procedural information. The resultant domain independent templates constitute a standardized means of representing design decisions and required interactions, that facilitate the organization overhead. The coupled, but otherwise independent, efforts of stakeholders in decentralized design can be focalized via consistent communication of required information content throughout the tenure of their relationship, thereby (1) ensuring the existence of mutually desirable solutions and (2) maintaining stakeholder autonomy over sub-problem considerations. Stakeholder assessment of interaction effects can be employed to guide system level tradeoffs so that solution quality is improved through a reduction in implicit biases (problem specific but non-representative of overarching objectives).</td></tr>
<tr><th colspan="2">Secondary Research Questions</th><th>Secondary Hypotheses</th><th>Tasks</th></tr>
<tr><td>I</td><td>How can design problems be modeled so that the reflection of changing information content and evolving stakeholder aspirations can be accommodated while maintaining structural consistency?</td><td>Individual decision-maker considerations may be modeled using domain independent, modular, reusable decision templates, based on Decision Support Problem constructs, that can be captured, archived, analyzed and manipulated on a computer. Stakeholder interactions may be formalized in a similar fashion, depending on their level of cooperation. The required “genericism” of the underlying decision models is achievable via a separation of the declarative (i.e., problem specific information) from the procedural (i.e., process specific information) flows of information. Process may be composed from templates.</td><td>▪ Development of modular, object-oriented building blocks for representing design decisions and interaction protocols.
▪ Separation of declarative from procedural information flows within the newly developed constructs.
▪ Complete modularization of the models so that both partial and complete (1) changes in problem formulation and (2) refinement of information content are facilitated.</td></tr>
<tr><td>II</td><td>How can the communication of information, required for the resolution of strongly coupled design problems, among collaborating stakeholders be structured so that their efforts are focalized and their subsequent interactions are rendered both effective and concise?</td><td>The interactions of collaborating stakeholders (throughout the tenure of their relationship) may be structured so that their respective progress is focalized and the existence of mutually desirable solutions is ensured. Required interactions can be made both efficient and effective through the exchange of decision-critical information content. Additionally, stakeholder autonomy over sub-problem considerations is maintained, while clarifying constraints stemming from both the system as well as from other sub-systems. Space filling experiments can be used to establish realistic targets for designer objectives and utilize resources more effectively, while reducing computational costs.</td><td>▪ Development of a systematic means of establishing a collaborative design space that is independent of the protocol used for striking tradeoffs.
▪ Formalization of the manner in which a collaborative design space may be explored and refined in order to establish stakeholder performance potential, set realistic targets for objective achievement, and identify mutually desirable regions of this collaborative design space established.</td></tr>
<tr><td>III</td><td>How can stakeholder interactions be guided so that design freedom is not reduced unnecessarily and system level performance is enhanced?</td><td>A strategy for sequencing the interactions of collaborating decision-makers and managing tradeoffs in collaborative design spaces can be developed based on the relative sensitivity of stakeholder system level objectives on both internal (under their control) and external (not under their control) design variables. The goal is to reduce the undesired and implicit effects of implicit biases associated with the problem at hand in order to improve shared resource utilization.</td><td>▪ Investigation of stakeholder objective responsiveness to internal and external variables, as well as achievement potential.
▪ Development of a coordination mechanism focused on guiding stakeholders in determining sequence and control assignment in co-design.</td></tr>
</table>

1.3.4 Research Vision - A Framework for Agile Collaboration in Engineering

Having elaborated upon the secondary research questions and hypotheses in Section 1.3.3, the overarching research vision, a picture of which may be formed by considering the one-to-one mapping between research questions, hypotheses, and tasks of the same number in Table 1-4, is now presented. In light of this bigger picture, presented by Secondary Research Questions 1 through 3, the Primary Research Question to be investigated in this research is reviewed: *How can collaboration in engineering design be modeled so as to facilitate the reflection of evolving stakeholder aspirations, while ensuring the existence of acceptable solutions and promoting the unbiased achievement of system level objectives?* It is in response to this question that a **F**ramework for **A**gile **C**ollaboration in **E**ngineering, based on the integration of innovative modeling techniques, systematic stakeholder focalization, and impact/sensitivity assessment, is developed.

An overview of the proposed **F**ramework for **A**gile **C**ollaboration in **E**ngineering (FACE) in terms of its various constituents is offered in Figure 1-10. In this figure, FACE is shown to be composed of two complementary, yet distinct elements, namely a **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod (CDSFM) and an **I**nteraction-**C**onscious **C**oordination **M**echanism (ICCM). While the first aspect is fixed, regardless of the manner in which stakeholder interactions are structured, the second is modular and can be switched out, depending on the particular problem at hand. Virtually any structured means of collaboration (whether game theoretic, negotiations based, optimization driven, cooperative, non-cooperative, etc.) requires the existence of a solution in order to function in its intended manner. This problem is addressed via the

CDSFM, which can be used in tandem with any of these methods as a preparatory step. This is emphasized by the solid box, surrounding the CDSFM in Figure 1-10. The ICCM, on the other hand, constitutes a viable alternative to currently instantiated collaboration schemes, that is most suited to decentralized *co-design*. Since the role fulfilled by this element may not be appropriate for all design processes, depending on enterprise level considerations such as the extent to which information may be shared among different stakeholders, it is not essential. Other mechanisms may be used its stead. This is indicated by the dashed outline, surrounding the ICCM in Figure 1-10. It is for these reasons that a distinction is made between the two complementary components, and a more general framework (rather a single, comprehensive method) is presented.

To summarize, the systematic means of constructing a design space composed of feasible solutions, offered is offered in this dissertation, is the more fundamental contribution. The CDSFM addresses a crucial aspect, the end result of which (i.e., the existence of a solution) is usually assumed. The interaction-conscious coordination mechanism instantiated in the ICCM, on the other hand, is meant only for a special set of circumstances, namely those suitable to and warranting *co-design*. Thus, although this body of work as a whole is grounded in an effort to facilitate and support this somewhat unconventional paradigm of consistent and extensive interaction, its usefulness and applicability is not limited to this *modus operandi*. Instead, as will be explored further in Chapters 4, 5, and 6, virtually any conflict resolution mechanism can be accommodated. With this in mind, the inherent benefits can also be divided into two complementary aspects as illustrated in Figure 1-10. The first sets the stage for the second, by ensuring the possibility of success. Thus, whereas the second requires the first to succeed, the converse is not the case. In fact, the systematic method for *identifying* an *establishing* the collaborative design space (i.e., CDSFM) is totally independent of the coordination mechanism for *exploring* and *managing* this collaborative design space in a system conscious fashion (i.e., ICCM).

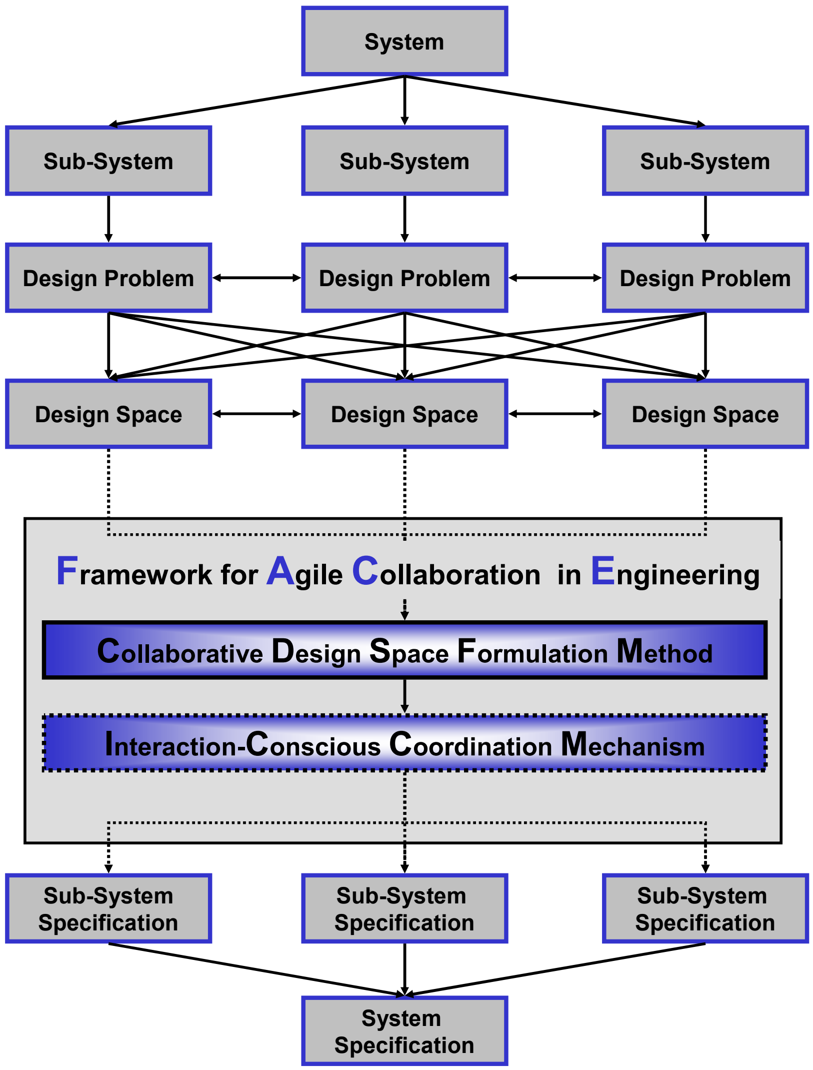

Figure 1-10 - A Framework for Agile Collaboration in Engineering

Taking a step back and contemplating the title, chosen to describe this work, three questions that deserve closer consideration come to mind.

Firstly, why is the body of work, documented in this dissertation, a framework? A *framework* is commonly defined as being a set of assumptions, concepts, values, and practices that constitutes a way of viewing reality [2]. In light of this consideration, the background, context, and philosophy expounded upon in Section 1.2 are both prerequisite to and culminate in the proposed **F**ramework for **A**gile **C**ollaboration in **E**ngineering. In object-oriented systems, a *framework* is a set of classes that embodies an abstract design, furnishing solutions to a number of related problems [101]. While the CDSFM aspect provides a solid foundation for any type of collaborative design, regardless of the exact nature of the ensuing communications, tradeoffs may be resolved in whatever manner chosen, an example of which is the complementary ICCM, developed in tandem. Considering that the proposed framework is composed of both essential and optional elements, as illustrated in Figure 1-10, it lays the foundation for decision-makers charged with the resolution of strongly coupled design problems to collaborate in an agile manner. Thus, although stakeholders guided consistently, they are nevertheless not restricted to following a preset format. Using the term *framework* thus emphasizes the ability to customize, tailoring one's approach to the particular problem at hand.

Secondly, what is agile about the proposed approach to conflict resolution? Agility is synonymous with legerity and nimbleness, usually describing the ease, speed, and precision with which movements and adjustments associated with unpredictable changes in reality are executed. Agility emerged as an engineering and enterprise related concept with the advent of *Agile Manufacturing* in the early 1990s. This was due in part to the end of the cold war and the consequent need for US manufacturing to transition from meeting defense to commercial interests, while retaining the option of switching back at a moments notice, should the need arise. Regarded as a business notion, rather than a buzzword, this umbrella term came to encompass a comprehensive slew of approaches aimed at focusing companies both internally and externally via supportive actions, communications, education, training (centered on greater concurrency), and tighter integration of activities [90]. The concept of *agility*, as modeled in this dissertation, is akin to the idea of *Agile Manufacturing*; the goal is to increase the reflection of current information content and support the ability of stakeholders to adapt to the dynamic considerations associated with complex design processes, characterized by limited/shared resources and control over their commitment. The central aim is to ensure the congruency of stakeholder efforts by focalizing the manner in which they proceed in the resolution of their respective design sub-problems. It is through increasing the frequency of their interactions and systematizing the communication of decision critical information content (depending on the manner in which the various design sub-problems are coupled) that the agility of stakeholders is increased. Stakeholders remain *agile* because potential problems in terms of irreconcilable mismatches are identified much earlier on in the design process. This stands in marked contrast to the majority of currently instantiated means of collaboration, where such mismatches are not identified until design sub-problems have been specified in their entirety. The earlier that collaborators are made aware of actual or even potential divergence, the easier it is for them to correct their course and ensure the convergence of their objectives to satisfying system level requirements. Additionally, stakeholders are able to adapt the framework to meeting enterprise level concerns and problem specific requirements.

Thirdly, what constitutes collaboration in activities associated with engineering design? The concept of *collaboration* can have many differing interpretations – cooperation, non-cooperation, outright competition, or even *co-design*, as advocated in this dissertation. Whether one particular instantiation is better than the next, greatly depends on the nature of the underlying conflict. Often, it is the (reward) structure of the business that dictates the level to which interacting stakeholders share information and the extent to which they are willing to compromise. This is especially true when considering a federated value chain where incentives to strategize and employ negotiation tactics supersede those of open cooperation. Although the implicit goal of this research is to provide a feasible alternative to current game theoretic means of conflict resolution, aimed at increasing the level of integration among stakeholders, these traditional protocols are also supported. This is due to the realization that cooperation as close as required for *co-design* may not always be (1) practical or (2) computationally feasible. Especially, because this mechanism constitutes the highest level of collaboration apart from perfect cooperation. It is important to realize that perfect cooperation, though destined to yield the best results, requires reformulation of constituent decisions as a single decision and thus conflicts with the notions of decentralized design and the continuous alignment of domain expertise with design sub-problem resolution, both central to this body of work. Consequently, the two components, emphasized in Figure 1-10, are clearly distinguished in this dissertation. As indicated, it was also for this reason that the decision was made to offer a more general **F**ramework for **A**gile

Collaboration in **E**ngineering, amenable to myriad levels of collaboration, rather than a **F**ramework for **C**o-**D**esign, restricted to one, sole mechanism. This framework can be used in concert with a number of different approaches and is not limited to the coordination mechanism, proposed in Section 5.1. This division also reflects the espousal of modularity as a solution principle throughout this dissertation.

Before proceeding, it is important to note that the novel means of modeling decision-centric design processes via templates, proposed in answering Research Question 1 is merely a means of instantiating the framework developed in response to Research Questions 2 and 3, aimed at reducing the associated computational burden. Implementation of this technology, documented in Chapter 3, is, however, by no means necessary to reap the benefits inherent in the concepts developed in Chapters 4 and 5. It is these latter aspects that comprise the crux of the research, presented in this dissertation. With this in mind, an overview of the research contributions is presented next.

1.3.5 Research Contributions

A brief summary of the fundamental goals pursued, requirements addressed, scope focused upon, scale of application, limitations of approach, and key assumptions underlying the **F**ramework for **A**gile **C**ollaboration in **E**ngineering (FACE) is provided in Figure 1-11. A discussion of the manner in which validation and verification will be addressed in this dissertation follows in Section 1.4.

Framework for Agile Collaboration in Engineering

Fundamental Goals

- ☑ Model design problems and interactions in an easily updateable fashion
- ☑ Coordinate interactions among collaborating domain experts at the decision level in light of dynamic design considerations
- ☑ Sequence interactions of stakeholders so that design freedom associated with collaborative design space is not closed unnecessarily
- ☑ Support the establishment, structuring, and management of collaborative design spaces to enable stakeholder "*co-design*"

Template-Based Approach to Collaborative Design

Fundamental Requirements

- ☑ Consistent representation of stakeholder design sub-problems, regardless of domain
- ☑ Consistent structuring of stakeholder interactions throughout the course of collaboration

Decision-Centric Perspective of Engineering Design

Scope

- ☑ Solution of Strongly Coupled Design Decisions
- ☑ Identification and Exploration of Collaborative Design Spaces
- ☑ Decentralized, System Conscious Management of Tradeoffs

Scale

- ☑ Multiple Strongly Coupled Design Variables (Demonstrated for 2,3, & 5+)
- ☑ Multiple Designers (Demonstrated for 2 & 3, Argued for n)
- ☑ Problems of Representative Complexity (Pressure Vessel & LCA Design)

Limitations

- ☑ Formalization of Mathematical Models Must Be Possible
- ☑ Data or Information for Decision-Making Must Be Complete

Key Assumptions

- ☑ Well Defined Design Problems
- ☑ Sufficient Information to Formulate Decisions Mathematically
- ☑ Clear Understanding of Design Problems, Design Sub-Problems, and Relationships
- ☑ Availability or Ability to Create Simulation Models
- ☑ Extrinsic, Non-Localized Domain Expertise
- ☑ Design Processes are Decision-Centric and Can Be Expressed Accordingly
- ☑ Designers Have a Certain Level of Expertise
- ☑ Designers Know What They Want

Figure 1-11 - A Summary of Goals, Requirements, Scope, Scale, Limitations, and Key Assumptions Relating to the Framework for Agile Collaboration in Engineering

As indicated, the research, documented in this dissertation, is centered on the development of a **F**ramework for **A**gile **C**ollaboration in **E**ngineering that is focused on providing a consistent level of decision support to designers, acting as stakeholders in the resolution of strongly coupled design problems over which they share control. Decision support, here, refers to the cumulative means of modeling, structuring, and negotiating solutions to stakeholder decisions and any required interactions. Consideration is also given to the effective structuring of design processes and proper reflection of decision critical information content alongside any dependencies. Emphasis is placed on development of theory, creation of domain independent constructs for characterizing and modeling decisions, formalization of interactions, and computer implementation of suitable models for use in a distributed product realization environment. The primary contribution, however, is that of a method for (1) systematically constructing and exploring collaborative design spaces and (2) managing the associated tradeoffs in a system conscious manner. These are referred to as the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod (CDSFM) and the **I**nteraction-**C**onscious **C**oordination **M**echanism (ICCM), respectively, and together comprise the **F**ramework for **A**gile **C**ollaboration in **E**ngineering

As a result of the proposed framework it will be possible for interacting stakeholders to collaborate effectively throughout the duration of their interaction, along an event-based design timeline; support is provided for achieving system level objectives, while satisfying design sub-problem constraints in light of evolving information content. Outcomes include: (1) the development of modular, flexible, computer interpretable decision and interaction templates, (2) the implementation of a novel modeling approach, based on the successful separation of declarative and procedural information flows, (3) the ability for interacting decision-makers to update design-decision models effectively and efficiently, and most importantly (4) the formalization of a communications protocol, providing a consistent interface between stakeholders, charged with solving coupled design sub-problems as well as ensuring the existence of mutually acceptable solutions, and (5) the means to determine stakeholder precedence in the resolution of coupled decisions via the assessment of design sub-problem impact on system level tradeoffs and design freedom retention. Potential future benefits include reduced time-to-market for derivative, adaptive, and variant designs and increased modularization of design and supply chains in enterprise design.

1.4 VALIDATION AND VERIFICATION OF THE PROPOSED METHODOLOGY WITHIN THIS DISSERTATION

Validation is defined as an act, process, or instance of validating; especially: the determination of the degree of validity of a measuring device. Validating is then defined as 1) making legally valid, granting official sanction to by marking, or confirming the validity of and 2) supporting or corroborating on a sound or authoritative basis (e.g., experiments designed to validate the hypothesis). Verification is the act or process of verifying or the state of being verified, the establishment of the truth, accuracy, or reality of. Both verification and validation are synonymous with the act of confirming [3]. The manner in which such a confirmation of ideas, concepts, or hypotheses is accomplished varies greatly from field to field. Consequently, the degree and nature of proof required differs accordingly. Research in engineering science, for example, is validated by means of simulation, empiricism/experimentation, and formal proof. Much the same is true for research in Psychology, relying mostly on empiricism, experimental method, and the natural science model. Philosophers rely on formal proofs and rhetorical persuasion. Verification in legal matters, however, is subject to interpretation and proper citation of relevant case law. The internal consistency of an argument thus becomes crucial. Much the same is true for validating engineering design methodology. With this in mind, Smith [228] states the following:

> *With respect to design research and development, the intent of the validation process is to show the research and development and its products to be sound, well grounded on principles or evidence, able to withstand criticism or objection, powerful, convincing, and conclusive; provable. In a practical sense, validation considerations can be interpreted as a major means of providing quality assurance.*

The validation strategy implemented in this thesis is based on the idea of the validation square (Figure 1-12) proposed by Pederson et al. [180] and strongly modeled after implementation by Seepersad [203]. The combined vision has recently been published as a chapter in "Decision-Based Design: Making Effective Decisions in Product and Systems Design" [211]. As indicated by Pederson and co-authors, validation and verification in engineering practice has traditionally taken the form of formal mathematical induction and/or deduction coupled with analytical and/or numerical extension. While this approach is ideally suited when applied to work that is rooted primarily in mathematics, application to research that is more subjective in nature requires additional rigor. As stated, the line of argument, required for validating advances in design methods such as those proposed in this thesis, is akin to that of legal research, where points are subject to interpretation and proper citation of case law. As Pederson and coauthors have noted, "knowledge validation (in such cases) becomes a process of building confidence in its usefulness with respect to a purpose" [180].

According to their framework, illustrated in Figure 1-12, the validation of design methods can then be accomplished through a combination of (1) *Theoretical Structural Validation*, (2) *Empirical Structural Validation*, (3) *Empirical Performance Validation*, and (4) *Theoretical Performance Validation*.

In this dissertation, *Theoretical Structural Validation* is accomplished by (1) critically reviewing relevant literature and (2) evaluating the implemented constructs with regard to comparative advantage, limitation, and acceptable domain of application. The majority of Chapter 2 is devoted to this effort. As pointed out by Seepersad, ample use of diagrams, flowcharts, and checklists can be extremely useful in ensuring internal consistency. *Empirical Structural Validation* is addressed through illustration of example relevance (i.e., ascertaining that the proposed methods are applicable to the examples considered, and that these are indeed representative of those problems (commonly encountered in engineering design) for which the approach to be demonstrated is intended). Also, the data associated with the example applications must be useable in supporting conclusions drawn. With this in mind, the appropriateness of each of the two examples, forming the bases for Chapters 7 and 8, as well as the tutorial example, used for illustration purposes in Chapter 6, is discussed in detail. *Empirical Performance Validation* is, in a sense, a measure of the method's usefulness. Validity with respect to this aspect can be established by using examples in such a way that their outcomes can serve as a means of quantitative evaluation. Suitable metrics for determining a method's usefulness should thus be closely related to objectives considered in the problem itself. In this dissertation, confidence in this aspect is established by quantitative and qualitative comparisons of results obtained using the proposed constructs with those resulting from the application of generally accepted methods. As intuited by Seepersad, another important aspect of this validation component is to establish that the resulting 'usefulness' is indeed a result of the method used and not just a matter of chance. In the case of engineering optimization, this can be achieved through demonstrating internal consistency and overall accuracy of data implemented in various examples. For instance, a number of different starting points may be employed, constraints relaxed, goals changed, the relative importance of goals altered, etc. Due to the nature of the developments and examples presented in this dissertation, however, empirical performance validation is more qualitative than quantitative in nature. This is because changes in many problem parameters effectively alter the problem being solved. Consequently, the focus is shifted to evaluation by comparison and confirmation of intuitiveness of results. Outcomes should make sense with respect to engineering judgment and be consistent with expectation. Additionally, attention will be paid to ease of implementation and intuitiveness of the method as a whole. Finally, the role of *Theoretical Performance Validation* in this dissertation is to extend confidence in the validity of the approach beyond the scope of the examples presented. This effort takes the form of establishing these as being representative of a larger class of problems, commonly encountered in engineering practice. General usefulness and future potential of the method can thus be inferred, through requiring a slight "*leap of faith*". The details of the validation strategy implemented in this thesis and the location of relevant material are summarized in Figure 1-12. The so called *"Validation Square"* will also serve as a running icon throughout this thesis to reinforce and foster reader awareness.

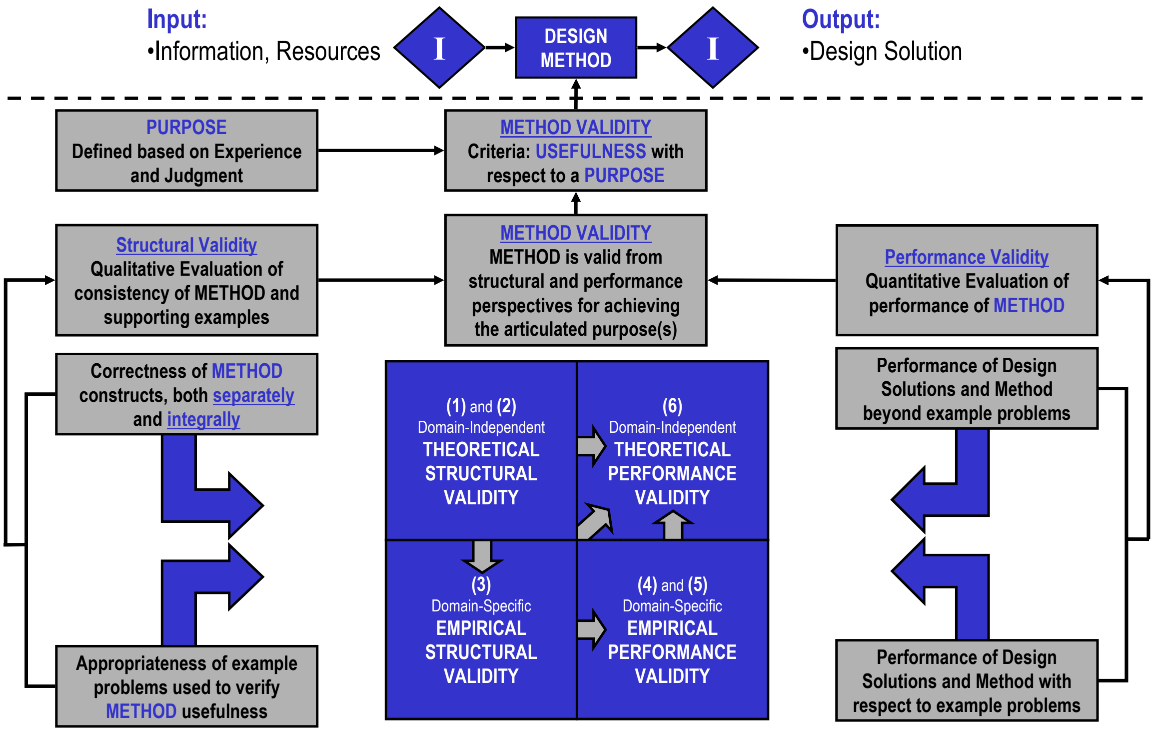

Figure 1-12 - The Validation Square (Modified from Ref. [211])

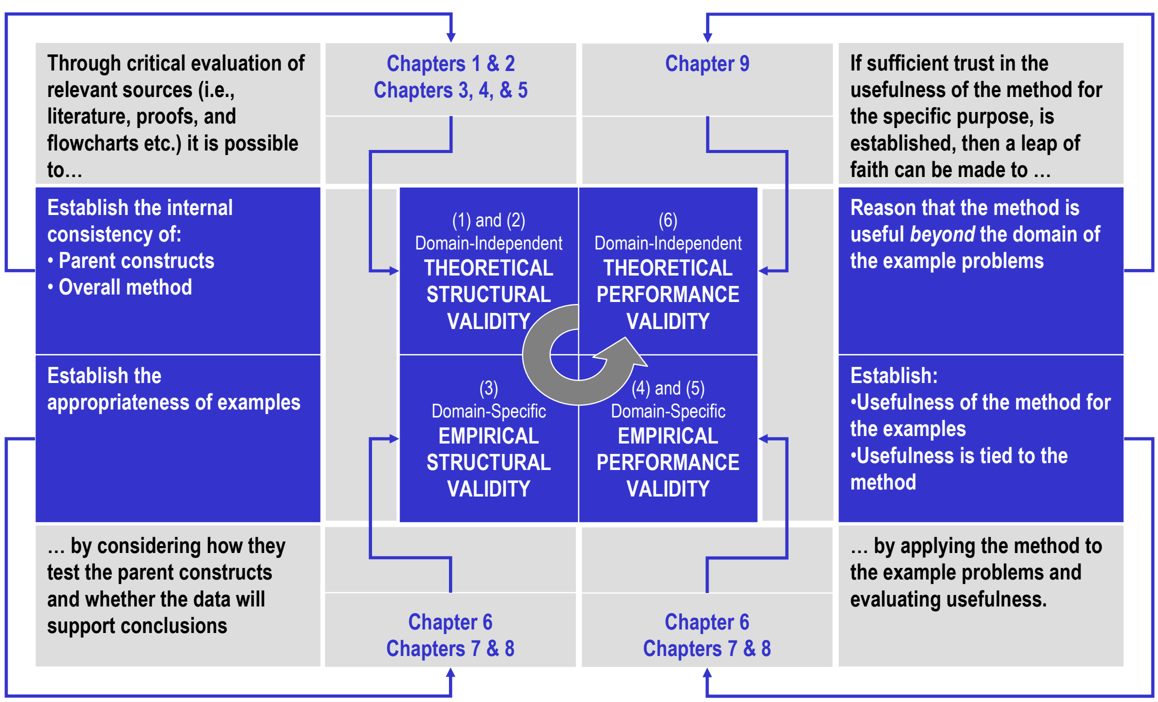

Figure 1-13 - Validation Strategy for Dissertation

1.5 ORGANIZATION OF THIS DISSERTATION

In this section, the organization of this dissertation is laid out. Chapters 1 through 3 lead up to the main contribution in Chapters 4 and 5. Chapters 6 thought 8 are focused on implementation, application, and attainment of results. Finally, contributions are reinforced, limitations clarified, and assertions made in Chapter 9. Individual chapters are organized so as to highlight key contributions and facilitate reader comprehension. The structure is built around the validation strategy, outlined in Section 1.4, as follows.

1.5.1 Answering Research Questions and Validating/Verifying Hypotheses within this Dissertation – A Roadmap

The organization of this dissertation is outlined in Figure 1-15. This diagram constitutes a roadmap to understanding the role that individual chapters play in cementing the validity of the hypotheses, formulated in response to the various research questions posed in Section 1.3. As in Figure 1-13, individual chapters are tied to relevant aspects of the validation and verification strategy outlined in Section 1.4. This figure also serves as a *running icon* and will be revisited periodically at the end of each chapter in order to (1) emphasize the purpose individual chapters fulfill in the structure of this dissertation, (2) highlight aspects pertinent to validation and verification, and (3) ensure cohesion of the text via inter-chapter connectivity.

As indicated in Section 1.4, validation and verification will be considered from various perspectives, the combined discussion of which, should build ample confidence in what is proposed. In fact, the structure of this dissertation is centered on this strategy, as illustrated in Figure 1-15. Each of the chapters plays a unique role in substantiating the claims, emanating from the various hypotheses formulated in response to the research questions posed. This is underscored in Figure 1-14, where the distribution of specific aspects of the overarching validation and verification strategy throughout this dissertation is hightlighted. As indicated, **Theoretical Structural Validation (TSV)** is addressed in Chapters 1 through 5, **Empirical Structural Validity (ESV)** and **Empirical Performance Validity (EPV)** in Chapters 3, 6, 7, and 8 and **Theoretical Performance Validity (TPV)** in Chapter 9, where all elements are tied together. A more detailed explanation follows.

The general context for this work is provided in Chapter 1. The discussion is designed to establish need, motivate the endeavor, scope out extent, justify the chosen approach, and delineate a strategy for validation and verification. With this in mind, Chapter 2 is dedicated to **Theoretical Structural Validation.** Pertinent research is reviewed and critically analyzed. This literature survey is focused on existing concepts and constructs for modeling tradeoffs, conflicts, processes, products, design decisions, as well as preferences and framed in terms of relevant background material. The discussion is tied to the general theme or context of decentralized, simulation-based complex systems design. Specific aspects of **Theoretical Structural Validation** are addressed in the beginning and ending sections of Chapters 3, 4, and 5 with respect to *Hypotheses 1*, *2*, and *3*, respectively. Further elements of this validation square component can also be found in Chapter 1.

Validation & Verification	Chapter								
	1	2	3	4	5	6	7	8	9
TSV	20%	50%	10%	10%	10%				
ESV			10%			30%	30%	30%	
EPV			10%			30%	30%	30%	
TPV									100%

Figure 1-14 - Validation and Verification within each Chapter

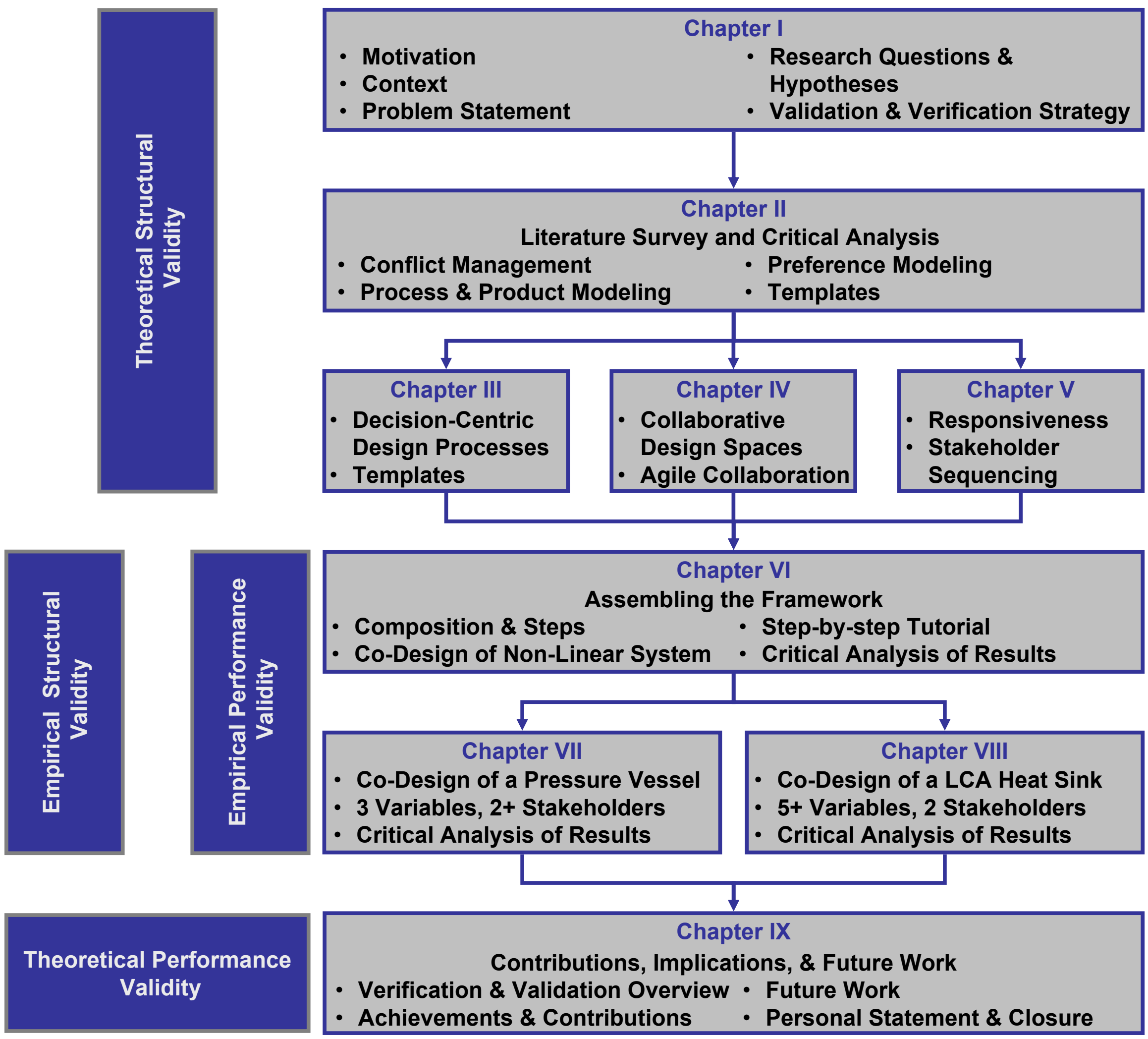

Figure 1-15 - Dissertation Roadmap

As one might expect, the literature survey, conducted in Chapter 2, is followed by the developments central to this dissertation. Specifically, template-based modeling of decision-centric, simulation based design processes is the subject of Chapter 3. Both decision templates for capturing decision critical aspects of stakeholder design sub-problems and interaction templates for striking required tradeoffs among conflicting objectives are formalized. Execution, persistence, and re-use are demonstrated via simple, but representative design examples – a helical spring and a pressure vessel – contributing to the establishment of **Empirical Performance Validity.** Construct modularity and genericism are also discussed. Chapter 4 is devoted to ensuring the existence of mutually acceptable solutions in the decentralized resolution of strongly coupled decisions. Specifically, a **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod (CDSFM) for systematically constructing and exploring collaborative design spaces is developed. Given that such a solution is indeed feasible, the question of how to properly sequence decisions made by constituent stakeholders arises. This subject is addressed in Chapter 5, where an **I**nteraction-**C**onscious **C**oordination **M**echanism (ICCM) for managing the associated tradeoffs in a system conscious manner is detailed.

Chapters 6, 7, and 8 comprise the core of **Empirical Performance Validation** in this dissertation. An argument for the **Empirical Structural Validity** of each of the examples considered in these chapters is made by illustrating relevance, as defined in Section 1.4. Consequently, each of the examples is implemented in turn to build confidence in the usefulness of the framework and its components as well as illustrate its application.

The comprehensive research vision is established in Chapter 6, where the proposed **F**ramework for **A**gile **C**ollaboration in **E**ngineering, composed of the building blocks synthesized in Chapters 3 through 5, is first (1) assembled and (2) applied. The application is focused on a system of non-linear equations and executed in tutorial fashion. Extensive comparisons to results obtained using more traditional means of conflict resolution are conducted. Although this example is extremely simple, it is relevant and representative of engineering challenges because it is strongly coupled and was designed to sport diametrically opposed objectives. Furthermore, it is appropriate because it is limited to two design variables and lends itself to graphic visualization, an important attribute considering the inherent complexity of the proposed approach.

Chapter 7 is focused on the decentralized design of a pressure vessel, a common design example that is ideally suited for the purpose of **Empirical Performance Validation** because (1) it has been used extensively throughout the literature in demonstrating tradeoff management, (2) it is limited to three design variables and tradeoffs can hence be visualized using color swatches, and (3) exhaustive search is feasible, allowing for objective, rather than subjective evaluation of results obtained. It is also through these characteristics and consideration of the historical nature of this application that **Empirical Structural Validity** is ascertained.

Chapter 8 is focused on building confidence in the scalability of the methods for problems characterized by more than five design variables and affirm the **Empirical Performance Validity** of the constructs . This is accomplished using a design example taken from the realm of materials design. Specifically, a Linear Cellular Alloy CPU heat sink is designed by two collaborating stakeholders – a structural and a thermal domain expert. Confidence in the **Empirical Structural Validity** of this example is established by considering that it is a design problem of substantial complexity and quite representative of the class of problems for which the method is intended.

For each of the examples, **Empirical Performance Validity** is addressed by evaluating the usefulness of the method and quality of results in comparison to those obtained using alternative means (i.e., games, optimization, and exhaustive search). The type and nature of the comparisons varies from one case to the next. This is because the goal is *implementation* and not *duplication*. Finally, research questions and corresponding hypotheses are revisited in Chapter 9, where a summary of their validation and verification throughout the dissertation is also provided. An overview of the achievements and contributions brought forth in this dissertation is also given and a discussion of inherent limitations and avenues for future exploration provided. The final component of the espoused validation strategy, namely **Theoretical Performance Validity**, is addressed by illustrating the extensiveness and relevance of the proposed methods beyond the scope illustrated in the example problems. The research detailed in this dissertation is then tied back to the overarching notion of designing complex systems effectively in the future. This is followed by a brief exposition of potential misconceptions in Section 9.6.

1.5.2 A Framework for Agile Collaboration in Engineering – Building Blocks and their Assembly

As indicated in the preceding sections, it should be clear that there are two primary shortcomings, common to contemporary means of conflict resolution. Firstly, virtually all of the methods proposed in the literature presuppose the existence of a mutually acceptable solution (i.e., a collaborative design space in the words, used throughout this dissertation). Secondly, a majority of these methods are aimed at supporting strategic, *ex post facto* collaboration. These deficiencies are addressed using a two-pronged approach, aimed at (1) guiding stakeholders through the process of creating a collaborative design space, ensuring the existence of mutually acceptable solutions and (2) striking the required tradeoffs in a transparent and system conscious fashion. It is important to note however, that the creation of a collaborative design space is required, regardless of the degree of cooperation among stakeholders.

This approach and its relation to the design process as a whole is illustrated in Figure 1-16. The decomposition of an engineering system (i.e., the motor) into sub-systems (i.e., its components) and assignment of responsibility/control to various stakeholders, based upon expertise is presupposed. Design support begins with the translation of design sub-systems into design sub-problems, modeled as decisions (and presented as response surfaces). The templates developed in support of Research Question 1 are means of facilitating their instantiation and ensuring uniformity of structure. The **F**ramework for **A**gile **C**ollaboration in **E**ngineering thus supports the formulation of design problems (coupled, due to their combined contribution to a common system and interdependent utilization of shared resources) as domain specific design sub-problems of standardized structure through *templatization*. The composition of the resultant design sub-spaces (i.e., the sub-system responses) into a shared collaborative design space (i.e., the system response), made up of mutually acceptable solutions, is consequently facilitated through the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod (CDSFM), synthesized in response to Research Question 2. Design processes may be composed via linking stakeholder decision templates using interaction templates and explored. The benefit of maintaining a clear division between coupled design sub-problems (as a result of consistently modular model architectures) is that their integrity is maintained. Consequently, each of the design sub-problems is resolved interdependently (i.e. via identification of design variable values producing acceptable sub-system responses in light of the overarching system response). The manner in which the required tradeoffs may be struck, while avoiding unnecessary reductions in design freedom is determined by implementing the **I**nteraction-**C**onscious **C**oordination **M**echanism (ICCM), developed in response to Research Question 3. This results in design specifications for either a sub-system or a component of the overarching system, considered at the onset of the design process.

The research documented in this dissertation thus deals with (1) the manner in which stakeholders resolve conflicts emanating from mismatched objectives in a system conscious manner and on a more fundamental level (2) the formalized establishment of collaborative design spaces, guaranteed to yield mutually acceptable solutions. The chapters of this dissertation are designed and structured in order to highlight these aspects separately, while maintaining cohesion with the overarching research vision of a comprehensive **F**ramework for **A**gile **C**ollaboration in **E**ngineering. The relationship between the elements employed to develop this vision (i.e., Research Questions, Design Foundations, Research Contributions, and Validation Examples) is illustrated in Figure 1-16.

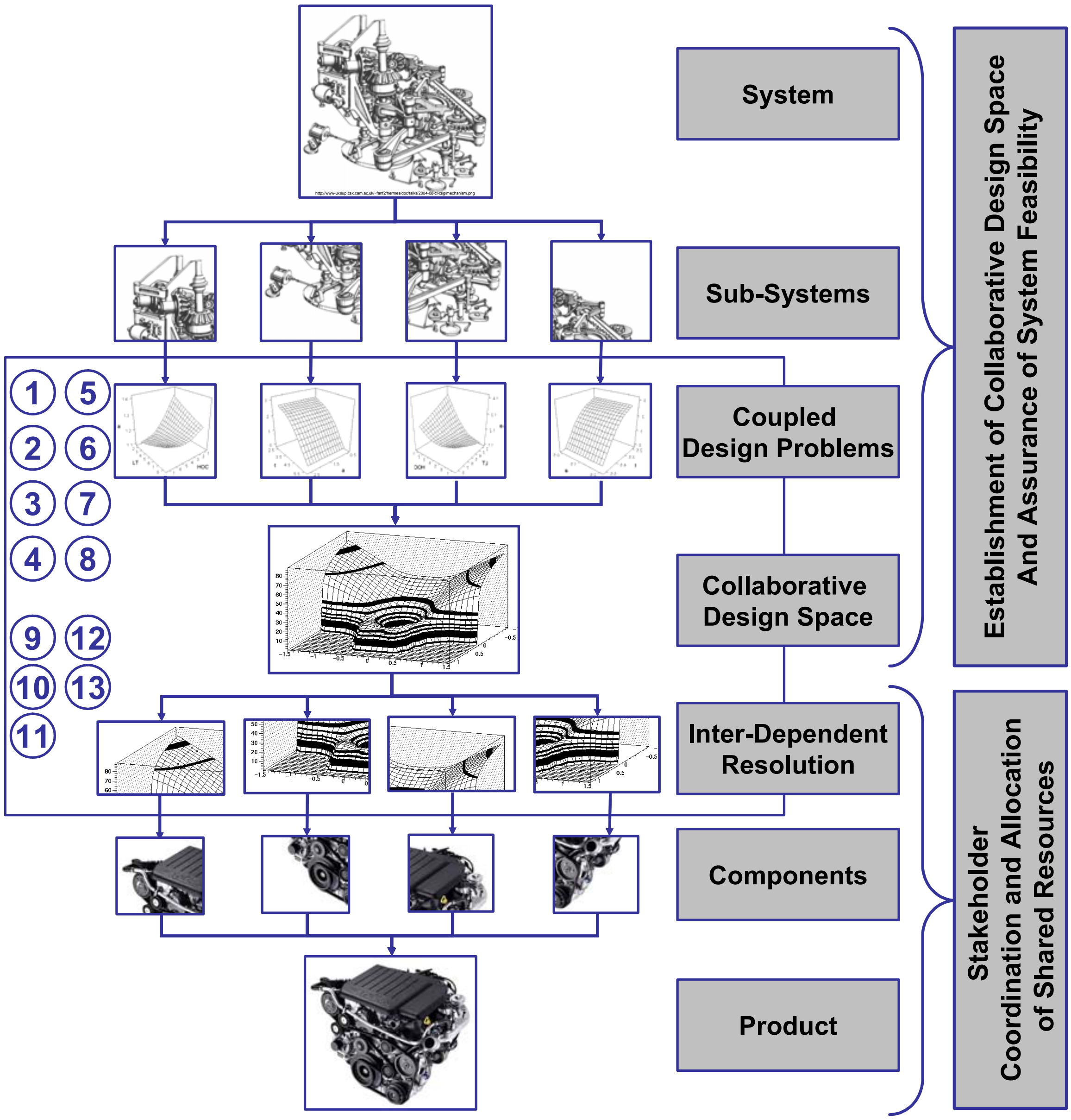

Figure 1-16 - System Feasibility vs. Conflict Resolution

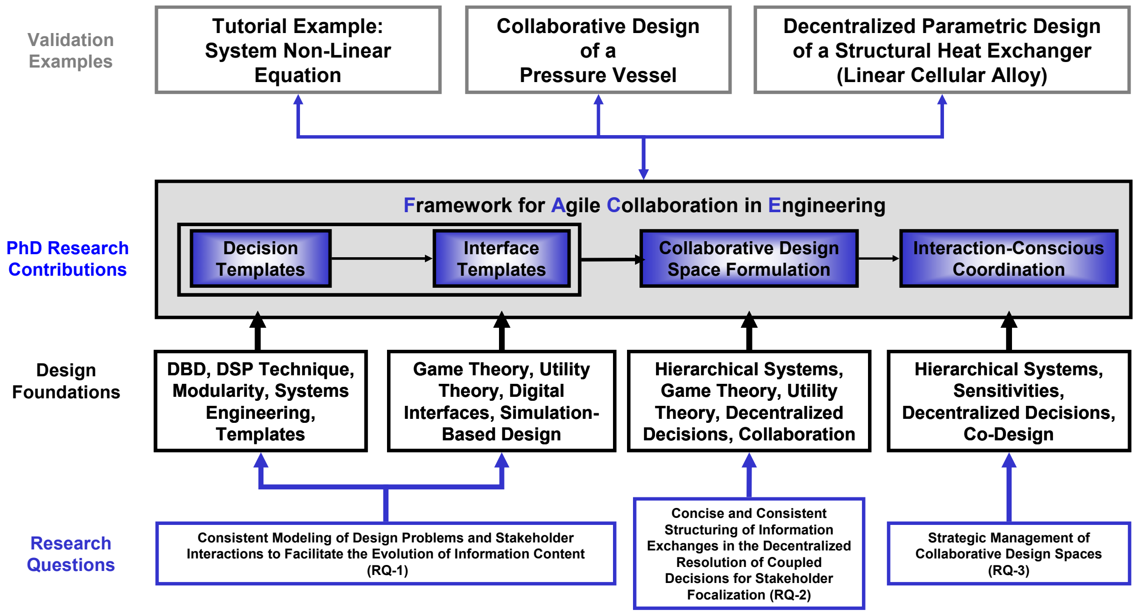

Figure 1-17 - Research Overview

1.6 A LOOK AHEAD

In this chapter the context for the research, detailed in this dissertation, was established. The notion of complexity in engineering systems and the associated impact on the manner in which engineering practice is carried out was explicated in Section 1.1. The fundamental requirements for the establishment of a methodical approach to ensuring congruent interactions among collaborating stakeholders, while maintaining agility in the execution of the design sub-processes they oversee were expounded upon in Section 1.2. Subsequently, the scope, scale, and focus of the research were established in Section 1.3 and the strategy for validating and verifying the proposed methodology introduced in Section 1.4. As indicated in Section 1.4, the significance of the proposed framework with respect to engineering design community as a whole is established in Chapter 2. Specifically, game theoretic means of conflict resolution, collaboration, and trade-off management (as employed within the engineering design literature) are critically reviewed in Section 2.1. This analysis is followed by a comprehensive overview of modeling in engineering design with regard to products (Section 2.3), processes (Section 2.4), and combinations thereof (Section 2.5). Due to the impact of preferences (and, specifically, the manner in which these are captured) on measuring design success, this subject is treated separately in Section 2.6. Since many of the advantages, characteristic of the proposed method, are derived from the concepts of templates and the notion of modularity, these subjects are covered in Sections 2.7 and 2.8, respectively.

CHAPTER 2 - ELEMENTS AND FOUNDATIONS OF A FRAMEWORK FOR AGILE COLLABORATION IN ENGINEERING

In this chapter, the author conducts a literature review of work that is foundational to the approach for agile collaboration, presented in this dissertation. All of the sections in this chapter address the aspect of ***theoretical structural validation***. Specifically, an overview of commonly accepted means and methods of managing conflict in engineering design is provided in Section 2.1, the subject of modeling products in engineering design is treated in Section 2.3, and that of modeling processes in Section 2.4. This is followed by a brief discussion in Section 2.5 of modeling products and processes jointly. Each of the commonly accepted means of product modeling, process modeling, and conflict resolution are presented in light of their respective advantages, shortcomings, and accepted domains of application. Due to the central importance of preferences in the resolution of conflict, Section 2.6 is devoted to the intricacies of their representation. The subject of templates is discussed in Section 2.7 and the notions of openness, flexibility, and modularity, each of central importance to this research, in Section 2.8. The role of this chapter within the validation strategy presented in the first chapter is clarified in Section 2.9 and the material presented in this chapter tied to the material presented in the previous and the next in Section 2.10. To be concise, elements of the various building blocks presented in this chapter are synthesized in Chapters 3, 4, and 5 to comprise the **F**ramework for **A**gile **C**ollaboration in **E**ngineering.

2.1 VALIDATION AND VERIFICATION WITHIN CHAPTER 2

As indicated in Section 1.5.1, the primary aim pursued in this chapter is the **Theoretical Structural Validation** of each of the hypotheses brought forth in this dissertation. As indicated in Figure 2-1, literature relevant to each of the contributions is critically reviewed and relevant gaps are identified. With regard to *Hypothesis 1*, common approaches to product modeling and process modeling are reviewed discussed in Sections 2.3 and 2.4, respectively. A novel alternative for the integrated modeling of products and processes is presented in Section 2.5. The notion of templates is presented in Section 2.7 and key concepts regarding flexibility, openness, and modularity are covered in Section 2.8. The background material for *Hypotheses 2* and *3* is presented predominantly in Section 2.2, where a comprehensive review of conflict management approaches (see Table 2-1) culminates in the identification of key research gaps, as summarized in Table 2-2. The modeling of preferences, which constitutes a core concept in this research, is reviewed in Section 2.6. Additional, background material and context is provided in Section 2.8.

2.2 MODELING AND MANAGING CONFLICT IN ENGINEERING DESIGN

As indicated in Chapter 1, the central theme of this dissertation is the decentralized, system-conscious resolution of tradeoff. With this in mind, the following sections are dedicated to reviewing fundamental aspects and practices of modeling and managing conflict in engineering design. The purpose is to identify and elaborate upon fundamental gaps in the research that require redress.

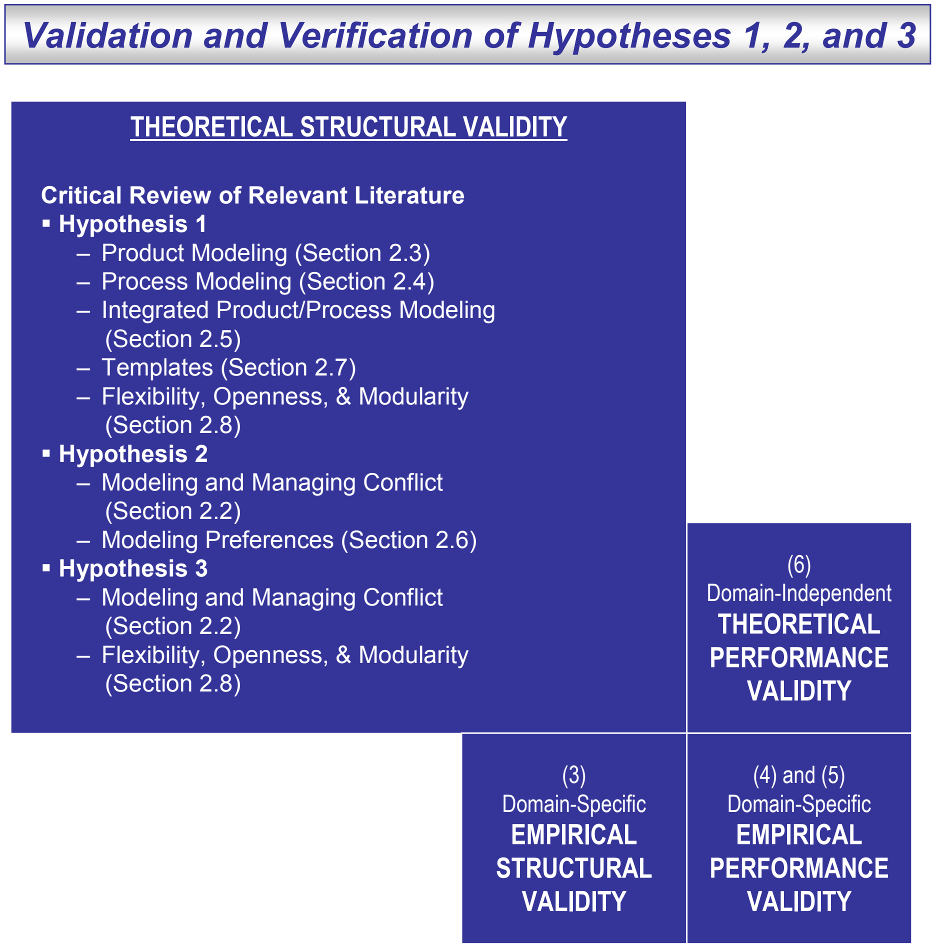

Figure 2-1 - Aspects of Validation and Verification Addressed in Chapter 2

2.2.1 Dependencies, Interactions, and the Assignment of Control in Engineering Design

As a direct result of the growing complexity of engineering problems, elaborated upon in Section 1.1, design efforts are becoming increasingly segmented. Systems are subdivided into myriad sub-problems, responsibility for the solution of which is assigned based on domain expertise, availability, cost, organizational structure, etc. Conflict resolution becomes a fundamental necessity, not only with respect to multiple, conflicting objectives, but also with regard to differences in priorities pertaining to the stakeholders, operating at each level of the system in question. Fundamental to the successful reconciliation of these contentions is effective interaction. It is the underlying hierarchical relationships that govern the nature of these interactions and determine whether they must be carried out on a one time or a continuous exchange-of-information basis.

On the most basic level, interactions among collaborating stakeholders should be considered in terms of the underlying informational dependencies, as embodied within the corresponding information flows. From this perspective decisions in engineering design processes are either *independent*, *dependent*, or *interdependent* (see Figure 2-2). *Independent* decisions do not require consideration of any other decisions or information generated through their resolution and can thus be made in isolation, regardless of temporal considerations. *Dependent* decisions require information obtainable only through the resolution of other decisions and must thus be considered in the sequence prescribed by the underlying information flows. Finally, *interdependent* decisions share information content, factor into one another, and must be considered concurrently. It is important to note that interdependent decisions are also often referred to as being *coupled*. In some instances it is possible to decouple the underlying relationships and impose a sequence, based on the identification and assertion of dominance. Such instances are referred to as being *weakly coupled*. *Strongly coupled* relationships, on the other hand, do not exhibit a clear dominance of one informational dependency over another and must thus be solved concurrently.

It is in regard to such *strongly coupled* relationships that conflict resolution becomes the most crucial. Since the clear dominance of one decision over another cannot be asserted, prioritization of sub-system objectives with respect to one another is subject to contention among individual stakeholders. Usually, these can only assess the impact of decisions within their own areas of expertise and are unable to gauge the affect their choices will produce outside of their domains. More importantly, improvements in system level performance often require sacrifices to be made at the sub-system level. Sub-systems, exceeding their expectations, may have to be restrained to improve the performance of those that fall short. In this manner, more balanced products may be obtained. Since system level tradeoffs require a more comprehensive level of understanding, the stakeholders charged with contributing to a highly segmented and decentralized process are inherently at a disadvantage in accommodating priorities other than their own. Iteration (due to mismatched objectives) is likely and they are forced to communicate in order to gain required information as well as assess their influence on one another. However, communication alone is not sufficient for supporting interactions.

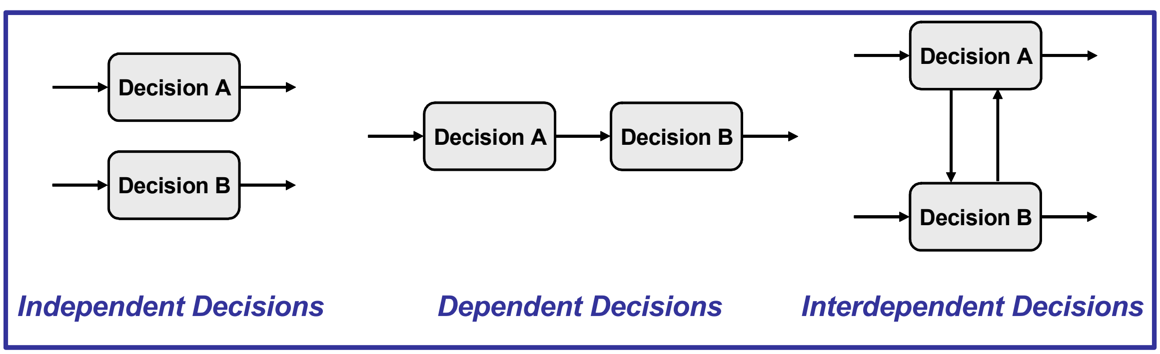

Figure 2-2 - Information Dependencies in Independent, Dependent, and Interdependent Decisions

The issue of effectively modeling the exchanges required for the resolution of *strongly coupled* problems throughout a product's design process has been addressed using a number of different mechanisms ranging from software frameworks (see, e.g., [87,162,268]) to the application of multi-disciplinary optimization approaches (see e.g., [23,119,156,229,231,232,266] and Section 2.2.3), negotiations (see, e.g., [121,201,202] and Section 0), and more fundamental game theoretic principles (see e.g., [39,126,136,187,270] and Section 2.2.5), to which an alternative is proposed in this dissertation.

2.2.2 Solution Algorithms, Communications Protocols, and Coordination Mechanisms

Means of resolving conflict among different decision-makers are commonly referred to as constituting either (1) *solution algorithms* or (2) *communications protocols*; the focus in this research is on (3) *coordination mechanisms*. While there is a certain degree of subjectivity involved in the associated definitions, clear differences do exist. *Solution algorithms* are highly automated and essentially autonomous once the required inputs have been provided, operating akin to black boxes. Consequently, control over the attainment of a solution is essentially relinquished. *Communications protocols* comprise rules of engagement and prescribe the content and format of communiqués. Stakeholder tradeoff strategies are usually captured in functional form, control relinquished, and solutions determined algorithmically.

The methods presented in this dissertation both provide a formalized method of eliciting decision critical information from stakeholders, as well as a consistent means of structuring their interactions along the duration of the engagement. Assessment and exploration are facilitated, in order to guide problem specific process customization. Rather than promoting one time interactions, focused on excising iteration, stakeholder activities are focalized via exchange of decision-critical information. The resulting *coordination mechanism* shares characteristics of both *solution algorithms* and *communications protocols*, although exceeding the functionality of both. While any similarities from the algorithmic perspective are relegated to the modeling level, as described in Chapter 3, formalized interchanges are discussed both in Chapters 4 and 5. Although many of these distinctions are subtle, a careful review of algorithms in Sections 2.2.3 and 2.2.4, as well as, protocols in Section 2.2.5 and 0 will result in a clearer picture.

2.2.3 The Role of Optimization in Engineering Design

Optimization (at least in mathematics) is the discipline concerned with the determination of functional maxima and minima, often subject to various constraints, that constitute the solutions being sought. A distinction is often made between a global optimum and myriad local optima. Clearly, the concept of an optimum implies certainty. Such a definitive quality is quite attractive especially in engineering design, a field traditionally concerned with determining (the best) form, function, and behavior for a particular set of requirements. The fact, that the very notion of being *the best* is usually followed by *for a particular purpose* indicates the inherent subjectivity in any assertion made regarding optimality, as discussed in further detail towards the end of this section.

The basic premise in any optimization is determining the proper combination of design variable values that will result in a desired effect. This requires weighing associated tradeoffs in terms of objective achievement. Here, a fundamental distinction exists between the consideration of a single and multiple measures of merit. Design variable interactions and effects on objective achievement are obscured as the number of "levers" increase. Similarly, increasing the number of objectives introduces the challenge of striking tradeoffs among these, as most appropriate for the particular situation at hand. It is this regard that has constituted a consistent source of contention in design theory.

While some view design as most properly driven by a single consideration, others have a better appreciation for the complexity inherent in any engineering related task. Rarely is there a single driver other than the underlying desire to generate revenue. Certain decision theorists argue that all other criteria can be reduced to the common denominator of profit, in effect condensing the practice of design to nothing more than the generation of alternatives and subsequent selection of the most suitable option. Basing an approach strictly on the maximization of profit, however, assumes total (almost omniscient) knowledge and makes no allowance for either synthesis or compromise. Consequently, although a perspective based on a single driver is ideally suited for economic analysis of the associated business case, it falls short of providing a meaningful framework for supporting the associated engineering processes. Thus while optimization provides a solid mathematical basis for algorithmic decision-making, the resulting optima often instill a false sense of confidence. This can be ascribed predominantly to the lack of formal means for incorporating subjective judgments (other than indirectly via simplifying assumptions).

Optimization essentially requires relinquishing control (*albeit* temporarily) to a third party (i.e., the chosen algorithm) much of the detail, required for a proper assessment of outcomes is hidden inside of the chosen black box. While this is usually a surmountable problem for a single decision-maker, dealing with a single black box, the loss of dominion, shared responsibility, and multiple black boxes associated with decentralized design severely complicate this issue. Consequently, "… interdisciplinary interaction (coupling) tends to present additional challenges beyond those encountered in a single discipline problem" [231]. It is here that Multi-Disciplinary Optimization (MDO) enters into the picture and fills the resulting void from an algorithmic perspective.

MDO has found widespread acceptance in many engineering disciplines (especially the Aerospace community) and focuses on the application of optimization methods to solving design problems via the concurrent incorporation of all disciplines relevant to a particular design problem. Often this field is also referred to as multidisciplinary design optimization and multidisciplinary system design optimization (MSDO). The underlying logic is that an optimum obtained in this concurrent manner must be superior to an optimum determined via sequential optimization of all the disciplines taken into consideration. Although exploitation of sub-system interactions is advantageous, they also dramatically increase a problem's level of complexity.

While piece-wise automated solution of a design decision is entirely acceptable when concerning a single designer who can review and evaluate outcomes based on his or her engineering judgment, it can become a liability when multiple levels of a hierarchy and the associated design sub-problems, assigned to different decision-makers are involved. It is in circumstances such as these that alternative coordination mechanisms that are not purely algorithmic, but involve the various stakeholders effected in a more intimate fashion, are more appropriate. A brief overview of single (see Section 2.2.3.1) and bi-level (see Section 2.2.3.2) MDO approaches follows.

2.2.3.1 Single Level Approaches

Single-Level optimization approaches are perhaps the most widely applied means of integrating the numerous sources of information factoring into any given design decision. This is true whether such decisions occur at the sub-system or the systems level. However, there are a number of shortcomings. Reliance on single-level techniques presupposes a centralized level of understanding that is comprehensive enough for effective interpretation and reconciliation of tradeoffs. A problem of scale also arises. As pointed out by Xiao [267], such a system level effort at integration and synthesis (especially within the context of concurrent engineering) becomes infeasible in complex multi-disciplinary problems. In aircraft design, for example, a single discipline contributes thousands of design variables as reported in Ref. [28]. Although some would hypothesize that such constraints will eventually subside as computational power increases and the efficiency of modeling techniques improves, much the same is true for the level of complexity associated with engineering practice. For example, response surface methodology [141], local approximation methods [128], and variable complexity modeling methods for global approximation [103] have been implemented to alleviate the computational burden resulting from systems level integration. Additionally, the requisite concentration of information in a single point of responsibility, although convenient from a management perspective, effectively thwarts any attempt at retaining agility. As a result, single-level optimization techniques are not suited for addressing the challenges presented in Chapter 1. The reader is referred to two commonly cited and rather thorough surveys of single-level optimization approaches and applications by Balling et. al [23] and Sobieszczanski-Sobieski et al. [233].

2.2.3.2 Bi-Level Approaches

Bi-level optimization approaches are focused on the decomposition of multi-disciplinary design problems into a single system-level problem and several discipline-specific sub-problems. Discipline level teams thus retain autonomy for making their respective decisions, thereby increasing parallelism. As such, bi-level approaches could be considered the algorithmic analogue to the efforts undertaken in this dissertation. Examples include Concurrent Sub-Space Optimization (CSSO) where sub-problems are solved concurrently, while conflicts are mitigated and feasibility is ensured at the systems level [229,266], Collaborative Optimization (CO) in which auxiliary variables take the place of coupled variables in each sub-problem [119,232], and Bi-Level Integrated System Synthesis (BLSS), in which system level problems are formulated using coupled variables only [118,230]. Overall, the primary limitation on each of these novel methods is the "curse of dimensionality" with respect to the coupled variables. This problem is addressed in this dissertation by placing the burden of system level optimization on individual stakeholders, charged with self-assessment of interaction-, contribution-, and responsiveness effects and focalized interaction.

2.2.3.3 Critical Analysis of Mathematical Optimization in Tradeoff Management

Single-level optimization approaches require inter-disciplinary (or inter-sub-problem) iteration in order to ensure feasibility (both at the system and sub-system levels) and an acceptable level of accuracy. The resultant increase in computational complexity is proportional to the number of components being integrated. While parameters that are unique to any particular sub-system can be relegated to the associated analysis routine, all coupled design factors must be integrated into a single system level optimization problem. Since this decision is subject to the same constraints as mathematical optimization, the shear number of parameters being considered can render a solution intractable. Lastly, domain independence disappears and control is necessarily relinquished to a single focal point. It is for these reasons that multi-disciplinary product realization problems must be addressed via decomposition into simpler, more easily manageable sub-problems and a greater degree of autonomy granted to the respective disciplinary teams [22]. Bi-level optimization approaches, though representative of decentralized design structure do not scale effectively due to computational complexity. Both single- and bi-level approaches are effective at solving static and independent problems, but fail to handle dynamic situations, common to the continuous evolution of information content in engineering design.

Despite the many positive contributions of MDO as a field of study to engineering design, the notion of an optimum continues to be misinterpreted and is often misunderstood. Mathematical certainty, though comforting, is necessarily based on assumptions and consequently highly subjective. We, as engineers, should thus never place more confidence in our results than we would place in any of the countless inputs into our mathematical models (i.e., constraints, goals, objectives, preferences, simulations, boundary conditions, weights, etc.). Reference to optima can be quite misleading and often results in a false sense of confidence regarding supposedly deterministic engineering specifications. It is for this reason that a few (this author included) view "…the selection of a single best design as an oversimplification of the problem" [201]. This is not to say that some solutions are not clearly superior to others.

In fact, it will always be possible to determine a *best solution*. This is true even when *satisficing*, as long as the bounds are adjusted appropriately. In this dissertation, any mention of a solution being *the best* solution, thus strictly implies a mathematical optimum based upon the best available information. The philosophy underlying this alternative interpretation of engineering practice is treated in Section 2.2.4.

2.2.4 The Role of Satisficing in Engineering Design and its Embodiment in the Decision Support Problem Technique

2.2.4.1 <u>Satisficing, Bounded Rationality, and the DSP Technique</u>

In the field of economics, *satisficing* is a behavior attempting to achieve at least a minimum level, but not necessarily the maximum value possible, as exemplified in the behavioral theory of the firm. This theory postulates that profit is note treated as a goal to be maximized, but as a constraint. Thus although a minimal critical level of profit must always be achieved, priority thereafter is placed on the attainment of other goals. In engineering design, *satisficing* implies the search for solutions that are good enough. Superiority from a systems perspective is ensured by seeking to reach required values for all measures of interest, rather than over-achieving the performance of any single measure at the cost of the others. The word *satisfice* was coined by Herbert Simon [218-221] in 1957 and is closely related to the concept of *bounded rationality*. In a nutshell, it is posited that people are only as rational as they must be, and in fact relax their rationality when it is no longer required. In terms of engineering design, this principle implies the search for an optimal solution within a sub-range of a problem's solution space, as defined according to the decision-maker's best estimate of the true region of interest in the case of compromise decisions and knowledge regarding the viability of alternatives in the case of selection decisions. A solution determined in this nature is said to be satisficing - superior but not optimal from the system's perspective.

As indicated in Section 2.2.3, optima are fragile, especially in light of engineering problems that are large in scale, high in complexity, and characterized by rapidly evolving considerations emanating from dynamic interactions. Thus, as the chimera of optimal solutions is rendered increasingly uncertain, *satisficing* solutions [221] that can be accepted with confidence are rendered increasingly sensible. The Decision-Support Problem Technique – openly expandable, continuously evolving, and highly adaptable – is an exemplar of synthesizing rationality and scientific formalism with practicality. This approach is based on certain key assertions:

- Design is a decision making process in which it is preferable that some of the decisions be made sequentially and others concurrently.
- Design involves hierarchical decision-making and the interactions between decisions, if any, must be taken into account.
- Design productivity can be increased by the use of analysis, visualization, and synthesis in complementary roles.

The Decision Support Problem Technique permits a designer to partition a problem into manageable processes and ensures that formulated problems and corresponding models represent close-enough representations of the real world that solutions will yield useful results (e.g., bounded rationality). It is composed of 4 phases and 6 steps that focus on planning, organizing, integrating, and measuring progress throughout the design process. The technique also provides the support and rationale for using human judgment in design synthesis, not accounted for in traditional approaches, while simultaneously attempting to manifest the scientific aspect of design.

2.2.4.2 The Decision Support Problem Technique

The DSP Technique is divided into Meta-Design [149] and Design [149], as indicated in Figure 2-3, an recent extension (see Ref. [161]) of the DSP Technique Phase-Event-Information PEI Diagram [32]. While the former (a.k.a. "Designing the Design Process"), as the name might suggest, is concerned with the bigger picture of organizing the decisions within the design process, the latter centers on decision specific aspects, specifically the representation of the design space in terms of decision support problems. Although related aspects of engineering such as ideation techniques and planning tools are also associated with the DSP Technique, the strength of its application without a doubt lies in assisting a designer in making required decisions along a design timeline.

At the basis of the DSP Technique is the realization that we have neither the ability nor the necessary information to create ***the*** model (a complete, all-purpose characterization of a system and its environment) of a real-world system. However, it is possible to formulate ***a*** model of the real world system we are interested in. In this way it is possible to isolate disciplinary considerations, placing each model in equilibrium with its environment. Each such model is based on the simplifying assumptions. The end result here is a series of less than optimal solutions or optimal solutions to a set of less-than-real problems. However, solutions of this type, stemming from imperfect models, negotiated so as to optimize often conflicting requirements (i.e., economical and technical), can be very useful in supporting a designer's search for superior and *satisficing* solutions to the original problem.

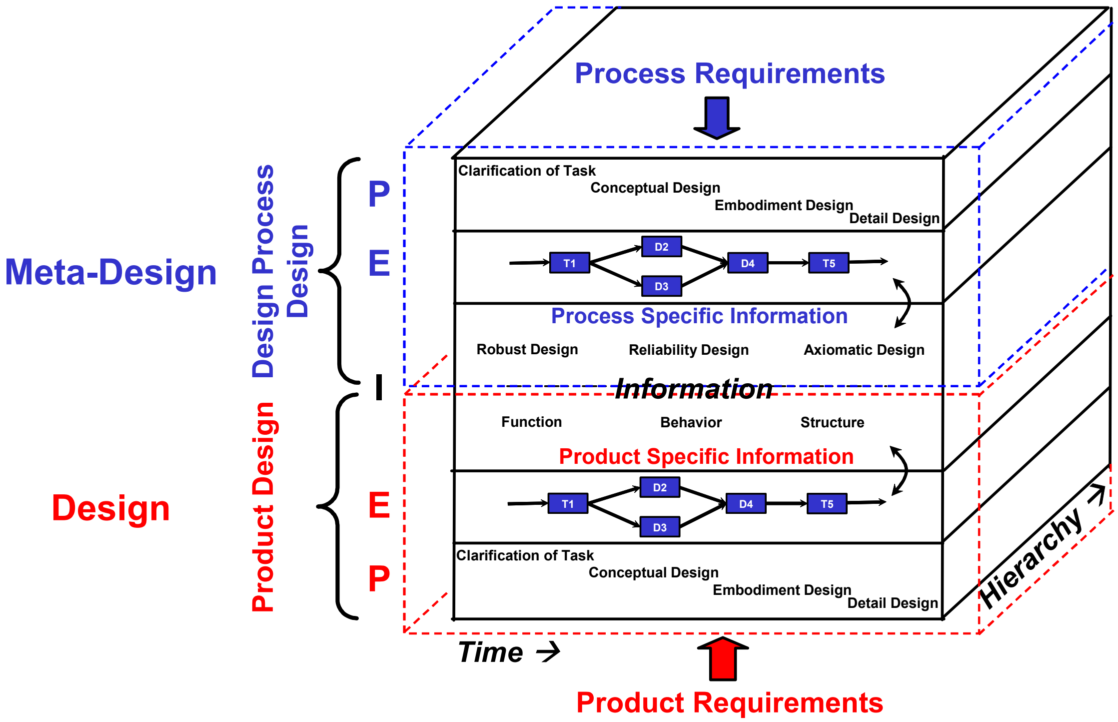

Figure 2-3 - The Integrated Design of Products and Design Processes

In the design of an artifact, a designer is thus confronted with two choices:

1. Creating a relatively simple model that can produce an exact solution to the assumptions given
2. Developing an approximate algorithm or heuristic based on a relatively complex model, representing the real world more precisely, the solutions to which may be considered to be *satisficing* (i.e., good enough to be acceptable, but neither exact nor optimal).

In an effort to find solutions to all problems it becomes a quasi necessity to accept solutions that are less than optimal, but nevertheless meet the most important criteria without undue sacrifices in function, cost, time, and other considerations. In this context, "*the significance of the Decision-Support Problem Technique in negotiating superior, satisficing solutions to engineering design problems is that of providing support for human judgment in the form of optimal solutions to Decision Support Problems (DSPs) into which the original problem has been partitioned.*" [155]. Recent advances by Panchal [161] delve into determining the extent and exactness of information required for making acceptable decisions, based on information economics.

Complex engineering systems are characterized by problems that are multileveled, multidimensional, and multidisciplinary. Often problems are loosely defined and open to both their environments and other bounding conditions. In essence virtually no problem can be defined sufficiently to produce a single optimal solution and superior, *satisficing* solutions must be found instead. By the same token, the acceptability of a design is likely to be judged on multiple levels of merit, not all of which are equally significant at all times. Required information is not always available when needed and may be both qualitative (soft) and quantitative (hard) in nature. The design as a whole progresses from the former to the latter as it takes shape. Finally systems posses the properties of all their subsystems and components plus other properties not possessed by them individually. Thus, there are many sets of related decisions, each collection of which may be modeled as a particular combination of decision support problems.

Design is the process of decision-making (both sequentially as well as concurrently). In this context an action specific activity is viewed as a *stage* and the condition of any design stage at a specific time as its *state*. Thus a state discloses the status of one or more stages at a time. The time-scales used within the stages are usually not the same and progress is thus measured in terms of milestones, towards the achievement of specific goal oriented activities. Thus, design managers establish the specifications and goals designers attempt to meet in the micro design of a project in macro design.

Engineering decisions are based on information from different disciplines and are improved through the repetition of analysis with inputs, constraints, and goals from previous iterations. Considering the multidisciplinary nature of design, it is crucial to rely on synthesis or heuristics. This becomes increasingly unmanageable as the scope of a problem increases and simplifications that reduce the real world correlation of the concept are often introduced. Thus, the importance of human judgment is great and "*the formulated problem and its model must be stated in sufficiently simple terms that finding a solution is a manageable process and, at the same time, they must be a close enough approximation of the real-world that the solution yields useful results"* [155]. There are two consequences. First, "real-world" optimization is impossible and second, engineers have no choice but to become *satisficers*, searching for 'good enough' alternatives.

In the context of the DSP Technique, *analysis* is defined as the process of decomposing a system into its constitutive elements. In this process the role of a computer is to provide effective high speed, large capacity, number processing capability in order to evaluate the behavior of the elements of a system. Repeatable analysis tends to improve a design and may be automated to a large degree. *Synthesis*, on the other hand, comprises the combination of parts into a whole. It is in this aspect that human judgment is crucial and computers may only be used to support designers in their ability to make decisions.

Consequently, the process of negotiating solutions within the context of the Decision-Support Problem Technique is structured in such a way so as to *harmonize the sterile analytical capabilities of the computer with the human ability to make decisions and use judgment* – combining their respective strengths in a synergistic manner.

The idea behind searching for *satisficing* rather than optimal solutions is the following: as stated, it is mathematically impossible to come up with optimal solutions to real world problems. When problems are simplified sufficiently so as to reduce their approximated complexity, limit interactions, and make non-exact solutions acceptable it is possible to negotiate *satisficing* solutions. Consequently, a paradigm shift must take place from looking at optimum designs as the best, most favorable designs, to defining them as superior from a set of feasible alternative solutions.

There are two alternative approaches to reaching such superior solutions.

1. Design improvement through iteration, making design variables firm in a sequential fashion.
2. Determination of design variables in simultaneous fashion in order to satisfy a set of constraints and optimize a set of objectives.

The first approach offers no means of providing systematic decision support and heavily relies on skill and experience. It is also likely to be much less effective and more costly than the second. Here, external intervention by the designer is necessary only in order to adjust problem formulation or input data. It is this second approach that is preferred within the context of the DSP Technique, since it is structured and hence repeatable. It is also amenable to being used in conjunction with a computer.

Within the DSP Technique, individual decisions are modeled in terms of Decision Support Problems. Each such DSP serves to partition "real-world" design problems into appropriate, more easily understandable units. A pattern may then be negotiated and interrelationships among DSPs structured so that their respective solutions complement each other, leading to a *satisficing* solution of the original problem. Optimal solutions of individual DSPs may also be established by using appropriate analysis. Finally, appropriate post solution analyses to validate solutions should be devised/conducted and the sensitivity of the *satisficing* solutions of the original problem to small changes in design variables tested.

Overall, the formulation of DSP's is helpful in formulating solutions to problems focusing on the following types of decisions:

- ***Selection*** – decisions made to indicate a preference for a single alternative among a set of feasible alternatives
- ***Compromise*** – decisions made to improve an alternative through modification
- ***Hierarchical*** – decisions made sequentially and/or concurrently when both selection and compromise are required.
- ***Conditional*** **–** decisions made explicitly taking risks and uncertainty into account

Once formulated for a particular context, the sum of all DSP Technique constituents (i.e. the technical briefs, the abstracts, problem statements, and word/mathematical formulations of the DSPs considered) represents the combined knowledge about the process of designing the product in question. Overall, the DSP Technique is thus based on the synthesis of three key elements:

1. A design philosophy

2. An approach for identifying and formulating DSPs
3. The software necessary for the solution of DSPs

The inherent potential and role/impact of applying the DSP Technique, however, changes as progress along a design timeline is made.

Operating within the paradigm of Decision-Based Design, the DSP Technique is suited best for supporting a designer in the making of decisions. Specifically, the focus is on providing a designer with the means of properly formulating decisions so that relevant information is accurately accounted for. No direct provision is made for acquiring required information, however, and inherent benefits in DSPT application are thus more significant during the latter stages of a design process. As an engineering artifact passes through the systems realization process (i.e., from initiation of concept on to design, manufacture, etc.) the information content of a design changes drastically. While the amount of knowledge about a product continually increases until all design variables are fixed, design freedom decreases proportionately. Design uncertainty behaves in the same manner as design freedom, decreasing with increasing information content. Consideration of stochastic uncertainty and risk (with regard to the achievement of objectives) is factored into the decision-making process through the infusion of utility theory as presented in Refs. [72,79,80]. Reliance on utility functions for the mathematical representation of preference stands in marked contrast to often-arbitrary Archimedean weighting factors or designer experience-dependent preemptive formulations. The DSP Technique also offer the ability to structure decisions based on hierarchical and coupled information flows throughout a products lifecycle [26,112].

Many of the trends, mentioned in Chapter 1, make the DSP Technique particularly relevant in today's working environment. Modern engineering problems demonstrate continuous evolution, characterized by complexity and uncertainty. Although required information is available almost instantaneously, cause and effect relationships tend to be largely multi-faceted, convoluting the nature of systems. Additional complexity emanates from dynamic interactions and decentralization. Technological progress, however, has fostered the development of computing power, capable of handling the complexity of structured components within the design process. Consequently, the role of designers will shift to focusing on those aspects that require structuring. It is in making subjective contributions in the form of insight, intuition, and judgment that the strength of designers in negotiating solutions lies. Simpler and significantly more structured components on the other hand will be automated in large.

2.2.4.3 Solving Uncoupled and Coupled DSPs

Since much of this dissertation deals with the decentralized, collaborative resolutions of strongly coupled decisions, a review[4] of coupled DSPs is warranted. As asserted previously, virtually all decisions encountered in design can be categorized as either *selection* among a set of feasible alternatives or the improvement of a given alternative through *compromise*. So much, at least, is true for decisions that can be made *independent*ly of any others involved in the design processes to which they pertain.

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[4] This review of coupled and hierarchical decision-making within the context of the DSP Technique draws on the combined work of Bascaran [24], Karandikar [111], and Smith [228], who each in their own right extended its applicability into the areas of concurrent engineering and hierarchical systems theory. However, the material is presented from a perspective suited to the developments presented in this dissertation. Some of the developments discussed in the following section, thus have implications on addressing decisions in the context of the processes to which they pertain. This is critical to the concepts developed in Chapters 3, 4, and 5.

There are, however those circumstances where a clear division is not possible and the lines between pure selection and synthesis become blurred. Reference is made here to those instances where decisions are either 1) *inter-dependent* (and should be solved concurrently) or 2) *dependent* on decisions made earlier on in a design process (and most be solved sequentially). The reader is referred to Section 2.2.1 and Figure 2-2.

2.2.4.4 <u>Single and Coupled Decisions</u>

It is important to define a few terms that will facilitate the discussion to follow. The underlying assumption, as stated, is that there are two types of decisions, namely selection and compromise. Constituent decisions, thus, pertain to either group and are considered in terms of the corresponding DSPs.

In order to model entire design processes, constructs capable of modeling them realistically are required. These are the coupled Decision Support Problems; hybrid constructs that can consist of any permutation of the basic components (e.g., coupled selection/selection, selection/compromise, compromise/compromise). Multiple instances of either component are also possible. Typically, however, problems can be modeled so that no more than three DSPs are coupled together (e.g., coupled selection/selection/compromise, selection/compromise/compromise, etc).

In the case of selection/selection [26], it is possible to encounter dependent attributes, dependent alternatives, or both. Compromise/compromise [26] allows for the constraints and goals of one DSP being functions of the variables of another. Finally, compromise/selection [111] may result from either selection attributes depending on compromise variables or compromise constraints and goals being functions of selection variables.

In the case of such *inter-dependent* decisions, coupling can be either weak or strong. In general, *weak coupling* implies that the influence between constituent DSPs is typically one way; *strong coupling* suggests a two-way flow of information between constituent DSPs, via system descriptors other than the deviation function. In the case of selection/selection DSPs, *weak coupling* would imply that the choice(s) made in the first, limit the feasible alternatives of the second; *strong coupling* would imply that the constituent selection DSPs affect the feasibility of their respective alternatives. For compromise/compromise DSPs, *weak coupling* implies that the goal functions of constituent DSPs are inter-dependent; *strong coupling* suggests that the constraints and goals of one DSP are functions of the variables of another. Finally, in the case of coupled selection/compromise, *weak coupling* suggests that coupled goals are part of the compromise DSP; *strong coupling* implies that the overall system goals are formulated as part of the selection DSP merit functions. Furthermore, two distinct relationships are possible with respect to coupled selection/compromise DSP. The *single model* of interaction means that the description of the compromise constraints and goals is represented through a single mathematical expression or model, whose relation to the selection alternatives is represented by one or more parameters or characteristic constants. A change in selection variables implies only a change on parameters of compromise DSP mathematical descriptors. The *multiple model* of interaction, implies that selection alternatives define different mathematical models altogether.

The coupled DSP constructs have much the same advantages and shortcomings as the constituents from which they are derived. While providing structure and maintaining domain independence, their synthesis and instantiation is problem specific. Though the DSPs are generic in terms of their word formulations, such genericism does not translate to their mathematical formulation. Instantiation is problem specific and reuse is limited to the exact configuration (at least from a *procedural* perspective), upon which the original template is based. Coupled DSP constructs greatly expand the range of decisions that can be modeled and the processes that can be represented. Unfortunately, interactions among DSPs are hard coded and thus problem as well as process specific. No interfaces for facilitating the connection of one DSP to another exist. In fact, it is the DSPs themselves that often serve as the interface, connecting various stakeholders, who in turn collaborate in providing *declarative* information. This confounds the issue by co-mingling contributions, considerations, and responsibilities of distinct domain experts. Thus, while the DSP Technique, thus far, is ideally suited for modeling design processes in a centralized fashion, decentralized design can only be supported in an *ad hoc* fashion.

Coupled Decision Support Problems have been applied in various contexts, such as the concurrent design of composite material structures and components [113], catalogue design involving the selection of heat exchanger concept and cooling fluid [26], hierarchical selection in gas turbine maintenance management [41], the design of spacecraft thermal control systems [235], ship design [228], and the generalized design of thermal systems [25].

When presenting the design process of a product in terms of the decisions required for its realization, it is convenient to think/operate in terms of hierarchies of decisions, as illustrated in the right half of Figure 2-4, where each box represents a decision. This line of thought is congruent with the fundamental notion of Decision Based Design as embodied in the DSP Technique. Decisions, serving as milestones in the development of a product, can thus be considered as the fundamental building blocks of a design process. As such, they offer a convenient means of representing the structure of the design process itself. With respect to decentralized design, they provide a consistent basis for structuring decision-maker considerations and structuring required information flows among collaborating stakeholders. In general, the main advantage in focusing on the arrangement of decisions within a design process lies in the ability to determine the nature of decision dependence and range of influence.

In the DSP Technique, the selection and compromise DSPs are employed to address independent decisions, while coupled DSPs are used to model hierarchies of decisions [24]. Any chosen solution scheme, however, must successfully capture the interactions between decisions and it is a further requirement to distinguish between those requiring sequential and simultaneous solution approaches. In the approach, developed in Chapters 3, 4, and 5, on the other hand, decision constructs are connected via interaction constructs to increase process modularity, interface consistency, and designer independence.

Design and integration of dependent subsystems into systems is an integral part of engineering design. The underlying relationships between components can be mapped in two ways *heterarchically* and *hierarchically* (Figure 2-4). The first representation shows relationships between different decisions as being unordered and asserts the inability to identify decision precedence or dominance. It is difficult to determine the quality, quantity, and direction of informational flow and the sequence of interactions is ill defined. In the second representation scheme, quality, quantity, and direction of information flow are clear and the sequence of interactions is well defined. Consequently, decisions are nicely structured so that it is possible to identify a single dominant parent decision.

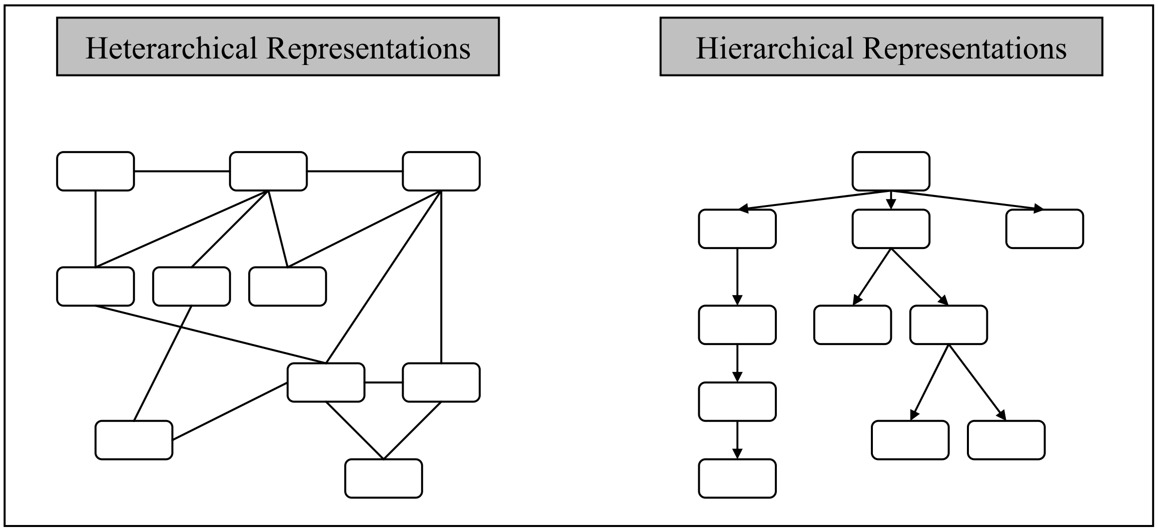


Figure 2-4 - Heterarchical and Hierarchical Representations [148]

Such a decision-based hierarchy can be implemented in terms of coupled DSPs, where the source for all decisions and information affecting the system is the dominant DSP. A further subdivision into simultaneous and sequential decision processes must follow. "In the former, interaction between the decisions is strong and two or more DSPs are solved concurrently as a single problem. In the latter, the hierarchy associated with the modeling of an artifact (as a system) is captured by separate decisions made at the levels at which they occur" [24]. A solution here would require the separate and sequential solution of two or more DSPs, the coordination of which becomes a much more critical issue. A sequential solution scheme would have to focus on coordinating the solutions of the component DSPs at often differing hierarchical levels. Examples of dual and multiple coupling relationships are illustrated in Figure 2-5. Further insight into structuring decisions according to an imposed hierarchy is given by Shupe [216].

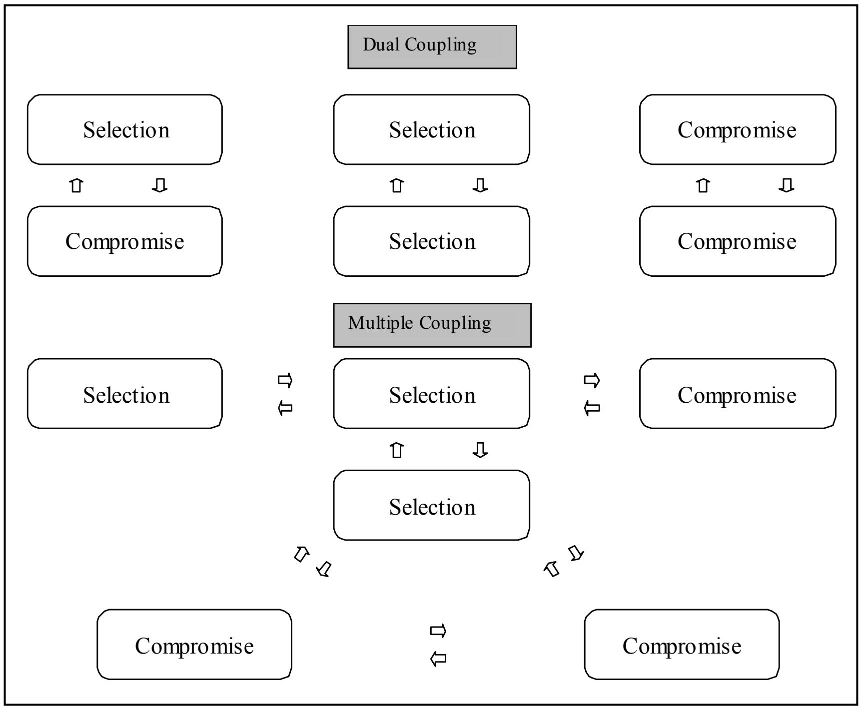


Figure 2-5 - Dual vs. Multiple Coupling

Once a hierarchy among the decisions involved in a particular process has been determined, the corresponding constructs must be formulated. While the basic constructs, sufficient for the consideration of independent decisions are covered in detail later (Section 2.3.1), a more detailed explanation of the hybrid constructs introduced in Section 2.2.4.2 follows.

2.2.4.5 <u>Coupled selection/selection DSPs</u>

There are a number of different ways in which selection DSPs can be coupled. Alternative coupling occurs when choosing an alternative in one selection problem conditions the selection of alternatives of another selection problem. Two different types of interactions are considered. In the first, all alternatives of one selection DSP become infeasible, unless a certain alternative of the other is chosen. In the second, the choice of a particular alternative in one selection DSP, excludes the choice of a specific alternative in the other. Either type of interaction is handled through the use of conditional constraints. It is the author's opinion however, that the use of uniqueness conditions and exclusionary constraints to deal with alternative interaction effects among coupled selection DSPs is only appropriate in certain instances when the selection DSPs have been reformulated as compromises. In fact, their use is contingent upon this reformulation. In many instances, however, when 1) coupling only takes place between alternatives or 2) attributes can be successfully de-coupled, coupled selection decisions can be combined into single selection decisions. Alternatives for this single selection problem would then be composed only of feasible combinations of the alternatives of the originally distinct selection decisions. This line of reasoning is in tune with the original definition of selection as the choice among a set of ***feasible*** alternatives, where the use of exclusionary constraints, implies the presence of infeasible choices. In those cases, however, where attributes cannot be successfully decoupled, the traditional approach relies on solution by means of iteration. This makes it virtually impossible to account for the interaction between the attributes of the coupled problems. Essentially several combinations are tried until a satisfactory solution is found. According to Bascaran, design problems, rarely involve more than a few coupled selection decisions, however, and exhaustive search remains a possibility. In those cases where exhaustive search is not feasible, heuristic means based on designer insight and experience can be used to speed up the process.

The strategy employed to represent interaction effects among coupled attributes is based on the assumption that qualitative information is adequate to represent the interaction effects. Evaluation of coupled attribute ratings is then accomplished through the use of a methodical comparison procedure, such as pair-wise comparison. This process, however, cannot be readily extended if the coupling extends to more than two selection DSPs, due to the inherent difficulty in evaluating the combined effect of more than two concepts at a time. The author feels that much of this issue can be avoided by carefully choosing attributes used for evaluation. Following certain elementary rules or guidelines for choosing evaluation criteria, such as those presented in [114], is recommended. This is also an instance where the use of utility theory in the merit function formulation may be advantageous as substantiated in Refs. [72,79,80]. When using utility theory, it is acceptable to have dependent attributes, as long as decision-maker preferences with regard to these attributes remain independent. Consequently, one should take great care that when coupled attributes cannot be avoided, to at least ensure that they exhibit the same monotonicity. Thus, while it may be acceptable to consider both annual fuel cost and fuel consumption, considering fuel cost and fuel economy would be a mistake. Consequently, coupled selection DSPs involving coupled attributes may also be considered in terms of a single, comprehensive selection DSP over feasible combinations of alternatives.

Formulation of a coupled selection/selection DSP involves the following steps[5]:

1. Identify alternatives.
2. Identify all attributes relevant to the selection DSP.
3. Determine relative importance of attributes with respect to each other.
4. Establish a scale for each attribute.
5. Rate alternatives with respect to independent attributes.
6. Create an array of ratings for coupled attributes – ratings correspond to each of the coupled attributes and have to be formulated as S dimensional arrays, where S represents the number of selection problems, coupled by the attribute under consideration. For each attribute the array contains the ratings for all combinations of the alternatives corresponding to all the coupled selection DSPs. For strongly coupled selection DSPs, an iterative procedure is followed, where all the possible combinations of alternatives are systematically considered.
7. Identify alternative coupling, keeping track of exclusionary conditions between alternatives.
8. Formulate and solve the coupled selection/selection problem
9. Validation and post-solution sensitivity analysis.

[5] Steps 1-4 must be repeated for each of the selection DSPs involved. Also, the above coupled selection/selection formulation is based on the fact that constituent selection DSPs have been reformulated as compromise DSPs. The result is a multi-objective, linear 0-1 variable optimization problem, the details of the solution of which are given in Ref. [24].

2.2.4.6 Coupled compromise/compromise DSPs

Synthesis in engineering design rarely occurs in isolation and problems can easily grow to encompass a large number of goals. At times, compromise decisions that are technically distinct can overlap with others in the form of shared goals. It is advantageous to be able to set up an internal hierarchy to govern the solution scheme. Interaction effects and decision-maker priorities can thus be incorporated into what essentially boils down to a superposition of preemptive and Archimedean formulations. While the first is used to separate different priority levels, the second accounts for preferences for goal precedence within each level.

1. Formulation of a coupled compromise/compromise DSP involves the following steps: Capture the interactions of DSPs in the formulation of the corresponding template.

2. Decide on the overall importance of constituent decisions and the corresponding criteria.

3. Regulate the flow of information in the hierarchy by setting up the appropriate deviation function for the coupled DSP. Goals corresponding to each constituent DSP of the coupled DSP hierarchy are then assigned priorities at different levels of the hierarchy of decisions. It is important to note that a hierarchy in this context is defined in terms of the preemptive satisfaction of goals at various priority levels, not physical decomposition.

4. Maintain the assigned hierarchy throughout the solution scheme.

In essence, this approach uses superposition of preemptive and Archimedean formulations, where priority levels are employed for decomposing the hierarchy and weights for identifying designer preferences at each priority level. Much of this approach depends on the specific problem at hand and designer insight, since hierarchical organization

2.2.4.7 Coupled selection/compromise DSPs

It is quite often in design that selection and compromise decisions are coupled. In a way, selection could be considered to be a special case of compromise. Since the former decision type is Boolean by nature and the latter continuous, joining the two poses inherent difficulties. It should thus come as no surprise that this construct is the most complicated hybrid. Differentiation between single and multiple model interactions, as described in Section 2.2.4.4, are possible.

Karandikar concludes that not much effort is required in the formulation of this construct and integration of the design process can be achieved successfully. There is an advantage in design cycle time and a better understanding of the design problem may be achieved due to the required consideration of interaction effects. In general, Karandikar suggests the use of the weakly coupled formulation whenever possible because of relative simplicity and the fact that a coupled parameter would appear explicitly as a goal. The strongly coupled formulation, on the other hand, should be chosen only then when 1) selection attributes are very important and 2) more than one attribute is coupled. In this case, the coupled parameter would appear as both a goal and an attribute.

It is the author's opinion that there is not much to be gained from reformulating either weakly or strongly (multiple model) coupled selection and compromise DSPs in terms of the coupled construct, requiring the reformulation of the constituent selection DSP as a compromise DSP. In the case of a weakly coupled problem, a hierarchy can usually be imposed through making simplifying assumptions and the constituent DSPs solved sequentially. In the case of a strongly coupled multiple interaction model, there is no way of avoiding an exhaustive search over all selection alternatives and the corresponding compromise solutions. This is due to the fact that different potential outcomes of the selection DSP will result not only in different input parameters but different mathematical formulations driving the compromise. By the same token, the outcome of the compromise will affect the performance of selection alternatives with respect to the attributes under consideration.

In the case of a single interaction model, although alternative performance with respect to the attributes under consideration depends on compromise outcomes, all of the selection alternatives depend on the same underlying mathematical model. Consequently, there may be an advantage to formulating a coupled construct. In essence different alternatives of the selection DSP constitute nothing more than different inputs to the same compromise problem. In a case where response surfaces can be developed, there may be the potential for significant computation cost/time savings.

Formulation of a coupled selection/compromise DSP involves the following steps[6]:

1. Identify alternatives.

[6] Steps 1-4 must be completed for each of the selection DSPs involved.

2. Identify all attributes relevant to the selection DSP.
3. Determine relative importance of attributes.
4. Establish a scale for each attribute.
5. Rate the alternatives with respect to each independent attribute.
6. Identify constraints and goals for the overall problem.
7. Integrate all the above information with the analysis model.
8. Validation and post-solution analysis

Regardless of the coupled construct employed, some of the general rules for the establishment of hierarchy are provided by Karandikar [111].

- Among compromise problems, conflicting goals must be placed at the same priority level or else the one at the higher priority will completely dominate the other. It is important to appreciate the effect of tradeoff among various goals.
- Among selection problems, the priority of the goals is dictated by the sequence in which the decisions are to be made and the type of coupling:
    - Goals for selection DSPs with shared/coupled attributes are formulated at the same level
    - Goals for selection DSPs with coupled alternatives can be modeled at various levels by modifying the uniqueness condition to yield exclusionary constraints

Unfortunately, these guidelines are heuristic in nature and heavily rely on both designer experience and access to relevant information. As stated previously, it is the author's opinion that the use of uniqueness conditions and exclusionary constraints to deal with alternative interaction effects among coupled selection DSPs is only appropriate in rare cases when the compromise formulation of the selection DSP is required. It is for these reasons that a separation of *declarative* and *procedural* information is advocated in Chapter 3.

2.2.4.8 Relevant Contributions to Modeling Hierarchical Systems of Decisions

In review, Bascaran [24] developed the hybrid DSP constructs to a significant degree and sought to model concurrency in design processes. Concurrent design, however, implies not only the simultaneous decision-making by distinct stakeholders, but also their convergence at decision points. Although a means of facilitating simultaneous decision-making in Distributed Collaborative Design and Manufacture (DCDM) would be ideal, the inherent difficulty in this endeavor is the intrinsically flawed notion of group preference, as pointed out by Arrow [18]. While the infusion of utility theory into DSP constructs (see, e.g., [72,79,80,203]) addresses many other issues associated with the reflection of designer preferences, (e.g., validity of preferences under conditions of risk and uncertainty, etc.), it does not offer a means of addressing group preference, *per se*. However, as will be illustrated in Chapters 3, 4, and 5, the necessity of relying on group preference can be avoided when enforcing the perpetual alignment of stakeholders with the design sub-problems assigned to them. Tradeoffs are managed using game theoretic and negotiation-inspired principles as well as utility theory for preference formulation. The goal is to handle *dependent* decisions and *inter-dependent* decisions with the same level of mathematical rigor as *independent* decisions. Ideally, governing (system level) preferences will not be sacrificed, concurrency maintained (even enhanced), and stakeholder efforts focalized towards win/win scenarios.

Karandikar [111] focused mainly on the exploitation of the coupled construct and its inherent potential for modeling concurrent engineering processes. The underlying idea was to formulate a coupled DSP template, allowing for the inclusion of different distributed entities in making the same decision. In his work the entire spectrum from material selection in designing for concept to manufacturability analysis in DFM was thus integrated into a single coupled DSP template. The clear disadvantage is the loss of agility in producing a non-modular template that is both problem and process specific. The idea of process-based vs. decision-based hierarchies was also underscored by focusing on the fact that concurrency of decisions within a given design process leaves a larger set of options open for the achievement of preferences. The main conclusion was that design freedom decreases rapidly when making design and manufacture related decisions sequentially. The cost of any modifications to earlier design decisions is thus high. If the designer had the flexibility to modify design decisions so that they are made concurrently, design freedom as a whole would increase. The net effect would be for the designer to have the flexibility to modify design decisions concerning dimensional synthesis at a later event, namely that of manufacturability analysis. Overall, the efficacy of concurrency in engineering design was demonstrated by illustrating the impact of increasing design knowledge about the object of design early on in the design process. This approach is akin to the underlying philosophy driving the development of the RTTB and the notion of a *digital interface*. However, the method suggested is for the integration of design and manufacture only and not a generalized way of modeling design decisions and processes and structuring stakeholder interactions as proposed in Chapters 3, 4, and 5. The proposed means lays the foundation for the effective investigation and exploration of design processes with respect to decision-maker interactions.

Smith [228] also stressed the inherent potential of concurrent decision-making in design processes. His focus, however, was on improving the efficiency and effectiveness of activities in the early stages of design. In concentrating on design for the lifecycle, the primary goal was the minimization of cost over the complete life cycle of a system while maximizing its quality and performance. It is often the early stages of design that have the most far-reaching effects. Usually, however, relevant decisions are based predominantly on qualitative information and the importance of taking advantage of existing design knowledge arises. This concept as well is a key development in the future evolution of decision support, that can greatly benefit from advances in data mining technologies. A further requirement, however, would be the parallel development of the means of incorporating such design knowledge actively into the decision-making process. In this dissertation this aspect is addressed through the novel means of modeling both design decisions and processes using modular templates that can be stored and archived, thus preserving product and process related information.

Smith also considered the importance of the bi-directional nature of information flow and the fact that many decisions in design are based on both upstream and downstream considerations. An inherent limitation of the sequential approach of modeling design processes is that information can only flow one way. In order to investigate the nature of goal interactions, logic tables were used. A similar approach may be suitable to the investigation of interaction effects between processes, decisions, and other parameters, that can be used to structure design processes themselves. The manner in which information flows among constitutive building blocks in the modeling approach of Chapter 3 is contained entirely within interaction templates, thus increasing design process agility via modularity.

Much of Smith's research focused on identifying, exploring, and modifying a feasible design space. Another area of concern was the development of requirements specifications in conceptual design. Finally, Smith focused on integrating analysis with synthesis and collecting relevant design data for optimal processing. This as well is an aspect relevant to the development of consistent decision support throughout the design process, since this should involve not only the means of taking into consideration relevant data, but also the resources of acquiring it.

The overall benefit of the hierarchical systems approach proposed by Bascaran, Karandikar, and Smith are the following:

- Structured process – designer can follow a set of procedures related to the formulation and solution of DSPs – which facilitates design tasks in making rational decisions, which are recorded for later reference by other users.
- Ability to incorporate both quantitative and qualitative information into the decision-making process – both experience and insight are utilized.
- Extension of the applicability of Decision Support Problems for the realistic modeling of design processes
- Facilitation of the incorporation of both technical and economic considerations.
- Ability to express phases of a design process in terms of single coupled DSP constructs.

- Establishment of decision hierarchies in design processes.
- Increase in the concurrency of the design process and conservation of design freedom

Overall, it can be said that from the perspective of simplicity, it is desirable to strive for sequential solution processes. Guidelines for structuring solution processes accordingly in the case of weakly coupled formulations are provided. From the standpoint of concurrency and quality, however, it is more beneficial resorting to simultaneous solution schemes, as focused upon in this dissertation. Key deficiencies lie in the fact that concurrent decision-making requires the quantification of constituent design parameters/criteria even though no reliable measures may exist to quantify all of them sufficiently. This limitation is quite similar to that encompassed in using utility theory, which in addition also requires quantification of uncertainty information. This challenge can be addressed in part through developing a means for facilitating the incorporation of evolving information content (Chapter 3) and a more dynamic coordination protocol among stakeholders (Chapters 4 and 5). Bascaran and co-investigators address this quantification issue predominantly through heuristic means such as the systematic development of decision constructs and rational use of scales, although more rigorous means are required. Aiding a designer in this aspect is a key requirement of decision support and may involve the further development of data mining techniques to make effective use of design knowledge. Another limitation of the proposed approach for concurrent engineering is the practicality of incorporating entire phases of a design process within a single decision construct. While, it is true that decisions are not unnecessarily constrained, as would be the case in a sequential solution scheme, and better solutions are possible by allowing for tradeoff among decisions, the computation cost associated with such an effort can be too significant to handle. Often it is argued that future improvements in computing power may be able to bridge such limitations. It is the author's opinion, however, that advances in computational resources are usually offset by analogous increases in the complexity of required engineering analyses, and limitations on the concurrency of decision-making are likely to persist. Consequently, this issue is addressed here via modularity and reliance on surrogate models.

With this in mind, the vast body of research reviewed, shows significant promise and constitutes a solid foundation for the development of a **F**ramework for **A**gile **C**ollaboration in **E**ngineering as envisioned in this dissertation. The scope of research addressed, is limited to supporting various decision-makers in making strongly coupled compromise decisions along an event-based design timeline. The main focus is ensuring the effectiveness of iterations via stakeholder focalization and provision of decision-critical information content. Consequently, concurrent interactions are formalized and efforts coordinated so as to ensure the attainment of win/win scenarios. With this in mind, predominant communications protocols from the realm of game theory are reviewed in the next section.

2.2.5 Game Theory and its Applications in Engineering Design

2.2.5.1 **The Constructs of Game Theory**

The most common game theoretic protocols, used to model strategic relationships among designers sharing a common design space, are *Pareto Cooperation, Stackelberg Leader/Follower,* and *Nash Non-Cooperation*. *Pareto Cooperation* is employed to represent *centralized* decision making, where all required information is available to every collaborating designer. A *Pareto optimal* solution is achieved when no single designer can improve his or her performance without negatively affecting that of another. *Stackelberg Leader/Follower* protocols are implemented to model sequential decision-making processes where the *Leader* makes his/her decision, based on the assumption that the *Follower* will behave rationally. The *Follower* then makes his or her decision within the constraints emanating form the *Leader's* choice. *Nash Non-Cooperation* is employed to model the solution of *strongly coupled* decisions, characterized by *interdependent information* flows, and is characteristic of decentralized design processes where stakeholders are required to tackle design sub-problems in isolation, due to organizational barriers, time schedules, and geographical constraints. *Non-Cooperative* protocols are focused on formulation of strategies that "rational" individuals should follow when their actions and objectives are affected by others. In Refs. [98,99,136] it is shown that mathematical models for *non-cooperative* behavior are suitable for formulating decisions in collaborative design.

The resulting protocol is particularly important in multi-functional design scenarios because of the non-required collocation of design experts and extensive coupling within the associated design spaces. In the pursuit of *Nash Solutions to* coupled design problems, decision-makers formulate Best Reply Correspondences (BRC) or Rational Reaction Sets (RRS). A BRC is a mapping (either a mathematically derived or a statistically fitted function) that relates the values of design variables under a designer's control to values of design variables determined by other stakeholders. For example, in a two designer scenario where Designer A controls design variable set X_A and Designer B controls variable set X_B, the BRC of the first designer is given by $BRC_A = f_A(x_B)$ and the BRC of second designer is given by $BRC_B = f_B(x_A)$. In order to calculate his/her BRC explicitly, a designer assumes values for the set of design variables not within his/her control and chooses values of his/her own design variables in order to maximize his/her payoff. Since the construction of a BRC is a computationally expensive process, evaluation of the actual model describing a given design space is usually limited to a few discrete points, over which a response surface model (or similar approximation technique) is fit to derive an explicit BRC in functional form. The underlying process, however, is prone to approximation errors that can be attributed to poor fidelity and low-order functional fit. The *Nash Equilibrium or Nash Solution* to a coupled problem, formulated using a *Non-Cooperative* game, is found by intersecting the BRCs pertaining to each of the designers involved. This solution has the characteristic that *no designer can improve his/her objective function unilaterally*. Reliance Nash equilibria for conflict management thus ensures that each decision-maker's strategy constitutes the optimal response to those of other decision-makers. The approach, commonly adopted for solving *Non-Cooperative* decision-making problems is to explicitly calculate the various BRCs and then find their intersection. This method represents the use of game theory as a *solution algorithm*, evocative of the standard optimization practices covered in Section

2.2.3, rather than a *communications protocol*. Hence, this solution method does not reflect the actual manner in which decisions are made by designers in a decentralized design process. Another solution technique for solving *Non-Cooperative* design problems involves making decisions in an iterative fashion. Although this solution approach more closely resembles interactions associated with decentralized decision-making, convergence and stability are not guaranteed. With this in mind, a critical review of game theoretic protocols as applied to conflict resolution in engineering design follows in Section 2.2.5.2.

2.2.5.2 Instantiations of Game Theoretic Protocols in Engineering Design

The numerous applications of game theoretic protocols in Engineering Design vary considerably in terms of underlying philosophy and implementation. Vincent [251] first recognizes that different disciplines converging in the design of a product can be modeled as players in a game. Rao implements the *cooperative* protocol in multi-objective structural optimization [187] and integrated control structure design [21]. Lewis subsequently extends the notion of a game to a design process. Specifically, he synthesizes constructs from Decision-Based Design, Game Theory, and Multidisciplinary Design Optimization in developing a systematic means of supporting systems synthesis via integration and coordination of domain-independent subsystem embodiment in Ref. [125]. In this work, Lewis implements cooperative, non-cooperative, and leader/follower protocols to solve mixed discrete continuous optimization problems associated with multidisciplinary design. In essence, his framework provides decision support for the formulation of multidisciplinary design problems, subsequent decomposition, modeling of required interactions, and solution as well as coordination of disciplinary mathematical models (see also Ref. [126]).

Hernández later builds upon the contribution of Lewis by implementing game theoretic principles to establish a mathematically supported *cooperative* framework that enhances the practical, effective, and efficient integration of enterprise design theory in Ref. [96]. He further provides an approach, appropriate for the formulation and solution of design problems in a manner consistent with this framework. Enterprise decisions are coordinated through a design formulation based on a game theoretical formulation of the enterprise design process, where the mantra is to "…satisfy locally and satisfice globally". Along these lines, Hernández recognizes the importance of collaboration through time, cognizant of the importance of change in information content – "It is a characteristic of the enterprise design activity that the final outcome is built from a search of a satisficing solution that is gradually refined". Further extensions of Lewis's foundational work by Hernández et al. include the formalization of interactions among two collaborating stakeholders [98,99]. In this work, BRCs are formulated based on stakeholder objective response to changes in coupled variables instead being computed for the response of independent variables to changes in other independent variables, as in the work of Lewis. Furthermore, the decision-maker who goes first in a given interaction is able to explicitly observe the impact of his/her actions on the overarching objective. Since the solution space resulting from this mode of interaction is better behaved, the creation of the required BRCs is facilitated.

Marston introduces the notion of Game-Based Design as "…the set of mathematically complete principles of rational behavior for designers in any design scenario” in Ref. [133]. Specifically, a multi-designer model of engineering design that accounts for *uncertainty*, *cooperation*, *non-cooperation*, and *coalitions* is developed using the mathematics of decision and game theory. In effect, Marston extends the foundational work of Lewis via inclusion and extension of utility theory for modeling uncertainty, the development of n-player strategic form games, and the proposition of a general framework for coalition form games [134-136].

Xiao explores the efficacy of different game theoretic protocols across the *clean digital interface*, proposed by Rosen, concluding that although game theoretic formulations in general can reduce iteration, aid in the quantifiable prediction of stakeholder actions, and limit the size of decision-maker problems, it is the Stackelberg game that is most representative of (and appropriate for) use in collaborative product development. Xiao also advocates increasing the local autonomy of engineering teams by separating, simplifying, and ”sequentializing” their activities, asserting the benefits of increased independence in coupled decision-making. Information exchanges between multi-disciplinary teams are structured to be one directional, focusing on complete information transfer from upstream to downstream activities; cooperation is assumed to occur only between teams in direct succession of one another with respect to a linear design process. The central mechanism thus relies on transferring autonomy for the resolution of coupled problems to a single interacting party, precluding the possibility of continuous interaction among collaborating stakeholders along a design timeline. Since, the focus of Xiao’s approach interfacing distinct phases of a design process, specifically design and manufacture, via reduced iteration and ranged solutions, this assumption is not only appropriate but effective. A summary of applications within the literature is provided in Table 2-1.

2.2.5.3 Negotiations and Bargaining as Mechanisms for Tradeoff Management

Not all means of conflict management are centered on one time interactions that require the *a priori* specification of a static tradeoff strategy. For example, *negotiation* is based on the use of observation and feedback in the dynamic adjustment of tactics to attain personal goals. *Negotiation* is "…the process whereby interested parties resolve disputes, agree upon courses of action, bargain for individual or collective advantage, and/or attempt to craft outcomes which serve their mutual interests, usually regarded as a form of alternative dispute resolution" [8]. Negotiation theory is founded upon decision analysis, behavioral decision making, game theory, and negotiation analysis, with the underlying aim of resolving adversarial situations to one's advantage. The implication is that parties oppose one another and are concerned primarily with the attainment of the most favorable outcome possible. Alternatively stated, successful negotiation involves determining those terms that comprise the minimum outcome the opposition is willing to accept. Clearly the notion of diametrically opposed objectives is inherent in this concept encouraging the formulation of carefully devised *strategies* in addition to conniving *tactics*, dynamically adjusted to adapt to evolving considerations.

Table 2-1 - Applications of Game Theoretic Protocols to Conflict Resolution in Design

Reference		Informational Dependence	Protocol Implemented / Degree of Cooperation	Frequency of Interaction	Responsibility Re-Assignment	Adaptability	Unique Aspect
Rao and Badhrinath	[187] [21]	Interdependent Decisions.	Cooperative	Single. Game Theory employed as solution algorithm.	None. Consistent with original design space control.	None. Re-formulation only.	Application of game theoretic principles to engineering.
Lewis et al.	[126]	Interdependent Decisions.	Cooperative, Non-Cooperative, and Stackelberg Leader/Follower, Strategic Form Games.	Single. Game Theory employed as solution algorithm.	None. Consistent with original design space control.	None. Re-formulation only.	Extension of the notion of a game to a design process. Integration of Decision-Based Design, Game Theory, and Multi-disciplinary Design Optimization; BRCs are computed for the response of independent variables to changes in other independent variables.
Hernández et al.	[98] [99] [96]	Interdependent Decisions.	Extensive Form Games with Observed Actions.	Single and Multiple. Game Theory employed as coordination mechanism and solution algorithm.	None. Consistent with original design space control.	Limited. Only with respect to solution refinement.	Coordination of enterprise decisions and recognition of importance of collaboration through time, formalization of two player interactions; BRCs are formulated based on stakeholder objective response to changes in coupled variables, resulting in better behaved solution spaces.
Marston and Mistree	[133] [136]	Interdependent Decisions.	Non-Cooperative, Strategic Form Games, reliance on BRCs.	Single. Game Theory employed as coordination mechanism and solution algorithm.	None. Consistent with original design space control.	None. Re-formulation only.	Formalization of a multi-designer model of engineering design that accounts for uncertainty, cooperation, non-cooperation, and coalitions. Integration of utility theory with game theoretic protocols.
Chanron et al.	[39] [40]	Interdependent Decisions.	Non-Cooperative, Strategic Form Games, reliance on iterative solution of BRCs.	Single. Solution method employed is iterative, however.	None. Consistent with original design space control. Existence of solution convergence dependent.	None. Re-formulation only.	Investigation of convergence behavior, criteria for Nash Equilibria and Pareto optimality, as well as solution stability in two as well as n-player games.

Table 2-1 - Applications of Game Theoretic Protocols to Conflict Resolution in Design…Continued

Reference		Informational Dependence	Protocol Implemented / Degree of Cooperation	Frequency of Interaction	Responsibility Re-Assignment	Adaptability	Unique Aspect
Xiao et al.	[267] [270]	Dependent and Interdependent Decisions.	Cooperative, Non-Cooperative, and Stackelberg Leader/Follower, Strategic Form Games, reliance on BRCs.	Single. Game Theory employed as coordination mechanism and solution algorithm.	Transfer of responsibility for the resolution of coupled problems to a single party.	Adaptable only within predefined range of solutions sought.	Application of game theoretic protocols in conjunction with Design Capability Indices in order to eliminate iterations at the Design/ Manufacture Interface. "Sequentialization" of design processes.
Hacker and Lewis	[91]	Interdependent Decisions.	Non-Cooperative, Strategic Form Games, use of BRCs, with reliance on a slight amount of cooperation in order to improve the follower's position.	Single. Game Theory employed as coordination mechanism and solution algorithm.	None. Consistent with original design space control.	Adaptable only within robust range of solutions identified.	Application of game theoretic protocols in conjunction with Type I Robust Design for two players. Introduction of slight degree of cooperation and consideration of BRC gradients.
Kalsi, Hacker, and Lewis	[109]	Interdependent Decisions, with reduction of downstream coupling.	Non-Cooperative, Strategic Form Games, reliance on BRCs.	Multiple, iterative, Game Theory employed predominantly as a solution algorithm.	None. Consistent with original design space control other than mutual consideration and feedback.	Adaptable only within robust range of solutions identified.	Inclusion of both Type I & II Robust Design. Locating robust design space ranges w.r.t. (1) control factor deviation and (2) unknown downstream control factors (modeled as noise).
Chen and Lewis	[44]	Interdependent Decisions.	Stackelberg Leader/Follower, Strategic Form Games, reliance on BRCs.	Single. Game Theory employed as coordination mechanism and solution algorithm.	None. Consistent with original design space control. Final decision made by Follower, who has limited flexibility through ranged specifications.	Adaptable only within predefined range of solutions sought.	Application of Stackelberg Leader/Follower protocol in conjunction with robust design approaches in order to achieve flexibility due to provision of ranged specifications.

It is important to note that *strategy* and *tactics* are often confused. *Tactics* is the collective name for methods of winning a small-scale conflict, performing an optimization, etc. This applies specifically to warfare, but also to economics, trade, games and a host of other fields such as negotiation. Examples include the quasi cliché and often debased tactics of walking out, good guy/bad guy, presentation of demands, limited authority, etc. Simply stated, *strategy* is the overall plan conceived in order to achieve an objective, *tactics* are the actual means used to attain said objective. In the context of game theory, strategies correspond to BRCs and tactics to any means aimed at influencing the strategies of another. Examples include the overstatement of targets, exageration of constraints, etc.

Traditional "hard-ball" negotiation is often referred to as adversarial *win/lose* negotiation (also referred to as *positional bargaining*). Alternative *win/win* approaches (as pursued in this dissertation) are aimed at the successful resolution of conflicts so that all parties benefit. Investigations and advances regarding the formalization of this win*/win* mode emerged in the 1970's. Perhaps the best known example of this approach (also referred to as *principled negotiation* or *mutual gains bargaining*) is "Getting to YES" by Roger Fisher, Bill Ury, and Bruce Patton [84]. Often the negotiation is framed as a problem to be solved as in the case of decentralized design. In concept, principled negotiation is a *win/win* approach with the aim of reaching a lasting agreement, rather than the tenuous equilibria, characteristic of traditional positional (*win/lose*) bargaining. The essential elements of principled negotiation include:

- Separation of the people from the problem they are faced with
- Focus on interests rather than positions

- Generation of a variety of options before settling on an agreement
- Insistence the any agreement be based on objective criteria

Examples of the applications of negotiations to engineering design include the efforts of Scott et al. who formalize the concept of negotiation as a means of dealing with imprecision and conflict resolution in Refs. [201,202]. Specifically, the Method of Imprecision (M_oI), employed extensively as a decision support tool for self contained design problems [17,123], is augmented to facilitate negotiations between groups in engineering design via identification of design and performance variables, specification of preferences over variable values, establishment of a trade-off strategy, and continued iteration and possible redesign as group preferences evolve. An alternative means for individual decision-makers in sequential design processes is proposed by Fernández in Refs. [72,77,78], focused on the communication of ranged sets of specifications and multi-attribute utility functions for encapsulating designer preferences with regard to tradeoffs and system performance. The predominant decision coordination mechanism, however, is focused on the implementation of game theoretic protocols in structuring interactions.

2.2.5.4 <u>Critical Analysis</u>

Applications of game theory in engineering design can be distinguished according to the underlying information flows they are meant to structure, as well as the degree of cooperation that defines stakeholder interactions. Other distinguishing characteristics emanate from the frequency of interaction, the manner in which responsibility is shared, and adaptability to changes in information content.

As indicated in Section 1.3.3, current decision coordination mechanisms in engineering design are often focused on streamlining the design process by excising iteration emanating from trial-and-error. This is achieved predominantly via the specification of ranged sets of solutions and the communication of semantically rich information content. While this is an effective *modus operandi* for changeovers associated with sequential, clearly distinct phases of a product realization process (e.g., Design and Manufacture), it is not in general suited for facilitating collaboration among decision-makers along a design timeline. Stakeholder interactions must be both effective and efficient in satisfying the constraints defining their respective design sub-problems while achieving system level objectives in an unbiased manner. A fundamental challenge lies in that considerations of interacting designers continuously evolve due to changes in understanding, model fidelity, and technology, to name a few. Current decision models and coordination mechanisms are quasi static and thus render the reflection of changes in information content virtually impossible without complete reformulation of both designer aspirations and interaction details. Forms of collaboration based on more frequent interactions have hitherto not been considered other than via *ad hoc* resolution of conflict in trial-and-error iteration and formal negotiation. This is due mainly to the fact that efficient updating of information content was thus far not possible.

Most of the game theoretic implementations, reviewed in Sections 2.2.5.1 through 2.2.5.3, can be considered to manage conflict by serving as either *solution algorithms*, *communications protocols*, or a combination thereof, referred to here as *interactions protocols* or *coordination mechanisms*. Algorithmic implementations are centered on reformulations of the sub-problem-specific objective functions in terms of a single, comprehensive objective function, reflecting the respective tradeoff strategies of the corresponding decision-makers. Instantiations of *communications protocols*, on the other hand, center on establishing a rational framework for interacting stakeholders to formulate their respective tradeoff strategies in a concise, coherent fashion. Finally, combinations are focused on providing both a consistent basis for sharing required information as well as furnishing a means of conflict management.

Among the game theoretic protocols, it is clear that *cooperative* behavior produces superior results to *non-cooperative* behavior. Traditionally, however, collaboration in engineering design has been modeled mainly using *non-cooperative* protocols. This is due to the fact that *full cooperation* requires (1) full access to the information critical to the resolution of each coupled decision, (2) interoperability of engineering tools and models, (3) cross-disciplinary interpretation of results, (4) information intensive interchanges, and (5) enormous computing power. Another potential shortcoming is that the required trade-off strategy is reduced to relative emphasis in a single objective function. On the other hand, *non-cooperative* protocols (of which the *Stackelberg* formulation is a subset), though computationally tractable, have other shortcomings. For example, the approximation of designer actions using Rational Reaction Sets (RRS) (a.k.a. Best Reply Correspondences (BRC)) can be a substantial source of error.

One of the fundamental drawbacks in relying on purely *non-cooperative* formulations is that the decisions of interacting stakeholders must be sufficiently formalized in order to support the required communications. In essence, interactions can thus only be supported once the coupled design sub-problems have been formulated and can be solved to derive the BRCs, required for capturing stakeholder strategies. Once these have been captured mathematically, coupled design problems can be solved either (1) concurrently via BRC intersection and the establishment of a *Nash Equilibrium* (see, e.g., [39,40,136]), (2) iteratively via explicit BRC exchange and consideration in design sub-problem solution, where improved solutions are possible via robust design techniques (see, e.g., [44,91,109]), or (3) via complete transfer of responsibility for making required system level tradeoffs and BRCs, alongside ranged sets of specifications, to a single stakeholder (see, e.g., [267,270]). In the first case achievement of a *Nash Solution* is dependent on whether the strategies converge, as investigated in Refs. [39,40], and iteration is likely. Although a certain amount of variability is accommodated in the second case, this is done *a priori* and in isolation. The underlying aim is that of guarding against wasteful iteration. This is also an aim in the third and final case, where adaptability is limited (due to loss of stakeholder dominion) to those ranges of design variables, specified in anticipation of eventual changes. Overall, these protocols are suited much better to supporting single interactions than extended and dynamic collaboration.

A fundamental limitation of each of the instantiations discussed is that changes in information content are neither considered nor accommodated explicitly. In a majority of cases, stakeholder strategies are captured, communicated, or predicted via BRCs and thus constitute static, uncompromising representations that do not allow for adjustment or modification outside the explicitly considered range (other than via complete reformulation). Furthermore, *non-cooperative* mechanisms encourage a myopic stance in resolving conflict that emphasizes sub-system performance. Since most protocols are based on single interactions, there is no provision for future refinement. Consequently, design sub-problem goals are likely to be exaggerated in order to assure satisfaction of local requirements. This can contribute to mismatched objectives, the resolution of which requires (trial-and-error) iteration. Chances of finding a mutually acceptable solution and reducing and/or eliminating iterations can be improved through the inclusion of ranged sets of specifications. This is evident especially in the research of Chen and Lewis [44], who seek to provide flexibility in multi-disciplinary conflict resolution. Specifically, these authors integrate the robust design concept into *Stackelberg Leader/Follower* games, developing ranges of solutions, rather than single solution points. Hacker and Lewis [91] and later Kalsi, Hacker, and Lewis [109] integrate aspects of both Type I and Type II Robust Design (i.e., robustness to variation in noise or uncontrollable factors and design parameters, respectively) into the resolution of conflict in order to reduce the effect of interacting decision-makers on one another. Each of these instantiations is aimed at reducing iteration (emanating from changes in stakeholder objectives) by making constituent decisions robust to changes in parameters outside of their control. A similar effect is achieved by Xiao et al., who aspire to ensure a crisp transition from design to manufacture via *digital interfaces* [267,270]. The mechanism for eliminating wasteful iteration is the adoption of *game theoretic* protocols (e.g., *Cooperative*, *Non-Cooperative*, and *Stackelberg Leader/Follower*) in conjunction with Design Capability Indices [46,222]. These common drawbacks to game theoretic means of conflict resolution are summarized in Figure 2-6.

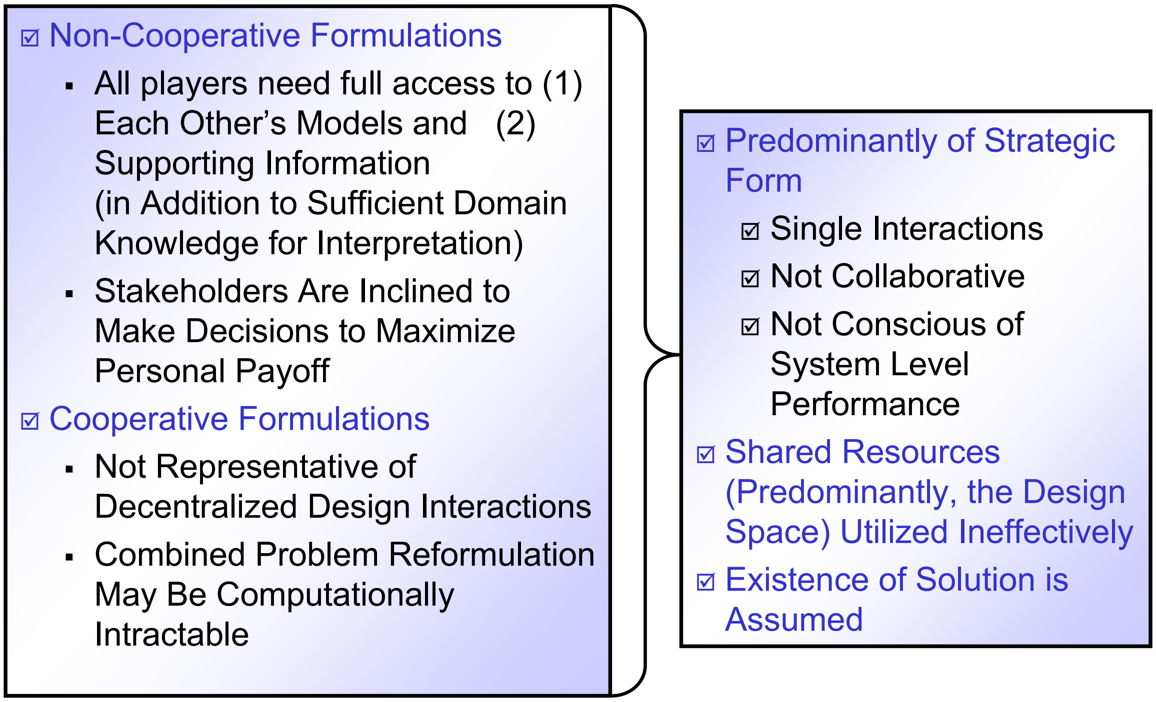


Figure 2-6 - Common Drawbacks to Game Theoretic Means of Conflict Resolution

2.2.6 Focus of Research in this Dissertation

Overall, the fundamental goal pursued in this dissertation is the resolution of conflict among interacting designers, charged with the resolution of coupled design sub-problems, in manner that facilitates the achievement of balanced system level tradeoffs. A key reflection is the preservation of stakeholder dominion. Additionally, consistency of interface, dynamic interaction to facilitate communication and reflection of updated information content, as well as, effective collaboration via exploration of a shared design spaces are considered.

In summary, current decision coordination mechanisms in engineering design are often focused on streamlining the design process by completely excising iteration emanating from *trial-and-error*. This is achieved predominantly via the specification of ranged sets of solutions and the communication of semantically rich information content.

While this is an effective *modus operandi* for changeovers associated with sequential or clearly distinct phases of a product realization process (e.g., design and manufacture), it is not in general suited for facilitating dynamic collaboration throughout the design timeline.

Stakeholder interactions must be both effective and efficient in satisfying the constraints defining their respective design sub-problems, while achieving system level objectives in an unbiased manner. A fundamental challenge lies in that considerations of interacting designers continuously evolve, due to changes in understanding, model fidelity, and technology, to name a few. Current decision models and tradeoff mechanisms are quasi static and thus render the reflection of changes in information content virtually impossible without complete reformulation of both designer aspirations and interaction details. By the same token, stakeholders do not actively participate in system level tradeoffs. Since these conflicts are usually resolved either algorithmically (i.e., BRC intersections in *Nash* games) or via responsibility transfer (i.e., BRC incorporation in design sub-problem formulations for *Stackelberg* games), decision-makers are no longer aligned with their respective domains of expertise.

Alternatively, once design sub-problems have been properly formulated and stakeholder preferences have been clarified, *negotiations* can be used to resolve the underlying conflicts in a more dynamic and self-reliant fashion, that maintains stakeholder sub-system autonomy. However, a majority of the associated tactics and hence also the corresponding mathematics are geared towards the maximization of personal payoff. Consequently, this mechanism is better suited to model loose cooperation or outright competition, and not sufficient to support *co-design*. Similarly, optimization allows for the succinct algorithmic execution of almost any tradeoff, but fails to support the communicative aspect of stakeholder interactions, severely hampering active stakeholder participation

It is noted that this review (summarized in Table 2-1), though representative, is not exhaustive. The intention is to illustrate the extent of applications that game theory has been afforded in the realm of engineering design. With this in mind, a critical comparison of the underlying protocols using the characteristics presented in Table 1-3 is provided in Table 2-2.

As evidenced in Section 2.2.5.2, different protocols have different strengths. Consequently, not every protocol is suitable to every situation. Although many of the comparative advantages of employing game theory, negotiations, and optimization in addressing the needs of collaboration in engineering design can be deduced from Table 2-2, a few stand out.

Many of the commonly instantiated means of managing conflict in decentralized environments are rooted in the assertion that interactions are required solely in order to make suitable tradeoffs among coupled problems. In the search for *Nash equilibria*, for example, solutions to coupled problems are found via intersection of BRCs. Clearly, this is only possible once all coupled sub-problems have been modeled in their entirety and appropriate strategies for tradeoff resolution can be formulated. Similarly, using *Stackelberg* games to model the transition from design to manufacture [267,270] requires transfer of completely formalized decision and analysis models in conjunction with stakeholder strategies. Since this communiqué constitutes the first decision critical interaction among the parties (charged with making the coupled decision) in the course of their relationship, the existence of a solution is an inherent assumption.

Table 2-2 - Comparative Performance of Various Approaches to Conflict Resolution

	Characteristic	Game Theory			Negotiations	Optimization	Proposed Framework
		Non-Coop	Coop	Stackel-berg			
Problem Formulation and Interaction Management	*1. Modularization and Alignment of Design Process and Domain Expertise*	✓	✗	✓	✓	✗	✓
	2. Support for Co-Formulation of Coupled Design Problem	✗	✗	✗	✗	✗	✓
	3. Support for Establishment and Exploration of Collaborative Design Space	✗	✗	✗	✗	✓	✓
	4. Stakeholder Retention of Sub-System Control Throughout the Design Process	✓	✗	✓	✓	✗	✓
	5. Decoupled Treatment of Problem Formulation and Solution	✗	✗	✗	✓	✗	✓
Concise Information Exchange	*6. Suitability as Communications Protocol*	✓	✗	✓	✗	✗	✓
	7. Suitability as Coordination Mechanism for Structuring Interactions						
	a. Cooperative Trade-Offs	✗	✓	✗	✓	✓	✓
	b. Non-Cooperative Trade-Offs	✓	✗	✓	✓	✓	✓
	c. Changeovers (e.g., Design to Manufacture)	✓	✗	✓	✓	✓	✓
	d. Co-Design	✗	✗	✗	✗	✗	✓
	8. Effectiveness of Iterations						
	a. Trial-and-Error Search for Feasible Solutions	✓	✓	✓	✓	✓	✓
	b. Convergent Focalization of Design Activities Based on Inter-Education	✗	✗	✗	✗	✗	✓
Balanced Achievement of Sub-system and System Level Objectives	*9. Supports Systemic Understanding of the Collaborative Design Space and the Determination of Realistic Targets*	✗	✗	✗	✗	✓	✓
	10. Suitability as Solution Algorithm	✓	✓	✓	✗	✓	✓
	11. Quality of Resultant Solution						
	a. Balancing Sub-System Objectives in Light of System Level Objectives	✗	✗	✗	✗	✓	✓
	b. Holistic Satisfaction of Objectives	✗	✓	✗	✗	✗	✓

Clearly, solution spaces, pertaining to the coupled design sub-systems must overlap (at least in part) in order for any of the commonly instantiated solution mechanisms (e.g., game theory, negotiations theory, multi-disciplinary optimization, etc.) to yield useful results. Should mismatches in the achievement of sub-system objectives in light of system level considerations be irreconcilable, the only recourse is iteration, as reflected in Table 2-2, specifically with regard to characteristics 8a and 8b. Obviously, the inherent cost is proportional to expended resources and the likelihood of discordances increases with (1) design progress and (2) system complexity.

In summary, thus far, such mismatches have been addressed only implicitly through iteration, yielding mutually acceptable results *ad infinitum*. Unfortunately, the information required to identify such mismatches is traditionally not communicated until all coupled design sub-problems have been formulated, analyzed, and solved explicitly. Clearly, significant resources have already been expended on behalf of the subsystems at this point. Rather than pursuing the quasi independent optimization of design sub-systems and conscious of the fact that global optimization is likely to be computationally intractable, the proposed approach is centered upon the modularization of interacting parties so that these can maintain their independence, while maintaining a big picture consciousness. Specifically, the focus is on the communication of key information throughout the course of a *design interaction*, defined here, as spanning the interim from design sub-problem formulation to the determination of any local optima and, finally, any attempts at global optimization. Consideration is also given to the assessment of stakeholder impact on shared design spaces.

Among instantiations of game theoretic protocols in engineering design the balanced achievement of system level objectives in decentralized decision-making is neither considered nor accommodated explicitly during conflict resolution. Furthermore, interactions leading up to the decision point in question are not supported explicitly. Both of these fundamental limitations are addressed in this dissertation. The proposed **F**ramework for **A**gile **C**ollaboration in **E**ngineering, motivated in Section 1.3.4, developed in Chapters 3 through 5, composed in Chapter 6, and applied in Chapters 7 and 8, provides the basis for establishing and effectively managing the collaborative design spaces associated with decentralized design. This is accomplished through (1) the effective identification of those regions within a design space that have the potential of yielding results, acceptable to all interacting parties and (2) the system conscious distribution of shared resources in resolving the associated tradeoffs. Though not the primary focus, the modeling, representation, and simulation of collaborative decision-centric design processes is stressed as an enabling technology in Chapter 3. With this in mind, a review of common approaches to modeling both products and processes in engineering design follows.

2.3 MODELING PRODUCTS IN ENGINEERING DESIGN

A fundamental contribution in this dissertation is the templatized modeling of decentralized design processes in a modularized reusable fashion. The focus of these design processes is the product being designed. The associated design problem is modeled in terms of the underlying design decisions. Since the goal is to facilitate the consideration of design problems in both a product- and process-centric fashion, a review of product modeling techniques is warranted.

2.3.1 Engineering Products and Design Problem Formulation

The natural way of conceptualizing product modeling in engineering design is usually to think of CAD and FEA models – two and three dimensional representations of the *form* and *behavior* of the product being designed. The process of design then consists primarily of the iterative reconciliation of predicted *behavior* with expected *function* via adjustment of *form*. This implies a rather informal process of solid modeling coupled with simulation-based trial-and-error. Often, a more formal approach is adopted that synthesizes information from such simulations with functional drivers in a semi automated fashion. In this vein, engineering products are treated in terms of the associated design problems. Since this in close agreement with the decision-centric focus adopted in this dissertation, products and design problems are treated quasi synonymously.

Any optimization problem of the form: given a set of requirements, minimize/maximize an objective, subject to a set of constraints constitutes a product model. Specifically, simulation models are usually employed to capture and simulate product *behavior* based on *form*, in a constant effort to achieve the desired *function*. The specific constructs used (in lieu of traditional optimization) for the purposes of product design (i.e., problem resolution) in this dissertation are the decision constructs of the DSP Technique, namely the selection and compromise DSPs. Rather than focusing on the traditional formulations of these fundamental information transformations, their utility-based formulations are focused upon instead. Their word and mathematical formulations are provided in Table 2-3 and Table 2-5 for the Utility-based selection DSP [72,79] (u-sDSP) and in Table 2-4 and Table 2-6 for the Utility-based compromise DSP (u-cDSP)

[203], respectively. It is upon these "blue prints" that the decision templates developed in Chapter 3 are built.

Table 2-3 - Word Formulation of the Utility-based selection DSP

Utility-based selection Decision Support Problem Word Formulation	
Given	Finite set of feasible alternatives.
Identify	The principal attributes influencing selection. The uncertainties associated with each attribute.
Assess	Decision-maker utility with respect to each attribute and with respect to combinations of attributes.
Evaluate	Each alternative using the decision-maker's utility functions.
Rank	Most promising alternative(s) based on expected utility.

Table 2-4 - Word Formulation of the Utility-based compromise DSP

Utility-based compromise Decision Support Problem Word Formulation	
Given	An alternative that is to be improved through modification. Model of the domain of interest. A set of independent system variables. A set of goals for the design.
Identify	Attributes of interest. The decision-maker's overall utility profile. System constraints.
Find	The values of design variables. The values of the deviation variables.
Satisfy	System constraints.
Minimize	The deviation function, which is a measure of the deviation of the system performance from that implied by the set of goals and their associated utilities.

Table 2-5 - Mathematical Formulation of the Utility-based selection DSP

Utility-based selection Decision Support Problem Mathematical Formulation		
Given	X_o	Vector of alternatives.
	o	Number of alternatives for the selection problem.
	p	Equality constraints
	q	Inequality constraints
	p+q	Number of system constraints
	m	Number of system goals
Identify	N	The number of system goals considered being attributes of interest for the selection problem at hand.
	$U = a + be^{cx} + dx$	The decision-maker's utility with respect to individual goals.
	$U = f_i\left[u_1(x_1), u_2(x_2), ..., u_m(x_m)\right]$ where, i = 1,…,m.	The decision-maker's utility with respect to the system as a whole.
	σ, μ or B_{lower}, B_{Upper}	Uncertainties associated with system goals for each alternative.
	$g_i(\underline{X})$	System constraint function, if required.
Find	$U = f_i\left[u_1(x_1), u_2(x_2), ..., u_m(x_m)\right]$	Respective Utilities of Selection Alternatives
Satisfy	$g_i(\underline{X}) = 0$, where j=1,…,p $g_i(\underline{X}) \geq 0$, where j=1,…,p	The system constraints that must be satisfied for the solution to be feasible. No restriction is placed on either linearity or convexity.
	$\left(\sum_{i=1}^{M} I_j R_{ij}\right) X_i + e_i^- - e_i^+ = 1$ Subject to: $e_i^- \cdot e_i^+ = 0$ and $e_i^-, e_i^+ \geq 0$	Selection System Goals for i = 1,…, m
Maximize	$U = f\left[u_1(x_1), u_2(x_2), ..., u_m(x_m)\right]$	Expected Utility
or		
Minimize	$Z = 1 - f\left[u_1(x_1), u_2(x_2), ..., u_m(x_m)\right]$	Deviation from Target Expected Utility of 1.

Table 2-6 - Mathematical Formulation of the Utility-based compromise DSP

Utility-based compromise Decision Support Problem Mathematical Formulation		
Given	n	Number of system variables
	p	Equality constraints
	q	Inequality constraints
	p+q	Number of system constraints
	m	Number of system goals
Identify	N	The number of system goals considered being attributes of interest for the compromise problem at hand.
	$U = a + be^{cx} + dx$	The decision-maker's utility with respect to goals.
	$U = f\left[u_1(x_1), u_2(x_2), ..., u_m(x_m)\right]$	The decision-maker's utility with respect to the system as a whole.
	σ, μ or B_{lower}, B_{Upper}	Uncertainties associated with system goals for each alternative.
	$g_i(\underline{X})$	System constraint function
Find	X_j, where j = 1,…,n	The values of the independent system variables.
	$U = f_i\left[u_1(x_1), u_2(x_2), ..., u_m(x_m)\right]$	Respective Utilities of System Goals
Satisfy	$g_i(\underline{X}) = 0$, where j=1,…,p $g_i(\underline{X}) \geq 0$, where j=1,…,p	The system constraints that must be satisfied for the solution to be feasible. No restriction is placed on either linearity or convexity.
	$A_i(\underline{X}) + d_i^- - d_i^+ = G_i$, where i = 1,…,m	The system goals that must achieve a specified target value as far as possible. No restriction is placed on either linearity or convexity.
	$X_j^{min} \leq X_j \leq X_j^{max}$, where j = 1,…,n Subject to: $d_i^- \cdot d_i^+ = 0$ and $d_i^-, d_i^+ \geq 0$	The lower and upper bounds on the system. Not needed because contained within the Utility Functions…
Maximize	$U = f\left[u_1(x_1), u_2(x_2), ..., u_m(x_m)\right]$	Expected Utility
or		
Minimize	$Z = 1 - f\left[u_1(x_1), u_2(x_2), ..., u_m(x_m)\right]$	Deviation from Target Expected Utility of 1.

2.3.2 Representation in Product Design

An important step in progressing towards the effective (standardized) modeling of products is their consistent representation. Due to the inherent and ubiquitous diversity of every aspect related to engineering design, standardization is difficult. Consequently, although information models are continuously being proposed, the advent of a single unifying standard is still in the distant future. However, there are two notable efforts that show significant promise - the Core Product Model (CPM) and the NIST Design Repository Project.

The Core Product Model (CPM) was developed by Fenves et al. [70] for representing design information throughout the design cycle of technical artifacts. Synthesized from a number of different projects, the primary objective was that of providing a base-level product model. The resultant model is independent of any specific software vendor, simple, openly expandable, and capable of accounting for a wide variety of products and processes. Additionally, CPM can capture information extensively, regardless of product or phase in the design process. Unlike most other product models, CPM is meant to facilitate information exchanges in the conceptual stages of design. In this aspect, CPM complements STEP (Standard for the Exchange of Product Model Data), which is more ideally suited for later stages.

Similarly, the NIST Design Repository Project is focused on the development of a framework for supporting the implementation and use of design repositories, with the intent of enabling knowledge-based design via capturing, sharing, and reusing design information. As such this project takes the view that design repositories are the natural progression from traditional engineering databases to a means of capturing evolutionary design information in product development. Proposed by Szykman et al. in Ref. [236] design repositories are shown to differ from traditional databases their capability of capturing evolutionary information generated during a design process. Databases, on the other hand, constitute archives of completed designs and consequently are only truly valuable once a design is completed.

The reader is referred to [151] for a comprehensive overview of issues relating to the successful integration of design and analysis as well as the role of simulation in product design, as discussed in the following section.

2.3.3 Simulation in Product Design

Other efforts have taken an object-oriented modeling approach. Notable efforts in this vein include: (1) the Composable Simulation Project [58,59,171,225,226], (2) the Multi-Representation Architecture [175-179,199,200,239], and (3) MOSAIC - Integrated Modeling and Simulation of Physical Behavior of Complex Systems [11-14,212,213]. According to Mocko [151], "…the object-oriented modeling approach, as leveraged from the software development domain, is a step in the natural progression of modeling mechanical systems". Tamburini [239] intuits that object-oriented modeling makes possible the creation of "physically relevant and easy-to-use components that support hierarchical structuring, reuse, and evolution of large and complex models covering multiple technology domains". The result is object accessibility via predefined ports, treatment of underlying implementation methods as black boxes, inheritance, reuse, storage, and adaptability. Simulation models developed in this fashion thus allow for "…

easy refinement and modification, necessary to support the evolutionary nature of the design process" [151].

The Composable Simulation Project is based on simulation models being composed from model constituents in an object-oriented, hierarchical fashion, multiple models being associated with a single system component, and model parameters being extracted automatically from sources such as CAD geometry and material properties. "The ultimate goal of composable simulation is to develop a modeling methodology that allows the designer to quickly and easily verify the behavior of the system being designed" [171].

COBs is an information modeling language that is aimed at "…next-generation stress analysis tools. COBs combine object and constraint graph techniques to represent engineering concepts in a flexible, modular manner". As such, COBs form the basis of the extended multi-representation architecture (MRA) [178] for analysis integration. This effort is targeted at environments that are characterized by significant part-, analysis-, and tool-diversity [178,179]. Design-analysis associativity is supported explicitly for the purposes of (1) automation and knowledge capture and (2) multidirectional relation management (for both design sizing and design checking). COBs are also an effective tool for representing and managing the complex constraint networks, commonly associated with engineering design analyses.

MOSAIC is focused on the improvement of integration in the modeling and simulation of products during the product development process. The fundamental aim is to develop an object-oriented model for product behavior. With this in mind, a product model is developed for the entire product development process and a prototype system developed. The goal is to support complex products with respect to both simulation and design [11].

Although both port-based models, COBs, and MOSAIC comprise significant steps in the direction of process reuse, neither is situated at a decision level. Each is tied more closely to the product level, specifically *function* and *behavior* as determined through composable simulations, inspired by *form*. Clearly, there is a long history of research and development in the domain of composable simulations in electrical engineering. This is attributable in part to the fact that inputs and outputs are fairly predictable. That is to say all of the basic components (i.e., resistors, capacitors, inductors, transformers diodes, motors, etc.) are related to one another on the basis of current. The net effect of components on one another is usually a change in current, resulting from a change in electric potential. The most prominent tool in this area is probably Spice (perhaps better as PSpice, the name given to its first PC version in the 1980's), which has been used since its earlier instantiations in the 1970's (then called CANCER - Computer Analysis of Non-Linear Circuits Excluding Radiation) in order to model circuits on a simulation basis. Though the technology and the underlying principles are neither theoretically nor technically incapable of modeling design processes at a higher level of abstraction, what has made this jump so difficult has been the lack of conformity to a single and predictable set of standards for presenting flows of information. Unlike current, these information flows are neither predictable nor consistent. Additionally, since most design processes occur at a higher level of abstraction the encapsulation of set transformations is much more difficult. The material presented in Chapter 3 is an example of an effort to bridge the resultant gap between design and simulation, as well as the associated limitations placed on reusability. With this in mind, the hybrid product/process information model comprising the basis for this effort is presented in Section 2.4.

2.3.4 From Product to Problem to Process

There has been a significant amount of research with regard to modeling both products and processes. While some efforts have been concerned mainly with focusing on either product or process related aspects separately, others have pursued a more integrated perspective. On the process side, relevant endeavors include the proposition of a Process Specification Language (PSL) by Schlenoff [197,198] and ISO 10303 STEP Standard AP 231 for Process-Engineering Data [4]. There are also a number of efforts that seek to reconcile product and process-centric perspectives. Examples include the Georgia Tech Process to Product Modeling Tool (GTPPM) developed by Lee, Eastman, and Sacks [63,194] and the Object-Oriented Modeling of Products and Processes, proposed by Gorti et al. [89]. Many of these efforts can be ascribed to overarching efforts relating to Product Lifecycle Management.

A major thrust in PLM is the integration of the value chain throughout the extended enterprise. Supply and design comprise two essential and complementary components of the value chain. As indicated in Section 1.1.2, a significant amount of work is currently being undertaken by the Supply Chain Council with regard to addressing modeling issues in supply chains. For example, the SCOR model [6] is developed to represent and measure supply chains in a standardized manner to enable improvements in supply chain operations through analysis of current processes and best practice emulation. Along these lines, numerous case studies have been conducted. For example, SCOR model is currently being extended to the Enterprise Transaction Model by Streamline SCM [5].

An analogous effort if currently underway with respect to activities associated with design processes. SRL research efforts are focused on modeling design chains from a decision based perspective, ensuring domain independence and interoperability among the various stakeholders involved in a product realization process. Consequently, models and methods are being developed to address the needs of the design effort on various levels of abstraction, so that the resulting hierarchy effectively supports the design activities of the engineering enterprise, as indicated in Figure 2-7. Product realization processes are modeled at varying levels of scope and detail depending on the purpose of the underlying modeling effort. For example, the intent behind modeling processes at the managerial level is mainly that of clarifying underlying relationships and information flows. At the designer level, on the other hand, the goal is to manage information flows, integrate stakeholders and tools, and facilitate engineering decision-making, as focused upon in this dissertation. Both ends of spectrum are crucial for modeling and integrating the design chain into supply chain. So far, both ends are addressed independently, in an isolated fashion.

Due to increasing globalization and outsourcing, the infrastructure supporting design activities is likely to become just as federated as those underlying the already vast network of suppliers involved in any product realization effort. It is due to this impending reality that the need for the integrated modeling of design and supply chains arises. This motivates the research with regard to proposing a generic, decision-based framework for enabling design chain integration, towards which the efforts documented here contribute. Before proceeding to consider integrated product and process modeling, however, more light will be shed on process-specific aspects in Section 2.4.

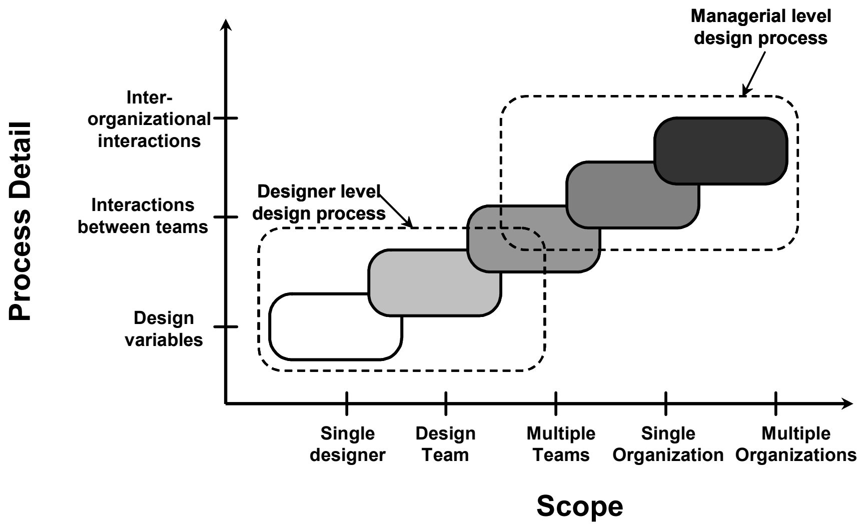


Figure 2-7 - Modeling Product Realization Processes at Various Levels of Abstraction

2.4 MODELING PROCESSES IN ENGINEERING DESIGN

Virtually all of the contributions, associated with the three hypotheses discussed in this dissertation, revolve around the notion of supporting tradeoffs in decentralized design. At the core of this effort is the associated design process, centered on reconciling the various coupled design problems, formulated as decisions. With this in mind, a discussion of process modeling techniques is warranted.

2.4.1 An Overview of Process Modeling Literature

At a modeling level, efforts range from those focused on capturing processes in order to support organizational decisions to those aimed at capturing and understanding designer intentions and extending the applicability of Artificial Intelligence. Adopting the Activity-Based view, the design process is viewed as a set of activities that can be subjected to organizational or scheduling analysis. Often graph-based and matrix-based methods are used for representation. The graph-based techniques rely on Activity-Net-based models [66], the earliest and most widely used techniques for modeling processes, to analyze and compare the processes based on complexity. In this vein, the design structure matrix (DSM) [67] is a popular means for representing both products and processes with regard to their underlying hierarchies. The main advantage of using DSM is the ability to identify both interactions and iterations in a design process. Browning and Eppinger [33] use DSM to model processes as sets of activities and process architectures as processes, along with their patterns of interaction. DSM is used for a variety of analyses including cost, schedule, risk tradeoff, probability of rework, level of interaction, complexity, iteration, and process improvement.

Shimomura et al. [215] portray design as a process of functional evolution where a design object, which includes function, is gradually refined over time. This is commonly referred to as the Functional-Evolution-Based approach to process modeling. The representation of this design object is based on the Function-Behavior-Structure (FBS) model [250]. One of the advantages of this technique is the ability to model the product (as an FBS model) and process (as functional evolution) in an integrated fashion. This model can be used to both trace the design process and capture design intent. From the Product-State-Evolution-Based perspective, the design process is considered to be a problem solving technique centered on dynamically moving around a so-called product state space [102], where a product state represents all the information describing the product at a given point in the design process.

Tomiyama, Yoshikawa, et al. [238,244] view design as a mapping of a point in the function space onto a point in the attribute space. Ullman [247] has also viewed the process of design as the refinement of a design from its initial state to its final state. Maimon and Braha [132] present the use of the Analysis-Synthesis-Evaluation (ASE) paradigm for representing design processes in terms of knowledge manipulation. Zeng and Gu [272] implement models similar to ASE for developing a mathematical model of the design process. Specifically, they develop a basic mathematical representation scheme to define objects involved in a design process for investigation. Adopting the Knowledge-Manipulation-Based view of design processes, the representation of design knowledge (via decomposition, case-based reasoning, and transformation) within the design processes is formalized as purported by Maher [131].

Finally, the Decision-Based view of modeling design processes centers on Decision-Based Design (DBD). Mistree et al. [142] view design as a process of converting information into knowledge about the product and decisions are the key markers used to determine the progression of design. Design processes can thus be modeled as sets of decisions. The Decision Support Problem (DSP) Technique [32,142,147,149,155], reviewed in Section 2.2.4.2, is a framework for design based on this mindset. The DSP Technique [146] palette contains entities for modeling design processes, and allows for the arrangement and rearrangement of procedures or activities essential to design. The entities in the palette are used to build hierarchies and model design processes independent of the domain of the design under consideration [142]. The entities considered within the palette (i.e., tasks, decisions, events, and phases) are used to transform information from one state to another. Key decision types in engineering are also identified within the DSP Technique. These are selection [80,144], compromise [143,210], and combinations thereof (i.e., coupled decision), as emphasized in Sections 2.2.4. These decisions serve as the backbone for modeling design processes. In order to generate information required for executing these decisions supporting tasks are performed.

At a representational level, the Process Specification Language (PSL) [197] is an effort pursued by the National Institute of Standards and Technology (NIST), aimed at standardizing the representation of discrete processes (i.e., processes described as individually distinct events such as production scheduling, process planning, workflow, business process re-engineering, project management, etc). Gorti and co-authors [89] propose an object-oriented representation for product and process design, focused on key elements of a design process – goals, plans, specifications, decisions, and context. The design artifact includes function, behavior, structure, and causal knowledge (i.e., relating objects to physical phenomena). Since the primary objective of the authors is to develop a comprehensive engineering knowledge-base, however, they do not focus on design process analysis.

At a computational level, design processes are commonly represented using commercial software applications such as ModelCenter® [107], FIPER [106], iSIGHT [207] and Hyperworks Process Manager™ [105]. The basic process element in this case is simulation code. The information captured using this process element in modeling processes with these applications is strictly related to the inputs, outputs, code to be executed, and the relationships between parameters. The design process is defined exclusively by the flow of parameter values between various software applications. This in effect links the problem specific (*declarative*) information to the design process specific (*procedural*) information. Consequently, reusability and adaptability are limited to parametric design where the set of parameters and their relationships remain the same. Mere addition or deletion of parameters requires reformulation of the underlying process. Design process descriptions thus cannot be reused even if the process remains the same and the parameters change. This poses a significant challenge for collaboration where contexts remain dynamic as products mature and control over design parameters is often shared.

2.4.2 Critical Analysis of Current Process Modeling Approaches

An overview of the predominant approaches to design process modeling is provided in Table 2-7. On the whole, tradeoffs occur between broadness in model applicability, granularity of information represented, and the extent of analyses that can be performed using each of the models considered. For example, PERT, Gantt Charts, IDEF0, and Activity-Net-based models are very general in terms of applicability, but can be used to represent information only in terms of required activities and time. Thus, while many of these models are quite effective for design process management and others furnish effective support for decision-making, analysis, and simulation with regard to the independent consideration of design problems, none comprise a comprehensive means of supporting the collaboration of interacting stakeholders along a design timeline. More importantly, current models can be extended, updated, and reused once they have been formulated only within a very limited range. This is due predominantly to the fused manner in which *declarative* (i.e., problem specific information) and the *procedural* (i.e., process specific information) information are handled (see Section 2.7.2). As a result of these limitations, it has thus far not been possible to model design processes at a level sufficient for (1) execution, (2) analysis, and (3) reusability, as required for effective collaboration among stakeholders along a design timeline.

Table 2-7 - An Overview of Process Modeling Efforts in Engineering Design

Process Modeling Effort		***View of Design***	***Modeling /Analysis Objective***	***Basic Units of a Process***
IDEF	*[1]*	Activity Based	Organizational Decisions	Activities, Information
DSM	*[67]*	Activity/Task Based	Organizational Decisions, Risk, Complexity, Probability of Rework, Iterations, etc.	Tasks
Shimomura	*[215]*	Functional Evolution	Capture Design Processes, Designer Intent, Trace Design Processes	Functional Realization, Functional Operation, Functional Evaluation
Ullman	*[247]*	Evolution of Product States	Process representation	Abstraction, Refinement, Decomposition, Patching Combination, Combination
Maimon	*[132]*	Knowledge Manipulation through ASE	Development of a Mathematical Theory for Design	Artifact Space, Specs, Analysis, Synthesis, Evaluation
Maher	*[131]*	Knowledge Manipulation	Development of Knowledge Based Systems	Decomposition, Case Based Reasoning, Transformation
Gorti	*[89]*	Goal Satisfaction	Development of Engineering Knowledge Base	Goal, Plan, Specification, Decision and Context
DSP Technique	*[155]*	Decision Based Design	Modeling, Analyzing, Debugging, Finding Inconsistencies in a Design Process	Phases, Events, Decisions, Tasks, Information

Having reviewed approaches to independently modeling products and processes in Sections 2.3 and 2.4, respectively, their integrated representation and simulation is considered in Section 2.5. This is a critical (and prerequisite) consideration for effectively supporting decentralized design, as pointed out in Section 1.3.3.1.

2.5 INTEGRATED MODELING OF PRODUCTS AND DESIGN PROCESSES

In simulation-based design, the *design process* represents the manner in which information, generated by simulation models, is utilized for satisfying design objectives through analysis, synthesis, and evaluation. These processes are inherently complex because of the interdependencies among simulation models at various scales. Given this inherent complexity of design processes, it is imperative that the *design processes themselves be designed appropriately* and *systematically*. Inefficient design processes can lead to longer design timelines, thereby contributing to higher costs [32]. The role of meta-design in product design is well acknowledged throughout the literature. According to Simon, "… design process strategies can affect not only the efficiency with which resources for designing are used, but also the nature of final design as well" [221]. Bras and Mistree [32] point out that "a necessary ingredient in increasing the efficiency and effectiveness of human designers is the modeling of design processes in a manner that can be analyzed, manipulated and implemented". The systematic design of design processes is thus crucial for the timely deployment of products. Panchal et al. highlight that design processes are a company's primary intellectual capital and should be designed, managed, and reused strategically [166].

In spite of the fundamental importance of meta-design in expending resources, it is not effectively supported by current Computer Aided Engineering (CAE) and Product Lifecycle Management (PLM) frameworks. Most CAE and PLM frameworks adopt a *tool-centric* view of design processes, according to which a design process is a network comprised of software tools employed for processing information. The adoption of a tool centric perspective in developing design frameworks, thus invariably focuses the underlying effort on *achieving interoperability* between 1) different tools that perform similar function (such as different CAD applications), 2) tools providing different functionality (structural analysis, crash, vibration, etc.), and 3) applications pertaining to different domains. Various standards such as STEP, XML, and UML are being developed to achieve interoperability between such tools. Recently, Peak et al. [174] proposed a *model-centric* perspective to support the further development of these frameworks . Specifically, a product information model comprises a central core, modified and populated using all relevant tools. Such a model-centric view constitutes a significant improvement over the tool-centric view, commonly espoused, because information is no longer tied solely to the particular tools used for its creation or modification. It is acknowledged that a model-centric perspective is important for realizing the seamless integration of information models, associated with different aspects of product design, and useful for guiding the development of CAE and PLM frameworks to support fine grained interoperability, as well as, the development of a collective product model. However, it is asserted that neither the *tool-centric* nor *model-centric* perspectives (alone or in concert) are adequate for effectively supporting meta-design.

A fundamental obstacle in furnishing the capability for meta-design is the inability of current tools to capture the problem solving aspect of design. In fact, such tools are primarily used to capture procedural aspects. Put another way, current tools do not capture *a) what* the design problem is, *b) how* the designer partitions the problem, and *c) how* different problems are related. Instead, current tools only capture the specific series of steps a designer adopts when solving the problem at hand in a quasi documentary fashion. Design problem changes can thus not be translated to the procedural information captured within the individual tools.

The word "*problem*" has been used to mean many different things in the engineering design community. In this dissertation, a problem is defined as being "either an obstacle to be overcome or a question to be answered". This definition is taken from Ref. [155] and differs from the text book definition of problem solving, where the problem is completely defined and can be solved using a predefined set of steps resulting in a unique solution (see Ref. [94]). In practical application, designers are faced with problems where neither complete information nor closed form solutions for solving a problem are likely to be available. Considering that the problem solving aspects of design are not currently captured in CAE and PLM frameworks, it is difficult to support meta-design.

The solution to this problem is posited to lie in adopting a decision-centric problem-solving approach to design. According to many researchers such as Hazelrigg [94], Muster and Mistree [155], and Thurston [241] the fundamental premise of decision-based design is that engineering design is primarily a decision-making process. A decision-centric approach is adopted in this dissertation because from a decision-centric perspective, meta-design is a meta-level process of designing systems that includes partitioning the system based on function, partitioning the design process into decisions, and planning the sequence in which these decisions are most appropriately made [148]. These aspects are addressed explicitly in Chapter 5.

Specific advantages of adopting a decision-centric perspective include the ease with which both *model-centric* and *tool-centric* views are generated. Furthermore, domain independent representation of design processes becomes feasible. Hazelrigg describes decision-based design as *omni-disciplinary,* "the seed that glues together the heretofore disparate engineering disciplines as well as economics, marketing, business, operations research, probability theory, optimization and others" [94]. Herrmann and Schmidt [95] describe a complete product development organization as a network of decision-makers who use and create information to develop a product. Although principles of decision-based design have been accepted in theoretical aspects of design research, they have not been implemented in design frameworks. Current tools do not capture information related to designers' decisions; decision related information is captured in the form of meta-data only (if at all).

The various challenges cited in the preceding paragraphs, call for an approach that distinctly captures and processes all three key components of design related information - *a)* design ***problem***, *b)* design ***process***, and *c)* ***product***. It is in this regard that the 3-P Information Model [161,164], rooted in decision-based design, modularity, and separation of *declarative* and *procedural* information is adopted. The modular separation of information associated with **p**roblem, **p**roduct, and **p**rocess enables designers to utilize existing knowledge, captured in the form of pre-defined process configurations, for more effectively designing a given product. The roles of these three components and the resultant key characteristics of the *3-P* approach are illustrated in Figure 2-8. As indicated, the 3-P Approach consists of three basic principles: (1) decision problem Focus, (2) modularity, and (3) separation of *procedural* and *declarative* information. The proposed approach facilitates the efficient exploration and reconfiguration of design processes, furnishing a much needed and essential basis for meta-design. In this context, processes themselves are viewed as systems that consist of sub-systems interacting with each other through well defined interfaces. A modular systems-based approach for design processes is employed in order to support reusability and composability of such processes. This aspect of the proposed strategy is related to material in Chapter 3. The separation of *declarative* information from *procedural* information (see Section 2.7.2) is used in order to increase reusability of processes for different products and decisions. Although developed within the context of the DSP Technique, the 3-P Information Model has implications reaching far beyond this particular instantiation of decision-centric design. The reader is referred to Refs. [161,164] for more information on this topic.

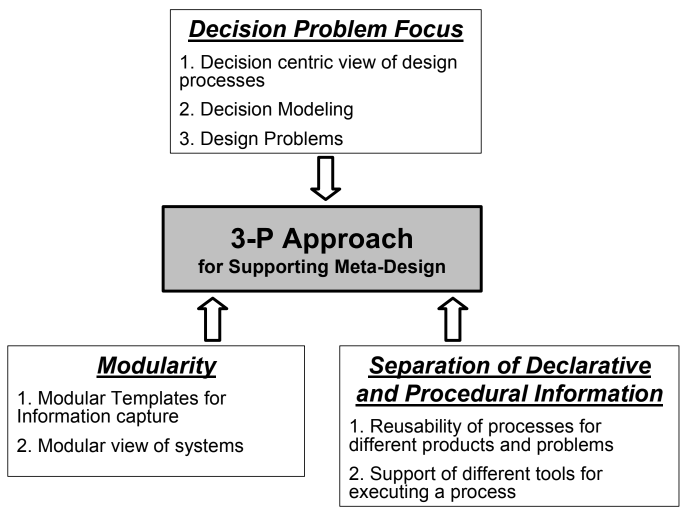


Figure 2-8 - Three Principles of the 3-P Approach [164]

The primary contribution of the research documented in this dissertation is identification of mutually acceptable regions of a collaborative design space and the subsequent resolution of the associated tradeoffs in the most non-biased manner possible. A fundamental prerequisite is the consistent modeling of decision-centric designer interactions based on coupling between design sub-problems. A design process in this context consists of series of decisions, carried out either sequentially or in parallel by (1) single designers acting in isolation and (2) multiple, interacting designers, collaborating in pursuit of a mutually beneficial solution to shared problems. Since it is assumed (and realistically so) that multiple interactions will be required in order to focalize the activities of the various stakeholders involved, it becomes clear that consistency is desirable – consistency with respect to the manner in which design sub-problems are modeled (i.e., problem), designers are interfaced (i.e., process), and design sub-spaces contribute to the overarching systems level (i.e., product). As indicated previously, a common denominator is required for reconciling differences in domain, discipline, and focus on the one hand and product and process specific aspects on the other. The most natural choice is focusing on design decisions as embodied within the 3-P Information Model.

Since designer preferences play a significant role in determining the final form, function, and behavior of an artifact as well as in formalizing the course design processes take, a brief discussion regarding their modeling follows.

2.6 MODELING PREFERENCES IN ENGINEERING DESIGN

In many ways, preferences can be considered to constitute the most influential, yet most underestimated, driver in the evolution of designs. Preferences affect the outcomes of decisions both directly, via the rather subjective translation of system level requirements to sub-system level requirements, as well as the correlation between differently termed, but closely related requirements at the same hierarchical level, and indirectly through the manner of their (mathematical) formulation. Since designer objectives typically differ in granularity, fidelity, or technical relevance from those specified by a customer adjustment is often required. For example, individual designers may want to infuse ranges of performance based on (1) forecasted demands of future product generations or (2) specifications made by other customers.

Typically, preferences are modeled via the use of weighted sums meant to balance tradeoffs among goals in an objective function by levering importance of said goals relative to one another. The procurement of decision-maker preferences can take two alternative forms. Is the *preemptive formulation* chosen, criteria must be satisfied in the order specified and the mechanics of the chosen construct are much like those of a multi-level filter. The "resolution" of the filter directly depends on the aspirations of the decision-maker. In cases where only monotonic preferences (i.e., the-higher-the-better or the-lower-the-better) are considered a hierarchically sorted rank ordering results. The same is true for the consideration of non-monotonic preferences. Depending on the bounds set by the decision-maker, even a single attribute may suffice to distinguish a single alternative, by ruling all others out. The advantage of implementing this formulation is that weights need not be determined explicitly and a simple ordering of preferences is sufficient to make a selection. The disadvantage, however, is that the notion of tradeoff is disregarded entirely. In the case of the *Archimedean formulation* weights for each of the attributes, to be taken into consideration, must be determined using methods such as pair-wise comparison or relative weighting. Some of the drawbacks inherent in weighted sums are that the resulting merit function restricts the expression of a decision-maker's preferences and requires or imposes both independence of a decision-maker's preferences for multiple attributes and linearity of those preferences with respect to changes in the measure of an attribute. Although a designer may value incremental changes in an attribute differently at different levels of that attribute or at different levels of other attributes, he/she is restricted to employing a single weight for each attribute. Additionally, imprecision in performance and associated risk are not addressed. In many cases a considerable amount of iteration is required in order to fine tune the weights so that results are representative of decision-maker preference. It is important to note that the manner in which these weights are determined only effects the ease and intuitiveness of their procurement, depending on the amount of available information and experience of the decision-maker in question. It has, however, no bearing on the way in which these preferences enter into the merit function.

Alternatively utility theory may be employed for capturing decision-maker preferences in functional form. Utility theory is part of a larger framework for the analysis of decisions under uncertainty. As such, the rules and procedures for decision-making are derived from sets of axioms and are certain to have a theoretically rigorous, mathematical basis. Although the use of utility theory alone is not suitable as a support mechanism for making decisions in engineering design, a decision support framework based on utility theory has a number of attractive characteristics. It is *rigorous*, *preference-consistent*, and *reflective of designer preferences. Rigorous*, here refers to the fact that utility theory is based on a set of clearly defined axioms or assumptions rather than heuristics and provides consistently reliable results when employed in a proper context. Since utility-theory facilitates the explicit and accurate incorporation of designer's preferences for multiple attributes as well as tradeoffs and uncertainty related to these attributes, it is also *preference-consistent*. Overall then, the method *reflects* designer preferences rather than *imposing* preferences upon a designer and rational decision-making (with rational defined as being consistent with a designer's preferences) is facilitated. This capability to model preferences quantitatively becomes especially significant when dealing with large numbers of objectives, for which simultaneous ad hoc consideration is extremely difficult and treatment of tradeoffs and uncertainty with respect to the attributes becomes crucial. Further benefits to engineering design are inherent in the ability to capture preferences in the form of utility functions, which may then be persisted, communicated between distributed entities, and propagated along a design timeline. Reliance on utility theory also facilitates the exploration of shared design spaces by multiple designers by furnishing a consistent (i.e., stakeholder specific) and context independent means of normalization. This in turn allows for the removal of problem specific achievement biases and in a sense provides a common denominator for weighing system level tradeoffs based on sub-system level performance measures.

In the context of a decision framework rooted in utility theory decision-makers must choose the most preferred alternatives, given that the consequences of these may be characterized by probability distributions rather than deterministic values for a set of attributes. Frameworks, implying the existence of utilities with the desirable property that expected utility might be employed as a guide for preference consistent decision-making, have been proposed by a number of different authors ([252], [196], [130], [83]). Implementation of utility theory thus requires satisfaction of the underlying axioms. Though more will be said on this topic in the final sections of Chapter 9, the reader is referred to any of the standard references cited above for more information. Since the underlying mathematical basis of utility theory, is not reinforced here, the reader is encouraged to consult Refs. [72,79,80,203] for additional insights.

It is important to note that the importance of preferences and the manner in which these are modeled on the outcome of engineering decisions is often underestimated. Scott [201] asserts that in modeling any design problem one must consider that not all preferences are likely to be modeled by an objective function *f*, seeking the best possible performance, and that there is no obvious or unique way of comparing different performance variables, usually not expressed in the same units. Additionally, requirements themselves are often imprecise. It is these challenges that the Method of Imprecision (M_oI) [122,159,262,263] is aimed at addressing by introducing the notion of preferences as mappings, represented by μ and restricted to the closed interval $[0,1]$, that take into consideration any imprecision (inherent in preliminary design) and provide a basis for comparison between performance with regard to different attributes. These mappings are divided according to whether they pertain to *customer* preferences (expressed as performance preferences $\mu_P : P \rightarrow [0,1]$) and *engineer* preferences (expressed as *design preferences* $\mu_D : D \rightarrow [0,1]$). It is argued that while *performance preferences* express customer requirements for potential performance values more completely than crisp targets, *design preferences* make possible the incorporation of performance aspects, not explicitly accounted for by the mapping *f*. The foundation of this approach is the realization that "…designs are often judged by criteria that are not calculated in an engineer's analysis" [201]. Often it is these criteria (not modeled in *f*) that end up (1) being incorporated into or (2) serving as the basis for negotiations with other stakeholders in the design process. This problem is mitigated through the specification of *design preferences* in the design decision problem.

The key realization, here, is that preferences guide the design process both explicitly during negotiations, as well as, implicitly during the formulation of targets for objectives. Preferences thus steer design decisions with regard to single objective performance and the manner in which tradeoffs are struck among competing objectives. Clearly, the associated effects, intricacies, and nuances can only be exacerbated by shared responsibility and preference aggregation. The aggregation of preferences, however, is a subject of much contention. While some assert that combining desires is unavoidable, others insist that doing so is fundamentally flawed and, though rather prevalent and quite necessary in practice, theoretically impossible. A more detailed discussion on this topic as well as other commonly made contentions is deferred to the final sections of Chapter 9.

In the case of Negotiations [201], combinatorial preferences are addressed via an aggregation function *P*, depending directly on the manner in which individual preferences are formalized. Other approaches focus on similar aggregation functions such as multi-attribute utility functions, as adopted in this dissertation. Reliance on utility theory (in the strict sense), however, requires adherence, submission, and subscription to the judgment of an appointed benevolent dictator. In the case of strongly coupled decisions that require concurrent resolution this is not always feasible, depending on the level of cooperation among the interacting parties. However, it is supposed in this dissertation that it is in all stakeholders' best interest to cooperate to the highest degree possible. Consequently, decision-makers are provided with a means to communicate effectively and ensure *win/win* scenarios for all those involved. The precise manner (i.e., responsibility transfer, BRC intersection, etc.) in which the resulting *co-*

designed solutions are determined is determined via sensitivity assessment. The key realization however, is that any scenario is guaranteed to satisfy all those involved, in essence making the potential perils of preference aggregation a moot point.

Since any formalism (i.e., mathematical) for making a decision must offer a means of representing comparable acceptability, reliance on numerical scales is quasi unavoidable. Converting often abstract preferences into such concrete numerical scales, however, is difficult to say the least. Consequently, even the most mathematically rigorous of approaches are subject to "subjectivity". Since the focus in this dissertation is on the reconciliation or accommodation of stakeholder preferences, rather than on the means of their proper assessment, accuracy of preferences is assumed. With this in mind, individual stakeholders are assumed to be domain experts, chosen for making their particular decision, based on said expertise. Consequently, it is posited that these decision-makers have the ability to transform or map preferences emanating from a higher or upstream level of the hierarchy to those of their immediate concern.

The author notes that any problem, centered on the satisfaction of more than a single objective, constitutes a decision guided by multiple criteria. Whether the corresponding preferences correspond to a single or to multiple decision-makers merely adds a degree of complexity. It is for this reason that it should come as no surprise that each of the approaches, reviewed in this section, has been applied (more or less successfully) to this problem. Whether one approach is more suited to a particular situation than another, in the end strictly depends on the correctness of its application and, of course, the situation at hand. That is to say, that the choice of approach is often determined by the amount of information available. However, mathematical rigor is not the only concern. Clearly, computational cost and time constraints have a significant bearing on virtually every engineering endeavor. No matter how perfect and accurate the model may be, results can only be as good as the information on which the conclusions leading to them are based. Since engineering is both art and science and subject to forces that cannot always be described with the precision ideally required, it is awareness of the underlying assumptions, pitfalls, and interaction effects that comes to matter.

2.7 TEMPLATES

Considering that one of the fundamental contributions in this dissertation is the templatized modeling of decentralized design processes in a modularized, reusable fashion, a discussion of templates is warranted. Thus, both the concept of templates in general and the separation of *declarative* from *procedural* information in particular are reviewed.

2.7.1 The Notion of Templates as Applicable to Engineering Design

A *template* is commonly defined to be (1) a pattern, used as a guide in making something accurately or (2) a document or file, having a preset format, used as a starting point for a particular application so that the format does not have to be recreated each time it is used.[7] The underlying implication thus is one of reusability, archivability, and guidance. Commonplace examples of templates include those found in Microsoft Office applications. A more pertinent example is that described for the DSP Technique templates described in Section 2.2.4. Although the concept of a template in this case is consistent with guidance, reuse and archivability are severely limited. While genericism

[7] Compiled from *www.dictionary.com*

is achieved at the level of the word formulation, mathematical formulations are application specific and not generic by any means. It is in this regard that *declarative* and *procedural* information is co-mingled. Instantiated templates in this context are custom tailored patterns, the usefulness of which is restricted strictly to the particular problem they were intended for. A caveat is that some additional leeway can be gained from insightful coding.

There are a number of reasons why design process modeling can benefit from templatization. Specifically, different products necessitate different design processes. Determining which such process is most appropriate for a particular product, in turn, requires its delineation before initiating the design of the product under consideration. The composition of design processes is often called *meta-design*. Despite the importance of this activity, current simulation-based design frameworks such as FIPER, ModelCenter, and iSIGHT do not support meta-design. This oversight can be attributed at least in part to the fact that these frameworks capture information about products, design processes, and the associated tools in a lumped fashion. Processes are captured in terms of the specific tools employed and the product information, associated with their use, thereby restricting the re-utilization (i.e., reuse via adaptation or customization) of instantiated processes for designing different products. This inherent inability to separate product-specific and process-specific information hinders the exploration of distinct design process options for realizing a product at a fundamental level; thereby hampering agility in product realization. With this in mind, a novel approach for modeling engineering design processes is presented in Chapter 3. A description of the underlying concepts follows.

2.7.2 Separating Declarative and Procedural Information

A majority of engineering modeling environments, as well as CAE and PLM frameworks (e.g., FIPER, ModelCenter, and iSIGHT), capture process information in a manner that is tightly integrated with the information specific to the product at hand. Hence, it is not possible to either reuse different process definitions to design a specific product, or reuse specific process aspects in designing a different product. A method for resolving this reusability issue is presented in Chapter 3. The method is based on the development of reusable templates for separating declarative and procedural information and extended into a template-based approach for supporting meta-design in [164].

Currently available information models and design support tools force designers to think in terms of the underlying *procedure* for solving a particular problem rather than conceptualizing and *declaring* the problem itself. The author believes that the effective separation of such *declarative* and *procedural* information is extremely important for developing more effective design support systems. Foreshadowing the extension to the DSP Technique in Chapter 3, design information is categorized in terms of being either *declarative* or *procedural* in nature, as illustrated in Figure 2-9. The information associated with design transformations and the product states is *declarative* information because it refers to what is done by the designer via that transformation. The mechanics of how that information transformation is carried out constitutes the *procedural* information; it details how that transformation is executed via a network of tasks. Declarative information thus captures all the pieces of information/knowledge and the associated relationships among them that represent the transformation to be carried out. After the designers have declared their design problem, it can be executed using many different processes. Configuration of the right process for that problem is the fundamental challenge in designing design processes. In this dissertation, this issue is centered exclusively on the determination of the most preferable sequence in conflict resolution as developed in Chapter 5.

The idea of separating *declarative* from *procedural* information is analogous to understanding the behavior of a system that is represented by a set of linear equations. The first step for understanding the system behavior is formulating (*declaring*) all the equations that correspond to the information/knowledge available to designers. Once the equations have been formulated, the next step is to select a *process* to be used for solving those equations simultaneously. Various algorithms (that correspond to the *processes* for solving the equations) such as Cramer's rule, Gaussian elimination, LU decomposition, the Jacobi method, etc. are available for solving such a set of linear equations. Appropriate selection of an algorithm (*process*) for the particular problem at hand, however, depends on characteristics such as diagonal dominance, sparcity of the resulting matrix, etc. The selection of the most appropriate process is thus analogous to designing the design process for executing a design transformation.

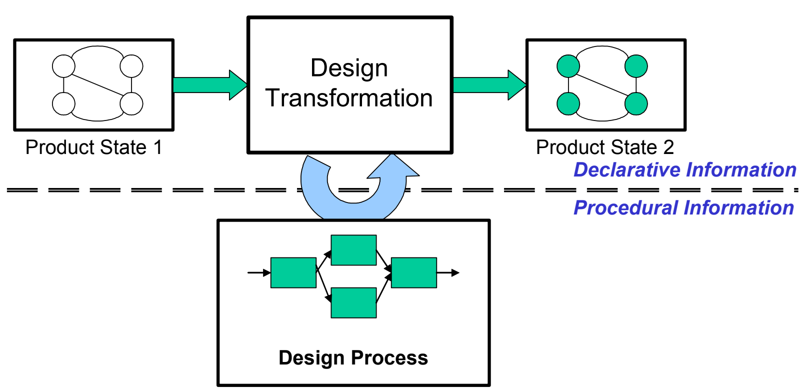


Figure 2-9 - Generic Information Transformation Template (adapted from [164])

One of the advantages inherent in separating *declarative* and *procedural* information is that this scheme forces designers to focus on design problem formulation before considering the details of solution. This is important because without appropriately formulating the design problem, the designers are likely to incur penalties associated with inefficient iteration and costly redesign due to associated oversights. A further advantage is that the reusability of design processes for solving different kinds of design problems is enhanced. Finally, the designing of design processes is supported in a systematic manner.

In summary, a *problem* defines a *declarative* interface specific to one or more process steps. The *process* is an implementation of this problem and describes the sequence in which constituent sub-problems are solved. Each of these sub-processes is associated with its own sub-process. The chosen principle of defining the interface independently of the implementation is *modularity*, as described alongside the philosophical underpinnings of flexibility and openness in the next section.

2.8 FLEXIBILITY, OPENNESS, AND MODULARITY

Flexible systems can be defined to be systems designed to maintain a high level of performance when operating conditions or requirements change in a predictable or unpredictable way [158]. A flexible system may have robustness designed into the system [182] and/or it may physically change in order to adapt to new conditions or requirements. "Flexible systems are designed to maintain a high level of performance through real time adaptations in their configuration and/or through robust parameter settings when operating conditions or requirements change in a predictable or unpredictable way. This definition implies that flexibility can be obtained through two modes: adaptability and robustness" [158]. Flexible Systems can actually be considered to constitute a subset of open systems. Modular architectures constitute another subset of open systems. Open Systems are defined as being capable of indefinite change, growth, and development over time [223], much like modular systems. The quantitative measures related to openness of a product are: *design freedom* [129,254,255,264,265], *robustness*, *complexity* [30,66,188,221] , *modularity* [157] (which is closely linked to complexity) and *coupling* [137,138]. According to Ulrich [249], a modular architecture has two properties:

1. "Chunks" implement one or a few functional elements in their entirety.
2. The interactions between "chunks" are well defined and are generally fundamental to the primary functions of the product.

A truly modular architecture is one in which (1) each ''chunk'' of the overall system accomplishes a single, specific function and (2) the interface between "chunks" is well defined [249]. Consequently, changes in one "chunk" do not require changes in other "chunks", thus providing a certain degree of flexibility to designers [234]. A notable caveat is that a design that is too modular requires different "Chunks" for each situation and may thus "not be flexible enough" [158]. A good example of an approach based on modular architectures from the realm of product family design is that proposed by Simpson et al. in Ref. [224]. As illustrated in this paper, open systems can be designed quite effectively via exploitation of modularity - a system can be continuously developed over time without having to redesign the entire system. In fact, single as well as multiple modules can be effectively replaced and updated. The additional aspect addressed via flexibility is that the adaptation of systems is accommodated and the retention of robustness over time ensured in the face of changes in requirements and/or operating conditions [158].

One of the main challenges in modeling any design effort, regardless of scale or scope, is standardizing the manner in which information and associated dependencies are represented. The underlying need for reusability of information translates this requirement into representing information in a domain neutral form that supports designers in providing and structuring required information content in a computationally archivable and reusable fashion. This in turn calls for a domain independent means of capturing design information. In order to facilitate designer interactions, required for effective collaboration from a decision-centric perspective, expression of information related to design decisions in a standardized format is also required. It is for this reason that a *modular template-based approach* to modeling design information is advocated. In order to effectively support engineering design processes, this notion translates to the development of reusable computational templates for modeling this information. Such computational templates, as developed in Chapter 3, should serve as building blocks – completely modular components that are standardized with respect to structure and interface architecture. Thus, although the format in which user information must be provided is prescribed, the information in and of itself is not. Additionally, to be effective in practice, such building blocks must also facilitate analysis and execution. The fact that individual components are modular and hence quasi interchangeable (due to consistently structured inputs and outputs) increases flexibility and makes design processes models openly adaptable.

A decision-centric design process modeling strategy is necessarily based on the assumption that processes themselves are hierarchical systems (see Figure 2-10) that can be progressively broken down into sub-processes, which in turn can be represented in terms of basic design process building blocks, namely the *information transformations*, discussed in the previous section. Specifically, the focus will be on developing modular, reusable models of information transformations with clearly defined inputs and outputs that facilitate hierarchical modeling of design processes. Due to their consistent structure, design processes modeled in this fashion provide the ability to easily archive and reuse design process knowledge at all levels of the model hierarchy.

The fundamental concept of constructing process templates from networks of design process building blocks is illustrated in Figure 2-11. The design process in this figure involves three (generic and modular) information transformations, namely, T1, T2, and T3. Each of these templates exhibits a different level of completion. T1 is a complete template, implying that all the information required for its execution is available. T3, on the other hand, has yet to be instantiated for the problem at hand and consequently, does not differ from its generic form. Thus, it is the information content, captured within these templates, that serves as the only differentiator among instantiated constructs; the underlying structure remains the same regardless of context or application. It is this modular systems-based architecture that allows for the separation of *declarative* and *procedural* information, as discussed in Section 2.7.2. The templates are defined based on the separation of these distinct aspects of design information, resulting in generic information transformation constructs that are instantiated as software templates.

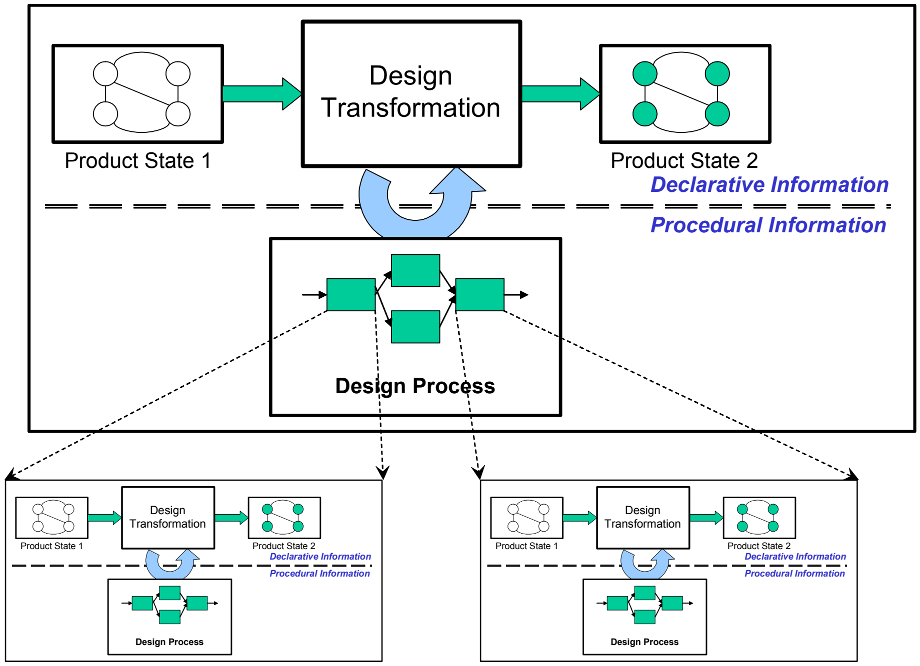


Figure 2-10 - Hierarchical Composability of Modular Templates in the 3-P Approach (adapted from [164])

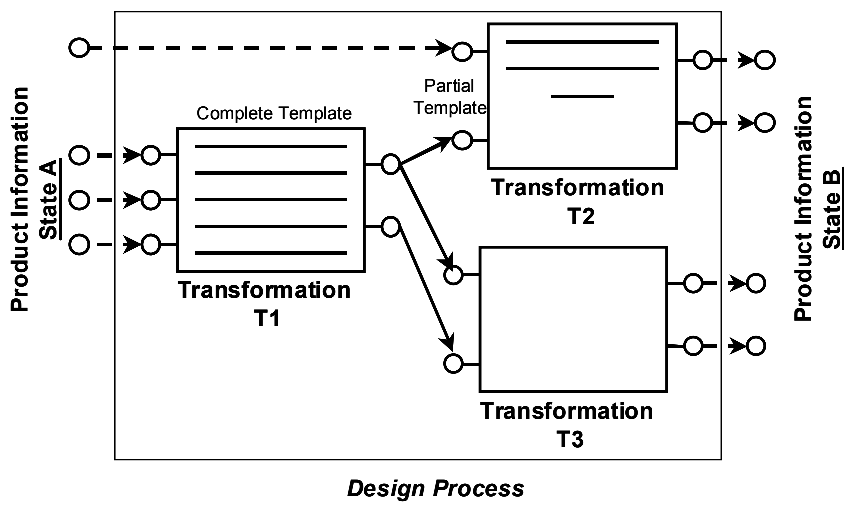


Figure 2-11 - Modeling Design Process using Process Templates

2.9 A NOTE ON VALIDATION

2.9.1 Theoretical Structural Validation of Hypotheses 1, 2, and 3

As indicated in Figure 1-13, Chapter 2 contains the presentation, discussion, and critical evaluation of literature pertinent to the development of the contributions made in Chapters 3, 4, and 5 in response to *Research Questions 1*, *2*, and *3*, respectively. With this in mind, discussions are focused on highlighting strengths and weaknesses of current approaches in order to justify the hypotheses, as introduced in Chapter 1. Relevant context is also provided and discussions are tied to the main themes of this dissertation whenever possible. It is emphasized, that while additional aspects of the *Theoretical Structural Validity* of the three central hypotheses addressed in this dissertation surface in Chapters 1, 3, 4, and 5, this Chapter constitutes the foundation for any ensuing arguments and elaborations. The basic role of this chapter in the validation and verification strategy is underscored in Figure 1-13 and Figure 2-1.

How has the discussion in Chapter 2 justified the propositions brought forth in Hypotheses 1, 2, and 3, contributing to their theoretical structural validation? The impetus in this dissertation is the development of a **F**ramework for **A**gile **C**ollaboration in **E**ngineering. This framework consists of three complementary components, addressed in reverse (or top-down) order for purposes of this discussion. It is noted however that the presentation of these topics in Chapters 3 through 5 proceeds in a bottom-up fashion.

The first component is an **I**nteraction-**C**onscious **C**oordination **M**echanism (ICCM), focused on avoiding unnecessary reductions in design freedom based on the mechanism, chosen for resolving the stakeholder conflicts. The second component is the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod (CDSFM), centered on ensuring the existence of a solution to strongly coupled design problems and the focalization of stakeholders for ensuring *win/win* situations. With this in mind, the basics and accepted domains of application for modeling informational dependencies, multi-disciplinary optimization, the DSP Technique, game theory, and negotiations are critically reviewed in Section 2.1. Additionally, the intricacies of preference representation and assessment are considered in Section 2.6. The third component is a **T**emplate-based **D**esign **P**rocess **M**odeling (TDPM) approach, developed for decentralized design processes that are bound to be highly interactive, consistently evolving, and necessarily multi-disciplinary. Due to the complexity and highly diversified nature of the associated interactions, consistency of representation is crucial. Ease of implementation, archivability, and reuse are also desirable. More importantly, however, the mechanics of decentralized design require consideration of both product and process simultaneously. With this in mind, formalized means of modeling products are considered in Section 2.3, those dealing with processes in Section 2.4, and finally those relating to their combined representation in Section 2.5. Finally, the principles of openness, flexibility, and modularity that serve as philosophical underpinnings of this research are compared and contrasted in Section 2.8.

Clearly, there is some overlap among the various research concentrations and their relevance to each of the three hypotheses. Consequently, though collectively exhaustive, these topics are by no means mutually exclusive. As such, the context for this research is established in terms of the requirements presented in Chapter 1 and the inherent shortcomings of currently available methods in addressing them.

2.9.2 Revisiting the Square

While **Theoretical Structural Validity** of each of the three Hypotheses is explored and established throughout the first five chapters of this dissertation, it is the exclusive focus of this chapter. Additional contributions with regard to this aspect of validation follow in Chapters 3, 4, and 5 with regard to *Hypotheses 1, 2*, and *3*, respectively. It is not until the next chapter that **Empirical Structural Validity** and **Empirical Performance Validity** are addressed. Although this discussion is limited to Hypothesis 3, analogous treatments, particularized for *Hypotheses 2* and *3* follow in Chapters 6, 7, and 8. The overall progress in validating and verifying the contribution documented here is summarized in Figure 2-12 and corresponds to the scheme presented in Figure 1-14.

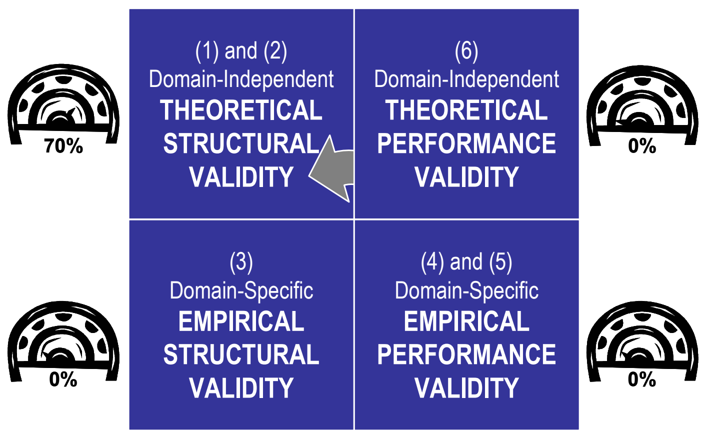


Figure 2-12 - Validation and Verification Progress through Chapter 2

2.10 A LOOK BACK AND A LOOK AHEAD

The stage for the design of complex engineering systems was set in Chapter 1. One of the key dimensions of complexity is based on the manner in which information is shared. Often, resulting dependencies are unilateral. In these cases, design processes lend themselves to sequentialization and many of the nuances, intricacies, and complications, characteristic of interdependent decisions, never arise. Clearly, strongly coupled decisions present the more compelling case for investigation what interactions in distributed collaborative design are concerned. Sometimes, control over common design parameters is shared evenly. At other times, inherent biases emanate from underlying physics, constraints, ambitiousness of preferences, mathematical problem formulation, etc. Whatever the context, there is a need for modeling both the decisions and the associated processes contributing to the realization of the products being designed in a consistent fashion. It is this element of the **F**ramework for **A**gile **C**ollaboration in **E**ngineering that is addressed in Chapter 3. Chapters 4 and 5, in order, address the coordinated assurance of win/win situations and the non-biased resolution of system-level tradeoffs.

2.10.1 Revisiting the Roadmap

As indicated in the beginning of this chapter, and highlighted in Figure 2-13, the main goal pursued in this chapter is that of presenting, reviewing, and critically analyzing literature relevant to every aspect of the **F**ramework for **A**gile **C**ollaboration in **E**ngineering presented in Chapters 3 through 5. With this in mind, existing concepts and constructs for modeling tradeoffs and managing conflicts were presented in Section 2.1. A discussion of product models followed in Section 2.3. The discussion then segued into the modeling of engineering processes (Section 2.4) before exploring the integrated consideration of products and processes in recent research endeavors (Section 2.5). Relevant intricacies of modeling preferences were covered in Section 2.6 and the notion of templates explicated in Section 2.7. Finally, relevant comments regarding several of the philosophical underpinnings of this research were made in Section 2.8. The overarching goal was to give the reader a solid foundation for understanding the material in the remaining chapters. Due to the breadth and depth of the material covered and addressed in this dissertation, the literature review, too, is necessarily rather comprehensive.

In terms of validation and verification, the focus of this Chapter is entirely on *Theoretical Structural Validation*. Research pertinent to each aspect of this dissertation is reviewed and critically analyzed. The discussion is framed in terms of relevant background material and tied to the contributions documented in subsequent chapters of this dissertation. Chapters 3, 4, and 5 are centered on *Theoretical Structural* and *Theoretical Performance Validation*.

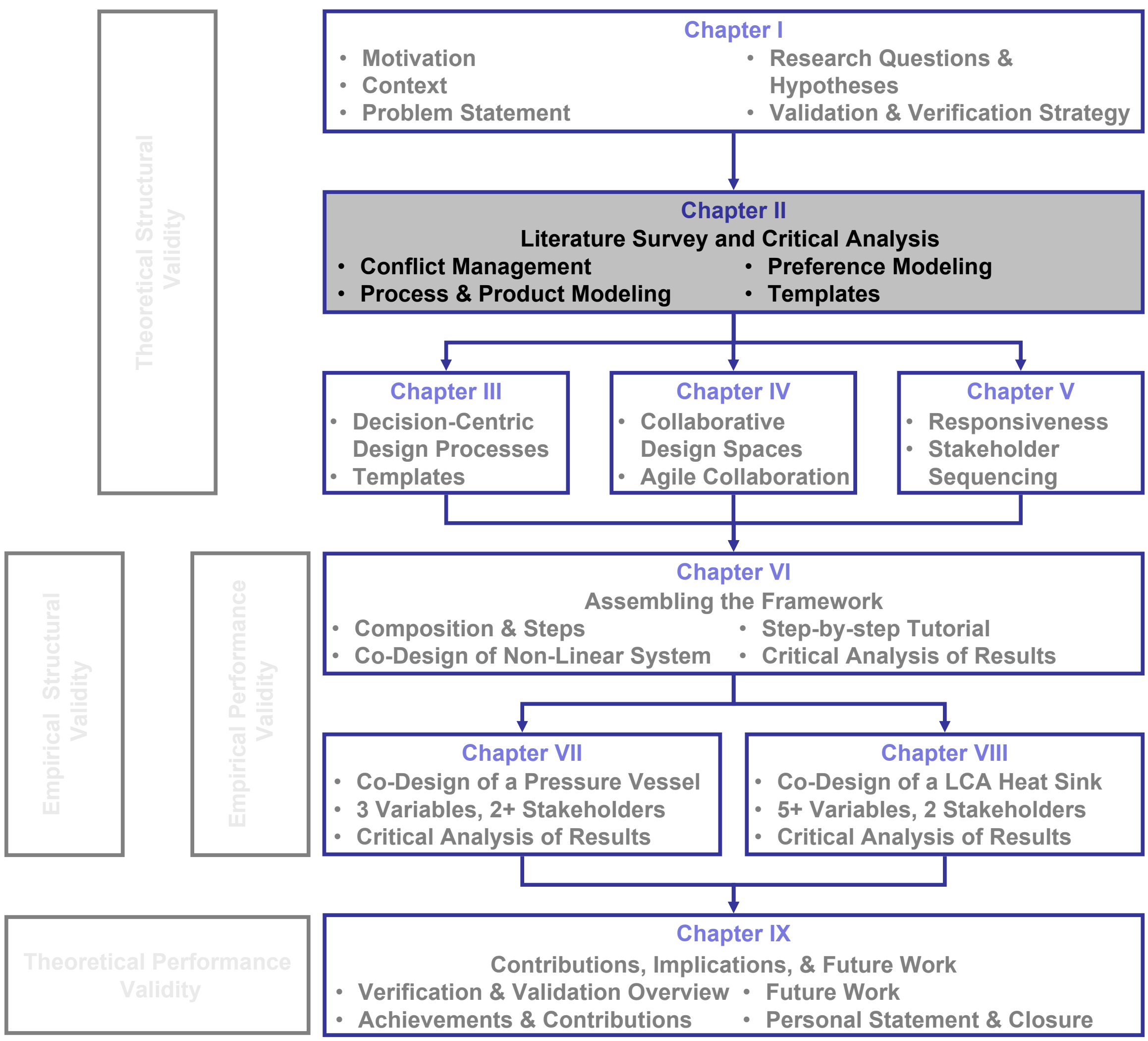


Figure 2-13 - Dissertation Roadmap

2.10.2 Assembling the Building Blocks

This chapter was dedicated to a comprehensive review of the literature relevant to each and every aspect of the contributions made in this dissertation. As such the critical review of processes, products, design decisions, preferences, templates, and elements of openness provide the foundation for understanding the relevance and novelty of the contributions made in each of the chapters to come.

CHAPTER 3 - TEMPLATE-BASED MODELING OF DECISION-CENTRIC DESIGN PROBLEMS AS PROCESSES

In this chapter, the author builds on the concepts introduced in Chapter 2 and develops the constructs for supporting single as well as multiple-stakeholder decision-centric design processes. The focus in developing a **T**emplate-based **D**esign **P**rocess **M**odeling (TDPM) approach is on sustaining and facilitating the activities of designers in allocating resources and striking tradeoffs among competing objectives in a manner that lends itself to the integration of their goals with those pertaining to other stakeholders. The decision-centric constructs introduced in this chapter are woven into the fabric of the overarching notion of a design equation and the underlying Decision Support Problem Technique in Section 3.1. In Section 3.3, decision templates are developed and described in detail. The instantiation and reuse of these generic information transformations, central to modeling the design processes controlled by single decision-makers in a completely modular fashion, is illustrated with respect to spring and pressure vessel design in Section 3.3.4. The notion of interaction templates is reconciled with the concept of the design equation and the chosen manner of modeling individual stakeholder considerations in terms of decision templates in Section 3.4. Representative interaction templates for cooperative and non-cooperative behavior among constituent stakeholders are developed and applied in conjunction with decision templates to illustrate the composition of a design process for the resolution of a strongly coupled design problem in Section 3.4.4. To strengthen the argument, one of the examples used for the illustration and instantiation of single decision-maker decisions is used. A critical analysis of the various constructs, their underlying assumptions, limitations, and advantages inherent in their application follows in Section 3.5. Finally the role of the decision templates, described in Section 3.3, and the interaction templates, described in Section 3.4, within the **F**ramework for **A**gile **C**ollaboration in **E**ngineering is clarified in Section 3.6, where relevant aspects of validation within this chapter are reinforced. Specifically, *theoretical* structural and performance aspects regarding the validation of *Hypothesis 1* are emphasized in addition to the *empirical* facets, previously discussed. Overall cohesion of this material with respect to the remainder of this dissertation is demonstrated in Section 3.7.

3.1 VALIDATION AND VERIFICATION WITHIN CHAPTER 3

As indicated in Section 1.5.1, the primary aim pursued in this chapter is the development of the proposed **T**emplate-based **D**esign **P**rocess **M**odeling (TDPM) approach and the **Theoretical Structural Validation**, **Empirical Structural Validation**, and **Empirical Performance Validation** of *Hypothesis 1*. As indicated in Figure 3-1, additional elements of **Theoretical Structural Validation**, building upon relevant aspects in Chapters 1 and 2 are presented in the sub-sections of Section 3.2. The **Empirical Structural Validation** of the TDPM approach is emphasized in Sections 3.3.4, 3.4.3, and 3.6.2, while **Empirical Performance Validation** is addressed in Sections 3.3.4, 3.4.3, and 3.6.3. Finally, a note of **Theoretical Performance Validation** is made in Section 3.6.4, although the majority of this discussion is deferred to Chapter 9.

3.2 REUSABLE DESIGN PROCESSES VIA MODULAR, EXECUTABLE, DECISION-CENTRIC TEMPLATES

3.2.1 Overview of the Contribution

While there have been many advances with respect to reusability and scalability of product architectures over the past several decades, little progress has been made in applying the same concepts to the underlying design processes involved in finalizing these. It is this aspect of design process design and reuse that is focused upon in this chapter. Design processes play a key role in product design and their configuration has a significant effect on both the efficiency and the effectiveness with which resources are committed. Design processes also directly influence the final design of the product under consideration. As such, more attention must be paid to the manner in which these processes are modeled so that they may be standardized, executed, analyzed, and stored, allowing for their leverage across product lines and reduction of product development times.

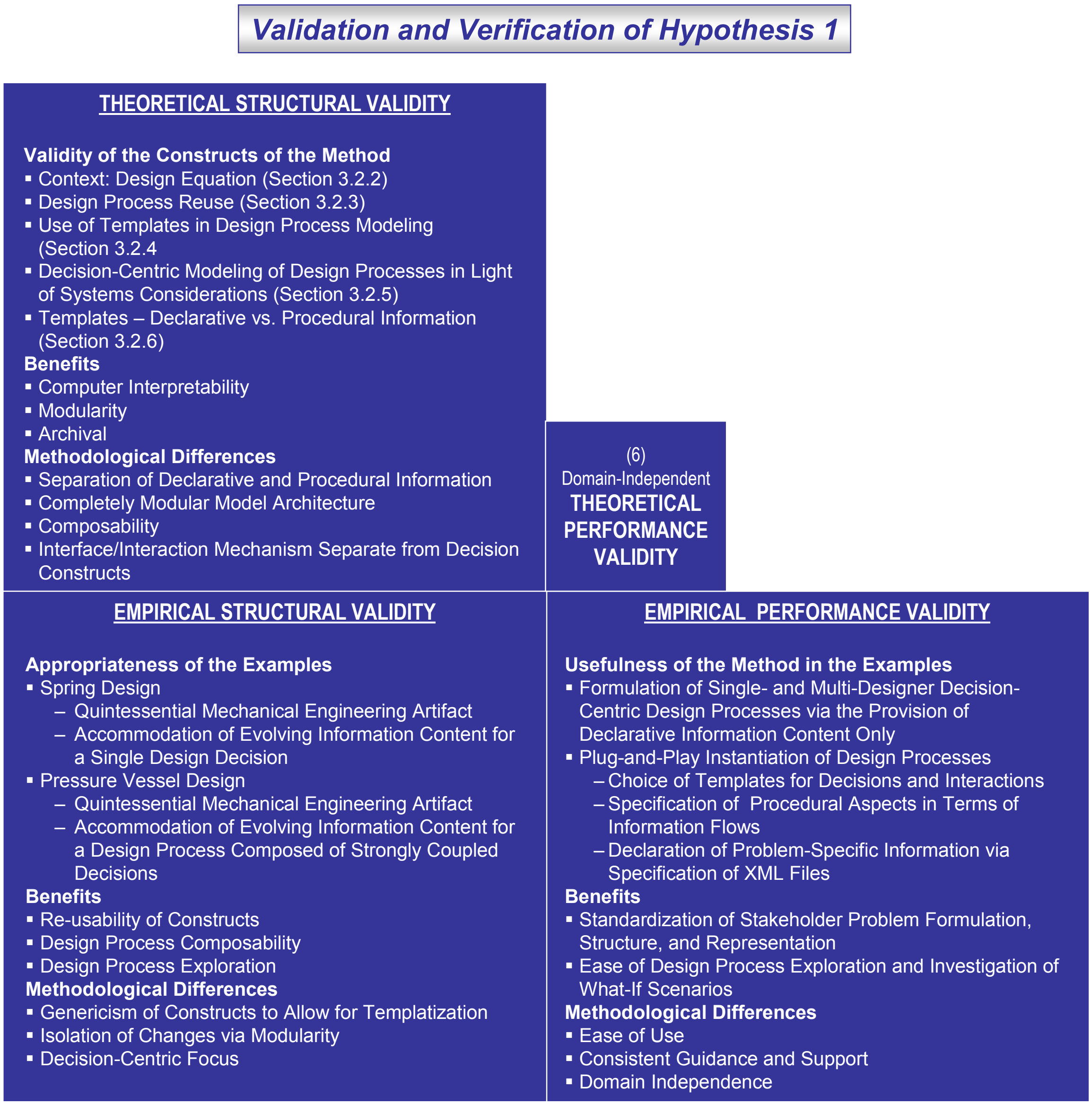


Figure 3-1 - Aspects of Validation and Verification Addressed in Chapter 3

Modularity and computer interpretability are key considerations in facilitating required adjustments as product considerations evolve and design requirements change. The vision is to effectively support the interaction intensive exchanges among collaborating stakeholders in decentralized design processes. Additionally, the generation of product portfolios is benefited. In this dissertation, a fundamental step in this direction is offered by presenting a method for modeling design processes as reusable process templates that can be captured, archived, analyzed and manipulated on a computer. Consideration is given to supporting both processes emanating from the design efforts of single designers as well as those of multiple designers in pursuit of differing objectives, collaborating in the resolution of a shared design problem. The role of the material presented in this chapter is to serve as a proof of concept for a technology enabling the implementation of the FACE methods presented in Chapters 4 and 5, thereby greatly facilitating the *co-design* of complex engineering systems.

3.2.2 Frame of Reference: The Design Equation

The developments in this chapter can be considered to be an instantiation of the design equation. As described in Section 1.2.3.2, the design equation is a conceptual-level algebraic relation that (1) maps design operands (i.e., product related design information) and design operators (i.e., information transformations) and (2) can be considered to be the overarching theoretical/mathematical construct to which this research makes a fundamental contribution. In addition to traversing many different hierarchical levels, the design equation can take on many different forms, synthesizing myriad information transformations. The information transformations that are focused upon in this dissertation, however, are the decision on one hand and the interaction on the other. While the decision arguably is the pinnacle of all other activities in the practice of design, at least within the decision-centric paradigm, the notion of an interaction is required whenever such a decision cannot be made in isolation (i.e., it is not independent or responsibility for its resolution is shared).

Within this conceptual framework, design processes can be considered on a number of different levels. A design process, however, must not necessarily involve either multiple decisions or multiple stakeholders. Nor must it traverse the span from the specification of customer requirements to product retirement. Instead, the basic requirement for a process is merely that a series of operations be performed in the making or treatment of an outcome. Often processes involve series of actions, functions, and changes aimed at bringing about a result and are characterized by the passage of time (chronological, event-based, etc.). On the most basic level, a design decision can thus be considered to constitute a process. In fact, it is only through (or as a result of) the underlying process that decision-making is possible. As with any process, *repeatability* is a fundamental concern. In the case of a process requiring interaction, *clairvoyance*, *consistency*, and *conflict management* become additional requirements. More importantly, however, engineering is characterized by and subject to change. Most designs continuously evolve. Since the input to one decision invariably affects its transformed output, which in turn constitutes the input to the next decision, changes are both ubiquitous and perpetual. Additionally, since most of engineering practice is team based and builds on complicated informational dependencies, any associated impediments are aggravated. It is the remediation of such basic difficulties that the discussion in this chapter is focused upon. Although the ultimate goal is the formalization and coordination of stakeholder activities in decentralized design processes, as discussed in Section 3.4, a prerequisite is the consistent formulation of design decisions by individual decision-makers. The templatized support of this fundamental activity is treated in Section 3.2.3.

3.2.3 Design Process Reuse

As stated in Section 1.2.1, the design process is considered to be an engineering enterprise's primary resource commitment. Although much attention has been paid to exploiting the reusability and scalability of products through product platform and product family design, not much attention has been paid to exploiting the design process and its *design*. This challenge of design process reuse (either partially or entirely) and adaptation is addressed by indefinitely leveraging existing design processes via reflection and accommodation of evolving information content.

This notion prompts the question: *How similar do two (or more) products have to be in order to reuse the processes underlying the design of one in designing the other?* The answer varies depending on the level of abstraction at which the processes are modeled. For example, the Pahl and Beitz [160] design process is widely applicable to almost any mechanical design problem. However, at a computational level, where the design process is defined as a series of computational operations, the reusability of design processes, thus far, has been extremely limited. It is with regard to reusability at this level that improvement is sought.

Consider a simple example, involving the design of two commonly employed mechanical components, namely, a pressure vessel and a spring, as pictured in Figure 3-2. While both of these products can be described (and in fact uniquely defined) in terms of geometric constraints and mathematical relations, they are nevertheless fundamentally different – with regard to the design parameters describing their *form*, *function*, and *behavior*. Hence, computational aspects of design processes are problem specific and cannot be directly leveraged from one problem to the next.

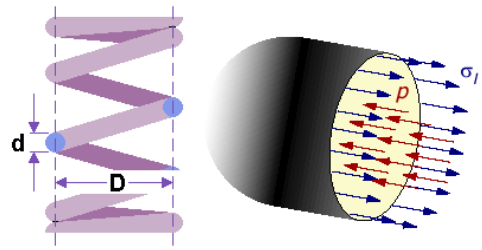


Figure 3-2 - Helical Spring and Pressure Vessel

When considering the design processes underlying the products in Figure 3-2, however, there are certain similarities that emerge. Each design process can be considered to be a sequence of decisions and supporting tasks. It is upon these information transformations that the generic design process model developed in this chapter is based. This model utilizes *templates* that can be executed, analyzed, stored, and reused, regardless of (1) context, (2) engineering domain, or (3) scale of the product considered. Specifically, it is design decisions and the interfaces required for effective collaboration among interacting decision-makers that are focused upon. The required "genericism" of the underlying process model is achieved via a separation of the *declarative* (i.e., problem specific information) from the *procedural* (i.e., process specific information) flows of information, as described in Section 2.7.2. It is at the hand of the spring and pressure vessel design examples that relevant concepts will be illustrated. Although these examples are rather simple in nature, they nevertheless constitute a convenient means of illustrating the novelty of the method with regard to supporting both individual and collaborating designers in the negotiation of solutions to design problems.

Having reviewed current process modeling techniques in Section 2.4, the needs for pursuing template-based design process modeling are elucidated in the next section. Basic requirements are subsequently established.

3.2.4 Modeling Design Processes as Templates

One of the main challenges in modeling any design effort, regardless of scale or scope, is formalizing the manner in which information flows and dependencies are represented. Another challenge lies in representing design processes in a domain neutral form that supports designers in providing and structuring required information content. This calls for a domain independent means of capturing design processes in an archivable and executable manner. In order to facilitate designer interactions required for effective collaboration, expression of design considerations in a standardized format is also required. It is for this reason that a template-based approach to modeling design processes is advocated. Clearly, the word *template* is appropriate in this context because it implies reusability, archivability, and guidance.

In order to effectively support engineering design processes, this notion translates to the development of reusable computational models that can serve as building blocks – completely modular components that are standardized with respect to structure and interface architecture. Such building blocks must also facilitate analysis, and execution. Currently, there is a lack of formal, executable, computational models for representing and reusing existing knowledge about design processes. The only knowledge that is readily available is confined either to designers' expertise or to descriptive/pictorial forms of documentation. This is a result of the predominantly narrative or symbolic nature of current models.

In order to address these challenges, the use of domain independent design process templates is proposed. These templates are composed from templates for commonly encountered information transformations and required interactions among these transformations. In this dissertation, the focus is primarily on decisions (see Section 3.2.6) and interactions, as required for decentralized, collaborative design (see Section 3.4). The *design process templates* resulting from the composition of *decisions templates*, that are succinctly interfaced using *interaction templates*, are also defined as computer-based representations of information transformations with well-defined inputs and outputs. These design process templates, analogously to the building block templates from which they are composed, can be executed, stored, analyzed, and reused, as illustrated in Section 3.4.

The fundamental concept of constructing process templates from networks of design process building blocks (i.e., decision and interaction templates) is illustrated in Figure 3-3. The design process in this figure involves three information transformations, namely, **T1**, **T2**, and **T3**. Each of these templates represents a different level of instantiation (or informational completeness). **T1** is a complete template, implying that all the information required for its execution is available. **T3** on the other hand has yet to be instantiated relevant to the problem at hand and consequently, does not differ in the least from the generic information transformation from which it will be derived.

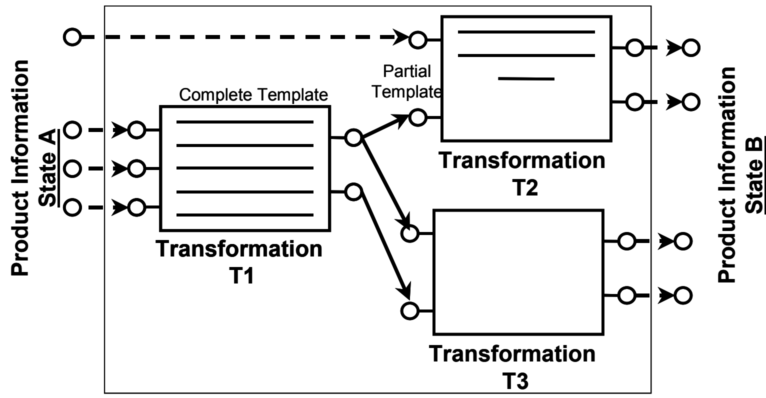


Figure 3-3 - A Design Process Modeled as a Network of Templates

3.2.5 Systems-Based Modeling of Decision-Centric Design Processes

The design process modeling strategy is based on two key assumptions: (1) design is a decision-centric activity and (2) design processes themselves are hierarchical systems. From a decision-centric standpoint, designing is a process of converting information that characterizes the needs and requirements for a product into knowledge about the product [110,145]. From the requirements to the final product, design processes are carried out through a number of phases. For example, the phases associated with Pahl and Beitz [160] design process are - planning and clarification of task, conceptual design, embodiment design and detailed design. Each phase is associated with *stages* of product information and information is converted from one *stage* to another via a network of transformations that operate on product information. These transformations can be carried out in a sequential (as shown in Figure 3-4) or parallel fashion (not shown). The transformations operate on product related information and convert this information from one *state* to another. The state of information refers to the *amount* and *form* of that information that is available for design decision-making. For example, *analysis* is a transformation that maps a product's form to its behavior, whereas, *synthesis* is a mapping from a product's expected behavior to its form. It is important to note that these transformations remain the same during different phases of the product realization process, as suggested by Figure 3-4.

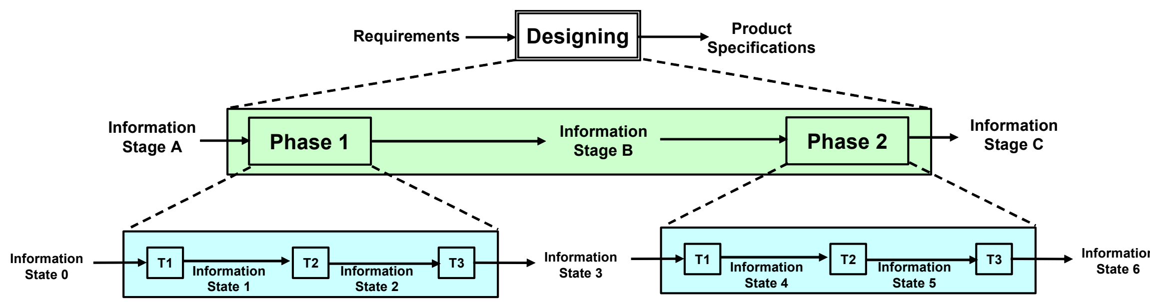


Figure 3-4 - A Sequential Design Process as a Series of Information Transformations

From a hierarchical systems standpoint, design processes can be progressively broken down into sub-processes that in turn can be represented in terms of basic design process building blocks, namely *information transformations*. Specifically, the focus is on developing modular, reusable models of information transformations with clearly defined inputs and outputs that facilitate hierarchical modeling of design processes. Due to their consistent structure, design processes modeled in this fashion provide the ability to easily archive and reuse design process knowledge at all levels of the model hierarchy. The coordination of various domain experts in decentralized design is also facilitated.

The design process model presented in this paper is an extension of the decision constructs developed within the DSP Technique proposed by Mistree and co-authors [32,110,145,146] and anchored in the work of Simon [218,221]. The DSP Technique consists of three principal components: a design philosophy rooted in systems thinking, an approach to identifying and solving Decision Support Problems (DSPs), and software (see Section 2.2.4.2). 'Systems thinking' encourages designers to view products and processes as systems interacting with the environment. In the DSP Technique, support for human judgment in designing is offered through the formulation and solution of DSPs, which provide a means for modeling decisions encountered in design. The DSP Technique allows designers to model design processes at various levels of abstraction [110], although it is important to note that the level of required software support is different at each such level.

As a part of the DSP Technique, a palette for modeling design processes using various entities such as phases, events, decisions, tasks, and systems was developed [146]. Since there is a support problem associated with each DSP Technique palette entity, the use and reuse of design process models and design sub-process models, created and stored by others, is thus facilitated. Due to the domain independence of the underlying constructs and the integrated systems perspective, the DSP Technique offers a solid foundation for developing computational models of reusable design processes, as envisioned in this chapter.

In the resulting model, the design processes are viewed as networks of information transformations, as indicated in Figure 3-4. Generic constructs can be developed for each of the most fundamental information transformations encountered in engineering design, including abstraction, composition, decomposition, interfacing, mapping, and synthesis. The corresponding support problems should be structured according to the overarching systems model envisioned in the DSP Technique. These information transformations are examples of tasks essential to supporting required design decisions. Since design tasks generate the information upon which design decisions are based, the espoused approach is decision-centric. Modeling a design process using such a decision centric approach involves developing networks of transformations with information-based interfaces. As stated previously, however, it is only decisions and interactions that are focused upon in this dissertation.

In order to facilitate reuse of design process models, the building blocks of design processes, however, must be generic. This requires modularity and domain independence. The aim is to facilitate design process reuse with respect to (1) hierarchical composition and (2) cross-domain application, respectively. The underlying relationship between these two dimensions is illustrated in Figure 3-5. Domain independence of decision templates is derived from the underlying DSP Technique constructs, as described in this section. Their hierarchical composability emanates from the novel application of modularity principles to design process building blocks as described in Section 3.2.6. The primary concept centers on a separation of the *declarative* and *procedural* aspects of design processes (see Section 2.7.2), resulting in generic information transformation constructs that are instantiated as software templates. In fact, it is the nature of the information content, captured within these templates, that serves as the only differentiator among instantiated constructs; the underlying structure remains the same regardless of context or application.

Having outlined the systems-based perspective upon which this research is based, a discussion of decision templates (used for modeling the considerations of individual designers) follows in Section 3.2.6. Subsequently, interaction templates (required for modeling design processes involving multiple decision-makers) are discussed briefly in Section 3.4.

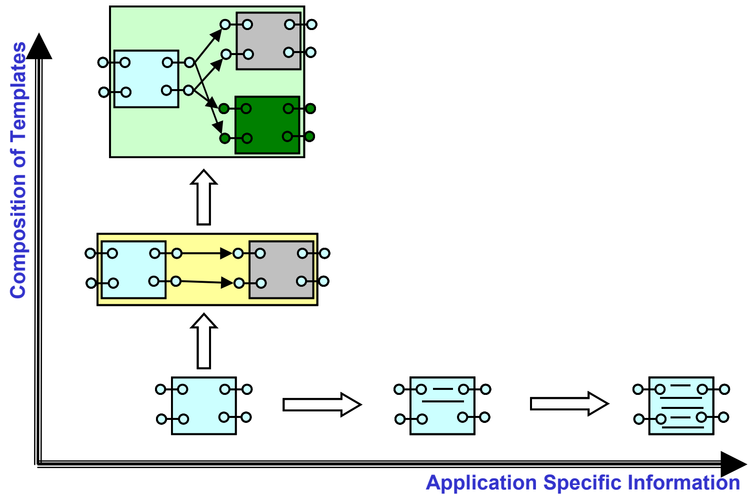


Figure 3-5 - Reusability of Design Processes with Regard to Hierarchical Composition and Cross-Domain Application

3.2.6 Templates

Building towards the consideration of design processes, subject to decisions made by multiple stakeholders, single decision-maker design processes are considered first. Ensuring consistency in the manner in which myriad designers organize, represent, and structure decision-critical information is absolutely crucial for effectively collaborating in decentralized environments. Since information invariably evolves along a design timeline (whether event-based or temporal) maintaining consistency represents an even greater challenge. The key realization is that although the actual information considered in a decision may change over time, the manner in which this information is used is likely to remain constant. That is to say that there are certain elements in any decision (expressed in mathematical terms) that can be captured on a generic level.

In the context of the design equation, discussed in Section 1.2.3.2, a transformation is an operator on information. Information flows in, is processed, changed, or mapped, and flows out, on to the next transformation. As in the case of any other function, inputs are thus converted into outputs. In the case of information transformations, the flow of information can be split into two distinct streams, the *declarative* and the *procedural*. While the first type of information is problem specific, the second is process specific. In other words, not all of the information, pertinent to an information transformation, conveys meaning related to the problem at hand. Instead, there is a substantial and equally important contribution conveying how that problem specific information is to be used or processed. It is for this reason that *selection* fundamentally differs from *compromise*, despite that fact that it can be reformulated to resemble it. In capturing procedural elements in template structure, *decisions* can be captured and reused for different situations and in different contexts. *Interactions* can be leveraged in a similar fashion as long as relationships among the outputs of one decision and the inputs to another remain constant. Thus, while *declarative* information can change indefinitely, *procedural* information is transformation specific. Design processes can thus be composed for representation, modeling, and simulation using the appropriate information transformations. In doing so, generic templates are instantiated via the provision of problem specific information. As will be indicated later, decision templates suffice for modeling independent decisions, assigned to individuals. In the case of dependent or coupled decisions, an interaction template is also required in order to model the relationship among related decisions and ensure the proper flow of information. In the case of *interactions* different protocols are thus captured using different *procedural* templates. Different processes are thus modeled

Although there are many more transformations in design (in fact, one might argue that the process of design is a network of serial and parallel transformations), only those transformations most relevant to collaboration are considered in this dissertation, namely *decisions* and *interactions*. In this chapter, the notion of a decision is formalized as a computer-interpretable generic construct that can be customized or instantiated for any arbitrary context solely via the provision of pertinent information content, as focused upon in Section 3.2.6. Similarly, different conflict resolution mechanisms are captured in interaction templates, as presented in Section 3.4.

3.3 DECISION TEMPLATES

The process modeling approach presented in this chapter centers on the concept of modularity, which pervades all aspects of the underlying architecture. In order to facilitate reusability of design processes across design problems, relevant information used to characterize them is segmented into three layers, as shown in Figure 3-6. Each of these layers (i.e., the *product information* level, the *process level*, and the *execution* level) is discussed in detail in Sections 3.3.1, 3.3.2, and 3.3.3, respectively. While a majority of the discussion in Sections 3.3.1 through 3.3.4 is focused on compromise, a brief discussion on selection follows in Section 3.3.5.

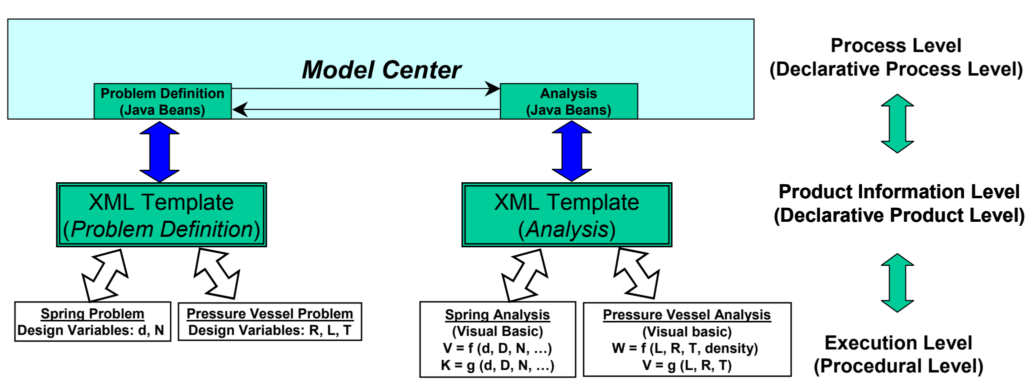


Figure 3-6 - Process Modeling Architecture

3.3.1 (Declarative) Product Information Level

In the layer corresponding to the product information level, only information, specific to the product being designed, is captured. Since this information is treated in a standardized manner, it can be used by different design processes. For example, the information associated with the design of either the spring or the pressure vessel, illustrated in Figure 3-2, can be categorized as being comprised of design variables, responses, parameters, constraints, goals, preferences, objectives, or analyses. This is illustrated in their respective compromise DSP formulations given in Table 3-1.

It is noted that the two problems are quite different and exhibit dissimilar variables and relationships among them. The goals and constraints are also different. However, although the product specific information used in each formulation is different, the inherent structure according to which this information is used remains the same. Hence, it is possible to standardize the structure of information so that the creation of generic process elements becomes possible. This is reflected in Figure 3-7, where the product information corresponding to these generic process elements is provided for both the pressure vessel design and the spring design example.

Table 3-1 - Compromise DSP for Pressure Vessel and Spring Designs

<table>
<tr><th>Pressure Vessel Design</th><th>Spring Design</th></tr>
<tr><td>
Given
Strength (S_t), Pressure (P), Density(ρ)

Some helpful relations:
Volume, V = $\pi\left[\frac{4}{3}R^3 + R^2L\right]$
Weight, W = $\pi\rho\left[\frac{4}{3}(R+T)^3 + (R+T)^2L - (\frac{4}{3}R^3 + R^2L)\right]$
Find
System variables:
Radius (R)
Length (L)
Thickness (T)
Values of Deviation Variables:
d1- (for weight goal)
d2- (for volume goal)
Satisfy
System constraints:
$S_t - \left(\frac{PR}{T}\right) \geq 0$
$R - 5T \geq 0$
$(40 - R - T) \geq 0$
$(150 - L - 2R - 2T) \geq 0$
System Goals (Normalized):
$d^-_{Volume} = 1 - \frac{V_{achieved}}{V_{target}}$
$d^-_{Weight} = 1 - \frac{W_{target}}{W_{achieved}}$
Bounds on System Variables:
$0.1 \leq R \leq 36$
$0.1 \leq L \leq 140$
$0.5 \leq T \leq 6$
Minimize
Deviation Function: $Z = w_1 d_1^- + w_2 d_2^-$
</td><td>
Given
Assumptions:
Some helpful relations:
Deflection of spring: $\delta = \frac{8FD^3N}{d^4G}$
Solid height of spring: H=Nd, H≤0.5 in
Stiffness of spring: $k = \frac{d^4G}{8D^3N}$
Volume of spring: $V = 0.25\pi^2 Dd^2(N+2)$

Find
System variables:
Wire diameter (d),
Number of coils (N)
Values of Deviation Variables: d+, d- for goals

Satisfy
System constraints:
$6.957x10^{-6}\frac{N}{d^4} \geq 1.1$
$Nd \leq 0.5$
System Goals (Normalized):
$53345.5\frac{d^4}{N} + d_1^- - d_1^+ = 1$
$0.0191\frac{1}{d^2(N+2)} - d_2^- + d_2^+ = 1$
Bounds on System Variables:
$N \geq 3.5$
$0.059 \leq d \leq 0.09$

Minimize
Deviation Function: $Z = w_1 d_1^- + w_2 d_2^+$
</td></tr>
</table>

The process modeling technique proposed in this chapter is analogous in architecture to that of a printed wiring board with a number of electronic components such as those shown in Figure 3-8. The *wiring* corresponds to the flow of information in a process and the *declarative* (process specific) information discussed next in Section 3.3.2 is thus "hardwired". The *chips* that are plugged into the board, on the other hand, do not define the manner in which the information is processed but the information (being processed) itself. Consequently, these chips correspond to the declarative (product specific) information, discussed in this section. A prime benefit is that the resulting reusability extends to both the chips and the board independently. Since *procedural* elements of information transformations are captured in the form of templates that are independent of the *declarative* aspects (i.e., the specific information considered), all features of the information transformations, ranging from the components to the underlying interactions, (represented by the "chips" and "wiring" in Figure 3-8, respectively) become modular. Both re-usability and reconfigure-ability are thus achieved.

cDSP "Chips"	Pressure Vessel		Spring	
Constraints	Stress: $\frac{PR}{T} - S_t \leq 0$ Thickness: $5T - R \leq 0$ Radius: $R + T - 40 \leq 0$ Length: $L + 2R + 2T - 150 \leq 0$		Minimum Deflection: $\delta = \frac{8FD^3N}{d^4G} \geq 1.1$ Maximum Solid Height: $H = N \bullet d \leq 0.5$	
Variables	Radius, Length, Thickness		Number of Coils, Wire Diameter	
Parameters	Density, Strength, Pressure		Applied Force, Coil Diameter, Shear Modulus	
Goals	Volume Target = 500000 m^3 Weight Target = 300 kg		Stiffness Target = lbf/in Volume Target = in^3	
Preferences	Volume Weighting Factor = 0.5 Weight Weighting Factor = 0.5		Stiffness Weighting Factor = 0.5 Volume Weighting Factor = 0.5	
Objective	**Maximize** Volume $V(R,L) = \pi\left[\frac{4}{3}R^3 + R^2L\right]$ **Minimize** Weight $W(R,T,L) = \pi\rho\left[\frac{4}{3}(R+T)^3 + (R+T)^2L - \left(\frac{4}{3}R^3 + R^2L\right)\right]$		**Maximize** Stiffness $k = \frac{d^4G}{8D^3N}$ **Minimize** Volume $V = \frac{1}{4}\pi^2Dd^2(N+2)$	
Analysis	**Inputs**	**Outputs**	**Inputs**	**Outputs**
	Radius, Length, Thickness, Density, Strength, Pressure	Volume, Weight	Wire Diameter, Coil Diameter, Shear Modulus, Number of Coils	Stiffness, Volume
Driver	**Optimization Algorithm** – Exhaustive Search, SQP, etc.		**Optimization Algorithm** – Exhaustive Search, SQP, etc.	
Response	**Design Variable Values** – Radius, Length, Thickness **Objective Function Value** - Z		**Design Variable Values** – Radius, Length, Thickness **Objective Function Value** - Z	

Figure 3-7 - Product Information Level (declarative product level) Information for Pressure Vessel and Spring Designs

The structure of the product information should be consistent with commonly adopted norms. In this research a widely accepted set of XML schemas is used. XML offers a convenient and standardized means of capturing information at the product information level and ensures that problem specific *declarative* information can be reused in different processes. For the simple example problem of designing both a pressure vessel and a helical spring through the use of a common template, the product information is stored in four XML templates: the *problem definition template*, the *constraints template*, the *goals and preferences template*, and the *analysis code template*. These templates, discussed next in Sections 3.3.1.1 through 3.3.1.4, correspond to the declarative product information "hidden" (or embedded) within the compromise DSP formulations shown in Table 3-1.

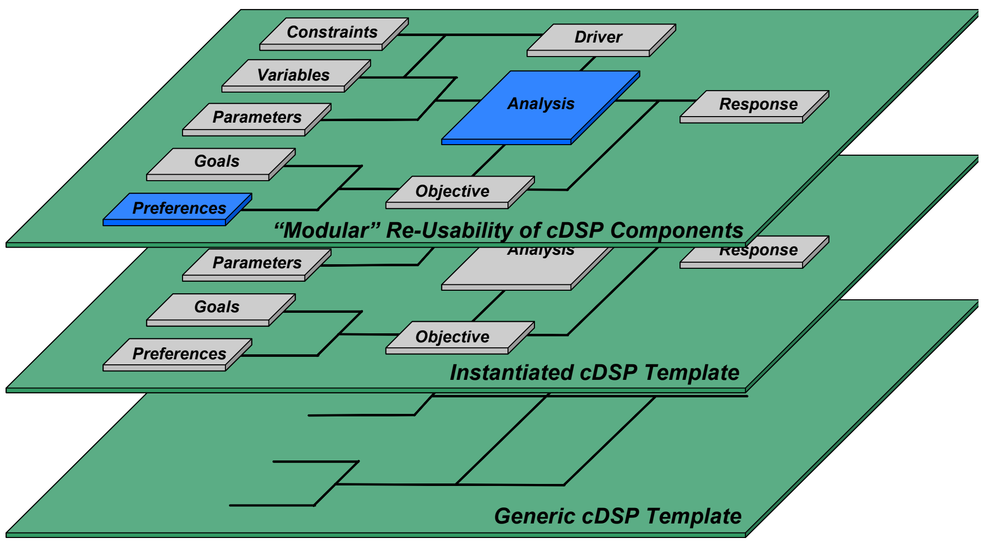


Figure 3-8 - Archival, Documentation, and Re-Use of Design Process Building Blocks

3.3.1.1 <u>Variables and Parameters Definition Template</u>

The template for defining design variables and parameters includes the following information about design variables: (a) Design Variable Name, (b) Type, (c) Unit, (d) Value, and (e) Lower Bound and Upper Bound. For the purposes of this chapter, all parameters are defined with equal lower and upper bounds, although this is by no means a requirement or limitation. The XML schema representation associated with the problem definition template is shown in Figure 3-9(a).

3.3.1.2 <u>Goals and Preferences Definition Template</u>

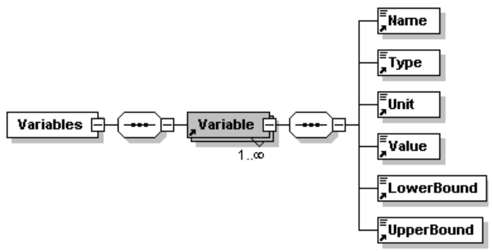
In this template, information about design goals and designer preferences regarding the manner of satisfaction desired for these goals is captured. The goals are formulated with target values for system responses. Preferences are associated with the various goals included in the compromise DSP formulation. Here, these preferences are modeled as weights on the deviation variables. The entities associated with such goals are: (a) Name, (b) Weight, (c) Target, and (d) Monotonicity, where monotonicity captures information regarding whether the goal is to be maximized, minimized, or matched as closely as possible. The XML schema associated with the goals and preference definition templates is shown in Figure 3-9(b).

3.3.1.3 <u>Constraints Definition Template</u>

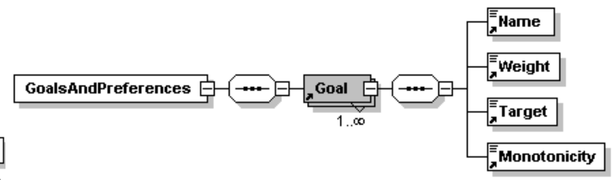
The constraints definition template includes information about various constraints on the system. The constraints are associated with a name and a string representing required mathematical operations. The XML schema representation associated with the constraints definition template is provided in Figure 3-9(c).

3.3.1.4 <u>Analysis Code Template</u>

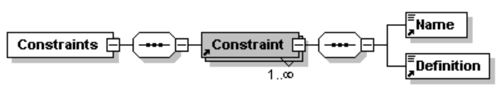
The analysis code is used to evaluate the system response resulting from changes in design variables. The information associated with the analysis code template includes (a) Inputs, which consist of Name, Type, Unit, and Value, (b) Outputs, which consist of Name, Type, Unit, and Value and (c) Execution. The "Execute" field captures the software application that needs to be invoked in order to obtain the desired system response. The XML schema associated with the analysis code template is also shown in Figure 3-9(d).



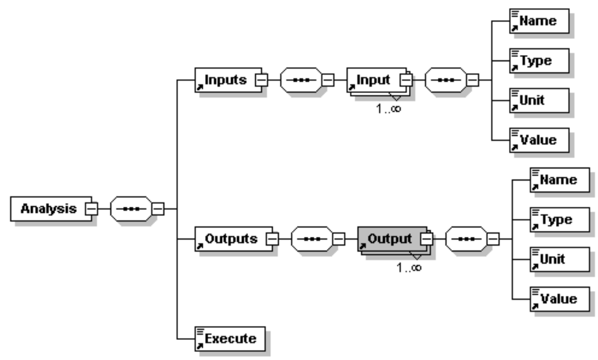
(a)
Schema Representation for Problem Definition



(b)
Schema Representation for Goals and Preferences



(c)
Schema Representation for Constraints



(d)
Schema Representation for Analysis Code

Figure 3-9 - Schemas for Product Information

3.3.2 (Declarative) Process Information Level

In the layer, corresponding to the Process Level, (1) required information transformations are identified and (2) required information flows are specified in accordance. In order to ensure complete modularity of information transformation templates, information flows are separated from information content, as indicated in Section 3.2.6. Effectively a clear distinction is made between *declarative* and *procedural* information content. In other words, only the mechanics of information transfer are captured at this *procedural* level, while problem specific information is defined separately at the *declarative* level. This results in a process map that remains the same irrespective of the application in which the process is used. Information content is thus effectively batched, according to the structure of the overarching template.

A simple example of a generic process map for the design of either a spring or a pressure vessel using the compromise DSP construct, discussed in Section 2.3.1, is given in Figure 3-10. The elements of this generic process include problem definition, analysis, constraint evaluation, goal evaluation, and an optimization routine. Each of these entities interacts with the product information layer through the product information templates discussed in Section 3.3.1. The information flows between these entities are generic and independent of the product being designed. For example, the flow of information between the analysis module and constraints evaluation include the problem name, an array of input names (i.e., design variables), and an array of input values. The actual input names and values are dependent of the problem and are extracted from the variables and parameters definition template discussed in Section 3.3.1.1.

The implementation of the declarative process level (as realized in this dissertation) relies on the use of ModelCenter® [183], developed by Phoenix Integration Inc. ModelCenter® allows for modeling design processes in terms of various simulation codes and the required information flows connecting them. Associated with each entity in this process are a set of JavaBeans that parse required information from appropriate XML files at the product information level and subsequently make this information available for processing in ModelCenter®. These Process elements are mapped to each other for a specific problem, in a manner that reflects the underlying (batched) information flows required by the generic templates. This mapping remains the same irrespective of the design problem in which the process is used. For example, the information flows and mappings relevant for the solution of a compromise DSP, will remain the same, whether the product being designed is a pressure vessel or a spring. In reference to the generic compromise decision template, pictured in Figure 3-8, the "wiring" remains consistent, regardless of what design problem (characterized in terms of "chips") is being solved.

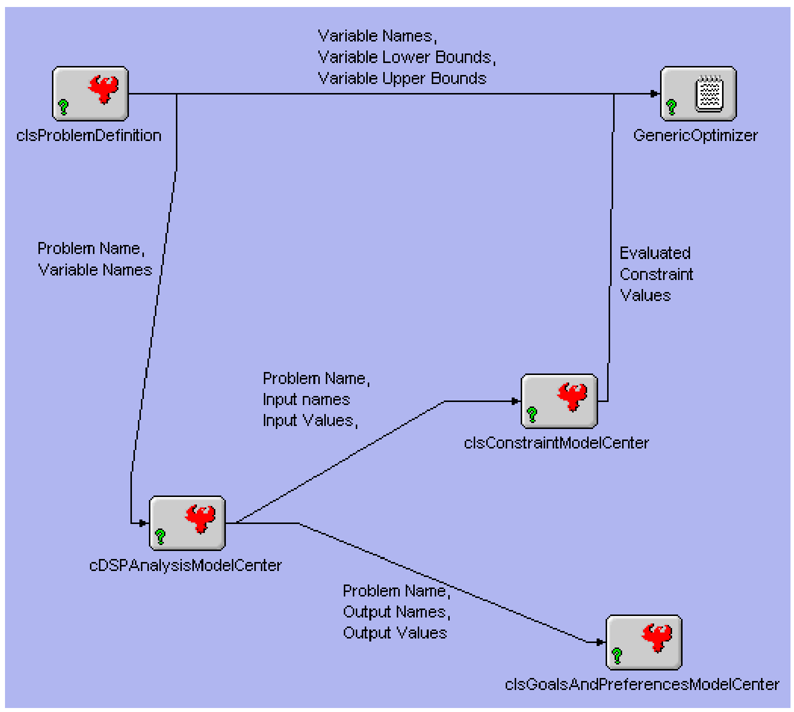


Figure 3-10 - Process Map for Spring/Pressure Vessel Design

3.3.3 (Procedural) Process Execution Level

The details of code execution are captured in the Execution Level layer. This level is specific to the design problem for which the process has been instantiated. Execution level codes interface only with the declarative problem formulation level (Section 3.3.1). Thus, there is no direct link between the process specification level (Section 3.3.2) and the execution level, discussed in this section. This architecture preserves the modularity of the design processes being modeled. For the design of the pressure vessel and the spring, the execution level codes (i.e., the analysis codes simulating the behavior of both the spring and the pressure vessel) have been written in Visual Basic, although any other model wrapped as a ModelCenter® component could also be used in the current instantiation of this modeling effort. It is important to note that these concepts can be implemented in virtually any object oriented programming language and is not platform dependent.

3.3.4 Results of Decision Template Use in Single Decision-Maker Design Processes

Specification of a design process in a template-based environment, such as that described in Sections 3.3.1 through 3.3.3, involves two basic steps. The first is the identification of the type of decision required (i.e., selection or compromise), the second is the provision and organization of decision-critical information according to the system, illustrated in Figure 3-7. While the first step corresponds to the specification of *procedural* information, the second step constitutes the provision of the *declarative* information, defining the product being designed. It is noted at this juncture that the choice of information transformation template invariably dictates which information is required and how this information is to be batched. Since both the pressure vessel and the spring designs constitute compromise decisions, the associated single decision-maker design processes differ only in terms of the declarative information provided by the designer charged with their resolution. This information is stored using the XML schemas, described in Section 3.3.1 and utilized according to the process captured in the decision template. The results obtained for the pressure vessel and spring design examples, using this generic process, (pictured in Figure 3-10) are summarized in Table 3-2 and Table 3-3, respectively. The author notes that these results have been verified and validated with exhaustive searches, based on more traditional problem formulations.

Table 3-2 - Results for Pressure Vessel Design Problem

Design Variable	Value
Radius (R)	4.45 mm
Length (L)	62.4 mm
Thickness (T)	0.5 mm
Objective function (Z)	0.4958

Table 3-3 - Results for Spring Design Problem

Design Variable	Value
Coil Diameter (d)	0.059 in
Number of Coils (N)	3.5
Objective function (Z)	0.655

Before proceeding to discuss the template based modeling of a design scenario involving a several stakeholders, a brief discussion of the difference in modeling compromise and selection follows.

3.3.5 Selection vs. Compromise

Although the fundamental differences between selection and compromise have been discussed in Section 2.2.4, their effect on the associated decision templates are worth addressing in brief. As indicated in Figure 3-11, the main difference between selection and compromise is the manner in which the associated information flows must be batched in order to effectively separate *declarative* from *procedural* information flows. Clearly, the system descriptors, emanating from the word formulations of the selection and compromise DSPs, differ as well. Additionally, there are more fundamental differences that distinguish a selection from a compromise decision. While the former dictates a choice from a predefined set of feasible alternatives, the alternative being generated in the latter are a result of the chosen optimization algorithm. More specifically, they are determined through the chosen granularity of the search, step size, termination criteria, etc. In a sense, one could thus simplify the fundamental difference between selection and compromise as being the sheer number of alternatives. While the former deals with essentially discreet elements, the possibilities in the latter are limited artificially, although they remain continuous in theory. Thus, while feasibility is assumed (*a priori*) in selection, it must be confirmed in compromise for each and every point being considered.

As noted in Chapter 2, an alternative view underscores the reformulation of the selection DSP as a compromise, as illustrated in Ref. [24]. Although, reformulation of selection as compromise, follows roughly the same mathematical structure, it requires altering the manner in which selection criteria and alternatives are specified, making it counter-intuitive. While such a reformulation may make sense from a programming perspective, when faced with a coupled selection-compromise decision, it is counter-productive from a template based view. Interfaces are treated as separate entities, handling all required mapping and translation of data. This stands in marked contrast to hard coding the manner in which selection and compromise decisions share information, resulting in a mixed discreet/continuous optimization problem, the results of which must be filtered for non-feasibility. The very point underlying the development of templates is to provide an intuitive means of modeling design processes that simultaneously prescribe and enforce consistent structure.

The benefits inherent in the templatization of selection decisions mirror those cited for compromise decisions. With respect to the ease of considering evolving information content, separation of *declarative* and *procedural* information allows for greater facility in changing alternatives as well as attributes taken into consideration. This is especially convenient when dealing with coupled selection-compromise. Having discussed the templatization of decision constructs, a discussion of interaction templates follows.

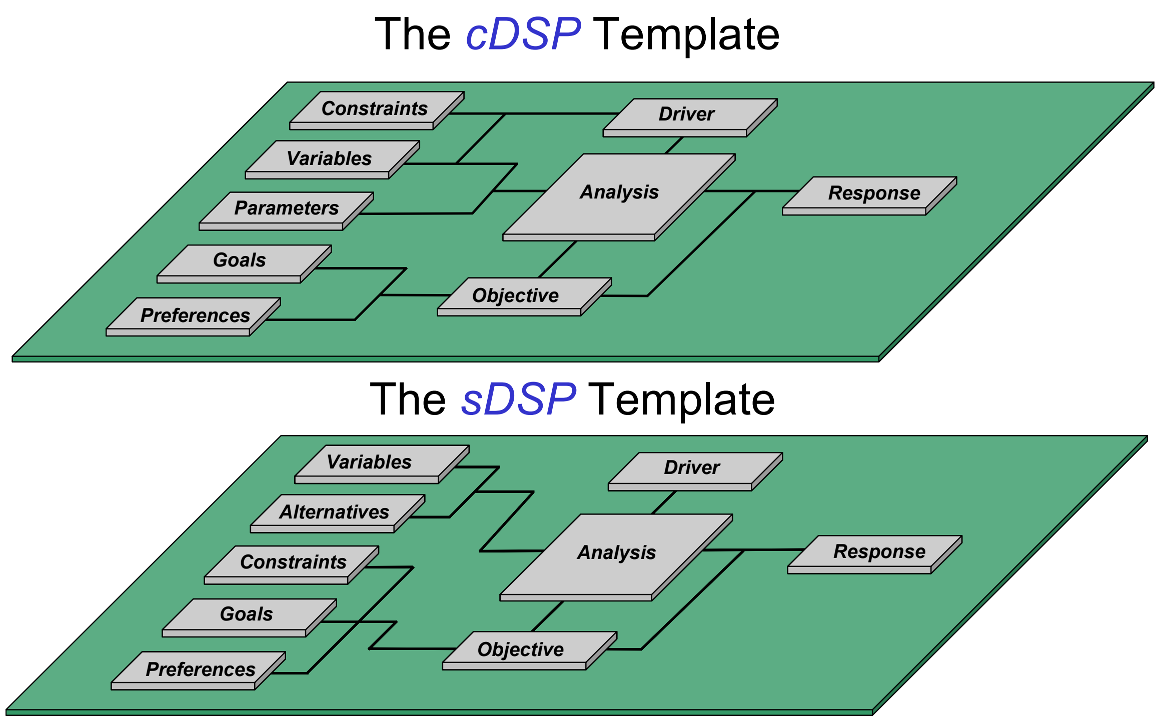


Figure 3-11 - The sDSP Template vs. the cDSP Template

3.4 INTERACTION TEMPLATES

The process modeling methods proposed in this chapter are aimed at facilitating the design of systems, complex enough to warrant resolution by interacting domain experts. The emerging class of multifunctional structure-material systems (discussed in Section 1.1) whose members often span multiple functional domains as well as length/time scales comprises a good example of such a system. A fundamental requirement for the applicability of the proposed modeling approach, however, is that the underlying design processes be clearly decomposable, allowing for the synthesis of expertise emanating from different designers with regard to each domain of interest. With this in mind, several aspects of this novel modeling approach that are instrumental to supporting collaborative design processes, involving the resolution of tradeoffs among interacting decision-makers, are discussed in this section. The pressure vessel example, relied on for illustration purposes in Section 3.3 and forming the basis of Chapter 7, serves as the vehicle for making salient points.

3.4.1 Design Processes with Multiple Decision-Makers

Although design problems can often be addressed adequately by a single designer, as illustrated for both the spring and the pressure vessel in Section 3.3, there are many instances when the expertise of more than a single decision-maker is required, due to limited domain knowledge, assignment of responsibility, value chain configuration, etc. The result is a need for effective collaboration in spite of distribution and tradeoff among conflicting objectives. In terms of the pressure vessel example, it is assumed here for demonstrative purposes that two designers (i.e., Designers A and B whose respective considerations are given in Figure 3-12) are collaborating in its realization. In this effort, Designer A's goal is to minimize the overall weight of the vessel, while Designer B is in pursuit of the maximum attainable volume. Both designers are subjected to the same set of constraints, but are in control of a different set of design variables. Specifically, Designer A has control over radius **R** and length **L**, while Designer B controls thickness **T** (see Figure 3-12).

Pressure Vessel Design				
cDSP "Chips"	Designer A (WGT)		Designer B (VOL)	
Constraints	Stress: $\frac{PR}{T} - S_t \leq 0$ Thickness: $5T - R \leq 0$ Radius: $R + T - 40 \leq 0$ Length: $L + 2R + 2T - 150 \leq 0$		Stress: $\frac{PR}{T} - S_t \leq 0$ Thickness: $5T - R \leq 0$ Radius: $R + T - 40 \leq 0$ Length: $L + 2R + 2T - 150 \leq 0$	
Variables	Radius, Length		Thickness	
Parameters	Density, Strength, Pressure		Density, Strength, Pressure	
Goals	Weight Target = 300 kg		Volume Target = 500000 m^3	
Preferences	Volume Weighting Factor = 0.5		Weight Weighting Factor = 0.5	
Objective	**Minimize** Weight $W(R,T,L) = \pi\rho\left[\frac{4}{3}(R+T)^3 + (R+T)^2 L - \left(\frac{4}{3}R^3 + R^2 L\right)\right]$		**Maximize** Volume $V(R,L) = \pi\left[\frac{4}{3}R^3 + R^2 L\right]$	
Analysis	**Inputs**	**Outputs**	**Inputs**	**Outputs**
	Radius, Length, Thickness, Density, Strength, Pressure	Weight	Radius, Length, Thickness, Density, Strength, Pressure	Volume
Driver	**Optimization Algorithm** – Exhaustive Search, SQP, etc.		**Optimization Algorithm** – Exhaustive Search, SQP, etc.	
Response	**Design Variable Values** – Radius, Length **Objective Function Value** - Z		**Design Variable Values** – Thickness **Objective Function Value** - Z	

Figure 3-12 - Design Sub-Problem Formulations for the Collaborative Design of a Pressure Vessel

In order to address the needs of collaborative design as explored in the remainder of this dissertation, a consistent means of modeling stakeholder activities is required. The decision templates introduced in Section 3.3 comprise such a means and allow for the consistent (i.e., standardized) formulation of both decision-maker perspectives, as illustrated in Figure 3-12. A primary benefit in this regard is that inputs and outputs of design sub-problem formulations can be more easily determined. This, however, does not address the additional complications introduced through decentralization. The ensuing collaborative design process must be managed effectively; interactions among stakeholders must be coordinated and information shared in light of dynamic considerations. Baring in mind that the required information consistently evolves along a design timeline (quality improves, uncertainty decreases, etc.), a fundamental need for an effective means of reflecting that updated information content in design decision-making emerges. It is through the successful separation of the *declarative* from the *procedural* information that this need is addressed also in this regard. The required level of modularity, however, can only be maintained via the development of an interface that is distinct from the decision templates being linked, thereby ensuring continued separation of the *declarative* and *procedural* information flows.

3.4.2 Interfaces in Engineering Design Processes

An interface in a design process separates or partitions multiple dependent or interdependent designers and their respective design activities. If there is a boundary between design activities, there must also be an interface in order for information to flow and interactions to take place. The nature of the flow determines the instantiation of the interface. Here, an interface is envisioned that is digital—only information (e.g., requirements, performance specifications, etc.) flows between partitioned design activities. The notion of such a digital interface is rooted in the idea of instantiating a "clean digital interface" between design and manufacture through the use of decision templates, as proposed by Rosen and co-authors [86]. Clean, in this context denotes the effective elimination of iterations emanating from mismatched objectives and manufacturing limitations via a complete transfer of responsibility for conflict resolution from design to manufacture. This stands in marked contrast to more traditional "over the wall" (i.e., trial-and-error) approaches, associated with Design for Manufacture (DFM). These concepts were subsequently extended as a means of linking interdependent decisions and applied in a distributed computing framework [86,87,271].

Although the issue of regulating exchanges among collaborating designers has been a subject of design research for a number of years, there are two elements, crucial to interfacing design activities and supporting collaboration along a design timeline, that have thus far not been resolved – evolution of decision critical information and connectivity. Consequently, it is required that (1) interface templates serve as domain-independent communications protocols for regulating the way in which experts (operating in different functional domains) share information for effective collaboration and (2) once instantiated, serve as a means for connecting decision templates to one another in a computer interpretable manner, allowing for design process analysis, exploration, and modification. The aim is to structure and coordinate stakeholder interactions so that collaboration is supported and both decision-makers and the decision constructs, used to model their aspirations, are consistently interfaced.

The resulting *interaction* templates serve to embody the coordination protocols, thereby ensuring that designer interactions are structured consistently along a design timeline. Appropriate templates are chosen based upon the underlying informational dependencies and organizational requirements. Consequently, design processes can easily be adapted to changing system level requirements and logistics, simply by changing the associated *interaction* template.

The notion of composing design processes by linking various decision templates via interaction templates, is illustrated in Figure 3-13 for the pressure vessel design scenario. In this figure, the decisions corresponding to the two design sub-problems illustrated in Figure 3-12 are instantiated as distinct decision templates. The information flow between the design decisions is represented by an interaction template that aptly captures the chosen interaction protocol. Interaction protocols have taken on many different instantiations, ranging from game theory (e.g., iterative non-cooperative techniques [39,40] and other non-cooperative as well as cooperative instantiations [21,98,99,126,133,136,267,270]) and negotiations [201,202]. The reader is referred to Section 2.1 for a more in-depth discussion. In this chapter, only cooperative and non-cooperative game theoretic protocols are considered. The premise is Designers A and B pursuing conflicting objectives, while being subject to a common set of constraints.

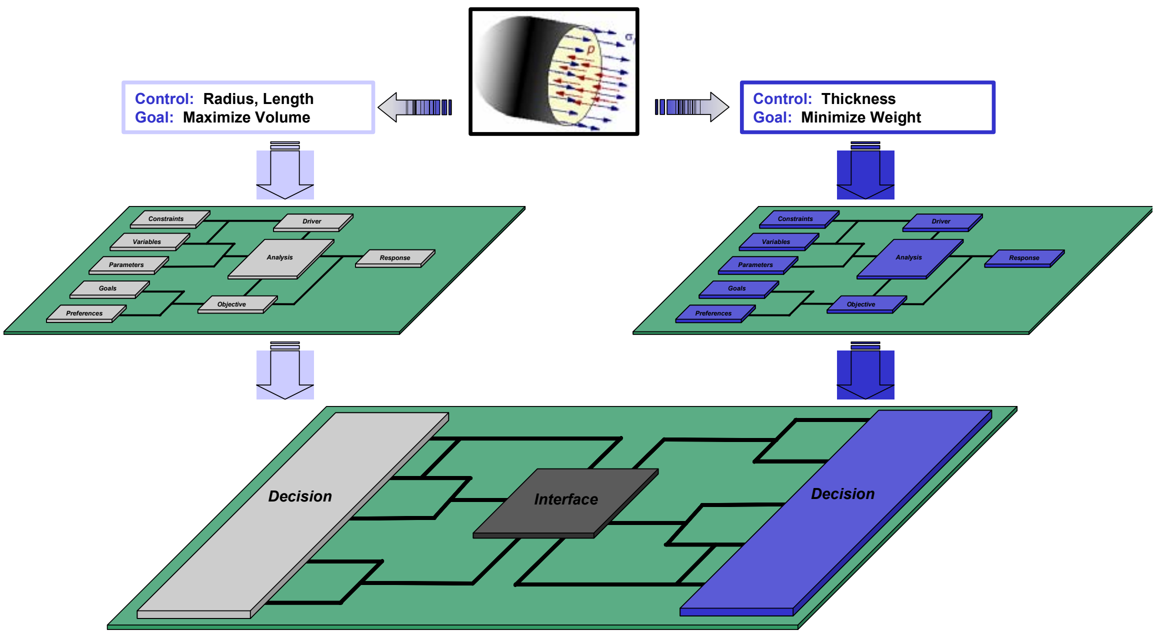


Figure 3-13 - Linking Decision Templates via Interaction Templates

3.4.3 Design Processes with Multiple Decision-Makers

The interface templates embodied in this dissertation consistently link the decision templates employed to capture and maintain the perspectives of the interacting decision-makers. The communication protocols or coordination mechanisms considered in this example (i.e., are those of *cooperative* or *non-cooperative* games) are instantiated as interaction templates such as that pictured in Figure 3-13. An interaction template, in this context, is best instantiated as a script (Visual Basic in this case) that captures the manner in which *declarative* information, emanating from either of the two decision templates is to be synthesized. For example, *full cooperation* essentially translates to virtual reformulation of the two decisions as a single decision, where tradeoffs among the various objectives are struck using an evenly weighted Archimedean sum. In the case of *non-cooperative* behavior, decision-maker seeks to achieve his or her goals, subject to a common set of constraints. This situation is modeled by automated BRC assessment and subsequent intersection. In an environment such as ModelCenter®, the resulting interaction templates are computational objects that can manipulated in much the same manner as the decision templates they are meant to interface. In fact, interaction template instantiation requires nothing more than making the proper connections between decision template inputs/outputs and interaction template inputs/outputs.

The fundamental drawback from a systems perspective in this latter, non-cooperative scenario is that the required decomposition results in two distinct, yet interdependent (i.e., coupled) design sub-problems. This division is indicated in Figure 3-14, where the system is divided among the interacting decision-makers, each of whom formulate strongly coupled design sub-problems, reflective of their goals, while remaining subjected to common set of constraints. It is the interdependent aspects of the design sub-problem formulations that cause the greatest difficulty in arriving at a viable solution from the systems perspective. Often regions of the coupled design space are eliminated unnecessarily due to the order in which constituent decisions are made or control over design parameters is assigned. These points are illustrated at the hand of the pressure vessel design example, where it is the combined outcome of the decisions corresponding to the design sub-problems (i.e., maximization of volume and minimization of weight, respectively), that composes the system solution. More on this subject follows in Chapters 4 and 5, the subject matter of which is dedicated entirely to addressing these issues.

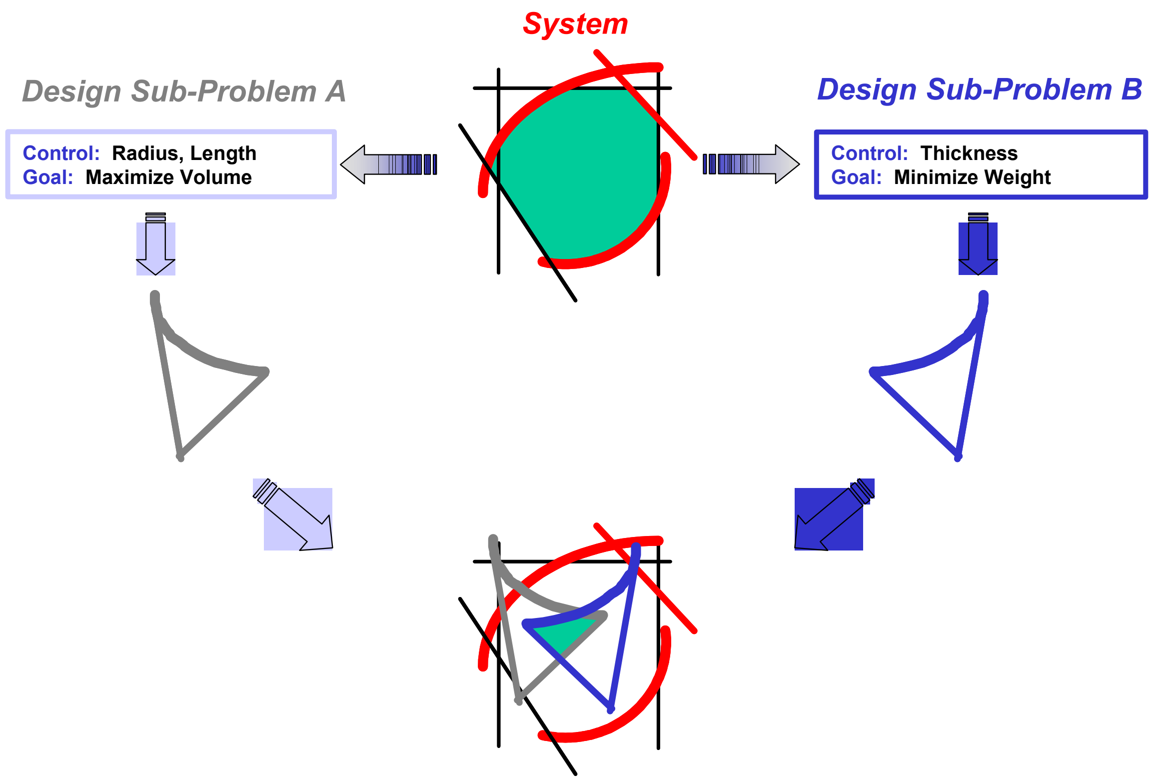


Figure 3-14 - The Effect of Design Space Decomposition

3.4.4 Communication Mechanisms and Their Effect on Design Processes

As evidenced in Table 3-4, the nature of the interaction protocol used to structure the collaboration among the interacting decision-makers has a significant effect on the outcome attained. This is to be expected. Predictably, the best outcome (i.e., Z = 0.4958) from a system's perspective is obtained for *full cooperation*, while there is a significant spread in objective values obtained for *non-cooperative* behavior, ranging from Z = 0.4976 to Z = 0.9077. In fact, the fully cooperative outcome among the two interacting decision-makers, each in pursuit of their own objectives, matches that obtained for a single decision-maker. In the case of non-cooperative behavior it is clear that the results obtained are directly affected by decision-maker precedence and design variable control. While in this particular case, the average effect of precedence and control on the objective value obtained is almost the same (i.e., Z = 0.2446 and Z = 0.2396 respectively), the comparative significance of these effects is problem specific and depends directly on problem specifics – constraints, design variable sensitivities, etc. It is noted, however, that while changing control over design parameters may not be feasible, depending on the particular design process at hand, changing precedence (i.e., the sequence in which design variables values are fixed by the designers assigned responsibility for doing so) in concurrent decision-making may prove to be a powerful means of improving system consideration.

Table 3-4 - Effects of (1) Interaction Protocol, (2) Order of Precedence, and (3) Design Variable Control on Design Process Outcome

	Cooperative	**Non-Cooperative**			
	Single Designer controls R, L, T	**A (controls T) B (controls R, L) A(WGT) preceding B(VOL)**	**A (controls R, L) B(controls T) A(WGT) preceding B(VOL)**	**A(controls R, L) B(controls T) B(VOL) preceding A(WGT)**	**A(controls T); B(controls R,L) ; B(VOL) preceding A(WGT)**
Radius	**4.45**	**10.40**	**2.50**	**9.95**	**4.45**
Length	**62.40**	**126.80**	**117.20**	**0.10**	**140.00**
Thickness	**0.50**	**1.16**	**0.50**	**1.99**	**0.50**
Weight	**299.91**	**3367.85**	**299.8796**	**851.0078**	**624.0082**
Volume	**4249.00**	**47773.55**	**2365.4667**	**4155.2669**	**9074.1128**
Z (Weight)	**--**	**0.9109**	**0.0000**	**0.6475**	**0.5192**
Z (Volume)	**--**	**0.9045**	**0.9953**	**0.9917**	**0.9819**
Z (System)	**0.4958**	**0.9077**	**0.4976**	**0.8196**	**0.7505**

As illustrated at the hand of the pressure vessel design problem, explored for two collaborating decision-makers with regard to (1) use of interaction protocol, (2) order of precedence, and (3) control over design variables in this section, the design process can have a significant effect on the outcome obtained. This is especially true in light of continuously evolving information content. It is a fundamental aim of this dissertation to provide a consistent means of interfacing collaborating decision-makers, whose design sub-problems are modeled in a consistent fashion. Using the modeling strategy presented in this chapter, it becomes possible to explore different design process scenarios and effectively leverage an engineering enterprise's intellectual capital [167]. More on the manner of best striking tradeoffs so that sub-system considerations are based with concerns at the systems level follow in Chapters 4 and 5.

It is noted that while changes in control constitute changes in *declarative* information, changes in precedence comprise changes in *procedural* information only. The point is that design process exploration is reduced to independent changes in *declarative* and *procedural* information. Modularity greatly reduces the effort involved in adaptation, modification, and exploration, since the effect of changes are contained and can consequently be managed with ease.

3.5 CRITICAL ANALYSIS

What are the challenges in modeling design processes? Design processes for mechanical systems are rather complex, often due to the inherent complexity of the product itself. Interactions and resultant iterations between various activities and stakeholders add to the complexity of product realization processes. Whitney [260] points out that the complexity of mechanical designs results from the multifunctional nature of the parts required to obtain efficiency. The underlying design processes involve many organizational units and engineering disciplines. Additionally, the level of human intervention comprises a barrier to process modeling.

Modeling design processes adds an additional degree of complexity because design processes cannot be described completely *a priori*. Downstream activities are very much dependent on the information generated by upstream activities and the associated level of uncertainty is consistently high. The inevitable result is a need for constant adaptation. Since realities evolve, so must the design processes subjected to them. The template-based process modeling approach, presented in this chapter greatly improves the agility of designers in reacting to and accommodating changes in any information content. The resulting computer-interpretable construct are easily adapted to accommodate interactions, characterized by shared design variables and dependent or inter-dependent information flows. Relevant communications may include ranges and/or sets of parameters, target values, etc., for coupled (i.e., dependent and interdependent) parameters that factor into computational models and analysis codes of partnered or teamed designers. Additionally, as illustrated in Section 2.4, engineering processes can be represented at various levels of detail, depending on the intended use of the resulting models. This stands in marked contrast to most traditional process modeling methods (e.g., Program Evaluation and Review Technique (PERT) [152,153], Gantt Charts [152], IDEF 0 [1], etc.) which capture information at the activity level only. As such, these tools are useful for making organizational decisions with regard to processes such as time utilization, resource allocation, task precedence, material flow, etc. Example applications of tools such as these include modeling manufacturing processes to study process characteristics, including time scheduling, material processing, assembly/disassembly and packaging. In a collaborative design scenario, models of processes are needed for understanding and coordinating collaborative work, thereby defining conflict management [172].

The fundamental advantages of the proposed approach over currently available design process modeling methods is the combinatorial effect of synthesizing representation with simulation and storage in a completely modular fashion. Since all of the constructs are formulated at the decision level their instantiation is not limited to any specific domain, discipline or level of abstraction. The only requirements are (1) that the decision-maker possess a level of expertise sufficient to make a decision, interpret data, map/translate requirements, and communicate these effectively, (2) that the decision-maker be rational, and (3) that the decision-maker have access to sufficient information for making a decision with the desired level of confidence. With respect to the facilitation of decentralized design activities, advantages over current methods are the standardization of the manner in which stakeholder considerations are formulated and considerable latitude in the choice, adaptation, and modification of communication protocol. The ability to change any template without having that change propagate to adjoining templates is also a fundamental contribution.

The result is a standardized means of representing stakeholder considerations that remains consistent, both in terms inputs (i.e., the manner in which information must be provided) as well as outputs (i.e., the manner in which information is produced). Consequently, although transformations may change, these changes do not affect the manner in which templates are interfaced. Another advantage emanates from the fact that decision-maker expertise is aligned consistently with responsibility. This is the case throughout the duration of a given design process and owed to the fact that the interface is a separate entity from the decision construct. The inherent advantage is that repeated interactions are possible without incurring the penalties usually associated with trial-and-error iteration (e.g., reformulation). Additionally, design changes are not limited by model extent. Similarly, tradeoffs must not be relegated to functional intersection.

The most important realization is that there is a tradeoff between (1) the broadness of model applicability, (2) the granularity of information that can be represented, and (3) the variety of analyses that can be performed using each of the models considered. For example, PERT, Gantt Charts, IDEF 0, and Activity-Net-based models are very general in terms of applicability, but can be used to represent information in terms of required activities and time only. Conversely, the kind of information being processed is not captured in any of these models. Due to these limitations, it has thus far not been possible to model design processes at a level sufficient for their (1) execution, (2) analysis, and (3) reusability, as required for effective *design* and *evolution* of *design processes*. It is precisely on addressing each of these three aspects in a consistent manner that this chapter is focused. The underlying purpose is that of creating a technological base for implementing the methods and mechanisms presented in Chapters 4 and 5. With this in mind, a discussion of the validation and verification of this approach to the decision-centric design process modeling of complex engineering systems follows in Section 3.6.

3.6 A NOTE ON VALIDATION

As stressed in Section 1.4, this chapter is focused exclusively on addressing the first research question, posed in this dissertation: *How can design problems be modeled so that the reflection of changing information content and evolving stakeholder aspirations can be accommodated while maintaining structural consistency?* With this in mind, a review of each aspect of the validation and verification strategy, pursued in this dissertation follows in Sections 3.6.1 through 3.6.3.

3.6.1 Theoretical Structural Validation of Hypothesis 1

Although the majority of *Theoretical Structural Validation* with regard to *Hypothesis 1* was addressed via critical review of the literature in Chapter 2, specifically Sections 2.3, 2.4, 0, 2.7, and 2.8, additional contributions were made in Section 3.1. Evaluation of the implemented constructs with regard to comparative advantage, limitation, and acceptable domain of application was addressed in Section 3.5. Overall, there are a number of inherent benefits to the proposed modeling technique. On the whole, there are three main functions, namely *computer interpretability*, *modularity*, and *archival*, that each in turn allow for the execution, re-use/reconfiguration, and documentation of design processes and any of their components, respectively. The fundamental methodological differences between the proposed design process modeling technique and other commonly available approaches are that (1) *declarative* and *procedural* models are effectively separated and (2) the process elements are composable as modular building blocks. Consequently, it is possible to effectively model design processes and sub-processes, regardless of functional domain or complexity. This is demonstrated with regard to designer specific sub-problem formulations in Section 3.3 and composition of collaborative design processes in Section 3.4.

3.6.2 Empirical Structural Validation of Hypothesis 1

Empirical Structural Validation is usually addressed through illustration of example relevance. Clearly, both springs and pressure vessels are quintessential mechanical engineering artifacts. As such they are representative of the discipline and its characteristic concerns. The primary goal in the validation and verification of Hypothesis 1 is that of building confidence in the capability of accommodating evolving information content. Though simple, the spring and pressure vessel examples are dissimilar enough to support the conclusion that the separation of *declarative* and *procedural* information allows for the creation of a computer-interpretable construct, generic enough to accommodate both the problem- and the process-specific requirements of either product. This principle serves as the basis for reflecting continuously evolving information content. There are myriad changes that can take place with regard to any given design process. The intent in the proposed modeling approach is to isolate these effects by providing the required level of modularity. The principal advantage of this novel modeling technique is the enhanced reusability of information and knowledge achieved via the separation of information pertaining to problem formulation, process, and execution. Confidence in this aspect is strengthened via (1) use of the same decision template to model both products and (2) integration of two distinct decision templates via various interaction templates. Both examples underscore the ability of this unique modeling approach to handle continuously evolving information content, as required by the methods presented in Chapters 4 and 5.

3.6.3 Empirical Performance Validation of Hypothesis 1

Empirical Performance Validation is, in a sense, a measure of the method's usefulness. Using the spring and pressure vessel examples (or any other design examples for that matter) in such a way that outcomes can serve as a means of quantitative evaluation is rather difficult, since subjective criteria such as ease of use are difficult to quantify. Suffice it so say that the effort involved in instantiating the same template for either design problem is minimal. In fact, the only required task is that of reading in the appropriate set of XML files, containing the *declarative* information. Similarly, changing communication protocols involves two steps, (1) choosing the appropriate template and (2) making the appropriate connections between decision template outputs and interaction template inputs, and vice versa. Since such a quasi plug-and-play approach was not previously available, it is asserted that at this point that the resulting 'usefulness' is indeed a result of the method used and not just a matter of chance. In general, the capabilities result as a direct consequence of infusing modularity into the fundamental constructs of the Decision Support Problem Technique and directly address the shortcomings of the various process modeling efforts reviewed in Chapter 2. In fact, it is through the consistent structuring of decision-maker considerations that it is possible to address both product specific concerns (reviewed in Section 2.3) and process specific aspects (reviewed in Section 2.4) of engineering design simultaneously and in a consistent manner. Furthermore, the outcomes of the design problems, documented in

Table 3-2, Table 3-3, and Table 3-4, make sense, are consistent with expectation, and rather intuitive with respect to engineering judgment. They have also been validated by exhaustive search, coded using more traditional problem specific programs. Additionally, the approach is relatively easy to implement, especially in an environment such as ModelCenter®, where functionality is easily extended further by leveraging application specific capabilities.

3.6.4 Theoretical Performance Validation of Hypothesis 1

As indicated in Section 1.4, *Theoretical Performance Validation* in this dissertation consists of extending confidence in the validity of the approach beyond the scope of the examples presented. As substantiated in Section 3.6.2, the test problems relied upon in this chapter are representative of a larger class of problems, commonly encountered in engineering practice. In Chapters 6, 7, and 8 confidence is built in the capability of the methods presented in this dissertation to handle the intricacies of more comprehensive design problems (e.g., involving further complications due to distribution, complexity, collaboration, multi-functionality, etc.). Specifically, their use is illustrated at the hand of the collaborative, multi-objective design of both a pressure vessel and a structural heat sink. Overall, the constructs, discussed in this chapter constitute the infusion of modularity into the indefinitely adaptable constructs of the DSPT. Since these fundamentals have already withstood the test of time, there are no conceivable theoretical limits to extending this method beyond the problems considered in this dissertation (at least in theory). This assertion is based in part on the virtually limitless freedom afforded us through object-oriented programming and continuous advances in computational power.

3.6.5 Revisiting the Square

Theoretical Structural Validity of each of the three Hypotheses is explored and established throughout the first five chapters of this dissertation. Although the **Empirical Structural** and **Performance Validity** of Hypotheses 2 and 3 are substantiated explicitly in Chapters 6, 7, and 8, these aspects of the espoused validation strategy with regard to Hypothesis 1 were addressed almost exclusively in this chapter. Keeping with schedule set in Figure 1-14, the overall progress in validating and verifying the contribution documented here is summarized in Figure 3-15.

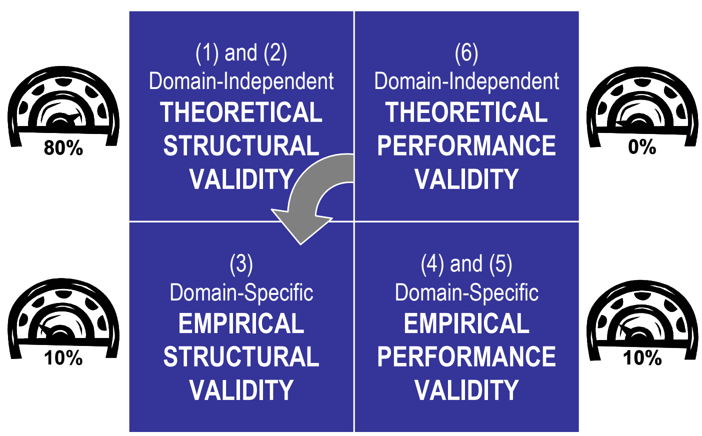


Figure 3-15 - Validation and Verification Progress through Chapter 3

3.7 A LOOK BACK AND A LOOK AHEAD

3.7.1 Revisiting the Roadmap

In this chapter, an approach for modeling design processes, based on a modular, decision-centric, template-based representation of design processes is presented. These proposed process templates are computer interpretable and archivable, allowing for the execution, re-use/reconfiguration, and documentation of design processes and any of their components, respectively. A modular, generic formulation of the process required for the solution of an independent compromise DSP is conceived and presented in Section 3.3, while the resolution of coupled compromise DSP is illustrated in Section 3.4. The underlying information model has been formalized and the resulting construct successfully implemented in ModelCenter®, as shown in Section 3.3.3. The developed process model is instantiated and validated for two examples (i.e., pressure vessel and spring design) in order to offer proof of concept for the proposed modeling technique. Finally, both reusability and composability of templates are emphasized via the succinct integration of interacting decision-makers, sharing responsibility for the design of the pressure vessel previously modeled for a single decision-maker.

As indicated in the beginning of this chapter, and highlighted in Figure 3-16, the main goal pursued in this chapter is that of presenting, demonstrating, and building confidence in a template-based means of design process modeling that aptly satisfies the logistical requirements for consistent decision formulation and concise communication among interacting domain experts. As such this chapter exposes the technological backbone, facilitating the implementation of the concepts developed in Chapters 4 and 5. The sum of total of the methods presented in Chapters 3 through 5 comprise the proposed **F**ramework for **A**gile **C**ollaboration in **E**ngineering. Specifically, it is the focus of the next chapter to introduce the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod. Subsequently, the **I**nteraction-**C**onscious **C**oordination **M**echanism is presented in

Chapter 5. In terms of validation and verification, the focus in both Chapters 4 and 5 is on Theoretical Structural and Theoretical Performance Validation.

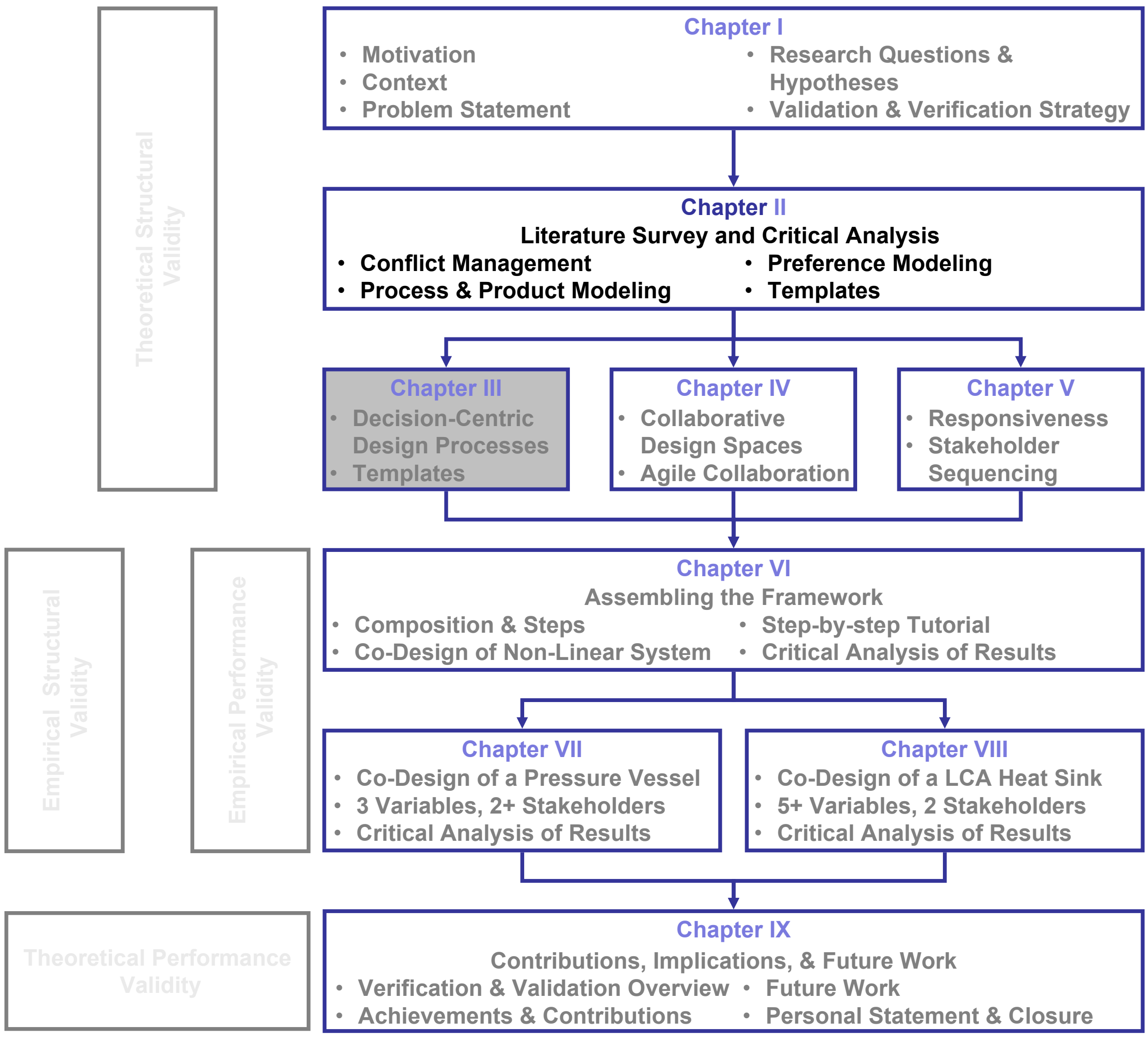


Figure 3-16 - Dissertation Roadmap

3.7.2 Assembling the Building Blocks

This chapter was devoted to the exposition of a novel approach to implementing virtually any means of conflict management that can be expressed in mathematical terms. As such, this template-based design process modeling approach constitutes the functional basis for the methods described in Chapters 4 and 5. Although the successful implementation of the **F**ramework for **A**gile **C**ollaboration in **E**ngineering is not dependent on the constructs discussed in this chapter, much of the added organizational and computational burden may be alleviated through their implementation.

It is emphasized that decisions and interactions form the basis for collaborative design efforts. Consistency of both design problem formulations and interactions along an event-based design timeline is ensured via the concretization of these crucial information transformations in template-based form. It is in the standardization of the manner in which design decisions (both single-designer and multi-designer) are formalized, that the true value of the contribution lies. The consequence is a common basis for the formulation of a collaborative design space and the subsequent resolution of conflict in light of achieving system, as well as sub-system objectives, in a non-biased fashion. Such a standard is quasi prerequisite to the successful negotiation of solutions to the *strongly coupled* design problems focused upon in this dissertation, especially when these are assigned to myriad domain experts pursuing potentially dissenting objectives. It is for this reason that the **T**emplate-based **D**esign **P**rocess **M**odeling (TDPM) approach, presented in this chapter forms a basis for (1) the embodiment of the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod of Chapter 4 and (2) the **I**nteraction-**C**onscious **C**oordination **M**echanism of Chapter 5.

CHAPTER 4 - AGILE COLLABORATION ALONG AN EVENT-BASED DESIGN TIMELINE

In this chapter, the concepts introduced in Chapters 2 and 3 are built upon to formalize a method for the *identification* and *establishment* of collaborative design spaces. The focus is on focalizing the activities of collaborating stakeholders in order to ensure the existence of solutions to the strongly coupled problems with which they are charged. Since the systematically established design space is composed of strictly feasible solutions, it serves as a means of leveling the playing field for all interacting stakeholders. In essence, win/win solutions are guaranteed and hysteresis associated with trial-and-error based reconciliation of mismatched objectives is successfully avoided. Irreconcilable differences are identified earlier in the design process, thereby ensuring coherence before any significant resource commitments have been made.

Specifically, the notion of collaborative design spaces is introduced in Section 4.1. Elements relating to the systematic establishment of collaborative design spaces are elaborated on in Section 4.3 and their effective exploration is discussed in Section 4.4. The elements discussed in Sections 4.3 and 4.4 are then synthesized into the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod (CDSFM), comprising the first half of the **F**ramework for **A**gile **C**ollaboration in **E**ngineering in Section 4.5. A critical analysis of this method follows in Section 4.6. Aspects of validation and verification as pertaining to this chapter are addressed in Section 4.7. Specifically, *theoretical structural* aspects regarding the validation of *Hypothesis 2* are emphasized. Finally, overall cohesion of this material throughout the remainder of the dissertation is established in Section 4.8.

4.1 VALIDATION AND VERIFICATION WITHIN CHAPTER 4

As indicated in Section 1.5.1, the primary focus in this chapter is the development of the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod (CDSFM) in response to *Research Question 2* and the completion of the **Theoretical Structural Validation** of the associated constructs. Although the majority of this aspect of validation was addressed in Chapters 1 and 2, the benefits associated with remediating the various gaps identified in Table 2-1 and Table 2-2 are underscored in Section 4.2. An overview of pertinent aspects is provided in Figure 4-1. It is noted that **Empirical Structural Validation** and **Empirical Performance Validation** of the CDSFM are addressed in Chapters 6, 7, and 8, while a discussion of **Theoretical Performance Validation** is deferred to Chapter 9.

4.2 COLLABORATIVE DESIGN SPACES

Before focusing on the question as to how collaborative design spaces can be identified and established effectively, the more appropriate question to address may be that of *what, exactly, constitutes a collaborative design space*?

4.2.1 Description

As indicated previously, the design processes of interest to this discussion are composed of strongly coupled decisions, responsibility for the resolution of which is assigned to different decision-makers. These in turn act as decentralized stakeholders in a process that invariably determines the final *form*, *function*, and *behavior* of the product being designed. This is not to say that each of the individual decision-makers is not themselves in charge of furnishing a product. Instead, it is merely an assertion that these products contribute (either directly or indirectly) to the performance of one or several objectives at the systems level. Thus they have an impact far outreaching the confines of the particular design sub-system from whence they emanate.

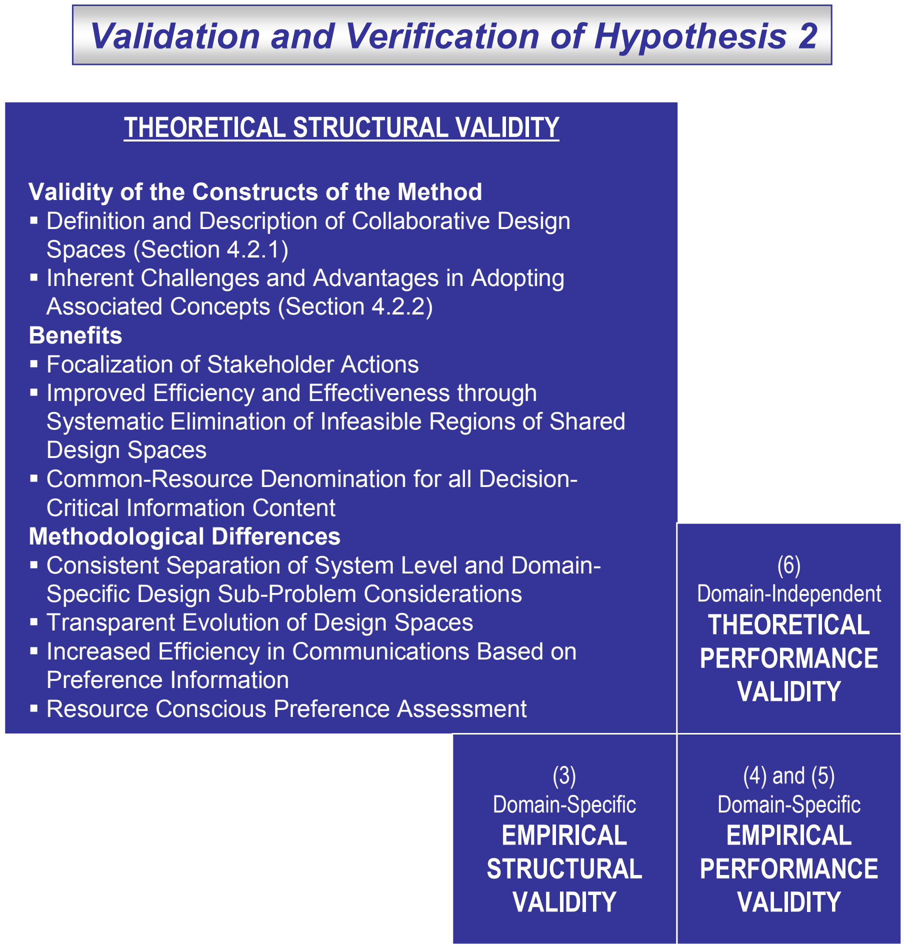


Figure 4-1 - Aspects of Validation and Verification Addressed in Chapter 4

A collaborative design space is best described by means of an example, which can be summarized as follows and mirrors the process depicted in Figure 4-2:

- A complex design problem is split into several problems of lower complexity, as indicated by the division of the strongly coupled design problem (focused upon in Chapter 6) into design sub-problems A and B in Figure 4-2. Often splits correspond to organizational lines or hierarchical levels, domains, and disciplines. Specific assignments are often made based on expertise. While distributing the workload dramatically decreases complexity on one side, decentralization increases them on the other.

- Additional problems arise from the need to translate requirements, specified for the performance of the overarching system to meeting objectives that are specified at the sub-system level. This is an important consideration because whether sub-systems are coupled or not, a one-to-one mapping is unlikely. This is underscored by the addition of constraints at the sub-system level with regard to both sub-systems in Figure 4-2.
- Stakeholders charged with the resolution of the various sub-systems that will eventually contribute to the performance of the overarching system are faced not only with system level constraints but also with considerations emanating (1) from their own domains and (2) originating in the sub-systems with which they share information. The extent to which these factors will impact specific stakeholder subsystems directly depends on the nature of the underlying information flows (i.e., dependence, inter-dependence, or interdependence). All of these considerations are reflected in the sub-system design problem formulations, as indicated in Figure 4-2.
- Individual stakeholders must then determine the best solution possible, based on the constraints placed upon them. These solutions map back into the systems level, where a solution to the system is determined from within the overlapping region of the various solution spaces. In the example, depicted in Figure 4-2, this region corresponds to the region marked “Collaborative Design Space” in Figure 4-3.

- Since additional constraints and assumptions enter the problem formulation at the sub-system level, the design space resulting from the combined consideration of the various sub-systems does not equal the original design space. This makes sense, since the results of global optimization rarely matches the results obtained from either serial or concurrent consideration of local constituents. This concept is underscored by the progression of the design spaces shown in Figure 4-3.

With this in mind, a *collaborative design space* corresponds to a design space incorporating both system level and sub-system level considerations. It can be thought of as the intersection produced when projecting feasible regions of the design spaces, corresponding to the design sub-problems into which the systems level problem was previously decomposed, back into the systems level. Due to the additional design sub-problem-specific constraints and objectives introduced, the product of decomposition, resolution, and recomposition does not necessarily match the original design space, as highlighted in Figure 4-3. It is quite likely that entire regions of a shared design space will inadvertently be eliminated from consideration. Since a systems level optimization, however, is not possible, it is more effective to operate in terms of the resultant collaborative design space.

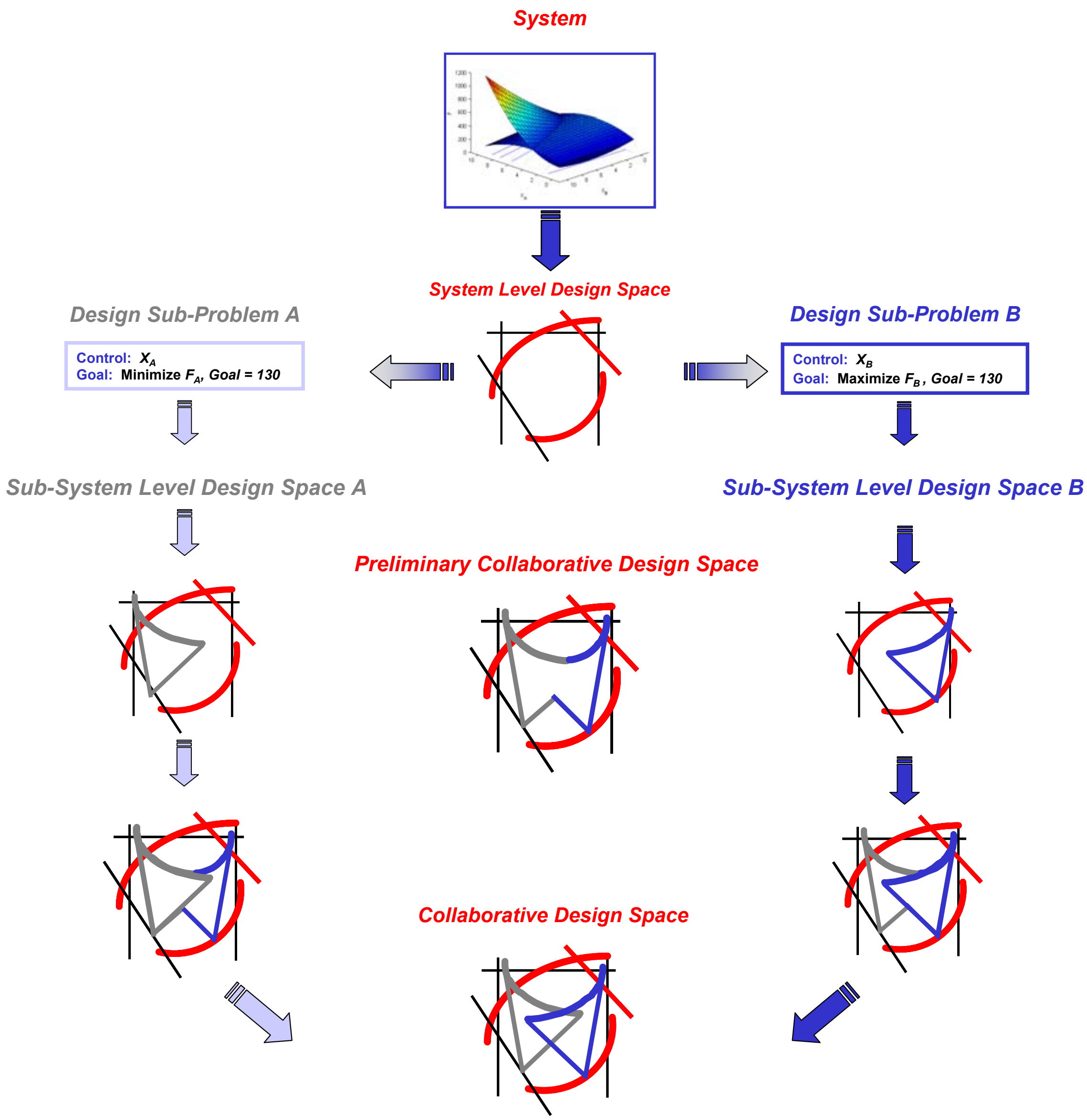


Figure 4-2 - Collaborative Design Space Formulation

As individual stakeholders proceed to determine solutions for their design problems, they are able to control only those design variables assigned to them. In the case of strongly coupled decisions, this means that the achievement of their objectives is impacted significantly by the actions of other stakeholders. In order to proceed, certain assumptions must be made, assumptions that may or may not turn out to be valid and can lead to inefficient and potentially divergent iteration.

One means of addressing this dilemma is to sequence the decisions made by interacting stakeholders. As indicated in Section 2.1, a number of possibilities exist, each differing in the amount of information that is shared and the extent of responsibility that is reassigned. In this manner, portions of each of the design spaces (corresponding to design sub-problems) are eliminated in progression based upon the objectives of other stakeholders. Since this reduction in design freedom is likely to result in unnecessary exclusions, based on sequence alone, solutions are likely to fall short of at least one stakeholder's expectations. This problem is aggravated by a persistent lack of information with regard to the potentially adverse affects of individual decisions on other stakeholders. The consequence is diminution of system level performance. It is these problems that are addressed in the next chapter. Specifically, the alternative perspective adopted in this dissertation separates the activities involved in the formulation of collaborative design problems from those involved in their solution. Typically collaboration is restricted to the mechanics of tradeoff management. Design problem formulation, on the other hand has been relegated almost exclusively to individual stakeholders, requiring them to act in isolation until the point of solution (typically BRC intersection). The primary assertion in this dissertation is that the key to ensuring consistently good solutions lies in structuring the process leading up to tradeoff management, rather than manipulating the manner in which such tradeoffs are struck. Although this is not to say that additional gains are not possible through choosing that mechanism most suited to the particulars of the problem at hand, as explored in the next chapter.

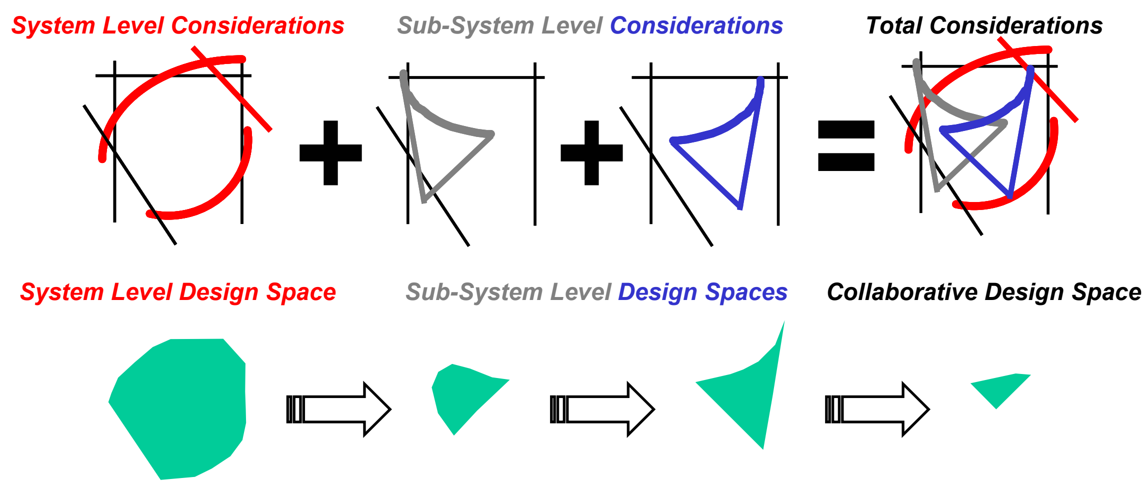


Figure 4-3 - Design Space Evolution

With this in mind, there are a number of terms that should be clarified for the remainder of this discussion, as well as the chapters to follow. A system is assumed to be described in terms of a problem statement and the specification of overarching requirements. It is presupposed that sub-system decomposition has already taken place. The methods described in this dissertation are concerned strictly with the resolution of conflict, once (1) said conflict has been completely defined in terms of level of dependence, (2) assignment of responsibility for objective achievement, and (3) division of control over shared parameters and design variables. All of these steps are inherent in the translation of a systems level design problem to systems level design decisions, mapping of these to resultant sub-system design problems, and subsequent translation to sub-system design decisions.

Although the exact nature of the governing relations at each of the levels of interest is not important, decision critical information must be quantifiable. Possibilities include quantitative behavioral descriptions at the system and sub-system levels as well as pertinent relationships among these (analytical, theoretical, stochastic, etc.). Decision-makers must possess ability for comprehension of both quantitative and qualitative aspects and competent interpretation.

Systems level objectives are typically specified in terms of preferences, goals, constraints, resources, etc., although the fidelity of their specifications may be too coarse for direct incorporation into sub-system level decision-making. It is here that the ability of stakeholders in synthesizing system and sub-system level considerations is assumed. Sub-systems are also defined in terms of preferences, goals, constraints, resources, etc., although a certain level of expertise is required to make the required inferences to reconcile the myriad levels. Finally, control assignment is a task usually carried out by systems engineers who map sub-systems to domains of expertise and assign responsibility to qualified decision-makers. It is at this level that organizational considerations such as outsourcing enter into the picture.

4.2.2 Advantages and Challenges in Adopting the Concept of Collaborative Design Spaces

There are several advantages in terms of thinking in terms of collaborative design spaces. First and foremost, designer efforts are focused on those regions that are feasible. Since infeasible regions are removed from consideration computational complexity is drastically reduced. Rather than dealing in abstract terms originating in intuited interpretations of how one stakeholder's considerations may affect one's own, interactions are crystallized with respect to what is physically meaningful to all parties.

The main challenges in focusing on collaborative design spaces as the fundamental basis for communication in the decentralized solution of coupled design problems relate to the representation of these spaces. Representation is fairly simple in problems characterized by two and even three design variables, since these lend themselves to graphical representation in Euclidian two and three space. This is illustrated in Chapters 6 and 7. The same is not true for collaborative design spaces of higher dimensionality (see e.g., Chapter 8), however, where the concept becomes much more abstract. Although visualization in this context is not any different from that which pervades all of engineering practice (since very few problems are limited to under four dimensions), two facts greatly complicate the matter. Firstly, multiple decision-makers are pulling the proverbial strings simultaneously. Secondly, the design space in question is actually composed of various "superimposed", sub-problem-specific design spaces.

The likelihood of non-convex regions of interest also is significantly higher for collaborative scenarios. This in turn translates to difficulty in effective communication. While ranges of design variables in combination with constraints can serve as an effective way of describing feasible regions of shared design spaces in the case of two and three dimensional problems (see Chapters 6 and 7), this approach does not scale well. As illustrated in Chapter 8, effective communications high complexity contexts require a set-based approach.

An additional challenge stems from the fact that a collaborative design space may not exist (at least initially). While this constitutes a serious problem, given that the implication is that stakeholder objectives are irreconcilable, making this realization early on in the design process is invaluable. Corrective action can immediately be taken, before further resources are expended. Examples of recourses in this situation include reassessment of preferences, relaxation of constraints, change of technological base, or any other resource augmentation.

A final point is that focusing on collaborative design spaces stresses the importance of considering performance potential. While the notion of rational preferences necessarily being independent of problem specific considerations is sound in theory, knowing what you want is relatively useless if you can't possibly achieve it. Such mismatches in preferences and achievable objectives, however, are quite useful when identified in a timely fashion. Though reassessment may be required, the upfront calibration process associated with any mathematical optimization problem is facilitated. This remains true even in those instances when decision-makers have considerable experience. While expertise can go a long way in making judgments regarding one's own domain, it is important to remember that what makes decentralized design such a formidable challenge is the element of partial control. The concept of a collaborative design space thus reconciles all relevant perspectives by compiling all decision-critical resources. The result is a clearer picture of the bottom line.

4.3 ESTABLISHING COLLABORATIVE DESIGN SPACES

As suggested in Figure 4-3, a distinction is made between a *preliminary collaborative design space* and a *collaborative design space*. While the former constitutes a "work in progress", the latter refers to a region of strict feasibility for all stakeholders. The **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod, focused upon in this chapter, is thus focused on establishing a collaborative design space by systematically evolving the preliminary collaborative design space, originating at the systems level, so that all pertinent considerations are accounted for.

4.3.1 Establishing a Preliminary Collaborative Design Space

The preliminary collaborative design space essentially constitutes a projection of system level considerations onto the sub-system level. Sub-problems associated with sub-systems are considered in terms of the associated design decisions. These decisions in turn are modeled using the appropriate DSP formulations presented in Section 3.3.1 in order to ensure representational consistency. The inherent effort can be significantly reduced via reliance on the templates detailed in Section 3.3.5. Templates are instantiated by declaring decision-critical information content based on interpretation of system level requirements and synthesis of sub-system considerations. The result is a model of the sub-system specific decision that serves as a foundation for a preliminary collaborative design space. Clearly, only unilateral (stakeholder specific) considerations are reflected at this point since no communication with opposing parties has taken place. Any judgment regarding feasibility in this context is considered as emanating from system level constraints rather than from shortfall of stakeholder preferences, focused upon next.

Each of the interacting decision-makers is tasked with determining preliminary values for objective targets, design variable ranges, and constraints, based on their domain-specific insight. Clearly, the ability of stakeholders to interpret system level requirements and map these to the sub-system level is assumed. Similarly, domain experts are expected to have an intuitive understanding how the performance of their sub-system factors into system level performance. Initial preference values can thus originate either at the systems level in the case of a one-to-one mapping or at the sub-system level. It is noted that only stakeholder specific considerations are incorporated at this time, while those of others are included in later stages. Initial ranges for design variables are usually based on system level constraints, unless tighter sub-system level requirements exist.

Subsequent to this initial assessment a stakeholder must communicate starting ranges for each of the (coupled) design variables under his or her control. Since each designer only has partial control over the manner in which his or her objectives are achieved), specific values (point solutions, ranges, and/or sets being considered by their counterparts) directly effect the options open to all others. Gaining a clear understanding of these additional constraints, originating at the sub-system level is crucial in determining the performance potential (i.e., what objective values any decision-maker may realistically hope to achieve). The resulting preliminary ranges (or sets), based solely on constraint satisfaction (and not preference consideration) are communicated among all stakeholders and serve as the basis for the *preliminary collaborative design space*, defined as being *strictly feasible*. Strict feasibility refers to the fact that no constraints are violated within the region in question. This is not to say, however, that potential solutions located within the area are necessarily acceptable. The net result is that all decision-makers are forced to start off on the same page. The main benefit is that the expenditure of resources on the exploration of infeasible design solutions is minimized via elimination of strictly infeasible regions of sub-system specific design spaces.

4.3.2 Establishing Unilateral Preferences

A key element in the achievement of system conscious solutions in *co-design*, as advocated in Chapter 5, is the establishment of realistically achievable targets. Realistic achievement in this context takes into consideration constraints emanating (1) from the systems level and (2) any other design sub-systems, strongly coupled to the system in question. The reason for relying on realistically achievable targets is to eliminate the artificial bias that emerges from implicitly weighting objectives by setting unachievable target values.

The process for establishing unilateral performance potential requires each domain expert to assume total control over all design variables affecting a given sub-system's performance. Values, ranges, and sets of constraints, variables, parameters, etc. for external parameters are derived from the information previously exchanged with regard to the determination of strict feasibility. In the case that a significant mismatch between what is desired and what is possible is identified, the current state of resources must be reassessed and any necessary adjustments made. The computational effort involved in effectively exploring an area of potentially astronomical extent (especially for more realistic engineering design problems) can be alleviated significantly through the use of space filling experiments such as Latin Hypercubes as well as more efficient experimental techniques [154].

Since it is not absolute achievement of objective values, but rather the extent to which individual decision-makers are satisfied, that matters, it is decision-maker preferences that serve as a basis for normalization. The benefit in this respect is that reliance on preferences (as captured in utility functions) allows for an independent and absolute basis for valuation and stands in marked contrast to the relative comparisons traditionally made. Moreover, any such valuations are independent of the particular sub-space considered and thus more modular.

The realistic targets, determined based on performance potential within the feasible regions of the respective sub-system design spaces, serve as the basis for assessing and capturing in functional form the preferences of individual designers. This is accomplished through the determination of utility functions. Single attribute utility functions are assessed based on individual stakeholder preferences and attitudes towards risk with respect to each objective. For details on the process involved in arriving at single attribute utility functions and requisite satisfaction of the underlying axioms, the reader is referred to a standard reference on utility theory [130,196,252]. Specifically, utilities are assessed based on the elicitation of specific performance levels (see Table 4-1) and the associated tolerance for risk as detailed in Ref. [79].

Designer preferences are assessed explicitly in order to (1) bound preferences in a two-sided, rather than a one-sided fashion as in traditional optimization and (2) arrive at richer representations of the underlying objectives (i.e., not necessarily linear, risk conscious). Properly assessed ranges for single attribute utility functions extend from *unacceptable* (i.e., $U_i = 0$) to *ideal* (i.e., $U_i = 1$) values as indicated in Table 4-1. Additionally, values deemed to be *undesirable* (i.e., $U_i = 0.25$), *tolerable* (i.e., $U_i = 0.5$), and *desirable* (i.e., $U_i = 0.75$) by the decision-maker in question are explicitly assessed. The advantage of such "banded" descriptions of preference is the ability to more easily identify (and subsequently eliminate) unacceptable solutions. These are automatically assigned a value of $U_i = 0$. Similarly, those solutions exceeding the level of performance specified as being ideal by the designer are automatically assigned a value of $U_i = 1$, successfully avoiding overvaluation. An additional advantage in the employment of absolute (rather than relative preference measures) as a problem independent means of normalizing design sub-system performance is their ease of incorporation into system level tradeoffs. Since utility functions capture the preferences of stakeholders in functional form they also provide a convenient means of encapsulation, suited for communication and persistence.

Table 4-1 - Definitions for Single Attribute Utility Function Assessment

Utility Value	Definition
1	The decision-maker's ideal attribute level—beyond which the decision-maker is indifferent to further improvements in the attribute.
0.75	The decision-maker is indifferent between obtaining a design alternative with a 'desirable' attribute value for certain and a design alternative with a 50-50 chance of yielding either a tolerable or an ideal attribute level.
0.5	The decision-maker is indifferent between obtaining a design alternative with a 'tolerable' attribute value for certain and a design alternative with a 50-50 chance of yielding either an unacceptable attribute value or an ideal attribute value.
0.25	The decision-maker is indifferent between obtaining a design alternative with an 'undesirable' attribute value for certain and a design alternative with a 50-50 chance of yielding either a tolerable or an unacceptable attribute value.
0	The decision-maker's unacceptable attribute level—beyond which he/she is unwilling to accept an alternative.

Traditional means of normalization based on performance potential have the disadvantage of positively valuing unacceptable solutions as long as these do not constitute extrema. Overemphasis of an easily obtained objective via overachievement constitutes another shortcoming. A caveat is that utility functions also have certain deficiencies. Since they are regressed to explicitly assessed points, as indicated in Table 4-1, they may or may not interpolate the end points. Consequently, the value of a particular solution to a designer may be inadvertently under- or over-represented. Checking utility measures against explicitly assessed values will significantly reduce errors emanating from poor functional fit. Reliance on utility theory, arguably also requires a higher level of both understanding and knowledge, as typically associated with the later stages of design processes.

4.3.3 Exploring the Collaborative Preliminary Design Space

Regions of each design sub-space, yielding feasible results for the stakeholder placed in charge of their resolution, are determined via space filling experiments. Potential solutions are evaluated based on the previously assessed utility functions. Without loss of generality, feasibility in this dissertation is defined as meeting or exceeding the level of utility deemed at least *desirable* by the stakeholder in question, corresponding to $U_i \geq 0.75$. This definition differs from that of *strict feasibility*, defined only in terms of constraint satisfaction and not objective achievement, upon which initial communications in establishing the *preliminary collaborative design space* were based. Should the feasible region determined in this manner be deemed too small, reassessment of considerations may be in order. Pertinent examples include the revision of unilateral preferences or the (further) relaxation of constraints. As always, any mismatches should be reconciled as they arise.

4.3.4 Determining Regions of Multilateral Feasibility and Establishing a Collaborative Design Space

Subsequent communications among interacting stakeholders are based on decision-critical information only. In the case of establishing a *collaborative design space*, this translates to the transmission of acceptable ranges (or sets of design variable combinations) for uncontrollable parameters yielding acceptable results for each party. Once the existence of feasible solutions for each of the interacting decision-makers has thus been assured, the intersection of regions of mutual interest within the *preliminary feasible design space* must be established. It is this intersection that constitutes the *collaborative design space* sought. This region is characterized primarily by the fact that all solutions, contained within it are guaranteed to be acceptable to all stakeholders involved. A *collaborative design space* can also be referred to as a coordinated design space in order to highlight differences between it and the vastly differentiated, individual efforts driving the unilateral exploration of uncoordinated design spaces leading up to its formulation.

4.4 EXPLORING COLLABORATIVE DESIGN SPACES

Since the collaborative design space reflects the considerations of all interacting stakeholders as well as those emanating at the systems level, it constitutes an accurate and holistic reflection of shared resources. It is over the allocation of these resources that conflicts arise. Typically, stakeholders fend for the satisfaction of their respective objectives. Often, their strategies reflect a desire to maximize personal payoff. Regardless of the nature of the design process from this point onward, however, the acceptability of any solution chosen from this systematically crafted region is guaranteed.

With this in mind, the search for superior solutions from the systems perspective is addressed in the next chapter.

Regardless of the solution algorithm, communications protocol, or coordination mechanism chosen for conflict management within this guaranteed feasible region of the design space, tradeoff resolution remains crucial. This task, however, is not as straightforward as it may seem. Careful consideration must be given to the manner in which preferences are aggregated in the case of hierarchical relationships and combinatorial effects are interpreted in the case of coalitions. This is also a key consideration for the interpretation of stakeholder BRCs and formulation of negotiation strategies. System utility is often calculated as an Archimedean sum, where weights are determined according to relative importance. Multiplicative forms of multi-attribute utility functions can also be employed, should the additional computational cost incurred be warranted based on expected gains in modeling interaction effects. The proper choice depends on which independence axioms (utility, additive, multiplicative, etc.) can be successfully satisfied.

A key realization is that just as *individual* decision-maker considerations are focused upon throughout the process of establishing the *collaborative design space*, it is individual performance that should be focused upon for any subsequent interactions. Many of the shortcomings, attributed to selection methods, optimization weighting schemes, group decision-making, etc., emanate from the manner in which preference are aggregated. Normalization is just as much of an area for contention. This is due to the fact that it is in these fundamental processes that biases are inadvertently introduced, serving to either over express or overemphasize one objective at the cost of another. The reader is referred to Refs. [72,79,80,191] for more information on this topic. In order to avoid this issue and ensure the non-biased attainment of system level objectives, as focused upon in the next chapter, it is the preferences of individual stakeholders that are implemented as successive filters through which potential solutions are fed. To offer an example, cooperative formulations usually advocate the evenly weighted combination of stakeholder objectives in a weighted Archimedean sum. While this approach is intended to eliminate any favoritism, this objective is only achieved successfully when (1) objectives are normalized, (2) normalization is based on realistically achievable targets, and (3) the design space itself is equally favorable to all decision-makers. More on each of these issues follows in the next chapter. Additionally, it is worth stressing that for the evenly matched case of two objectives, for example, $U_{System} \geq 0.75$ does not necessarily imply $U_A, U_B \geq 0.75$. Instead, U_A could be as high as $U_A = 1$ and U_B as low as $U_B = 0.5$. Clearly, this is not what is desired in the pursuit of an evenly matched solution. Consequently, either (1) filters must be activated in order to eliminate such unsuitable solutions and ensure that $U_A, U_B \geq 0.75$, or (2) the desired level of system level utility must be adjusted to $U_{System} \geq 0.89$. This latter option however is overly restrictive since a number of desirable solutions are likely to be eliminated, making the former the better choice.

Collaborative design spaces that are deemed as being too extensive can be systematically reduced by filtering for higher levels of stakeholder utility. By the same token, regions that are determined to be too small can be augmented by lowering the corresponding requirements. The minimum quality of solutions making up the *collaborative design space* can easily be adjusted and the underlying models refined accordingly. Preferences are extremely powerful forces in mathematical optimization. Often preferences are regarded as being strictly objective and consequently can neither be questioned nor revised throughout a design process. This often results in inadvertently skewing results towards a single objective. Though constituting a moot point within the confines of a collaborative design space, being overly ambitious may restrict other designers to the point of making the achievement of their objectives impossible. On the other hand, limiting an extensive *collaborative design space* to those solutions guaranteeing a higher level of satisfaction for all involved reduces the inherent computational cost and increases the level of fidelity that is feasible for exploration. As previously mentioned, the computational burden of doing so can be reduced through reliance on experimental design techniques. The approach taken in this dissertation is one of regressing surrogate models over adaptively refined design spaces. It is important to note, however, that solutions obtained via reliance on meta-models should always be verified using the original models used in constructing them.

4.5 A COLLABORATIVE DESIGN SPACE FORMULATION METHOD

The various aspects of the procedure described in Sections 4.1 through 4.4 can be formalized as a series of procedural steps, constituting the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod. These steps are summarized in Figure 4-4.

Given:

- ☑ ***System*** – problem statement, description, overarching requirements, sub-system decomposition, translation of system design problem to system design decision and sub-system design problem to sub-system design decision

- ☑ ***Governing Relations*** – quantitative behavioral description at the system and sub-system level as well as pertinent relationships among these (analytical, theoretical, stochastic, etc.) and qualitative comprehension for competent interpretation
- ☑ ***System Objectives*** – preferences, goals, constraints, resources, etc.
- ☑ ***Sub-System Objectives*** – preferences, goals, constraints, resources, etc.
- ☑ ***Control Assignment*** – mapping of sub-systems to domains of expertise and qualified decision-makers

With this in mind, the steps of the proposed method are as follows:

Step 1a - Establish domain sub-problems in terms of decision templates via interpretation of sub-system level particulars in the context of system level requirements.

Step 1b - Determine targets, ranges, and constraints as appropriate for each of the decisions corresponding to design sub-problem resolution in light of system level considerations.

Step 2 – Communicate preliminary ranges for design variables under immediate control in order to provide a starting point of reference from which interacting stakeholders can launch their respective explorative activities.

Step 3a – Establish a preliminary ***collaborative design space***, reflecting the considerations of other stakeholders, as implied by the preliminary ranges for design variables, communicated in Step 2.

Step 3b – Determine realistic targets, ranges, and constraints for each of the design sub-problems within the established ranges, ***assuming total control*** over all (including shared) design variables.

Step 3c – Determine stakeholder utilities for objectives and ensure that these are realistically achievable within the range considered. Iterate, should utilities not be achievable, or reassess preferences in light of what is feasible.

Step 3d – Determine feasible ranges for or sets of design variables, pertaining to other stakeholders, over which control was assumed during design sub-space exploration.

Step 4 – Communicate feasible ranges for design variables that are uncontrollable (i.e., controlled by other stakeholders) that make achievement of desirable objective performance based on adjustment of controllable design variables possible.

Step 5 – Determine regions of the collaborative design space that yield desirable results, based on the ranges for design variables (allowing for the satisfaction of co-designer preferences, communicated in Step 4.

Step 6 – Communicate desirable regions of the collaborative design space in terms of ranges or sets of suitable design variable values.

Step 7 – Establish the ***intersection*** of regions of the collaborative design space and the design sub-problem specific design sub-spaces that contain feasible solutions for all interacting decision-makers in terms of design variable ranges or sets.

Step 8 – Communicate overlapping region of collaborative design space, determined in Step 7, to all interacting decision-makers.

It is noted that these steps are numbered according to their sequence in the **F**ramework for **A**gile **C**ollaboration in **E**ngineering (see Figure 6-2) composed and applied in Chapter 6. They provide the basis for the establishment of a collaborative design space and thus guarantee the existence of a mutually acceptable solution, regardless of the final means of tradeoff reconciliation adopted.

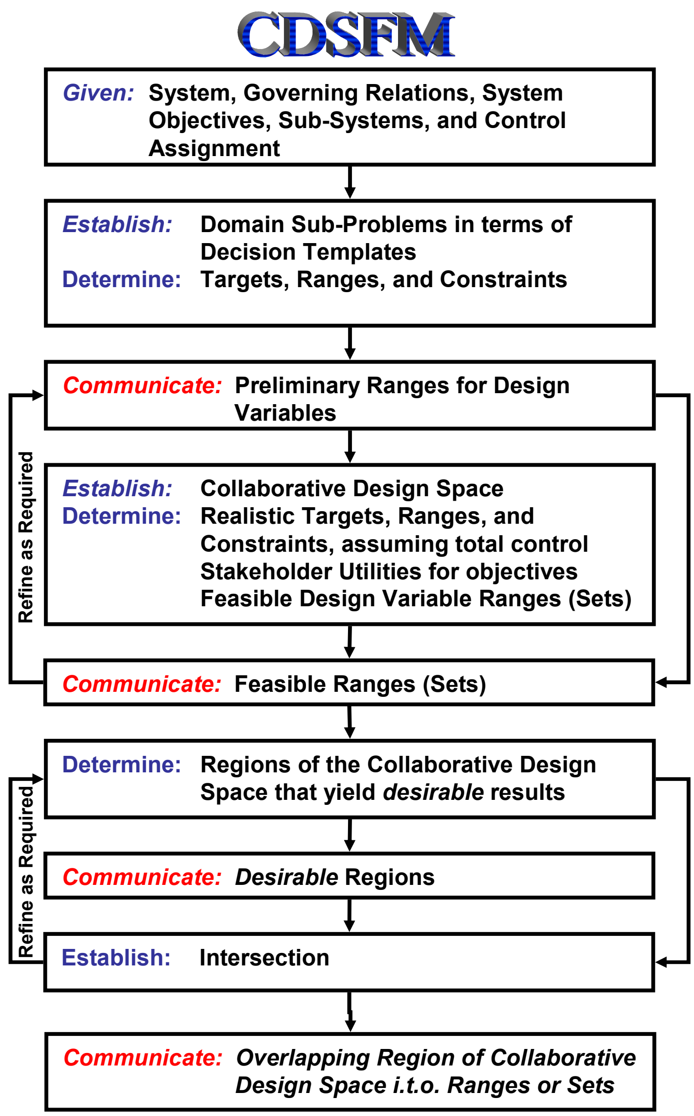


Figure 4-4 - The Collaborative Design Space Formulation Method

4.6 CRITICAL ANALYSIS OF THE COLLABORATIVE DESIGN SPACE FORMULATION METHOD

4.6.1 Overview of the CDSFM

The main in advantage in focusing on the identification, formulation, and subsequent management of *collaborative design spaces* is that a certain quality of solutions can be guaranteed. The associated threshold can be progressively refined via filtering to ensure higher levels of performance for all decision-makers. Similarly, its size can be increased by relaxing performance requirements, should the need arise. It is noted that the central benefit of the implementation of this aspect of FACE is that all of the solutions in the resultant collaborative design space are guaranteed to be mutually desirable. Once such a design space has been successfully established any protocol can be adopted in order to arrive at a final solution to the strongly coupled problem at hand. An additional advantage is that the efforts of interacting designers are not wasted on exploring regions of the design space that are infeasible (for any of the other stakeholders) and thus unfruitful from a systems perspective. In the absence of overlapping areas of interest, stakeholders can progressively relax the constraints inherent in their preferences (i.e., lower their target utilities) until such overlap exists. Based on the associated satisfaction level, designers can then either reassess their expectations or seek alternative resources (e.g., a different technological base, etc.). Proceeding based on an adjusted system level bias (i.e., changing the manner in which the tradeoffs among the stakeholder utilities are weighted) as dictated by overarching design requirements at the systems level is another option when looking at the utility of the system. It is noted that equal weighting essentially implies the absence of such a controllable bias.

Disadvantages of this approach emanate from the increased communication requirements. An argument can be made that increased upfront work in this regard, significantly reduces rework, emanating from mismatched objectives not identified in a timely fashion. Increased interactions inevitably also increase the number of computations. Reliance on space filling experiments, coupled with more advanced experimental designs, and response surface methodology can alleviate the associated burden, the extent of which depends on the situation at hand. As will be substantiated via application to problems of increasing complexity in Chapters 6, 7, and 8, however, slight increases in logistical complexity can easily be justified with significant improvements in the quality of results obtained.

4.6.2 Implications of the CDSFM

One of the primary advantages of implementing this first aspect of FACE, namely the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod (CDSFM) is that the evolution of solutions to coupled design problems is geared towards the identification, exploration, and management of collaborative design spaces. Such collaborative design spaces are composed exclusively of feasible solutions, where feasibility is defined as meeting the declared requirements of all stakeholders. The benefit of this approach is that irreconcilable mismatches in stakeholder requirements are defined earlier on in the design process, rather than delaying their discovery to the point of conflict resolution. This approach ensures congruence of design activities, regardless of the means chosen for the striking of tradeoffs among competing sub-systems.

This is a significant result. Every problem is different and characterized by a unique set of circumstances. Consequently, it can be asserted that some solution schemes are more properly suited to some problems than others. Which scheme is best from an organizational perspective is a function of the nature of the underlying informational dependence, level of stakeholder cooperation, and enterprise structure. Which scheme is suited best from a quality of solution perspective is an entirely different matter. It is a commonly known fact that the nature of the design process, characterized predominantly by the chosen protocol in decentralized design, has a notable impact on the product. Unfortunately, this determination oftentimes can only be made in retrospect. In focusing on the *a priori* assurance of mutually acceptable results, much of the associated risk and (unacceptable) variability is eliminated. Consequently, there are no bad results. Instead some answers are merely a little better than others. This point is substantiated in each of the following four chapters.

4.7 A NOTE ON VALIDATION

As stressed in Section 1.4, this chapter is focused exclusively on addressing the second research question, posed in this dissertation: *How can the communication of information, required for the resolution of strongly coupled design problems, among collaborating stakeholders be structured so that their efforts are focalized and their subsequent interactions are rendered both effective and concise?* With this in mind, a brief review pertinent aspects of the validation and verification strategy follows.

4.7.1 Theoretical Structural Validation of Hypothesis 2

Although the majority of *Theoretical Structural Validation* with regard to *Hypothesis 2* was addressed via critical review of the literature in Chapter 2, specifically Sections 2.1, 2.4, 0, and 2.6, additional contributions were made throughout this chapter. On the whole, it should be emphasized that comparative evaluation of the method presented in this chapter is difficult. The notion of ensuring the existence of a solution to a coupled design problem has thus far been neglected. In fact, the possibility of reconciling stakeholder objectives is usually assumed. The only means of remediation (although probably more aptly described as a last resort) is trial-and-error iteration. On the whole, however, no guidance is offered to address this concern. The movement thus far has been towards excising iteration from design processes. An unfortunate bi-product has been the elimination of communication prior to the requisite point of resolution. This poses a significant problem, especially in the context of increasingly federalized networks. Communication is crucial in the achievement of synergy. To be successful, however, communication must be targeted effectively. What is offered in this chapter is a systematic means of focalizing decision-maker interactions through the structured communication of decision-critical information content.

Evaluation of the implemented constructs with regard to comparative advantage, limitation, and acceptable domain of application is addressed in Section 4.6. On the whole, the principles underlying utility theory, game theoretic protocols in extensive form (upon which the method is partially based), design of experiments, and response surface methodology are sound. The value proposition seems clear: Success is essentially guaranteed, making any means of tradeoff management a viable option.

Clearly, some choices are better than other, as illustrated in the Chapters 5, 6, 7 and 8. The fact, however, remains that loosing is extremely difficult in *win/win* situations and effectiveness of stakeholder interactions is certain.

4.7.2 Revisiting the Square

Although **Theoretical Structural Validity** of each of the three Hypotheses is explored and established throughout the first five chapters of this dissertation, this chapter is focused exclusively on the substantiation of *Hypotheses* 2. Evidence of **Empirical Structural Validity** and **Empirical Performance Validity** for *Hypothesis 2* is deferred to Chapters 6, 7, and 8. The overall progress in the overarching validation and verification strategy closely follows the scheme outlined in Figure 1-14 and is summarized in Figure 4-5.

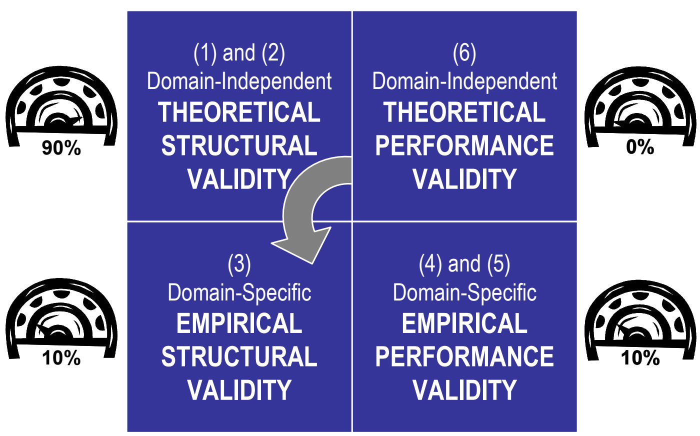


Figure 4-5 - Validation and Verification Progress through Chapter 4

4.8 A LOOK BACK AND A LOOK AHEAD

4.8.1 Revisiting the Roadmap

In this chapter, a systematic approach for the identification and formulation of collaborative design spaces is offered. Specifically, the concept of a collaborative design space is presented in Section 4.1 and its establishment explored in Section 4.3. Progressively, the topics of formalizing the notion of preliminary collaborative design spaces, determining unilateral preferences, exploring preliminary collaborative design spaces, and determining regions of multilateral feasibility are addressed in leading up to the establishment of collaborative design spaces. The exploration of said regions is undertaken in Section 4.4. Inherent tasks are formalized as steps of the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod in Section 4.5. Critical analysis follows in Section 4.6, before elements of validation and verification in this chapter are highlighted in Section 4.7.

As indicated in the beginning of this chapter, and highlighted in Figure 4-6, the main goal pursued in this chapter is that of formalizing a systematic means of identifying, establishing, and exploring a collaborative design space. The importance of this key concept lies in that it effectively captures the confluence of all resources relevant to a shared design space. It is through the establishment of such a common basis that stakeholder activities are focalized and interactions geared towards the achievement of a mutually beneficial goal. Since an explicit outcome of the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod is the assurance of at least a single feasible solution, a fundamental shortcoming of solution algorithms, communications protocols, and coordination mechanisms has been addressed. The consequence is that virtually any conceivable means of tradeoff management chosen thereafter (even random selection) is bound to be successful. The CDSFM in conjunction with the **I**nteraction-**C**onscious **C**oordination **M**echanism (ICCM), presented in the next chapter, comprises the **F**ramework for **A**gile **C**ollaboration in **E**ngineering. The novel approach to modeling design processes, discussed in the previous chapter constitutes a technological base for the framework's implementation. Thus, while this chapter was focused exclusively on the Theoretical Structural Validation of Hypothesis 2, the next chapter is devoted entirely to addressing these aspects with respect to Hypothesis 3.

4.8.2 Assembling the Building Blocks

This chapter was dedicated to a detailed exposition of concepts underlying the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod. The systematic synthesis of requirements for strict and practical feasibility into a single construct capturing all relevant resources is invaluable in ensuring effective collaboration. It is the consequent assurance of mutually acceptable results that makes the consideration of *co-design* feasible.

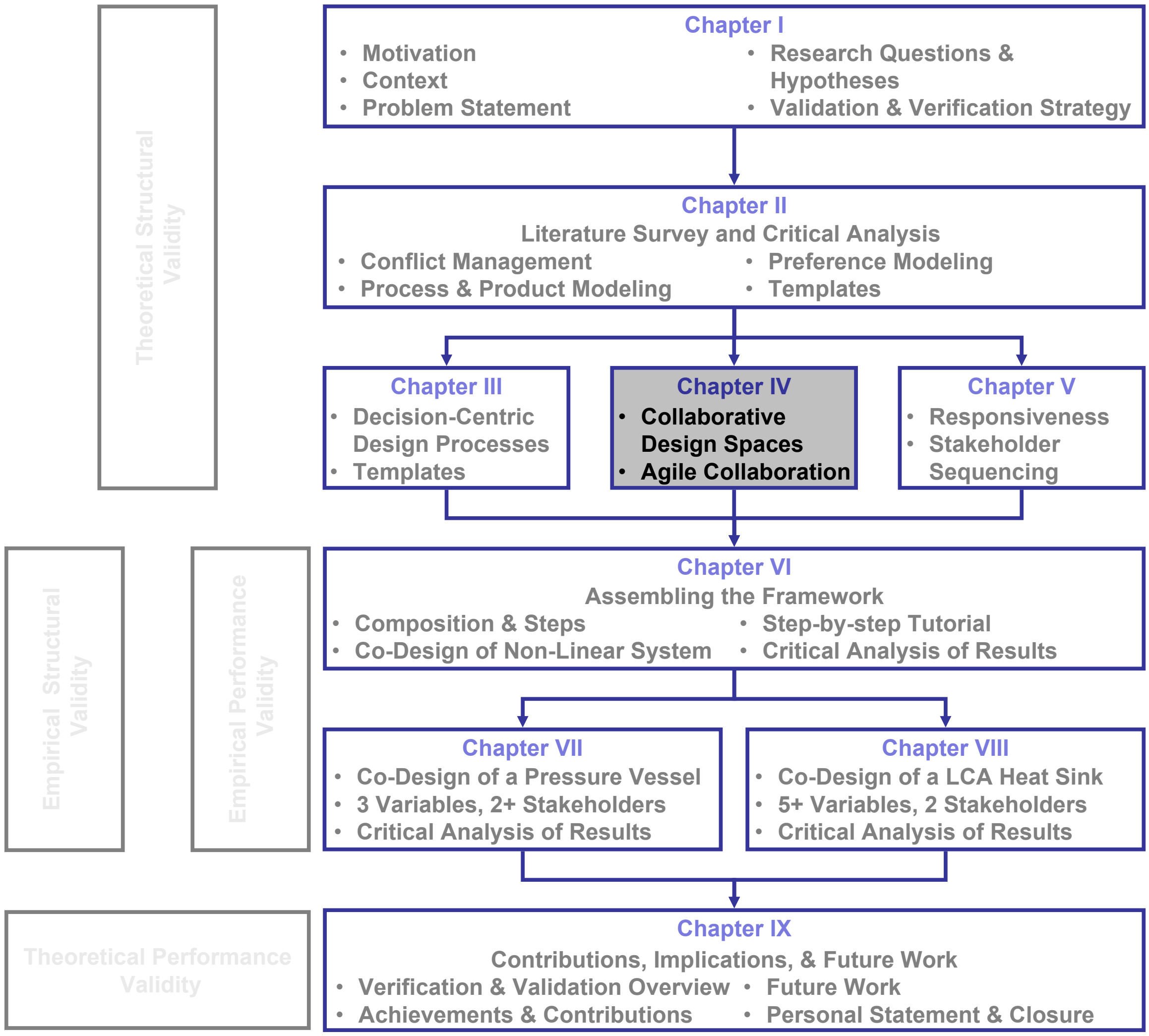


Figure 4-6 - Dissertation Roadmap

CHAPTER 5 - SYSTEM CONSCIOUS RESOLUTION OF TRADE-OFFS IN COLLABORATIVE DESIGN SPACES

The concepts introduced in Chapters 2, 3, and 4 are extended in this chapter to formulate a coordination mechanism for *exploring* and *managing* a collaborative design space established using the CDSFM. The focus is on reducing the inadvertent effects produced by biases (inherent to both product and process) on objective performance, while ensuring the reflection of those deliberately specified. Emphasis is placed on self-assessment of responsiveness to changes in shared and unshared design variables and parameters, thereby making stakeholders more self sufficient and supporting modularity in decision-centric design processes. The goal is to establish *a priori* which communications protocol, solutions algorithm, or coordination mechanism is likely to have the most beneficial results from a systems perspective. Responsiveness indicators are used in conjunction with considerations such as informational burden, organizational structure, ease of implementation, solution stability, and performance potential to make a proper determination. The underlying objective is to move beyond strategic collaboration towards *co-design*, presented here as an alternative approach to conflict management that is based on a higher degree of stakeholder involvement in the actual solution process. Although implementation of the method presented in Chapter 4 ensures reaching *win/win* scenarios, differences in solution quality continue to exist. Superior results at the systems level can be achieved by balancing sub-system level performance and avoiding any unnecessarily skewed results.

Specifically, the concept of system-conscious tradeoff management is discussed in Section 5.1. Stakeholder responsiveness and performance potential are presented as fundamental indicators of the effect of decision-maker sequence on system-level performance in Section 5.3. The suitability of different protocols to conflict management based on problem specific considerations is elaborated upon in Section 5.4. The elements discussed in Sections 5.1 through 5.4 are synthesized into the **I**nteraction-**C**onscious **C**oordination **M**echanism (ICCM), comprising the second half of the **F**ramework for **A**gile **C**ollaboration in **E**ngineering in Section 5.5. A critical analysis of this mechanism follows in Section 5.6. Aspects of validation and verification as pertaining to this chapter are addressed in Section 5.7. Specifically, *theoretical structural* aspects regarding the validation of *Hypothesis 3* are emphasized. Finally, overall cohesion of this material the remainder of the dissertation is established in Section 5.8.

5.1 VALIDATION AND VERIFICATION WITHIN CHAPTER 5

As indicated in Section 1.5.1, this chapter is focused on the development of the **I**nteraction-**C**onscious **C**oordination **M**echanism (ICCM) in response to *Research Question 3* and the completion of the **Theoretical Structural Validation** of the associated constructs. Although the majority of this aspect of validation was addressed in Chapters 1 and 2, the benefits emanating from the remediation of the myriad gaps identified in Table 2-1 and Table 2-2 are underscored in Section 5.2. An overview of pertinent aspects is provided in Figure 5-1. It is noted that **Empirical Structural Validation** and **Empirical Performance Validation** of the ICCM are addressed in Chapters 6, 7, and 8, while a discussion of **Theoretical Performance Validation** is deferred to Chapter 9.

5.2 SYSTEM CONSCIOUS RESOLUTION OF TRADEOFFS IN COLLABORATIVE DESIGN SPACES

Making a decision, based upon the consideration of multiple interrelated (strongly coupled) measures of merit necessarily requires trading off the performance of one objective as compared to that of another. Although this notion of tradeoff is inherent in any preemptive formulation, reliance on weighting schemes is the generally accepted norm. This is true for those objectives located at the same level of a hierarchy as well as those emanating from different hierarchical levels. At the systems level the achievement of one sub-system level objective is often favored over that of another. Since system level performance is often calculated as a weighted sum, it should not come as a surprise that the system in these cases is (mathematically) blind to inherent biases. This remains true as long the combined performance of all objectives reflects specified thresholds.

Thus, while any result in this manner will be mathematically correct, whether it is representative of system level intent is another matter entirely.

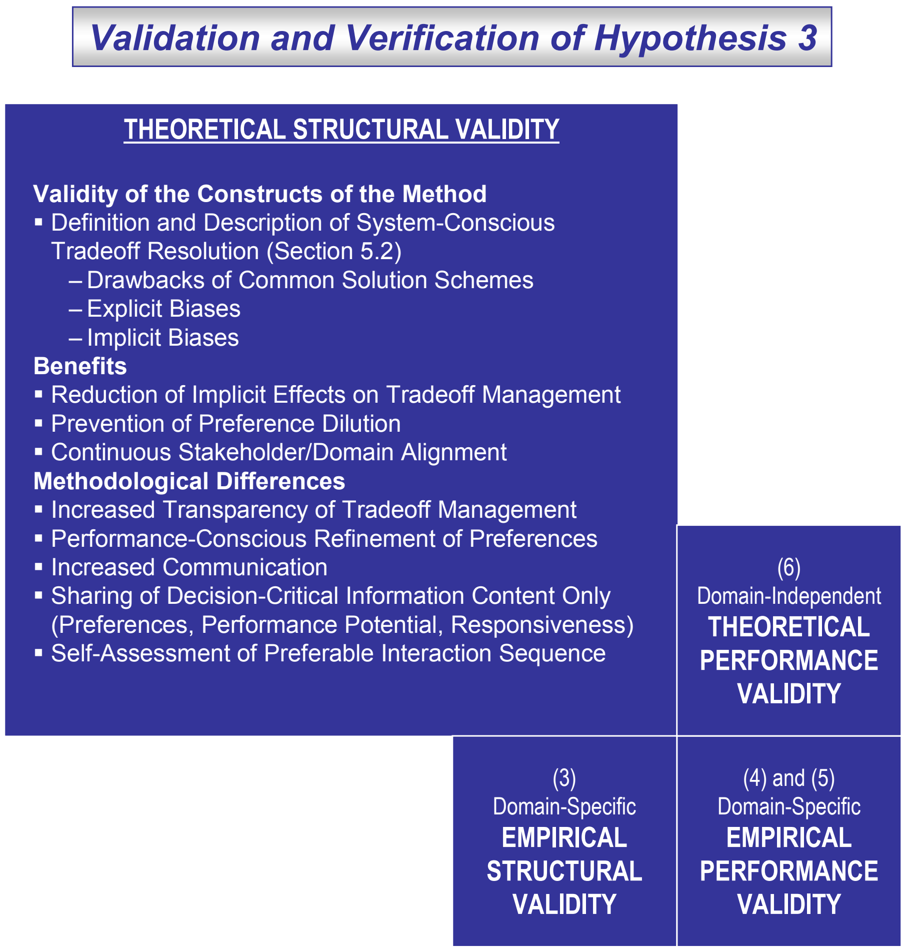


Figure 5-1 - Aspects of Validation and Verification Addressed in Chapter 5

In order to better explain the latitude and potential variability in seemingly equivalent results, a simple example is offered. Consider two objectives A and B, assigned to Designers A and B, respectively, and both normalized between 0 and 1. The combined effect of these objectives contributes equally to system level performance. Consequently both of these criteria are weighted equally in the Archimedean sum used for evaluation purposes at the systems level, where an objective value of 0.8 is required. While all of the scenarios in Table 5-1 meet this requirement mathematically, clearly only Scenario 2 is in line with system level expectation[8]. This, however, is a point that is often overlooked. In the case of the other scenarios, the balance is inadvertently tipped towards the achievement of the objective pertaining to either Designer A (see Scenario 1) or Designer B (see Scenario 2). This is an example of what is considered to constitute an *implicit* bias in this dissertation – implicit because the result favors one designer over the other, contrary to system level preference. Another example of an *implicit* bias includes problem specific bias, resulting from either the inherent nature of a shared design space (or region within a shared design space) being more favorable to the achievement of one designer's objectives than those of another or through the specifications of unrealistic preferences for objective achievement. It is this challenge that is addressed (in part) by the CDSFM of Chapter 4.

Table 5-1 - Example of Implicit Bias

	Objective A	Weight A	Objective B	Weight B	System
⋮	⋮	⋮	⋮	⋮	⋮
Scenario 1	1.0	0.5	0.6	0.5	0.8
Scenario 2	0.8	0.5	0.8	0.5	0.8
Scenario 3	0.6	0.5	1.0	0.5	0.8
⋮	⋮	⋮	⋮	⋮	⋮

An *explicit* bias on the other hand is intentionally and unambiguously imposed by weighting one objective more heavily than another. This case is underscored by the scenarios shown in

[8] The word expectation is used in the sense of intention and is not to be confused with the statistical, utility, or value theory interpretation.

Table 5-2. Although performance at the sub-system level remains consistent, system level performance varies considerably. The most important difference to note is that while both implicit and explicit bias can affect system level performance equally, only explicit bias is consistent with system level intent. In the case that explicit and implicit biases are mixed (see Table 5-3), it is virtually impossible to tell (at least for realistic levels of complexity) which effect is the dominant one. Put another way, the tradeoffs desired at the systems level and those actually occurring at the sub-systems level can inadvertently cancel one another out. Due to the level of involvement, awareness of the tradeoffs occurring in actuality may or may not propagate past the immediate event horizon. This is particularly dangerous in communications protocols that focus on the sequential resolution of design freedom.

Extrapolating from the combinations shown in Table 5-1, Table 5-2, and Table 5-3 (Scenario 9) it becomes clear that there is a quasi infinite number of objective performance and weighting factor combinations that will yield the same numerical result from the systems level. The point is that the distribution of resources among the various subsystems can be affected (1) *explicitly* via specification of desired resource distributions at the systems level, (2) *implicitly* via skewed distributions of stakeholder payoffs at the sub-system level or (3) via a combination of both. Since implicit or combinatorial effects obscure the true mechanics of a problem, the key is to ensure that the balance is tipped only intentionally, as a result of control, rather than by chance.

Table 5-2 - Example of Explicit Bias

	Objective A	Weight A	Objective B	Weight B	System
⋮	⋮	⋮	⋮	⋮	⋮
Scenario 4	0.6	0.0	1.0	1.0	1.00
Scenario 5	0.6	0.1	1.0	0.9	0.96
Scenario 6	0.6	0.2	1.0	0.8	0.92
Scenario 7	0.6	0.3	1.0	0.7	0.88
Scenario 8	0.6	0.4	1.0	0.6	0.84
Scenario 9	0.6	0.5	1.0	0.5	0.80
Scenario 10	0.6	0.6	1.0	0.4	0.76
Scenario 11	0.6	0.7	1.0	0.3	0.72
Scenario 12	0.6	0.8	1.0	0.2	0.68
Scenario 13	0.6	0.9	1.0	0.1	0.64
Scenario 14	0.6	1.0	1.0	0.0	0.60
⋮	⋮	⋮	⋮	⋮	⋮

Table 5-3 - Example of Combination Implicit/Explicit Bias

	Objective A	Weight A	Objective B	Weight B	System
⋮	⋮	⋮	⋮	⋮	⋮
Scenario 15	1.0	0.75	0.2	0.25	0.8
Scenario 16	0.8	1.0	0.4	0.0	0.8
Scenario 17	0.4	0.0	0.8	1.0	0.8
Scenario 18	0.2	0.25	1.0	0.75	0.8
⋮	⋮	⋮	⋮	⋮	⋮

Since the majority of collaboration mechanisms are either algorithmic or focus on the upfront provision of information and one time interactions, design space subtleties resulting in implicit biases are unlikely to be discovered. Often control is relinquished to a third party; tradeoff strategies are elicited using processes that allow decision-makers only limited insight into the nature of their interdependence. One of the fundamental aims in decentralizing design decisions is the incorporation of specialized expertise in the decision-making process. With this in mind, reliance on tradeoff strategies that do not allow for the reflection of said expertise is rather counterproductive. To clarify, the advantage of relying on expertise is the ability to interpret domain specific cause and effect, an asset equally important to the formulation of coupled design problems and their solution. Once the wheels are set in motion, the only opportunity for correction, adjustment, or refinement arises from iteration required as a result of infeasibility or irreconcilable objectives. This is not to say that traditional means of conflict resolution aren't useful when applied in a proper context. In fact, acceptable results can be obtained quite efficiently once their existence is ensured. This traditionally presupposed aspect however was already addressed in the previous chapter. In this chapter, the focus is placed on sequencing.

Since decision-makers tend to behavior consistently with the maximization of their personal payoffs, there is a strong correlation between the degree of achievement of stakeholder objectives and their precedence in determining values for shared design variables. This is true regardless of any bias of the coupled problem towards a particular designer. The net potential detriment of choices, made by one stakeholder, on those options available to another (via unnecessary reductions in design freedom), can be reduced significantly as a result of the strategy outlined in Chapter 4. This is not to say, however, that the prospect for tweaking or fine tuning these results no longer exists. With this in mind, a method for determining the order of stakeholder decisions, most amicable to the balanced achievement of system level objectives, is developed in Sections 5.3 and 5.4. The resulting CDSFM is concretized as a succinct number of steps in Section 5.5

5.3 ASSESSING STAKEHOLDER RESPONSIVENESS AND PERFORMANCE POTENTIAL

5.3.1 Improving Results Obtained in Decentralized Decision-Making

In light of the discussion provided in Section 2.2.1, the strength of interaction effects and the dependence of the underlying information flows are usually determined primarily by the manner in which information is shared among the coupled problems. Thus, a determination whether one decision depends on another is often made without a detailed assessment of the strength of the underlying relationships. While dependence has been considered in making individual stakeholder decisions robust to those made by others (see Refs. [267,269,270]), doing so effectively reduces design freedom unnecessarily and defeats the purpose of aligning design sub-problem control with decision-maker expertise at what one might consider the most crucial point in the design process being considered. Additionally, the danger of irreconcilable objectives and extensive trial-and-error iteration is significant.

While these are fundamental concerns in design processes that are not systematically focalized, many of these shortcomings are remediated via collaborative design space formulation. It is as a result of the CDSFM developed in Chapter 4, that the existence of a mutually acceptable solution is guaranteed. Consequently, virtually any solution mechanism (even random choice) will be successful. The extent to which such a result will suit the demands of collaborating stakeholders as well as satisfy the overarching systems level objectives, however, can vary greatly. Variability in these satisfaction levels is due primarily to 1) degree of mismatch among stakeholder preferences and 2) the strength of the coupling among constituent design sub-problems, both of which have a bearing on the size and "topology" of the collaborative design space.

The first aspect of polarization is addressed through the determination of realistic targets and the communication of decision critical information content in the formulation of a collaborative design space. In fact it is through the CDSFM that this variability is systematically reduced to acceptable levels, where acceptability is *co-defined* interactively. Even when the set of possible outcomes has been reduced to a mutually acceptable set, however, the opportunity for further improvement remains. The aim in *co-design*, as pursued in this chapter, is that of striking a balance among stakeholder objectives that is unprejudiced from the systems perspective. As indicated previously, the establishment of a collaborative design space guarantees the *a priori* existence of mutually acceptable solutions. Consequently, it is viable to choose whatever conflict resolution mechanism is desired. This choice, however, has a direct implication on the way in which the balance among stakeholders is tipped.

As exhaustively discussed in previous chapters, traditional protocols have favored algorithmic resolution, sequential decision-making, or control transfer. Clearly, the outcomes resulting from the imposition of such structure are usually highly one sided and consequently suboptimal where the systems level is concerned. It is a fundamental goal in this dissertation to offer an alternative that is focused on mitigating variability with regard to stakeholder satisfaction levels, the second aspect of polarization cited. Bearing this in mind, there are two primary aspects – responsiveness and potential – that should be taken into consideration before making a decision regarding the sequence of stakeholder contributions that is most likely to result in an outcome that is non-biased from the systems perspective. Responsiveness can be split into three separate indicators, namely sensitivity, power, and leverage, defined in Sections 5.3.2, 5.3.3, and 5.3.4, respectively. The topic of decision-maker potential is addressed in Section 5.3.5.

In summary, the fundamental aspect distinguishing coupled from independent decisions is that of shared control. Consequently both *extrospective* and *introspective* factors come to bear; sequencing assessments are made based upon decision-maker *sensitivity*, *power*, and *leverage* in the context of *performance potential*. It is based upon these indicators of stakeholder responsiveness that the resulting **I**nteraction-**C**onscious **C**oordination **M**echanism is developed in the sections to follow.

5.3.2 Determining Stakeholder Sensitivity

Extrospective analysis refers to the close examination of external factors impacting individual stakeholder performance (as examined in this section) and internal factors allowing a stakeholder to impact the performance of others (see Section 5.3.4). A simple yet powerful way of *extrospective* analysis with regard to impact on personal payoff is consideration of *sensitivity* – the magnitude of a change in objective function value resulting from a change in a design variable not under the immediate control of a given decision-maker. There are a number of ways to measure *sensitivity*. The chosen means in this dissertation focuses on computing derivatives of a stockholder's objective function value with respect to shared design variables not under his or her control. Another approach might focus on statistical analysis based on the calculation of the covariance of stakeholder objective achievement with external design variables and the strength of the resulting correlation.

The granularity with which the required assessment is made can be adjusted to reflect the number of decision-makers engaged in the design process and the detail of information required. Thus, *sensitivities* can be calculated (1) separately for each and every external design variable or (2) in combinatorial fashion. While the first has the advantage of yielding information, detailed enough to enable a stakeholder to pinpoint the exact origin of his or her woes, it is the net combined effect of one stakeholder on another that has the more immediate bearing on identifying the most suitable sequence. Increasing the fidelity in this assessment is quite useful in resolving any emergent conflicts.

5.3.3 Determining Stakeholder Power

Introspective analysis refers to the close examination of internal factors impacting individual stakeholder performance. A simple yet powerful way of *introspective* analysis is consideration of *power* – the magnitude of a change in objective function value resulting from a change in a design variable under the immediate control of a given decision-maker. There are a number of ways to measure *power*. The chosen means in this dissertation focuses on computing derivatives of a stockholder's objective function value with respect to shared design variables under his or her immediate control. Another approach might focus on statistical analysis based on the calculation of the covariance of stakeholder objective achievement with internal design variables and the strength of the resulting correlation.

The granularity with which the required assessment is made can be adjusted to reflect the number of decision-makers engaged in the design process and the detail of

information required. Thus, *powers* can be calculated (1) separately for each and every internal design variable or (2) in combinatorial fashion. While the first has the advantage of yielding information, detailed enough to enable a stakeholder to pinpoint the exact origin of his or her impact, it is the net combined effect of total stakeholder control that has the more immediate bearing on identifying the most suitable sequence. The *power* of a given stakeholder can also be seen as his or her ability to correct for actions taken by other stakeholders. Comparing *power* with *sensitivity* allows for a determination of whether a decision-maker is influenced more by internal or external factors, placing him or her at either a strategic advantage of disadvantage, respectively. Increasing the fidelity in this assessment is quite useful in resolving any emergent conflicts.

5.3.4 Determining Stakeholder Leverage

Stakeholder leverage is the second component of *extrospective* analysis and refers to the degree to which internal factors allow a given stakeholder to impact the performance of others. *Leverage* is the magnitude of a change in the objective function value of another stakeholder, resulting from a change in a design variable under one's immediate control. There are a number of ways to measure *leverage*. The chosen means in this dissertation focuses on computing derivatives of another stockholder's objective function value with respect to shared design variables under one's own control. As such *leverage* is the "reciprocal" of *sensitivity*. To clarify, the *sensitivity* of Designer A constitutes the *leverage* of Designer B in a two stakeholder scenario. Another approach might focus on statistical analysis based on the calculation of the covariance of stakeholder objective achievement with external design variables and the strength of the resulting correlation.

The granularity with which the required assessment is made can be adjusted to reflect the number of decision-makers engaged in the design process and the detail of information required. Thus, *leverages* can be calculated (1) separately for each and every external design variable or (2) in combinatorial fashion. While the first has the advantage of yielding information, detailed enough to enable a stakeholder to pinpoint the most likely source of his or her woes, it is the net combined effect of one stakeholder on another that has the more immediate bearing on identifying the most suitable sequence.

Increasing the fidelity in this assessment is quite useful in resolving any emergent conflicts. The notion of *leverage* is most important in situations requiring (or deteriorating to) negotiation. It is an indication of how much influence one designer can exert over another in the pursuit of his or her personal objectives. As such it is a quantification of the bargaining power each stakeholder possesses. In making a sequencing assessment the usefulness of this indicator is the clarification of how far reaching a particular stakeholders decision is likely to be.

5.3.5 Determining Stakeholder Performance Potential

While each of the indicators of responsiveness, discussed in Sections 5.3.2 through 5.3.4 contributes to a comprehensive picture of the manner in which different stakeholders influence one another, this information is fairly useless and can potentially be rather misleading if not considered within the proper context. Context, in this case, refers to a basis for interpretation. What is required is a baseline, better quantifying the degree to which stakeholders can influence one another.

Each of the indicators effectively provides information regarding the strength of the associated effect – a change in response resulting from a change in design variable values. This effect is expressed in terms of the slope, represented by each of the derivatives. Knowing the slope, however, is of little use in determining the absolute change in value without knowing the associated step size. Step size, in turn, is design variable specific. Depending on the number of dimensions considered and the size of the (more than likely non-convex) design space, there is significant potential for inundating a stakeholder with information of only limited usefulness.

The focus is on balancing and bounding potential performance. The approach taken in this dissertation thus centers on considering the total variability associated with a response; this is the feature of greatest importance to pinpointing the potential for undesirable biases. Consideration of variability in objective response thus has the advantage of furnishing the required perspective. The performance potential of each designer is best determined through conducting space filling experiments, analogous to those conducted in determining realistic stakeholder preferences in Chapter 4.

5.3.6 Determining Stakeholder Dominance over Collaborative Design Spaces

A final consideration in making a sequencing determination is the extent to which any stakeholder dominates a collaborative design space (or particular region thereof) with respect to each any every aspect discussed in Sections 5.3.2 through 0. The net result is a more comprehensive picture of the dynamics among different stakeholders. The evaluation of dominance essentially constitutes the consideration of each characteristic on a grid of points, evenly spaced points throughout the region of interest. This space filling experiment allows for the formulation of a comprehensive understanding of the interactions among various stakeholders. In terms of determining an appropriate sequence, assertions such as “90% of the time, Designer A is more sensitive to choices made by Designer B, than Designer B is to choices made by Designer A” is much more useful than sensitivity information on a point by point basis. Clearly, the higher the fidelity of the evaluation, the more accurate the resulting picture is likely to be.

A useful means of capturing this bigger picture consciousness is through the use of simple two-dimensional matrices, called the Sensitivity-Power-Leverage (SPL) Matrices in this dissertation. These matrices capture the effect of each stakeholder on every other stakeholder with regard to the three basic dimensions of responsiveness – sensitivity, power, and leverage – as pictured in Figure 5-2. Each such matrix facilitates the representation of the relationship among all stakeholders with regard to a particular measure of responsiveness in terms of their relative domination. The net benefit of this simple tool is the ability to gain a basic “snapshot” understanding of the otherwise intricate dynamics of a collaborative design space.

Sensitivity

	A	B	C
A		(I)%	(J)%
B	(1-I)%		(K)%
C	(1-J)%	(1-K)%	

Power

	A	B	C
A		(L)%	(M)%
B	(1-L)%		(N)%
C	(1-M)%	(1-N)%	

Leverage

	A	B	C
A		(X)%	(Y)%
B	(1-X)%		(Z)%
C	(1-Y)%	(1-Z)%	

Figure 5-2 - Sample SPL Matrix

5.3.7 Clarifications Regarding the Calculation of Responsiveness Indicators

A few clarifications are in order with regard to the calculation of each of the measures of responsiveness discussed in the preceding sections. First and foremost, It is important to note that all derivates should be taken with respect to the preferences of the decision-maker in question, rather than raw objective value changes. The reason for focusing on the responsiveness of stakeholder utilities to changes in design variable values is that doing so produces and estimation in absolute terms. Objectives, measured on different scales are normalized with respect to the way in which they are valued by each stakeholder. This is in line with the assumption that the individual stakeholders are the domain experts, most qualified for interpreting and weighing tradeoffs with respect to their assigned decisions. Hence it is their preferences that should be consistently taken into consideration throughout the decision-making process.

The calculation of the required derivatives in the case of closed-form or explicit mathematical relations is straight forward. The only complication arises from the correct application of the chain rule with respect to the utility calculations. Should explicit relations not be available, a meta-model can be constructed based upon an experiment designed to suit the intricacies of the particular design space in question. Since the resulting surrogate model, expressed in terms of a regressed response surface, is mathematically no different from a closed form relation, determining the required derivatives is fairly simple.

Depending on the design in question, focusing on absolute changes in derivative values may be more appropriate. The key aim in making a sequencing determination is to pinpoint and alleviate inherent biases. Consequently, it is the magnitude of a change in objective value, rather than the direction of said change, that comes to be more significant.

In those cases where a single stakeholder controls more than a single design variable, all calculations involving the effect of that stakeholder on the objectives of another should take into consideration their combined effect on response. Control of multiple design variables constitutes a concentration of influence. In light of this realization, it is emphasized, once more, that it is the sensitivity in absolute terms that is considered in determining the most appropriate sequence.

Depending on the complexity of the underlying simulations, reliance on surrogate models may be advisable, regardless of whether explicit relations exist. As in the case of the successive design space reductions in Chapter 4, there are many intrinsic benefits associated with this practice. As will be demonstrated in Chapter 8, the inherent reductions in computational expense are significant, while losses in accuracy can be remediated through continuous refinement of surrogate models and careful evaluation of the accuracy of fit. An additional advantage on the reliance of surrogate models for design space exploration is that formulation of a better picture of underlying trends may be possible. Decreased computational cost leads to more efficient exploration. Thus, exhaustive search may become a viable alternative, even for the most complex of problems. As long as the fit of the surrogate model in question is reasonably good, there is no inherent disadvantage in doing so. Such comprehensive exploration of a given design space is particularly valuable in ascertaining dominance, as explored in Section 5.3.6.

5.4 SEQUENCING STAKEHOLDER CONTRIBUTIONS

As one might expect, the only sure way of determining the optimal sequence for a particular design process is post-solution evaluation of all possibilities. Clearly, hindsight is 20/20, but *after the fact clairvoyance* is not very helpful, while actively engaged in the process. As acknowledged by Herbert Simon in Ref. [221], "… design process strategies can affect not only the efficiency with which resources for designing are used, but also the nature of final design". Both the effectiveness of resource use and the quality of the outcomes obtained are direct consequences of the process implemented. In the absence of strongly coupled parameters, the notion of a process translates to a single decision, solved via mathematical optimization, heuristics, etc. In the case of decentralized decision-making, to which this dissertation is devoted, this process consists of two basic building blocks – decisions and interactions.

Decisions capture the considerations of individual stakeholders, while interactions capture the manner in which information is shared among different decisions and decision-makers, as well as the manner in which final tradeoffs among competing objectives are struck. The primary link is that of strongly coupled parameters and the resultant informational inter-dependence. The finesse in designing decentralized design process lies in recognizing the nuances that make a particular problem special. Examples of such intricacies include shared design spaces, inherently biased towards achieving the objectives of a single stakeholder, overly ambitious goals, targets, and preferences, constraints that are too restrictive, improperly (i.e., inconsistent, arbitrary, or relative) normalized objectives, different fidelity models, etc.

A majority of these challenges are systematically addressed via the CDSFM presented in the previous chapter. The net result is the guarantee of a minimally acceptable level of achievement for all stakeholders. Such a *satisficed* solution, however, can be vastly improved via critical evaluation of stakeholder responsiveness and performance potential. The prime consideration is to promote balance among stakeholder-specific goals. Unfortunately, there is no crystal ball and nothing can be predicted with certainty. However, the interpretation of the indicators discussed in Sections 5.3.2 through 5.3.4 within the context of stakeholder performance potential, as elaborated upon in Section 5.3.5, can be used to make an effective assessment as to the sequence most likely to result in balanced sub-system level objectives. In doing so, the SPL Matrices of Section 5.3.6 are quite useful in organizing relevant information and forming a comprehensive picture. With this in mind a few general guidelines are summarized in Figure 5-3. Additional, explanations follow.

The primary consideration in any sequencing assessment is the context. How does the *performance potential* of each designer compare to that of the others involved? It is always possible that even within *win/win* situations, certain designers just cannot lose. For one reason or another, their criteria are consistently attained to a significantly higher degree than those of any other, as reflected in the respective SPL Matrices. Such a stakeholder cannot be disappointed and the objective thus becomes raising the performance of all others as closely as possible to his or her level. Since the collaborative design space inherently favors such a decision-maker, he or she should be placed last in any chosen sequence. The second consideration emanates from *sensitivity*. The objectives of stakeholders with a comparatively high level of *sensitivity* are more likely to be negatively influenced as a result of choices made by other decision-makers, than the objectives of stakeholders with a low comparative level of *sensitivity*. Consequently, higher *sensitivity* moves stakeholders up in the sequence. By the same token, since leverage essentially constitutes the complement to *sensitivity*, higher *leverage* moves stakeholders down in the sequence. Finally, *power* serves as a means of placing the relative significance of the other indicators in perspective. This is due to the fact that a stakeholder's *power* rating is an indication of the extent to which he or she remains in control of his or her own domain and can correct for the adverse effects of other stakeholders on the achievement of his or her objective. Thus a high *power* rating can move a stakeholder with a high *sensitivity* rating down in the sequence and vice versa. Similarly, a high *power* rating can also reduce the effective *leverage* of one stakeholder on another and consequently move him or her up in the sequence.

Clearly, any interpretation of these indicators is highly subjective and best understood at the hand of an example application. With this in mind, a detailed explanation is given with respect to the interpretation of these indicators in making the most appropriate sequencing decisions in each of the examples, presented in Chapters 6, 7, and 8. It is important to note that this interpretation of indicators assumes the context of *co-design*. Depending on the desired outcome for the design process in question other interpretations may be suitable.

Note: Indication depends on strategy pursued…

Responsiveness Indicator				
Sensitivity	Power	Leverage	Interpretation	Indication
Hi	Lo	Lo	High Dependence. Little Control. Compliance.	(SLP) – Assume Precedence.
Hi	Hi	Lo	Relative Dependence. Limited Control. Compliance.	(SLP) – Assume Precedence.
Hi	Lo	Hi	High Dependence. Little Control. Relative Influence.	(SPL) – Assume Precedence.
Hi	Hi	Hi	Relative Dependence. Limited Control. Relative Pull.	(SLP) – Cede/Assume Precedence
Lo	Lo	Lo	Relative Dependence. Limited Control. Relative Pull.	
Lo	Hi	Lo	Virtual Independence. Significant Control. Relative Influence.	(SPL) - Cede Precedence.
Lo	Lo	Hi	Relative Dependence. Limited Control. Consequential Pull.	(SLP) - Cede Precedence.
Lo	Hi	Hi	Virtual Independence. Significant Control. Ascendancy.	(SLP) - Cede Precedence.

Figure 5-3 - Implications of Stakeholder Responsiveness Indicators

In the absence of such information, tradeoff inefficiencies are aggravated by the limited sight of event horizon for each decision-maker involved. The extent of stakeholder awareness directly depends to the amount of information he or she is privy to. This, in turn, is a direct consequence of the level of cooperation. It is an explicit goal of co-design to increase stakeholder understanding of cause and effect, augmenting *interaction-consciousness*. It is here that the alternative to the protocols, traditionally implemented for addressing the challenges associated with decentralized design, becomes relevant. *Co-design*, as described further in Section 6.2.2, provides the most powerful context for leveraging the indicators discussed here. The notion of *co-design* emanates from the need for consistent interactions among collaborating stakeholders and the focalization of their efforts towards the achievement of a common goal. It is also grounded in systems thinking and is based on elements extracted from games of extensive form, principled negotiation/mutual gains bargaining, benevolent dictatorship, sensitivity analysis, mathematical optimization, and the DSP Technique. Though results obtained via *co-design* require a higher degree of interaction than their non-cooperative counterparts, results are consistently superior and approach fully cooperative solutions in the limit, as will be cemented in Chapters 6 through 8.

Clearly, there are a number of considerations to weigh when choosing the proper method of interaction for collaborating designers – level of expertise, extent of cooperation, level of trust, resource availability, etc. Consequently, it would be a mistake to prescribe highly interactive protocol such as co-design. In fact, co-design may not be suited to the particular task at hand. Certain organizational considerations may require non-cooperative behavior. While sequencing assessments are not relevant to the determination of Nash equilibria, they can be extremely helpful in the case of Stackelberg formulations. Since the level of insight into a problem varies considerably, as indicated in Table 5-4, of several of the indicators may prove useful regardless of context.

In this author's experience, the most effective means of resolution is that of the semantically rich reassignment of control to that decision-maker consistently having the greatest disadvantage throughout a collaborative design space. This comprises the basic means of conflict resolution in *co-design*. Relative advantages and disadvantage in this context are functions of *responsiveness* and *performance potential* as determined through the means documented in Section 5.3, used a basis for determining the most appropriate sequence. It is important to stress that only preference information is required by any stakeholder in determining the effect of his or her decision on the objectives of other stakeholders. Since collaborators have been systematically focalized throughout the design process, there is not need for extrapolation or interpretation of simulation models falling outside of a particular stakeholder's area of expertise. It is emphasized that the efficiency of this approach is greatly improved as a result of the elimination of infeasible regions of the shared design space from consideration. By the same token, the assurance of a *win/win* scenario (resulting from the CDSFM) provides substantial motivation for cooperative behavior. The synthesis of the concepts, presented in Sections 5.1 through 5.4 follows in the next section.

Table 5-4 - Comparative Evaluation of Interaction Mechanisms

Interaction Mechanism	Stakeholder Insight	Control	Typical Biases
Full Cooperation	Complete awareness and shared access to the specific considerations of all domains.	Relinquished to third party.	Skewed performance measures introduced by weighting and normalization schemes as well as specification of unrealistic targets.
Co-Design	Substantial awareness and ability to determine level of stakeholder-specific satisfaction for every potential solution.	Transferred to that designer determined to be at a consistent disadvantage.	Stakeholder sequence.
Stackelberg	Limited to individual considerations and stakeholder tradeoff strategies in the form of BRCs/RRSs	Bounded by precedence and stakeholder BRCs.	Stakeholder sequence and accentuation of sensitivities due to partial control inter-dependent objectives.
Nash	Domain specific.	Relinquished to BRC/RRS intersection.	Ineffective use of design space and tendency to favor higher performance potential stakeholders.
Reassignment	Domain specific.	Reassigned to a single stakeholder.	Strict maximization of personal payoff and consequent disregard for objectives of other stakeholders.

5.5 AN INTERACTION-CONSCIOUS COORDINATION MECHANISM

The various aspects of the procedure described in Sections 5.1, 5.3, and 5.4 can be summarized as a series of procedural steps. These steps are numbered according to their sequence in the **F**ramework for **A**gile **C**ollaboration in **E**ngineering composed and applied in Chapter 6. With this in mind, the existence of a collaborative design space, as established via the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod in Chapter 4, is both presupposed and prerequisite. These steps constitute the essence of the **I**nteraction-**C**onscious **C**oordination **M**echanism, summarized in Figure 5-4.

Step 9a – Establish the design sub-problem (i.e., stakeholder) specific ***performance potential within*** the ***region of overlap***, constituting the revised collaborative design space.

Step 9b – Determine the ***design sub-problem objective performance sensitivity to design variables controlled by other stakeholders***. Consider separately (1) sensitivity of design sub-problem specific objective achievement to changes in uncontrollable (i.e., controlled by other stakeholders) design variables, (2) sensitivity of design sub-problem specific objective achievement to changes in controllable design variables, and (3) the impact of changes in controllable design variables on the objective achievement of other stakeholders, referred to here as *sensitivity*, *power*, and *leverage* respectively.

Step 10 – Communicate domain specific (stakeholder) ***sensitivity assessments*** in order to enable self assessment of precedence and ensure transparency for co-formulation of a system conscious tradeoff strategy.

Step 11a – Establish stakeholder precedence based on the various measures ***responsiveness***, communicated in Step 10.

Step 11b – Determine those ***design variable values most likely to produce desired design sub-problem results***, in light of the chosen sequence of resolution.

Step 12 – Communicate design variable values in the according to the sequence determined in Step 11.

Step 13 – Determine a ***balanced solution to the coupled design problem.***

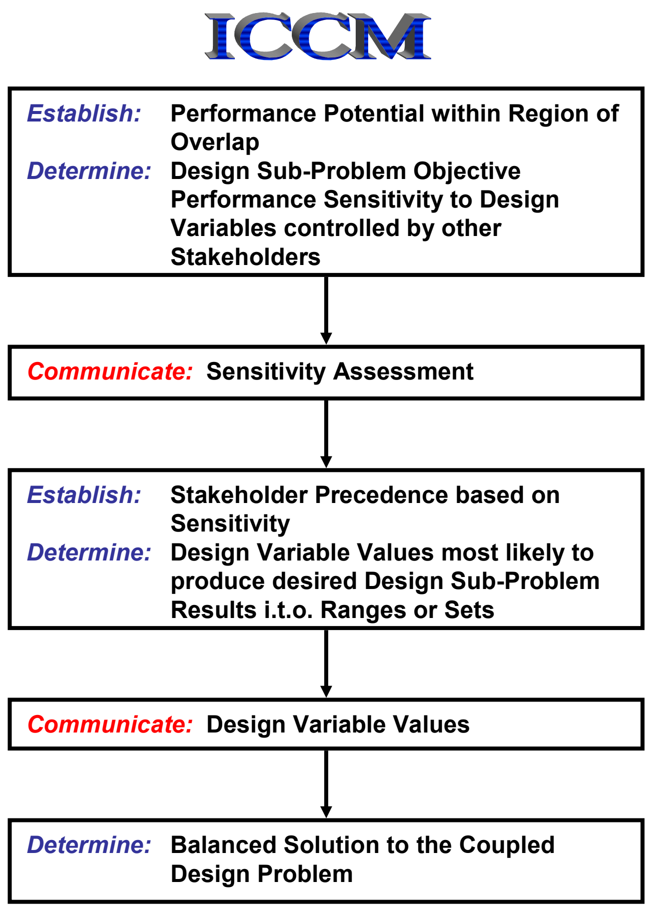


Figure 5-4 - The Interaction-Conscious Coordination Mechanism

5.6 CRITICAL ANALYSIS OF THE INTERACTION-CONSCIOUS COORDINATION MECHANISM

5.6.1 Overview of the ICCM

System-conscious resolution of tradeoffs, as promoted in this chapter, focuses on increasing the awareness of each decision-maker with respect to the manner and the degree to which the collaborative design process is likely to affect him or her. The goal is to avoid unnecessary reductions in design freedom resulting from *ad hoc* sequencing of decision-makers. By providing a platform for self-assessment of responsiveness along various key dimensions, each decision-maker is able to form an educated opinion about the sequence most likely to benefit all stakeholders equally. At the very least, this knowledge will facilitate subsequent negotiations by bringing all those involved onto the same page. It is important to recall, that due to the implementation of the CDSFM a certain minimum level of satisfaction has already been guaranteed, making those involved more likely to continue to cooperate.

Clearly any decision based on the information gained through the sequencing assessment associated with the ICCM is subjective. However, it is now an informed subjective decision, offering a clear advantage over trial-and-error. The exact protocol, most likely to yield balanced results is situationally dependent - enterprise considerations, extent of cooperation, level of information sharing, etc. have a fundamental impact. Whatever the chosen tradeoff strategy, however, it is likely to benefit from the information, obtained as a result of considering the various indicators.

Given that (1) this research is primarily focused on the decentralized solution of strongly coupled problems and (2) the ultimate quality of a solution is usually judged via a weighted average of the various stakeholder objectives at the systems level, the goal of this research in reducing the effects of implicit biases by increasing stakeholder awareness is justified. The embodiment of the ICCM in conjunction with the CDSFM forms a solid foundation for *co-design* with the context of the **F**ramework for **A**gile **C**ollaboration in **E**ngineering, presented in this dissertation.

5.6.2 Implications of the ICCM

The proposed approach rests on two fundamental assumptions. The first is that the Stackelberg or leader/follower protocol is the best suited or most representative game theoretic protocol for distributed collaborative design as established in Ref. [267]. The second is that extensive form games are appropriate for situations where not all decisions either can be or should be made simultaneously and interactions are dynamic by nature as purported in Ref. [96]. In such multi-stage games with observed actions (1) all players know previously chosen actions and (2) all players move simultaneously in each stage. It is important to note here, that "simultaneous" does not preclude players from choosing not to move. This essentially reduces to a staged Stackelberg game that is representative of designers collaborating in a shared endeavor, keeping each other abreast of evolving considerations.

Though *co-design* is quite interactive, it is far removed from fully cooperative protocols. For one, shared access to all computational models and simulation codes is not required. Individual stakeholders must only be aware of the net effect of changes in design variables on stakeholder payoffs. Since this information is easily captured in response surface models based on space filling experiments, the associated computational burden is rather small. More importantly, decision-makers are not required to relinquish control over their respective domains of expertise. The net effect is that individual stakeholders are better able to assess their own contributions to shared endeavors, thereby more closely reflecting the increasingly federalized architectures of engineering design. In contrast, full cooperation, as modeled within engineering design thus far, requires the reformulation of the individual design sub-problems as a single problem weighing inherent tradeoffs in algorithmic fashion. This requires ceding control to a third party. This party can be embodied in the form of a software agent, mythical systems level designer, or one of the stakeholders. The last embodiment is also treated as a third party, since his or her role is assumed to have shifted from pursuing the maximization of personal payoff to maximization of system level performance. Since tradeoffs at the system level in *cooperative* formulations are most often made using weighting factors, the solution falls victim to all the inherent biases, discussed in Section 5.1. Consequently, solutions that emphasize the overachievement of one subsystem, while others barely meet minimum requirements, may appear overly attractive from a numerical perspective. In the case of *non-cooperative* formulations, it is the requirement for *a priori* formulation of tradeoff strategies that poses the most significant barrier. Since this mode of conflict resolution is focused on the optimization of stakeholder responses to potential moves of an opponent, it falls subject to the *greedy heuristic*. In other words, the successive optimization of each sub-system may result in rather non-optimal results at the systems level. In effect, solutions that should (and in fact were intended to) be made concurrently, are made in sequence. The result is the unnecessary reduction of design freedom, brought on by the requirement to make a decision with insufficient information. The goal in the ICCM is to provide such decision-critical information without incurring the computational burden usually associated with doing so.

This is especially true in the case of Nash solutions, based solely on strategy intersection. Due to the increased level of human involvement, the objectives of at least one stakeholder may be improved in Stackelberg formulations. Since the majority of traditional protocols are highly opaque and severely limit stakeholder insight, solutions are directly dependent on the relative importance accorded their underlying objectives. There is no mechanism for course correction. It is this aspect that is addressed through the systematic consideration of fundamental indicators. While uncovering subtle nuances may not pose a significant challenge for simple problems, the difficulty inherent in their identification, understanding, and interpretation increases with design space complexity. The ICCM, presented in this chapter is aimed at providing individual stakeholder with a structured means of improving their understanding of their own design spaces, as well as of the manner in which the underlying process in which they share is likely to affect them. The results are increased awareness and an improved platform for collaboration that does not require relinquishing control.

5.7 A NOTE ON VALIDATION

As stressed in Section 1.4, this chapter is focused exclusively on addressing the third research question, posed in this dissertation: *How can stakeholder interactions be guided so that design freedom is not reduced unnecessarily and system level performance is enhanced?* With this in mind, a brief review pertinent aspects of the validation and verification strategy follows.

5.7.1 Theoretical Structural Validation of Hypothesis 3

Although the majority of *Theoretical Structural Validation* with regard to *Hypothesis 3* was addressed via critical review of the literature in Chapter 2, specifically Sections 2.1, 2.4, 0, and 2.6, additional contributions were made throughout this chapter. Comparative evaluation of the method presented is postponed to Chapters 6, 7, and 8, where the results of decentralized decision-making, based on the **I**nteraction-**C**onscious **C**oordination **M**echanism offered in response to *Research Question 3*, are compared with results emanating from more traditional protocols. The notion of considering decision-specific aspects in the resolution of tradeoff has been addressed thus far only via robust design techniques. However, the focus in such research was not that of excising iteration by making stakeholder decisions robust to one another. Solutions obtained in this manner traded off quality for stability in an effort to reduce the total variability possible. The goal in this dissertation is that of eliminating (or at least reducing) the effects of inherent biases on decision outcomes. The intent is to improve system level performance through gaining a better understanding of interaction effects and communicating key pieces of information. A better understanding of the dynamics coupling one decision to another is useful, regardless of what protocol is implemented. When used in the context of co-design, s advocated here, the implication is more effective use of collaborative design spaces via avoidance of unnecessary reductions in design freedom based on improper sequencing. Systematic coordination of stakeholders is reinforced through increased communication and self-assessment of responsiveness, allowing for the consistent alignment of stakeholder with their respective domains of expertise. This is a key advantage for increasingly federalized networks. Gauging performance potential serves to manage expectations and provides the context for interpreting response information.

Evaluation of the implemented constructs with regard to comparative advantage, limitation, and acceptable domain of application is addressed in Section 5.6. On the whole, the principles underlying the calculation of mathematical derivatives, design of experiments, and response surface methodology are sound. The value proposition is the reduction of implicit biases from tradeoff management, ensuring the accurate reflection of explicit biases. The result is a more consistent match between the objectives formulated at both the system and sub-system levels.

5.7.2 Revisiting the Square

Although **Theoretical Structural Validity** of each of the three Hypotheses is explored and established throughout the first five chapters of this dissertation, this chapter is focused exclusively on the substantiation of *Hypotheses 3*. Evidence of **Empirical Structural Validity** and **Empirical Performance Validity** for *Hypothesis 3* is deferred to Chapters 6, 7, and 8. The overall progress in validating and verifying the contribution documented here is summarized in Figure 4-5, where percentages correspond to the schedule specified in Figure 1-14. As indicated, this chapter thus concludes the discussion of **Theoretical Structural Validity** in this dissertation.

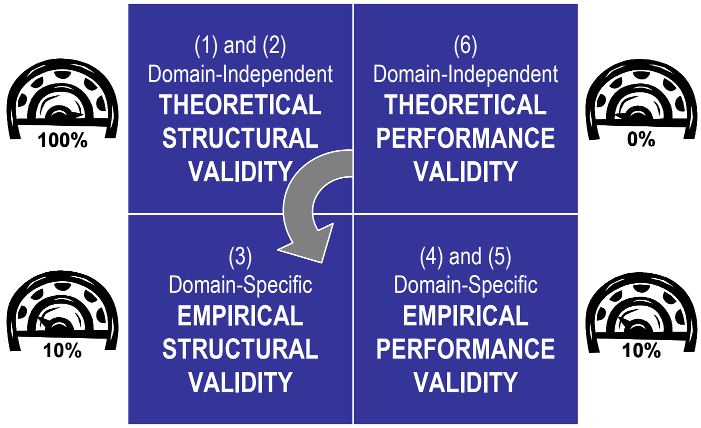


Figure 5-5 - Validation and Verification Progress through Chapter 5

5.8 A LOOK BACK AND A LOOK AHEAD

5.8.1 Revisiting the Roadmap

In this chapter, a concise mechanism for evaluating stakeholder inter-dependence and coordinating and sequencing their interactions in determining a solution within the collaborative design spaces, determined via the CDSFM, is offered. Specifically, the notions of implicit and explicit biases as well system conscious tradeoff management are introduced in Section 5.1. The concepts of stakeholder responsiveness in the context of performance potential and dominance are reviewed in Section 5.3. The interpretation of the indicators, presented in Section 5.3, is discussed in Section 5.4 and the associated tasks are formalized as steps of the **I**nteraction-**C**onscious **C**oordination **M**echanism in Section 5.5. A critical analysis follows in Section 5.6. Finally, elements of validation and verification in this chapter are highlighted in Section 5.7.

As indicated in the beginning of this chapter, and highlighted in Figure 5-6, the main goal pursued in this chapter is that of formalizing a systematic means of uncovering biases inherent in a collaborative design space and using the resulting knowledge as a means of identifying that sequence of stakeholder contributions most likely to result in balanced objective achievement. Although intended specifically for *co-designing* engineering products, the increased stakeholder awareness of the bigger picture connecting hem through the associated design process, is also useful in the context of more traditional protocols. For example, increased interaction consciousness can be used to improve results in Stackelberg interactions and serve as a basis for crafting a negotiating strategy to maximize personal payoff. Since the computational cost of *co-design* in the **I**nteraction-**C**onscious **C**oordination **M**echanism is far less than that associated with fully cooperative scenarios and the consistent alignment of stakeholders with their respective domains is ensured, this protocol constitutes an effective alternative to existing solution algorithms and communications protocols. The results, however, are amazingly close to those obtained via full-cooperation, as illustrated in Chapters 6, 7, and 8. The ICCM in conjunction with the **C**ollaborative **D**esign-**S**pace **F**ormulation **M**ethod (CDSFM), presented in the previous chapter, comprises the **F**ramework for **A**gile **C**ollaboration in **E**ngineering. The novel approach to modeling design processes, discussed in the Chapter 3 constitutes a technological base, facilitating the framework's implementation. Thus, while this chapter was focused exclusively on the **Theoretical Structural Validation** of *Hypothesis 3*, the following three chapters are devoted entirely to addressing empirical aspects of validation with regard to *Hypotheses 2* and *3*.

5.8.2 Assembling the Building Blocks

This chapter was dedicated to a detailed exposition of concepts underlying the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod. The systematic synthesis of requirements for strict and practical feasibility into a single construct capturing all relevant resources is invaluable in ensuring effective collaboration. It is the consequent assurance of mutually acceptable results that makes the consideration of *co-design* feasible.

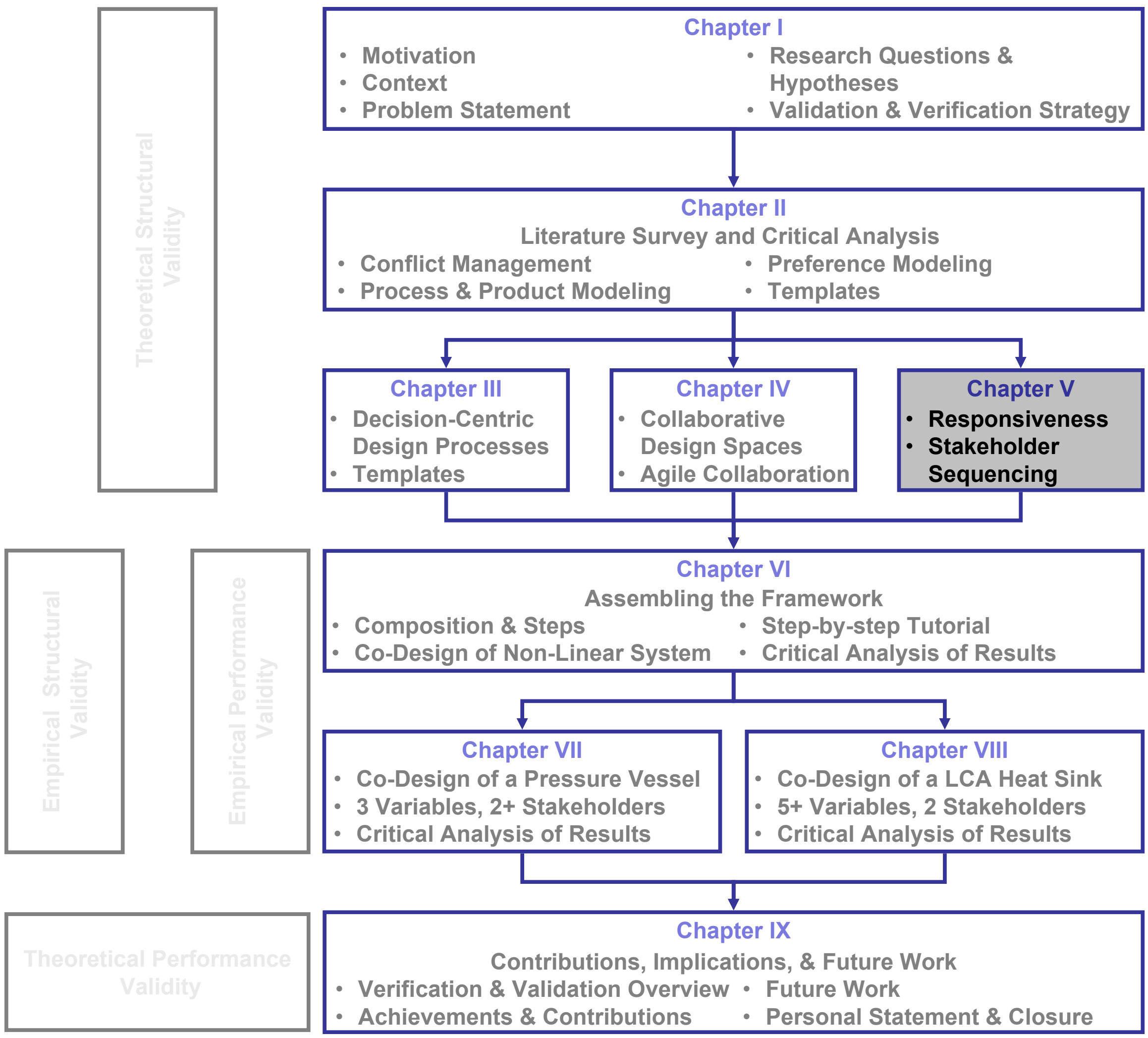


Figure 5-6 - Dissertation Roadmap

CHAPTER 6 - FACE: A FRAMEWORK FOR AGILE COLLABORATION IN ENGINEERING

The goal in this chapter is to demonstrate in tutorial fashion the application of the **F**ramework for **A**gile **C**ollaboration in **E**ngineering at the hand of a simple example, involving a system of non-linear equations. This will occur with respect to both the establishment of a collaborative design space and the transparent, system-conscious resolution of tradeoff. The focus is on assembling the building blocks, developed in Chapters 3, 4, and 5 and presenting a coherent picture of the resulting framework. With this in mind, an overview of this framework is presented in Section 6.1, followed by an overview of the example in Section 6.3. The tutorial follows in Section 6.4. The results obtained are critically analyzed with respect to outcomes emanating from the application of more traditional (and readily) accepted means of problem resolution in Section 6.5. The notion of conflict management within the overarching framework is clarified in Section 6.6, whereas *theoretical* and *empirical* validation and verification of *Hypotheses 1, 2,* and *3* are addressed in a combined fashion in Section 6.7. As in other chapters, the establishment of cohesion follows in Section 6.8.

6.1 VALIDATION AND VERIFICATION WITHIN CHAPTER 6

As indicated in Section 1.5.1, the **F**ramework for **A**gile **C**ollaboration in **E**ngineering is synthesized from the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod and the **I**nteraction-**C**onscious **C**oordination **M**echanism, developed in Chapters 4 and 5, respectively, in this chapter. The chosen method of implementation is the **T**emplate-based **D**esign **P**rocess **M**odeling approach, developed in Chapter 3. With this in mind, the discussion in the sections to follow is devoted to the **Empirical Structural Validation** and **Empirical Performance Validation** of the TDPM, the CDSFM, and the ICCM, posed in response to *Research Questions 1, 2*, and *3*, respectively. While the System of Non-Linear Equations, chosen for simplicity and overall transparency, is ideally suited for an illustration of the methods in tutorial fashion, confidence in the scalability of the methods to more realistic problems is established in Chapters 7 and 8. Making the case for **Theoretical Performance Validity** is deferred to Chapter 9. Specific aspects of this effort are summarized in Figure 6-1 and addressed in more detail in Section 6.7.

6.2 COMPOSING THE FRAMEWORK

6.2.1 Distilling the Niche - Concise Interactions and Effective Management of Collaborative Design Spaces

As indicated in Section 2.1, there are many motivations for facilitating effective information exchanges in engineering design processes. The focus in this dissertation, however, is on balancing the achievement of sub-system goals in light of system level requirements. The aim is to seek out more evenly matched solutions, the bias (i.e., weighting) of which can be controlled explicitly. In contrast to most instantiations of game theoretic protocols in engineering design, which focus on solving *coupled* design problems either algorithmically or by minimizing/eliminating required interactions, as indicated in Section 2.2.5, it is sought here to make these interactions effective. Preliminary efforts in this direction, thus far, have required individual stakeholders to relinquish or transfer control over their respective domains of expertise in order to achieve solutions to *strongly coupled* design problems. This has been facilitated via (1) the communication of ranged sets of design solutions (to be refined by downstream decision-makers) [267,270] or (2) by desensitizing design sub-problems to coupled parameters [44], for example.

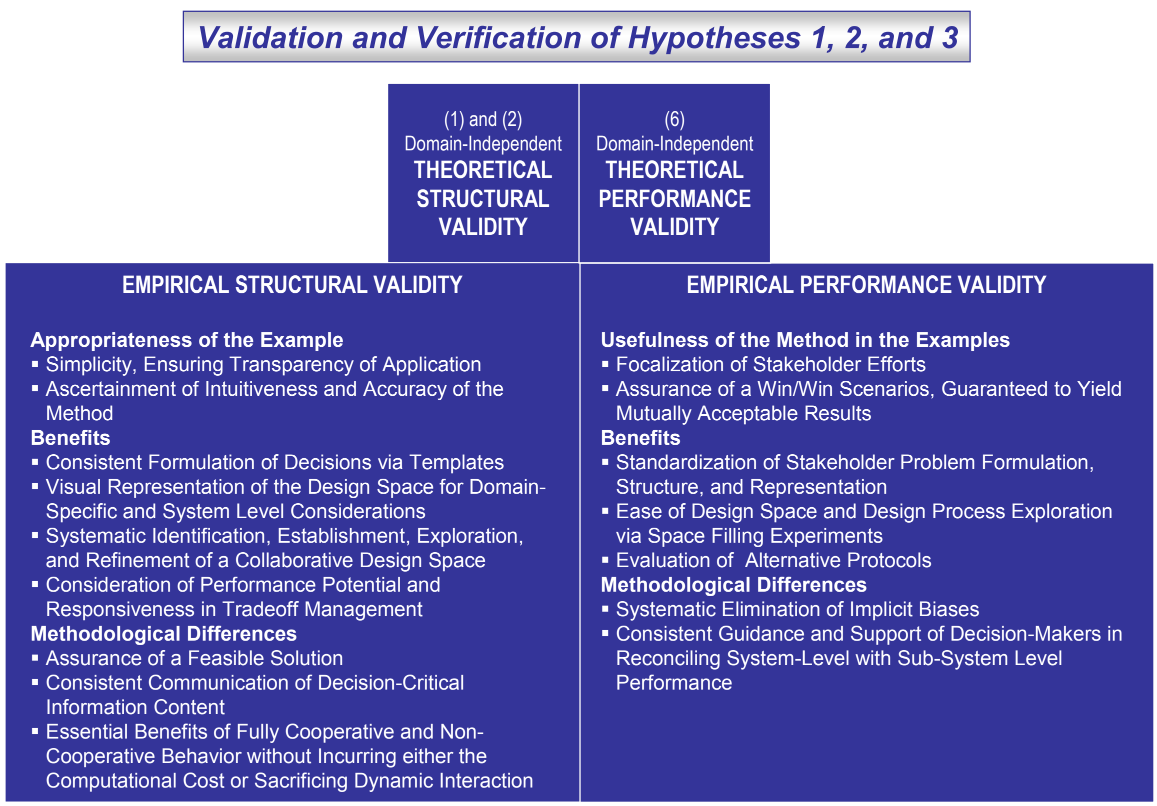


Figure 6-1 - Aspects of Validation and Verification Addressed in Chapter 6

Other examples include the creation of a *clean digital interface* between design and manufacture in Refs. [192,193,267,270]. While these mechanisms may be appropriate in circumstances when an actual handoff from one phase of a product realization process to another occurs, they are not suited for collaborative design efforts requiring repeated interactions along a design timeline, as focused upon in this dissertation.

In collaborative, decentralized design scenarios that cannot be decoupled (or sequenced) and require the concurrent consideration of multiple interrelated sub-systems, it is considered paramount that individual stakeholders retain dominion over the design sub-problems which they have been assigned throughout the duration of a given design process. This is especially important, bearing in mind that models are generally valid only within the narrow bounds, considered during their formulation. Changes exceeding these bounds require careful consideration and potential reformulation of the associated simulations. A clear understanding of domain specific assumptions, tradeoffs, and implications is thus crucial. Rather than reducing complexity of the resulting design process via centralization, this author advocates the support of decentralized decision-making via standardization and modularization of the underlying models (see Chapter 3), supported by effective coordination of the required interactions (see Chapters 4 and 5). In this manner, stakeholders are able to retain dominion over their respective sub-problems and work synergistically towards mutually agreeable solutions.

A majority of available models constitute static representations; they are incapable of effectively incorporating evolving information content, while preserving the underlying manner in which the decisions are structured. Considering that responsibility for design sub-problems is often transferred during the course of a design process (in order to facilitate conflict resolution) this is a fundamental shortcoming. The static nature of the underlying models limits this transfer to the communication of a design space "snapshot" that is particular to the current state of information. In consideration of this, loss of stakeholder dominion is highly undesirable, since an in-depth understanding of the domain models and any underlying assumptions and limitations is required to make cogent inferences beyond the communicated nugget of expertise. A change, deviating beyond the bounds within which the model is valid, requires decision model reformulation by the originating domain expert. Costly iteration is likely. A fundamental requirement for interfacing interacting decision-makers throughout the duration of their relationship, thus, is a domain independent means of modeling design problems that can be amended indefinitely. For this purpose, modular, domain independent decision templates, based on the mathematical constructs of the Decision Support Problem Technique [32,110,145,148], are developed in Chapter 3 and have been published in Ref. [168]. Since the focus in this chapter is on the formalization of interactions among distributed stakeholders, rather than on the models used to represent their perspectives, the details of their formulation are not repeated. Suffice it to say, that the resulting decision templates provide a modular, computer interpretable means for design problem formulation that serves as the basis for enabling consistent and dynamic interactions. With this in mind, it is the manner in which the interacting stakeholders obtain, exchange, and integrate information, emanating from their respective design sub-problems, and effectively establish a collaborative design space – *enabling agile co-design* – that is elaborated upon in the following sections.

6.2.2 Developing the Niche - A Framework for Agile Collaboration in Engineering

As indicated in Section 1.3, the central contribution, documented in this dissertation, consists of a two-fold proposition for an alternative to current (and predominantly game theoretic) means of conflict resolution. The first aspect deals with the establishment of a collaborative design space, composed of a set of solutions, acceptable to all interacting stakeholders. The resulting **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod was the subject of Chapter 4. The second aspect is centered on the system conscious resolution of the inherent tradeoffs among competing objectives, both on the system and sub-system level. Chapter 5 was focused on explicating the **I**nteraction-**C**onscious **C**oordination **M**echanism, developed in response to this challenge. The paradigm shift (inherent or implied by the material presented in the three preceding chapters) that is advocated in this vein is to move beyond *strategic collaboration* towards *co-design*[9]. With this in mind, the author asserts that sharing key pieces of information at earlier stages and, in fact, throughout the course of the ensuing interaction is the preferable *modus operandi* for *co-designing* an artifact. In fact, the earlier potential mismatches are identified, the less severe their impact is likely to be. Relying on the majority of currently instantiated protocols such detrimental disparities do not surface until the execution of algorithmic trade-offs, as pointed out in Refs. [39,40], where the requirements for convergence and the stability of equilibria are investigated. It is for this reason that the majority of the corresponding schemes can be considered to constitute *defacto* solution algorithms rather than communications protocols. Generally, what is needed is (1) a comprehensive means of facilitating the system-conscious formulation of design sub-problems, (2) the communication of required information content as stakeholder considerations evolve, and (3) the accommodation of those solution mechanisms most suited to the problem at hand.

A suitable framework for accomplishing these ends is presented in this section. The role of the proposed **F**ramework for **A**gile **C**ollaboration in **E**ngineering and its constituents for effective co-design are highlighted for the case of systems design in Figure 1-16, where the encircled numbers correspond to the steps of the coordination mechanism detailed in Figure 6-2. The framework is derived from the building blocks detailed in Chapters 3 through 5 and assembled here. The resulting Scheme for Successful Co-Design, pictured in Figure 6-2, essentially consists of the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod (Steps 1-8) applied in tandem with the **I**nteraction-**C**onscious **C**oordination **M**echanism (Steps 9-13). As indicated in Figure 1-17, it is these two aspects of systematic co-design in conjunction with the template based approach to modeling design decisions that comprise FACE in its entirety.

The relationship between the various building blocks and the nature of their composition are detailed in Figure 1-17. It is noted, once more, that reliance on decision and interface/interaction templates is merely an enabling technology, aimed at facilitating and reducing the increased effort underlying *co-design*. Neither type of template, however, is prerequisite for effective implementation of the framework. It is important to make a careful distinction between the overarching framework, comprised of all the aspects covered in Chapters 3 through 5, and its constituents, as these can be applied independently of one another (provided that a solution exists). Thus, *Steps 1* through *8*

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[9] The term *co-design* is used in this dissertation to stress the aspiration to support the joint or mutual concurrence of stakeholders *to the same extent, throughout the duration of their interactions,* rather than merely striking tradeoffs based on immutable representations of preferences, assessed prior to engagement.

correspond to the establishment of a collaborative design space that is certain to contain solutions that are acceptable to all interacting parties via the CDSFM of Chapter 4, while *Steps 9* through *13* constitute the system conscious resolution of stakeholder tradeoffs as formalized in the ICCM of Chapter 5. Specifically *Steps 1* through *4* are focused on the formulation and exploration of design sub-problems as well as the characterization of co-dependence in terms of parameter ranges, used to establish the gross extent of a potential, shared design space. *Steps 5* through *8* are centered on the subsequent refinement of this space in order to ensure the existence of an adequate solution. Both system and sub-system performance potentials are established in *Steps 9* through *10*, prior to a strength assessment of interaction effects in *Steps 10* through *11* and the designation of stakeholder precedence in fixing values of design variables to determine the solution to the coupled system in *Step 13*. It is noted that *Steps 9* through *13* can be replaced with any of the more traditional protocols discussed in Section 2.1, including traditional optimization, thereby making the framework adaptable to supporting any conceivable relationships, encountered in design. By the same token, *Steps 3* through *13* and any variation thereof can be formalized in an interaction/interface template, similar in nature to those described in Chapter 3. A more detailed description of the steps involved in the method follows.

The following information is assumed as being given at the onset of the design process being considered. Thus, this information is either readily available to the designers involved or obtainable by reasonable effort (i.e., through research, investigation, database query, computation, analysis etc.):

- ☑ ***System*** – problem statement, description, overarching requirements, sub-system decomposition, translation of system design problem to system design decision and sub-system design problem to sub-system design decision

- ☑ ***Governing Relations*** – quantitative behavioral description at the system and sub-system level as well as pertinent relationships among these (analytical, theoretical, stochastic, etc.) and qualitative comprehension for competent interpretation

- ☑ ***System Objectives*** – preferences, goals, constraints, resources, etc.

- ☑ ***Sub-System Objectives*** – preferences, goals, constraints, resources, etc.

- ☑ ***Control Assignment*** – mapping of sub-systems to domains of expertise and qualified decision-makers

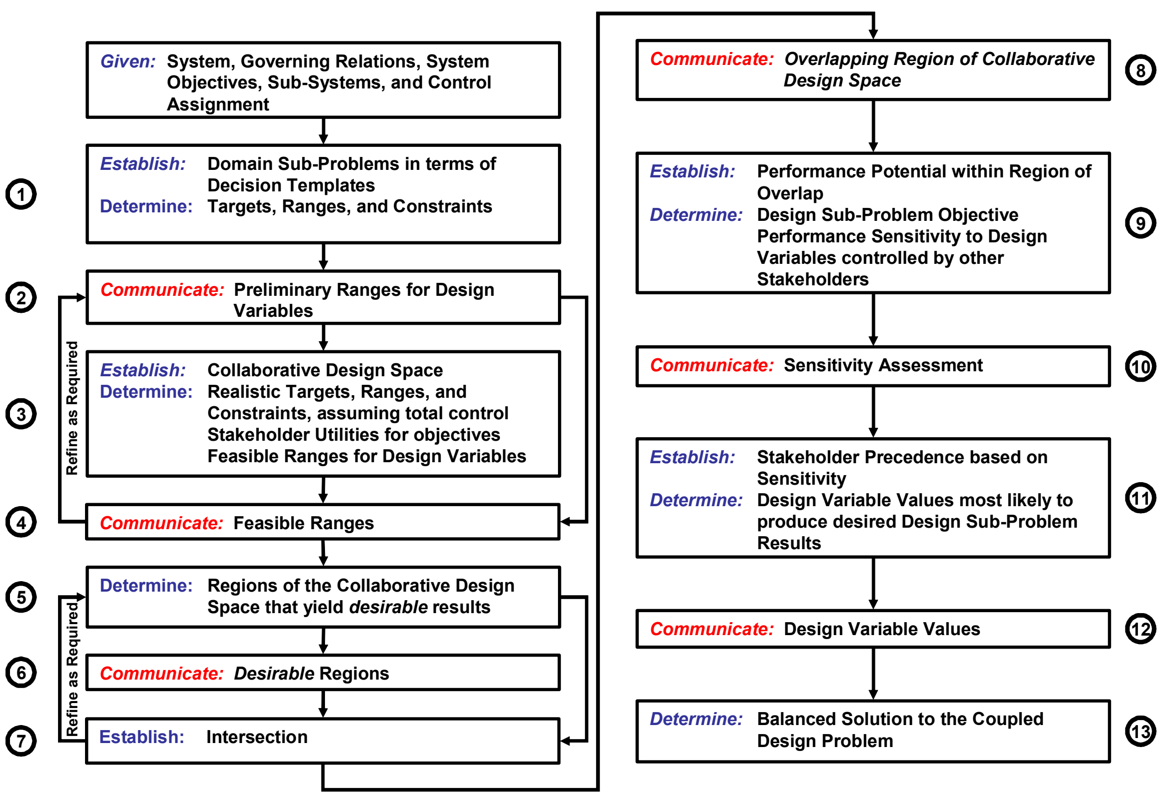


Figure 6-2 - Scheme for Successful Co-Design

With this in mind, the steps of the proposed **F**ramework for **A**gile **C**ollaboration in **E**ngineering are presented in Figure 6-2 and subsequently described in detail:

Step 1a - Establish domain sub-problems in terms of decision templates via interpretation of sub-system level particulars in the context of system level requirements.

Step 1b - Determine targets, ranges, and constraints as appropriate for each of the decisions corresponding to design sub-problem resolution in light of system level considerations.

Step 2 – Communicate preliminary ranges for design variables under immediate control in order to provide a starting point of reference from which interacting stakeholders can launch their respective explorative activities.

Step 3a – Establish a preliminary ***collaborative design space***, reflecting the considerations of other stakeholders, as implied by the preliminary ranges for design variables, communicated in Step 2.

Step 3b – Determine realistic targets, ranges, and constraints for each of the design sub-problems within the established ranges, ***assuming total control*** over all (including shared) design variables.

Step 3c – Determine stakeholder utilities for objectives and ensure that these are realistically achievable within the range considered. Iterate, should utilities not be achievable, or reassess preferences in light of what is feasible.

Step 3d – Determine feasible ranges for or sets of design variables, pertaining to other stakeholders, over which control was assumed during design sub-space exploration.

Step 4 – Communicate feasible ranges for design variables that are uncontrollable (i.e., controlled by other stakeholders) that make achievement of desirable objective performance based on adjustment of controllable design variables possible.

Step 5 – Determine regions of the collaborative design space that yield desirable results, based on the ranges for design variables (allowing for the satisfaction of co-designer preferences, communicated in Step 4.

Step 6 – Communicate desirable regions of the collaborative design space in terms of ranges or sets of suitable design variable values.

Step 7 – Establish the ***intersection*** of regions of the collaborative design space and the design sub-problem specific design sub-spaces that contain feasible solutions for all interacting decision-makers in terms of design variable ranges or sets.

Step 8 – Communicate overlapping region of collaborative design space, determined in Step 7, to all interacting decision-makers.

Step 9a – Establish the design sub-problem (i.e., stakeholder) specific ***performance potential within*** the ***region of overlap***, constituting the revised collaborative design space.

Step 9b – Determine the ***design sub-problem objective performance sensitivity to design variables controlled by other stakeholders***. Consider separately (1) sensitivity of design sub-problem specific objective achievement to changes in uncontrollable (i.e., controlled by other stakeholders) design variables, (2) sensitivity of design sub-problem specific objective achievement to changes in controllable design variables, and (3) the impact of changes in controllable design variables on the objective achievement of other stakeholders, referred to here as *sensitivity*, *power*, and *leverage* respectively.

Step 10 – Communicate domain specific (stakeholder) ***sensitivity assessments*** in order to enable self assessment of precedence and ensure transparency for co-formulation of a system conscious tradeoff strategy.

Step 11a – Establish stakeholder precedence based on the various measures ***responsiveness***, communicated in Step 10.

Step 11b – Determine those ***design variable values most likely to produce desired design sub-problem results***, in light of the chosen sequence of resolution.

Step 12 – Communicate design variable values in the according to the sequence determined in Step 11.

Step 13 – Determine a ***balanced solution to the coupled design problem.***

As highlighted by the "communication" boxes in Figure 6-2, the close involvement of decision-makers, charged with the resolution of strongly coupled decisions, is highlighted by the relatively frequent exchanges of information among them. As can be seen from the steps listed above and numbered accordingly in Figure 6-2, interacting stakeholders alternate domain and design sub-problem specific exploration with the communication of relevant information content. The underlying strategy is that of ensuring continuous congruency of the associated efforts towards the achievement of a common, mutually beneficial goal. The necessity of iterative reformulation or refinement is also indicated stressed using the cyclic arrows shown. As a direct consequence of the frequent interactions among designers, irreconcilable mismatches are identified as they arise; misdirection of efforts and consequent rework are minimized. This stands in marked contrast to more traditional communications protocols in which *ex post facto* tradeoffs are struck based on strategies that we established *a priori*.

6.3 A TUTORIAL EXAMPLE – DECENTRALIZED SOLUTION OF A SYSTEM OF NON-LINEAR EQUATIONS

Having presented the steps involved in the proposed alternative to current game theoretic instantiations of solution algorithms and communications protocols in the previous section, its application is demonstrated on a step-by-step basis in this section. In order to substantiate and evaluate this novel approach to conflict management, extensive comparisons to results obtained using more traditional protocols are conducted in Section 6.5.

Since the mechanics involved in FACE are rather complex, a rather simple example is chosen to illustrate the intricacies of its application. Specifically, a system of non-linear equations, given by

$$F_A = 2.5x_A^2 + x_A x_B^2 - 30x_A + 200$$
$$F_B = -5x_B^2 - x_A x_B + 50x_B + 200$$

and illustrated in Figure 6-3, is focused upon. Despite its relative simplicity, this example exhibits the central characteristics of the type of problem towards the resolution of which FACE is targeted. The system of non-linear equations exhibits diametrically opposed objectives, pursued by distinct stakeholders, each controlling different shared design variables and competing with respect to a common set of resources. One of the primary reasons for choosing this two dimensional example is the ability of illustrating the evolution of the collaborative design space pictorially. Similarly the mathematics are relatively simple, so as not to detract from the method. The precise nature of the role that this example plays in the overarching validation strategy with respect to Empirical Performance Validation and Theoretical Performance Validation is outlined in Section 1.4 and reviewed in Section 6.7. With this in mind, the basic problem description is as follows:

Control over the coupled problem is split between Designers A and B who manipulate x_A and x_B, respectively. It is Designer A's goal to minimize F_A and Designer B's intention to maximize F_B. The desired performance for Designer A is $T_A \leq 130$, while the desired performance for Designer B is $T_B \geq 290$. Clearly, these objectives are in direct conflict, as evidenced by the opposite concavity of the surfaces depicted in Figure 6-3. Both design variables are constrained to the open interval $x_i \subseteq [0,10]$. The contour plot, depicted in Figure 6-4, illustrates the projection of objective function values for Designer A as a series of dashed lines and those of Designer B as a series of solid lines. Within the given design variable ranges, objective function values for Designers A and B vary between $110 \leq F_A \leq 1150$ and $100 \leq F_B \leq 325$.

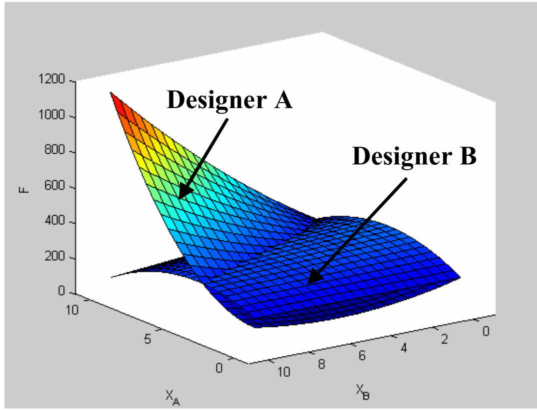


Figure 6-3 - Surface Plot of Non-Linear System

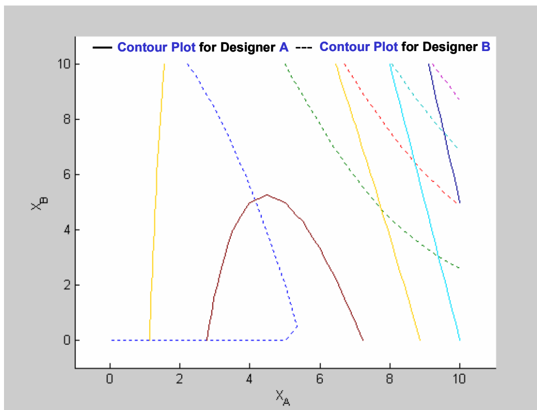


Figure 6-4 - Contour Plot of Non-Linear System

Thus, the system is specified in terms of the problem statement, description, and requirements. The system ahs also been decomposed into two sub-systems, assigned to Designers A and B, respectively. Each of these is governed by both sub-system specific requirements such as the minimization of F_A and maximization of F_B, and system level requirements such as the limitation of design variables to the open interval $x_i \subseteq [0,10]$. The governing relations in this case are given in terms of the closed form system of non-linear equations, which double as design sub-system specific objectives. Besides the constraints placed on the values from which the design variables may be chosen (comprising the shared resources), no additional constraints exist from the system's perspective. Additional constraints will arise solely as a result of stakeholder specific goal pursual. Each of the Designers A and B is considered to be an expert with respect to achieving the objectives associated with the domains, characterized by F_A and F_B. Since both of these objectives depend on each of the design variables over which control is shared and cannot be decoupled based on an argument of *near decomposability* [221], this problem is a good example of a *strongly coupled* decision. This decision is assumed to require decentralized, distributed resolution based on enterprise structure. Having carefully taken stock of the so called ***"Given"*** aspects of this example, a step-by-step tutorial follows in Section 6.4.

6.4 EMPLOYING THE FRAMEWORK FOR AGILE COLLABORATION IN ENGINEERING - AN ILLUSTRATED, STEP-BY-STEP TUTORIAL

As indicated in Section 6.1, the focus in this chapter is on structuring the interactions of stakeholders charged with solving a strongly coupled design problem, rather than on the proper formulation of sub-problems. Consequently, the discussion that follows is focused predominantly on the interactive, decentralized exploration of the system of non-linear equations introduced in Section 6.3 by two designers. Each of the steps pertaining to the interactions protocol, outlined in Section 6.2.2, is completed with respect to the tutorial example. As a point of reference to the reader, the evolution of the shared design space (governing the behavior of the system of non-linear equations) associated with these steps and the changing nature of the communicated information content is illustrated in Figure 6-5. The encircled numbers correspond to the equally numbered FACE steps for *co-design*. A detailed discussion of individual steps follows.

6.4.1 Instantiation and Exploration of Domain Specific Design Sub-Problems

Considering the progression indicated in Figure 6-2 and Figure 6-5, Designers A and B are presented with a system composed of a set of non-linear equations and charged with achieving targets $T_A \leq 130$ for F_A and $T_B \geq 290$ for F_B, respectively, where F_A and F_B constitute the two sub-systems into which the system is decomposed.

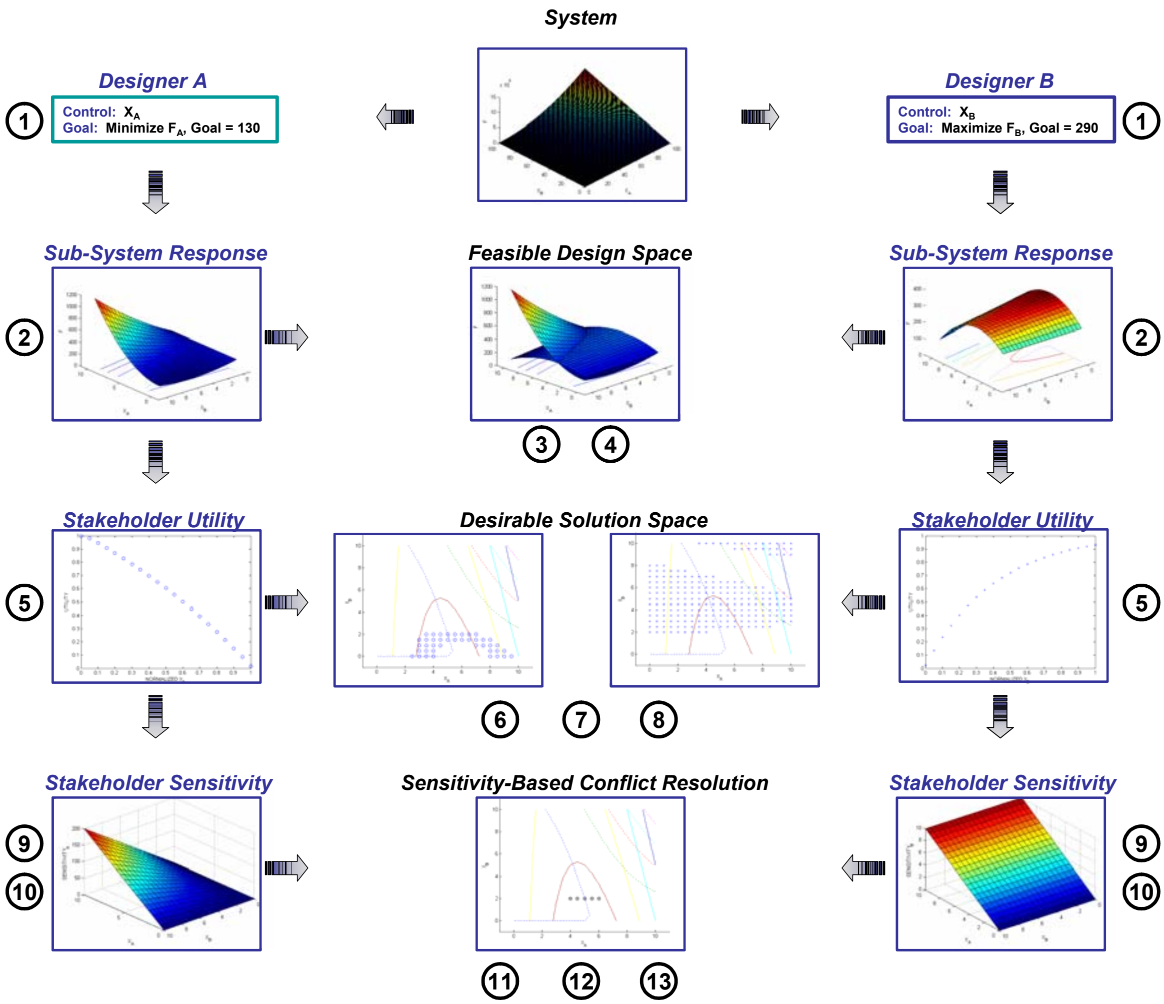


Figure 6-5 - Evolution of Design Space Based on the Proposed Communications Protocol

Step 1a - Establish domain sub-problems in terms of decision templates via interpretation of sub-system level particulars in the context of system level requirements.

Each of the sub-problems associated with these sub-systems is considered in terms of the associated design decisions. These decisions can be modeled consistently using the compromise DSP formulation presented in Section 3.3.1. In order to facilitate the associated effort and guide the various domain experts through the process of formalizing their respective decisions, the compromise decision templates detailed in Section 3.3.5 can be employed for this purpose. The instantiated template for this particular design example is depicted in Figure 6-6, where the considerations of both Designers A and B are reflected side by side. Clearly, some of the information shown (i.e., preferences for target achievement) is determined in later steps.

System of Non-Linear Equations				
cDSP "Chips"	**Designer A (F_A)**		**Designer B (F_B)**	
Constraints	**x_A:** $0 \le x_A \le 10$ **x_B:** $0 \le x_B \le 10$		**x_A:** $0 \le x_A \le 10$ **x_B:** $0 \le x_B \le 10$	
Variables	**x_A**		**x_B**	
Parameters	**N/A**		**N/A**	
Goals	**F_A** Target = 130		**F_B** Target = 290	
Preferences	**F_A** Weighting Factor = 0.5 **F_A** Utility = $U_A = 2.02 - e^{0.69}$		**F_B** Weighting Factor = 0.5 **F_B** Utility = $U_B = 1.02 - e^{-2.40}$	
Objective	**Minimize** F_A $F_A = 2.5x_A^2 + x_A x_B^2 - 30x_A + 200$		**Maximize** F_B $F_B = -5x_B^2 - x_A x_B + 50x_B + 200$	
Analysis	**Inputs**	**Outputs**	**Inputs**	**Outputs**
	x_A, x_B	F_A	x_A, x_B	F_B
Driver	**Optimization Algorithm** – Exhaustive Search, SQP, etc.		**Optimization Algorithm** – Exhaustive Search, SQP, etc.	
Response	**Design Variable Values** – x_A **Objective Function Value** - Z		**Design Variable Values** – x_B **Objective Function Value** - Z	

Figure 6-6 - Decision Templates for Domain Sub-Problems

Step 1b - Determine targets, ranges, and constraints as appropriate for each of the decisions corresponding to design sub-problem resolution in light of system level considerations.

Each of the interacting decision-makers is tasked with determining preliminary values for objective targets, design variable ranges, and constraints, based on their domain-specific insight. This assumes the ability of the various decision-makers to interpret system level considerations and translate these to the sub-system level. For example, a domain expert is expected to have an intuitive understanding of the manner in which sub-system performance will contribute to requirements set at the systems level. In terms of the problem considered here, it is Designer A's goal to minimize F_A and Designer B's intention to maximize F_B. The desired performance for Designer A is $T_A \leq 130$, while the desired performance for Designer B is $T_B \geq 290$. Although somewhat contrived in this example, these targets correspond to the performance specs that each designer deems appropriate for his or her sub-system (in light of system level requirements). At the systems level, both design variables are initially constrained to the open interval $x_i \subseteq [0,10]$. This means that, although each of the designers has the power to reduce the range corresponding to the design variable under his or her control further, any such changes may not exceed these overarching bounds.

Step 2 – Communicate preliminary ranges for design variables under immediate control in order to provide a starting point of reference from which interacting stakeholders can launch their respective explorative activities.

Having completed a preliminary exploration of their respective domains, each of the designers in turn communicates a starting range for the design variables under his or her control. It is noted at this point that when dealing with larger numbers of design variables, reliance on sets in lieu of ranges is required in order to account for the combinatorial (interaction) effects of these variables on objective achievement. Although designers are aware of system level requirements, it is assumed that they can accurately interpret these only with respect to their own personal area of expertise. Additionally, certain organizational barriers at the enterprise level may prevent individual decision-makers from being privy to information content exceeding that strictly required for resolving their respective design sub-problems. As discussed in the previous step, sub-system considerations may place additional limitations on overarching system level requirements. Since each of the designers only has partial control over the manner in which his or her objective are achieved (due to the strongly coupled nature of this design problem), specific values (point solutions, ranges, and/or sets being considered by their counterparts) have a direct effect on the manner in which the design of the various sub-systems may proceed. Clearly, this information is also crucial in determining what is realistically achievable. In order to ensure that all stakeholders start off on the same page (and to not waste precious resources, investigating infeasible regions of a design space), preliminary ranges are communicated among all stakeholders (Designers A and B in this case).

6.4.2 Establishing Collaborative Design Spaces

Step 3a – Establish a preliminary ***collaborative design space***, reflecting the considerations of other stakeholders, as implied by the preliminary ranges for design variables, communicated in Step 2.

Both designers are able investigate feasible ranges for design variables by assuming full control over all pertinent parameters over the initial range of $x_i \subseteq [0,10]$. In doing so, Designer A determines the overall performance potential to be $110 \leq F_A \leq 1150$, while that of Designer B is $100 \leq F_B \leq 325$. Since there are no explicit constraints introduced by either design sub-problem, the preliminary design space is not reduced in extent beyond the limits given as systems level considerations. The computational effort involved in effectively exploring an area of potentially astronomical extent (especially for more realistic engineering design problems) can be alleviated significantly through the use of space filling experiments such as Latin Hypercubes [154].

Step 3b – Determine realistic targets, ranges, and constraints for each of the design sub-problems within the established ranges, ***assuming total control*** over all (including shared) design variables.

A key element in the achievement of system conscious solutions in *co-design* is the establishment of targets for objectives that are realistically achievable. Realistic achievement in this context takes into consideration (1) the constraints emanating not only from the systems level, but also from other design sub-systems, strongly coupled to the system in question and (2) the artificial bias that emerges from implicitly weighting objectives by setting unachievable target values. While the first aspect is addressed in terms of communicating aspects relevant to gaining a working understanding of the manner in which sub-systems interact, the second aspect is mitigated by using decision-maker preferences as a basis for normalization. This end is achieved via reliance on utility theory, as discussed in the next sub-step.

In order to establish what is realistically achievable for each of the domains in question, domain experts assume total control over all designer variables affecting their sub-systems performance as in the initial determinations made regarding their respective performance achievement potentials. In doing so, values for these (external and effectively uncontrollable) parameters, ranges, and sets of constraints, variables, parameters, etc. are taken from the information, communicated in *Step 2*. The achievement potential, determined in *Step 3a* should clearly indicate whether targets (derived from system level requirements, domain expertise, etc.) are realistic. It is at this point that irreconcilable mismatches among the system and sub-systems or among sub-systems are first identified as dichotomies between what is desired and what is possible given current resources. Irrespective of preconceived notions, it is likely that stakeholder preferences will also be influenced by what is attainable. With this in mind, these preferences must be expressed in a quantitative format and are consequently assessed in the next sub-step.

Step 3c – Determine stakeholder utilities for objectives and ensure that these are realistically achievable within the range considered. Iterate, should utilities not be achievable, or reassess preferences in light of what is feasible.

As indicated in *Steps 3a* and *3b*, realistic targets are determined based upon potential performance within the feasible region of the shared design space. These targets are then used to assess and capture in functional form the preferences of individual designers. This is accomplished through the determination of utility functions. Single attribute utility functions are assessed based on individual stakeholder preferences and attitudes towards risk with respect to each objective. For details on the process involved in arriving at single attribute utility functions and satisfaction of the underlying axioms, the reader is referred to Section any standard reference on Utility Theory [130,196,252], or the work of this author in Ref. [79].

As indicated in Section 2.6, designer preferences are assessed explicitly in this work in order to (1) bound preferences in a two-sided, rather than a one-sided fashion as in mathematical minimization or maximization and (2) arrive at richer representations of the underlying objectives (i.e., not necessarily linear, risk conscious). Properly assessed ranges extend from *unacceptable* (i.e., $U_i = 0$) to *ideal* (i.e., $U_i = 1$) values and are provided for both Designers A and B in Table 6-1. The corresponding utility functions are $U_A = 2.02 - e^{0.69 * F_A}$ and $U_B = 1.02 - e^{-2.40 * F_B}$, respectively. It is noted here that an additional advantage is the employment of preferences as a problem-independent means of normalizing design sub-system performance for consideration in system level tradeoffs. Such an absolute measure stands in marked contrast to the relative evaluation resulting form the use of achievable ranges of objective values for normalization. It is also noted that the utilities calculated for objective achievement should always be checked against the ranges listed in Table 6-1. The reason for such a check is that utility functions are fitted or regressed and consequently may not interpolate the end points, and consequently under- or over-representing the value of a particular solution to a designer.

Checking the tabulated values will significantly reduce errors emanating from poor functional fit.

Table 6-1 - Designer Utilities for Objective Achievement

Preference	Ideal	Desirable	Tolerable	Undesirable	Unacceptable
Utility Value	1	0.75	0.5	0.25	0
Designer A	130.0	147.7	160.6	171.6	180.0
Designer B	290.0	260.1	240.0	227.9	220.0

Step 3d – Determine feasible ranges for or sets of design variables, pertaining to other stakeholders, over which control was assumed during design sub-space exploration.

Making use of the utilities assessed in Step 3c, those regions of each design sub-space, yielding feasible results (defined here as having a utility $U_i \geq 0.75$) can be effectively determined via space filling experiments. In the case considered here, such exploration indicates that Designer A can obtain good results for $x_A \subseteq [2,10]$, while Designer B requires $x_B \subseteq [1,9]$. What is more important for co-designing a solution to the system of non-linear equations and establish the collaborative design space, however, is the limitations placed by each stakeholder on the values taken on by design variables controlled by other stakeholders. In fact, it is these that will determine the extent and evolution of the collaborative design space. Since the design variables of Designer A constitute the constraints of Designer B and vice versa, the extent of the collaborative design space that is feasible is determined to be $x_A \subseteq [0,10]$ and $x_B \subseteq [0,2.5]$. These values can be confirmed graphically in this special two dimensional case by studying the feasible design spaces associated with each of the design sub-problems pictured for Designers A and B, in Figure 6-7 and Figure 6-8, respectively. Once again, it is emphasized that irreconcilable mismatches should be reconciled as soon as they arise.

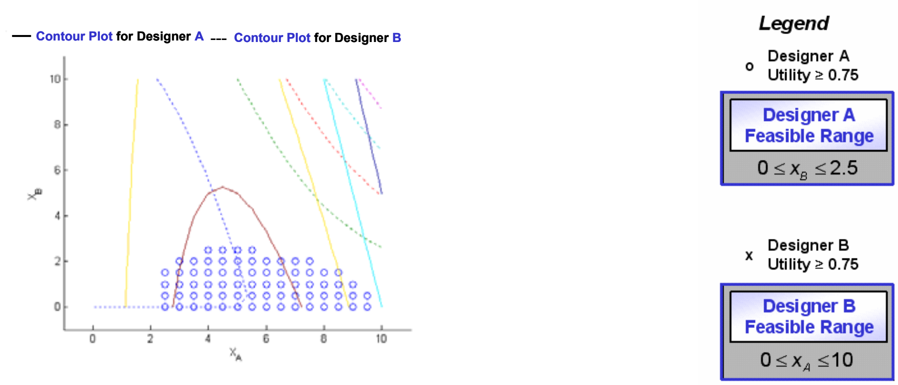


Figure 6-7 - Feasible Design Space for Designer A

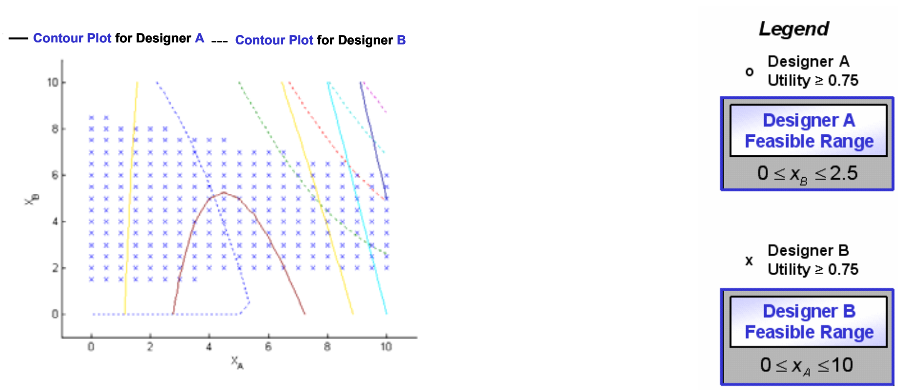


Figure 6-8 - Feasible Design Space for Designer B

Step 4 – Communicate feasible ranges for design variables that are uncontrollable (i.e., controlled by other stakeholders) that make achievement of desirable objective performance based on adjustment of controllable design variables possible.

The ranges communicated among the interacting designers in this case, are those indicated in the legends of in Figure 6-7 and Figure 6-8, namely $x_A \subseteq [0,10]$ and $x_B \subseteq [0,2.5]$. It is noted, once again, that in the case of more complex problems involving higher dimensionalities, these communications are likely to take on the form of sets of design variable combinations.

Step 5 – Determine regions of the collaborative design space that yield desirable results, based on the ranges for design variables (allowing for the satisfaction of co-designer preferences, communicated in Step 4.

The required determination regarding the regions of the collaborative design space, yielding mutually desirable results, is made using the utility functions U_A and U_B, representing the preferences steering each of the design sub-problem in conjunction with the objective functions F_A and F_B and the reduced ranges for x_A and x_B determined in combining those found in *Step 3d* and those communicated in *Step 4* in an additional set of space filling experiments. The ranges considered are thus $x_A \subseteq [2,10]$ and $x_B \subseteq [1,2.5]$, as illustrated in Figure 6-9 and Figure 6-10 for Designers A and B, respectively.

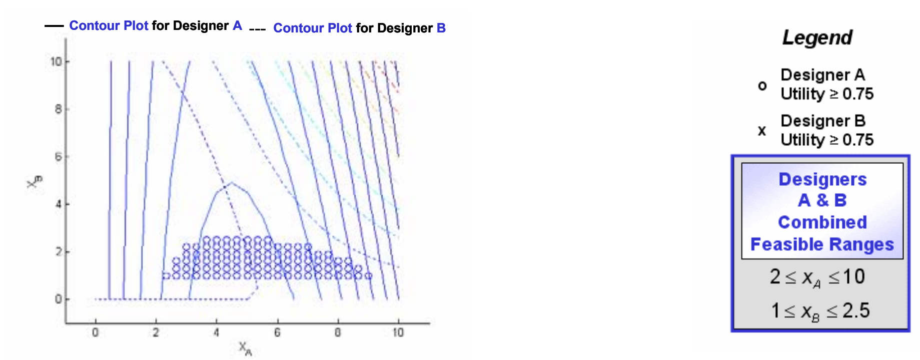


Figure 6-9 - Sub-System Conscious Feasible Design Space for Designer A

Figure 6-10 - Sub-System Conscious Feasible Design Space for Designer A

Step 6 – Communicate desirable regions of the collaborative design space in terms of ranges or sets of suitable design variable values.

The ranges communicated among the interacting designers in this case, are those indicated determined in the coupling-conscious exploration of design sub-spaces in *Step 5*, namely $x_A \subseteq [0,10]$ and $x_B \subseteq [0,2.5]$. It is noted, once again, that in the case of more complex problems involving higher dimensionalities, these communications are likely to take on the form of sets of design variable combinations.

Step 7 – Establish the ***intersection*** of regions of the collaborative design space and the design sub-problem specific design sub-spaces that contain feasible solutions for all interacting decision-makers in terms of design variable ranges or sets.

Establishing the intersection of regions of mutual interest is not as straightforward as it may sound. Careful consideration must be given to the manner in which the combinatorial effect of the various preferences is interpreted. System utility is calculated as an evenly weighted Archimedean sum. This, however, means that $U_{System} \ge 0.75$ does not necessarily imply $U_A, U_B \ge 0.75$. Instead, U_A could be as high as $U_A = 1$ and U_B as low as $U_B = 0.5$. Clearly, this is not what is desired in the pursuit of an evenly matched solution. Consequently, either (1) filters must be activated in order to eliminate such unsuitable solutions and ensure that $U_A, U_B \geq 0.75$, or (2) system level utility must be restricted to $U_{System} \geq 0.89$ for the evenly matched case of two objectives. This latter option, however is overly restrictive since a number of desirable solutions are likely to be eliminated, making the former the better choice.

In each decision-maker's independent identification and assessment of areas of the design space that are likely to yield desirable results in light of their assessed preferences, the extent of satisfaction clearly effects the extent of the feasible design space. This is indicated by the reduction in overlap resulting from increasing the desired level of satisfaction from $U_i \geq 0.75$ in Figure 6-12 to $U_i \geq 0.85$ in Figure 6-13. Thus, being overly ambitious may restrict other designers to the point of making the achievement of their objectives impossible. On the other hand, limiting an extensive collaborative design space to those solutions guaranteeing a higher level of satisfaction for all involved, reduces the inherent computational cost and increases the level of fidelity that is feasible for exploration. As previously mentioned, the computational burden of doing so can be reduced through reliance on experimental design techniques.

The overall effects of the manner in which the value of solutions is determined on the extent of the individual as well as the collaborative design spaces can be observed by comparing and contrasting Figure 6-12, Figure 6-13, and Figure 6-14.

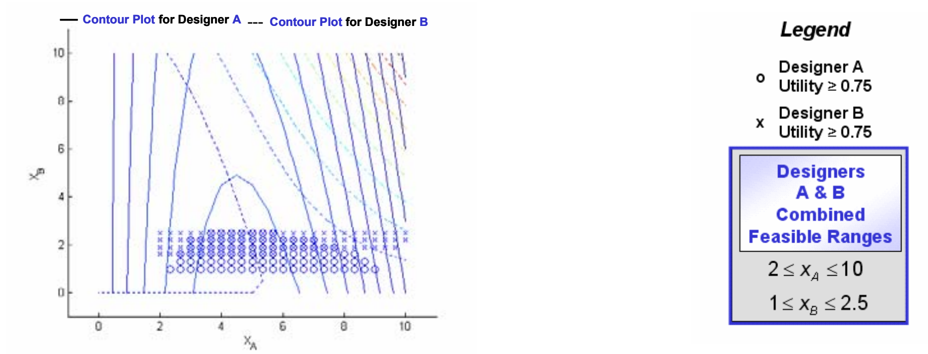


Figure 6-11 - Intersection of Sub-System Conscious Feasible Design Spaces

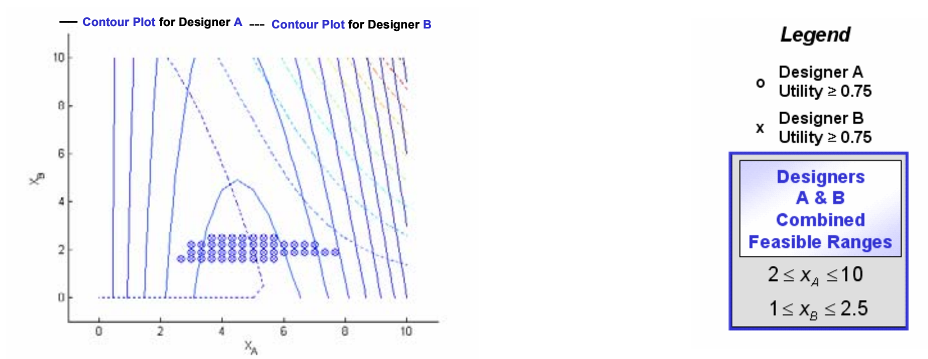


Figure 6-12 - Feasible Design Space Guaranteed to Yield Mutually Desirable Solutions

Step 8 – Communicate overlapping region of collaborative design space, determined in Step 7, to all interacting decision-makers.

As indicated in Figure 6-12 and Figure 6-13, there are a significant number of points within the shared design space that will result in solutions that range from being *desirable* to quasi *ideal* for both decision-makers. The resulting overlap is illustrated for combined utilities $U_{System} \geq 0.75$ and $U_{System} \geq 0.89$ in Figure 6-14. This intersection is then communicated and used as a basis for sensitivity assessment.

Although the region of the design space pictured in Figure 6-12 is perfectly suitable for further exploration, the design space pictured in Figure 6-13 meets more stringent requirements. This reduced area offers a higher level of performance for both decision-makers, as well as being sufficiently large for investigation of system level tradeoffs, and is consequently agreed upon after careful consideration. It is noted that the central benefit of the implementation of FACE is that all of the solutions in this design space are guaranteed to be mutually desirable. *Once such a design space has been successfully established any protocol can be adopted in order to arrive at a final solution to the strongly coupled problem.* An additional advantage is that the efforts of interacting designers are not wasted on exploring regions of the design space that are infeasible (for any of the other stakeholders) and thus unfruitful from a systems perspective. In the absence of overlapping areas of interest, stakeholders can progressively relax the constraints inherent in their preferences (i.e., lower their target utilities) until such overlap exists. Based on the associated satisfaction level, designers can then either reassess their expectations or seek alternative resources (e.g., a different technological base, etc.). Proceeding based on an adjusted system level bias (i.e., changing the manner in which the tradeoffs among the utilities of Designers A and B are weighted) as dictated by overarching design requirements at the systems level is another option when looking at the utility of the system. In the case considered here, equally weighted system level objectives have been assumed, thus not introducing such a controllable bias.

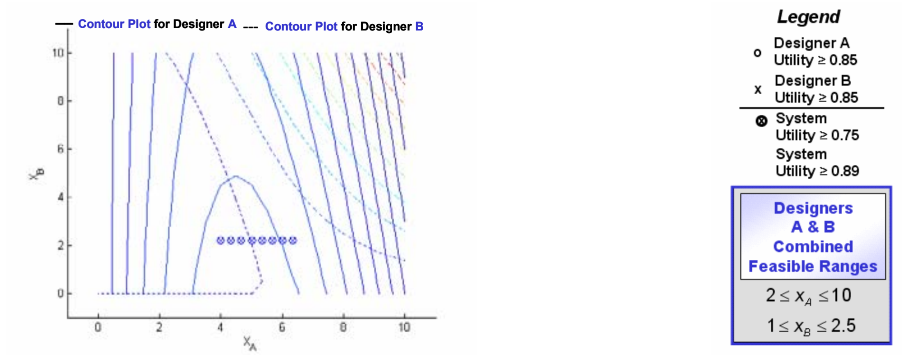


Figure 6-13 - Feasible Design Space Guaranteed to Exceed Mutually Desirable Solutions

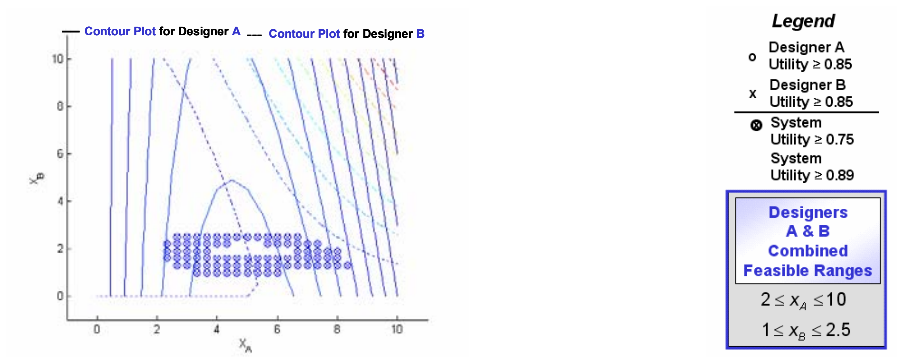


Figure 6-14 - Comparison of Feasible Design Space based on System Utility ≥ 0.75 & ≥ 0.89

6.4.3 System Conscious Conflict Resolution

Step 9a – Establish the design sub-problem (i.e., stakeholder) specific ***performance potential within*** the ***region of overlap***, constituting the revised collaborative design space.

Given the range communicated in *Step 8*, each of the designers must consider what is attainable in the agreed upon region of the design space (communicated either in terms of ranges or in the more likely case of non-convex design spaces in terms of sets). Based on this performance potential, (1) the feasible design space may be refined further by increasing the granularity of the space filling experiments and (2) sounder sequencing decisions may be made. Successive refinements of this design space are illustrated in Figure 6-15, where the final range for subsequent steps is determined to be $x_A \subseteq [3.945, 5.750]$ and $x_B \subseteq [2.000, 2.245]$. The performance potential for Designer A in this region is determined to range from a minimum of $U_A = 0.862$ to a maximum of $U_A = 0.984$ with an average performance of $U_A = 0.932$. The performance potential for Designer B on the other hand averages $U_B = 0.861$, ranging from $U_B = 0.832$ to $U_A = 0.886$. This translates to a system utility that is guaranteed to lie between $U_{System} = 0.874$ on the low end and $U_{System} = 0.912$ on the high end.

System Utility	Stakeholder Utility	X_A - MIN	X_A - MAX	X_B - MIN	X_B - MAX
> 0.80	>0.75	2.780	7.420	2.000	2.645
>0.80	>0.85	3.330	6.430	2.000	2.395
>0.89	>0.85	3.945	5.750	2.000	2.245

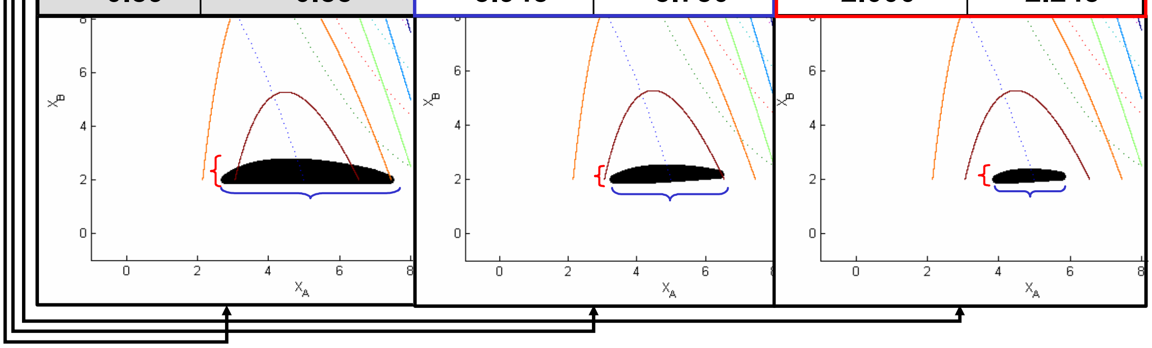


Figure 6-15 - Utility-Based Feasible Design Space Refinement

Step 9b – Determine the ***design sub-problem objective performance sensitivity to design variables controlled by other stakeholders***. Consider separately (1) sensitivity of design sub-problem specific objective achievement to changes in uncontrollable (i.e., controlled by other stakeholders) design variables, (2) sensitivity of design sub-problem specific objective achievement to changes in controllable design variables, and (3) the impact of changes in controllable design variables on the objective achievement of other stakeholders. These measures of responsiveness are referred to here as *sensitivity*, *power*, and *leverage* respectively.

Each designer, in turn, proceeds to determine his/her sensitivity to changes in design variables (Step 10), controlled by the other party. Specifically, the sensitivities of Designers A and B with respect to the achievement of their objectives F_A and F_B are given by $S_A = \frac{\partial U_A}{\partial x_B} = \frac{\partial U_A}{\partial F_A}\frac{\partial F_A}{\partial x_B}$ and $S_B = \frac{\partial U_B}{\partial x_A} = \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial x_A}$, respectively. The power of each designer to affect his of her objective attainment is calculated according to $P_A = \frac{\partial U_A}{\partial x_A} = \frac{\partial U_A}{\partial F_A}\frac{\partial F_A}{\partial x_A}$ and $P_B = \frac{\partial U_B}{\partial x_B} = \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial x_B}$. Finally, the leverage that one designer may assert over another in the event that negotiations take place is determined according to $L_A = \frac{\partial U_B}{\partial x_A} = \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial x_A}$ and $L_B = \frac{\partial U_A}{\partial x_B} = \frac{\partial U_A}{\partial F_A}\frac{\partial F_A}{\partial x_B}$, effectively constituting the complement of the sensitivities, calculated previously. In each of these cases, $\frac{\partial U_A}{\partial F_A} = -0.6933229138e^{0.69332291938F_A}$, $\frac{\partial U_B}{\partial F_B} = 2.4019576625e^{2.4019576625F_B}$, $\frac{\partial F_A}{\partial x_A} = 5x_A + x_B^{\;2} - 30$, $\frac{\partial F_A}{\partial x_B} = 2x_A x_B$, $\frac{\partial F_B}{\partial x_A} = -10x_B - x_A + 50$, and $\frac{\partial F_B}{\partial x_A} = x_B$. It is important to assess these measures of responsiveness with respect to designer utilities rather than raw objective achievement. Doing so, simultaneously normalizes any such measures and illustrates the net effect of any associated changes on designer satisfaction. The results of this assessment are provided in Table 6-2.

Table 6-2 - Indicators of Responsiveness in Feasible Collaborative Design Space

Indicator	Sensitivity	Power	Leverage
Average (Designer A)	15.48	82.30	0.82
Average (Designer B)	0.82	9.27	15.48
Domination (Designer A)	100%	100%	0%
Domination (Designer B)	0%	0%	100%

Step 10 – Communicate domain specific (stakeholder) ***sensitivity assessments*** in order to enable self assessment of precedence and ensure transparency for co-formulation of a system conscious tradeoff strategy.

In order to facilitate each stakeholder's assessment with respect to where he or she stands, the results (summarized in Table 6-2) are communicated. In this manner each of the interacting decision-makers is able to make a determination as to the range of payoffs that are possible as well as to who stands to gain or lose the most. Additionally, a better evaluation of the suitability of various protocols can be made by considering the particulars ("topological" intricacies) of the specific design space under consideration.

6.4.4 Investigating and Interpreting Stakeholder Responsiveness in Sequencing and Control Assignment

Step 11a – Establish stakeholder precedence based on the various measures of ***responsiveness***, communicated in Step 10.

Once each designer is able to form a comprehensive picture of his or her own responsiveness as well as that of other stakeholders, a determination as to the sequence most likely to produce a balanced or system conscious result can be made. A brief analysis or interpretation of the results, presented in Table 6-2 follows.

In terms of *sensitivity*, Designer A exhibits a dependence on x_B, the design variable controlled by Designer B, that outweighs the reliance of Designer B on x_A by a factor of almost 20. Conversely, the *leverage* Designer A may exert on Designer B is 1/20 that which Designer B might exert on Designer A. The critical indicator of responsiveness in this scenario, however, is that of the *power* exerted by each of the designers. Although the *power* of Designer A is only 9 times that of Designer B, the magnitude of this indicator is more than 5 times that of Designer A's *sensitivity* and more than 100 times Designer A's *leverage*. By the same token, although Designer B's *power* is more than 11 times his or her *sensitivity*, it is only 2/3 the magnitude of the *sensitivity* of Designer A. Since these comparisons are based on average measures of responsiveness, the extent of dominance for each indicator throughout the reduced design space is also taken into consideration. As shown in Table 6-2, the *sensitivity* of Designer A outweighs that of Designer B over the entirety of the region analyzed. The same is true for the *power*. With respect to *leverage*, the opposite is true, as would be expected based on this measure's relationship to *leverage*. These results are summarized in the SPL matrices of Figure 6-16. Another factor in evaluating a sequence likely to produce a balanced achievement of objectives on the systems level is that of performance potential. The edge in this regard clearly pertains to Designer A, whose lowest level of satisfaction in the design space being considered, exceeds the average level of satisfaction attainable by Designer B.

Based on the overall picture, provided by these indicators and the performance potential over the reduced region, established in *Step 9a*, the recommendation is thus for Designer B to take the lead by either (1) assuming precedence and fixing the value of x_B

before Designer A chooses x_A or (2) assuming total control over and responsibility for determining the final tradeoff. In the spirit of co-designing a solution, it is the first option that is pursued.

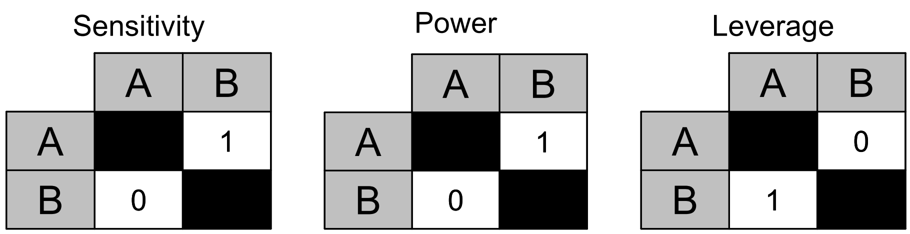


Figure 6-16 - Responsiveness throughout the Collaborative Design Space

Step 11b – Determine those ***design variable values most likely to produce desired design sub-problem results***, in light of the chosen sequence of resolution.

It is in this step that the sequence of design variable fixation, determined in Step 11a is executed. Based on this sequence Designer B must choose a suitable value for x_B (usually one likely to maximize personal payoff) and communicate said value to Designer A, who in turn will chose the value for x_A, yielding the highest payoff for him or her possible. Depending on the particular protocol chosen for accomplishing this step, Designer B may or may not have any insight into Designer A's strategy. In the absence of a BRC, Designer B should choose that value of x_B, having the lowest average sensitivity as well as the tightest distribution. Results obtained in this manner can be thought of as being robust to choices made by other stakeholders. Should Designer B be privy to Designer A's strategy in terms of a BRC or similar information, consideration of robustness is not required. Instead, the best course of action is for Designer B to determine that value of x_B, prompting Designer A to choose that value of x_A, yielding the most beneficial outcome. In this particular case, no such information is assumed to be available. It is note, once more, that any solution (possible within the collaboratively established region of the design space currently being considered) is a good solution, meeting or exceeding the expectations of either designer. With this in mind, Designer B chooses $x_B = 2.25$.

Step 12 – Communicate design variable values according to the sequence determined in Step 11.

As might be expected, the values determined to be the most amenable to obtaining a favorable solution are communicated in the order determined. In this case, the value of $x_B = 2.25$, chosen by Designer B is provided to Designer A.

Step 13 – Determine a ***balanced solution to the coupled design problem.***

Having received the value for x_B, Designer A must now chose that value of x_A that combined with Designer B's choice will maximize his or her payoff. In this case, no other stakeholders follow Designer A. Consequently, his or her choice finalizes the design as well as the underlying design process. If there were additional stakeholders involved, Designer A would be required to go through considerations quite similar to those faced by Designer B in *Step11b*. Regardless, $x_A = 4.98$ results in the highest payoff for Designer A, given Designer B's decision. This choice yields a final design solution of $(x_A, x_B) = (4.98, 2.25)$ with $U_A = 0.90$, $U_B = 0.87$, and $U_{System} = 0.89$. Considering the ranges of performance possible within the region considered and the natural bias of the design space towards the objectives of Designer A, this solution is quite balanced. It is stressed, once more, that the goal in pursuing a co-designed solution is not that of maximizing the utility of the system. Instead, solutions that are more evenly approximate the ambitions of all stakeholders are sought.

Before proceeding, a number of observations are made. As explicated in Section 5.1, there are a number of factors to consider in determining the manner in which a final design solution is best decided upon. The manner in which these indicators are interpreted strongly depends on the intricacies of the design space in question as well as any enterprise level concerns. For example, it may be more suitable to transfer responsibility from one designer to another (as in DFM) than sequentially choosing design variables values. Additionally, regardless of the indications derived from investigating the responsiveness of design sub-problem objective achievements to different stimuli, it is important to consider potential achievement possible.

Clearly, there are a number of different schemes for sequencing the various designers. Relevant scenarios and the resulting designs are summarized in Table 6-3. The solution scheme, chosen in this example corresponds to that of Designer B having precedence without being aware of the strategy pursued by Designer A. It can be seen that in the case of Designer B, reliance on BRCs does not improve performance as in the case of Designer A. This can be explained by considering the both the extremely low sensitivity of Designer B on one hand and his or her high leverage on the other. Thus, Designer B's objective attainment is mostly dependent on the portion controlled by him or her, while Designer A is greatly influenced by factors out of his or her control. Since the design space, as a whole, however, is biased towards the satisfaction of Designer A's objectives, however, Designer A retains an inherent advantage despite his or her high sensitivity. In general, it is asserted that more information is always preferred since it reduces the chances of adversely affecting the decision made by the stakeholder to whom precedence has been granted. As might be expected, total assignment of control improves subsystem level performance, resulting in the upper limits of performance potential for whatever designer is given control. Unfortunately, doing so often pushes the performance of the other stakeholders to their lower limits, defeating the purpose of co-design. Due to the increased potential of Designer A, however, a higher systems level utility is possible. From these comparisons it becomes clear that control and sequence greatly influence the final outcome of any decision. Two additional observations are made.

Considering the arguments and indications regarding designer responsiveness one might wonder why Designer B is favored, when Designer B so clearly dominates solutions obtained using traditional protocols. The answer lies in the facts that (1) the co-designed solution lies in a region of the design space not explored by any of these protocols and (2) responsiveness assessments are specific to the regions over which they are made. Thus, the picture suggested by Table 6-2 applies only to the small region, refined in Figure 6-15. This particular region is more favorable to the goals of Designer A that those of Designer B. Proceeding though the FACE method has thus effectively refocused conflict resolution to an area amicable to balancing system level objectives. Reducing the design space in this manner reduces problem interaction specific bias and reduces computational cost associated with exploring larger areas. This region is effectively stepped over by the other protocols, as indicated by the solutions provided in Section 6.5

Based on a consideration of sensitivity alone, Designer A would be given precedence in making the final determination. This is due to the fact that the sensitivity of Designer

A is a function not only of x_B, but also x_A. The sensitivity of Designer B, on the other hand, increases only with respect to x_B. As indicated in Table 6-3, however, this would be a mistake in seeking a more even balance of sub-system level performance. Consequently, the importance of considering the entire picture painted by the other indicators in conjunction with the performance potential is underscored. Thus, although the system level utility is slightly lower for a majority of the decision in which Designer B is given precedence, each such scenario matches constituent stakeholder utilities more evenly. Nevertheless, it is important to note that any of these solutions represent mutually desirable performance achievements, since they emanate from the feasible region of a methodically constructed collaborative design space.

6.4.5 A Note on the Reflection of Evolving Information Content

Clearly, any design process involving such a high degree of "introspection" is quite intensive, not only from a computation but also a formulation perspective. Each communication among the various stakeholders constitutes an evolutionary step in the information content particular to the problem at hand. This is true regardless of whether one considers changes at the system or the sub-system level. In the case considered in this chapter, the aspect of the various design sub-system undergoing the most changes is that of ranges for design variables being considered. In many cases, each such change will require model reformulation as extensively discussed in Chapter 3.

Table 6-3 - The Impact of Stakeholder Sequence on System & Sub-System Level Trade-Offs

Stakeholder Sequence	x_A	x_B	U_A	U_B	U_{System}	F_A	F_B
Total Control (Designer A)	5.20	2.00	0.98	0.84	0.91	132.4	269.6
Total Control (Designer B)	3.95	2.25	0.86	0.89	0.87	140.4	278.2
Precedence (Designer A) w/o BRC	5.20	2.25	0.90	0.87	0.89	137.8	275.4
Precedence (Designer B) w/o BRC	4.98	2.25	0.90	0.87	0.89	137.7	275.8
Precedence (Designer A) w/ BRC	5.20	2.00	0.98	0.84	0.91	132.4	269.6
Precedence (Designer B) w/ BRC	4.98	2.25	0.90	0.87	0.89	137.8	276.0

Similarly, irreconcilable mismatches spanning all or a sub-group of interacting stakeholders are likely to require a greater extent of iteration, also benefiting from a separation of declarative and procedural information. Much the same is true for any subsequent executions of an instantiated design process, necessitated by changes emanating form different parts (both up- and down-stream) of the design chain or the launch of derivative products.

6.5 CRITICAL ANALYSIS OF FACE BY COMPARISON TO TRADITIONAL PROTOCOLS

The application of the proposed alternative to conflict management in decentralized design was illustrated using a simple example in the previous section. Having explored and extensively analyzed a number of possible co-design scenarios, a detailed comparison to results obtained using more traditional game theoretic protocols follows. It is important to note that these protocols are applied in the manner most commonly instantiated. Consequently, the entire design space is considered and unbounded maximization of stakeholder payoffs is pursued.

6.5.1 Non-Cooperative Solution

The *non-cooperative* solution is modeled using a *Nash* protocol, in which each of the interacting Designers determines his/her best response to an assumed set of actions by the other party, as described in Section 2.2.5. The design sub-problems associated with individual designers are formulated as separate compromise Decision Support Problems (cDSPs) [143,155]. The solution of these cDSPs results in a set of BRCs, which encapsulate the designers' rational reactions. The *Nash Solution* is determined by intersecting or overlapping these BRCs. A particular solution can be chosen from within the resulting solution space, should multiple intersections exist. The mathematical formulation and solution of a *non-cooperative* game, using the cDSP, is shown in Figure 6-17. Although *non-cooperative* behavior is not usually desirable in collaborative design, the associated models can be useful in resolving conflict without tedious iteration (provided that a feasible solution exists), as indicated in Section 2.1.

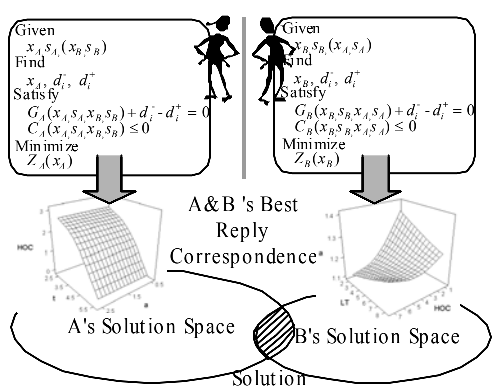


Figure 6-17 - Formulation and Solution of a Non-Cooperative Game using cDSPs in Engineering Design (adapted from Xiao [270])

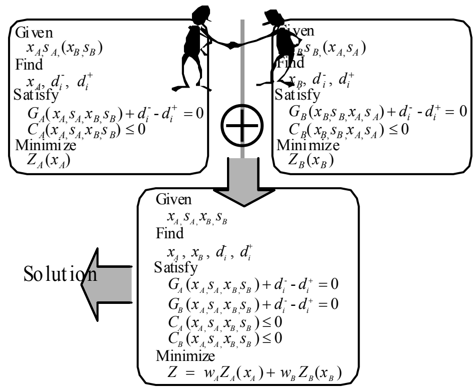


Figure 6-18 - Formulation and Solution of a Cooperative Game using cDSPs in Engineering Design (adapted from Xiao [270])

The Best Reply Correspondences, constituting the strategies for Designers A and B in achieving their assigned objectives during the solution of the system of non-linear equations introduced in Section 6.3 are

$$BRC_A = \frac{\partial F_A}{\partial x_A} = 5x_A + x_B^2 - 30$$

$$BRC_B = \frac{\partial F_B}{\partial x_B} = 10x_B - x_A + 50$$

Thus, the optimal values of design variables for minimizing F_A and maximizing F_B, given the manner in which control over the two design variables is divided, are determined by $x_A = \frac{30 - x_B^2}{5}$ and $x_B = \frac{50 - x_A}{10}$, respectively. These BRCs are superimposed on the contour plot (see Figure 6-4) in Figure 6-18. They are indicated by a series of "o" marks (for Designer A) and "x" marks (for Designer B), respectively. Their intersection at point $(X_A, X_B) = (1.25, 4.88)$ is indicated by a triangle and constitutes the *Nash Solution* to this two player *non-cooperative* game. The corresponding objective values are $F_A = 196.17$ and $F_B = 318.85$, respectively. Considering the BRCs, it also becomes clear that within the initial range of $x_i \subseteq [0,10]$, solutions are only found on the interval $x_i \subseteq [0,6]$, where objective function values range from $110 \le F_A \le 326$ and $200 \le F_B \le 325$, for each of the two Designers. Considering this *Nash Solution* in light of the best and worst solutions possible within the feasible ranges of x_A and x_B, it becomes apparent that only the objectives of Designer B are closely approximated, while those of Designer A fall considerably short.

6.5.2 Non-Cooperative Stackelberg Solution

The *Stackelberg Leader/Follower* protocol is a subset of *Non-Cooperative* Game Theory and is best suited when one stakeholder dominates the decision-making process (i.e., the informational dependence is strongly one-sided). Nevertheless it is also commonly employed when sequential resolution of a design process is more practical from an organizational perspective. The primary goal is that of eliminating iteration, traditionally associated with sequential interactions. In the *Stackelberg* formulation a *Leader* is chosen and assigned priority. The *Follower's* actions are predicted and considered accordingly in the solution of the *Leader's* design problem. This is usually accomplished via the formulation of a BRC. Once the *Leader* has fixed the values of his/her design variables, control is given to the *Follower*, who proceeds to determine the most suitable values of his/her design variables given the Leader's choice. Clearly the order in which stakeholder objectives are considered has a significant impact on the nature of the solution and the *Leader* is thus almost always at a tremendous advantage.

With respect to the example, there are two possible scenarios, corresponding to either of the two interacting designers taking the lead. Each produces drastically different results. In the first scenario, Designer A is the *Leader* and Designer B the *Follower*.

Correspondingly, Designer A formulates his/her decision, taking into consideration Designer B's most likely course of action (i.e., BRC_B). Once Designer A has made his/her determination, Designer B follows suit. The outcome is $(X_A, X_B) = (0.02, 5.47)$, corresponding to objective function values $F_A = 200.00$ and $F_B = 323.81$, respectively. The second scenario, pitches Designer B as the *Leader* against Designer A as the *Follower*. Correspondingly Designer B predicts the actions of Designer A and takes these into active consideration during the decision process using BRC_A. The resulting solution is $(X_A, X_B) = (1.58, 4.84)$, leading to objective function values of $F_A = 195.88$ and $F_B = 317.22$, respectively. The results from both scenarios are plotted for comparison in Figure 6-19. It is important to note that uncertainty usually associated with *Stackelberg* games, regarding the prediction of *Follower* actions, has been removed from this example by using the actual closed-form BRCs (and not regressed response surfaces) to model this response within the *Leader's* problem formulation. The solution obtained is thus an example of the best achievable answer associated with this scenario. Obviously, improvements are possible by considering robustness or ranged solution sets, as pointed out in Section 2.2.5.

6.5.3 Non-Cooperative Stackelberg with Control Transfer

Another possibility for the *non-cooperative* resolution of the inherent conflict between the two stakeholders is the absolute transfer of control to a single decision-maker. This stands in marked contrast to other *non-cooperative* protocols which preserve shared control over design variables and only differ in terms of the sequence in which the required decisions are made. Designers, given complete control over a domain, are likely to pursue their own objectives, in lieu of making more balanced tradeoffs. Besides a desire to maximize personal payoff, this is due in part to their inherent inability to (1) incorporate/evaluate preferences at the systems level and (2) interpret preferences of collaborators in light of lacking response information. Consequently, there are two possible scenarios. The first centers on Designer A assuming complete responsibility for making the coupled design decision. In the second scenario Designer B is placed in charge of solving the system. The solution in the former is $(X_A, X_B) = (6.00, 0.00)$ (marked with a circle in Figure 6-19) and has associated with it the objective function values $F_A = 110.00$ and $F_B = 200.00$. The outcome in the latter is $(X_A, X_B) = (0.00, 5.00)$, indicated by the square in Figure 6-19. Objective function values for Designers A and B are $F_A = 200.00$ and $F_B = 325.00$, respectively. Clearly these results are located at opposite ends of the spectrum. This is to be expected since stakeholders here are interested first and foremost in pursuing their own objectives.

6.5.4 Cooperative Solution

Cooperative resolution of coupled decisions usually constitutes reformulation of constituent design sub-problems as a single decision with multiple objectives (analogous to those governed by the individual decision-makers). In this case, individual compromise DSP formulations, associated with each designer, are merged in order to formulate a single compromise DSP for the combined decision problem, the solution of which represents the overarching system level decision (see Figure 6-18). Tradeoffs among the competing objectives are usually weighted in a manner that reflects system level prioritization. Here, an evenly matched Archimedean weighting scheme has been chosen; equal weights have been assigned to all objectives in the weighted sum. Achievement of objectives is normalized by the range of objective function values that may be achieved over the feasible range of design variables. The *cooperative* solution is determined to be $(X_A, X_B) = (0.00, 5.00)$, corresponding to objective function values $F_A = 200.00$ and $F_B = 325.00$, respectively. This solution is marked by a square in Figure 6-19. It is important to note that this result, though the consequence of equal weighting, is biased towards achieving the objectives of Designer B. In fact, these have been overachieved substantially, as indicated in Table 6-4. This is a direct consequence of the nature of the collaborative design space and the manner in which objectives are evaluated. Specifically, it is the aspect of normalization, required for a weighted sum, which introduces the biggest challenge. While normalization with respect to the best and worst attainable solutions makes sense from the perspective of strict maximization and minimization, the risk of overachievement of certain objectives and significant underachievement with respect to others is significant, as illustrated here.

6.5.5 Comparison and Contrast of Results

It is clear from both Section 6.4.4 and Sections 6.5.1 through 6.5.5 that solutions to the system of non-linear equations introduced in Section 6.3 vary widely, within the feasible ranges of the design variables considered. A majority of these solutions (see Table 6-4) are inherently biased towards the achievement of Designer B's objectives. Consequently these are clustered closely together in the vicinity of Designer B's global optimum (see Figure 6-19). The only solution, not included in this group, is that corresponding to a complete transfer of control to Designer A. As pointed out in Section

6.5.4 for the case of *cooperative* interaction models, this consistent bias is due largely to the underlying relationship among competing objectives within the shared design space, as well as the manner in which these are normalized. Algorithmic conflict resolution, based on the use of stakeholder BRCs (that are derived via design sub-problem objective optimization and represent static, *non-cooperative* design strategies), also does not remediate this inherent bias. In fact, results obtained in this manner tend to be inferior to *cooperative* solutions. With this in mind, an alternative coordination mechanism, aimed at facilitating more balanced conflict resolution via goal-oriented co-design, was introduced in Section 6.2.2 applied in a tutorial fashion in Section 6.4.

As evidenced by the results, reported in Figure 6-19 and Table 6-4, the *co-designed* solution, obtained via the proposed mechanism, is superior even to the *cooperative solution*. Although this may seem suspect at first, there is a perfectly reasonable explanation. To be specific, it is the manner in which the goals are formulated and design freedom is reduced in the traditional approach that renders it ineffective in this scenario. Had (1) a feasible collaborative design space been established and (2) system and sub-system objectives been treated separately, prior to any attempt at managing the conflict inherent therein, the *cooperative* solution would match a *co-designed cooperative* solution with the same Archimedean weighting. With this in mind, the extent to which the objectives of Designer A fall short of his/her requirements is indicated by the over-/under-achievement of objectives indicated in parentheses below the corresponding utilities (U_A and U_B) resulting from each of the protocols in Table 6-4. These numbers underscore the extent of the mismatch and the inherent bias in this problem towards achieving (and over-achieving) the objectives of Designer B. It is only through the goal-oriented interactions, associated with *co-designing* this system, that this conflict is successfully addressed and those solutions favoring the achievement of all objectives over the overachievement of just a few are successfully identified. The central mechanism explored in this chapter facilitates design problem exploration at the system as well as the sub-system level.

Table 6-4 - Comparison of Results Obtained Using Myriad Means of Conflict Resolution

Protocol	(X_A, X_B)	F_A	F_B	U_A	U_B	U_{SYS}	*Symbol*
Nash Solution	**(1.25,4.88)**	**196.17**	**318.85**	**0** (-32%)	**1** (+141%)	**0.5**	△
Stackelberg (Lead: Designer A)	**(0.02,5.47)**	**200.00**	**323.79**	**0** (-40%)	**1** (+148%)	**0.5**	✚
Stackelberg (Lead: Designer B)	**(1.58,4.84)**	**195.85**	**317.22**	**0** (-32%)	**1** (+139%)	**0.5**	◇
Cooperative Solution	**(0.00,5.00)**	**200.00**	**325.00**	**0** (-40%)	**1** (150%)	**0.5**	□
Complete Control: Designer A	**(6.00,00.0)**	**110.00**	**200.00**	**1** (+40%)	**0** (-29%)	**0.5**	○
Complete Control: Designer B	**(0.00,5.00)**	**200.00**	**325.00**	**0** (-40%)	**1** (150%)	**0.5**	□
Co-Designed Solution	**(4.98,2.25)**	**131.26**	**268.40**	**0.90** (0%)	**0.87** (0%)	**0.89**	✹

(x%) – Indicates Over- or Underachievement, Compared to Preference Range

Comparing the results obtained in Section 6.4.4, using the proposed communications protocol for dynamic coordination, with those obtained in Sections 6.5.1 through 6.5.5 via more traditional game theoretic conflict resolution schemes, it is clear that interactions based strictly upon BRC usage are likely to exclude a fair number of desirable solutions. This is supported by the clustering of solutions in Figure 6-19 and the illustration of regions of the shared design space meeting or exceeding the targets posed in the example, as focused upon in traditional optimization, in Figure 6-20.

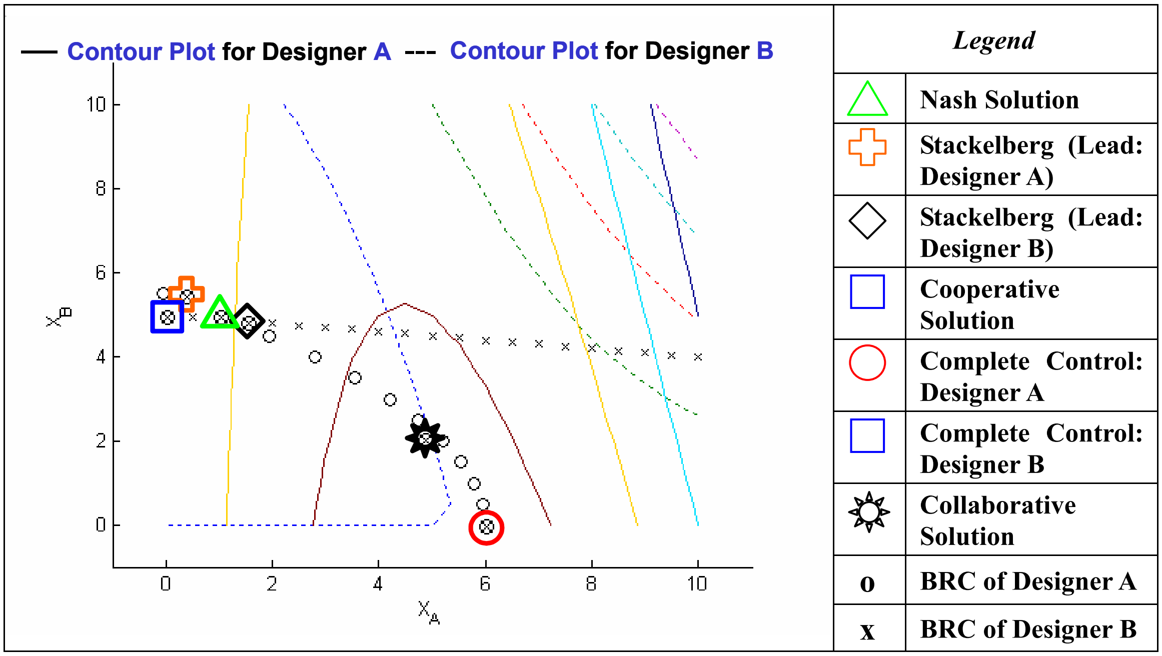


Figure 6-19 - Contour Plot of Non-Linear System, Stakeholder BRCs, and Solutions using Various Protocols

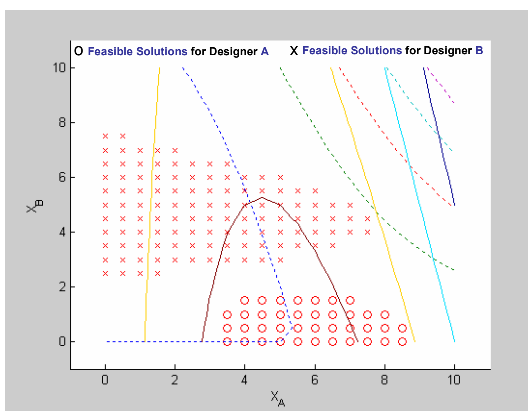


Figure 6-20 - Regions of the Collaborative Design Space Meeting or Exceeding Designer Goals in Traditional Formulation

Striving strictly to minimize or maximize the objective responses, pertaining to interacting individuals, unnecessarily eliminates acceptable regions of the shared, system level design space. Often this results in the absence of mutually desirable solutions (see

Figure 6-20), causing an often lengthy process of *trial-and-error* iteration. Moreover, solutions tend to be dominated by those objectives having lower sensitivities and more attainable goals. This is evident from Figure 6-7 through Figure 6-11, where larger regions of the collaborative design space are occupied by the "x" marks of Designer B than the "o" marks representing acceptable solutions for Designer A. Traditional solution schemes, based on *static* and *non-cooperative* strategies are thus likely to yield solutions that reflect the specific and inherent mathematical intricacies of problem formulation, rather than benefiting system response. The proposed coordination protocol provides for the effective and collaborative exploration of shared design spaces and ensures more balanced results by reducing inherent biases and facilitating dynamic interactions.

It is stressed once more that although the proposed coordination mechanism is intended to serve as an alternative to currently instantiated means of conflict resolution, the associated framework for ensuring the existence of feasible solutions can also be used in conjunction with more traditional game-, negotiations-, and optimization-based solution algorithms as indicated in 6.2.2. The inherent benefit in the modular architecture of the proposed approach is the support provided in establishing the groundwork for resolving coupled problems by virtually any means, appropriate to the particular problem at hand. Consequently, the framework is adaptable to many other hierarchical relationships, commonly associated with design processes and their corresponding interactions. Specific examples (not suited to *co-design*) include the transfer of responsibility for determining design parameters from upstream (e.g., design) to downstream (e.g., manufacturing) decision-makers and the *non-cooperative* behavior of entities in certain types of value chains. While the former have been handled predominantly through trial-and-error iteration and Stackelberg games, the latter has been addressed extensively through negotiations and Nash games.

6.6 CONFLICT RESOLUTION WITHIN THE FRAMEWORK

As indicated in Section 2.1, there are many possible means of conflict resolution in engineering design, ranging from traditional optimization to game theoretic formulations. The choice of the most appropriate collaboration mechanism for a particular application are problem and process dependent (see Section 5.6). A primary assertion made in this dissertation is that the manner in which a design process is constructed can have a far greater effect on solution quality than the computational mechanics underlying the reconciliation of stakeholder objectives. Similarly, the aim of increasing decision-maker agility is far better served via structured communications of decision-critical information content and design process modularization than (1) separation of activities until the point of resource commitment and (2) potential transfer of domain specific models.

It is important to notice that the system utilities of any of the potential *co-design* scenarios or sequences, the results of which are summarized in Table 6-3 are far better than any of those obtained using the traditional protocols. This trend can be attributed to the increased level of cooperation inherent in the interactive identification and subsequent exploration of a space of mutually desirable solutions. It is a well established fact that cooperative behavior will usually yield the best results. *Co-design*, as developed in this dissertation merely takes cooperation to another level by ensuring the consistent communication of strategic information throughout the design process in which the collaborating stakeholders are engaged and making it thus computationally feasible.

The most widely applicable aspect of FACE, however, is that of successfully identifying those areas of a design space that are suitable to the achievement of the objectives of all interacting stakeholders, formalized as the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod. Often this translates to more effective use of common resources, as indicated by the various levels of over- and under-achievement indicated in Table 6-4. Considering that all of the shared resources associated with these design processes (and considered during mathematical resolution) are projected in terms of the collaborative design space, it is the overarching systems level strategy (as reflected in protocol chosen, weights assigned, etc.) that will ultimately determine the manner in which these are dispensed. A wide spectrum of enterprise level concerns and degrees of cooperation can thus be accommodated while ensuring the existence of solutions, all the while sharing minimal information content on an as-needed basis. The precise manner in which this required information is disseminated is also amenable to problem or process specific customization and/or mathematical optimization. The aspect of autonomous decision-maker sequencing, formalized as the **I**nteraction-**C**onscious **C**oordination **M**echanism, unique to *co-designing* a coupled system, is merely a means of further solution refinement. These two components of the framework, focused upon in this chapter, are thus clearly distinct. With this in mind, specific aspects of validation and verification addressed are reviewed in the next section.

6.7 A NOTE ON VALIDATION

As indicated previously, the primary contributions of this dissertation are those emanating from Research Questions 2 and 3. Thus, while aspects of **Empirical Structural Validity** and **Empirical Performance Validity** with regard to Hypothesis 1 are addressed primarily in Chapter 3, this chapter is focused on substantiating these aspects with regard to Hypotheses 2 and 3.

6.7.1 Empirical Structural Validation of Hypotheses 2 and 3

As indicated in Figure 1-13 and Figure 1-15 **Theoretical Structural Validity** is established mainly in Chapters 1 and 2, as well as, in sections of Chapters 3, 4, and 5. This chapter, on the other hand, is designed to build confidence in the aspect of **Empirical Performance Validity**, as discussed in Section 6.7.2. Doing so effectively, however, requires the establishment of **Empirical Structural Validity**. As indicated in Section 1.4, this is accomplished mainly through making an argument for the appropriateness of the examples chosen to test the proposed method on. Since the aim of this chapter is to give the reader a detailed understanding of the manner in which different aspect of FACE are best deployed, the chosen example is simple, perhaps overly so. Nevertheless, the system of non-linear equations is representative of problems typically encountered in engineering design. More importantly, it is because of this relative simplicity that accuracy of results and intuitiveness of the method can be ascertained. In fact, the main reason for choosing an example of a strongly coupled decision that consists of no more than two design variables is that of making visual representation of the resulting design space (as well as associated performance aspects and stakeholder sensitivities) possible. Had a higher dimensional example been chosen, many of the nuances of an approach that is rather complex by nature would most likely have been occluded and lost on the reader. Specifically, it is through limiting the design space to two design variables that performance can be expressed in the third dimension.

The concept of a design space with feasible and infeasible regions becomes increasingly abstract as the number of dimensions increase. Since (1) this concept is central to the contributions made in this dissertation and (2) engineering design seldom is limited to two dimensions, it is important for the reader to be able to follow the discussion for the more realistic examples of Chapters 7 and 8. It is the author's hope to facilitate the formation of a working understanding by providing a visual image that can serve as an analogue or metaphor in later chapters. Additionally, the relative simplicity of the problem ensures that additional noise factors, affecting the analysis of results obtained, are not hidden in the numbers. The goal was to design a test case that was devoid of any distractions and easily solvable by exhaustive search in order to have a more objective view of the quality of solutions obtained. Finally, it is important to note that although mathematically simple, this problem constitutes an extreme case of mismatched objectives. In fact, the equations were manipulated so that the objective they represent are diametrically opposed.

6.7.2 Empirical Performance Validation of Hypotheses 2 and 3

Substantiation of **Empirical Structural Validity** is particularly important, considering that the aspect of **Empirical Performance Validity,** to which the majority of this chapter is dedicated is a measure of the method's usefulness (in a sense). It is thus crucial to be able to distinguish between coincidences and benefits derived as a result of the methods being validated. This goal is best served by choosing a transparent example, such as the non-linear system of equations described here.

This example is used in such a way that the evaluation of outcomes is possible both from a subjective and an objective perspective. Both of these components are important. While subjective aspects focus more on ease of use and intuitiveness, objective evaluation is centered on quantitative comparison of results obtained to those produced by more traditional (and well accepted) approaches. Since this example is solved in a step-by-step fashion with ample explanation, true to tutorial format, no pretenses are made about the effort involved in applying this approach. Virtually every aspect is detailed. The results obtained in applying the proposed methods are critically compared to those resulting from myriad other protocols, both quantitatively and quantitatively, as well as visually. Since comparisons are also made with respect to the actual global mathematical optimum, determined via exhaustive search, a certain degree of objectivity is ensured. The underlying models were also tested extensively for a number of different scenarios, in the process of which a comprehensive understanding of the design space, crucial to subsequent interpretation of results, was obtained. Finally, the outcomes make sense and are consistent with expectation.

6.7.3 Revisiting the Square

Theoretical Structural Validity of each of the three Hypotheses was explored and established in the first five chapters of this dissertation. Having substantiated the **Empirical Structural** and **Performance Validity** of Hypothesis 1 in Chapter 3, significant progress towards ascertaining these aspects of the validation strategy for Hypotheses 2 and 3 was made in this chapter. Additional, evidence in support of this claim will be provided in the following two chapters, each in turn highlighting distinct aspects of the method and inducing different stresses on performance. The overall progress in validating and verifying the various contributions of this dissertation is summarized in Figure 6-21 in accordance with the schedule of Figure 1-14.

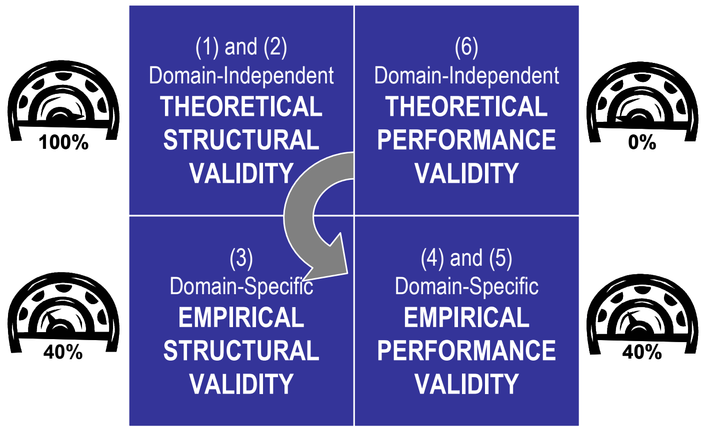


Figure 6-21 -Validation and Verification Progress through Chapter 6

6.8 A LOOK BACK AND A LOOK AHEAD

6.8.1 Revisiting the Roadmap

As indicated in the beginning of this chapter, and highlighted in Figure 6-22, the main goal pursued was that of composing the elements developed in Chapters 3 through 5 into a consistent and coherent whole and successful apply the resulting **F**ramework for **A**gile **C**ollaboration in **E**ngineering to a relatively transparent problem in tutorial fashion. The focus of the next chapter is to cement the empirical validation and verification commenced in this chapter by exploring the applicability and performance of the framework and its constituents to a representative engineering design problem, the responsibility over which is shared by more than a couple of designers. While the focus in this chapter was on a step-by-step implementation of the proposed methods, the focus in each of the two subsequent design examples will be on scalability and extensibility.

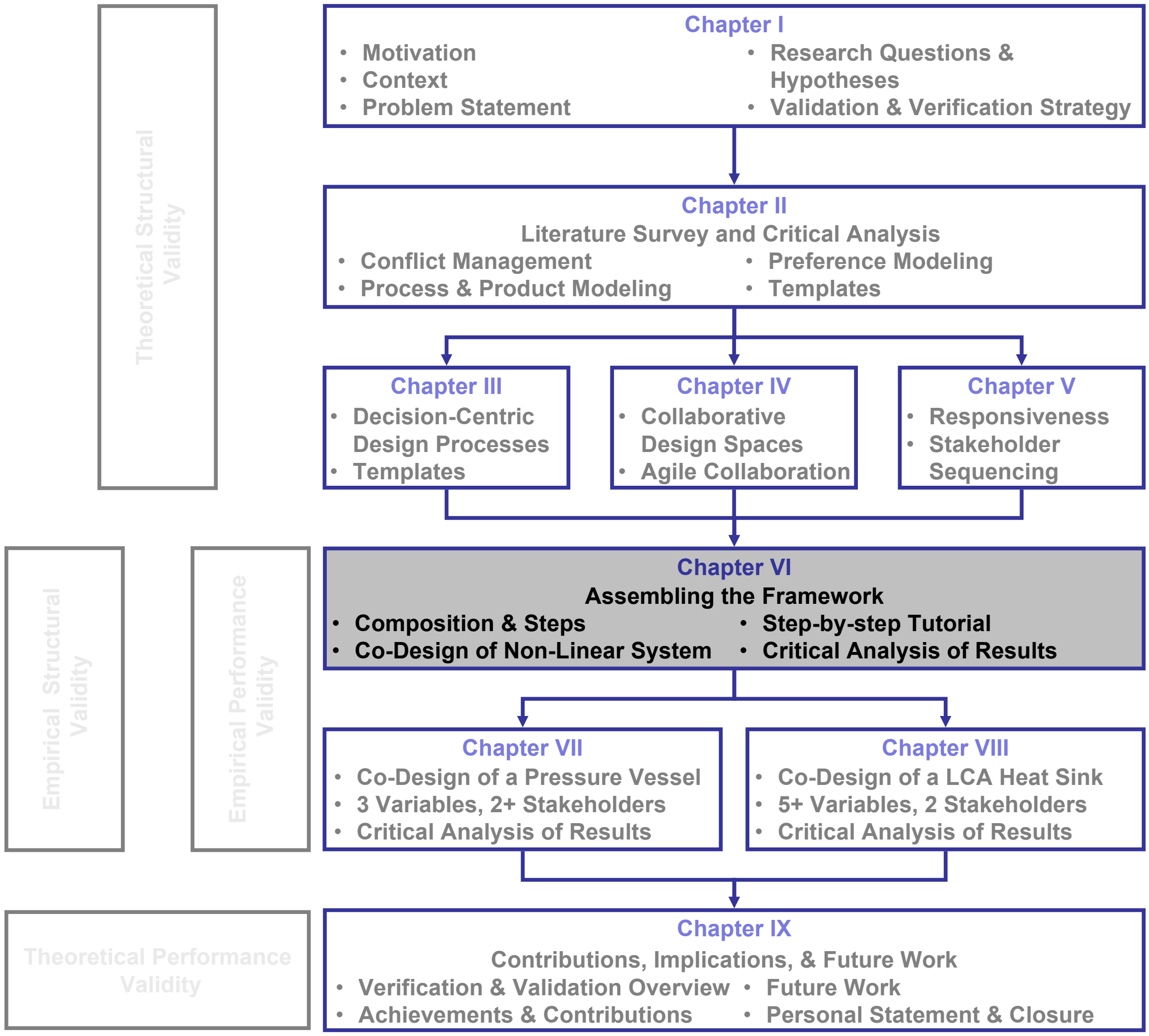


Figure 6-22 - Dissertation Roadmap

6.8.2 Assembling the Building Blocks

In this chapter the aspects of the **F**ramework for **A**gile **C**ollaboration in **E**ngineering, developed in Chapters 3 through 5 were assembled. The resultant method can be considered to consist of two integral, but distinct parts, namely (1) a structured means for effectively identifying, exploring, and managing collaborative design spaces and (2) a coordination mechanism for co-design, an alternative interactions protocol for conflict resolution, centered on continued communication, concise coordination, and non-biased achievement of overarching system as well as sub-system objectives. Both aspects are based on structuring the interactions of decision-makers, acting as stakeholders in the solution of *strongly coupled* design problems, and ensuring more balanced solutions, as illustrated through application to a simple example. They are embodied as the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod and the **I**nteraction-**C**onscious **C**oordination **M**echanism, respectively.

On the whole, stakeholders are guided through the (1) establishment and assessment of collaborative design spaces, (2) identification and exploration of regions of acceptable performance, (3) progressive reduction of ranges in design variables considered, and (4) assessment of design sub-problem sensitivity. Most importantly, stakeholder dominion over design sub-system resolution is preserved throughout the duration of a given design process. Goal-oriented collaboration that (1) more accurately represents the mechanics underlying product development and (2) facilitates interacting stakeholders in achieving their respective objectives in light of system level priorities via improved utilization of shared design spaces and avoidance of unnecessary reductions in design freedom is thus supported. Continued interactions are rendered both more effective as well as efficient, thereby constituting a *viable alternative* to well established game theoretic means of structuring interactions and *a solid foundation for moving beyond strategic collaboration towards co-design.*

CHAPTER 7 - COLLABORATIVE DESIGN OF A PRESSURE VESSEL

The author's primary goal in this chapter is the *empirical* validation with regard to *structure* and *performance* of *Hypotheses 2* and *3*. Confidence in *empirical structural* validity is established with regard to the appropriateness of the design problem considered. *Empirical performance* validity is established through demonstrating the usefulness of the proposed approach in supporting a number of designers in making strongly coupled decisions. This aim is pursued using an example focusing on the collaborative design of a pressure vessel by first two and then three designers, sharing control over a common design space and pursuing conflicting objectives. The implementation of relevant aspects of the framework are illustrated in great detail with a focus on the intricacies of managing the inherent conflict among the interacting stakeholders.

The details of the pressure vessel design problem are introduced in Section 7.1. Details regarding the appropriateness of this example to the overall validation and verification strategy pursued in this dissertation are provided in Section 7.3. Section 7.4 contains the details of the application of the framework in supporting the efforts of two designers, problem complexity is increased in Section 7.5, where the total number of designers is increased to three. Results obtained in both cases are compared to those emanating from addressing the same problem using more traditional means in Section 7.6. Continuity and coherence with respect to the remainder of the dissertation are established in Section 7.7.

7.1 VALIDATION AND VERIFICATION WITHIN CHAPTER 7

As indicated in Section 1.5.1, the **F**ramework for **A**gile **C**ollaboration in **E**ngineering, first synthesized in Chapter 6, is applied to an example of more realistic and representative complexity in this chapter. The focus is on cementing the **Empirical Structural Validation** and **Empirical Performance Validation** of the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod and the **I**nteraction-**C**onscious **C**oordination **M**echanism, posed in response to *Research Questions 2* and *3*, respectively. The Collaborative Pressure Vessel Design example is chosen to illustrate the scalability of the methods to more than two designers. The problem is partitioned so as to stress the method with regard to the assurance of a win/win scenario. Specific aspects of this effort are summarized in Figure 7-1 and addressed in more detail in Section 7.3. Although, the process of verifying the **Empirical Structural Validation** and **Empirical Performance Validation** of *Hypotheses 2* and *3* is concluded in Chapter 8, all considerations regarding **Theoretical Performance Validity** are deferred to Chapter 9.

7.2 PRESSURE VESSELS

7.2.1 Applications of Pressure Vessels in Engineering Practice

Pressure Vessels are something of a quintessential example for the illustration of activities associated with collaborative design, perhaps attributable to their ubiquity. In short, pressure vessels can be defined as structures, designed to contain fluids at pressures differing from those of their surroundings, while manifesting no change in the volume occupied by the fluid. Common examples of pressure vessels include gas tanks (i.e., propane, oxygen, nitrogen, etc.), recompression chambers, the habitat of submarines and space ships, nuclear reactors, and both pneumatic and hydraulic reservoirs. Usually pressure vessels are designed to withstand a certain pressure at a certain temperature, commonly referred to as the *Design Pressure* and the *Design Temperature*. Since the there is an inherent element of danger and pressure vessel design is tightly regulated by various design codes. Examples include those published by the American Society of Mechanical Engineering (ASME) on the North American continent and the Pressure Equipment Directive of the European Union (PED) and Japanese Standards Association (JIS) in the international arena. For more information the reader is referred to Refs. [8,10].

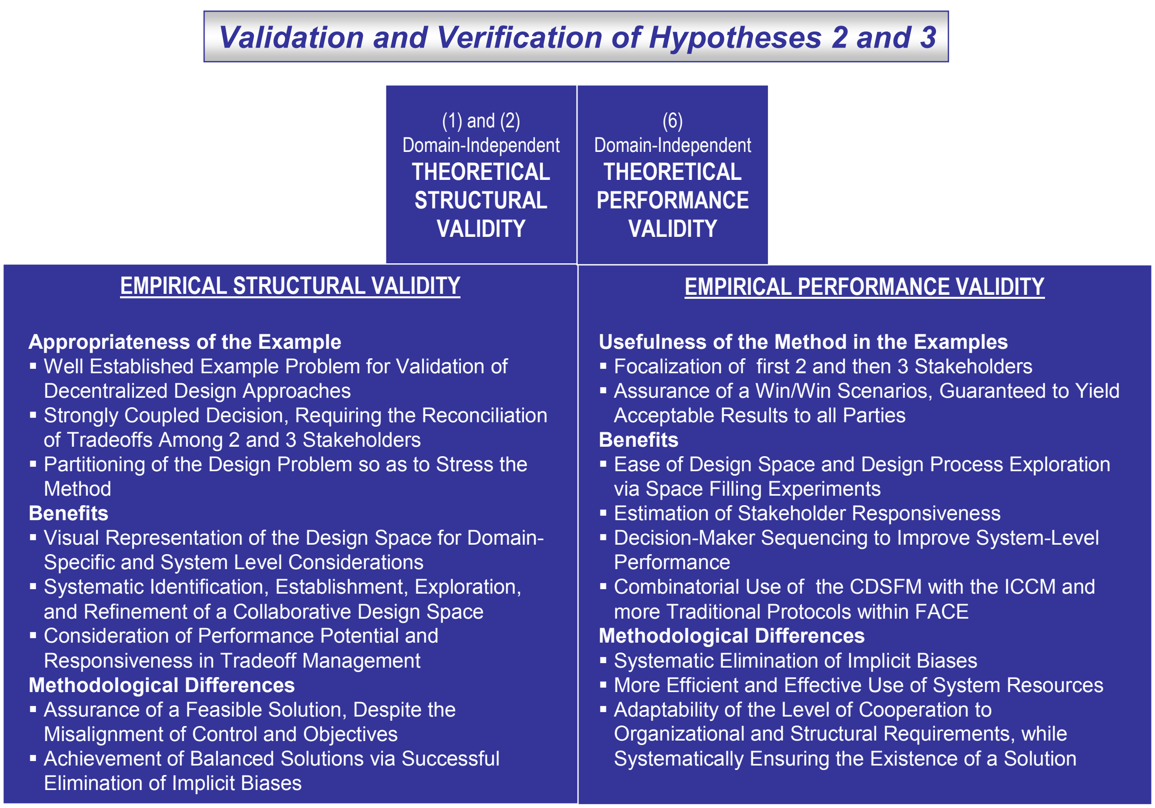


Figure 7-1 - Aspects of Validation and Verification Addressed in Chapter 7

The focus in this example is on the design of *thin-walled* pressure vessels, generally defined as having a radius that is more than five times the magnitude of wall thickness.

This relationship of $5T - R \leq 0$ constitutes a common constraint. Additionally, the thin-walled assumption allows for the assumption of a plane state of stress, where principal stresses are aligned with the chosen coordinate systems (see Figure 7-2). The resulting subclass of engineering problems involves stresses in thin plates or free surfaces of structural elements. It is through assuming that the third and smallest principal stress is zero that a three-dimensional state of stress can be reduced to a two-dimensional one. Since the remaining two principal stresses lie in a plane, these simplified 2D problems are called plane stress problems [65].

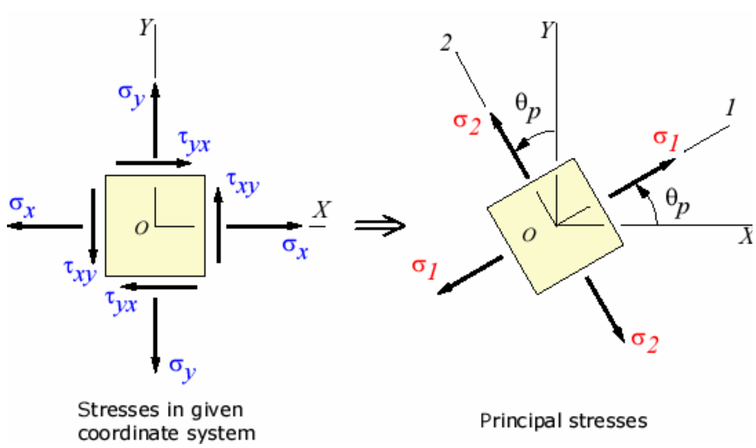


Figure 7-2 - Principal Stresses for a Plane Stress Element [65]

Clearly there are many different types of pressure vessel, although the two main classifications are based on whether the vessel is spherical or cylindrical in nature, as illustrated in Figure 7-3. While the stress exerted on the walls of a spherical pressure vessel remains constant regardless of directionality, this is not the case for the cylindrical design considered here. For this type of vessel, a careful distinction is made between the *longitudinal* and *circumferential* or *hoop* stress. These are often denominated as σ_l and σ_h (σ_{circ} , here), respectively, and defined in Section 7.2.2. The primary reason for choosing to align the coordinates used for analysis along the longitudinal and transversal axes is to take advantage of axial symmetry. The effect of choosing such an axisymmetric coordinate system is the effective elimination of shear stresses and the alignment of the principal stresses (i.e., σ_l and σ_h) with the chosen coordinate axes. In terms of the element depicted in Figure 7-2, σ_l corresponds to σ_x and σ_h to σ_y, both of which are aligned with the principal axes without the need for coordinate transformation.

It is noted that since the value of hoop stress is twice the value of the longitudinal stress, it is this value that typically serves as a design constraint (i.e., $\sigma_{circ} = \frac{PR}{T} \leq S_t$). Furthermore it is assumed that the pressure in this application is exerted from the inside. Although the equations, given in Section 7.2.2 hold true regardless of whether pressure is being contained or kept out, the sign of the pressure changes from being positive to being negative. With this in mind, relevant relationships, pertinent to pressure vessel design are elaborated upon in the following section.

7.2.2 Governing Equations

Although cylindrical pressure vessels can have myriad end configurations (flat, rounded, tapered, etc.), the example considered in this chapter is composed of a cylindrical tube of constant cross section, sealed off by two hemispherical pieces of equal diameter, as illustrated in Figure 7-4.

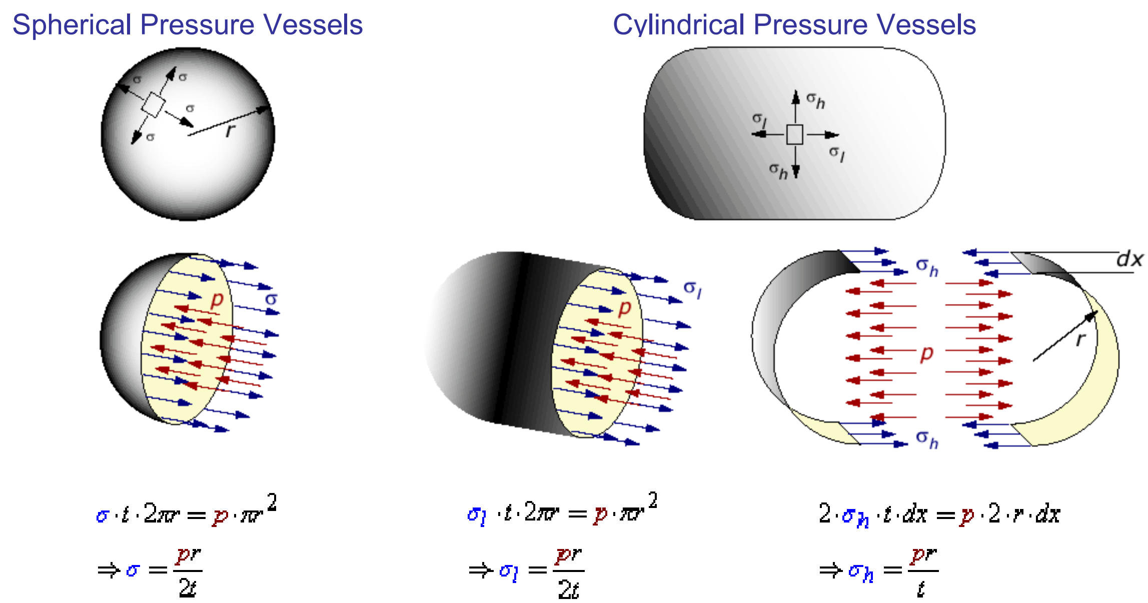


Figure 7-3 - Spherical and Cylindrical Pressure Vessels [65]

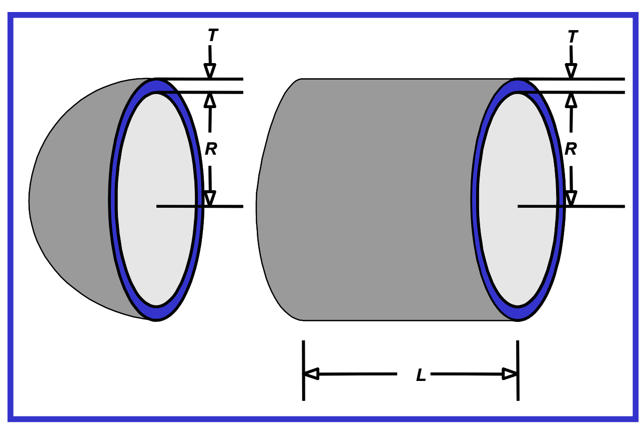


Figure 7-4 - Cylindrical Pressure Vessel with Hemispherical Ends

The relations and parameters factoring into the design of such a thin-walled pressure vessel are considered in terms of the various cDSP descriptors they correspond to, as follows. There are a total of three design variables, namely the inner radius of the pressure vessel, denoted by R, the overall length of the midsection, denoted by L, and the wall thickness T. This thickness is constant for both the mid and end sections. Other parameters of interest are the density ρ and strength S_t of the chosen material and the Design Pressure *P*, which the vessel will have to withstand. Both the material and the operating pressure are assumed to be given. Design Temperature is not considered in this example. The various objectives associated with this design are the minimization of weight, the maximization of volume, and the minimization of cost. The overall weight of the pressure vessel is given by

$$W(R,L,T) = \pi\rho\left[\frac{4}{3}(R+T)^3 + (R+T)^2 L - \left(\frac{4}{3}R^3 + R^2 L\right)\right]. \qquad (7.1)$$

As one might expect, this is a straight forward calculation centered on multiplying the volume of material used by the material's density. Consequently, weight is affected by all three design variables. Pressure vessel volume is calculated according to

$$V(R,L) = \pi\left[\frac{4}{3}R^3 + R^2 L\right]. \qquad (7.2)$$

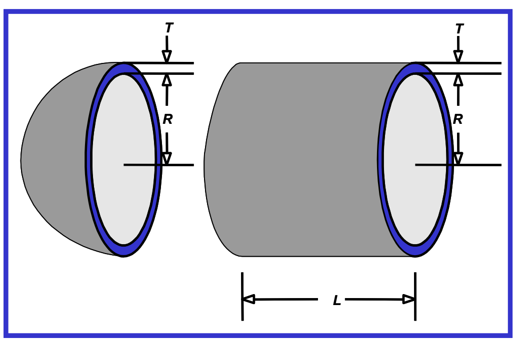
It is important to note that the volume calculation is independent of thickness and that ***R*** is the inner diameter of the pressure vessel. The thickness ***T*** is measured from ***R*** outward and constitutes the difference between inner and outer radii. The final objective is cost, estimated according to

$$C(R,L,T) = 0.6224RTL + 1.7881R^2T + 3.1611T^2L + 19.8621RT^2. \qquad (7.3)$$

This relation is adopted from the work of Sandgren [195] and has been used previously in the illustration of Game-Based Design by Marston [133].

The achievement of these objectives, assigned to various stakeholders in the example, are subject to a number of constraints. The first constraint is the requirement that the hoop stress (in this case the maximum principal stress as explained in Section 7.2.1) not exceed the ultimate tensile strength of the chosen material. This is expressed as $\sigma_{circ} = \frac{PR}{T} \leq S_t$. Additionally, in order to ensure that the thin-walled pressure vessel assumption is not violated, the radius must be at least five times the thickness. Hence, $5T - R \leq 0$. Additionally, constraints are placed on the overall dimensions of the pressure vessel both with respect to the longitudinal and transversal dimensions, given by $L + 2R + 2T - H_{PV} \leq 0$ and $R + T - \frac{W_{PV}}{2} \leq 0$, respectively. In these expressions H_{PV} is the overall allowable height of the envelope occupied by the pressure vessel and W_{PV} is the total acceptable width. It is noted that all of these constraints are stated as inequality constraints in the format, typically used in traditional optimization, although this clearly is not a required. Relevant parameters are summarized in Figure 7-5.

Designing a Pressure Vessel



Variable Bounds (in.)

$R_{min} \leq R \leq R_{max}$

$L_{min} \leq L \leq L_{max}$

$T_{min} \leq T \leq T_{max}$

Important Relations

$$W(R,L,T) = \pi\rho\left[\frac{4}{3}(R+T)^3 + (R+T)^2 L - \left(\frac{4}{3}R^3 + R^2 L\right)\right]$$

$$V(R,L) = \pi\left[\frac{4}{3}R^3 + R^2 L\right]$$

$$C(R,L,T) = 0.6224RTL + 1.7881R^2T + 3.1611T^2L + 19.8621RT^2$$

Constraints

$$\frac{PR}{T} - S_t \leq 0$$

$$5T - R \leq 0$$

$$R + T - \frac{W_{PV}}{2} \leq 0$$

$$L + 2R + 2T - H_{PV} \leq 0$$

Figure 7-5 - Relevant Considerations in Pressure Vessel Design

7.2.3 Parametric Design of Pressure Vessels

Clearly, any original design effort is much more comprehensive than what is studied here. Original design would warrant the designer freedom over choosing material, topology, geometry, etc. In this case, stakeholders have been limited to determining the values for each of the three design variables, subject to the constraints discussed in Section 7.2.2, in pursuit of their respective objectives.

7.2.4 Single and Multiple Stakeholder Design Processes for Pressure Vessels

The main difference between single and multiple stakeholder design processes is the assignment of control over the various design variables factoring into a given decision. When a single designer is charged with solving a problem, that designer is the sole stakeholder and consequently has absolute control over the manner in which tradeoffs among competing objectives are struck. Since this is a point that has been stressed extensively throughout this dissertation it will not be reiterated here. Two cases are considered in the sections to follow. Section 7.4 is focused on pressure vessel *co-design* by two stakeholders, while Section 7.5 is dedicated to exploring the scalability of the proposed framework to three decision-makers. In the first case one of the two designers controls two design variables and the other one; two objectives are considered. In the second case, each of the three designers controls a single design variable; three objectives are considered. With this in mind a brief overview of validation and verification in this chapter follows.

7.3 VALIDATION AND VERIFICATION OF THE HYPOTHESES THROUGH THIS EXAMPLE

As indicated previously, this chapter is focused primarily on substantiating the **Empirical Structural Validity** and **Empirical Performance Validity** of Hypotheses 2 and 3. Specifically, the aim is to illustrate the extensibility of the methods proposed in this dissertation to design processes involving a larger number of decision-makers. The discussion is centered on the quality of results produced and the manner in which these compare to the outcomes obtained using readily accepted techniques. Note of relative ease of implementation and overall usefulness is also made. Consequently, less emphasis is placed on details associated with step-by-step implementation. Aspects, unique to this example, of course are expounded upon when pertinent to the discussion.

7.3.1 Empirical Structural Validation of Hypotheses 2 and 3

As indicated in Figure 1-13 and Figure 1-15 **Theoretical Structural Validity** is established mainly in Chapters 1 and 2, as well as, in sections of Chapters 3, 4, and 5. This chapter, much like the previous one, is designed to build confidence in the aspect of **Empirical Performance Validity**, as discussed in Section 7.3.2. Doing so effectively, requires the establishment of **Empirical Structural Validity**. As indicated in Section 1.4, this is accomplished mainly through making an argument for the appropriateness of the example chosen to test the proposed methods. The aim of this chapter is to underscore the scalability of FACE to more realistic design applications, especially with regard to the extent of their decentralization. A case for its overall usefulness is also made. Nevertheless, the example is simple enough to allow for careful scrutiny of the results obtained. The transparency of the problem is as important as (if not more important than) that (1) with which the method is being implemented and (2) the solution is analyzed. Although, the key concept of a collaborative design space associated with the pressure vessel is not as easily visualized and explored as in the two-dimensional tutorial example, explored in Chapter 6, it is possible to convey a working understanding to the reader using three-dimensional plots in conjunction with color maps. That is to say, that solution quality is correlated with color warmth. As indicated previously, it is this author's belief that most readers are visually oriented and comprehension of any (complex or convoluted) process is aided by the ability to picture the underlying mechanics. The goal is to extend the concepts explored in Chapter 6 and slowly building up to the complex engineering design example, tackled in Chapter 8, where due to higher dimensionality any attempt at comprehensive visualization (with the exception of projections) is futile.

As in the case of the system of non-linear equations, relative simplicity ensures that additional noise factors, affecting the analysis of results obtained, are not hidden in the numbers. Despite the increase in complexity over the previous example, even high fidelity exhaustive search is feasible and will be used in order to construct a more objective view of the quality of solutions obtained. The pressure vessel problem is strongly coupled, whether control is shared by two or three designers. As will be pointed out in later sections, the manner in which control is divided allows for the exploration of what happens when influence and affect are one sided.

As Marston indicates in Ref. [133], the example of pressure vessel design has been used successfully for the purpose of illustrating game theoretic principles in engineering design by Rao and coauthors in Ref. [186] and Lewis and Mistree in Ref. [127]. Despite the acknowledgement that designing a pressure vessel is not naturally a multi-player design, a single objective formulation being more common, Marston nevertheless relies on this example to illustrate the application of his decision and game theory based design framework. To reiterate, Rao and coauthors focus on the development of analytical solutions for both cooperative and non-cooperative two-player scenarios. The efforts of Mistree and Lewis are complementary in so far that the focus is on the identification of cooperative and non-cooperative equilibria when analytical solutions are not feasible. Marston extends these efforts by considering three players and non-deterministic parameters. Bargaining solutions in the context of grand coalitions are also considered. Since it is a fundamental aim in this research to offer a viable alternative to traditional game theoretic instantiations as well as addressing some of the fundamental shortcomings of decentralized design strategies thus far, the pressure vessel design problem is deemed ideally suited as a starting point.

Moreover, pressure vessels are some of the most basic components implemented in the practice of mechanical engineering. Yet, they are also among the most highly regulated. Despite the relative mathematical simplicity of the cases typically used for the validation of decentralized design techniques, the resulting problems are nevertheless complex enough to illustrate pertinent aspects of tradeoff management. Additionally, control over the various objectives associated with pressure vessel design, such as the maximization of volume, the minimization of weight, and the minimization of cost, is easily divided among different stakeholders. Since each of these objectives, defined in Section 7.2.2, is a function of at least two of the three design variables over which control is shared, the affect of decision-maker choices on the options available to those with whom they interact is readily observable. It is precisely because of the resultant transparency of this design example that it is suited for validation and verification.

7.3.2 Empirical Performance Validation of Hypotheses 2 and 3

Substantiation of **Empirical Performance Validity,** to which the remainder of this chapter is devoted, is aimed at building confidence in the methods' overall usefulness. It is thus crucial to be able to distinguish between coincidental and consequential benefits derived from its application. This goal is best served by choosing a relatively transparent example, such as the design of a pressure vessel where engineering judgment can be relied upon (at least in part) to evaluate the intuitiveness of results.

This example is used in such a way that the evaluation of outcomes is possible both from a subjective and an objective perspective. Each of these components is important. While subjective aspects focus more on ease of use and intuitiveness, objective evaluation is centered on quantitative comparison of results obtained to those produced by more traditional (and well accepted) approaches.

In this example, scalability with respect to the extent of decentralization is demonstrated. The benefits of FACE in resolving conflicts among first two and then three designers with respect to the same problem are documented. Based on the success of doing so effectively without any significant increase in the degree of complexity, an argument is made for the extensibility of FACE to *n* designers. It is important to note that although this example is not presented in tutorial fashion, no pretenses are made about the effort involved in applying FACE. Aspects, relevant to the discussion are emphasized as appropriate. Both quantitative and qualitative comparisons are made and parallels drawn with respect to the usefulness of this approach and those traditionally relied upon in Section 7.6. Moreover, traditional protocols are applied in conjunction with elements of FACE in order to illustrate the adaptability of this framework to myriad situations and the more fundamental and far reaching benefits, inherent within the approach espoused. As in the previous example, a certain degree of objectivity is ensured by making comparisons with respect to the global (mathematical) optimum, determined by means of exhaustive search. It is noted that extensive exploration of the design spaces associated with each of the designers for a number of different scenarios lead to a comprehensive understanding of the problem, instrumental in the interpretation of results. Finally, the outcomes make logical sense and are consistent with engineering expectation.

7.3.3 Revisiting the Square

As the reader may recall, **Theoretical Structural Validity** of each of the three Hypotheses was explored and established in the first five chapters of this dissertation. Having substantiated the **Empirical Structural** and **Performance Validity** of Hypothesis 1 in Chapter 3, further progress towards cementing these aspects of the validation strategy for Hypotheses 2 and 3 is made in this chapter. Emphasis is placed on building confidence in the extensibility of FACE to engineering design problems of representative complexity. The first step in doing so, namely establishing the potential to effectively support *n* designers, is accomplished in this chapter. The second step, centered on ascertaining the value of FACE in addressing problems of *n* dimensions is focused upon in Chapter 8. The desired outcome is that of building confidence in the suitability of the methods proposed in this dissertation for facilitating the design of complex engineering systems. The overall progress with regard to validation and verification is summarized in Figure 7-6, where percentages correspond to Figure 1-14.

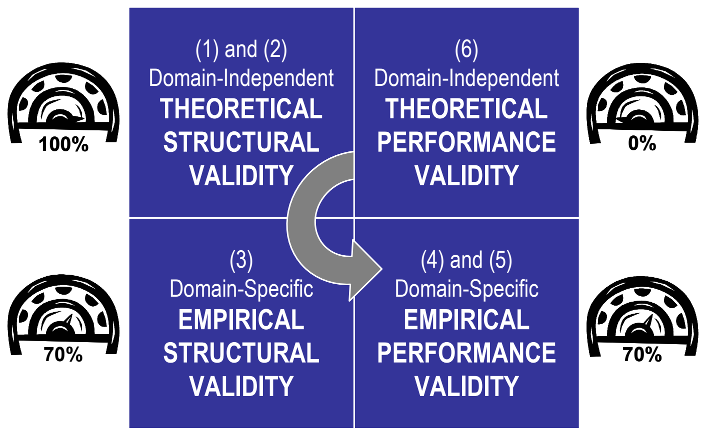


Figure 7-6 -Validation and Verification Progress through Chapter 7

7.4 COLLABORATIVE DESIGN OF A PRESSURE VESSEL BY TWO DESIGNERS

7.4.1 Problem Statement and Development of Example

As indicated in Section 7.2.1, there are many different applications for pressure vessels. The application, focused upon in this example is that of a container for general use in the chemical, food, pharmaceutical, power, ink, and adhesives industries. The general working conditions for such a device are characterized by operating pressures that vary from 90 to 200 psi, working temperatures (although not explicitly considered here) and that vary from 100 to 300 ^{o}F, resistance to corrosion, and resilience to changes in temperature. Typically, devices for this type of application, are made of stainless steels. The particular composition of stainless steel (see Table 7-1 for an example) is often selected based upon criteria such as resistance to corrosion, resistance to oxidation and sulfidation, toughness, cryogenic strength, resistance to abrasion and erosion, surface finish, strength under elevated temperatures, thermal conductivity, etc. Weighing the associated tradeoffs leads to the choice of *304 stainless steel*. This steel is the standard "18/8" stainless steel and often considered to be the most versatile of all the stainless steel grades. It is commonly used for manufacturing equipment for food processing, heat exchangers, beer barrels, wine storage tanks, and containers for chemical transport. Additionally, it has excellent forming and welding properties and is thus ideally suited for the intended application. Typical mechanical properties for this material are shown in Table 7-2.

Table 7-1 - Typical Chemistry of 304 Stainless Steels (% Max. Unless Range)[10]

Stainless Steel	C	Mn	P	S	Si	Cr	Ni
304	0.08	2	0.045	0.03	1	18.0 to 20.0	8.0 to 10.5
304L	0.03	2	0.045	0.03	1	18.0 to 20.0	8.0 to 12.0

Table 7-2 - Typical Mechanical Properties of 304 Stainless Steel (Annealed)[11]

Yield Strength .2% Offset (PSI)	Ultimate Strength (PSI)	Elongation (% in 2")	Hardness (RB)	Hardness (BHN)	Impact IZOD (ft/lbs)	Modulus of Elasticity in Tension (PSI)
35000	84000	55	80	149	110	28.0 x 106

In this particular situation, further requirements are that the pressure vessel not exceed dimensions (Length x Width x Height) of 70.0 x 28.0 x 28.0 (in) and that it be able to withstand a maximum working pressure of 150.0 (psi). Since the chosen material is 304 stainless steel, this means that the ultimate tensile strength is 84,000 (psi), as indicated in Table 7-2. Additionally, the customer requires that the container not exceed a weight of 75 (lbs) and have a capacity of at least 7,500 (in^3). These system level requirements are summarized in Table 7-3.

Responsibility for determining values for the design variables controlling the form, function, and behavior of the pressure vessel (in this case R, L, and T, as described in

[10] Information obtained from Wilkinson Steel and Metals, A Division of Premetalco Inc.
[11] Information obtained from Wilkinson Steel and Metals, A Division of Premetalco Inc.

Section 7.2.2) is shared among two designers. Each of these designers is considered to be a domain expert who acts as a stakeholder in a common design process. These two stakeholders will be referred to as Designers A and B, with the objectives of minimizing weight and maximizing volume, respectively. Based on what might be described as an organizational or enterprise level decision, Designer A is assigned control over design variables R and L. Designer B, on the other hand, is given the responsibility of determining a suitable value for T in the process of pursuing his or her objectives.

Table 7-3 - System Level Design Requirements for Two Designer Problem

Design Parameter	Max. Height (in)	Max. Length (in)	Max. Width (in)	Max. Working Pressure (psi)	Material	Max. Weight (lbs)	Min. Capacity (in^3)
Requirement	**70**	**28**	**28**	**150**	**304 Stainless Steel**	**75**	**7500**

The following sections are focused on the manner in which these requirements are translated with respect to each of the two sub-systems. This process involves the synthesis of given system level requirements and emergent sub-system level considerations with domain expertise and problem specific insight. Often, requirements are translated, mapped, and interpreted in order to have a direct effect at the level of granularity, pertinent to the specific problem at hand. As indicated in Section 2.6, there are both obvious (direct) as well as more subtle (indirect) means by which stakeholder expertise is infused into the design process. In this particular example, the system level requirements are unambiguous and directly map to sub-system level objectives on a one-to-one basis. Consequently, it is the more indirect aspects that are focused upon. Specifically, the mechanisms considered are those of (1) preference assessment on the subsystem level as explored in Section 7.4.3 and (2) tradeoff management on the systems level as discussed in Section 7.4.4. As illustrated previously, the evolution of the design sub-spaces on one hand and the collaborative design space on the other is greatly influenced by the encapsulated stakeholder input. It is a fundamental goal of this research to make the implicit nature of this contribution explicit.

7.4.2 Domain Specific Considerations – Statement of Design Sub-Problems

7.4.2.1 <u>Weight Considerations</u>

As indicated in Section 7.4.1, Designer A is charged with the minimization of pressure vessel weight. The overarching customer (or system level) requirement is that a total weight of 75 lbs not be exceeded. The design of the pressure vessel will be conducted based upon the *thin-walled* assumption, explicated in Section 7.2.2. This supposition, however, requires that R and T be constrained by to $5T - R \leq 0$. Consequently, the weight is determined by

$$W(R,L,T) = \pi\rho\left[\frac{4}{3}(R+T)^3 + (R+T)^2 L - \left(\frac{4}{3}R^3 + R^2 L\right)\right]. \qquad (7.4)$$

As evident from this relationship, pressure vessel weight is a function of R, L, and T. Although control over R and L has been assigned to Designer A, T, the final parameter, is governed by Designer B. Since the desired material of the pressure vessel has also been specified as 304 stainless steel, the density ρ of the material is known to be 0.282 lbs/in^3. A constraint emanating from this specification and that of a working pressure of 150 psi is the that the hoop stress not exceed the ultimate tensile strength of the material. This is expressed as $\sigma_{circ} = \frac{PR}{T} \leq S_t$. Additional system level specifications relate to the envelope occupied by the final structure. While the height is restricted to 70 in, both the length and width are restricted to 28 in. Since the type of pressure vessel being designed is a cylindrical pressure vessel with rounded ends, this translates to $H_{PV} = 70$ and $W_{PV} = 28$. Consequently, the design is constrained by $L + 2R + 2T - 70 \leq 0$ and $R + T - 14 \leq 0$.

7.4.2.2 <u>Volume Considerations</u>

As indicated in Section 7.4.1, Designer B is charged with the maximization of the overall capacity of the pressure vessel. The overarching customer (or system level) requirement is that a minimum volume of 7500 in^3 be achieved. Pressure vessel volume is determined by

$$V(R,L) = \pi\left[\frac{4}{3}R^3 + R^2L\right]. \tag{7.5}$$

As indicated by this equation, volume is a function of R and L alone and does not depend on T. This results in a unique condition that is an extreme example of the interdependence that can result among stakeholder sharing control over a strongly coupled problem. Clearly, Designer A depends on the choice made by Designer B, and vice versa. While Designer has the ability to influence the evolution of his or her design at least in part, however, Designer B has absolutely no control over the achievement of his of her objective. This example, rare though not unheard of, thus underscores the importance of systematic communication and the determination of tradeoffs in a system conscious manner.

As indicated for the case of Designer A, the design of the pressure vessel will be conducted based upon the *thin-walled* assumption. Additionally, Designer B is subject to the same system level requirements communicated to Designer A. Consequently, both stakeholders are governed by the same set of constraints. Due to the one-to-one mapping of system level to sub-system level objectives, no additional constraints, particular to either designer arise.

The objectives of both stakeholders depend on design variables outside their immediate control. While partial dependence is not unusual, total dependence as in the case of Designer B is rare. Yet, it is in part because of this unique situation that this problem was chosen. The intent is to stress the methods, proposed in this dissertation, and investigate their usefulness in non-trivial situations. Like the tutorial problem of Chapter 6, the design of the pressure vessel constitutes a good example of a strongly coupled problem that cannot be decoupled based on an argument of *near decomposability* [221] (over the entire design space). Having carefully taken stock of the so called ***"Given"*** aspects of this example, the determination of a mutually desirable solution follows in two stages. Specifically, a collaborative design space is systematically established via the CDSFM in Section 7.4.3 and associated tradeoffs resolved using the ICCM in Section 7.4.4. In an attempt to avoid tedious repetition and augment (rather than saturate) the reader's understanding of the methods and their application, only pertinent aspects of FACE are dwelled upon.

7.4.3 Collaborative Design Space Formulation

As indicated, the discussion in this section is based upon the application of the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod, developed in Chapter 4. With this in mind, each of the sub-problems is considered in terms of the associated design decisions.

These decisions are modeled consistently in terms of the compromise DSP formulation presented in Section 3.3.1. The process of doing so is facilitated through the employment of the templates detailed in Section 3.3.5. The instantiated templates for this particular design example are depicted in Figure 7-7, where the considerations of both Designers A and B are reflected side by side. Clearly, some of the information shown (i.e., preferences for target achievement) is not determined or refined until later on in the CDSFM process, once a preliminary design space has been established.

Collaborative Pressure Vessel Design by 2 Designers		
cDSP "Chips"	**Designer A (WGT)**	**Designer B (VOL)**
Constraints	σ_{circ} : $\frac{PR}{T} - S_t \leq 0$ T: $5T - R \leq 0$ R: $R + T - 14 \leq 0$ L: $L + 2R + 2T - 70 \leq 0$	σ_{circ} : $\frac{PR}{T} - S_t \leq 0$ T: $5T - R \leq 0$ R: $R + T - 14 \leq 0$ L: $L + 2R + 2T - 70 \leq 0$
Variables	R, L	T
Parameters	ρ, σ_{circ}, P	ρ, σ_{circ}, P
Goals	$WGT_{Target} = 60$ ***lbs***	$VOL_{Target} = 8500$ ***in³***
Preferences	$w_{WGT} = 0.5$ $U_{WGT} = \mathbf{1.9697 - e^{0.6854 * \bar{F}_{WGT}}}$	$w_{VOL} = 0.5$ $U_{VOL} = \mathbf{1.0253 - e^{-2.0809 * \bar{F}_{VOL}}}$
Objective	**Minimize** Weight $W(R,L,T) = \pi\rho\left[\frac{4}{3}(R+T)^3 + (R+T)^2 L - \left(\frac{4}{3}R^3 + R^2 L\right)\right]$	**Maximize** Volume $V(R,L) = \pi\left[\frac{4}{3}R^3 + R^2 L\right]$
Analysis	**Inputs:** R, L, T, ρ, σ_{circ}, P **Outputs:** *Weight*	**Inputs:** R, L, T, ρ, σ_{circ}, P **Outputs:** *Volume*
Driver	**Optimization Algorithm** – Exhaustive Search, SQP, etc.	**Optimization Algorithm** – Exhaustive Search, SQP, etc.
Response	**Design Variable Values** – *R,L* **Objective Function Value** - Z_{WGT}	**Design Variable Values** – *T* **Objective Function Value** -Z_{VOL}

Figure 7-7 - Instantiation of Domain Specific Design Templates for Two Stakeholders

Prior to any communication with other stakeholders, preliminary values for objective targets, design variable ranges, and constraints must be determined based on domain-specific insight. Often this process requires the synthesis of system level and sub-system level requirements. In this example, Designer A refines the customer target for weight from $WGT_{Target} \leq 75$ *lbs* to $WGT_{Target} = 60$ *lbs*, due to a realization that the remainder of the specifications make it feasible to exceed customer demands. Similarly, Designer B realizes that several other orders, though for larger capacity pressure vessels, share the same basic set of requirements. Consequently, the capacity objective is adjusted from $VOL_{Target} \geq 7500\ in^3$ to a more ambitious $VOL_{Target} = 8500\ in^3$.

These refined specifications, reflect what each designer deems appropriate for his or her sub-system (in light of system level requirements). At the systems level, the design variables are initially constrained based on the maximum size of the envelope specified by the customer. Since these constraints are placed on the combinatorial effects of design variables, control over which is shared, it is not possible to translate these directly to acceptable ranges for these design variables. Consequently, each of the designers must rely on the system level requirements and his or her engineering judgment in determining the initial ranges for his or her design subspace. The resulting ranges for R, L, and T are as follows: $R \subseteq [5,15]$, $L \subseteq [5,50]$, $T \subseteq [0.1,1]$. It is noted that although each of the designers has the power to reduce the range corresponding to the design variable under his or her control, the combined effect of any such changes must not violate any system level constraints. It is these preliminary ranges that comprise the first communication among interacting stakeholders and serve as a basis for determining what each stakeholder may realistically hope to achieve. This ensures that all stakeholders start off on the same page (and do not waste precious resources, investigating clearly infeasible regions of a design space).

A preliminary collaborative design space is established based upon the implications of this communiqué, which in turn is explored by each decision-maker with respect to the satisfaction of their respective objectives. In accordance with the CDSFM, full control over all pertinent parameters is assumed over the entirety of the initial dimensions and infeasible regions eliminated. Appropriate adjustments are made to the ranges, sets, or discrete alternatives and the collaborative design space refined accordingly. Based on this initial assessment, the *thin-walled* constraint is violated by some of the potential design variable combinations. Specifically, those regions of the design space that result in $R + T \geq 14$ must be excluded. Had a single designer been in control of both R and T, this region of infeasibility could have been identified earlier.

Having successfully refined the preliminary collaborative design space so that no strictly infeasible designs are included, the viability of targets, initially set by each of the stakeholders must be established. This is accomplished in part by determining the performance potential within each design sub-space. This corresponds to the "projection" of the system level design decision (modeled in terms of the collaborative design space) onto each of the domain decisions (modeled in terms of design sub-spaces) being considered. Realistically feasible ranges or sets of values are determined for each of the design variables by assuming control over the entire preliminary collaborative design space. Consequently, the performance potential of Designer A is determined to be $14 \leq F_A \leq 1598$ and that of Designer B $916 \leq F_B \leq 34399$. This means that both of the primary customer objectives are independently achievable.

The customer targets for objective achievement, obtained from system level requirements, are then used to assess and capture in functional form the preferences of individual stakeholders. This is accomplished through the determination of utility functions. The assessed ranges, constituting the basis for these quantitative expressions of preference extend from *unacceptable* (i.e., $U_i = 0$) to *ideal* (i.e., $U_i = 1$) values and are provided for both Designers A and B in Table 7-4. The corresponding utility functions are $U_A = 1.97 - e^{0.69*F_A}$ and $U_B = 1.03 - e^{-2.08*F_B}$, respectively. It is noted, once again, that these single attribute utility functions are based on objective function values that are normalized by the preference ranges, acceptable to each designer.

Table 7-4 - Designer Utilities for Objective Achievement by Two Stakeholders

Preference	Ideal	Desirable	Tolerable	Undesirable	Unacceptable
Utility Value	1	0.75	0.5	0.25	0
Designer A *(Weight)*	60	65	67	72	75
Designer B *(Volume)*	8500	8200	8000	7800	7700

Making use of these utilities, those regions of each design sub-space, yielding feasible results (defined here as having a utility $U_i \geq 0.75$) can be effectively determined via space filling experiments. In the case considered here such exploration is still possible using the actual models and indicates the regions, varying in color from orange to red, depicted in Figure 7-8 and Figure 7-9 for Designers A and B, respectively. In Chapter 8, the inherent complexity of the problem dictates the usage of (step-wise refined) surrogate models.

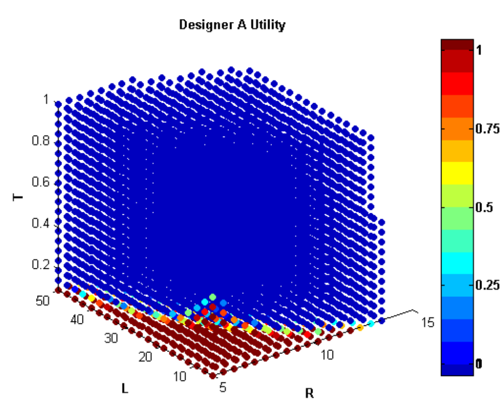


Figure 7-8 - Sub-Design Space Performance for Designer A

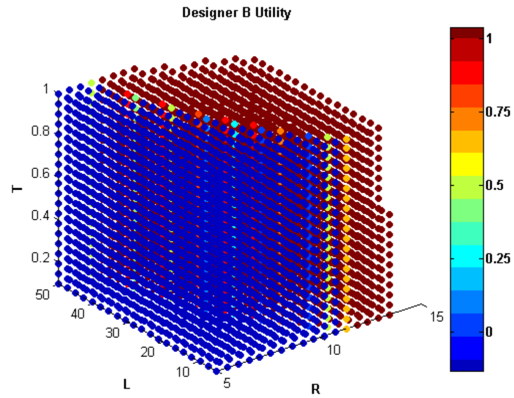


Figure 7-9 - Sub-Design Space Performance for Designer B

It is important to recall that although the preliminary collaborative design space contains solutions that are amenable to the preferences of each designer independently, the actual feasibility of these solutions is subject to combined limitations; the design variables choices made by Designer A constitute constraints for Designer B and vice versa. Values for design variables, suitable to both stakeholders, can be confirmed graphically. It is these ranges (or sets in this case) that make up the collaborative design space, formulated as a result of completing *Steps 1* through *8* of the FACE. Unlike the special two-dimensional case studied in Chapter 6, however, color maps must be employed to aid in the visualization of a three dimensional design space. With this in mind, the shared design space is pictured in Figure 7-10, where evenly weighted system utility is plotted. The collaborative design space of Figure 7-11 comprises the intersection of those regions of Figure 7-10 that yield feasible solutions for Designer A (see Figure 7-12) and Designer B (see Figure 7-13), respectively. It is emphasized that in the event of a null intersection, mismatches must be reconciled at once through reassessment of preferences, changes in technological base, relaxation of constraints, etc.

As can be seen from Figure 7-12, only the smallest values of ***T*** are capable of meeting the stringent weight requirement for the pressure vessel design. This translates to the collaborative design space of Figure 7-11 being relatively small. Thus, although Designer B has little control over the achievement of his or her own objectives, the amount of leverage that he or she may exert on Designer A is substantial. Having successfully established this region of mutual feasibility, the effect of stakeholder sequencing is explored in the next section.

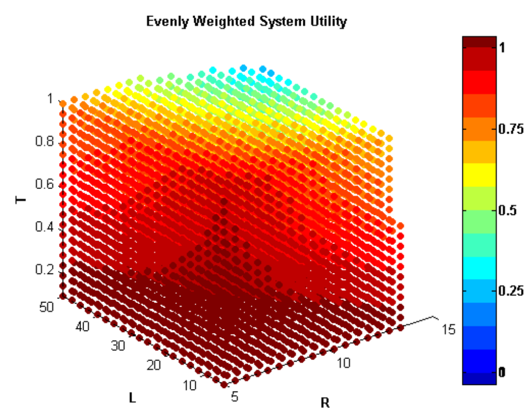


Figure 7-10 - Evenly Weighted System Level Performance Throughout the Design Space

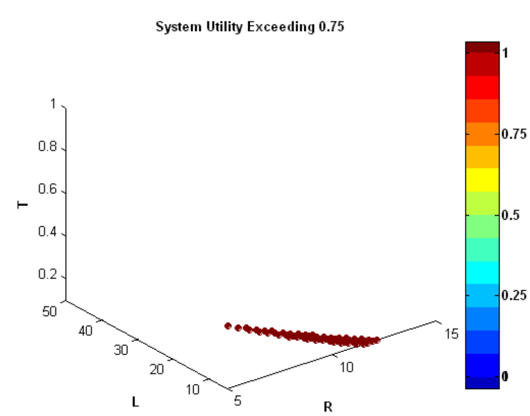


Figure 7-11 - Collaborative Design Space $(U_A, U_B \geq 0.75)$

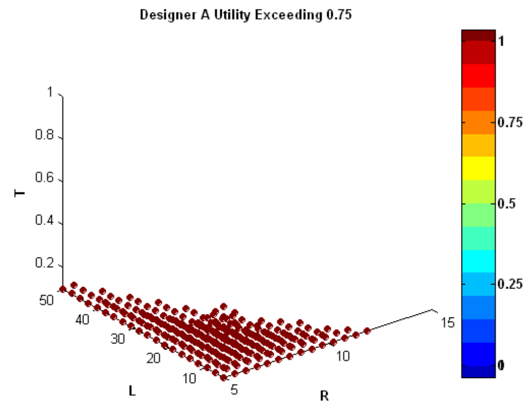


Figure 7-12 - Feasible Regions of the Design Space for Designer A $(U_A \geq 0.75)$

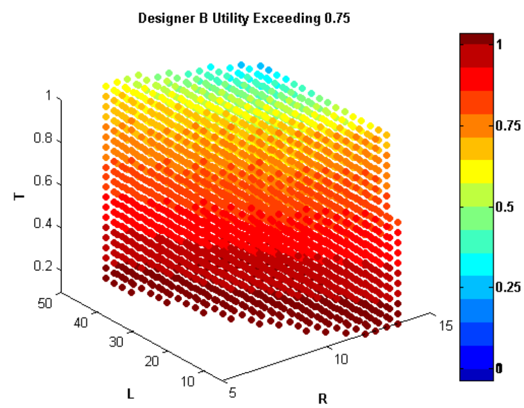


Figure 7-13 - Feasible Regions of the Design Space for Designer B $(U_B \geq 0.75)$

7.4.4 Interaction-Conscious Coordination of Stakeholders

The discussion in this section is based upon the application of the **I**nteraction-**C**onscious **C**oordination **M**echanism, developed in Chapter 5. It is noted that the central benefit of following the steps of CDSFM in Section 7.4.3 is that all of the solutions in the established collaborative design space (see Figure 7-11) are guaranteed to be mutually desirable. *Although any protocol can be adopted in order to arrive at a final solution to this strongly coupled problem, once such a design space has been successfully established, the focus in this dissertation is on interaction conscious resolution.*

Consequently, it is a *co-designed* solution that is focused upon here; the ICCM is employed.

Although, a set of design variable combinations, rather than a contiguous range, is associated with the collaborative design space communicated among the interacting stakeholders, this set is roughly contained within the following envelope: $R \subseteq [8.684, 11.842]$, $L \subseteq [5.000, 23.947]$, and $T \subseteq [0.1, 0.111]$. The performance potential for Designer A in this region is determined to range from a minimum of $U_A = 0.751$ to a maximum of $U_A = 1$ with an average performance of $U_A = 0.880$. The performance potential for Designer B on the other hand averages $U_B = 0.936$, ranging from $U_B = 0.799$ to $U_B = 1$. This translates to a system utility that is guaranteed to lie between $U_{System} = 0.797$ on the low end and $U_{System} = 1$ on the high end.

Having established the performance potential for each of the stakeholders, interaction effects are considered in detail. Specifically, (1) sensitivity of design sub-problem specific objective achievement to changes in uncontrollable design variables, (2) sensitivity of design sub-problem specific objective achievement to changes in controllable design variables, and (3) the impact of changes in controllable design variables on the objective achievement of other stakeholders are considered. These measures of responsiveness are referred to as *sensitivity*, *power*, and *leverage*, respectively in the discussion that follows.

Each designer, in turn, proceeds to determine his/her responsiveness to changes in design variables, controlled by the other party. Specifically, the *sensitivity* of Designers A and B with respect to the achievement of their objectives F_A and F_B are given by

$$S_A = \frac{\partial U_A}{\partial T} = \frac{\partial U_A}{\partial F_A}\frac{\partial F_A}{\partial T} \tag{7.6}$$

$$S_B = \frac{\partial U_B}{\partial R} + \frac{\partial U_B}{\partial L} = \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial R} + \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial L}, \tag{7.7}$$

respectively. The *power* of each designer to affect his of her objective attainment is calculated according to

$$P_A = \frac{\partial U_A}{\partial R} + \frac{\partial U_A}{\partial L} = \frac{\partial U_A}{\partial F_A}\frac{\partial F_A}{\partial R} + \frac{\partial U_A}{\partial F_A}\frac{\partial F_A}{\partial L} \tag{7.8}$$

$$P_B = \frac{\partial U_B}{\partial T} = \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial T}. \tag{7.9}$$

Finally, the *leverage* that one designer may assert over another in the event that negotiations take place is determined according to

$$L_A = \frac{\partial U_B}{\partial R} + \frac{\partial U_B}{\partial L} = \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial R} + \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial L} \tag{7.10}$$

$$L_B = \frac{\partial U_A}{\partial T} = \frac{\partial U_A}{\partial F_A}\frac{\partial F_A}{\partial T}. \tag{7.11}$$

This effectively constitutes the complement of the sensitivities, calculated previously. Designer sensitivity, power, and leverage are summed at each point sampled throughout the design space, in order to obtain a more comprehensive understanding of the resultant net effect on objective performance. Certain cases may warrant a higher level of fidelity, achievable via the investigation of responsiveness on a variable-specific basis.

In each of these cases,

$$\frac{\partial U_A}{\partial F_A} = -0.6854e^{0.6854F_A} \tag{7.12}$$

$$\frac{\partial U_B}{\partial F_B} = 2.0809e^{2.0809F_B} \tag{7.13}$$

$$\frac{\partial F_A}{\partial R} = 2\pi\rho\left(2T^2 + 4RT + TL\right) \tag{7.14}$$

$$\frac{\partial F_A}{\partial T} = \pi\rho\left(4\left(R+T\right)^2 + 2\left(R+T\right)L\right) \tag{7.15}$$

$$\frac{\partial F_A}{\partial L} = \pi\rho\left(T^2 + 2RT\right) \tag{7.16}$$

$$\frac{\partial F_B}{\partial R} = \pi\left(4R^2 + 2RL\right) \tag{7.17}$$

$$\frac{\partial F_B}{\partial L} = \pi R^2 \tag{7.18}$$

$$\frac{\partial F_B}{\partial T} = 0 \tag{7.19}$$

It is reiterated at this point that measures of responsiveness should be assessed with respect to designer utilities rather than raw objective value achievement. Doing so, simultaneously normalizes any such measures and illustrates the net effect of any associated changes on designer satisfaction. The results of this assessment are provided in Table 7-5 and serve as the basis for precedence determination by ensuring a certain degree of systems transparency for all stakeholders.

Table 7-5 - Indicators of Responsiveness for Two Stakeholders in Feasible Collaborative Design Space

Indicator	Sensitivity	Power	Leverage
Average (Designer A)	458.97	8.80	516.24
Average (Designer B)	516.24	0	458.97
Domination (Designer A)	51%	100%	49%
Domination (Designer B)	49%	0%	51%

As indicated by the results, reported in Table 7-5 and summarized in the SPL matrices of Figure 7-14, Designers A and B exhibit roughly the same level of sensitivity and hence leverage. This is underscored by the remarkably even split among these stakeholders in terms of domination throughout the design space. This is quite interesting, considering that Designer A controls both R and L, while Designer B only controls T, the one design variable not factoring into his or her own decision. This is underscored by Designer B's power. Designer A does not fare much better however, emphasizing that Designer A is only at a slight advantage what the achievement of his or her objective is concerned. It is clear that this problem is a quintessential example of a strongly coupled decision. However, due to the severity of the interdependence and the bilateral lack of control, only cooperative behavior is likely to yield acceptable results. This is especially true in lieu of the systematic formulation of a collaborative design space. Levels of achievement vary widely throughout the original design space, characterized by a substantial number of feasible solutions for Designer B (see Figure 7-9), but only a small number of acceptable designs for Designer A (see Figure 7-8). As one might expect in such a strongly coupled decision, very few of these solutions overlap, as indicated in Figure 7-11, producing a collaborative design space that is fairly small. Nevertheless, focalization of stakeholder efforts in this region reduces this disparity in levels of achievement to comparable levels; $0.75 \le U_A \le 1$ for Designer A and $0.77 \le U_B \le 1$ for Designer B. In light of this discovery, neither stakeholder has an edge and playing field has been successfully leveled.

Sensitivity

	A	B
A		0.51
B	0.49	

Power

	A	B
A		1
B	0	

Leverage

	A	B
A		0.49
B	0.51	

Figure 7-14 - Responsiveness for Two Stakeholders throughout the Collaborative Design Space

Based on the overall picture, provided by these indicators and the performance potential over the reduced region, it is evident that the two stakeholders are evenly matched what performance within the collaborative design space is concerned. Nevertheless, system level considerations are better served by Designer A taking the lead. To be precise, Designer A has non-zero *power* response and achievement potential, slightly inferior to that of Designer B. Since Designer B has a null level *power* response any decision made by him or her is somewhat arbitrary, especially when information regarding Designer A's strategy is missing. Even in the event that Designer B is privy to such information, it makes more sense for Designer A to take charge of their combined contribution to the overarching system. With this in mind, the chosen sequencing scheme is the transfer of control to Designer A alongside Designer B's BRC. The resulting design solution is $(R,L,T)=(11.76,5.00,0.10)$ with $U_A=1$, $U_B=1$, and $U_{System}=1$.

The range of performance possible even within this region, composed exclusively of mutually acceptable solutions, is remarkable (see Table 7-6). As one might expect, ceding control to either designer in the absence of information regarding the level of satisfaction to be expected by the opposing party, invariably results in the maximization of their respective objectives. The associated impact on system level utility is predictable, being slightly better in the case of Designer A being in control. System level performance in the case of control transfer to Designer B alongside Designer A's BRC information is almost as good as that obtained using the chosen solution scheme. That is to say, that although practically speaking, the ideal performance levels of both Designers are exceeded, the mathematical degree of overachievement is slightly less. A final comparison is made with the completely cooperative solution, determined via reformulation of the stakeholder design sub-problems as a single design problem with the objective to optimize system level objective performance (taken to be the evenly weighted Archimedean sum of stakeholder objectives). This solution is representative of the global optimum in this scenario. As expected, this case comprises the best answer, at least from a mathematical perspective, striking the most even balance in terms of overachievement of both the weight and volume objectives.

Having explored the *co-design* of a pressure vessel by two stakeholders in this section, an additional objective is added in the next. The aim is to explore the scalability of the methods and mechanisms proposed in this dissertation to the mitigation of conflict among larger numbers of stakeholders.

Table 7-6 - The Impact of Stakeholder Sequence on System & Sub-System Level Trade-Offs

Stakeholder Sequence	R	L	T	U_A	U_B	U_{System}	F_A	F_B
Total Control (Designer A) w/o BRC	11.19	5.97	0.10	1	0.77	0.89	56.7	8226.8
Total Control (Designer B) w/o BRC	11.68	7.43	0.10	0.76	1	0.88	64.2	9858.6
Total Control (Designer A) w/ BRC	11.76	5.00	0.10	1	1	1	59.9	8987.1
Total Control (Designer B) w/ BRC	10.63	10.34	0.10	1	1	1	60.0	8698.5
Cooperative	11.60	5.00	0.10	1	1	1	58.4	8650.1

7.5 COLLABORATIVE DESIGN OF A PRESSURE VESSEL BY THREE DESIGNERS

It is noted that since the basic problem statement, case development, assumptions underlying analysis, simulation, and requirements match those of the two designer example in Section 7.4, only differing aspects are highlighted. Additional explanation is furnished as pertinent to the discussion at hand.

7.5.1 Problem Statement and Case Development

As indicated, the application is the same as that detailed for the example of Section 7.4. The only relevant difference is the specification of an additional requirement (a maximum cost of USD 85) by the customer. An overview of relevant system level requirements is provided in Table 7-7.

Responsibility for determining values for the design variables controlling the form, function, and behavior of the pressure vessel (in this case R, L, and T, as described in Section 7.2.2) is shared among three designers. Each of these designers is considered to be a domain expert who acts as a stakeholder in a common design process. These three stakeholders will be referred to as Designers A, B, and C, with the objectives of minimizing weight, maximizing volume, and minimizing cost, respectively. Based on what might be described as an organizational or enterprise level decision, Designer A is assigned control over design variable R, Designer B is given the responsibility of determining a suitable value for T, and Designer C is charged with fixing L.

Table 7-7 - System Level Design Requirements for Three Designer Problem

Design Parameter	Max. Height (in)	Max. Length (in)	Max. Width (in)	Max. Working Pressure (psi)	Material	Max. Weight (lbs)	Min. Capacity (in^3)	Max. Cost (USD)
Requirement	**70**	**28**	**28**	**150**	**304 Stainless Steel**	**75**	**7500**	**85**

7.5.2 Domain Specific Considerations – Statement of Design Sub-Problems

7.5.2.1 <u>Weight Considerations</u>

As indicated in Section 7.5.1, Designer A is charged with the minimization of weight. The overarching customer (or system level) requirement is that a total weight of 75 lbs not be exceeded. The reader is advised that all of the assumptions and constraints governing the system in the two designer case apply equally in the three designer scenario.

$$W(R,L,T)=\pi\rho\left[\frac{4}{3}(R+T)^3+(R+T)^2L-\left(\frac{4}{3}R^3+R^2L\right)\right]. \tag{7.20}$$

As evident from this relationship, pressure vessel weight is a function of R, L, and T. Although control over R has been assigned to Designer A, T is controlled by Designer B and L by Designer C.

7.5.2.2 <u>Volume Considerations</u>

As indicated in Section 7.5.1, Designer B is charged with the maximization of the overall capacity of the pressure vessel. The overarching customer (or system level) requirement is that a minimum volume of 7500 in^3 be achieved. Pressure vessel volume is determined by

$$V(R,L)=\pi\left[\frac{4}{3}R^3+R^2L\right]. \tag{7.21}$$

As indicated by this equation, volume is a function of R (controlled by Designer A) and L (assigned to Designer C). Pressure vessel volume does not depend on T, the only design variable controlled by Designer B. This maintains the unique condition, discussed in Section 7.4.2.2. Thus, all designers depend on the choices made by one another.

Designers A and C, however, have at least partial control over the achievement of their respective objectives. Designer B, on the other hand, is virtually powerless, other than possessing a significant amount of leverage over each of the other stakeholders. This situation will be investigated in light of the intricate relationships, coupling the various objectives, in Section 7.5.4.

7.5.2.3 Cost Considerations

As indicated in Section 7.5.1, Designer C is charged with the minimization of the pressure vessel's cost. The overarching customer (or system level) requirement is that a maximum cost of USD 85 not be exceeded. The cost[12] of the type of pressure vessel being designed is computed based on

$$C(R,L,T) = 0.6224RTL + 1.7881R^2T + 3.1611T^2L + 19.8621RT^2. \quad (7.22)$$

As indicated by this equation, cost is a function of R (controlled by Designer A), T (controlled by Designer B), and L (assigned to Designer C).

As in the two-designer scenario of Section 7.4, the objectives of all stakeholders depend on design variables outside their immediate control. Once again, Designer B has no control over the achievement of his or her objectives, but as investigated later on, a significant amount of bargaining power with the other stakeholders. Having carefully taken stock of the so called ***"Given"*** aspects of this example, both from a systems and a subsystems perspective, the determination of a mutually desirable solution follows. As before, this is accomplished in two stages. A collaborative design space is systematically

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[12] This relation is adopted from the work of Sandgren in Ref. [195] as used previously by Marston in Ref. [133].

established via the CDSFM in Section 7.5.3, before associated tradeoffs are resolved using the ICCM in Section 7.5.4.

7.5.3 Collaborative Design Space Formulation

Paralleling the discussion in Section 7.4.3, the discussion in this section is based upon the application of the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod, developed in Chapter 4. With this in mind, each of the sub-problems is considered in terms of the associated design decisions. These decisions are modeled consistently in terms of the compromise DSP formulation presented in Section 3.3.1. The process of doing so is facilitated through the employment of the templates detailed in Section 3.3.5. The instantiated templates for this particular design example are depicted in Figure 7-15, where the considerations of Designers A, B, and C are reflected side by side. Clearly, some of the information shown (i.e., preferences for target achievement) is not determined or refined until later on in the CDSF process, once a preliminary design space has been established.

Prior to any communication with other stakeholders, preliminary values for objective targets, design variable ranges, and constraints are determined based on domain-specific insight. Often this process requires the synthesis of system level and sub-system level requirements. In this example, Designer A refines the customer target for weight from $WGT_{Target} \leq 75\ lbs$ to $WGT_{Target} = 60\ lbs$, due to a realization that the remainder of the specifications make it feasible to exceed customer demands. Similarly, Designer B realizes that several other orders, though for larger capacity pressure vessels, share the same basic set of requirements. Consequently, the capacity objective is adjusted from

$VOL_{Target} \geq 7500\ in^3$ to a more ambitious $VOL_{Target} = 8500\ in^3$. Designer C realizes that meeting the customer constraint on price, given as $CST_{Target} \leq 85$, is better represented by $CST_{Target} = 41$ in order to ensure a healthy profit.

Collaborative Pressure Vessel Design by 3 Designers			
cDSP "Chips"	**Designer A (WGT)**	**Designer B (VOL)**	**Designer C (CST)**
Constraints	σ_{circ}: $\frac{PR}{T} - S_t \leq 0$ T: $5T - R \leq 0$ R: $R + T - 14 \leq 0$ L: $L + 2R + 2T - 70 \leq 0$	σ_{circ}: $\frac{PR}{T} - S_t \leq 0$ T: $5T - R \leq 0$ R: $R + T - 14 \leq 0$ L: $L + 2R + 2T - 70 \leq 0$	σ_{circ}: $\frac{PR}{T} - S_t \leq 0$ T: $5T - R \leq 0$ R: $R + T - 14 \leq 0$ L: $L + 2R + 2T - 70 \leq 0$
Variables	R	T	L
Parameters	ρ, σ_{circ}, P	ρ, σ_{circ}, P	ρ, σ_{circ}, P
Goals	$WGT_{Target} = 60$ ***lbs***	$VOL_{Target} = 8500$ ***in³***	$CST_{Target} = 41$ ***USD***
Preferences	$w_{WGT} = 0.\overline{3}$ $U_{WGT} = \mathbf{1.9697 - e^{0.6854 * \bar{F}_{WGT}}}$	$w_{VOL} = 0.\overline{3}$ $U_{VOL} = \mathbf{1.0253 - e^{-2.0809 * \bar{F}_{VOL}}}$	$w_{WGT} = 0.\overline{3}$ $U_{CST} = \mathbf{1.9622 - e^{0.6887 * \bar{F}_{CST}}}$
Objective	**Minimize** Weight $W(R,L,T) = \pi\rho\left[\frac{4}{3}(R+T)^3 + (R+T)^2 L - \left(\frac{4}{3}R^3 + R^2 L\right)\right]$	**Maximize** Volume $V(R,L) = \pi\left[\frac{4}{3}R^3 + R^2 L\right]$	**Minimize** Cost $C(R,L,T) = 0.6224RTL + 1.7881R^2T + 3.1611T^2L + 19.8621RT^2$
Analysis	**Inputs:** R, L, T, ρ, σ_{circ}, P **Outputs:** *Weight*	**Inputs:** R, L, T, ρ, σ_{circ}, P **Outputs:** *Volume*	**Inputs:** R, L, T, ρ, σ_{circ}, P **Outputs:** *Cost*
Driver	**Optimization Algorithm** – Exhaustive Search, SQP, etc.	**Optimization Algorithm** – Exhaustive Search, SQP, etc.	**Optimization Algorithm** – Exhaustive Search, SQP, etc.
Response	**Design Variable Values** – *R* **Objective Function Value** - Z_{WGT}	**Design Variable Values** – *T* **Objective Function Value** - Z_{VOL}	**Design Variable Values** – *L* **Objective Function Value** - Z_{CST}

Figure 7-15 - Instantiation of Domain Specific Design Templates for Three Stakeholders

These refined specifications, reflect what each designer deems appropriate for his or her sub-system (in light of system level requirements). As in the two designer case, careful consideration of system level requirements in light of domain specific insights results in the following ranges for ***R***, ***L***, and ***T***: $R \subseteq [5,15]$, $L \subseteq [5,50]$, $T \subseteq [0.1,1]$. As in any other case considered, each of the designers has the power to reduce the range corresponding to the design variable under his or her control. However, the combined effect of any such changes must not violate any system level constraint. These preliminary ranges constitute the first communication among the interacting stakeholders and serve as the basis for determining what each stakeholder may realistically hope to achieve. This ensures that all stakeholders start off on the same page (and do not waste precious resources, investigating clearly infeasible regions of a design space).

A preliminary collaborative design space is established based upon the implications of this communiqué, which in turn is explored by each stakeholder to ascertain feasibility. In accordance with the CDSFM, each party assumes full control over all pertinent parameters and eliminates infeasible regions of the initial design space. Appropriate adjustments are made to the ranges, sets, or discrete alternatives and the collaborative design space refined accordingly, so that no strictly infeasible designs are included. Next, the viability of targets, initially set by each of the stakeholders is established by determining the performance potential within each design sub-space. Consequently, the performance potential of Designer A is determined to be $14 \leq F_A \leq 1598$, that of Designer B is established as $916 \leq F_B \leq 30151$ and that of Designer C found to be $7 \leq F_C \leq 963$. This means that all of the primary customer objectives are at least independently achievable.

Stakeholder preferences may now be captured in functional form, based on system level requirements and sub-system level refinements; utility functions are assessed. The elicited ranges, constituting the basis for these quantitative expressions of preference extend from *unacceptable* (i.e., $U_i = 0$) to *ideal* (i.e., $U_i = 1$) values and are provided for all designers in Table 7-8. The corresponding utility functions are $U_A = 1.97 - e^{0.69*F_A}$, $U_B = 1.03 - e^{-2.08*F_B}$, and $U_C = 1.96 - e^{0.69*F_B}$ for Designers A, B, and C, respectively. It is noted, once again, that these single attribute utility functions are based on objective function values that are normalized by designer preference ranges.

Table 7-8 - Designer Utilities for Objective Achievement by Three Stakeholders

Preference	Ideal	Desirable	Tolerable	Undesirable	Unacceptable
Utility Value	1	0.75	0.5	0.25	0
Designer A *(Weight)*	60	65	67	72	75
Designer B *(Volume)*	8500	8200	8000	7800	7700
Designer C *(Cost)*	41	52	65	74	85

These utilities serve as the basis for determining those regions of each design sub-space, yielding feasible results via space filling experiments. In this dissertation this translates to design solutions of utility $U_i \geq 0.75$. The performance potential of Designers A, B, and C throughout the shared design space is indicated in Figure 7-16, Figure 7-17, and Figure 7-18, respectively. The evenly weighted systems level utility is plotted in Figure 7-28 to underscore the effect of tradeoffs throughout the design space.

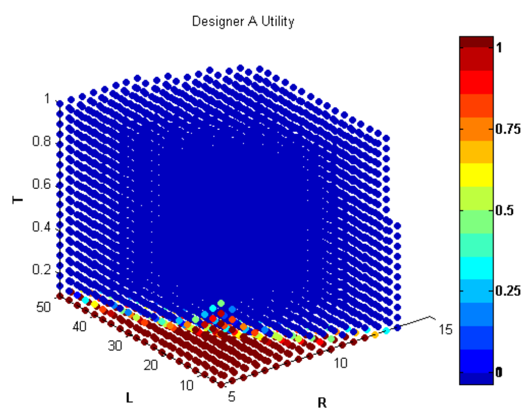

Figure 7-16 - Sub-Design Space Performance for Designer A

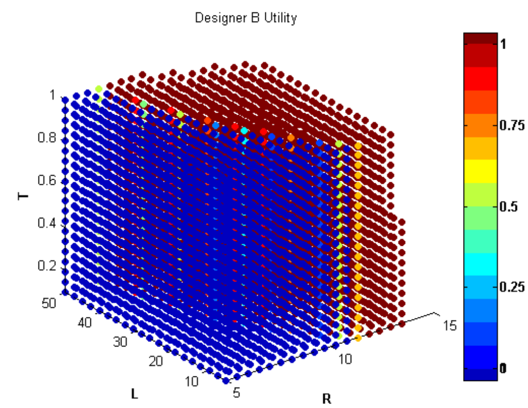

Figure 7-17 - Sub-Design Space Performance for Designer B

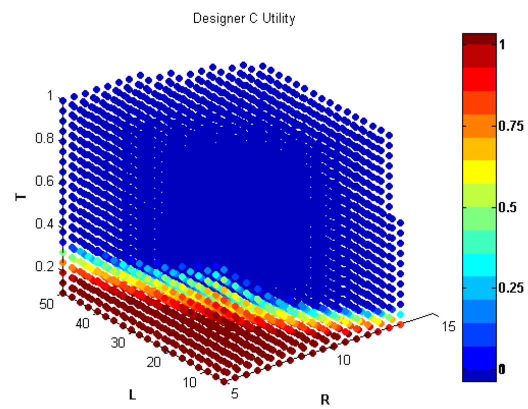

Figure 7-18 - Sub-Design Space Performance for Designer C

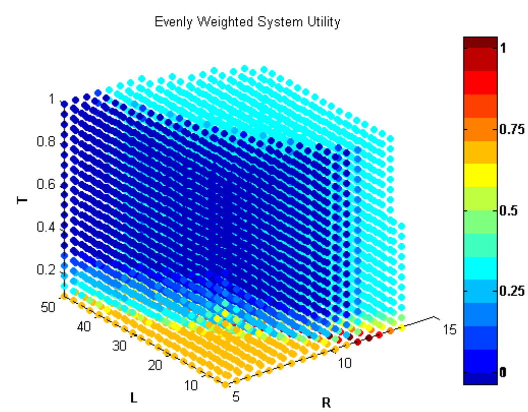

Figure 7-19 - Collaborative Design Space for Designers A, B, and C

Those portions, meeting these feasibility criteria are indicated in Figure 7-20, Figure 7-21, and Figure 7-22 (in order) for Designers A, B, and C. As in the two-designer case, the feasibility of solutions is subject to the combined limitations of all interacting designers. The resulting overlap in these ranges (or sets) make up the collaborative design space, formulated as a result of completing *Steps 1* through *8* of the FACE. Due to the relatively low number of dimensions, considered in this design example, graphical representation is possible. This is indicated in Figure 7-23, where evenly weighted systems utility meeting the feasibility criteria of all stakeholders is plotted. As always, mismatches are to be reconciled as soon as they are identified. Null intersections are remedied via reassessment of preferences, changes in technological base, relaxation of constraints, etc.

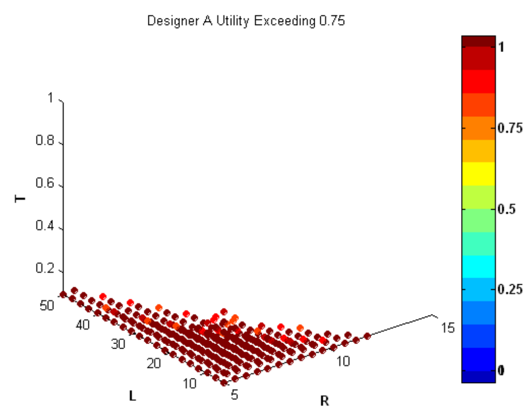

Figure 7-20 - Feasible Regions of the Design Space for Designer A $(U_A \geq 0.75)$

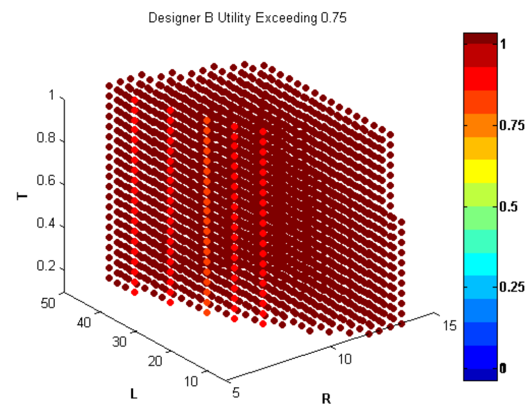

Figure 7-21 - Feasible Regions of the Design Space for Designer B $(U_B \geq 0.75)$

As can be seen from these four figures, the Designer A has the smallest feasible region within the shared design space; only the smallest values of ***T*** are capable of meeting the stringent weight requirement for the pressure vessel design. The next smallest area of feasibility is that of Designer C, whose objectives seem to coincide to a large degree with those of Designer A. Designer B has the most design freedom and in spite of relatively little control, substantial leverage over both Designers A and C. The simultaneous satisfaction of all stakeholder objectives translates to the collaborative design space of Figure 7-23 being relatively small. Having successfully established this region of mutual feasibility, the effect of stakeholder sequencing is explored in the next section.

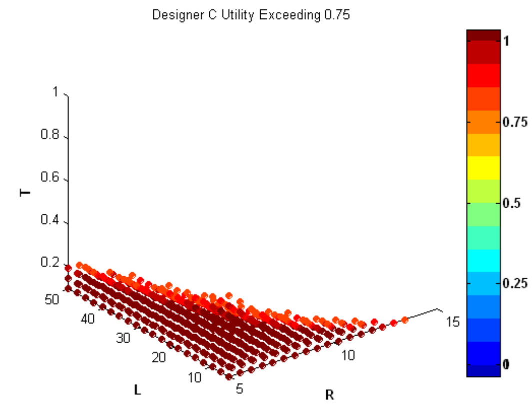

Figure 7-22 - Feasible Regions of the Design Space for Designer C $(U_C \geq 0.75)$

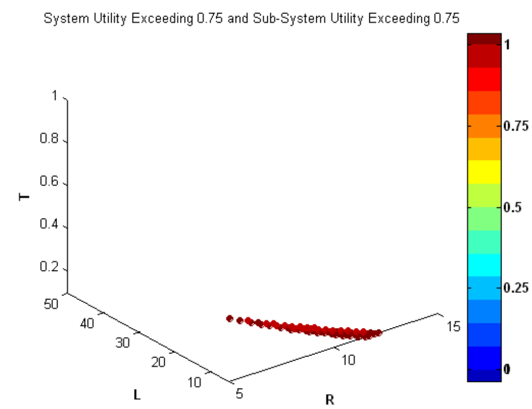

Figure 7-23 - Collaborative Design Space $(U_A, U_B, U_C \geq 0.75)$

7.5.4 Interaction-Conscious Coordination of Stakeholders

The following discussion parallels that of Section 7.4.4 and is based upon the application of the **I**nteraction-**C**onscious **C**oordination **M**echanism, developed in Chapter 5. With this in mind, the collaborative design space (see Figure 7-23), established via the CDSFM in Section 7.5.3 is systematically explored in search of a *co-designed* solution employing the ICCM.

Although, a set of design variable combinations, rather than a contiguous range, is associated with the collaborative design space communicated among the interacting stakeholders, this set is roughly contained within the following envelope: $R \subseteq [8.684, 11.842]$, $L \subseteq [5.000, 23.947]$, and $T = [0.1, 0.105]$. As is to be expected, this envelope is slightly smaller than that initially determined for the two-designer case. While the addition of the cost objective does not reduce the maximum and minimum values for the ***R*** and ***L***, the value of ***T*** is more highly constrained. It thus becomes apparent that Designer C is quite dependent on Designer B. In fact, the strength of this dependency exceeds that of Designer A on Designer B.

The performance potential for Designer A in this region ranges from $U_A = 0.750$ to a maximum of $U_A = 1$ with an average performance of $U_A = 0.873$. The performance potential for Designer B on the other hand averages $U_B = 0.949$, ranging from $U_B = 0.769$ to $U_B = 1$. Finally, Designer C essentially cannot fail as any point in this collaborative design space will yield a performance of $U_C = 1$. The cumulative effect of these performance potentials is a system utility that is guaranteed to lie between $U_{System} = 0.841$ and $U_{System} = 1$. It thus becomes clear that the performance potential for the three designer problem is slightly higher on average than that for the two designer analogue. This is due in large to the reduced range of T considered and the extremely high sensitivity of Designer C to this parameter.

Having established the performance potential for each of the stakeholders, interaction effects are considered in terms of stakeholder sensitivity, power, and leverage. Specifically, each designer, proceeds to determine his/her responsiveness to changes in design variables, controlled by other parties. The sensitivity of Designers A, B, and C with respect to the achievement of their objectives F_A, F_B, and F_C and are given by

$$S_A = \frac{\partial U_A}{\partial L} + \frac{\partial U_A}{\partial T} = \frac{\partial U_A}{\partial F_A}\frac{\partial F_A}{\partial L} + \frac{\partial U_A}{\partial F_A}\frac{\partial F_A}{\partial T} \quad (7.23)$$

$$S_B = \frac{\partial U_B}{\partial R} + \frac{\partial U_B}{\partial L} = \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial R} + \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial L} \quad (7.24)$$

$$S_C = \frac{\partial U_C}{\partial R} + \frac{\partial U_C}{\partial T} = \frac{\partial U_C}{\partial F_C}\frac{\partial F_C}{\partial R} + \frac{\partial U_C}{\partial F_C}\frac{\partial F_C}{\partial T} \quad (7.25)$$

The *power* of each designer to affect the satisfaction of his or her objective is calculated according to

$$P_A = \frac{\partial U_A}{\partial R} = \frac{\partial U_A}{\partial F_A}\frac{\partial F_A}{\partial R} \quad (7.26)$$

$$P_B = \frac{\partial U_B}{\partial T} = \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial T} \quad (7.27)$$

$$P_C = \frac{\partial U_C}{\partial L} = \frac{\partial U_C}{\partial F_C}\frac{\partial F_C}{\partial L} \quad (7.28)$$

Finally, the *leverage* that one designer may assert over another in the event that negotiations take place is determined according to

$$L_A = \frac{\partial U_B}{\partial R} + \frac{\partial U_C}{\partial R} = \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial R} + \frac{\partial U_C}{\partial F_C}\frac{\partial F_C}{\partial R} \quad (7.29)$$

$$L_B = \frac{\partial U_A}{\partial T} + \frac{\partial U_C}{\partial T} = \frac{\partial U_A}{\partial F_A}\frac{\partial F_A}{\partial T} + \frac{\partial U_C}{\partial F_C}\frac{\partial F_C}{\partial T} \quad (7.30)$$

$$L_C = \frac{\partial U_A}{\partial L} + \frac{\partial U_B}{\partial L} = \frac{\partial U_A}{\partial F_A}\frac{\partial F_A}{\partial L} + \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial L} \quad (7.31)$$

These expressions effectively constitutes the complements of the sensitivities, calculated previously. As indicated, designer *sensitivity*, *power*, and *leverage* are summed at each point sampled throughout the design space, in order to obtain a more comprehensive understanding of the resultant net effect on objective performance. Certain cases may warrant a higher level of fidelity, achievable via the investigation of responsiveness on a variable-specific basis.

In each of these cases,

$$\frac{\partial U_A}{\partial F_A} = -0.6854e^{0.6854F_A} \tag{7.32}$$

$$\frac{\partial U_B}{\partial F_B} = 2.0809e^{2.0809F_B} \tag{7.33}$$

$$\frac{\partial U_C}{\partial F_C} = -0.689e^{0.689F_C} \tag{7.34}$$

$$\frac{\partial F_A}{\partial R} = 2\pi\rho\left(2T^2 + 4RT + TL\right) \tag{7.35}$$

$$\frac{\partial F_A}{\partial T} = \pi\rho\left(4\left(R+T\right)^2 + 2\left(R+T\right)L\right) \tag{7.36}$$

$$\frac{\partial F_A}{\partial L} = \pi\rho\left(T^2 + 2RT\right) \tag{7.37}$$

$$\frac{\partial F_B}{\partial R} = \pi\left(4R^2 + 2RL\right) \tag{7.38}$$

$$\frac{\partial F_B}{\partial L} = \pi R^2 \tag{7.39}$$

$$\frac{\partial F_B}{\partial T} = 0 \tag{7.40}$$

$$\frac{\partial F_C}{\partial R} = 0.6224TL + 3.5762RT + 19.8621T^2 \tag{7.41}$$

$$\frac{\partial F_C}{\partial T} = 0.6224RL + 1.7881R^2 + 6.3222TL + 39.7242RT \tag{7.42}$$

$$\frac{\partial F_C}{\partial L} = 0.6224RT + 3.5762RT + 19.8621T^2 \tag{7.43}$$

It is emphasized once more that measures of responsiveness should be assessed with respect to designer utilities rather than raw objective value achievement. Doing so, serves as a consistent means of normalization and accentuates any associated changes on designer satisfaction. The results of this assessment are provided in Table 7-9. The associated systems transparency serves as the basis for precedence determination.

Table 7-9 - Indicators of Responsiveness for Three Stakeholders in Feasible Collaborative Design Space

Indicator	Sensitivity	Power	Leverage
Average (Designer A)	460.39	7.31	681.63
Average (Designer B)	491.05	0	650.96
Average (Designer C)	190.57	2.76	951.45
Domination (Designer A)	55%	100%	0
Domination (Designer B)	45%	0	27%
Domination (Designer C)	0%	0	73%

It is noted that the indicators reported here are cumulative with respect to all other parties considered. As indicated by the results, reported in Table 7-9 and summarized in the SPL matrices of Figure 7-24, Designers A and B exhibit roughly the same level of sensitivity. This is underscored by the remarkably even split among these stakeholders in terms of domination throughout the design space. Designer C is by far the least sensitive and simultaneously exerts the highest degree of leverage. Designers B and C share domination with respect to this parameter throughout the design space. Although Designer A has the second highest leverage on average, he or she never dominates both Designers B and C at the same point. Nevertheless, Designer A sports the highest level of power (more than double than that of Designer C). Designer B has zero ability to influence the achievement of his or her objective.

As in the two-designer example, the strength of the interdependence emphasized by the *sensitivity*, *power*, and *leverage* levels of Table 7-9 makes cooperative behavior the sole contender for yielding acceptable results. It is noted, however, that the systematic construction of a collaborative design space has made this example a win/win situation regardless of the protocol chosen. Levels of achievement vary widely throughout the original design space, characterized by a substantial number of feasible solutions for Designer B (see Figure 7-21), but only a small number of acceptable designs for Designers A (see Figure 7-20) and C (see Figure 7-22). As one might expect in such a strongly coupled decision, very few of these solutions overlap, as indicated in Figure 7-23, producing a collaborative design space that is fairly small. Nevertheless, focalization of stakeholder efforts in this region reduces this disparity in levels of achievement to comparable levels; $0.75 \le U_A \le 1$ for Designer A, $0.77 \le U_B \le 1$ for Designer B, and $U_C = 1$ for Designer C. In light of this discovery, no single stakeholder has an unfair advantage and the playing field has been successfully leveled, making this a true win/win situation.

Sensitivity

	A	B	C
A		0.547	1
B	0.453		0.732
C	0	0.268	

Power

	A	B	C
A		1	1
B	0		0
C	0	1	

Leverage

	A	B	C
A		0.453	0
B	0.547		0.268
C	1	0.732	

Figure 7-24 - Responsiveness for Three Stakeholders throughout the Collaborative Design Space

Based on an overall assessment of these indicators in conjunction with the performance potential over the reduced region, it becomes evident that all three stakeholders are matched fairly evenly what performance within the collaborative design space is concerned. Nevertheless, system level considerations are served slightly better by Designer taking the lead. While both Designer A and C possess non-zero *power* responses, the achievement potential of Designer A is inferior to that of Designer B. More importantly, Designer C cannot be slighted; every point within the collaborative design space either meets or exceeds his or her ideal level of objective performance. As in the previous case, it is Designer B's null *power* response that renders any decision made by him or her somewhat arbitrary, especially when information regarding Designer

A's strategy is missing. Even in the event that Designer B is privy to such information, it makes more sense for Designer A to take charge of their combined contribution to the overarching system (recall that Designer C cannot be disappointed). With this in mind, the chosen sequencing scheme is the transfer of control to Designer A alongside BRCs for both Designers B and C. The resulting design solution is $(R,L,T)=(10.63,10.34,0.10)$ with $U_A=1$, $U_B=1$, $U_C=1$, and $U_{System}=1$. Even in the absence of stakeholder response information, it is advisable to transfer control to Designer A. As shown in Table 7-10, doing so results in slightly more evenly distributed overachievement of preference levels.

Although the variation of performance possible within this systematically constructed region, composed exclusively of win/win scenarios, is noticeable, the quality of the solutions displayed in Table 7-10 is remarkable. As might be expected, ceding control to any of the three designers in the absence of information regarding the level of satisfaction to be expected by the opposing parties, invariably results in the maximization of their respective objectives. This is the logical consequence; in the absence of intelligence regarding the tradeoff strategies of other stakeholders, each entity is concerned with increasing their margin in fear of being slighted. In this example, system level utility is not altered significantly by changing control, masking the tradeoffs that occur among the designers.

System level performance in the case of control transfer alongside the communication of strategies is equivalent from a satisficing frame of reference, since the ideal performance levels of all designers are exceeded. From a mathematical perspective, however, the degree of overachievement most balanced for Designer C. This is due to the fact that Designer C is weighing tradeoffs among two designers that are at slight disadvantages (compared to his or her own performance). A final comparison is made with the completely cooperative solution, determined via reformulation of stakeholder design sub-problems as a single design problem with the objective to optimize system level objective performance (taken to be the evenly weighted Archimedean sum of stakeholder objectives). This solution is representative of the global optimum in this scenario. As expected, this case comprises the best answer, at least from a mathematical perspective, striking the most even balance in terms of overachievement of weight, volume, and cost objectives.

Having explored the extensibility of *co-design* to more than two stakeholders in this section, the results of both the two and three designer scenarios are reviewed in light of answers emanating from the application of traditional protocols in the next section.

Table 7-10 - The Impact of Stakeholder Sequence on System & Sub-System Level Trade-Offs

Stakeholder Sequence	R	L	T	U_A	U_B	U_C	U_{System}	F_A	F_B	F_C
Total Control (Designer A) w/o BRC	11.19	5.97	0.10	1	0.77	1	0.92	56.7	8226.8	29.0
Total Control (Designer B) w/o BRC	11.68	7.43	0.10	0.76	1	1	0.92	64.2	9858.6	32.4
Total Control (Designer C) w/o BRC	11.76	15.20	0.10	1	0.77	1	0.92	59.5	8223.8	28.2
Total Control (Designer A) w/ BRC	10.63	10.34	0.10	1	1	1	1	60.0	8698.1	29.5
Total Control (Designer B) w/ BRC	10.79	8.89	0.10	1	1	1	1	58.7	8511.1	29.2
Total Control (Designer C) w/ BRC	11.76	5.00	0.10	1	1	1	1	59.9	8987.1	30.9
Cooperative	11.44	5.49	0.10	1	1	1	1	57.9	8521.1	29.8

7.6 RESULTS AND DISCUSSION OF EXAMPLE APPLICATION OUTCOMES

7.6.1 Critical Analysis of Results

The most meaningful comparisons of the results obtained using FACE are those derived from contrasting them with the completely cooperative solutions, documented in the final rows of Table 7-6 and Table 7-10. These completely cooperative solutions can be regarded as being the best win/win results within the design space. As pointed out in Sections 7.4.4 and 7.5.4, there is a high degree of concurrence. This is due in large part to the execution of this solutions mechanism within the collaborative design space, identified as a result of CDSF, and reliance on designer preferences for normalization purposes. In order to illustrate the comparative performance of *co-designed* solutions with traditional protocols, however, further comparisons are required. A brief comparison with Nash equilibria, obtained over the original design space and (in the case of the three designer example the systematically constructed collaborative design space) follows.

The BRCs for Designers A and B in the two-designer case of Section 7.4 are plotted in Figure 7-25 and Figure 7-26, respectively. As underscored by these strategies and their intersection in Figure 7-27, the use of non-cooperative game theory as a means of conflict resolution is not advisable in this scenario. ***T*** does enter into Designer B's objective function. Consequently, from the perspective of Designer B any value of ***T*** within the system confines will do. This is not to imply that Designer B is ambivalent, however. In fact, the degree of Designer B's leverage over Designer A can serve as a valuable bargaining chip. Although absence of control in the case of Designer B is extreme, the point is that though mathematically rigorous, game theory, as traditionally applied in engineering design is not necessarily useful for all scenarios. Often the existence of a mutually acceptable solution is presupposed. As underscored by Figure 7-28, however, win/lose and lose/lose situations are the most likely results in the absence of a systematic approach to conditioning a design space as advocated in this dissertation.

The Nash Equilibria for the two-designer case are plotted in Figure 7-27 and documented in

Table 7-11. Clearly, all of these potential Nash solutions are unacceptable. While the objectives of Designer A are met or even exceeded in a number of cases, those of Designer B fall considerably short. The impossibility of reconciling stakeholder desires is underscored further by the absence of overlap in the original (unconditioned) design space of Figure 7-28. It is clear from these results that reliance on traditional protocols aimed at optimizing objective response produces poor results, especially, when compared to those obtained via *co-design*.

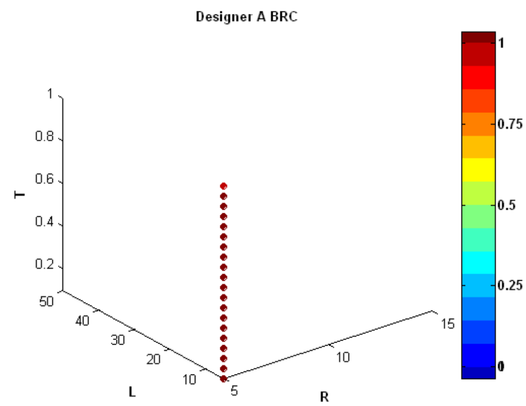

Figure 7-25 - Best Reply Correspondence for Designer A

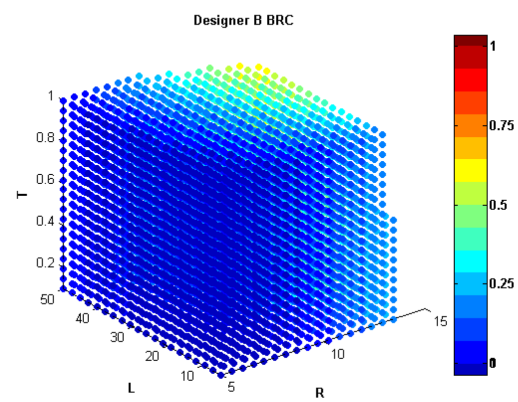

Figure 7-26 - Best Reply Correspondence for Designer B

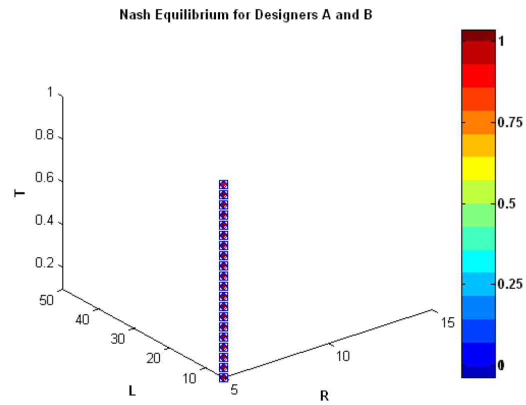

Figure 7-27 - Nash Equilibria for Designers A and B via BRC Intersection

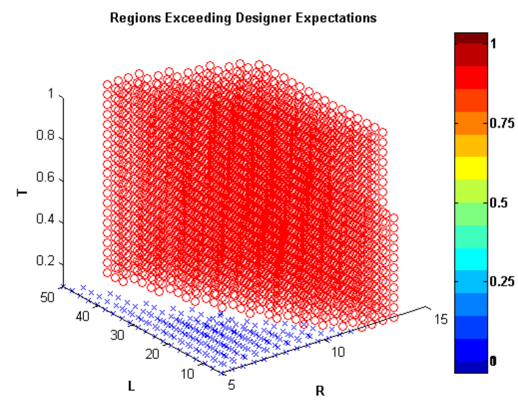

Figure 7-28 - Regions Meeting and Exceeding Designer Expectations

Table 7-11 - Nash Equilibria for Two Designers throughout Original Design Space

R	L	T	U_A	U_B	U_{System}	F_A	F_B
5	5	0.1	1	0	0.5	13.512	916.3
5	5	0.147	1	0	0.5	20.068	916.3
5	5	0.195	1	0	0.5	26.727	916.3
5	5	0.242	1	0	0.5	33.488	916.3
5	5	0.289	1	0	0.5	40.353	916.3
5	5	0.337	1	0	0.5	47.321	916.3
5	5	0.384	1	0	0.5	54.394	916.3
5	5	0.432	0.895	0	0.448	61.573	916.3
5	5	0.479	0.471	0	0.235	68.857	916.3

In the three designer case of Section 7.5, similar observations can be made. The BRCs for Designers A, B, and C are plotted in Figure 7-29, Figure 7-30, and Figure 7-31, respectively. As underscored by these strategies and their intersection in Figure 7-32, the use of non-cooperative game theory as a means of conflict resolution is not advisable in this scenario either. As in the two-designer case, ***T*** does enter into Designer B's objective function. Additionally, it is important to note that the larger the number of designers, involved in a decision becomes, the more problematic the application of strategic form non-cooperative games becomes. In fact, the likelihood of an intersection existing in the absence of stakeholder coordination prior to the point of making the decision is quite slim. Often the existence of a mutually acceptable solution is presupposed. As underscored by Figure 7-32, however, win/lose and lose/lose situations are the most likely results in the absence of a systematic design space conditioning approach such as that advocated in this dissertation. As indicated by the warmth of the Nash equilibria plotted (based on an evenly weighted Archimedean sum of stakeholder utilities), the expectations of Designer B are consistently underachieved. The degree of this shortfall can be surmised by considering the high caliber that the Nash Equilibria represent for Designers A and C, as shown in Figure 7-29 and Figure 7-31, respectively, and contrasting it with the poor performance of Designer B's objectives at these points (see Figure 7-30). A quantitative comparison (see Table 7-12) of these non-cooperative results reveals that every Nash Equilibrium is absolutely unacceptable to Designer B. Meanwhile, the expectations of Designers A and C are exceeded in every circumstance. While this fact is not unexpected in light of this stakeholder's inherent lack of control, reliance on a quasi algorithmic solution mechanism does nothing to remedy this unfortunate set of circumstances. As in the two-designer case, the poor performance of traditional protocols aimed at optimizing objective response, especially, when compared to those obtained via *co-design,* is underscored.

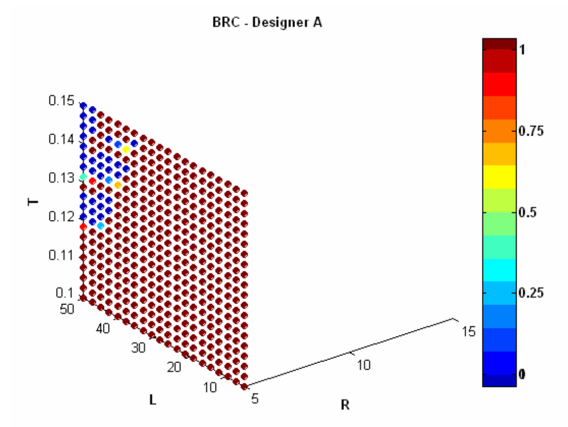

Figure 7-29 - Best Reply Correspondence for Designer A

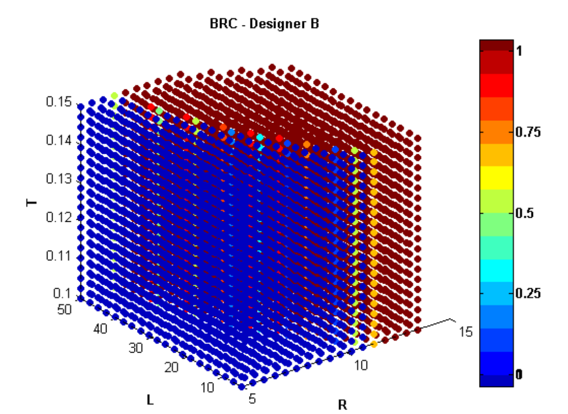

Figure 7-30 - Best Reply Correspondence for Designer B

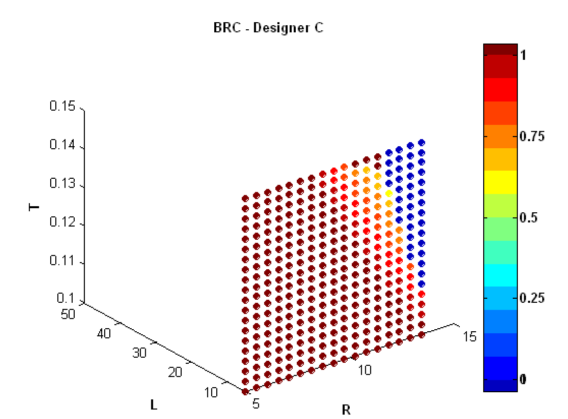

Figure 7-31 - Best Reply Correspondence for Designer C

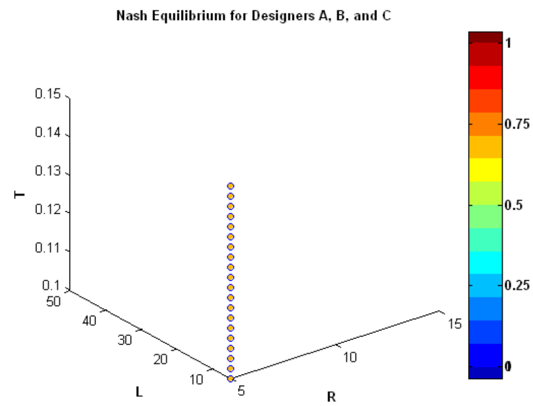

Figure 7-32 - Nash Equilibria for Designers A, B, and C via BRC Intersection

Table 7-12 - Nash Equilibria for Three Designers throughout Original Design Space

R	L	T	U_A	U_B	U_C	U_{System}	F_A	F_B	F_B
5	5	0.100	1	0	1	0.667	916.3	7.177	13.512
5	5	0.103	1	0	1	0.667	916.3	7.397	13.873
5	5	0.103	1	0	1	0.667	916.3	7.397	13.873
5	5	0.105	1	0	1	0.667	916.3	7.619	14.235
5	5	0.108	1	0	1	0.667	916.3	7.842	14.597
5	5	0.111	1	0	1	0.667	916.3	8.067	14.960
5	5	0.113	1	0	1	0.667	916.3	8.293	15.323
5	5	0.116	1	0	1	0.667	916.3	8.521	15.686
5	5	0.118	1	0	1	0.667	916.3	8.751	16.049
5	5	0.121	1	0	1	0.667	916.3	8.982	16.413
5	5	0.124	1	0	1	0.667	916.3	9.215	16.777
5	5	0.126	1	0	1	0.667	916.3	9.449	17.142
5	5	0.129	1	0	1	0.667	916.3	9.685	17.507
5	5	0.132	1	0	1	0.667	916.3	9.922	17.872
5	5	0.134	1	0	1	0.667	916.3	10.161	18.237
5	5	0.137	1	0	1	0.667	916.3	10.402	18.603
5	5	0.139	1	0	1	0.667	916.3	10.644	18.969
5	5	0.142	1	0	1	0.667	916.3	10.888	19.335
5	5	0.145	1	0	1	0.667	916.3	11.134	19.702
5	5	0.147	1	0	1	0.667	916.3	11.381	20.068

As indicated in the previous paragraphs, the basic usefulness of game theoretic protocols as traditionally applied within the engineering design community is staked on the existence of at least a single common solution. In order to illustrate (1) the openness of FACE and (2) the fundamental value of CDSFM, regardless of the final solution mechanism chosen, the quality of Nash equilibria obtained within the collaborative design space is considered next.

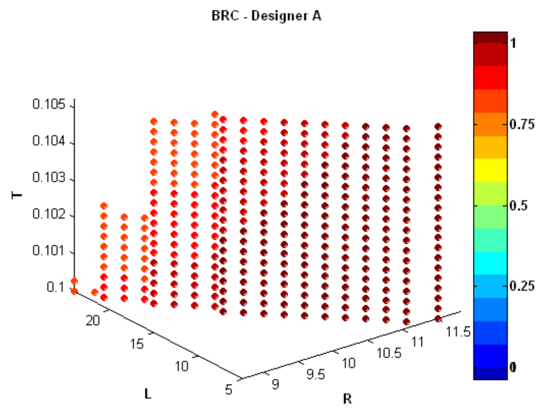

Figure 7-33 - Best Reply Correspondence for Designer A

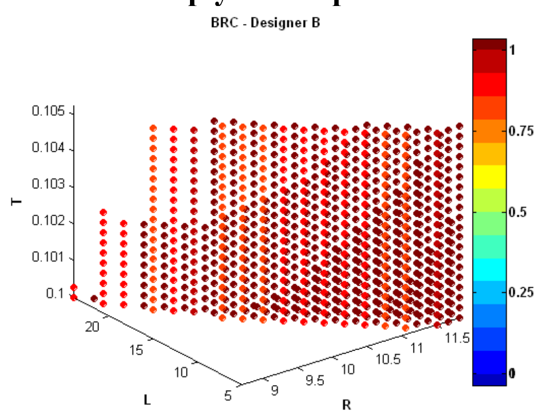

Figure 7-34 - Best Reply Correspondence for Designer B

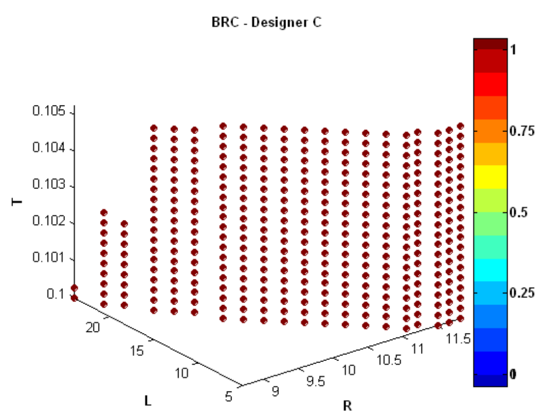

Figure 7-35 - Best Reply Correspondence for Designer C

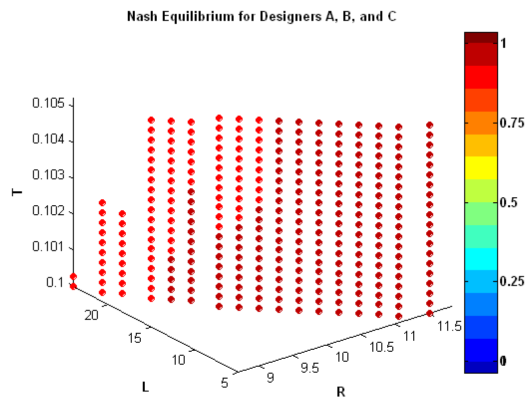

Figure 7-36 - Nash Equilibria for Designers A, B, and C in a Conditioned Design Space via BRC Intersection

As can be readily observed from Table 7-13 the quality of the results, obtained using a strategic form, non-cooperative game within FACE, is significantly better than that of the solutions obtained through the application of game theory in lieu of CDSFM. Although, only those Nash Equilibria, yielding the highest system level utilities are reported in Table 7-13, the lowest level of performance corresponds to $U_{System} = 0.85$. The performance potential of Designers A varies from $U_A = 0.750$ to $U_A = 1$, that of Designer B from $U_B = 0.75$ to $U_B = 0.89$. Meanwhile, the performance of Designer C never deviates from $U_C = 1$. Clearly, Designer B is still at a disadvantage what average performance is concerned. However, not a single solution would be deemed unacceptable. In fact, all of the solutions obtained by applying a non-cooperative protocol within FACE are desirable to all stakeholders.

It is thus underscored that FACE can be employed successfully in conjunction with a number of different protocols, ranging from the cooperative to the non-cooperative. While *co-design* yields the most balanced solutions, design space conditioning ensures that any means of stakeholder coordination turns out to be fruitful.

Table 7-13 - Nash Equilibria for Three Designers in a Conditioned Design Space

R	L	T	U_A	U_B	U_C	U_{System}	F_A	F_B	F_B
11.510	5.000	0.100	1.00	0.89	1.00	0.96	57.594	8467.4	29.713
11.510	5.000	0.100	1.00	0.89	1.00	0.96	57.755	8467.4	29.802
11.510	5.000	0.101	1.00	0.89	1.00	0.96	57.915	8467.4	29.891
11.510	5.000	0.101	1.00	0.89	1.00	0.96	58.076	8467.4	29.980
11.510	5.000	0.101	1.00	0.89	1.00	0.96	58.237	8467.4	30.069
11.510	5.000	0.101	1.00	0.89	1.00	0.96	58.398	8467.4	30.159
11.510	5.000	0.102	1.00	0.89	1.00	0.96	58.558	8467.4	30.248
11.510	5.000	0.102	1.00	0.89	1.00	0.96	58.719	8467.4	30.337
11.510	5.000	0.102	1.00	0.89	1.00	0.96	58.880	8467.4	30.426
11.510	5.000	0.102	1.00	0.89	1.00	0.96	59.041	8467.4	30.516
11.510	5.000	0.103	1.00	0.89	1.00	0.96	59.201	8467.4	30.605
11.510	5.000	0.103	1.00	0.89	1.00	0.96	59.362	8467.4	30.695
11.510	5.000	0.103	1.00	0.89	1.00	0.96	59.523	8467.4	30.784
11.510	5.000	0.104	1.00	0.89	1.00	0.96	59.684	8467.4	30.873
11.510	5.000	0.104	1.00	0.89	1.00	0.96	59.844	8467.4	30.963

Designer B having no direct influence over the achievement of his or her objective results in the inadequate performance of non-cooperative tradeoff management on its own accord. This is true for either scenario of this example problem. Designer B's decision only impacts the performance of Designer A (in the two-designer scenario) and Designers A and C (in the three-Designer scenario), to each of which Designer B is ambivalent. It is this set of circumstances that causes the game-based protocols to fail. Though, somewhat extreme and admittedly contrived, this situation is nevertheless conceivable, especially considering the complexity and intricacy of the hierarchies underlying a wealth of complex engineering systems. Furthermore, it is in an effort to test the limits of the methods proposed in this dissertation that these are successively subjected to sets of circumstances that offer substantial challenges along different dimensions. It is for this reason that the manner in which control was divided among the stakeholders in this example differs from the more intuitive division used by Marston for the validation of Game-based Design in Ref. [133].

7.6.2 Impact of Employing the Framework for Agile Collaboration in Engineering

As indicated in Section 7.6.1, the methodical formulation of collaborative design spaces in conjunction with the interaction-conscious coordination of stakeholders, inherent in the application of FACE for *co-design*, allows for the solution of a problem otherwise only solvable via complete cooperation. As indicated in Chapters 1 and 2, it is often assumed in the application of game theory to engineering design that solutions exist. Suboptimal solutions are often accepted at the price of "efficiency" with regard to reductions in the number of communications made among the stakeholders. There are two possible consequences: (1) the conflict is deemed unsolvable or (2) ineffective communication, based on negotiation strategy or simple trail-and-error results. Both penalties directly defeat the stated purpose of increasing competence in decentralized decision-making. In this example it is illustrated that desirable results can indeed be achieved even in the direst of circumstances. However, a paradigm shift is required. Thus, *co-design* succeeds where traditional means in the context of optimization cannot.

In this example, those ranges or sets of values yielding acceptable results (i.e., those meeting or exceeding designer expectations) for each of the design decisions are identified through space filling experiments of increasing granularity. Due to the relatively well behaved nature of the design problem, these experiments were executed on the closed form expressions serving as design models. As indicated in Sections 4.3 and 4.4, in the case of computationally complex design problems, response surfaces fitted over increasingly smaller regions can be employed in tandem with actual models. Estimates will generally improve alongside surrogate model fidelity. This is illustrated in Chapter 8.

Additionally, much of the computational effort is reduced by effectively identifying those areas of a shared design space that warrant further investigation. Since those areas that do not contain feasible solutions are not considered in the searches, stakeholders are focalized on those regions that have the highest likelihood of success. Although not explicitly focused upon in this discussion, the dynamic reflection of updated information content (associated with each of the communications among the stakeholders, required for progressing towards the determination of a mutually beneficial solution) is greatly facilitated through reliance on templates such as those developed in Chapter 3. While decision templates aptly capture all decision critical aspects of the design sub-problems individual stakeholders are charged with, interaction templates can be used to facilitate the exploration of the collaborative design space, composed of their respective design sub-spaces.

In summary, the pressure vessel design scenario explored in this chapter is a prime example of a strongly coupled decision that can easily result in extensive negotiation. It is also an example of a case where sole reliance on BRCs really makes no practical sense; one of the designers controls an aspect not factoring into the achievement of his or her own objective. In consideration of this even non-cooperative leader follower approaches are not strictly suited. Thus, two observations are made (1) non-cooperative protocols are quasi guaranteed to result in poor solutions when employed as traditionally envisioned and (2) cooperative protocols, though failsafe are impractical. Meaningful design results are produced only as a result of employing FACE; either via the application of CDSFM in conjunction with (1) ICCM for the purposes of *co-design* or (2) a more traditional protocol, chosen based upon enterprise considerations. The result of either strategy is a practical design process based on mutual education and consistent progression towards a mutually beneficial solution.

7.7 A LOOK BACK AND A LOOK AHEAD

7.7.1 Revisiting the Roadmap

As indicated in the beginning of this chapter, and highlighted in Figure 7-37, the main goal pursued was demonstrating the usefulness of the **F**ramework for **A**gile **C**ollaboration in **E**ngineering for successfully coordinating the efforts of three designers. The underlying intent was that of building confidence in the scalability of the associated methods beyond the three stakeholders considered to *n*. Although the example considered was representative of typically encountered engineering problems, it was mathematically simple. The focus of the next chapter is to finalize the empirical validation and verification commenced in the previous chapter and cemented in this chapter by exploring the applicability and performance of the framework and its constituents to a highly complex engineering design problem, requiring the use of surrogate models for effective exploration.

7.7.2 Assembling the Building Blocks

In this chapter the **F**ramework for **A**gile **C**ollaboration in **E**ngineering, illustrated in Chapter 6, was applied to an engineering design problem of representative complexity. Special consideration was given to the manner in which both two and three stakeholders resolve essentially the same strongly coupled design problem. Both components of FACE were treated separately, making a careful distinction between the benefits obtained from the implementation of the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod and the application of the **I**nteraction-**C**onscious **C**oordination **M**echanism. With this in mind, co-designed results were compared to cooperative and non-cooperative solutions obtained using traditional protocols both in isolation and in concert with **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod. The usefulness of the underlying methods was thus substantiated by demonstrating the vast improvement in the quality of objective performance. Consequently, it can be asserted that any means of conflict resolution can benefit from the proper conditioning of a shared design space. Continued interactions (rendered both more effective as well as efficient through systematization) constitute the basis for moving towards win/win situations. The degree to which the expectations of interacting stakeholders are met can further be improved by taking responsiveness and performance potential into consideration, making *co-design* a viable alternative to strategic collaboration.

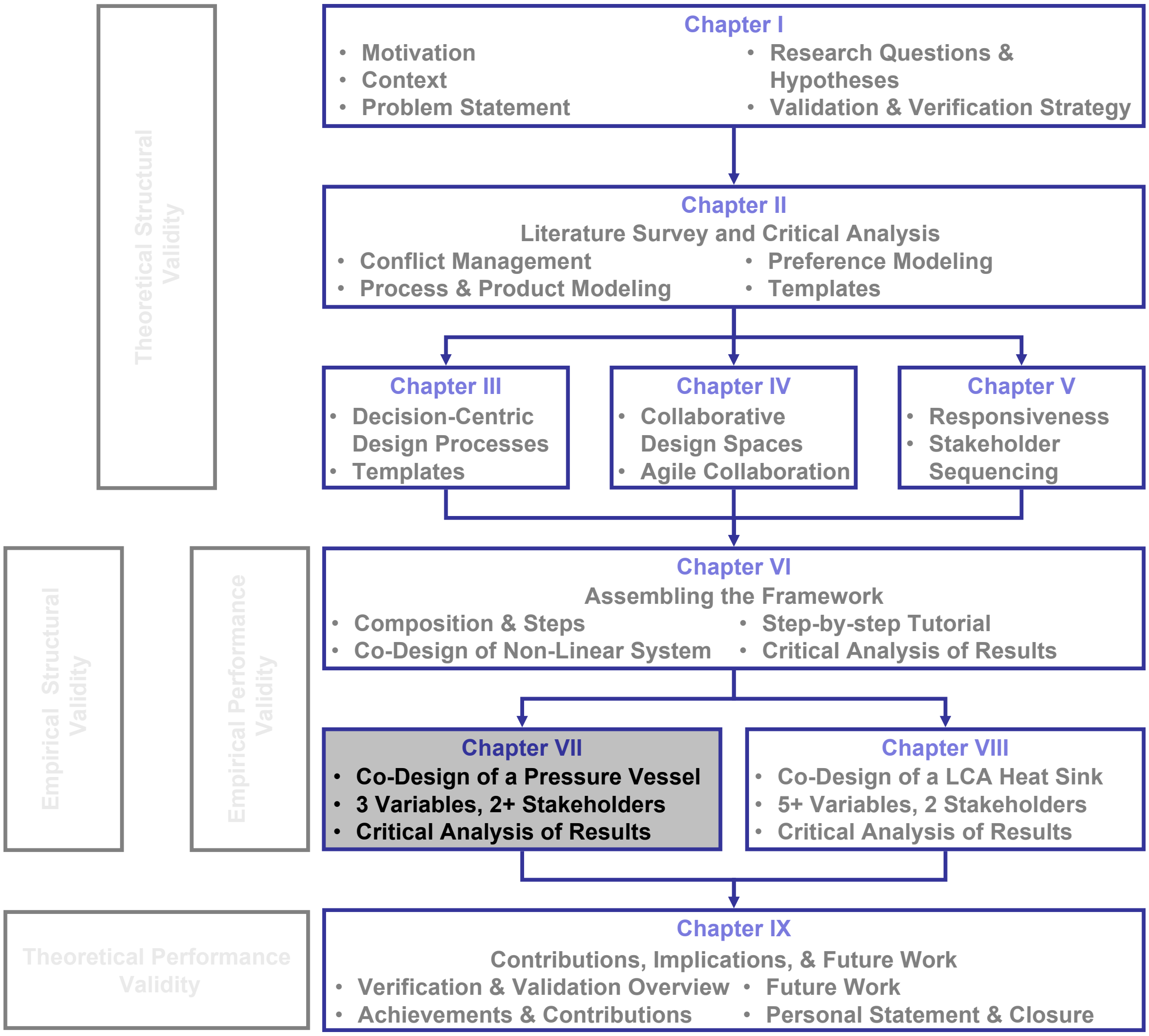

Figure 7-37 - Dissertation Roadmap

CHAPTER 8 - COLLABORATIVE DESIGN OF A STRUCTURAL HEAT EXCHANGER

The primary purpose pursued in this chapter is the further substantiation of *empirical* validation with regard to *structure* and *performance* of *Hypotheses 2* and *3*. As in Chapter 7, confidence in *empirical structural* validity is established with regard to the appropriateness of the specific design problem considered. *Empirical performance* validity is addressed through demonstrating the usefulness of the proposed approach in supporting two domain experts, sharing control over a common design space and pursuing conflicting objectives, in making the tradeoffs, characterizing their strongly coupled decisions. This aim is pursued using an example focusing on the collaborative design of a Linear Cellular Alloy (LCA) Heat Exchanger for conjoint heat transfer. The implementation of each aspect of the framework is illustrated with a focus on the intricacies of managing the inherent conflict among the interacting stakeholders for a design problem of considerable complexity, far exceeding that of the problems considered previously.

The details of the heat exchanger design problem are introduced in Section 8.1. Details regarding the appropriateness of this example to the overall validation and verification strategy pursued in this dissertation are deliberated in Section 8.3. Section 8.4 contains the details of the application of the framework in supporting the efforts of the structural and thermal domain experts. Results obtained are critically evaluated in Section 8.5. Finally, continuity and coherence with respect to the remainder of the dissertation are established in Section 8.6.

8.1 VALIDATION AND VERIFICATION WITHIN CHAPTER 8

As indicated in Section 1.5.1, the **F**ramework for **A**gile **C**ollaboration in **E**ngineering, first synthesized in Chapter 6, is applied to an example of high complexity with regard to both the number of design variables considered and the underlying simulation models in this chapter. The focus is on finalizing the process of establishing the **Empirical Structural Validation** and **Empirical Performance Validation** of the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod and the **I**nteraction-**C**onscious **C**oordination **M**echanism, posed in response to *Research Questions 2* and *3*, respectively. The chosen example is that of a Structural Heat Exchanger, the outcome of which is highly sensitive to the sequence in which the domain specific (i.e., structural and thermal) decisions are made. Due to the high dimensionality of this example, visualization of the collaborative design space is no longer possible; projections are only of limited use in focalizing stakeholder efforts and understanding interactions. Specific aspects of this effort are summarized in Figure 8-1 and addressed in more detail in Section 8.3. Based upon the successful conclusion of **Theoretical Structural Validation**, **Empirical Structural Validation,** and **Empirical Performance Validation** with this chapter, **Theoretical Performance Validation** can finally be addressed in Chapter 9.

8.2 LINEAR CELLULAR ALLOYS

8.2.1 Applications of Linear Cellular Alloys in Engineering Practice

Linear cellular alloys (LCAs) [120,205] are ordered, metallic cellular or honeycomb materials with extended prismatic cells, as illustrated in Figure 8-2. LCAs or prismatic cellular materials are well-suited for multifunctional applications in which the material is required to meet multiple performance objectives. Prismatic cellular materials have a combination of properties that make them suitable for a range of multifunctional applications such as ultra light structures, fuel cell and battery subsystems, energy absorption systems, and heat exchangers (as focused upon in this dissertation) [68,88,92]. A newly developed, flexible manufacturing process enables extensive tailoring of prismatic cellular materials, such as these, for multifunctional applications. Via a thermo-chemical extrusion fabrication process developed by the Lightweight Structures Group at the Georgia Institute of Technology, LCAs or prismatic cellular materials can be produced with nearly arbitrary two-dimensional topologies and dimensions, metallic base materials, and wall thicknesses as small as 50 μm [57].

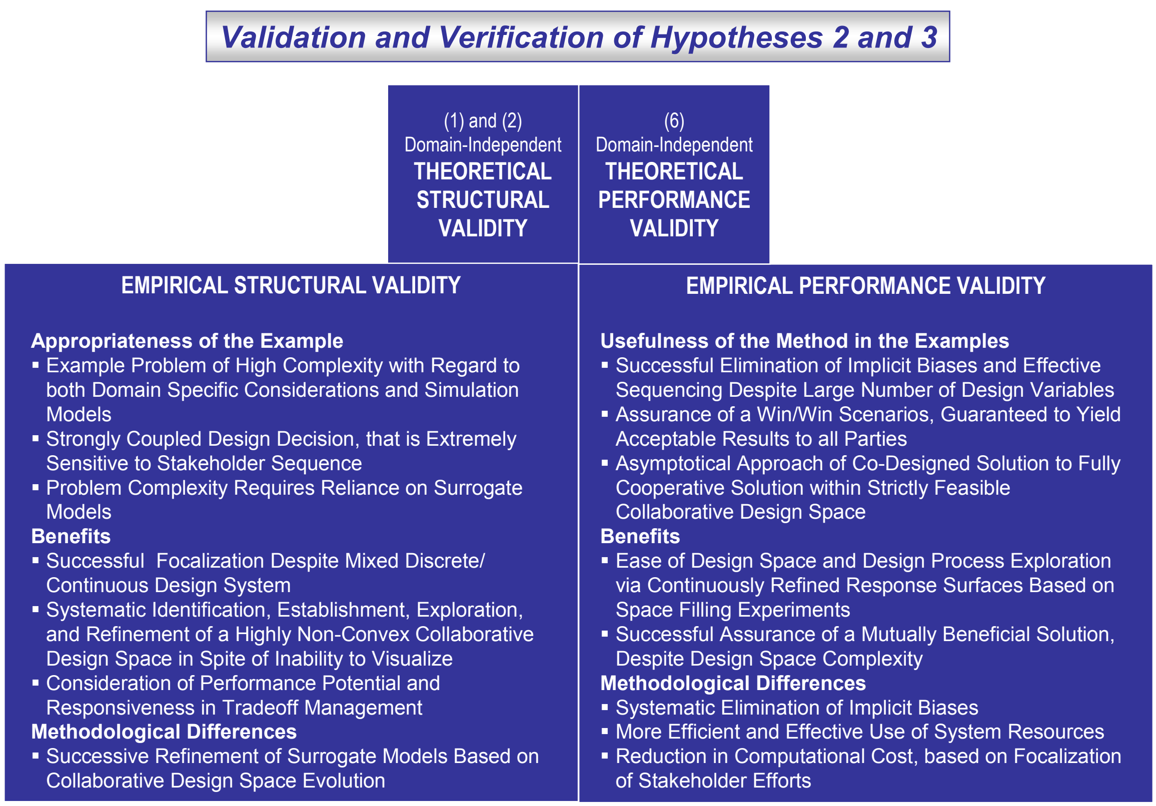

Figure 8-1 - Aspects of Validation and Verification Addressed in Chapter 8

In the fabrication process, metal oxide powder-based slurries are (1) extruded through a customized die (that facilitates in-plane topological and dimensional tailoring of the cellular material), (2) reduced in a hydrogen environment, and (3) sintered at high temperature to form metallic cellular structures, as illustrated in Figure 8-13. Several base materials have been successfully processed, including steels, Nickel-based alloys, and copper. Due to the extensive freedom afforded by the fabrication process for tailoring the two-dimensional topologies and dimensions of cells and cell walls, a rich array of materials design possibilities are available, providing a host of challenges for designing these materials for multifunctional applications that require compromises between disparate goals and objectives.

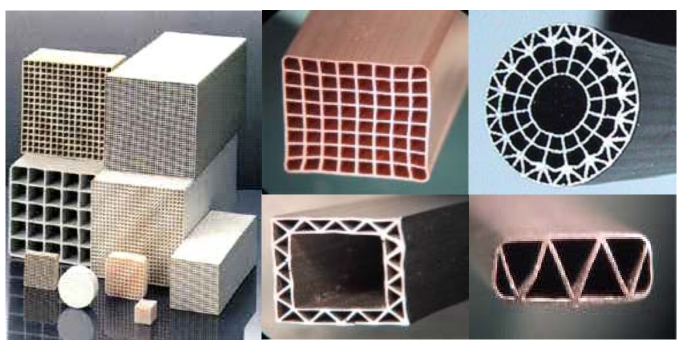

Figure 8-2 - Ordered, Prismatic Cellular Materials

Although there are many potential applications that could benefit from exploiting the unique capabilities of LCAs, the example chosen for validation and verification purposes in this chapter is the design of a forced convection CPU heat sink. Heat sinks are commonly defined as objects or environments capable of absorbing heat from other objects with which they are in (either direct or radiational) contact. This is accomplished by stabilizing thermal mass and heat dissipation [8]. Although radiation often plays a minor role, the primary mechanisms for heat transfer in this application are conduction and convection. Consequently, it is these effects that are focused upon. Often a thermal interface material (TIM) (e.g. silicone oil filled with aluminum oxide, zinc oxide, or boron nitride), also called thermal grease, is used to improve heat transfer by direct contact. The most common class of heat sinks consist of finned, high conductivity metal structures made of copper or aluminum, combined with a fan to increase airflow and thereby maintain a larger thermal gradient via steady replacement of heated air.

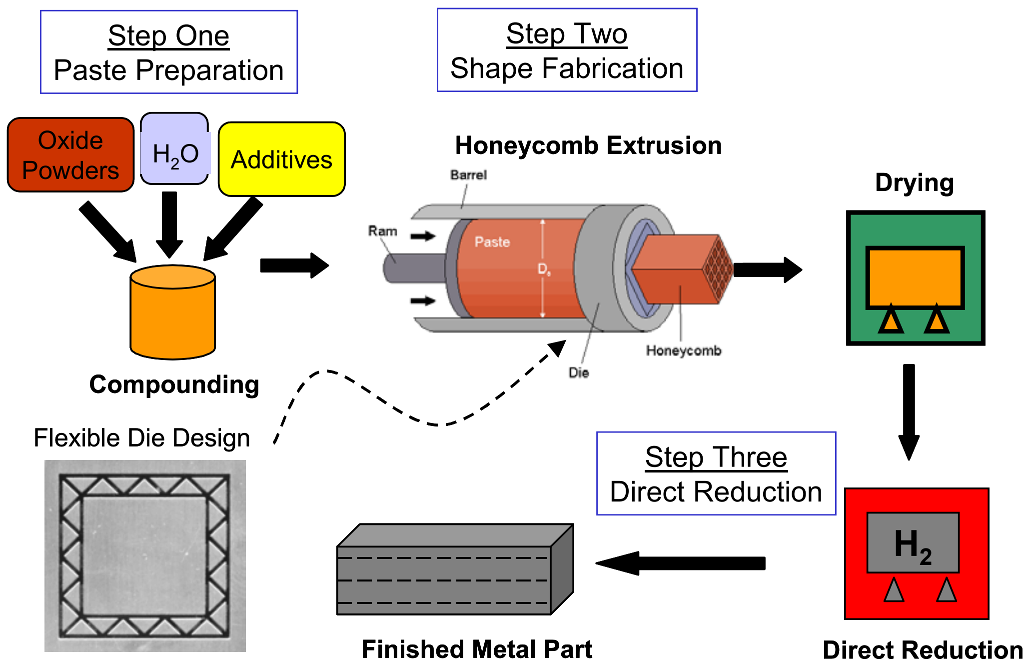

Figure 8-3 - LCA Production (courtesy of Lightweight Structures Group)

8.2.2 Governing Equations and Underlying Models

In the present example, prismatic cellular material is designed for a structural heat exchanger application in which the cellular material is expected to dissipate heat via conduction and convection *and* to support structural loads. The example is abstracted from potential applications such as actively cooled skins in high performance aerospace vehicles or combustor liners in gas turbine engines. As clarified further in Section 8.4.1, the goal for the present example is to determine (parametrically) appropriate cell aspect ratios and sizes to achieve functional goals for objectives from two distinct physical domains: (1) overall steady state heat transfer, Q_{Total}, and (2) overall structural elastic stiffness in the x- and y-directions, E_x/E_s and E_y/E_s, respectively (normalized by the solid modulus, E_s, of the base material in the cell walls).

The device illustrated in Figure 8-4 is a sample structural heat exchanger, comprised of a prismatic cellular material or LCA. It has fixed overall width (***W***), depth (***D***), and height (***H***). It is insulated on the left, right, and bottom sides and is subjected to a heat source at constant temperature, $\boldsymbol{T_s}$, on the top face, as indicated in Figure 8-5 and Figure 8-6. The mechanism for heat dissipation is forced convection via air with entry temperature, $\boldsymbol{T_{in}}$, and total mass flow rate, $\dot{M}$. The flow rate is variable, but it is linked to the available pressure head through a representative characteristic fan curve. Steady state, incompressible laminar flow is assumed. The solid material in the device is copper. The thermal conductivity, $\boldsymbol{k_s}$, of copper samples fabricated with the thermo-chemical extrusion process has been measured to be 363 W/m-K (Ref. [53]).

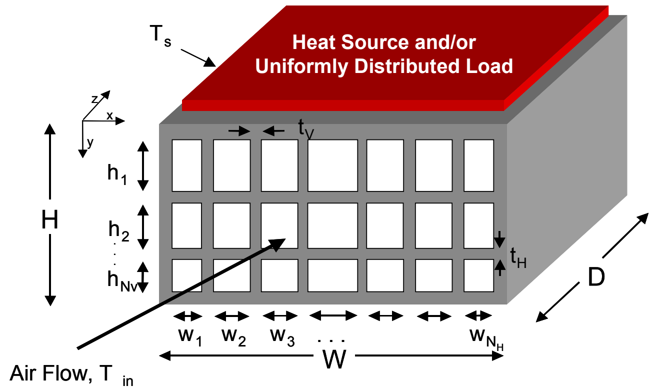

Figure 8-4 - Compact, Forced Convection Heat Exchanger with Rectangular, Prismatic, Cellular Materials [207]

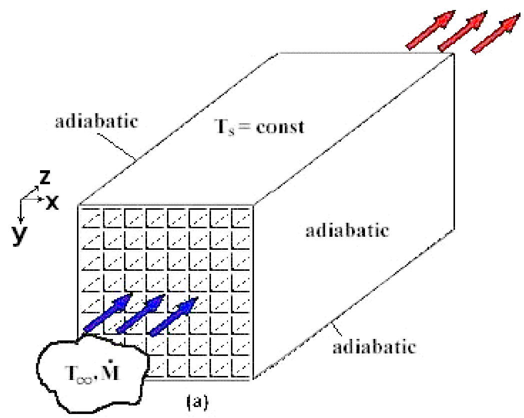

Figure 8-5 - LCA Model for Heat Transfer Analysis [204]

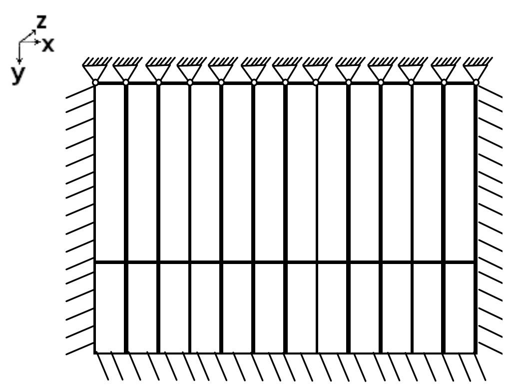

Figure 8-6 - Thermal FEA Boundary Conditions

From a structural perspective, the associated model is based upon a adaptation of the "99 Line Topology Optimization Algorithm", developed by Ole Sigmund [217] and extended by Seepersad in her PhD research [204] for the purposes of designing robust product-material systems. The underlying truss structure approach is used to model the structural performance of the LCAs by approximating each cell wall as a frame element. Primary consideration is given to the maximization of in plane elastic stiffness, estimated as a fraction of total width or height occupied by the cell walls. The expressions corresponding to the x- and y- components are approximated by

$$\tilde{E}_x \big/ E_s \cong \frac{t_h \left(N_v + 1\right)}{H} \tag{8.1}$$

$$\tilde{E}_y \big/ E_s \cong \frac{t_v \left(N_H + 1\right)}{W} \tag{8.2}$$

It is assumed that (1) loading is axial, (2) there are no imperfections, and (3) elastic deformation is strictly the result of axial extension or compression (i.e., no bending contribution). It is noted that although the work of Seepersad also takes buckling into consideration, this aspect is not considered here. The reader is referred to Ref. [204] for more detailed information on the structural models used in the determination of structural properties. Since the basis for the thermal model, later extended, revised, and improved upon by Seepersad were initially developed by Choi and the author, a more detailed explanation of this aspect follows.

As indicated in the previous section, the focus in this chapter is on the design of a structural heat exchanger using LCA technology. Consequently, equal emphasis is placed on the determination of thermal characteristics. There are three general mechanisms by which heat tends to move from regions of higher temperature to regions of lower temperature, namely *conduction*, *radiation*, and *convection*. It is noted that convection although historically regarded as a proper mechanism of heat transfer, is in reality not a mechanism in its own right. Convection is really the result of the combined effect of conduction and fluid flow and is thus sometimes referred to as conjoint heat transfer.

The movement of hot or cold portions of a fluid together with conductive heat transfer from a body results in enthalpy transfer that serves to lower the temperature of the body emitting heat. A distinction is usually made between free and forced convection, differing in the manner by which the fluid to which the surfaces of body are exposed is propelled. In free convection buoyancy and gravity are the agitators, whereas artificial means (e.g., fans, stirrers, etc.) are employed in forced convection. Since the heat exchanger that is focused upon in this section is a heat sink for a personal computer, the equations of interest from the thermal perspective are those relevant to *forced convection*. With this in mind, a brief explanation of the thermal analysis model, coded in MATLAB® follows.

Thermal analysis consists of two parts. The first is aimed at modeling the thermal behavior of the structural material, the second at modeling the changing properties of the fluid flowing through each of the structural voids. The finite element approach employed in this investigation (see Figure 8-7) is somewhat unique in so far that sections of the structure, rather than the structure as a whole, are analyzed one at a time. This is akin to the way in which finite difference codes work. The inherent advantage is that there is no need to calculate immense stiffness matrices, reducing computational complexity. Additionally, this procedure facilitates the determination of changing properties of the convective fluid and the incorporation of these to the thermal analysis of the structure. In essence, this is what a coupled ANSYS/FLOTRAN analysis accomplishes.

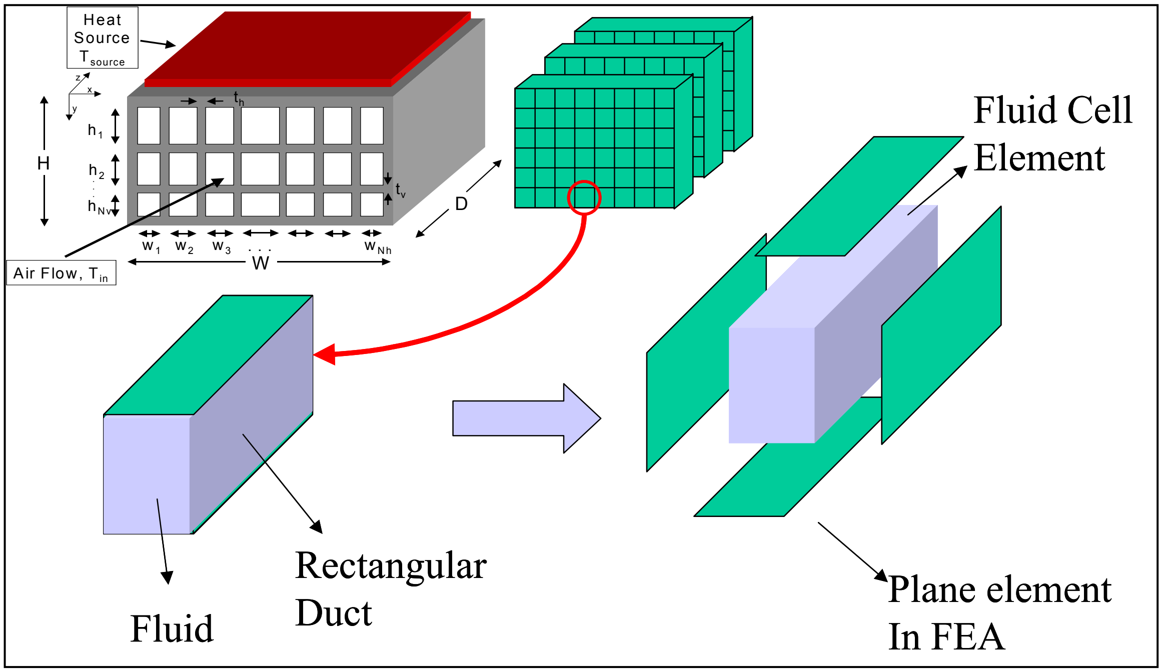

Figure 8-7 - Modeling Approach for Thermal Analysis of LCA Performance

With this in mind, a brief overview of the linear (four node) rectangular and fluid elements, developed for the purposes of this investigation, follows.

The finite element used for LCA thermal analysis is shown in Figure 8-9. As indicated, geometrically, the element is defined by length (a) and width (b). Each of the four nodes (1, 2, 3, and 4) has one degree of freedom – temperature. The element also takes into consideration internal heat generation as indicated by the black arrows, as well as convection effects on either face. This is indicated by the light blue arrows pointing away from either face. The governing equation for steady state heat transfer in plane systems is given by

$$f(x,y) = -\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) - \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right), \quad (8.3)$$

where $\boldsymbol{T}$ is the temperature (in ^{o}K), $\boldsymbol{k_x}$ and $\boldsymbol{k_y}$ are the thermal conductivities of the material (in W m^{-1} ^{o}K^{-1}) along the $\boldsymbol{x}$ and $\boldsymbol{y}$ directions respectively, and $\boldsymbol{f}$ is the internal heat generation per unit volume (in W m^{-3}). For convective boundary conditions, the natural boundary conditions are a balance of energy transfer across the boundary due to conduction and/or convection (i.e., Newton's Law of Cooling) [189]:

$$k_x \frac{\partial T}{\partial x} n_x + k_y \frac{\partial T}{\partial x} n_y + \beta\left(T - T_\infty\right) = \hat{q}_n, \tag{8.4}$$

where $\boldsymbol{\beta}$ is the convective conductance (or the convective heat transfer coefficient) (in W m^{-2} ^{o}K^{-1}), $\boldsymbol{T_\infty}$ is the ambient temperature of the surrounding fluid, and $\hat{q}_n$ is the specified heat flow. The first two terms account for heat transfer by conduction, the third for heat transfer by convection; the term on the right hand side accounts for the specified heat flux, if any [189]. The system illustrated in Figure 8-4 is thus described by the following relationship:

$$\left[K^e + H^e\right]\left\{T^e\right\} = \left\{F^e\right\} + \left\{P^e\right\}, \tag{8.5}$$

where $\boldsymbol{K^e}$ is the stiffness of the element, $\boldsymbol{H^e}$ describes the influence the convection on each node, $\boldsymbol{T^e}$ is the temperature of the element, $\boldsymbol{F^e}$ is the internal heat generation of the element, and $\boldsymbol{P^e}$ is used to define the convection on the top and bottom faces of the element. The interpolations functions for a linear (four node) rectangular element used are:

$$\psi_1 = \left(1 - \frac{\bar{x}}{a}\right)\left(1 - \frac{\bar{y}}{b}\right) \tag{8.6}$$

$$\psi_2 = \left(\frac{\bar{x}}{a}\right)\left(1 - \frac{\bar{y}}{b}\right) \tag{8.7}$$

$$\psi_3 = \left(\frac{\bar{x}}{a}\right)\left(\frac{\bar{y}}{b}\right) \tag{8.8}$$

$$\psi_4 = \left(1 - \frac{\bar{x}}{a}\right)\left(\frac{\bar{y}}{b}\right) \tag{8.9}$$

The elemental stiffness matrix (for an isotropic material with $k_x = k_y$) is defined by:

$$K_{ij} = \int_0^b \int_0^a k \left[\frac{\partial \psi_i}{\partial x} \frac{\partial \psi_j}{\partial x} + \frac{\partial \psi_i}{\partial y} \frac{\partial \psi_j}{\partial y} \right] dxdy \tag{8.10}$$

The convective coefficients on an elemental basis are determined through:

$$H_{ij} = \int_0^b \int_0^a \psi_i \psi_j T_i \left(\beta_T + \beta_B \right) dxdy \tag{8.11}$$

Internal heat generation is accounted for by:

$$\left[F \right] = \int_0^b \int_0^a w \hat{q}_n dxdy \tag{8.12}$$

Convection on the top (T) and bottom (B) surfaces is given by:

$$\left[P \right] = \int_0^b \int_0^a w \beta_T T_T^\infty dxdy + \int_0^b \int_0^a w \beta_B T_B^\infty dxdy \tag{8.13}$$

Using the interpolation functions for a linear (four node) rectangular element, the stiffness matrix (for an isotropic material with $k_x = k_y$) may be determined to be:

$$[K] = \frac{k}{6} \begin{bmatrix} 2\left(\frac{a}{b}+\frac{b}{a}\right) & \left(\frac{a}{b}-\frac{2b}{a}\right) & \left(\frac{-a}{b}-\frac{b}{a}\right) & \left(\frac{-2a}{b}+\frac{b}{a}\right) \\ \left(\frac{a}{b}-\frac{2b}{a}\right) & 2\left(\frac{a}{b}+\frac{b}{a}\right) & \left(\frac{-2a}{b}+\frac{b}{a}\right) & \left(\frac{-a}{b}-\frac{b}{a}\right) \\ \left(\frac{-a}{b}-\frac{b}{a}\right) & \left(\frac{-2a}{b}+\frac{b}{a}\right) & 2\left(\frac{a}{b}+\frac{b}{a}\right) & \left(\frac{a}{b}-\frac{2b}{a}\right) \\ \left(\frac{-2a}{b}+\frac{b}{a}\right) & \left(\frac{-a}{b}-\frac{b}{a}\right) & \left(\frac{a}{b}-\frac{2b}{a}\right) & 2\left(\frac{a}{b}+\frac{b}{a}\right) \end{bmatrix} \tag{8.14}$$

Similarly, the matrix of convective coefficients computed to be:

$$[H] = \frac{ab\left(\beta_T + \beta_B\right)}{9} \begin{bmatrix} 1 & \frac{1}{2} & \frac{1}{4} & \frac{1}{2} \\ \frac{1}{2} & 1 & \frac{1}{2} & \frac{1}{4} \\ \frac{1}{4} & \frac{1}{2} & 1 & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{4} & \frac{1}{2} & 1 \end{bmatrix} \tag{8.15}$$

The following matrix gives heat generation on a nodal basis:

$$[F] = \frac{ab\hat{q}_n}{4}\begin{bmatrix}1\\1\\1\\1\end{bmatrix} \tag{8.16}$$

Finally, the effects of convective boundary conditions are accounted for through:

$$\left[P\right] = \left(\beta_T T_T^{\infty} + \beta_B T_B^{\infty}\right)\left(\frac{ab}{4}\right)\begin{bmatrix}1\\1\\1\\1\end{bmatrix} \tag{8.17}$$

The fluid element, detailed in Figure 8-8, is used to calculate the conductivity of the fluid, viscosity, Reynolds Number, Prandtl Number, Nusselt Number, convective coefficients, and hydraulic diameter of the fluid passed through the structural voids, using the inlet temperature and mass flow rate. The convective coefficient $\boldsymbol{h}$ is stored in the fluid cell slot and used as both β_T and β_B in the $\boldsymbol{P}$ matrix. The following equations are used to calculate the convective coefficients.

$$Nu = 6.163/(1+e^{(1.329-ratio)/2.889}) \text{ \textit{(Laminar Flow),}} \tag{8.18}$$

where *ratio* is the aspect ratio of the duct.

$$Nu = \frac{(fr/8)\cdot \mathrm{Re}\cdot \mathrm{Pr}}{1.07+12.7(fr/8)^{0.5}\cdot(\mathrm{Pr}^{2/3}-1)} \text{ \textit{(Turbulent Flow),}} \tag{8.19}$$

where ***fr*** is the friction factor.

$$h = \frac{Nu\cdot k}{D_h} \tag{8.20}$$

Nodal temperatures for each of the four elements making up a rectangular duct are then calculated using the FEA formulation of the Linear (Four Node) Rectangular Finite Element. An average of the four nodal temperatures pertaining to each element is taken and assigned as the surface temperature. This information, in turn, is then used to calculate the exit temperature T_{out} and the total heat transfer rate by the fluid within each cell $\dot{Q}$, respectively by

$$T_{out} = T_{surface} - (T_{surface} - T_{in})e^{-hA/\dot{m}C_p} \tag{8.21}$$

$$\dot{Q} = \dot{m}C_p(T_{out} - T_{in}) \tag{8.22}$$

Finally, the calculated T_{out} is assigned as T_{in} of the next layer and the process repeated.

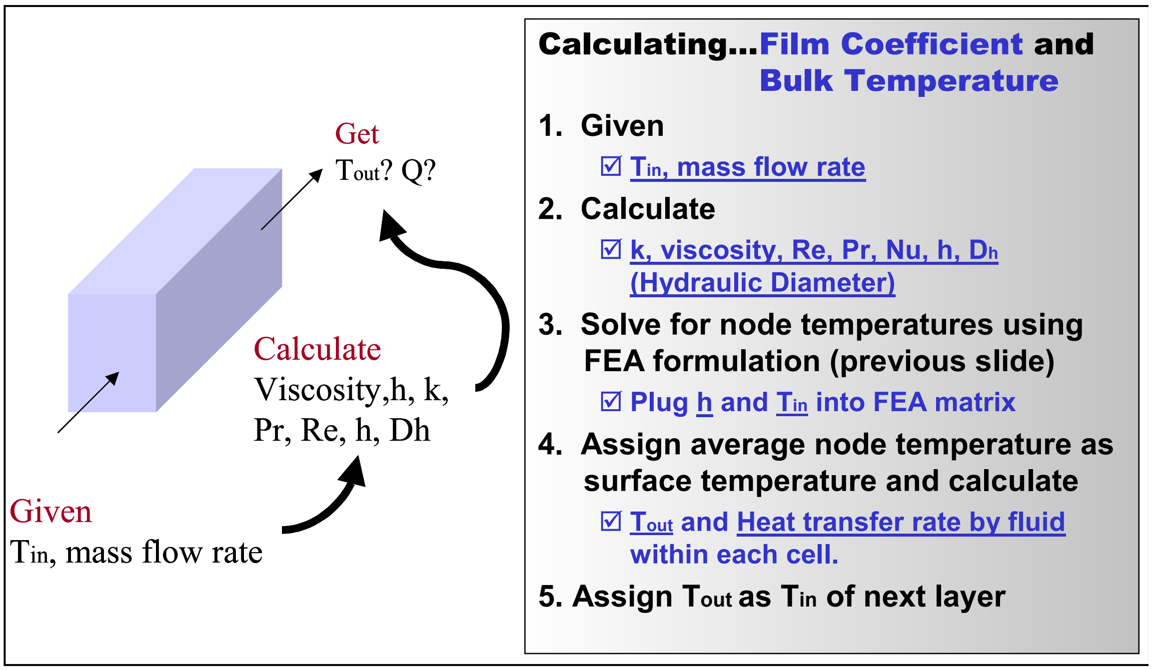

Figure 8-8 - Overview of Fluid Element Calculations

Since neither the cross sectional topology nor the boundary conditions vary along the direction of extrusion, two dimensional models are sufficient for determining structural performance. This is not true for the thermal model; fluid properties change as heat is convected away from the structure. Due to the initial requirements of creating an analysis module fast and efficient enough to make topology design possible, the 3D thermal analysis module had to be interfaced with the 2D structural model as indicated in Figure 8-10. In order to add modeling/analysis capability of the two-dimensional cross section (determined as a result of topology design with regard to structural considerations) in the third dimension, a fundamental requirement was the reliance on previously determined information. Since structure in topology design is determined through the successive determination of solid and void areas, the most important piece of information is the status (i.e., activity/inactivity) of nodes.

The nodes in question comprise the endpoints of frame elements that determine the constant cross-section of the LCAs. Each node has four degrees of freedom (i.e., 2 displacements, 1 rotational, and 1 temperature). The information derived from the structural considerations is a two dimensional grid of active nodes, as determined by the active frame elements. The challenge lies in effectively adding a third dimension, used to analyze the convective properties of the structure. Since the cross section is modeled in terms of one-dimensional elements, this translates to modeling thermal characteristics in the third dimension using two-dimensional elements. Although a three dimensional element might be better suited to model the thermal behavior of a three-dimensional structure, this would require the specification of two-dimensional elements for modeling the cross section and thus significantly increase the computational burden from a structural perspective without significantly improving solution quality. In essence, the element used is a plate element, capturing two-dimensional geometry and variation of degrees of freedom, while maintaining constant behavior in the third dimension. It is noted, however, that in the simplified parametric design example of this chapter, this nuance is effectively avoided and is only commented on for completeness.

Modeling three-dimensional geometry in terms of a combination of one-dimensional and two-dimensional elements has several consequences, the most significant of which can be explained by elaborating on the nature of plate elements. As plate elements are two-dimensional analogues to beams they do not capture all the effects associated with the three dimensional geometries they are meant to model. In this case, conduction throughout the thickness of the plate element is not modeled explicitly. In order to differentiate between elements of different thickness, the thermal conduction coefficient on an area basis is multiplied by the thickness of the structure. In order to minimize the effects of modeling three-dimensional structures via one- and two-dimensional elements, several other assumptions are made:

- Negligible pressure drop at the inlet
- Negligible heat conduction along the direction of extrusion
- Constant surface temperature throughout a given element, equal to average duct wall temperature (because temperature difference of adjacent duct walls is very small)
- Fluid temperature difference between inlet and outlet is very small

Each of these assumptions was tested extensively. Solutions obtained using this model and finite difference codes as well as professional FEA packages were remarkably close.

The routine used to conduct thermal analysis for LCA structures in MATLAB® is shown in Figure 8-11. The thermal module in MATLAB® starts with specifying input parameters, such as node numbers in the x, y, and z directions, inlet temperature and mass flow rate of the fluid, as well as thermal conductivity of the material. Nodes and elements for the LCA structure are then generated based upon these input parameters. These nodes and elements are first formed in the x-y plane and extruded along the z-axis. This is done in order to ensure consistency of structural and thermal analyses. It is thus possible to model any type of cross sectional geometry as long as it is composed of rectangular (shown in Figure 8-10) or triangular (not shown) cells.

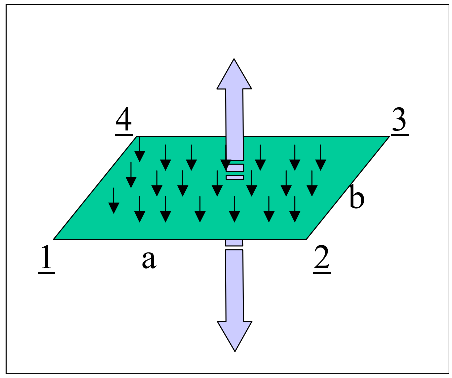

Figure 8-9 - Linear (Four Node) Rectangular Thermal Element

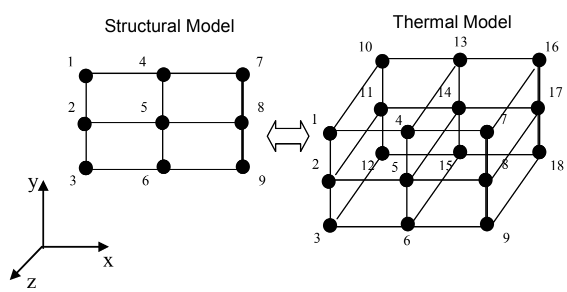

Figure 8-10 - Structural and Equivalent Thermal Node Numbering Schema

The node numbering scheme, implemented within the MATLAB code, is illustrated at the hand of a simple 2 by 2 LCA design in Figure Figure 8-10. The thermal model is fully compatible with the structural model. In fact, it is formed via extrusion along the z-axis, as indicated in the previous paragraph. Although, this example shows only a single slice of the structure along the z-direction, an arbitrary number may be used, as required for a particular analysis. Clearly, larger number of slices improves model fidelity. As indicated, the thermal element is a rectangular plane element while the structural element is a one-dimensional line element. Nevertheless, thermal elements are numbered in the same pattern as nodes corresponding to the structural elements, so as not to duplicate global node and element numbers in the z direction. More specifically, node numbering for structural elements follows the pattern indicated in the left half of Figure 8-10. The equivalent thermal model then builds on the numbering scheme of the structural model as shown in the right half of the same figure. Consequently, material properties such as conductivity, thickness, etc., assigned to the structural model, can be directly inherited by the thermal model. This is especially important since the thickness of any given element is likely to change based on the results of the preceding optimization loop and is thus consistently applied to both structural and thermal models.

After formulating nodes and elements, boundary conditions are defined by fixing the attributes of the corresponding nodes. The temperature attribute, for example has two properties one being the temperature and the other being its status (fixed or not). Temperatures that are imposed as boundary conditions are thus marked as fixed. Much the same is true for heat flux, the other possible boundary condition for thermal analysis as implemented here.

Once the boundary conditions are imposed the structure is solved on a layer-by-layer basis (along the direction of extrusion). For each layer, the property calculation module first calculates fluid (air) properties (e.g., *film coefficient*, ***Re, Pr***, ***k***, *kinematic viscosity*, ***Nu*** (for laminar or turbulent flow), etc.), given inputs of air inlet temperature T_{in} and mass flow rate $\dot{M}$. Global stiffness ***K***, ***H***, ***P***, and ***F*** matrices are then formulated for each layer. Since each of these matrices is just for the layer in question, sizes are considerably smaller than global stiffness matrices corresponding to the entire structure. Since the solver makes use of the 'sparse' matrix capability of MATLAB (which is significantly faster than ordinary matrix operations involving matrices with large numbers of zeros), computational efficiency is improved further. The output of the solver is the numerical value of temperatures for all nodes corresponding to the given boundary condition.

Calculated nodal temperatures are then used to calculate other fluid properties, specifically the outlet temperature T_{out} and heat transfer rate Q_{Total}. The outlet temperature of the fluid is stored alongside other fluid cell properties and used to assign the outlet temperature of the current cell as the inlet temperature of the interfacing cell within the next layer. Heat transfer rates for each fluid cell are also stored as fluid cell properties, to be summed over all slices at the conclusion of the analysis routine to determine the total heat transfer rate by the fluid (corresponding to the total heat drawn from the CPU in the example considered here).

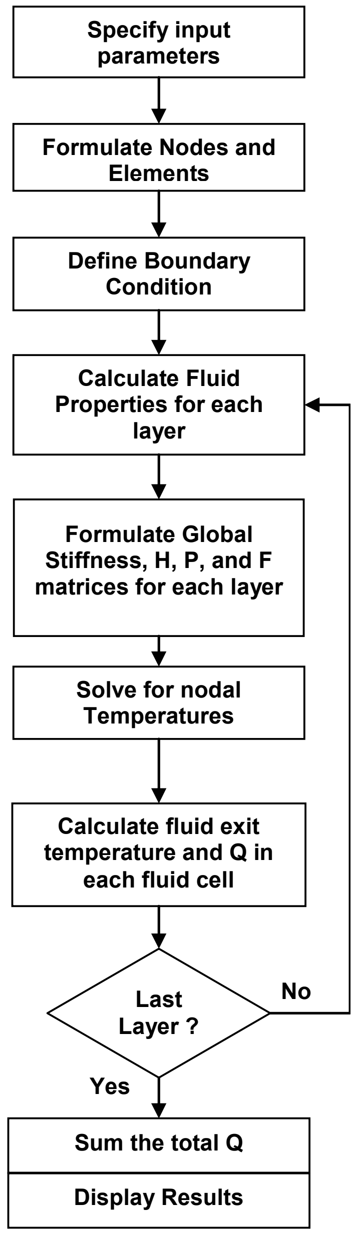

Figure 8-11 - MATLAB® FEA Analysis Routine

8.2.3 Parametric Design of Structural Heat Exchangers

Clearly, any original design effort is much more comprehensive than what is studied in this example. Original design would warrant the designer a much higher degree of freedom, choosing material, topology, geometry, etc. For example, the shape of individual channels would not be limited to rectangular cross-sections. For this example, the prismatic cellular structure is comprised exclusively of rectangular cells that are consistent throughout each row and column of the resultant structural LCA matrix. While gradation is not permitted, size, shape (i.e., aspect ratio), and number of cells can vary uniformly (i.e., $h_i = \not{c}$ and $w_i = \not{c}$). This stands in marked contrast to a graded structure, where each row of cells may assume a different height $\boldsymbol{h_i}$ and each column a different width $\boldsymbol{w_i}$ as suggested in Figure 8-4. In either case, the only restriction on cell height and width is that the sum total of all cells must fit within the specified dimensions, while ensuring sufficient space for vertical cell walls of variable thickness, $\boldsymbol{t_v}$, and horizontal walls of variable thickness, $\boldsymbol{t_h}$. Although the thickness of vertical and horizontal walls can differ, individual wall thicknesses cannot. The numbers of cells in the horizontal and vertical directions are designated $\boldsymbol{N_h}$ and $\boldsymbol{N_v}$, respectively, and determined by the corresponding number of nodes in the y- and x-directions (i.e., ***nodey*** and ***nodex***, respectively). Thus, $N_h = nodey - 1$ and $N_v = nodex - 1$. Additional design variables include the overall height of the heat exchanger ***H*** and the fluid velocity ***v***, as derived from the total mass flow rate $\dot{M}$ and heat exchanger cross-section. Each of these parameters is indicated in Figure 8-4.

The structural and thermal domain experts are thus limited to parametric design with respect to determining the values for six design variables (i.e., ***nodex***, ***nodey***, ***H***, $\boldsymbol{t_h}$, $\boldsymbol{t_v}$, and ***v***), subject to the problem specific constraints introduced in Section 8.4.1. Obviously, better thermal as well as structural performance can be achieved by relaxing some of these constraints. For more information regarding performance improvements in LCA design due to grading (non-uniform cell widths and cell heights as well as wall thicknesses) and topological variation (non-rectangular) the reader is referred to Ref. [204].

8.2.4 The Multi-Functional Design Process for LCA Structural Heat Exchangers

The main difference between single and multiple stakeholder design processes is the division of control over the various design variables factoring into a given decision. The manner in which control over relevant design variables is shared can significantly impact the outcome. When a single designer is charged with solving a problem, that designer is the sole stakeholder and consequently has absolute control over the manner in which tradeoffs among competing objectives are struck. As a point of reference, the LCA design process for a single designer charged with the resolution of the required tradeoffs between structural and thermal objectives is illustrated in Figure 8-12. When control is shared, however, striking the required tradeoffs is convoluted. This is especially true in an example as complex as the product/material system considered here, where the sole number of parameters (even when controlled by a single decision-maker) makes balancing the achievement of objectives a formidable task. It is also worth noting that the models underlying each of the domains being considered require a significant amount of domain expertise and are greatly influenced by the boundary and initial conditions, at least partially outside of immediate stakeholder control. Additionally, it is worth emphasizing that this is a mixed discrete continuous design problem, resulting in a discontinuous design space. In contrast to the examples considered in Chapters 6 and 7, communications among designers must thus be conducted in terms of sets. Since this is a point that has been stressed extensively throughout this dissertation it will not be reiterated here.

An overview of the LCA design process, involving planning of a manufacturing process, the specification of a base topology as well as material, and the refinement of the associated cellular structure via structural and thermal analysis, is provided in Figure 8-13. In this example, it is the strongly coupled compromise decision (i.e., the final decision in the sequence) that is focused upon. The outputs of the decision attributed to the material scientist, thus constitute the inputs (or *Givens*) for the parametric *co-design* of the structural heat exchanger, based on both thermal and structural considerations. This process is explored further detail in Section 8.4. With this in mind, a brief overview of validation and verification in this chapter follows.

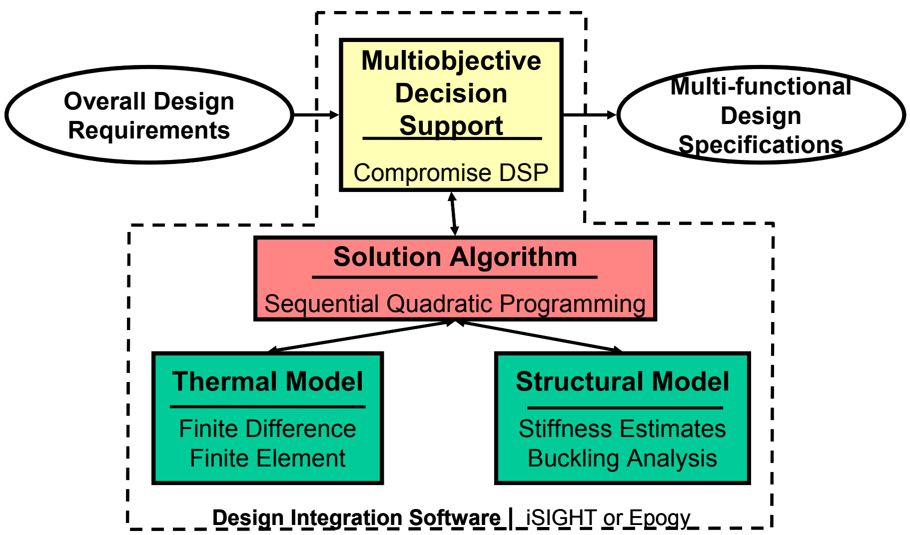

Figure 8-12 - Single Stakeholder LCA Structural Heat Exchanger Design Process [204]

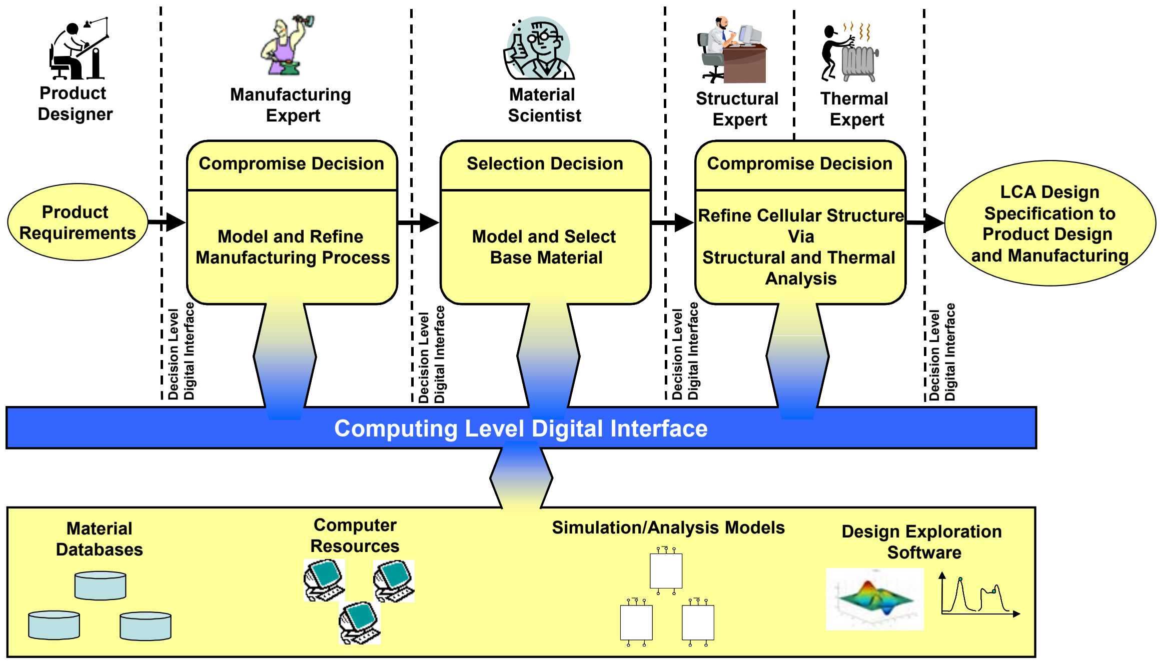

Figure 8-13 - The LCA Structural Heat Exchanger Design Process

8.3 VALIDATION AND VERIFICATION OF THE HYPOTHESES THROUGH THIS EXAMPLE

Akin to the previous chapter, this chapter too is focused primarily on substantiating the **Empirical Structural Validity** and **Empirical Performance Validity** of Hypotheses 2 and 3. Specifically, the aim is to illustrate the extensibility of the methods proposed in this dissertation to design problems of substantial complexity involving both discrete and continuous variables. Control for a strongly coupled decision, based on domain-specific performance models, is shared among two designers. It is important to note that the use of surrogate models for effective exploration of design spaces is required due to computational limitations. This point further underscores the appropriateness of this example in testing the extensibility of the methods to engineering problems of representative complexity. The discussion is centered on the quality and intuitiveness of results produced and the manner in which these compare to global optimum determined via exhaustive search. Note of the required level of effort and the overall usefulness of the methods in negotiating a solution to this example is also made. Consequently, less emphasis is placed on details associated with step-by-step implementation. Aspects, unique to this example, of course are expounded upon when pertinent to the discussion at hand.

8.3.1 Empirical Structural Validation of Hypotheses 2 and 3

As indicated in Figure 1-13 and Figure 1-15 **Theoretical Structural Validity** is established mainly in Chapters 1 and 2, as well as, in sections of Chapters 3, 4, and 5. This chapter, much like the previous two, is designed to build confidence in the aspect of **Empirical Performance Validity**, as discussed in Section 8.3.2. Doing so effectively, requires the prior establishment of **Empirical Structural Validity**. As indicated in Section 1.4, this is accomplished mainly through substantiating the appropriateness of the example chosen to test the proposed methods. The aim of this chapter is to underscore the scalability of FACE to complex design applications, especially with regard to the larger numbers of design variables, lack of closed form expressions, computational limitations, requiring the use of meta-models, and mixed discrete/continuous design variables resulting in discontinuous data sets. In solving this strongly coupled design problem, a case for its overall usefulness is also made. (1) Use of efficient analysis codes and (2) effective elimination of regions of the shared design space exhibiting unacceptable levels of performance, allow for a sufficient reduction in computational cost to make the determination of a reference solution via exhaustive search feasible. Attainment of such a reference design is extremely helpful in scrutinizing and evaluating the results obtained. This is especially true considering that the multidimensional collaborative design space, associated with the design of an LCA structural heat exchanger is not easily visualized. Although various projections can be produced, the usefulness of these in gaining a comprehensive understanding of objective relationships is quite limited.

As in the previous two examples, exhaustive search constitutes a feasible means of constructing a more objective view of the quality of solutions obtained. The LCA structural heat exchanger design example is strongly coupled. An interesting facet of this particular problem is that not all of the design variables affect the performance of both designers, providing one of them with the means to shift or compensate objective performance.

Overall, it can be asserted that LCAs pertain to an emerging class of product/material systems, exceeding (multi-functional) performance possible using traditional materials with respect to heat transfer, strength, stiffness, impact resistance, etc. The analysis and design of such complex systems calls for the bridging multiple length and time scales, as discussed in Section 1.1 and illustrated in Figure 8-14. The associated design processes require the close cooperation of multiple domain experts whose respective insights are required for integrating the underlying models. This is a need that strategic cooperation cannot fulfill. LCA design is thus representative of where engineering practice is headed and constitutes a prime example of the type of application for which the methods devised in this dissertation are intended. As indicated previously, LCA design examples, involving designing multifunctional cellular material structures for applications such as structural heat exchangers or actively cooled structural panels that are required to resist structural bending and membrane forces while transferring heat away from high heat flux regions, have been investigated extensively by Seepersad. Ref. [204] should be consulted for further details regarding assumptions underlying models, performance criteria, potential, implications, etc. The associated design processes have been explored by Seepersad et al. in [207,208]. In each of these examples designers from multiple disciplines—including structural mechanics, thermal sciences, materials science, and manufacturing—are engaged in the materials design process. Distributed software resources are integrated and utilized. The collaborative design process is modeled as a series of decisions, and the decisions of multiple designers are coordinated mathematically. Solutions to these multi-objective decisions are obtained via robust concept exploration that includes science-based models, fast-analysis meta-models, robust design techniques, and multi-objective decision-making models. Additional aspects are addressed in the PhD dissertations of Fernández [73], Panchal [161], and Choi [49].

8.3.2 Empirical Performance Validation of Hypotheses 2 and 3

Substantiation of **Empirical Performance Validity,** to which the remainder of this chapter is devoted, is aimed at building confidence in the methods' overall usefulness. Consequently, the ability to distinguish between coincidental and consequential benefits derived from its application is crucial. Unlike the examples, discussed in Chapters 6 and 7, chosen for their relative simplicity, the LCA design example was chosen for its complexity. Consequently, it is not transparent. Nevertheless, engineering judgment can be relied upon (at least in part) to evaluate the intuitiveness of results, alongside ease of use. These aspects contribute to the subjective evaluation of designs. Objective evaluation is centered on quantitative comparison with global (mathematical) optima. Additionally, comparisons to reference designs are used.

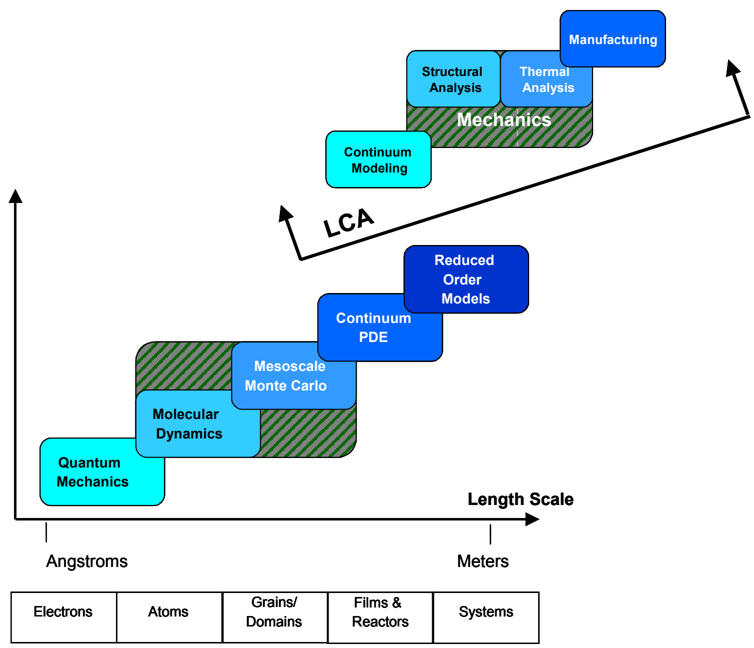

Figure 8-14 - A Hierarchy of Length and Time Scales for LCA Design [207]

In this example, scalability with respect to larger numbers of design variables is demonstrated. The benefits of FACE in resolving conflicts among two domain experts, pursuing mismatched objectives related via convoluted interactions, are demonstrated. An argument is made for the extensibility of FACE to *n* design variables, based on successful resolution despite complexity via reliance on staged surrogate models. As in the previous example, no pretenses are made about the effort involved in applying FACE. Aspects, relevant to the discussion (such as the discrete continuous nature of the design space) are emphasized as appropriate. Both quantitative and qualitative comparisons are made and parallels drawn with respect to the usefulness of this approach and those traditionally relied upon in Section 8.5. It is noted that extensive exploration of the design spaces associated with each of the designers for a number of different scenarios as well as co-development of the thermal analyses models by the author lead to a comprehensive understanding of the problem, instrumental in the interpretation of results. Finally, the outcomes make logical sense and are consistent with engineering expectation.

8.3.3 Revisiting the Square

As the reader may recall, **Theoretical Structural Validity** of each of the three Hypotheses was explored and established in the first five chapters of this dissertation. Having substantiated the **Empirical Structural** and **Performance Validity** of Hypothesis 1 in Chapter 3 and that of Hypotheses 2 and 3 in Chapters 6 and 7, further progress towards cementing the validity of the latter hypotheses is made in this chapter. Emphasis is placed on building confidence in the extensibility of FACE to engineering design problems of representative complexity. Having accomplished the first step in this effort (namely that of establishing the ability to effectively support *n* designers in Chapter 7), the second step (centered on ascertaining the value of FACE in addressing problems of *n* dimensions) is focused upon in this chapter. The desired outcome is that of building confidence in the overall suitability of the methods proposed in this dissertation for facilitating the design of complex engineering systems. The overall progress in validating and verifying the contributions documented within this dissertation corresponds to the agenda set in Figure 1-14 and is summarized in Figure 8-15.

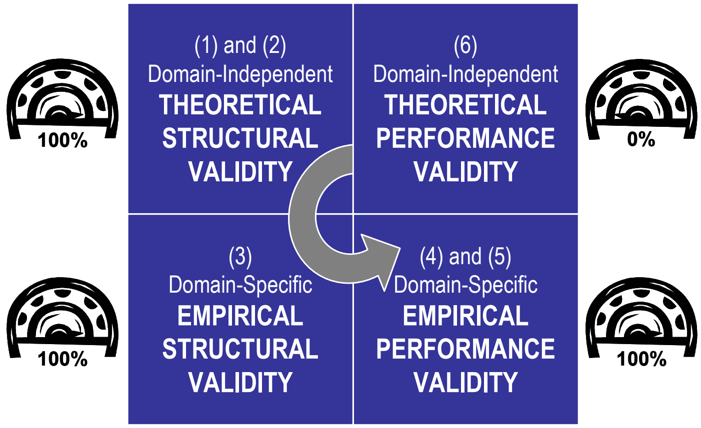

Figure 8-15 - Validation and Verification Progress through Chapter 8

8.4 COLLABORATIVE DESIGN OF A LCA STRUCTURAL HEAT EXCHANGER BY TWO DESIGNERS

8.4.1 Problem Statement and Development of Example

Considering the ubiquity of computers and the continuously increasing requirements placed upon their performance, it is not surprising that there are many different modes, mechanisms, and instantiations of CPU heat sinks. Several examples, based on technologies such as fins, heat pipes, Peltier cooling, and vapor phase refrigeration, are shown in Figure 8-16.

In this dissertation, the focus is on convectively cooled structural heat exchangers constructed of Linear Cellular Alloys (LCAs). Although there are myriad other multi-functional LCA applications (some novel, others pervasive), their use in heat sink design constitutes a design challenge of adequate complexity for validating and verifying the methods proposed here. The general requirements for a CPU heat sink are both thermal and structural in nature. On one side it is required that the heat exchanger remove enough heat from the chip so as to ensure stability during steady state operation as well as avoid overheating and reduce the potential for meltdown. On the other side, the structure must be rigid enough to withstand the relatively high compressive forces exerted during installation and by clamps used to ensure good thermal contact (see Figure 8-17).

Figure 8-16 - Examples of CPU Heat Sink Designs

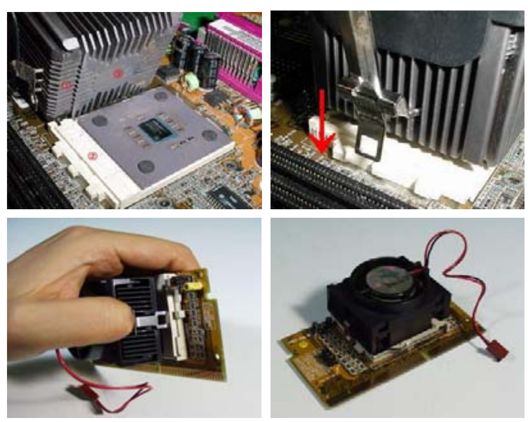

Figure 8-17 - Steps Involved in CPU/Heat Sink Assembly

In this specific example, it is required that the LCA heat sink effectively cool a CPU with a maximum operating temperature of 343.15 K. The overall dimensional restrictions are that the heat sink not exceed (Length x Width x Height) of 80.0 x 80.0 x 80.0 (mm). Additionally, the customer requires that the heat sink perform in a number of different operating environments (i.e., cases ranging in size and cooling capacity) with maximum internal (ambient) temperatures of 311.15 K. Furthermore, the customer intends to use an 80 mm fan for producing the required airflow. These system level requirements are summarized in Table 8-1.

Table 8-1 - System Level Design Requirements for LCA Heat Sink

Design Parameter	Max. Height (mm)	Max. Length (mm)	Max. Width (mm)	Max. CPU Operating Temperature (K)	Max. Ambient Temperature (K)	Fan Size (mm)
Requirement	**80**	**80**	**80**	**150**	**311.15**	**80**

Responsibility for determining values for the design variables controlling the form, function, and behavior of the LCA (in this case ***nodex***, ***nodey***, ***H***, t_h, t_v, and ***v***, as described in Sections 8.2.2 and 8.2.3) is shared among two designers. Each of these designers is considered to be a domain expert (*structural* and *thermal*) who acts as a stakeholder in a common design process. These two stakeholders will be referred to as Designers A and B, with the objectives of maximizing overall stiffness (in both x- and y-directions) and maximizing total heat transfer, respectively. Based on what might be described as an organizational or enterprise level decision, Designer A is assigned control over design variables ***nodex***, ***nodey***, and ***H***. Designer B, on the other hand, is given the responsibility of determining suitable values for t_h, t_v, and ***v*** in the process of pursuing his or her objectives.

The following sections are focused on the manner in which these requirements are translated with respect to each of the two domain specific sub-systems. This process involves the synthesis of given system level requirements and emergent sub-system level considerations with domain expertise and problem specific insight.

8.4.2 Domain Specific Considerations – Statement of Design Sub-Problems

8.4.2.1 Structural Considerations

As indicated in Section 8.4.1, Designer A is charged with ensuring a level of stiffness, sufficient to withstand the clamping force required to ensure sufficient thermal contact, as well as the substantially higher forces that the heat sink is subjected to during installation. This effectively translates to minimization of compliance[13].

$$c = [D]^{-1}[K][D] \tag{8.23}$$

Compliance is measure of energy and can be thought of as the inverse of stiffness. Minimizing compliance is thus tantamount to maximizing overall structural elastic stiffness in the x- and y-directions, given by $\tilde{E}_x / E_s$ and $\tilde{E}_y / E_s$, respectively. In doing so, Designer A has control over design variables ***nodex***, ***nodey***, and ***H***.

The overarching customer (or system level) requirement is that the structural integrity of the heat sink be maintained. In the domain expert's experience the maximum allowable compliance for a heat sink that could be assembled either by either a person or a machine is $c = 15$. Additional system level specifications relate to the envelope occupied by the final structure not exceed total height $H = 80\ mm$.

8.4.2.2 Thermal Considerations

As indicated in Section 8.4.1, Designer B is charged with the maximization of the total heat transfer Q_{Total} drawn from the CPU in order to ensure consistent operation and

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[13] It is noted that the compliance matrix is often represented by $[s]$, while $[c]$ is reserved for the stiffness matrix.

prevent failure. In doing so, Designer B has control over design variables $\boldsymbol{t_h}$, $\boldsymbol{t_v}$, and $\boldsymbol{v}$. For details regarding the analysis model, the reader is referred to Section 8.2.2.

A unique aspect particular to this problem, though not uncommon in engineering practice is that only two of three design variables, namely $\boldsymbol{t_h}$ and $\boldsymbol{t_v}$, controlled by Designer B are shared with Designer A. The third parameter (i.e., $\boldsymbol{v}$), while having a substantial effect on the total heat transfer possible, does not influence compliance in the least. Control over fluid velocity thus affords Designer B the ability to shift his or her performance and adjust for any decisions made by Designer A. While this reality would constitute a significant source of leverage in negotiation tactics (especially in the case of non-disclosure), it is treated here as a means of reconciling mismatched objectives and ensuring the existence of feasible solutions. It is noted however, that significant increases in flow rate, and hence $\boldsymbol{v}$ increase both cost and noise and are thus unlikely to be desirable from a systems level perspective.

The intent in choosing the problem setup discussed in this section is to stress the methods, proposed in this dissertation, and to investigate their usefulness in non-trivial situations. Like the examples of previous chapters, the design of a structural heat exchanger constitutes a good example of a strongly coupled problem that cannot be decoupled based on an argument of *near decomposability* [221]. Considering the mixed discrete/continuous nature of this problem and the fact that structural and thermal criteria favor completely different geometries mismatches in this example are accentuated.

8.4.2.3 <u>Combined Structural/Thermal Considerations</u>

Before proceeding to *co-designing* a solution to this system, a few observations are worth making. As noted in Section 8.4.1, the Designer A controls the number of vertical (***nodex***) and horizontal (***nodey***) members and the overall height (***H***) of the structure. Considering that the primary objective of this stakeholder is to minimize compliance, a measure of the energy storable in a structure due to deformation that is inversely proportional to the overall stiffness of the structure, the following trends are to be expected: (1) preference of thicker over thinner members, (2) preference of a larger number of thinner members in lieu of fewer, thicker members, (3) preference of a larger number of members, perpendicular to the direction of primary force exertion, and (4) preference for balanced or symmetrical geometries. Considering the overarching volume fraction constraint (material, representing the primary resource in this example) thicker vertical and thinner horizontal wall thicknesses are likely. Keeping in mind that the clamping force acts largely along the vertical axis, structural performance is likely to benefit from a larger number of vertical members.

Designer B controls the thickness of both vertical (t_h) and horizontal (t_v) walls and the velocity of the fluid (***v***) passing through the heat exchanger, as noted in Section 8.4.1. Considering that the primary objective of this stakeholder is to maximize the total heat transfer Q_{Total} from the surface of the chip, the following trends are to be expected: (1) preference of larger numbers of members, (2) preference of vertical over horizontal members, (3) preference of thicker members in the vertical and thinner members in the horizontal direction, (4) preference of a larger number of thinner members in lieu of fewer, thicker ones, and (5) regardless of topology, increased fluid velocities will increase heat transfer.

Overall, a larger number of members increases the total wetted perimeter of the structure (i.e., increases the surface area available for convection). Due to the conductive aspect of this conjoint heat transfer application, vertical members are likely to have a greater effect than horizontal members. Considering the overarching volume fraction constraint, discussed in Section 8.4.3, this is likely to translate to a larger number of vertical members than horizontal members.

Having carefully taken stock of the so called ***"Given"*** aspects of this example, the determination of a mutually desirable solution follows in two stages. A collaborative design space is systematically established via the CDSFM in Section 8.4.3 and associated tradeoffs are resolved using the ICCM in Section 8.4.4. In an attempt to avoid tedious repetition and augment (rather than saturate) the reader's understanding of the methods and their application, only aspects of FACE not previously dwelled upon are detailed.

8.4.3 Collaborative Design Space Formulation

As indicated, the discussion in this section is based upon the application of the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod, developed in Chapter 4. As in the previous examples, each of the sub-problems is considered in terms of the associated design decisions. These decisions are modeled consistently in terms of the compromise DSP formulation presented in Section 3.3.1. The process of doing so is facilitated through the employment of the templates detailed in Section 3.3.5. The instantiated templates for this particular design example are depicted in Figure 8-18, where the considerations of both Designers A and B are reflected next to one another. Clearly, some of the information shown (i.e., preferences for target achievement) is not determined or refined until later on in the CDSFM process, once a preliminary design space has been established.

<table>
<tr><th colspan="5">Collaborative LCA Structural Heat Exchanger Design by 2 Designers</th></tr>
<tr><th>cDSP "Chips"</th><th colspan="2">Designer A (Compliance)</th><th colspan="2">Designer B (Heat Transfer)</th></tr>
<tr><td>Constraints</td><td colspan="2">H : $H \le 80$
volfrac: $volfrac \le 0.60$</td><td colspan="2">v : $1 \le v \le 5$
volfrac: $volfrac \le 0.60$
$T_{surface}$: $T_{surface} = 343.15$
T_{in} : $T_{in} = 311.15$</td></tr>
<tr><td>Variables</td><td colspan="2">nodex, nodey, H</td><td colspan="2">t_h, t_v, v</td></tr>
<tr><td>Parameters</td><td colspan="2">$\rho_{material}, I, E, A, volfrac$</td><td colspan="2">$\rho_{fluid}, T_{in}, T_{\infty}, T_{out}, T_{surface}$
$k, h, Re, Nu, Pr, fr, \beta, c_p, \dot{m}$</td></tr>
<tr><td>Goals</td><td colspan="2">$C_{Target} = 7$</td><td colspan="2">$Q_{Total\_Target} = 220$ W</td></tr>
<tr><td>Preferences</td><td colspan="2">$w_C = 0.5$
$U_C = 1.9516 - e^{0.6535*\bar{F}_c}$</td><td colspan="2">$w_Q = 0.5$
$U_Q = 1.0168 - e^{-2.0864*\bar{F}_Q}$</td></tr>
<tr><td>Objective</td><td colspan="2">Minimize Compliance
$c\ (H, t_h, t_v, nodex, nodey) = [D]^{-1}[K][D]$</td><td colspan="2">Maximize Total Heat Transfer
$Q_{Total}(H, t_h, t_v, nodex, nodey, v) = \rho C_p V (T_{out} - T_{in})$</td></tr>
<tr><td rowspan="2">Analysis</td><th>Inputs</th><th>Outputs</th><th>Inputs</th><th>Outputs</th></tr>
<tr><td>H, t_h, t_v, nodex, nodey</td><td>Compliance</td><td>H, t_h, t_v, nodex, nodey, v</td><td>Total Heat Transfer</td></tr>
<tr><td>Driver</td><td colspan="2">Optimization Algorithm – Exhaustive Search, SQP, etc.</td><td colspan="2">Optimization Algorithm – Exhaustive Search, SQP, etc.</td></tr>
<tr><td>Response</td><td colspan="2">Design Variable Values – H, t_h, t_v
Objective Function Value - Z_C</td><td colspan="2">Design Variable Values – nodex, nodey, v
Objective Function Value - Z_Q</td></tr>
</table>

Figure 8-18 - Instantiation of Domain Specific Design Templates for Two Stakeholders

Prior to any communication with other stakeholders, preliminary values for objective targets, design variable ranges, and constraints must be determined based on domain-specific insight. As in previous examples, this process requires the synthesis of system level and sub-system level requirements. In this example, Designer A must interpret the customer requirement of ensuring structural integrity of the device during assembly. In the domain expert's experience the maximum allowable compliance for a heat sink that could be assembled either by either a person or a machine is $c = 15$. This value will serve as the upper bound of the acceptable for. Upon consideration closer inspection of competing products, the structural domain expert determines a value of $c_{Target} = 7$ to be a suitable ideal to strive for. The additional customer requirement that the final structure not exceed total height $H = 80\ mm$ is incorporated as a constraint. In the absence of an explicitly specified target Designer A chooses $H = 40\ mm$.

In the case of Designer B's sub-problem, the overarching customer (or system level) requirement is that a maximum operating temperature of 343.15 K not be exceeded. In his or her analysis, this designer assumes a constant temperature at the chip interface for the model. Although, it may seem more intuitive to model the CPU as having constant heat flux, the idea is to design a heat sink that is capable of removing enough heat to keep the chip below 1) its maximum operating temperature or 2) its melting temperature (in the case of potential over-clocking).

Two additional customer requirements further complicate Designer B's task. Firstly, the customer requires that the heat sink perform in a number of different operating environments (i.e., cases ranging in size and cooling capacity) with maximum internal (ambient) temperatures of 311.15 K. Secondly, it is the customer's intention to use an 80 mm fan in conjunction with the commissioned heat sink. In light of these specifications, Designer B determines that a total heat transfer of $Q_{Total} = 180\ W$ should be sufficient. However, Designer B further considers that improvements in computational performance are usually accompanied by increases in cooling requirements. In hopes of being able to reuse this design for future products (thus eliminating further design costs), Designer B sets the total heat transfer objective at an ambitious $Q_{Total\_Target} = 220\ W$. The thermal designer's experience further indicates that results in this range require a solid to void ratio of at least 3:2, based upon interactions between conductive and convective effects. Consequently, a volume fraction of no higher than 60% solid will be required. Since this limitation will serve as a stakeholder imposed constraint, directly affecting Designer A, it will have to be communicated promptly.

This fact, underscores that unlike previous examples, the translation of system to sub-system level requirements is not transparent here. Each of the stakeholders refines given specifications, based upon his or her respective domain expertise. Due to the level of interdependence among the various sub-systems, it is thus not until the system level requirements are interpreted with respect to domain specific considerations that a comprehensive picture can be formed. Consequently, design sub-space exploration (for gauging performance potential) does not make sense until all constraints are clarified. This is accomplished through a preliminary exchange of information, focused on clarifying the problem at hand. Such a review, focused on the clarification of constraints is crucial for avoiding potentially detrimental mismatches originating from differing assumptions that may or not be uncovered at a later point in time. In this example, Designer A is made aware of the volume fraction of 70%, required for acceptable thermal performance. Designer B, on the other hand learns of Designer A's intent to reduce the overall height of the LCA to as little as 40 mm. Both pieces of information are crucial for the designers in proceeding with their respective analyses. In fact, the overall cross-sectional area is a fundamental requirement for Designer B's determination of a feasible range for ***v***, based upon flow rates for potential fan selections.

Once interaction effects (e.g., constraints originating at the sub-system level) have been distilled, the next crucial step consists of each stakeholder exploring his or her design sub-space. Specifically, a detailed assessment with respect to the achievability of both system level and sub-system level goals in light of constraints is required. Since (1) combinatorial effects of constraints often affect design variables in non-intuitive ways and (2) control is shared, determining acceptable ranges for design variables is rather difficult. The initial ranges for design variables considered within each of the design sub-spaces are based on system specifications and engineering judgment. The resulting ranges for variables ***nodex***, ***nodey***, ***H***, $\boldsymbol{t_h}$, $\boldsymbol{t_v}$, and ***v*** are $nodex \subseteq [6,18]$, $nodey \subseteq [6,18]$, $H \subseteq [0.040, 0.080]$, $t_h \subseteq [0.0012, 0.0030]$, $t_v \subseteq [0.0012, 0.0030]$, and $v \subseteq [1,3]$.

These ranges serve as a basis for establishing the performance potential of each designer. Due to the complexity of this example, however, design sub-spaces are explored using surrogate models. These surrogate models are based on space filling experiments (in this case a full factorial design) conducted over the feasible ranges of each design variable. Depending on the quality of the fit, either first or second order response surface will be used. These response surfaces follow the functional forms of Equations (8.24) and (8.26) for Designer A and Equations (8.25) and (8.27) for Designer B. Reliance on any higher order models is likely to increase computational complexity without improving the quality of results obtained. All of the models used in this example were regressed using the "rstool" function in Matlab®R14.

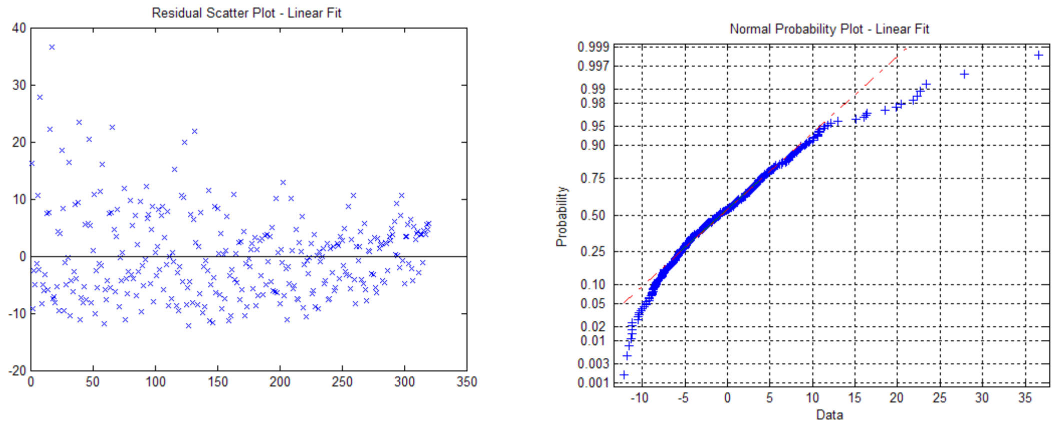
$$b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 \quad \} \quad \text{Linear Terms} \tag{8.24}$$

$$b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 + b_6x_6 \quad \} \quad \text{Linear Terms} \tag{8.25}$$

$$\left.\begin{array}{l} b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 + \ldots \end{array}\right\} \text{Linear Terms}$$
$$\left.\begin{array}{l} \ldots + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{14}x_1x_4 + b_{15}x_1x_5 + \ldots \\ \ldots + b_{23}x_2x_3 + b_{24}x_2x_4 + b_{25}x_2x_5 + \ldots \\ \ldots + b_{34}x_3x_4 + b_{35}x_3x_5 + \ldots \\ \ldots + b_{45}x_4x_5 + \ldots \end{array}\right\} \text{Interaction Terms} \tag{8.26}$$
$$\left.\begin{array}{l} \ldots + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{44}x_4^2 + b_{55}x_5^2 \end{array}\right\} \text{Quadratic Terms}$$

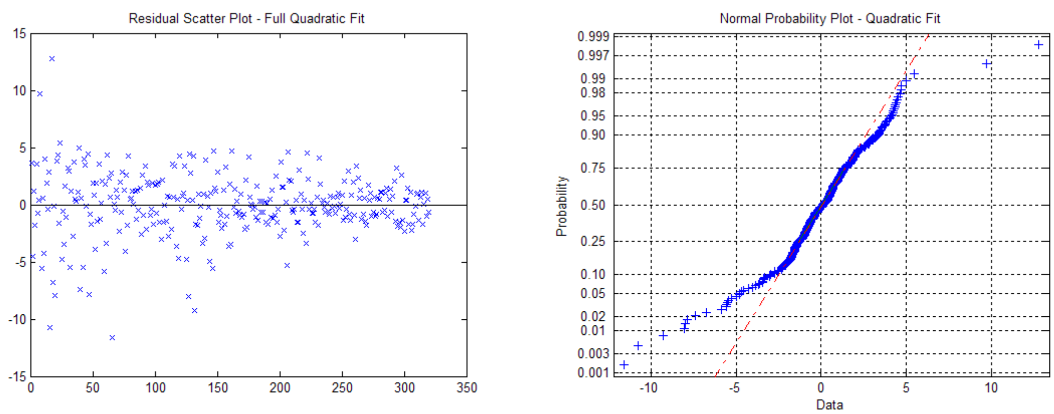
$$\left.\begin{array}{l} b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 + b_6x_6 \ldots \end{array}\right\} \text{Linear Terms}$$
$$\left.\begin{array}{l} \ldots + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{14}x_1x_4 + b_{15}x_1x_5 + b_{16}x_1x_6 + \ldots \\ \ldots + b_{23}x_2x_3 + b_{24}x_2x_4 + b_{25}x_2x_5 + b_{26}x_2x_6 + \ldots \\ \ldots + b_{34}x_3x_4 + b_{35}x_3x_5 + b_{36}x_3x_6 + \ldots \\ \ldots + b_{45}x_4x_5 + b_{46}x_4x_6 + \ldots \\ \ldots + b_{56}x_5x_6 + \ldots \end{array}\right\} \text{Interaction Terms} \tag{8.27}$$
$$\left.\begin{array}{l} \ldots + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{44}x_4^2 + b_{55}x_5^2 + b_{66}x_6^2 \end{array}\right\} \text{Quadratic Terms}$$

In the case of Designer A, the root mean squared errors for fitting a meta model to compliance were RMSE = 7.424 (linear fit) and RMSE = 2.7992 (full quadratic fit). Due to the poor quality of these models, response surfaces were fit to the reciprocal of compliance (i.e., 1/compliance) instead, improving the overall quality of fit to RMSE = 0.0088002 (linear case) and RMSE = 0.0032054 (full quadratic case). The superior quality of the response surface model “reciprocal fit”, is supported by the residual scatter and normal probability plots pictured in Figure 8-19 and Figure 8-20 for compliance and Figure 8-21 and Figure 8-22 for 1/compliance.



(a) **(b)**

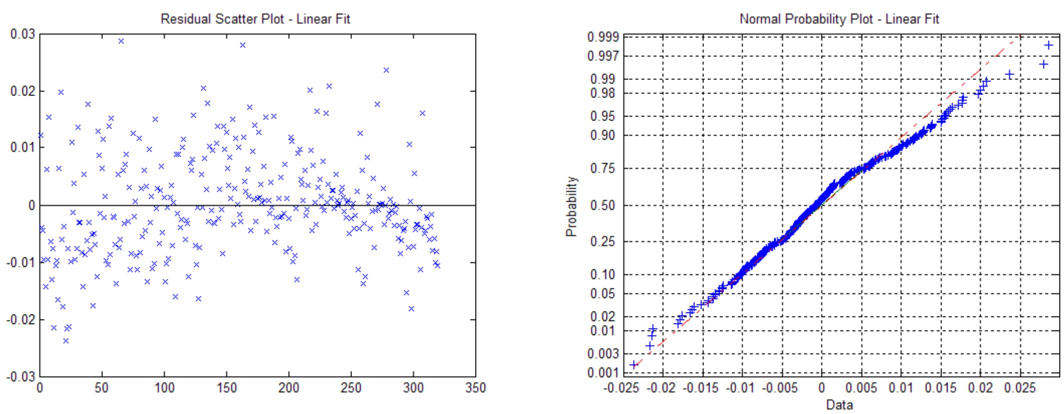
Figure 8-19 - Residual Scatter and Normal Probability Plots for Linear Fit to Compliance



(a) **(b)**

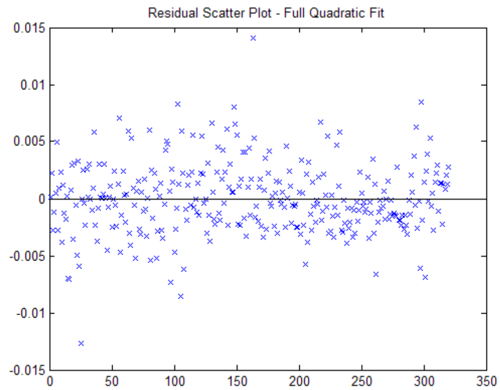
Figure 8-20 - Residual Scatter and Normal Probability Plots for Full Quadratic Fit to Compliance

With respect to the “reciprocal fit” meta-model, it can be asserted that the full quadratic fit provides a better reflection of the true behavior of compliance over the design space than the linear model. Although both RSME values are quite low, indicating a good approximation of the true objective response, the RSME of the full quadratic regression is slightly lower. The distribution of residual values is both tighter and more uniform in the higher order model, as evident from a visual comparison of Figure 8-22(a) with Figure 8-21(a). Finally, a contrast of the normal probability plots of Figure 8-22(b) with Figure 8-21(b) indicates that there is less deviation from the normal distribution line in the case of the quadratic model. This suggests a predominance of random over systematic error. It is important to note that although, a second order model is suited best for approximating the response of Designer A at this stage in the design process, lower or higher order models may be more appropriate at other stages. The quality of the fit should thus be re-evaluated at each stage along the design process, especially considering that the collaborative design space is continuously evolving.

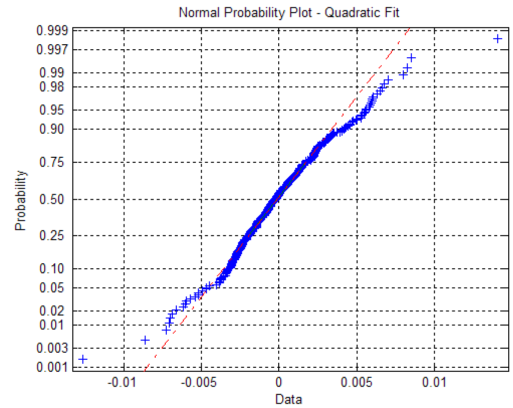


(a) **(b)**

Figure 8-21 - Residual Scatter and Normal Probability Plots for Linear Fit to 1/Compliance



(a)



(b)

Figure 8-22 - Residual Scatter and Normal Probability Plots for Full Quadratic Fit to 1/Compliance

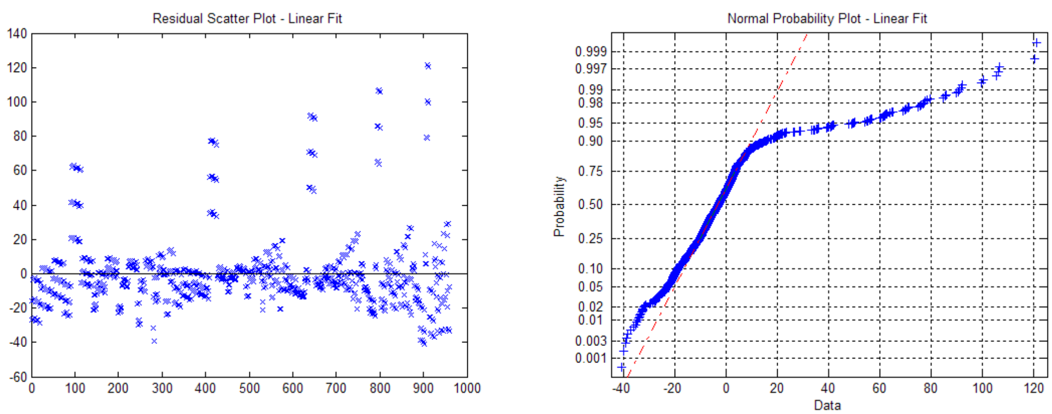
The surrogate model relied upon by Designer A for preliminary exploration purposes is given by Equation (8.28), where x_1 = ***nodex***, x_2 = ***nodey***, x_3 = ***H***, x_4 = $\boldsymbol{t_v}$, and x_5 = $\boldsymbol{t_h}$. This model is used to evaluate the performance of the system with respect to the minimization of compliance the structural objective. The performance potential of the structural domain expert is thus determined to range from $c = 2.58$ to $c = 103.24$. Clearly, there are a number of solutions that either meet or exceed this designer's goals. The majority, however, falls considerably short of the required $c = 15$.

$$\begin{aligned}
&0.052688 - 0.0010709x_1 - 0.0011251x_2 + 0.081916x_3 - 52.087x_4 - 45.613x_5 + \ldots \\
&\ldots + 0.00011135x_1x_2 - 0.013733x_1x_3 + 2.325x_1x_4 + 1.8179x_1x_5 + \ldots \\
&\ldots + 0.0069689x_2x_3 + 1.225x_2x_4 + 1.9555x_2x_5 + \ldots \\
&\ldots - 153.93x_3x_4 - 270.18x_3x_5 + \ldots \\
&\ldots + 14489x_4x_5 + \ldots \\
&\ldots - 0.00014015x_1^2 - 0.00014923x_2^2 + 2.806x_3^2 + 13557x_4^2 + 13999x_5^2
\end{aligned} \tag{8.28}$$

In the case of Designer B, the RMSE for fitting a meta-model to total heat transfer were RMSE = 21.503 (linear fit) and RMSE = 17.097 (full quadratic fit). In this case, no significant improvements were possible through reciprocal regression. Relying on higher order models could potentially improve the statistical fit. However, such a model would likely be misleading. Though having a lower RMSE, a model that interpolated the regularly repeating patterns of clustered observations (corresponding to the vertical bands in the residual scatter plots for the linear (see Figure 8-23) and quadratic (see Figure 8-24) fits, respectively) would significantly skew any results and thus result in a false sense of confidence. Relying on a lower order model with a higher RMSE, on the other hand, constitutes a more realistic representation of the actual phenomena. Although not capturing all of the nuances of the design space, the regressed response constitutes a weighted average of actual observations. The effect of several observations that deviate substantially is thus balanced by a larger number of observations, more closely resembling a predictable trend and making the resulting model more representative.

From analyzing the observations upon which the surrogate models are based it becomes clear that several variable combinations result in performance aberrations. In this example, such spikes result (in large) from the inclusion of discrete variables. Although both continuous and discreet variables are sampled using space filling experiments (full factorial designs in this case), stepped changes in discreet variables are more likely to produce discontinuous jumps in performance. Another point worth making is that the feasible design space is not necessarily either convex or continuous. A surrogate model that is produced by combining set levels of variable values thus spans the vertices of an envelope that is likely to include both feasible and infeasible values.

Although the quadratic model of Figure 8-24 has the lower RMSE the linear fit of Figure 8-23 constitutes the better model of thermal response. Although the second order model has a tighter band (compare Figure 8-23(a) with Figure 8-24(b)) it not as balanced as the first order model. Specifically, the quadratic model seems more patterned. This observation is underscored by the closer approximation of the normal distribution line resulting from a linear fit (contrast Figure 8-24(b) with Figure 8-23(b)). This, in turn, suggests the predominance of random over systematic error. As in the case of the thermal designer, it is important to note that although, a first order model is better suited to approximating the response of Designer B at this stage in the design process, a higher order model may be more appropriate at future stages.



(a) **(b)**

Figure 8-23 - Residual Scatter and Normal Probability Plots for Linear Fit to Total Heat Transfer

The surrogate model used by Designer B for preliminary exploration purposes is given by Equation (8.29), where x_1 = ***nodex***, x_2 = ***nodey***, x_3 = ***H***, x_4 = $\boldsymbol{t_v}$, x_5 = $\boldsymbol{t_h}$, and x_6 = ***v***. The performance potential of the thermal domain expert is thus determined to range from $Q_{Total} = 0\ W$ to $Q_{Total} = 205\ W$. Although this performance satisfies the required minimum $Q_{Total} = 180\ W$ for at least a few points in the design space, it falls considerably short of the desired $Q_{Total} = 220\ W$. A reassessment of design sub-space considerations is thus required in order to decrease the risk of chip failure in case of end-user over-clocking. An additional motivation is the production of a design that will be capable of cooling the next generation of CPUs (likely to run hotter).

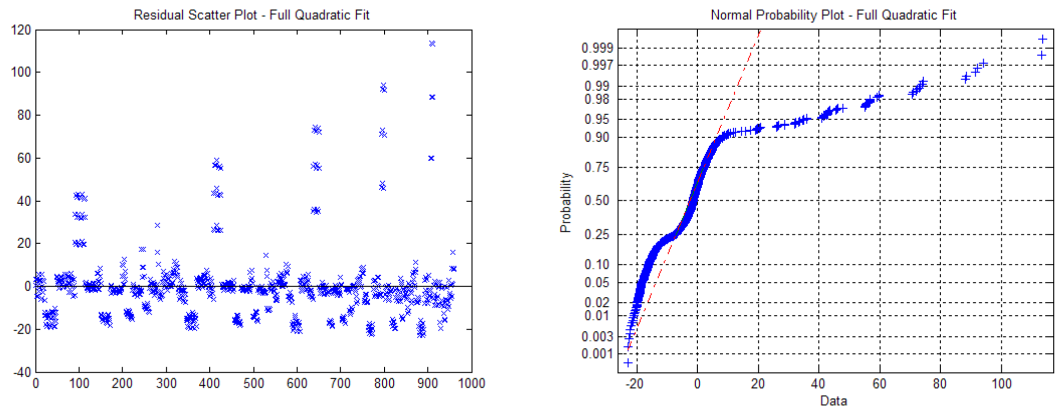


Figure 8-24 - Residual Scatter and Normal Probability Plots for Full Quadratic Fit to Total Heat Transfer

$$112.41 - 4.9389x_1 - 7.5118x_2 - 383.39x_3 + 1087.9x_4 - 459.77x_5 - 20.85x_6 \qquad (8.29)$$

In light of Designer B's performance potential it becomes clear that achievable performance falls considerably short. Those values of thermal performance that meet or exceed the minimum heat transfer requirements are achieved predominantly for structures, exceeding 60 *mm* in height. This makes sense since longer channels offer improved convection. The consequence is that design freedom must be increased either via relaxing constraints, changing targets, or changing resource constraints. It is the latter of these options that will be pursued in this example. As in any problem of this complexity, there are a number of different levers that can be used to shift or boost performance potential. While Designer B has little control over either the temperature inside the computer case (specified as an ambient temperature of 311.15 K by the customer) or the material composition of the LCA (determined to be a copper alloy with solid conductivity of 0.363 kW/mK), another option remains. From the thermal perspective, one of the key degrees of freedom is the airflow, specifically the velocity of the fluid being passed through the heat exchanger. Typically, that aspect of a fan, generating the required air flow for a conjugate heat sink that can be controlled is the volumetric flow rate. For the purpose of heat transfer analysis, however, it is the velocity of the air passing across the exposed surfaces of the heat sink that comes to bear. This velocity, in turn, directly depends on the area through which the volume of air is forced. Thus, given a channel of fixed size, the smaller the area is, the higher the velocity will be. Cheaper fans perform at up to 35 CFM. Considering the dimensional constraints, specified by the customer, this translates to minimum attainable velocities ranging from 2.581 m/s to 5.162 m/s for LCAs of $H = 80\ mm$ and $H = 40\ mm$, respectively. Some high performance fans are capable of producing flow rates in excess of 66 CFM at maximum pressures of 43 Pa and 2000 RPM, resulting in fluid velocities, ranging from 4.9 m/s to 9.7 m/s. Others can produce flow rates up to 114 CFM at 2750 RPM, resulting in attainable velocities ranging from 8.4 m/s to almost 17 m/s, depending on cross sectional area. Since these calculations are based on the assumption of an open channel and considering that the volume fraction is (1) constrained to 70% solid and (2) likely to be exhausted in striving towards the minimization of compliance, actual velocities, achievable with commercially available fans for any of the cross sectional areas considered here, are likely to exceed 10 m/s.

Increasing air velocity $\boldsymbol{v}$ until thermal objectives are satisfied seems like the perfect solution. Designer A is no longer constrained by the requirements of Designer B, who in turn is almost guaranteed to achieve his or her target, regardless of any choices made by

Designer A. However, there are limits to increasing ***v***, the two most important being noise and cost. Both of these are proportional to fan capacity. Consequently, performance targets should be met even for the lowest capacity fans. Since Designer B does not have control over ***H***, he or she must also design for the maximum possible value of this design variable, and hence the lowest possible ***v***. Discounting (the lowest possible velocity, attainable using the lowest capacity fan) for portions of the channel occupied by horizontal and vertical walls, this value turns out to be approximately 5 m/s. The collaborative design space can be extended accordingly.

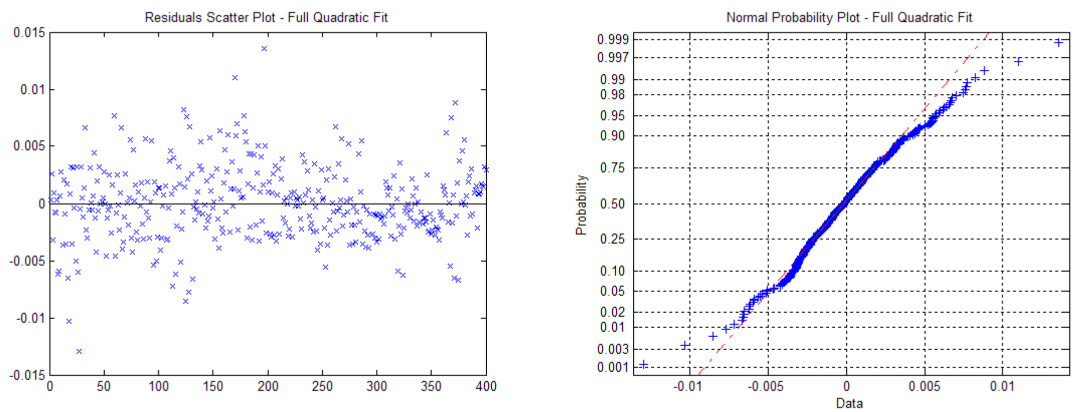
Based on the considerations of both designers, the adjusted ranges are as follows $H \subseteq [0.060, 0.080]$ and $v \subseteq [1,5]$. These adjustments are a compromise between the initial specifications of both designers and ensure that all stakeholders start off on the same page and (1) do not waste precious resources by investigating clearly infeasible regions of a design space or (2) unnecessarily sacrifice performance based on artificial constraints. Although the change in the velocities considered merely serves to shift the performance of Designer B and has no effect on Designer A, the adjustment in the possible heights allowed by Designer A have a fundamental effect on both stakeholders.

In accordance with the CDSFM, full control over all pertinent parameters was thus assumed by each designer over the entirety of the initial design space and any required adjustments to the ranges, sets, or discrete alternatives being considered were exchanged. The design variable ranges, reflecting the associated adjustments are as follows: $nodex \subseteq [6,18]$, $nodey \subseteq [6,18]$, $H \subseteq [0.060, 0.080]$, $t_h \subseteq [0.0012, 0.0030]$, $t_v \subseteq [0.0012, 0.0030]$, and $v \subseteq [1,5]$.

The preliminary collaborative design space that is established based upon this communiqué requires the refinement of surrogate models for each of the domain specific responses and serves as a basis for determining what each stakeholder may realistically hope to achieve. The corresponding surrogate model used by Designer A for exploring the preliminary collaborative design space is given by Equation (8.28), where x_1 = ***nodex***, x_2 = ***nodey***, x_3 = ***H***, x_4 = $\boldsymbol{t_v}$, and x_5 = $\boldsymbol{t_h}$.

$$\begin{aligned}
&0.054965 - 0.00099631x_1 - 0.0011678x_2 + 0.18699x_3 - 54.332x_4 - 49.866x_5 + \ldots \\
&\ldots + 0.00011691x_1x_2 - 0.012646x_1x_3 + 2.3221x_1x_4 + 1.7953x_1x_5 + \ldots \\
&\ldots + 0.0065086x_2x_3 + 1.2334x_2x_4 + 2.0105x_2x_5 + \ldots \\
&\ldots - 129.52x_3x_4 - 232.37x_3x_5 + \ldots \\
&\ldots + 14529x_4x_5 + \ldots \\
&\ldots - 0.00014775x_1^2 - 0.00015291x_2^2 + 1.2354x_3^2 + 13637x_4^2 + 14245x_5^2
\end{aligned} \tag{8.30}$$

The fit of this full quadratic reciprocal fit model (RMSE = 0.0032993) is extremely good, especially when compared to its inverse (RMSE = 2.9623). Much the same is true for a linear regression, when comparing RMSE = 0.0092034 for the reciprocal fit with RMSE = 7.7809). The quality of the full quadratic reciprocal fit model is supported by the residuals scatter plot of Figure 8-25(a) and the normal probability plot of Figure 8-25(b). As might be expected, the overall fit of the meta-model over the refined (in this case reduced) region of the design space has improved substantially.



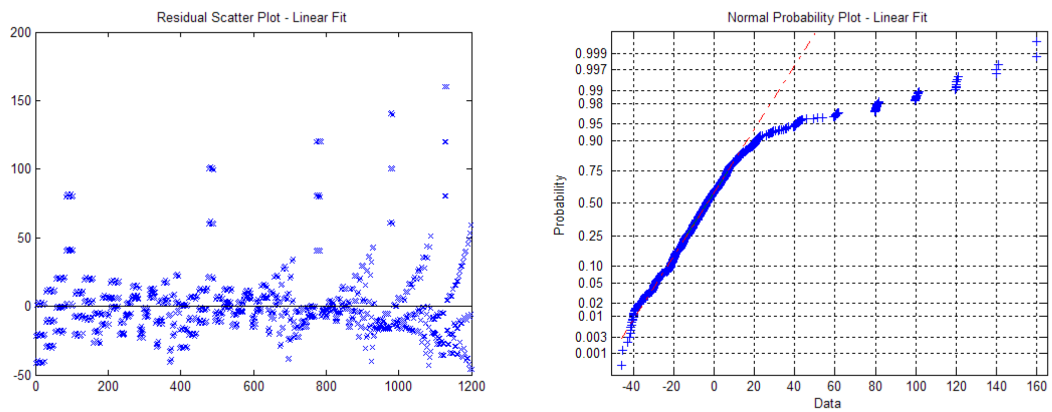
(a) **(b)**

Figure 8-25 - Residual Scatter and Normal Probability Plots for 1/Structural Response Surface Model of Preliminary Collaborative Design Space

The updated surrogate model used by Designer B for the purpose of exploring the preliminary collaborative design space is given by Equation (8.29), where x_1 = ***nodex***, x_2 = ***nodey***, x_3 = ***H***, x_4 = $\boldsymbol{t_v}$, x_5 = $\boldsymbol{t_h}$, and x_6 = ***v***.

$$202.02 - 6.6741x_1 - 8.833x_2 - 1179.3x_3 + 139.12x_4 - 981.62x_5 - 19.908x_6 \tag{8.31}$$

Although the statistical fit of this linear regression (RMSE = 25.007) is not as good as that of a full quadratic model (RMSE = 19.208), the linear model better approximates the behavior of the thermal objective response as illustrated by Figure 8-26. As might be expected, the overall fit of the meta-model over the refined (in this case increased) region of the design space has deteriorated.



(a) **(b)**

Figure 8-26 - Residual Scatter and Normal Probability Plots for Thermal Response Surface Model of Preliminary Collaborative Design Space

Exploration by each decision-maker is based upon the satisfaction of his or her respective objectives, assessed and captured in functional form based upon customer and system level requirements. The preferences of individual stakeholders are captured through the determination of utility functions. The assessed ranges, constituting the basis for these quantitative expressions of preference extend from *unacceptable* (i.e., $U_i = 0$) to *ideal* (i.e., $U_i = 1$) values and are provided for both Designers A and B in Table 8-2. The corresponding utility functions are $U_A = 1.95 - e^{0.65*F_A}$ and $U_B = 1.02 - e^{-2.09*F_B}$, respectively. As in all previous examples, these single attribute utility functions are based on objective function values that have been normalized by the preference ranges, deemed acceptable by each designer.

Table 8-2 - Designer Utilities for Objective Achievement by Two Stakeholders

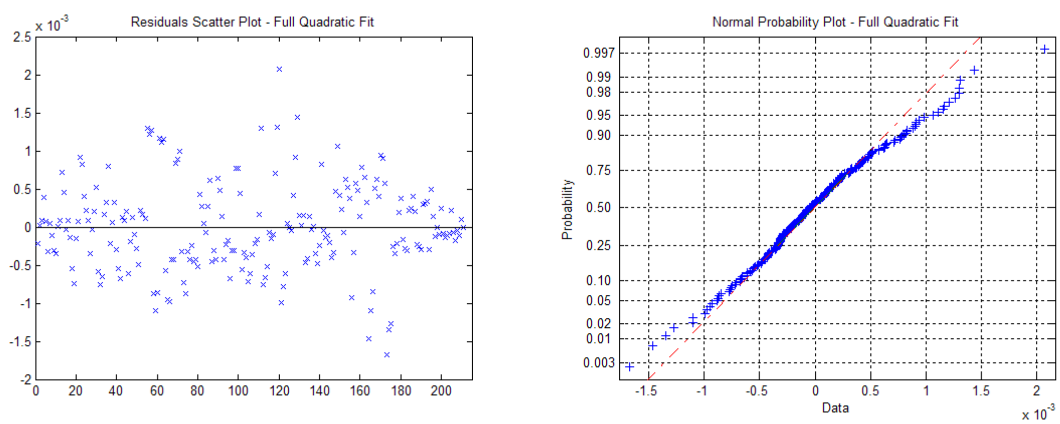
Preference	Ideal	Desirable	Tolerable	Undesirable	Unacceptable
Utility Value	1	0.75	0.5	0.25	0
Designer A *(Compliance)*	7	9	7	14	15
Designer B *(Total Heat Transfer)*	400	366	343	330	320

Making use of these utilities, those regions of each design sub-space, yielding feasible results (defined here as having a utility $U_i \geq 0.75$) can be effectively determined via exploration of the response surfaces given by Equations (8.30) and (8.31). As in all previous cases considered, it is important to recall that although the preliminary collaborative design space contains solutions that are amenable to the preferences of each designer independently, the actual feasibility of these solutions is subject their combined limitations; the design variable choices made by Designer A constitute constraints for Designer B and vice versa. Thus, it is determined that the feasible design space must be refined further to meet the requirements of Designers A and B simultaneously. This leads to Designer A adjusting the ranges of the variables under his or her control (i.e., ***nodex***, ***nodey***, and ***H***) to $nodex \subseteq [12,18]$, $nodey \subseteq [6,10]$, and $H \subseteq [0.060,0.080]$, respectively. Similarly, Designer B reduces the ranges of $\boldsymbol{t_h}$, $\boldsymbol{t_v}$, and ***v***, considered in generating the response surface models used for subsequent exploration to $t_h \subseteq [0.0012,0.0026]$, $t_v \subseteq [0.0012,0.0016]$, and $v \subseteq [1,5]$ in order.

Structural performance in the resulting collaborative design space is approximated using the surrogate model given by Equation (8.32), where x_1 = ***nodex***, x_2 = ***nodey***, x_3 = ***H***, x_4 = $\boldsymbol{t_v}$, and x_5 = $\boldsymbol{t_h}$. It is noted once more that reliance on surrogate models based upon successively reduced regions is relied upon to ensure a reasonable level of accuracy.

$$
\begin{aligned}
&0.035815 + 0.00076645x_1 - 0.0029746x_2 + 0.35222x_3 - 47.124x_4 - 46.922x_5 + \ldots \\
&\ldots + 0.00011716x_1x_2 - 0.0090149x_1x_3 + 1.0515x_1x_4 + 0.76141x_1x_5 + \ldots \\
&\ldots - 0.012047x_2x_3 + 2.1379x_2x_4 + 3.3506x_2x_5 + \ldots \\
&\ldots - 182.93x_3x_4 - 324.02x_3x_5 + \ldots \\
&\ldots + 14241x_4x_5 + \ldots \\
&\ldots - 0.000084622x_1^2 - 0.00020111x_2^2 + 2.5443x_3^2 + 15777x_4^2 + 16052x_5^2
\end{aligned}
\qquad (8.32)
$$

The fit of this full quadratic model (RMSE = 0.00060629) is quite good, especially when compared with that of a linear regression (RMSE = 0.0040317). This is substantiated by considering the residual scatter plot of Figure 8-27 (a) and the normal probability plot of Figure 8-27(b). As might be expected, the overall fit of the meta-model over the refined region of the design space has improved even further. Although this trend of continuous improvement also holds for the non-reciprocal regressions (i.e., RMSE = 1.0275 for a full quadratic and RMSE = 4.0424 for a linear regression), the quality of the reciprocal (i.e., 1/c) models is clearly superior.



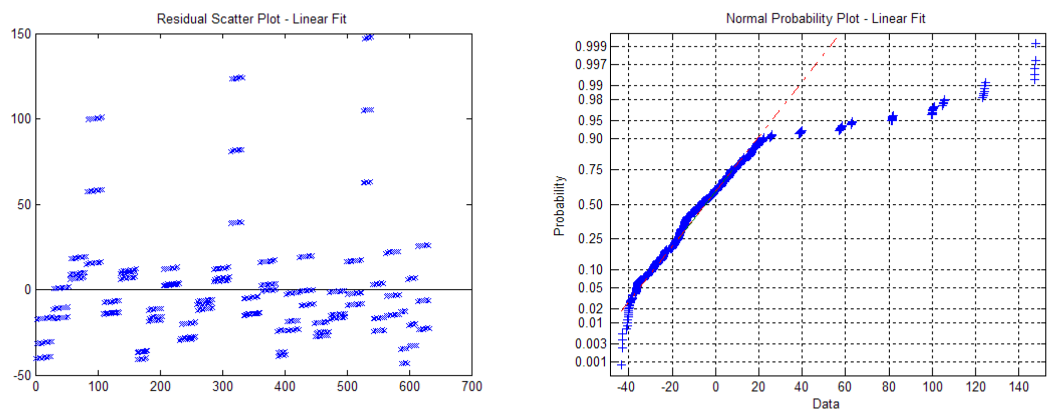
(a) **(b)**

Figure 8-27 - Residual Scatter and Normal Probability Plots for 1/Structural Response Surface Model of Collaborative Design Space

Thermal performance in the resulting collaborative design space is given by Equation (8.33), where x_1 = ***nodex***, x_2 = ***nodey***, x_3 = $\boldsymbol{H}$, $x_4 = \boldsymbol{t_v}$, $x_5 = \boldsymbol{t_h}$, and $x_6 = \boldsymbol{v}$.

$$311.96 - 7.9279x_1 - 5.1424x_2 - 2777.2x_3 - 490.52x_4 - 1789x_5 - 21.163x_6 \qquad (8.33)$$

Although the statistical fit of this linear regression (RMSE = 32.512) is not as good as that of a full quadratic model (RMSE = 25.775), the linear model better approximates the behavior of the thermal objective response as illustrated by Figure 8-28. Unlike the case of structural performance, however, the overall fit of the meta-model over the refined region of the design space has deteriorated further. This can be attributed to the assessment of an equal number of samples over a smaller area, making any aberrations due to discreet variables more systematic.



(a) **(b)**

Figure 8-28 - Residual Scatter and Normal Probability Plots for Thermal Response Surface Model of Collaborative Design Space

It is noted that unlike previous examples, values for design variables, suitable to both stakeholders, cannot be confirmed graphically. Nevertheless, it is the resulting sets of acceptable design variable combinations that make up the collaborative design space, formulated as a result of completing *Steps 1* through *8* of the FACE. Having successfully established this region of mutual feasibility, the effect of stakeholder sequencing is explored in the next section.

8.4.4 Interaction-Conscious Coordination of Stakeholders

The discussion in this section is based upon the application of the **I**nteraction-**C**onscious **C**oordination **M**echanism, developed in Chapter 5. It is noted that the central benefit of following the steps of CDSFM in Section 8.4.3 is that all of the solutions in the established collaborative design space are guaranteed to be mutually desirable. *It is emphasized once more that any protocol can be adopted in order to arrive at a final solution to this strongly coupled problem, once a collaborative design space has been successfully established.* This fact was substantiated in Chapter 7. *The focus in this chapter, however, returns to interaction conscious tradeoff management.* Consequently, the ICCM is employed in order to arrive at a *co-designed* solution.

Although, a set of design variable combinations, rather than a contiguous range, is associated with the collaborative design space communicated among the interacting stakeholders, this set can roughly be described using the following envelope:

$nodex \subseteq [12,18]$, $nodey \subseteq [6,10]$, $H \subseteq [0.060, 0.080]$, $t_h \subseteq [0.0012, 0.0026]$, $t_v \subseteq [0.0012, 0.0016]$, and $v \subseteq [1,5]$. The performance potential for Designer A in the collaborative design space is determined to range from $U_A = 0.751$ to $U_A = 0.878$, averaging $U_A = 0.801$. The performance potential for Designer B, on the other hand, averages $U_B = 0.792$, ranging from $U_B = 0.750$ to $U_B = 0.850$. This translates to a system utility that is guaranteed to lie between $U_{System} = 0.756$ on the low end and $U_{System} = 0.860$ on the high end.

Having established the performance potential for each of the stakeholders, interaction effects are investigated in greater detail. Specifically, (1) sensitivity of design sub-problem specific objective achievement to changes in uncontrollable design variables, (2) sensitivity of design sub-problem specific objective achievement to changes in controllable design variables, and (3) the impact of changes in controllable design variables on the objective achievement of other stakeholders are considered. These measures of responsiveness are referred to as *sensitivity*, *power*, and *leverage*, respectively in the following discussion.

Each designer, is required to independently determine his/her responsiveness to changes in design variables, controlled by other parties. Specifically, the *sensitivities* of Designers A and B with respect to the achievement of their objectives F_A (i.e., *c*) and F_B (i.e. Q_{Total}) are given by

$$S_A = \frac{\partial U_A}{\partial t_h} + \frac{\partial U_A}{\partial t_v} = \frac{\partial U_A}{\partial F_A}\frac{\partial F_A}{\partial t_h} + \frac{\partial U_A}{\partial F_A}\frac{\partial F_A}{\partial t_v} \tag{8.34}$$

$$S_B = \frac{\partial U_B}{\partial nodex} + \frac{\partial U_B}{\partial nodey} + \frac{\partial U_B}{\partial H} = \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial nodex} + \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial nodey} + \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial H} \tag{8.35}$$

respectively. The *power* of each designer to affect his of her objective attainment is calculated according to

$$P_A = \frac{\partial U_A}{\partial nodex} + \frac{\partial U_A}{\partial nodey} + \frac{\partial U_A}{\partial H} = \frac{\partial U_A}{\partial F_A}\frac{\partial F_A}{\partial nodex} + \frac{\partial U_A}{\partial F_A}\frac{\partial F_A}{\partial nodey} + \frac{\partial U_A}{\partial F_A}\frac{\partial F_A}{\partial H} \tag{8.36}$$

$$P_B = \frac{\partial U_B}{\partial t_h} + \frac{\partial U_B}{\partial t_v} + \frac{\partial U_B}{\partial v} = \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial t_h} + \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial t_v} + \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial v} \tag{8.37}$$

Finally, the *leverage* that one designer may assert over another in the event that negotiations take place is determined according to

$$L_A = +\frac{\partial U_B}{\partial nodex} + \frac{\partial U_B}{\partial nodey} + \frac{\partial U_B}{\partial H} = +\frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial nodex} + \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial nodey} + \frac{\partial U_B}{\partial F_B}\frac{\partial F_B}{\partial H} \tag{8.38}$$

$$L_B = \frac{\partial U_A}{\partial t_h} + \frac{\partial U_A}{\partial t_v} = \frac{\partial U_A}{\partial F_A}\frac{\partial F_A}{\partial t_h} + \frac{\partial U_A}{\partial F_A}\frac{\partial F_A}{\partial t_v}\,. \tag{8.39}$$

As evident from Equations (8.34) through (8.39), total Designer *sensitivity*, *power*, and *leverage* are considered throughout the design space. Additive effects are considered at each point in order to determine a more comprehensive indication of the net effect on objective performance that is to be expected. Certain cases may warrant a higher level of fidelity, achievable via the investigation of responsiveness with respect to each of the design variables separately. Naturally, weighted measures of responsiveness can also be accommodated should additional fidelity be needed.

In each of these cases,

$$\frac{\partial U_A}{\partial F_A} = -0.6535e^{0.6535F_A} \tag{8.40}$$

$$\frac{\partial U_B}{\partial F_B} = 2.0864e^{2.0864F_B} \tag{8.41}$$

$$\frac{F_A}{nodex} = \frac{F_A}{x_1} = \frac{1}{RSM_S^{\,2}}\begin{pmatrix} 0.00076645 + 0.00011716x_2 - 0.0090149x_3 + \ldots \\ \ldots + 1.0515x_4 + 0.76141x_5 - 2\times 0.000084622x_1 \end{pmatrix} \tag{8.42}$$

$$\frac{F_A}{nodey} = \frac{F_A}{x_2} = \frac{1}{RSM_S^{\,2}}\begin{pmatrix} -0.0029746 + 0.00011716x_1 - 0.012047x_3 + \ldots \\ \ldots - 182.93x_4 - 324.02x_5 + 2\times 0.00020111x_2 \end{pmatrix} \tag{8.43}$$

$$\frac{F_A}{H} = \frac{F_A}{x_3} = \frac{1}{RSM_S^{\,2}}\begin{pmatrix} 0.35222 - 0.0090149x_1 - 0.012047x_2 + \ldots \\ \ldots - 182.93x_4 - 324.02x_5 + 2\times 2.5443x_3 \end{pmatrix} \tag{8.44}$$

$$\frac{F_A}{t_h} = \frac{F_A}{x_4} = \frac{1}{RSM_S^{\,2}}\begin{pmatrix} -47.124 + 1.0515x_1 + 2.1379x_2 + \ldots \\ \ldots - 182.93x_3 + 14241x_5 + 2\times 15777x_4 \end{pmatrix} \tag{8.45}$$

$$\frac{F_A}{t_v} = \frac{F_A}{x_5} = \frac{1}{RSM_S^{\,2}}\begin{pmatrix} -46.922 + 0.76141x_1 + 3.3506x_2 + \ldots \\ \ldots - 324.02x_3 + 14241x_4 + 2\times 16052x_5 \end{pmatrix} \tag{8.46}$$

$$\frac{F_B}{nodex} = \frac{F_B}{x_1} = -7.9279 \quad (8.47)$$

$$\frac{F_B}{nodey} = \frac{F_B}{x_2} = -5.1424 \quad (8.48)$$

$$\frac{F_B}{H} = \frac{F_B}{x_3} = -2777.2 \quad (8.49)$$

$$\frac{F_B}{t_h} = \frac{F_B}{x_4} = -490.52 \quad (8.50)$$

$$\frac{F_B}{t_v} = \frac{F_B}{x_5} = -1789 \quad (8.51)$$

$$\frac{F_B}{v} = \frac{F_B}{x_6} = -21.163 \quad (8.52)$$

It is noted that RSM_s in Equations (8.42) through (8.46) denotes the evaluation of the meta-model at the point being considered. As previously, all measures of responsiveness are assessed with respect to designer utilities rather than raw objective values. Doing so, serves as a consistent (and appropriate) means of normalization and directly illustrates the net effect of any associated changes on designer satisfaction. The results of this assessment are provided in Table 8-3 and serve as the basis for precedence determination by ensuring a certain degree of systems transparency for all stakeholders.

Table 8-3 - Indicators of Responsiveness for Two Stakeholders in Feasible Collaborative Design Space

Indicator	Sensitivity	Power	Leverage
Average (Designer A)	0.38	7956.4	2372.3
Average (Designer B)	2372.3	16.06	0.38
Domination (Designer A)	0%	100%	100%
Domination (Designer B)	100%	0%	0%

As indicated by the results, reported in Table 8-3 and summarized in the SPL matrices of Figure 8-29, Designer A maintains a consistent advantage over Designer B throughout the entire design space. This is supported by enormous differences in *sensitivity*, *power*, and *leverage*. Specifically, Designer A is quasi insensitive to the actions of Designer B, has virtually complete control over the achievement of his or her objectives, and significant influence over thermal performance. Finally, these assertions can be made at every point (sampled) throughout the design space. Designer B, on the other hand, is extremely *sensitive* and has virtually no *leverage* over Designer A's objective achievement. The relative spike in *power* responsiveness for Designer B can be attributed almost entirely to the independently controlled design variable $\boldsymbol{v}$. Consequently, this example, too, can be considered to constitute a quintessential example of a strongly coupled decision. Although the dependence of Designer B on Designer A, far outweighs that of Designer A on Designer B, it must be recalled that this is only true within the systematically formulated collaborative design space. In lieu of the conversion of these fundamentally mismatched objectives into a win/win scenario, only cooperative behavior is likely to yield acceptable results. Levels of achievement vary widely throughout the original design space and few of these overlap. The primary difficulty with a problem of this complexity is the identification of a collaborative design space. This is not an easy feat, considering the convoluted relationships among form, function, and behavior, exacerbated by shared control and decentralization. Focalization of stakeholder efforts in this region reduces this disparity in levels of achievement to comparable levels; $0.75 \leq U_A \leq 0.88$ for Designer A and $0.75 \leq U_B \leq 0.85$ for Designer B. Although neither stakeholder has a strict advantage in terms of performance potential, consideration of the responsiveness indicators suggests a greater likelihood of superior system performance when ceding control to Designer B.

Sensitivity

	A	B
A		0
B	1	

Power

	A	B
A		1
B	0	

Leverage

	A	B
A		1
B	0	

Figure 8-29 - Responsiveness for Two Stakeholders throughout the Collaborative Design Space

To be precise, Designer A's significantly lower *sensitivity* and considerably higher *power* rating suggests that he or she maintains a consistently better ability to correct for decisions made by Designer B. Conversely, Designer B would have little to no ability to affect the outcome of Designer A's decision, other than via changing ***v***. Since the Design freedom in ***v*** is likely to be exhausted in this collaborative design space (as suggested by previous exploration). With this in mind, the chosen sequencing scheme is the complete transfer of control and responsibility for the coupled decision to Designer B. The resulting design solution is $(nodex, nodey, H, t_h, t_v, v) = (18, 10, 0.080, 0.0026, 0.0016, 5.0)$ with $U_A = 0.869$, $U_B = 0.850$, and $U_{System} = 0.859$.

Having explored the *co-design* of a structural (conjugate) heat exchanger by two collaborating domain experts in this section, several observations regarding the significance of the results obtained and the example as a whole are made in the following section.

8.5 RESULTS AND DISCUSSION OF EXAMPLE APPLICATION OUTCOMES

8.5.1 Critical Analysis of Results

As indicated by the results, summarized in Table 8-4, system level considerations are better served by Designer B not only taking the lead, but completely assuming control. In fact, this solution matches that obtained through complete cooperation, determined via reformulation of the stakeholder design sub-problems as a single design problem with the objective to optimize system level objective performance (taken to be the evenly weighted Archimedean sum of stakeholder objectives). This solution is representative of the global optimum in this scenario. This case comprises the best answer, at least from a mathematical perspective, striking the most even balance in terms of overachievement of both the compliance and total heat transfer objectives. The fact that the *co-designed* solution thus equals its asymptotic completely cooperative ideal in this example is a significant result - this solution is achieved without reformulation of the constituent design problems as a single design problem.

This collaborative design space is quite polar. All other protocols produce the same result - $(nodex, nodey, H, t_h, t_v, v) = (18, 10, 0.077, 0.0026, 0.0016, 5.0)$ with $U_A = 0.877$, $U_B = 0.768$, and $U_{System} = 0.822$ - as indicated in Table 8-4. Although this solution does not significantly alter system level utility, the distribution of objective level performance between the two designers is substantial (at least what Designer B is concerned). Another interesting observation is that the value of information regarding the opposition's tradeoff strategy is essentially zero. That is to say that knowing how the other party will respond, does not improve either designer's decision-making ability from the systems perspective. This is consistent with the notion of a solution mechanism based upon BRC intersection. Unfortunately, solutions (that are more balanced from the systems perspective) seldom lie on either designer's (optimization driven) performance curve.

Table 8-4 - The Impact of Stakeholder Sequence on System & Sub-System Level Trade-Offs

Stakeholder Sequence	*nodex*	*nodey*	H	t_h	t_v	V	U_A	U_B	U_{System}	F_A	F_B
Total Control (Designer A)	18	10	0.077	0.0026	0.0016	5	0.877	0.768	0.822	7.88	206.63
Total Control (Designer B)	18	10	0.08	0.0026	0.0016	5	0.869	0.850	0.859	7.97	214.29
Precedence (Designer A) w/ BRC	18	10	0.077	0.0026	0.0016	5	0.877	0.768	0.822	7.88	206.63
Precedence (Designer B) w/ BRC	18	10	0.077	0.0026	0.0016	5	0.877	0.768	0.822	7.88	206.63
Precedence (Designer A) w/ BRC	18	10	0.077	0.0026	0.0016	5	0.877	0.768	0.822	7.88	206.63
Precedence (Designer B) w/ BRC	18	10	0.077	0.0026	0.0016	5	0.877	0.768	0.822	7.88	206.63
Cooperative	18	10	0.08	0.0026	0.0016	5	0.869	0.850	0.859	7.97	214.29

As in any scenario when meta-models (of dubious quality) are relied upon for design space exploration, the accuracy and correctness of the results should be questioned. For example, it is advisable to ensure that no constraints have been violated due to poor fit, lack of fidelity or other inaccuracy and/or error. Additionally, it is important to evaluate results using higher precision models. Sometimes this is possible through increased fidelity exploration and regression of yet another surrogate model over an even smaller area of the design space in question. Other times, given that the result is good enough, defined here as meeting or exceeding the requirements of all stakeholders involved, mere verification of the design solution using the original model may be sufficient. Given the rather poor fit of the meta-model for thermal response, this is the approach taken here. Comparing the objective function values obtained using the regressed model (i.e., $F_A = 7.97$ and $F_B = 214.29$) with those determined using the original model (i.e., $F_A = 7.82$ and $F_B = 236.37$), it is clear that the surrogate model errs on the side of conservatism and is thus acceptable. Moreover, given the size of the heat sink considered, volumetric flow rate, and volume fraction, these results are quite reasonable. An illustration of the final design is provided for visualization in Figure 8-30.

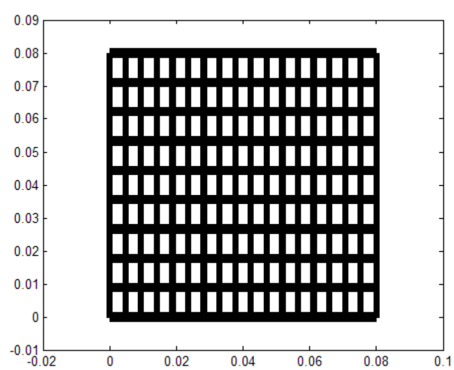


Figure 8-30 - Cross Section of Co-Designed Structural (LCA) Heat Exchanger

Admittedly, the scenario considered in this chapter may seem contrived. For example, many would argue that a volume fraction constraint of 70% solid is too high or that the cell walls are rather thick. Similarly, assigning the structural designer control over the number of cells and the thermal designer control over the thickness of the walls separating them seems counterintuitive. It is important to note, however, that these complications were introduced deliberately in order to improve the example's suitability as a test problem. The explicit aim, as stated in Section 8.3 was to assess the performance of the proposed methods with respect to problems of representative complexity. Although this approach may result in the product itself being less realistic, it significantly increases the aspect of realism what complexity of industrial engineering problems is concerned.

Another interesting facet, particular to this problem is the nature of the underlying interdependence among the two stakeholders, exacerbated by the manner that control is shared and information flow is convoluted. For example, it is clear that air velocity has a profound impact on the overall thermal performance of the heat sink. What makes this fact interesting, however, is that control of this variable constitutes a unilateral means of shifting the feasible range of this stakeholder's design space. In other words, since the height of the heat exchanger is controlled by the structural designer, control over the air velocity gives the thermal designer a means of improving total heat transfer for any structure. However, it is not until the height is decided upon by the structural domain expert that an exact figure for the total possible heat transfer can be calculated accurately.

It is not uncommon that designers (thermal and structural in this case) share most of the design variables, governing the performance of a strongly coupled design problem – all save one (*fluid velocity* here). It is the existence of this solitary factor that allows the thermal designer considerable leeway. For example, increasing the fluid velocity by 5 m/s can increase total heat transfer by up to 38% for the same set of design variables. In fact, it was only through the adjustment of this factor that the thermal designer was able to shift his or her performance so that the collaborative design space was not unnecessarily constricted. In the absence of the thermal stakeholder's ability (or willingness) to do this, structural performance would have been sacrificed unnecessarily.

In a more extreme case, irreconcilable differences in objective performance might also have resulted, yielding an empty set for the collaborative design space and requiring iterative design problem reformulation.

The point is that there can be alternate means of achieving desired performance that do not necessarily require sacrificing performance with respect to another aspect. Clearly, other means of improving thermal performance exist – reducing the temperature of the convecting fluid, introducing cross flow, or changing the underlying technological base by switching to Peltier cooling, heat pipes, or vapor phase cooling. Despite their various advantages, however, these technologies though novel are not (cost effective) and for all intents and purposes are not accessible to the designer. It is thus a burden on each stakeholder to differentiate between actual and perceived limitations and determine the extent of his or her true dependence on decisions made by other stakeholders.

While such "out of the box" possibilities tend not to be explored until all other avenues have been exhausted due to associated costs, difficulties, etc., coupled problems are often over-constrained as an implicit consequence of anticipated down stream negotiations. Specifically, stakeholders may plan for a tactical advantage in bargaining for concessions, and thus aim to retain artificial slack. This type of behavior constitutes one of the primary reasons why non-cooperative behavior tends to significantly under-perform cooperation.

Having critically reviewed the results and emphasized some of the rather unique aspect of this example, a few observations on particular advantages, derived from FACE are made in the following section.

8.5.2 Impact of Employing the Framework for Agile Collaboration in Engineering

One of the most important aspects of this example is the high degree of complexity associated with each of the domains and the models relied upon for exploring them. Stakeholders may carry out their explorative activities by studying underlying mathematical, analytical, experimental, etc. models or through theoretical reasoning. Any of these means, however, requires an in-depth understanding of the models, their underlying assumptions, proper interpretation, and limitations. It is in situations such as this one that consistent and continuous alignment of expertise with design sub-problem resolution is desirable. Handoffs or control transfers requiring independent interpretation of information far exceeding competence is not just undesirable, but not recommendable. The presence of discrete variables and basic computational intensity make strict reliance on Best Reply Correspondences (and as a matter of fact, any effort of capturing complex tradeoff strategies in functional form) rather difficult.

With this in mind, the chosen approach focuses on strategic exchanges of information among collaborating entities and is aimed at focalizing their activities. Concerns regarding excessive computational costs, usually associated with are addressed via reliance on continuously refined surrogate models. As described in Chapters 4 and 5, new surrogate models are constructed, each time the collaborative design space is reduced in size and fitted to each of the reduced areas being considered. Ideally, surrogate model could be constructed that included only feasible designs. However, doing so would substantially increase computational intensity. The approach implemented in this dissertation thus focuses on the continuous refinement of meta-models via staged reduction of the spaces over which these are regressed. Care must be taken to ensure feasibility before a final design is chosen. The result is improved fidelity, as well as accuracy, in areas where it is needed, without wasting computational resources on areas of a design space falling short of either designer or system expectations.

It is noted that although preliminary performance tests can be (and were) conducted using the actual analysis models, computational difficulty prevents formation of a comprehensive picture of the design space. Consequently, surrogate models are relied upon in order to more effectively explore the various design spaces and form a detailed picture of potential performance, interactions, and tradeoffs. Reliance on response surfaces also facilitates the determination of the responsiveness indicators, relied upon in much of this research. In order to impart to the reader a sense of the benefits inherent in the advocated means of exploration, a few figures follow.

In the first stage of collaborative design space exploration in this example the computational cost was reduced from an average of 0.05 seconds per iteration for the structural model and 1.66 seconds per iteration for the thermal model to 0.000022 seconds per iteration for their combined exploration. To put it another way, total run times are reduced from 16.95 seconds for the structural and 1209.66 seconds (which increased to 8005.86 seconds in later refinements) for the thermal model to 0.062 seconds. What makes this comparison even more drastic is that these figures correspond to the execution of minimum 243 structural and 729 thermal sample points required for generating a full quadratic response surface model and a total of 28350000 points for higher resolution exploration of the shared design space. As a point of reference, it is noted that these figures pertain to computational experiments conducted using Matlab®

Version 7.0.1.24704 (R14) Service Pack 1 on a 3.2GHz IBM Pentium 4 with 2 GB of RAM, running Microsoft Windows XP Professional Version 2002 Service Pack 2.

8.6 A LOOK BACK AND A LOOK AHEAD

8.6.1 Revisiting the Roadmap

As indicated in the beginning of this chapter, and highlighted in Figure 8-31, the main goal pursued was demonstrating the usefulness of the **F**ramework for **A**gile **C**ollaboration in **E**ngineering in the context of supporting the decentralized resolution of a design problem of substantial complexity. The LCA structural heat exchanger is an example of the emerging class of complex product-material systems, discussed in Section 1.1. The intent underlying investigation of this example was that of building confidence in the scalability of the associated methods to *n* dimensions. The LCA design problem is characterized by six design variables that are both discrete and continuous in nature. The underlying analysis codes are quite complex and performance with respect to both *structural* and *thermal* objectives are closely intertwined. Additionally, exploration via analytical expressions (as focused upon in previous examples) was not possible due to the inherent computational complexity. Consequently, the use of surrogate models for effective design space exploration was required. Successful resolution of the strongly coupled decisions, associated with this example concludes the empirical aspect of validation and verification commenced in Chapter 3 and continued in Chapters 6 and 7.

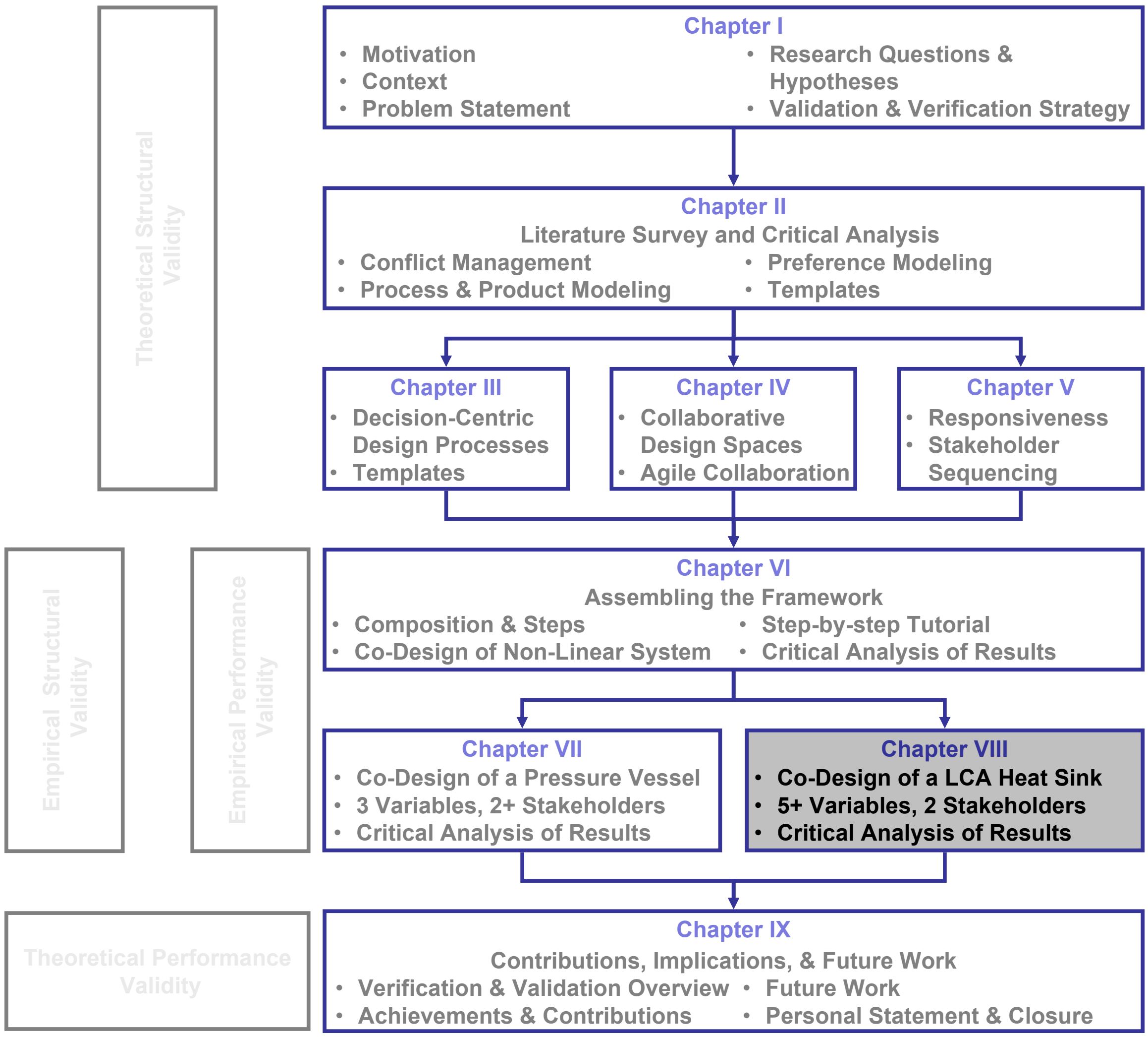


Figure 8-31 - Dissertation Roadmap

8.6.2 Assembling the Building Blocks

As in the previous chapter, the aspects of the **F**ramework for **A**gile **C**ollaboration in **E**ngineering, developed in Chapters 3 through 5 and synthesized in Chapter 6, were used in concert. Consequently, thermal and structural design spaces were explored systematically in order to identify, establish, and manage a collaborative design space. Subsequently, the efforts of domain experts were coordinated to support the *co-design* of a solution, characterized by the non-biased achievement of system- as well as sub-system-level objectives. The usefulness of FACE in supporting the realization of a complex engineering problem, such as that embodied by the LCA structural heat exchanger was substantiated. Relying on successively refined meta-models in lieu of the mathematical models themselves illustrated computational feasibility. It was emphasized that the fidelity of surrogate models can be adjusted in order to suit resource constraints, including computational capabilities, time pressure, and lack of data. Discounting for the associated sources of error, the underlying models can be updated as needed, improving the quality of the results obtained. Regardless, FACE serves as a structured means of progression even in those circumstances when stakeholder strategies cannot be formulated mathematically over the extent of the design space and *ad hoc* trial-and-error would normally prevail. The viability of *co-design* as an alternative to *strategic collaboration* is thus corroborated.

CHAPTER 9 - VERIFICATION, VALIDATION, FUTURE AVENUES OF EXPLORATION, AND CLOSING REMARKS

In this dissertation elements of a **F**ramework for **A**gile **C**ollaboration in **E**ngineering, geared towards the continuous support of domain experts, acting as stakeholders in the decentralized design of an artifact, are developed. Specifically, three main contributions are made – (1) a **T**emplate-based **D**esign **P**rocess **M**odeling (TDPM) approach is developed, (2) a **C**ollaborative **D**esign **Sp**ace **F**ormulation **M**ethod is formalized, and (3) an **I**nteraction-**C**onscious **C**oordination **M**echanism is presented. Each of these aspects contributes to the coordination and sequencing of stakeholders so that design freedom, associated with collaborative design spaces is not reduced unnecessarily. As a whole, these contributions support the establishment, structuring, and management of collaborative design spaces to make stakeholder *co-design* a viable and effective alternative to currently instantiated means of conflict resolution. It is important to note that in this effort the developments stemming from *Hypotheses 2* and *3* constitute the primary contributions of this research – a systematic means of (1) attaining win/win scenarios and (2) promoting solutions to strongly coupled design problems that are balanced from the systems perspective. The contribution emanating from *Hypothesis 1*, though novel in its own right, is merely a means to an end, an enabling technology that significantly reduces the computational and administrative burden inherent in continuous communications of decision critical information along an event-based design timeline.

In this chapter the development of the **F**ramework for **A**gile **C**ollaboration for **E**ngineering is brought to a close. There are four crucial elements in this endeavor. The first, addressed in Section 9.1, is the review of Research Questions and Research

Hypotheses in the context of the chosen validation strategy (i.e., the Validation Square). Relevant achievements and contributions delineated in this dissertation are summarized in Section 9.2 and critically reviewed in Section 9.3. Finally, avenues of future investigation are presented alongside specific recommendations in Section 9.4, followed by a few closing remarks in Section 9.6. Closure is thus achieved by framing the developments, presented throughout this dissertation within the underlying philosophy and overarching research effort, first introduced in Chapter 1, thus completing the proverbial circle.

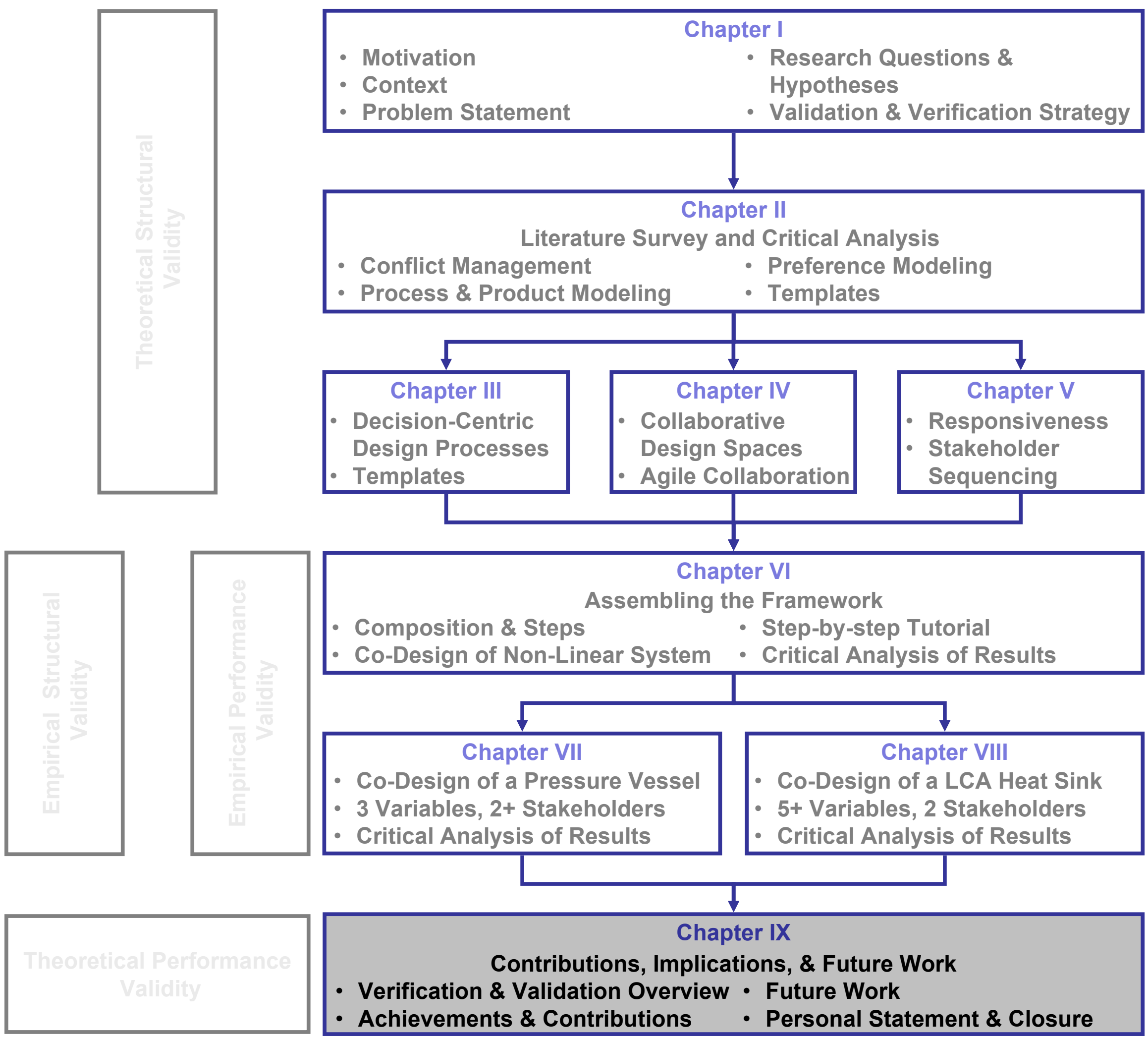


Figure 9-1 - Dissertation Roadmap

9.1 VERIFICATION AND VALIDATION OF THE RESEARCH HYPOTHESES

In this section, the validation of the methods that were proposed in response to the research questions formulated in Chapter 1 is completed. The research questions and corresponding hypotheses are revisited in Section 9.1.1. The validation of the constructs as implemented throughout this dissertation is subsequently reviewed in the context of Figure 1-13 (repeated here as Figure 9-2 for the reader's convenience) in Section 9.1.2.

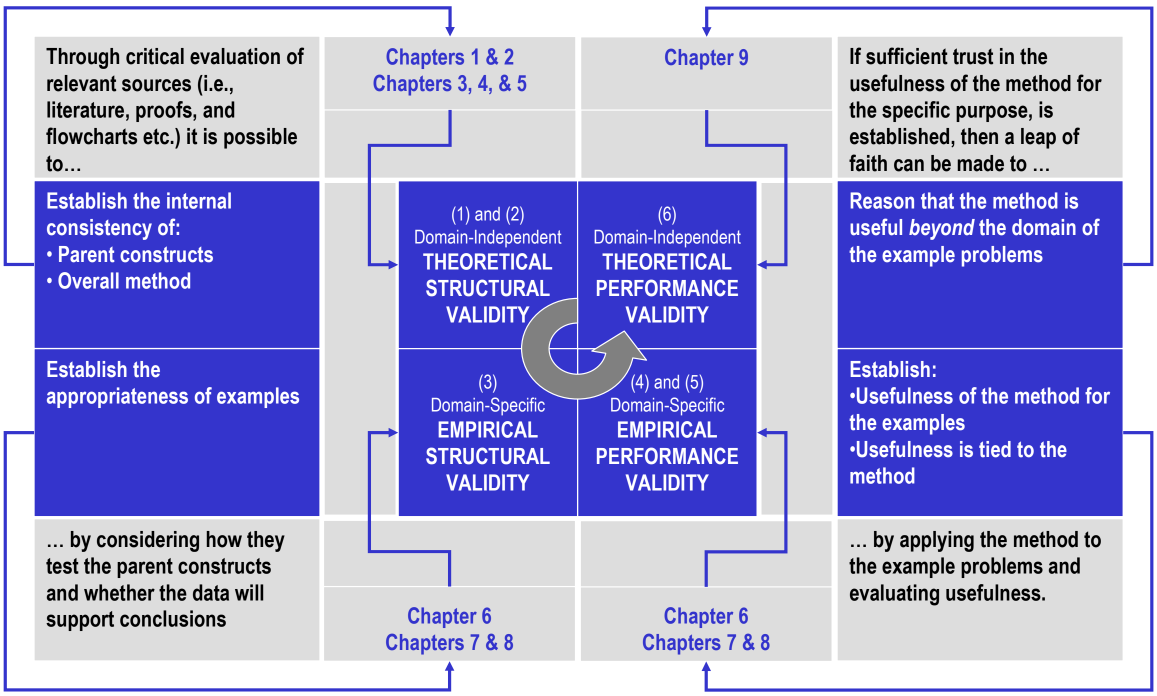


Figure 9-2 - Dissertation Validation Strategy

9.1.1 Revisiting the Research Questions and Hypotheses

Writing a PhD dissertation that is grounded in research, involves posing meaningful research questions, establishing hypotheses for addressing them, developing methods grounded in these hypotheses, and finally building confidence in the validity and usefulness of research contributions. The chosen strategy for accomplishing this task is the validation square, introduced in Section 1.4. Before, reviewing the process of validation with respect to each of the aspects considered in this approach, each of the research questions and hypotheses is revisited.

As discussed in Section 1.3.2, the principal research question, investigated in this dissertation is:

Primary Research Question: *How can collaboration in engineering design be modeled so as to facilitate the reflection of evolving stakeholder aspirations, while ensuring the existence of acceptable solutions and promoting the unbiased achievement of system level objectives?*

This primary research question is considered in terms of three secondary research questions. Specifically, Research *Question 1* is addressed in Section 1.3.3.1 and forms the basis for discussion in Chapter 3, *Research Question 2* is presented in Section 1.3.3.2 and addressed in Chapter 4, and *Research Question 3* is introduced in Section 1.3.3.3 and focused upon in Chapter 5. The three secondary research questions and hypotheses are summarized below. Following each set of research questions and hypotheses is a figure, summarizing hypothesis-specific aspects of **Theoretical Structural Validation**, **Empirical Structural Validation**, **Empirical Performance Validation**, and **Theoretical Performance Validation**, discussed in further detail in Sections 9.1.2.1, 9.1.2.2, 9.1.2.3, and 9.1.3, respectively.

Research Question 1: *How can design problems be modeled so that the reflection of changing information content and evolving stakeholder aspirations can be accommodated while maintaining structural consistency?*
Hypothesis 1: *The considerations of individual decision-makers can be modeled using domain independent, modular, reusable decision templates, based on Decision Support Problem constructs that can be captured, archived, analyzed and manipulated on a computer.*

Validation and Verification of Hypothesis 1

THEORETICAL STRUCTURAL VALIDITY

Validity of the Constructs of the Method
- Product Modeling (Section 2.3)
- Process Modeling (Section 2.4)
- Integrated Product/Process Modeling (Section 2.5)
- Templates (Section 2.7)
- Flexibility, Openness, & Modularity (Section 2.8)
- Context: Design Equation, Design Process Reuse, Use of Templates in Design Process Modeling, Decision-Centric Modeling of Design Processes in Light of Systems Considerations, Templates – Declarative vs. Procedural Information (Section 3.2)
- Research Gaps (Table 2-7)

Benefits
- Computer Interpretability, Modularity, Archival

Methodological Differences
- Separation of Declarative and Procedural Information
- Completely Modular Model Architecture
- Composability

THEORETICAL PERFORMANCE VALIDITY

Usefulness of the Method beyond the Examples
- The Pressure Vessel Design Example is a Strongly Coupled Design Problem, Solved in a Decentralized Environment
- Both the Pressure Vessel and Spring Design Examples are Representative of the more General Class of Engineering Problems towards which the Method is Targeted
- The Pressure Vessel and Spring Design Examples are Sufficiently Different to Illustrate the Genericism and Extent of Reusability, inherent in the TDPM technique
- Problems of Higher Complexity with Regard to the Number of Stakeholders and the Number of Design Variables are Addressed in Chapters 6, 7, and 8
- Due to the Openness, Flexibility, and Modular Construction of the Templates, These are Easily Modified to Accommodate Additional Requirements

EMPIRICAL STRUCTURAL VALIDITY

Appropriateness of the Examples
- Spring Design
  - Quintessential Mechanical Engineering Artifact
  - Accommodation of Evolving Information Content for a Single Design Decision
- Pressure Vessel Design
  - Quintessential Mechanical Engineering Artifact
  - Accommodation of Evolving Information Content for a Design Process Composed of Strongly Coupled Decisions

Benefits
- Re-usability of Constructs
- Design Process Composability
- Design Process Exploration

Methodological Differences
- Genericism of Constructs to Allow for Templatization
- Isolation of Changes via Modularity
- Decision-Centric Focus

EMPIRICAL PERFORMANCE VALIDITY

Usefulness of the Method in the Examples
- Formulation of Single- and Multi-Designer Decision-Centric Design Processes via the Provision of Declarative Information Content Only
- Plug-and-Play Instantiation of Design Processes
  - Choice of Templates for Decisions and Interactions
  - Specification of Procedural Aspects in Terms of Information Flows
  - Declaration of Problem-Specific Information via Specification of XML Files

Benefits
- Standardization of Stakeholder Problem Formulation, Structure, and Representation
- Ease of Design Process Exploration and Investigation of What-If Scenarios

Methodological Differences
- Ease of Use
- Consistent Guidance and Support
- Domain Independence

Figure 9-3 - Summary of Validation and Verification with Regard to Hypothesis 1

Research Question 2: *How can the communication of information, required for the resolution of strongly coupled design problems, among collaborating stakeholders be structured so that their efforts are focalized and their subsequent interactions are rendered both effective and concise?*

Hypothesis 2: *The existence of feasible solutions can be ensured through the collaborative construction, exploration, and management of collaborative design spaces by all interacting parties, contributing to and pursuing a common set of overarching systems level objectives. The resulting means of focalization ensures the existence of a solutions and is thus independent of the manner in which the final tradeoffs are struck.*

Validation and Verification of Hypothesis 2

THEORETICAL STRUCTURAL VALIDITY

Validity of the Constructs of the Method
- Modeling and Managing Conflict (Section 2.2)
- Modeling Preferences (Section 2.6)
- Definition and Description of Collaborative Design Spaces and Advantages in Adopting Associated Concepts (Section 4.2)
- Research Gaps
  - Communications Protocols (Table 2-1)
  - Conflict Management (Table 2-2)

Benefits
- Systematic Focalization of Stakeholders and Elimination of Infeasible Regions of Shared Design Spaces
- Common-Resource Denomination for all Decision-Critical Information Content

Methodological Differences
- Consistent Separation of System Level and Domain-Specific Design Sub-Problem Considerations
- Transparent Evolution of Design Spaces
- Resource Conscious Preference Assessment

THEORETICAL PERFORMANCE VALIDITY

Usefulness of the Method beyond the Examples
- The Pressure Vessel Design Example is a Strongly Coupled Design Problem, Solved in a Decentralized Environment for both 2 and 3 Designers.
- The Structural Heat Exchanger Example is Representative of Engineering Challenges Encountered in Practice with Respect to both Complexity and Strength of Implicit Biases.
- Both Examples are Representative of the more General Class of Engineering Problems towards which the Method is Targeted but are Designed to Stress the Methods in Different Aspects, Beyond What is Typically Encountered in Engineering Practice.
  - Design Problem Partitioning in Pressure Vessel Example
  - Responsibility Assignment in LCA Design Example
- Due to the Openness, Flexibility, and Modular Construction of all Aspects of the CDSFM, Modifications to Accommodate Additional Requirements are Simple

EMPIRICAL STRUCTURAL VALIDITY

Appropriateness of the Examples
- Non-Linear System - Simplicity, Ensuring Transparency of Application and Ascertainment of Intuitiveness and Accuracy of the Methods
- Pressure Vessel - Well Established, Strongly Coupled, Suited for Exploring 2 & 3 Stakeholder Design Processes, Method Stressed Based on Partitioning
- Structural Heat Exchanger - High Complexity, Need for Surrogate Models, Strongly Coupled, Extremely Sensitive to Sequence

Benefits
- Consistent Formulation of Decisions via Templates
- Systematic Identification, Establishment, Exploration, and Refinement of a Collaborative Design Space
- Performance Conscious Tradeoff Management

Methodological Differences
- Assurance of a Feasible Solution
- Consistent Communication and Systematic Focalization Based on Dynamic Interaction

EMPIRICAL PERFORMANCE VALIDITY

Usefulness of the Method in the Examples
- Successful Focalization Myriad Stakeholders in Different Scenarios
- Assurance of a Win/Win Scenarios, Guaranteed to Yield Acceptable Results to all Parties for Examples of Varying Complexity

Benefits
- Ease of Design Space and Design Process Exploration via Space Filling Experiments in Combination with Surrogate Models Conducted on Successive Refinement
- Estimation of Stakeholder Responsiveness
- Combinatorial Use of the CDSFM with the ICCM and more Traditional Protocols within FACE

Methodological Differences
- Systematic Elimination of Implicit Biases
- More Efficient and Effective Use of System Resources
- Adaptability of the Level of Cooperation to Organizational and Structural Requirements, while Systematically Ensuring the Existence of a Solution

Figure 9-4 - Summary of Validation and Verification with Regard to Hypothesis 2

Research Question 3: *How can stakeholder interactions be guided so that design freedom is not reduced unnecessarily and system level performance is enhanced?*
Hypothesis 3: *Various measures of responsiveness may be employed in conjunction with performance potential to gauge individual stakeholder impact on problem resolution, eliminate implicit bias, and improve performance from the systems perspective.*

Validation and Verification of Hypothesis 3

THEORETICAL STRUCTURAL VALIDITY

Validity of the Constructs of the Method
- Modeling and Managing Conflict (Section 2.2)
- Flexibility, Openness, & Modularity (Section 2.8)
- Definition and Description of System-Conscious Tradeoff Resolution (Section 5.2)
  - Drawbacks of Common Solution Schemes, Explicit Biases, and Implicit Biases
- Research Gaps
  - Communications Protocols (Table 2-1)
  - Conflict Management (Table 2-2)

Benefits
- Reduction of Implicit Biases on Tradeoff Management
- Prevention of Preference Dilution
- Continuous Stakeholder/Domain Alignment

Methodological Differences
- Increased Transparency of Tradeoff Management
- Performance-Conscious Refinement of Preferences
- Increased Communication of Decision-Critical Information and Self-Assessment-Based Sequencing

THEORETICAL PERFORMANCE VALIDITY

Usefulness of the Method beyond the Examples
- The Pressure Vessel Design Example is a Strongly Coupled Design Problem, Solved in a Decentralized Environment for both 2 and 3 Designers.
- The Structural Heat Exchanger Example is Representative of Engineering Challenges Encountered in Practice with Respect to both Complexity and Strength of Implicit Biases.
- Both Examples are Representative of the more General Class of Engineering Problems towards which the Method is Targeted but are Designed to Stress the Methods in Different Aspects, Beyond What is Typically Encountered in Engineering Practice.
  - Design Problem Partitioning in Pressure Vessel Example
  - Responsibility Assignment in LCA Design Example
- Due to the Openness, Flexibility, and Modular Construction of all Aspects of the ICCM, Modifications to Accommodate Additional Requirements are Simple

EMPIRICAL STRUCTURAL VALIDITY

Appropriateness of the Examples
- Non-Linear System - Simplicity, Ensuring Transparency of Application and Ascertainment of Intuitiveness and Accuracy of the Methods
- Pressure Vessel - Well Established, Strongly Coupled, Suited for Exploring 2 & 3 Stakeholder Design Processes, Method Stressed Based on Partitioning
- Structural Heat Exchanger - High Complexity, Need for Surrogate Models, Strongly Coupled, Extremely Sensitive to Sequence

Benefits
- Systematic Sequencing of Stakeholders based on Responsiveness Estimation
- Performance Conscious Tradeoff Management

Methodological Differences
- Improvement of System Performance Based on Systematic Discovery and Elimination of Implicit Biases
- Successive Refinement of Surrogate Models Based on Collaborative Design Space Evolution

EMPIRICAL PERFORMANCE VALIDITY

Usefulness of the Method in the Examples
- Self-Assessed Sequencing of Myriad Stakeholders in Scenarios of Differing Complexity
- Consistent Improvement of Solution Quality via Implicit Bias Elimination
- Essential Benefits of Both Fully Cooperative and Non-Cooperative Behavior without Incurring either the Computational Cost or Sacrificing Dynamic Interaction

Benefits
- Responsiveness Estimation via Space Filling Experiments
- Performance Potential Contextualized Interpretation of Stakeholder Responsiveness
- Usefulness of Indicators in Combination with Traditional Protocols within FACE

Methodological Differences
- Systematic Elimination of Implicit Biases
- More Efficient and Effective Use of System Resources

Figure 9-5 - Summary of Validation and Verification with Regard to Hypothesis 3

Answering each of these questions involves the validation of the corresponding hypotheses. Aspects of this verification process are documented throughout this thesis, as indicated in Figure 9-2.

9.1.2 Testing the Validity of the Proposed Methods

An overview of the validation strategy pursued in this thesis is given in Section 1.4. As indicated it is based on the validation square [180,211] and formulated accordingly (see Figure 1-12). The goal is to build confidence in the validity and usefulness of the proposed methods from each of the four viewpoints (as represented by the various quadrants). Three of these viewpoints, namely **Theoretical Structural Validity**, **Empirical Structural Validity**, and **Empirical Performance Validity**, have been addressed in great detail throughout previous chapters of this dissertation as indicated in Figure 9-2. Although the details of the respective arguments will not be repeated here, all aspects will be tied together in terms of their combined effect. **Theoretical Performance Validity**, the final quadrant not previously discussed, will be addressed within Section 9.1.3.

9.1.2.1 <u>Theoretical Structural Validation</u>

As indicated in Section 1.4, *Theoretical Structural Validation* in this dissertation is addressed by (1) critically reviewing relevant literature and (2) evaluating the implemented constructs with regard to comparative advantage, limitation, and acceptable domain of application. A precursory review of research, documented in the literature, relevant to all hypotheses is provided throughout Chapter 1. Several sections are tailored towards specific research questions however. Thus, Sections 1.3.3.1, 1.3.3.2, and 1.3.3.3 are focused on *Hypotheses 1*, *2*, and *3*, respectively. With respect to *Hypothesis 1*, the majority of the relevant literature is reviewed in Chapter 2. Specifically, commonly implemented product models are reviewed in Section 2.3 and popular process modeling techniques in Section 2.4. The required paradigm shift of considering the design of design processes alongside the design of the product is discussed in Section 2.5, while several of the technical concepts upon which the template-based modeling technique is based are presented in Section 2.7. Additionally, some of the philosophical underpinnings are reviewed in Section 2.8. Certain elements of theoretical structural validity are also addressed in Chapter 3, when pertinent to the development of the **T**emplate-based **D**esign **P**rocess **M**odeling approach. With regard to *Hypotheses 2* and 3, aspects of *Theoretical Structural Validation* are also predominantly addressed in Chapter 2. Specifically, the topic of modeling and managing conflict in engineering design is reviewed in Section 2.1, while process modeling is discussed in Section 2.4. The importance of modeling products and processes in an integrated fashion is discussed in Section 2.5. Finally the intricacies inherent in representing preferences and incorporating these into the decision-making process are elaborated upon in Section 2.6. Additional contributions with regard to *Hypothesis 2* are made in Section 4.6, where developed constructs are evaluated with regard to comparative advantage, limitation, and acceptable domain of application in the context of the **C**ollaborative **D**esign **Sp**ace **F**ormulation **M**ethod formalized in Chapter 4. Similar contributions with regard *Hypothesis 3* are made in Section 5.6 in support of the **I**nteraction-**C**onscious **C**oordination **M**echanism, to the development of which Chapter 5 is devoted.

9.1.2.2 Empirical Structural Validation

Building confidence in **Empirical Structural Validity** requires substantiation of the appropriateness of the examples chosen to test the proposed methods. There are four distinct examples of increasing complexity, used to accomplish this task in this dissertation. Specifically, the spring and pressure vessel examples are used to illustrate the implementation of the TDPM in response to *Research Question 1*, while the set of non-linear equations, the collaborative pressure vessel design, and the parametric structural heat exchanger design examples are used to illustrate the implementation of the CDSFM and ICCM, offered in response to *Research Questions 2* and *3*, respectively. Each of the examples was chosen for a specific purpose. While the system of non-linear equations was elected predominantly for its relative transparency, the pressure vessel and LCA design examples were selected to illustrate complexity with regard to the number of stakeholders and the number of design parameters, respectively. All of the examples considered are representative of engineering design and express strong coupling. Specific arguments regarding the well-suitedness of the various examples are made in Sections 3.6.2, 6.7.1, 7.3.1, and 8.3.1.

9.1.2.3 Empirical Performance Validation

Empirical Performance Validity is a measure of the method's usefulness (in a sense). It is thus crucial to be able to distinguish between coincidences and benefits derived as a result of the methods being validated. This goal is best served by relying on examples that are either transparent or whose solutions are either known, intuitive, or verifiable. Moreover, each of the examples is used in such a way that careful evaluation of outcomes is possible both from both a subjective and an objective perspective. While subjective aspects focus more on ease of use and intuitiveness, objective evaluation is centered on quantitative comparison of results obtained to those produced by more traditional (and well accepted) approaches. In some instances, visual evaluation is also possible. Since comparisons are made with respect to the global mathematical optima in many cases, as determined by exhaustive search, a certain degree of objectivity is ensured. A comprehensive understanding of the design space for each example instrumental in interpreting results obtained. Additionally, consistency of outcomes and agreement with expectation was affirmed. In summary, each of the problems chosen for the purpose of **Empirical Performance Validation** meets these criteria as substantiated in Sections 3.6.3, 6.7.2, 7.3.2, and 8.3.2.

Having reviewed **Theoretical Structural Validation**, **Empirical Structural Validation**, and **Empirical Performance Validation** as addressed in this dissertation, the only remaining aspect, namely **Theoretical Performance Validation,** is discussed in the next section.

9.1.3 Completing the Square

Theoretical Performance Validity is based on establishing that the proposed methods are useful beyond the scope of the examples presented in this dissertation. In essence, this reduces to demonstrating that the chosen example applications are representative of the larger class of problems for which the developments are intended. Supporting arguments form the basis of **Empirical Structural Validation** and allow for the inference of the applicability and usefulness of the methods in general. To reiterate, the general class of problems (for which the constructs presented in Chapters 3, 4, and 5 are valid) can be defined by the following characteristics:

- Design problems can be formulated in terms of design decisions.

- Design decisions are strongly coupled (although uncoupled and weakly coupled design decisions can also be addressed).
- Decision-critical information is available and attainable.
- Simulation is possible either via explicit, analytical, or statistical models.
- Responsibility for making design decisions is assigned according to expertise. Decision-makers are thus considered to be domain experts and are assumed to have the ability to interpret decision-critical information within the context of their respective decisions.
- Decision-makers know what they want. Uncertainty or "fuzziness" with regard to preferences is not allowed, although refinement and evolution of information content can be accommodated.
- Decision-makers are rational as defined by the axioms of utility theory.
- Consequences of choices are well understood. At the very least the associated risks can be quantified.
- Decision-makers are capable of interpreting the wishes of other stakeholders based on preference information and thus able to serve as "benevolent dictators".
- Responsibility for decisions is assigned to individuals
- It is in the decision-makers best interest to behave cooperatively. Conversely, decision-makers do not have any reason to behave non-cooperatively.
- Informational dependencies among coupled decisions are known - inputs, outputs, and information flows can be established among constituent decisions.

- Preferences for tradeoffs among competing objectives at the systems level are known. In the absence of this information, system level objectives are fairly represented by choosing equal weights.

Each of the problems used for building confidence in the empirical performance of (1) the **T**emplate-based **D**esign **P**rocess **M**odeling approach, (2) the **C**ollaborative **D**esign **Sp**ace **F**ormulation **M**ethod, and (3) the **I**nteraction-**C**onscious **C**oordination **M**echanism are characterized by these criteria. Furthermore, while not all examples are mutually exclusive, they are collectively exhaustive with respect to the unique aspects they are meant to emphasize. Each of the strongly coupled design problems, whose decentralized solution is required, differs substantially with respect to complexity. With this in mind, the primary purpose of the tutorial example was to illustrate in a transparent fashion, each of the proposed methods. The aim of the collaborative pressure vessel design example was to illustrate the scalability of the methods beyond two designers. Finally, the primary purpose of the LCA design example was two fold, focusing on the consideration of large numbers of design variables and the associated incorporation of surrogate models for simulation purposes. Comprehensively, the examples illustrate the extensibility of the methods presented in this dissertation beyond simple test problems to those considered in practice, as embodied by both the pressure vessel and the LCA design examples. Fundamentally, there is no theoretical limitation based upon the means and methods implemented. Computational concerns can be addressed through reliance on surrogate models and assurance of their meeting acceptable levels of variability. Since the example problems form a sub-group of the more general class of problems defined by these characteristics, it is argued by induction that the proposed methods are useful for the general class of problems addressed. Although even broader application may be possible, it has not been validated by the research documented in this dissertation.

9.1.4 Validation Summary

As indicated in Section 1.4 and emphasized in Figure 9-6, validation and verification will be considered from various perspectives, the combined discussion of which, should build confidence in what is proposed. With this in mind, the overarching context of the work presented here was provided in Chapter 1. The discussion was designed to establish need, motivate research, clarify relevant assumptions, scope out extent, and justify the approach taken. Aspects of **Theoretical Structural Validation** were addressed in Chapter 2, where existing literature was surveyed. Well-established methods, concepts, and constructs, fundamental to the contributions made in this dissertation, were presented, critically reviewed, and analyzed. Due to the extensive nature of the subject matter, substantial ground was covered. Specifically, the topics considered were the modeling and management of conflict in engineering design, the (isolated and integrated) modeling of products and processes, the modeling of preferences, and the use, purpose, and applicability of templates. In each case, relevant background material was provided and the discussion tied to the general theme or context of decentralized, decision-centric simulation-based design.

The contributions made in response to each of the three pairs of research questions and hypotheses (in ascending order) were addressed in Chapters 3, 4, and 5, respectively. Specifically, a novel means of modeling stakeholder decisions and interactions in terms of modular, computer interpretable templates was detailed in Chapter 3. In Chapter 4, a method for identifying and establishing a collaborative design space with the benefit of guaranteeing solutions to coupled design problems, responsibility for the resolution of which is shared, was developed. Subsequently, a mechanism for promoting system conscious tradeoffs among competing objectives, ideally suited for co-design, was detailed. Importance in each of these chapters was placed on substantiating the internal consistency of the concepts, constructs, methods, or mechanisms, as well as the resulting amalgamations, extensions, and analogues of the material reviewed in Chapter 2. The contributions of Chapter 4 (i.e., the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod) and Chapter 5 (i.e., the **I**nteraction **C**onscious **C**oordination **M**echanism) constitute the proposed **F**ramework for **A**gile **C**ollaboration in **E**ngineering; the subject matter of Chapter 3 (i.e., the **T**emplate-based **D**esign **P**rocess **M**odeling approach) is the proposed means of instantiation. It is emphasized at this juncture that each of these aspects has utility in isolation and is not necessarily dependent on the others.

In Chapter 6, the implementation of the proposed **F**ramework for **A**gile **C**ollaboration in **E**ngineering was demonstrated via application to a simple example; a system of non-linear equations was *co-designed* in tutorial fashion. Results obtained were compared to solutions emanating from reliance on generally accepted methods in order to build confidence in the **Empirical Performance Validity** of the various contributions. An argument for the **Empirical Structural Validity** of the example was made by illustrating relevance, as defined in Section 1.4. The second and third quadrants of the validation square were addressed further in Chapters 7 and 8, where problems of increasing complexity were tackled. Finally, an argument for **Theoretical Performance Validity** was made in this chapter, concluding the validation and verification effort in this dissertation (see Figure 9-6).

In summary, the hypotheses posited in light of the three secondary research questions posed in Chapter 1 of this dissertation have thus been verified with regard to each quadrant of the validation square. With this in mind, it is asserted that the primary research question has been answered successfully. *Given the context of decentralized decision-centric design, the successful resolution of strongly coupled design problems (by any means) can be promoted via the systematic focalization of stakeholder efforts. This is accomplished through the co-construction and co-management of collaborative design spaces. Furthermore, increasing decision-maker awareness of performance potential, responsiveness, and impact can facilitates the elimination of implicit biases, thereby advancing the balanced achievement of system level objectives. Increased demands placed on stakeholders as a result of closer and more consistent interaction can be alleviated through reliance on domain independent, modular, reusable templates for modeling the considerations of individual decision-makers that can be captured, archived, analyzed and manipulated on a computer.* With this in mind, a concise overview of the most relevant contributions made in this research follows in Section 9.2.

9.2 ACHIEVEMENTS AND RESEARCH CONTRIBUTIONS

As indicated in Chapter 1, the primary research question addressed in this dissertation is:

> ***Primary Research Question:*** *How can collaboration in engineering design be modeled so as to facilitate the reflection of evolving stakeholder aspirations, while ensuring the existence of acceptable solutions and promoting the unbiased achievement of system level objectives?*

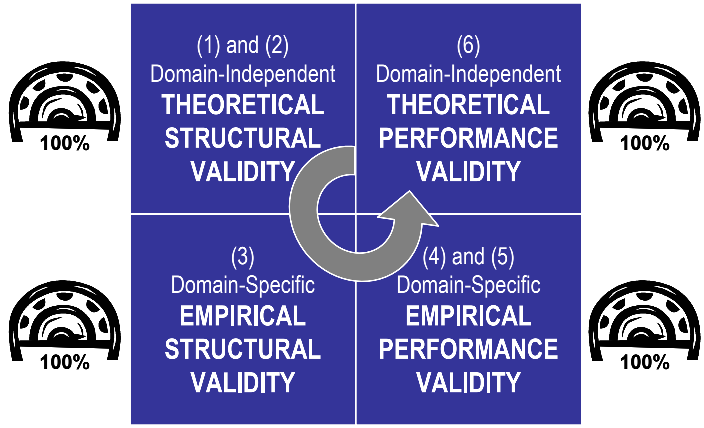


Figure 9-6 - Validation and Verification Progress through Chapter 9

In response to this question, three distinct contributions are offered, as summarized in Figure 9-7. The first is the development of a **T**emplate-based **D**esign **P**rocess **M**odeling approach, focused on the consistent representation of stakeholder considerations throughout the duration of their interaction. The resulting building blocks comprise a standardized means of capturing decision-critical information, regardless of domain, and offer the advantage of allowing for the continuous alignment of decisions and pertinent expertise. The templatized decision and interaction constructs have the advantage of being both reusable and computer interpretable. More importantly, they are composable, allowing for the consistent support of single as well as multiple decision-maker design processes. This in turn facilitates the exploration of collaborative design spaces and contributes to a more comprehensive picture of impact, interaction, and sensitivities of stakeholders to dynamic considerations. Considering the immediate impact of the design process on the product being produced, this is a tremendous advantage. Although composable simulations have been pervasive in fields such as electrical engineering, their integration into decision-making level activities had previously not been entertained.

Due to the ubiquitous and pervasive nature of decisions composable templates, formulated at this level, comprise a common denominator for the integration of activities, regardless of domain, discipline, or level of abstraction. Additionally, both synchronous and asynchronous activities can be more easily reconciled.

Up until now, the existence of a solution to coupled design problems has been presupposed. Mismatched and irreconcilable objectives have thus invariable resulted in iteration. Considering that one of the fundamental aims in related research has been that of excising iteration, trial-and-error is clearly not the best recourse. With this in mind, the second major contribution in this dissertation is that of the **C**ollaborative **D**esign **S**pace **F**ormulation **M**ethod. Specifically, congruity and synergism in stakeholder efforts is ensured via the consistent communication of decision-critical information. Decision-makers are focalized towards mutually acceptable regions of shared design spaces. In fact, it is the resulting collaborative design space that is viewed as the most appropriate nexus for all activities, since it represents the point of confluence for shared resources and constraints, as well as conflicting objectives. There are two primary benefits to identifying, formulating, and managing collaborative design spaces – (1) increased computational efficiency by eliminating unsuitable regions of design spaces from consideration and (2) assurance of a win/win scenario. Moreover, this contribution is independent of the final protocol being implemented for striking the required tradeoffs among the myriad sub-systems. This ensures flexibility for accommodating enterprise level concerns and increases the chances of alternative protocols yielding acceptable results. Overall, the CDSFM is the most significant outcome of this research, having the most profound and far reaching implications.

The third contribution is the **I**nteraction-**C**onscious **C**oordination **M**echanism that in conjunction with the CDSFM gives rise to the notion of *co-design*. The focus in this aspect is on increasing stakeholder awareness of implicit system biases and interaction effects, thereby ensuring more balanced objective achievement. The concept relies on improving the quality of solutions at the system level, by reducing the implicit effects of intrinsic interactions and making the system transparent to explicit tradeoffs. Overall, the quality of solutions, obtained via *co*-design, approaches that possible only through full cooperation, without incurring the prohibitive computational cost, usually associated with this protocol. Additionally, the focus is on the communication decision-critical information (i.e., responsiveness indicators, performance potential, preferences) only, alleviating the burden associated with interpretation exceeding one's expertise.

Each of these three fundamental contributions are part of the overarching vision of a **F**ramework for **A**gile **C**ollaboration in **E**ngineering as presented in Section 1.3.4. On the whole, the contributions contained in this dissertation can be summarized as follows:

- Preservation of stakeholder autonomy over design sub-problems throughout the duration of collaboration
- Consistent formulation of evolving stakeholder considerations
- Coordination of stakeholders interactions along an event-based timeline
- Formalization of modular, computer interpretable templates
- Alternative coordination mechanism focused on dynamic collaboration rather than strategic form conflict resolution
- Systematic focalization of stakeholder contributions via formulation and management of collaborative design spaces

- Improved achievement of system level (performance/product) objectives via stakeholder responsiveness assessment and sequencing

Framework for Agile Collaboration in Engineering

☑ Interaction-Conscious Coordination Mechanism
- Concise – focused on the communication of required information only
- Collaborative – involves all stakeholders at the same level
- Balanced – elimination of implicit system biases

☑ Collaborative Design Space Formulation Method
- Focalized – assurance of congruous and synergistic stakeholder efforts
- Dynamic – interactive, relay of up-to-date information content
- Feasible – systematic formulation of collaborative (win/win) design spaces

☑ Template-based Design Process Modeling
- Consistent – invariant throughout the duration of stakeholder interactions
- Modular – standardized for flexibility, ease of assembly, and "repair"
- Computer Interpretable – executable and analyzable
- Reusable – allow for partial or total salvage from previous instantiations
- Composable – made or created by putting together parts or elements

Figure 9-7 - Summary of Fundamental Research Contributions

Before elucidating and expounding upon future research opportunities in Section 9.4, some of the fundamental limitations of this research effort are reviewed in Section 9.3.

9.3 A CRITICAL ANALYSIS AND REVIEW OF THE LIMITATIONS OF THIS RESEARCH

Besides the fundamental assumptions underlying this research presented in Section 9.1.3, there are three main aspects to limitations of the methods developed in this dissertation. The first relates to the need for at least semi-cooperative behavior, the second to the increased burden placed on stakeholders in terms of required communications, and the third to the quantification associated with reliance on utility theory. Each will be reviewed briefly in the paragraphs to follow.

While formalized interactions, as embodied within the overarching DSPT framework, have thus far focused on instantiations of *clean digital interfaces,* for single, sequential interactions based on (1) the embodiment of game theoretic interaction protocols as in Refs. [97,136,267,269,270] and (2) the propagation of semantically rich information content alongside ranged sets of specifications as in Refs. [72,77,78], the focus in this dissertation is on structuring continued interactions throughout the duration of a stakeholder relationship. The resultant protocol could be considered to constitute a *dirty digital interface* so that advantages inherent in separating *declarative* from *procedural* information flows are exploited as described in Ref. [168]. The corresponding templates capture dependencies both between interacting decision-makers and the associated design parameters [77,78]. Mappings and translations between various models, databases, etc. are also accommodated. The resulting interaction protocols facilitate sharing critical information as required by underlying information flows. The goal of interaction templates, such as those proposed here, is to capture the *procedural* elements of commonly encountered interactions at the decision level of interaction. It is through such templates, that the linking of decision models pertaining to interacting stakeholders is greatly facilitated.

A caveat regarding the template-based design process modeling approach, presented in Chapter 3 is in order. One must recognize that the value and ease of implementing a template-based design approach increases with the quantity and quality of information available. Thus, while it is possible to formulate templates, at least structurally, even in the early stages of design, the information and knowledge gained by exercising the resulting models becomes more concrete as the design matures. The advantage of relying on completely modular templates is the provision of a consistent means of capturing and exploiting knowledge that reflects evolving information content throughout the design process.

The resulting network of decisions then becomes a computer analyzable process template for the design process in question. This is true whether this process involves a single or multiple decision-makers. The fundamental assumption in this regard is the availability of required information and the ability to make the appropriate interpretations. On a more fundamental level, additional information is required to focalize decision-maker efforts. Effective reliance on the means and methods presented in this dissertation thus also requires a certain degree of cooperation.

Despite the obvious advantages of increasing stakeholder agility by increasing the availability of information, cooperative solution mechanisms may not be appropriate in all situations. Often, design problems are split along disciplinary and organizational lines. Consequently, responsibility for their resolution is shared in spite of individualistic expectations and performance measures. A majority of efforts, focused on supporting collaborative decision-making, center on one-time interactions and their improvement via the communication of richer information content. The underlying aim is the improvement of solution quality as well as reduction and/or elimination of required iterations. The premise in this dissertation is the identification and subsequent remediation of mismatches via consistent communications. The resultant burden on the stakeholder exceeds that of non-cooperative behavior, while falling significantly short of that associated with full cooperation.

The final aspect relates to the prevalent use of utility theory in this research, a more in-depth discussion of which follows in Section 9.6. Despite its mathematical rigor, utility theory alone is not a design or decision support methodology. Utility theory is most appropriate for clarifying decision-maker preferences and indicating the preferred alternative from one among a set of feasible alternatives. Strictly speaking, however, a designer should place no bounds on alternatives open for consideration. Instead, feasibility should be dictated strictly by the nature of a decision-maker's preferences. This, however is highly impractical in the context of engineering design and effective use of utility theory for decision support in engineering design is contingent upon its application within a proper context—a context that provides for the effective use of engineering judgment for *formulating* decisions. Although the decision templates are used in this dissertation to provide this context, several other drawbacks remain. In using utility functions to indicate preference, the functional form of designer's preferences is no longer restricted. However, the designer's preferences must now obey the tenets of utility theory. This means that no uncertainty with regard to these preferences is allowed and a designer must know what he/she wants. Although, this is ideally the case, exploration of a design space is severely limited. Similarly, utility functions only hold for the designer and context for which they were assessed. Lastly, designers must be able to establish the uncertainty associated with alternatives quantitatively (at least approximately). As a design progresses, however, improved estimates may be taken advantage of. In this aspect, certain allowances are made in this dissertation. Utility theory is used mainly as a means of assessing, quantifying, and communicating preferences. In this aspect, decision-maker preferences are also used as a basis for normalization. Derivatives are taken with regard to their effect on designer satisfaction, thus accentuating the role that preferences play in the design process. Finally, performance potential is considered to constitute a fundamental prerequisite for assessing useful utilities for design. Although stakeholder preferences are ideally absolute and independent of any other considerations, engineering is a highly resource driven activity. Thus, knowing what you want is useful, but can lead to misguided design decisions when the specified needs are not attainable based upon the resource available. Risk is not explicitly considered; however the facility for doing so remains. Having reviewed the fundamental limitations of this research in light of underlying assumptions, future avenues of exploration are presented in Section 9.4.

9.4 RESEARCH OPPORTUNITIES AND RECOMMENDATIONS

With respect to the **T**emplate-based **D**esign **P**rocess **M**odeling approach, presented in Chapter 3, the overarching goal of this research was to formalize a *declarative* design process modeling technique, centered on decision-centric design processes. In working towards achieving this end, the compromise DSP has successfully been implemented as a modular, reusable, template-based design process building block, taking advantage of the consistent and application-independent structure of this construct. Future efforts should center on formalizing additional information transformations (e.g., abstraction, composition, decomposition, and mapping) in an analogous fashion. The goal is that of creating a platform for more closely integrating activities relating to simulation and decision-making in engineering design processes, taking full advantage of existing software frameworks and collaborative platforms in the process. This requires: *(1)* mapping information schemas defined at various levels of abstraction, *(2)* developing a design process repository *(3)* developing metrics for characterizing individual information transformations and their compositions, *(4)* formalizing interactions among the stakeholders involved in a shared design effort, *(5)* exploring design process architecture and developing design process families, and *(6)* investigating effects of stakeholder control on design processes and value chain modularity.

With respect to the **C**ollaborative **D**esign **S**pace **E**xploration **M**ethod, presented in Chapter 4, the overarching goal of this research was to formalize a systematic means of focalizing the activities of decision-makers acting as domain-experts in a decentralized engineering environment. In working towards achieving this end, one of the fundamental requirements is the effective description and communication of the collaborative design space that constitutes the basis for all subsequent interactions. While series and sets of point solutions are effective, they can be prohibitive as the number of variables and decision-makers increases. Consequently, the potential of seeking ranged sets of solutions or even families of solutions as in the practices of the Toyota Motor Company [254] have more promise. A key area of research in this regard is the development of more concise means of capturing the data associated with multi-dimensional, non-convex and potentially mixed discrete/continuous design spaces so that the conciseness and precision of communications can be assured. It is also warranted to investigate the correlation between the size of a collaborative design space and the ability to effectively use the myriad communications protocols available to designers.

With respect to the **I**nteraction**-C**onscious **C**oordination **M**echanism, presented in Chapter 5, the overarching goal of this research was to increase stakeholder awareness of interaction effects. While derivatives provide a reliable means of determining responsiveness throughout the design space, investigation of statistical measures in this regard is warranted. Measures such as the covariance of effects and the resultant correlation have the potential of yielding a finer granularity, increased precision picture of the manner in which objective achievements are related. Investigation of better uses of derivate information when combined with successively refined surrogate models is also needed. Specific considerations of interest relate to the assessment of what quality of fit is required to make reasonably accurate predictions. An area of special concern is the characteristically poor fit associated with stepped levels of discrete variables in a mixed discrete continuous design space. Finally, the integration of such predictors into the formulation of tradeoff strategies and negotiating tactics for non-cooperative interaction protocols provides another interesting opportunity for future investigation. Additionally, accurate predictions of the effect of various aspects of shared design spaces on stakeholder objectives would greatly enhance the effective assignment of control and responsibility during design process design.

Overall, this author believes that this research is a stepping stone towards the top-down design of design processes, based upon and aided by reliance on existing design process knowledge. The ability to rely upon a repository of design process building blocks will greatly facilitate the original, adaptive, derivative and variant design of products and serve as a springboard for the effective evolution of product portfolios by engineering enterprise. The potential of these concepts can be leveraged further by formalizing tie ins with research efforts stemming from the domains of Product Lifecycle Management (PLM) and Supply Chain Management (SCM), especially in light of recent trends in moving beyond Activity Based Costing (ABC) towards Activity Based

Management (ABM). Though many of these movements are focused on manufacturing activities, their active integration into engineering design is only a matter of time. As access to information improves and systems become increasingly capable of taking full advantage, the management of design processes, where the majority resources are committed is imminent. With this in mind, the template-based means of modeling decision-centric design processes provide a solid foundation for serving as a springboard. This is especially true in light of the fact that decisions (as constructs) are domain independent. Additionally, inherent facility promotes interfacing these constructs with decisions (both at the same and at differing hierarchical levels) on one hand and with myriad sources of data on the other. The vision in this regard would be to move beyond the realization of the design equation towards its integration with an enterprise resource management equation. In this vein, interesting opportunities may emerge from the integration of real options analysis and portfolio management into strategic meta-design.

9.5 A SUMMARY OF THE DISSERTATION

Often, design problems are coupled and their concurrent resolution by interacting stakeholders is required. The ensuing interactions are characterized predominantly by degree of interdependence and level of cooperation. Since tradeoffs, made within and among sub-systems, inherently contribute to system level performance, bridging the associated gaps is crucial. With this in mind, effective collaboration, centered on continued communication, concise coordination, and non-biased achievement of system level objectives, as addressed in this dissertation, is becoming increasingly important.

Thus far, research in distributed and decentralized decision-making has focused primarily on conflict resolution. Game theoretic protocols and negotiation tactics have been used extensively as a means of making the required tradeoffs, often in a manner that emphasizes the maximization of stakeholder (personal) payoff over system level performance. More importantly, virtually all of the currently instantiated mechanisms are based upon the *a priori* assumption of the existence of solutions that are acceptable to all interacting parties. No explicit consideration has been given thus far to ensuring the convergence of stakeholder design activities leading up to the coupled decision and the associated determination of values for uncoupled and coupled design parameters. Consequently, unnecessary and costly iteration resulting from mismatched objectives has been quasi unavoidable.

In this dissertation, the author advocates moving beyond *strategic collaboration* towards *co-design*. With this in mind, an alternative coordination mechanism, centered on sharing key pieces of information throughout the process of determining a solution to a coupled system was substantiated. Specifically, the focus was on (1) establishing and assessing collaborative design spaces, (2) identifying and exploring regions of acceptable performance, and (3) preserving stakeholder dominion over design sub-system resolution throughout the duration of a given design process. The fundamental goal in this research is to establish a consistent framework for goal-oriented collaboration that (1) more accurately represents the mechanics underlying product development and (2) facilitates interacting stakeholders in achieving their respective objectives in light of system level priorities. This is accomplished via improved utilization of shared resources and avoidance of unnecessary reductions in design freedom. Comparative performance of the proposed method is established using representative examples of differing complexity.

The novel approach to modeling design processes, discussed in Chapter 3 addresses both the problem of ensuring consistency of representation and alleviation of the increased burden associated with communication intensive interaction models such as those proposed for *co-design* in Chapters 4 and 5. Moreover, it is both representational and computer interpretable. Striking the final tradeoffs in the proposed approach, once mutual acceptability has been assured (see Chapter 4), may be accomplished through a number of mathematical communications protocols for transferring information between decision-makers. The proper protocol may be chosen based upon the nature of the relationship (i.e., independent, dependent, interdependent) and extent of cooperation (e.g., full cooperation, non-cooperation, competition, etc.) between the interacting designers, as well as any enterprise level concerns (e.g., the extent to which information may be shared among the various entities). It is in this regard that the *co-design* alternative to existing coordination mechanisms is offered in Chapter 5.

Although difficult to illustrate in writing, the main benefit of relying on the presented template-based approach is that design process exploration becomes feasible. That is to say, that existing design processes can be adapted through the provision of either *declarative* or *procedural* information. Specifically, product specific aspects can be changed by altering the inputs to any of the templates instantiated, while process specific information can be altered by changing the templates themselves. This is illustrated via the multi-decision-maker design example in Section 3.4. Despite the fact that various coordination mechanisms are explored, the results of which are documented in Table 3-4, making the associated design process changes requires nothing more than instantiating the appropriate interaction template; the decision templates remain untouched. Consequently, design process exploration becomes feasible. This stands in marked contrast to the segregated exploration and independent optimization of design sub-problems, since reliance on the proposed means of modeling makes system-level optimization feasible.

It is important to realize that the methods presented in this dissertation comprise a feasible alternative to currently instantiated protocols. However, they are not mutually exclusive. Instead, any mathematically sound protocol (e.g., Nash, Pareto, and Stackelberg games, as well as negotiations and mathematical optimization) may be incorporated and organizational as well as structural needs accommodated. The aspect that is both crucial and novel is the ability to gain and retain confidence in the existence of a mutually acceptable solution and avoidance of irreconcilable differences throughout the course of the stakeholder relationship.

Recalling the many challenges emanating from the consideration of systems of continuously increasing complexity, the research documented in this dissertation contributes to a more ambitious effort centered on developing a comprehensive, systems-based approach to support interactive, collaborative design and fabrication of multifunctional materials in a distributed product realization environment. Several issues are critical for such collaborative materials design activities, including (1) facilitation and management of collaborative decision-making, (2) robust, secure connection and integration of heterogeneous, distributed software applications and databases, and (3) effective information exchange and integration. These issues are addressed by building upon previously developed intellectual foundations in (a) robust design and concept exploration, (b) multi-objective, collaborative, decision-centric simulation-based design, and (c) decentralized, web-based, distributed computing. While the research conducted by this author is centered primarily on formalizing interactions associated with collaborative efforts in this vein of research, there is significant potential for novel contributions in bridging the gaps associated with connecting qualitative and quantitative aspects on one hand and detailed intricacies with the big picture on the other. Within the grand scheme of the research documented in the dissertations originating in the Systems Realization Laboratory (specifically, Seepersad [204], Panchal [161], Choi [49], Mocko [150], and Fernández [73]) there is consistent trend towards making the required connections in an effort to exceed tomorrow's expectations by conceptualizing and maturing the required frameworks, methods, tools, and technologies today.

Most of these efforts originate from a common set of intellectual foundations starting with Decision Support Problem Technique and building on extensions such as the *Robust Concept Exploration Method* (RCEM) [42,43], a framework for integrating science-based models and experimentation, robust design techniques, and multi-objective design decision-making tools. Scaffolding the elements of such a broad basis facilitates exploring complex, multi-objective, hierarchical, collaborative design spaces using simulation and analysis codes, statistically designed experiments, and fast-analysis meta-models, in conjunction with on-going research in distributed, collaborate design decision-making. The resulting *distributed, collaborative design* approach facilitates integrating design activities via mathematical coordination of the individual decisions of designers and other agents involved in the design process. This approach involves establishing domain-independent decision models or templates, expanding the scope of local decisions, and implementing mathematical coordination mechanisms based on game theory and approximate models of the information and strategies of designers (e.g., [91,100]). The research documented here constitutes an extension of these more fundamental efforts. The boundaries between discrete decisions and tasks are identified as *digital interfaces* in Refs. [76,77]. Process-level digital interfaces facilitate formalized interaction among designers via established communications protocols and pathways for decision- and task-critical information and knowledge. It is at this level that the contributions made in this dissertation are most directly applicable. On a computing level, digital interfaces facilitate identification, conversion, and transfer of relevant information between software applications (including design exploration, simulation, and database agents). In addition, the development of decentralized frameworks for integrating distributed software resources over the internet, such as *X-DPR* [47,48,162], provide a solid foundation for integrating the decision-makers in charge of their management. *X-DPR* is an open computing framework in which engineers can integrate their own software applications, residing on their own machines, with a library of other engineering tools over the internet. Using the *X-DPR* system, multiple designers can model a design process collaboratively using visual tools and execute the process online by connecting tasks with distributed engineering services available in the global library. The research presented by this author addresses the reconciliation of the underlying objectives, thus complementing interoperability on the computational level. It is by integrating and extending these multi-faceted intellectual and computing foundations that the systems-based, materials design approach proposed in Ref. [207,208] is established.

In closing, a number of additional comments regarding the perspectives adopted in this dissertation are in order.

9.6 CLOSING REMARKS

While there is certainty and elegance in mathematical rigor, nothing is absolute in a world "tainted" by subjectivity. It is interesting to note that much of design theory is devoted to prescription via the imposition of structure, rather than the development of methods that more readily accommodate practical considerations associated with engineering. As a result, methods acclaimed for their contributions in one field are often forced on practitioners in another. Fearful of violating the tenets underlying the original concepts, few (if any) allowances are made for differences distinguishing domains of application. Although, this is done in hopes of securing the same advantages, the contrary is the more likely outcome. It is this author's opinion that much more is to be gained from making the proper allowances *a priori* by customizing the methods to the domains in which they are to be applied, rather than forcing the user to customize his or her approach or the problem itself *a posteriori*. The research documented in this dissertation constitutes a compromise between what is mathematically correct and what is computationally tractable in the world of design, while discounting for practical limitations on available information, sources of uncertainty, and resource constraints, making all required assumptions explicit.

With regard to this dissertation, a fundamental challenge lies in the reconciliation of the potential benefits of ensuring mathematical rigor with regard to the reflection of stakeholder preferences (via utility theory) and strategies (via BRCs), inherent in the application of decision theory and game theory, with the strict and impractical demands placed on their implementation. Everything comes at a price and it is asserted that no theoretical proposition is comprehensive enough to allow for *carte blanche* application in every context. Thus, while principles, quasi fundamental to the study of decision-making in economics, cannot be refuted in light of the assumptions underlying their inception, their application in the realm of engineering design requires a certain degree of adaptation. Every sufficiently verified and validated theory constitutes a contribution to a constantly evolving knowledge base. It is the responsibility of the research community to be sufficiently open minded to appreciate inherent potential and judicious enough to recognize limitations and shortcomings of all such contributions, especially when these constitute an attempt at reconciling theory with practice. Further advances in the field of engineering design are contingent upon the evolution of the existing knowledge base, possible only through acceptance, vision, and the courage to continuously challenge and at times defy the artificial boundaries of the dominant paradigm of accepted thought. Continuous progress requires a consistent effort and is thus ensured only through evolution, revolutions being few and far between.

In this section the theoretical foundations of the proposed **F**ramework for **A**gile **C**ollaboration in **E**ngineering are both explored and delineated. The underlying purpose is to clarify the stance taken and justify any divergence from the mainstream. With this in mind, core concepts, stemming from the various disciplines upon which this research draws and their specific interpretation in this body of work are reviewed.

9.6.1 On Mutual Trust and Rules for Collaboration

One of the most fundamental notions to economics is that of equilibrium, usually defined as “a condition in which all acting influences are canceled by others, resulting in a stable, balanced, or unchanging system” [2]. A fundamental mechanism for effectively resolving associated conflicts is that of game theory. An *equilibrium* of a game then is an outcome in which the strategies adopted by the players are jointly self-supporting. The common view takes equilibrium to be the *Nash equilibrium*. The notion of such an equilibrium (at least in games of strategic form), however, hinges on many assumptions, many of which can be traced to the consideration of a static state of the world - a snapshot in time. It should thus come as no surprise that research relating to decentralized design activities, thus far have been directed at minimizing interactions among collaborating stakeholders. This perspective, however, is not representative of the increasingly dynamic nature of interactions within globalized engineering enterprise. This is especially true in light of increasingly federalized value chains that are no longer reminiscent of yesterdays highly static vertically and horizontally integrated businesses.

In order to remain competitive in a consistently changing environment, what is required is the development and propagation of *mutual trust* as a basis for conducting business. According to Philip Evans and Bob Wolf, “we spend more money negotiating and enforcing transactions that we do fulfilling them” [69]. In fact, they estimate that the cost of cash transactions in 2000 alone accounted for over half of the US GDP on a non-governmental basis. “We spend more money [and time] negotiating and enforcing transactions than we do fulfilling them.” As exemplified by the commonly cited examples of the Toyota Motor Company and the Linux community, agreements can indeed be enforced by *mutual trust*, rather than via sanction of legal contract or legitimized authority. The result is a significant reduction in transaction costs. Evans and Wolf point out that while operation on the basis of *mutual trust* is not a recent phenomenon, the extent of its reach is. It is becoming increasingly commonplace for strangers and even competitors to operate on the basis of trust, perhaps indicative of the emergence of a new paradigm for conducting business that is focused more on intricate relationships and coalitions, boldly treading the expansive grey spanning the divide between the more traditional black and white. The formula for success in this new breed of community, where most interactions occur on small exchanges rather than a comprehensive network, is based on reaching the *inner circle of trust*.

> *"And of course, where trust is the currency, reputation is a source of power. In a sparse network, such as most markets and hierarchies, power derives from controlling or brokering the flow of information and often, therefore, from restricting it. In a dense network, however, information simply flows around the would-be choke point. Under those circumstances, there is more power in being an information source than an information sink. Consequently, individuals are motivated to maximize both the visibility of their network and their connections to those who are themselves broadly connected. That, in turn, feeds the information density of the network." [69]*

It is precisely this new and emerging manner of conducting business that the means and methods promoted in this dissertation is meant to address. In the face of a society where technology is rapidly eroding traditional barriers, as ominously pointed out by Thomas Friedman in his latest futuristic/presentist book entitled The *World Is Flat: A Brief History of the Twenty-first Century* [85], the only means of staying competitive is via adaptation. Technology that has placed virtually any and all information at our fingertips has shrunk the world in manner that makes people, physically located at opposite ends of the world, neighbors. The net effect is inevitable sourcing driven by the most basic and powerful factor of all cost. It is only through managing relationships and collaborating in the manner most effectively taking advantage of globally distributed resources that long term economic survival is possible. As developing nations effectively leapfrog those that used to lead them (in the not so distant past) by embracing and exploiting information technologies, we must evolve our own core competencies and adapt. As our future lies in the balance, we must shift our focus from smaller to bigger pictures, shift from micro- to macro-management, and focus on research, rather than development. In terms of engineering, our core competency will lie in our ability to *design* design processes so that they are modular, openly expandable, adaptable, and efficient. More importantly, however, we will have to manage the relationships associated with their execution by facilitating, supporting, and guiding the required interactions. The future revolves around and centers on information. It is in the manipulation of data, the extraction of information flows, and the dissemination (and or administration) of knowledge that the next revolution dawns. Considering that the playing field has once again been leveled, our fate lies in the balance. It is through harnessing the full potential of globally sourced resources by consistently striking the proper compromises that we may best realize our potential and assume a dominant role in a new world where the rules of yesterday no longer apply. We must thus adapt, continue to innovate, adapt, and innovate…

> *It is in the interstices of the human network – rather than in the minds of a few wunderkinder – that most real innovations are born. And so it is transaction costs that constrain innovation by constraining opportunities to share different and conflicting ideas, skills, and prejudices. "Detroit people are far more talented than people at Toyota," remarks Toyota president Fujio Cho, with excessive modesty." But we take averagely*

> *talented people and make them work as spectacular teams." The network, in other words, is the innovator. [69]*

Thus far, it can be said that trust has not constituted a viable substitute for contractually guaranteed obligations and highly hierarchical relationships of authority. Clearly, the limits of hierarchical organizations are closely tied to the overall size of the associated organizations. It is for this reason that larger organizations tends to be more inefficient than smaller ones…doesn't scale well. Need a more modular approach to deal with increasingly federalized architectures. Self-assessment and independence are more highly valued, supporting independence, concurrent and congruent activities rather than sequentialized redundancy and inefficiency. As a whole, it time will tell whether organizations that supplant trust for contracts can gain more from collaboration than they stand to lose from loss of bargaining power. The hypothesized by Evans and Wolf, *low transaction costs will buy more innovation than high monetary incentives*. Thus, "…a dense, self-organizing network is prerequisite of large-scale trust. Large-scale trust drives down transaction costs. Low transaction costs, in turn, enable lots of small transactions, which create a cumulatively deepening, self organized network" [69]. The **F**ramework for **A**gile **C**ollaboration in **E**ngineering, presented here, comprises a first step towards realizing this vision. As underscored by the Toyota Production System and the Linux Community, this alternative to existing *modi operandi* is not only viable, but highly successful. In fact, it is this alternative that may in time prove to become the dominant paradigm.

9.6.2 On Rationality and its Bounds

Much of the content in this dissertation builds upon advances made within the context of the Decision Support Problem Technique. All achievements that have emanated from its proponents, however, are grounded in the work of a true visionary, a polymath, who made his mark on a number of fields such as cognitive psychology, computer science, economics and philosophy - Herbert Simon (June 15, 1916–February 9, 2001). Simon is perhaps most famous for coining the terms *bounded rationality* and *satisficing* [218,219,221]. It is precisely upon these concepts that much of the work presented in this dissertation draws.

Bounded rationality stems from a reaction to the basic and, perhaps unrealistic, assumption of *hyper-rationality*, common to much of economic theory. In short, the prevalent assumption in much of social science (especially *rational choice theory*) is that the behavior of *rational* human entities, can be aptly defined by strict adherence to a set of axioms and that such agents would never do anything in opposition to their preferences. Many of these principles have been translated to AI. What Simon points out is that most human beings are only rational by degrees, being emotional or irrational in the remainder of their actions [220]. *Rationality* thus has its bounds and "…boundedly rational agents experience limits in formulating and solving complex problems and in processing (receiving, storing, retrieving, transmitting) information" [261]. Most importantly, such agents are only as rational as required by the realities they face, relaxing their rationality outside of the constraints (i.e., time, resources, information, etc.) placed upon them. Considering that resources are limited, perfect knowledge is quasi impossible to attain, and uncertainties abound, optimization in the traditional sense is nonsensical. It is much more realistic for entities to seek out minimum levels of variables, after the achievement of which attention is focused on the attainment of other goals. The implied paradigm shift is one of seeking out solutions that are not necessarily the best, but nevertheless good enough – in a sense *satisficing* instead of *optimizing*. In the context of economics, *satisficing* behavior is characterized by seeking minimum levels of variables, rather than striving for the optimal values possible. In cybernetics, the "theoretical study of communication and control processes in biological, mechanical, and electronic systems" [2], *satisficing* is optimization taking into active consideration the costs of optimization and obtaining information (also called *information economics*). In the context of engineering design as presented in this dissertation, *bounded rationality* focuses on the search for an optimal solution (in the mathematical sense) within a sub-range of a problem's solution space, as defined according to the decision-maker's best estimate of the true region of interest in the case of *compromise* decisions and knowledge regarding the viability of alternatives in the case of *selection* decisions. A solution determined in this nature is said to be *satisficing* - superior but not optimal from the system's perspective.

The fundamental premise is that the quality of our decisions cannot exceed that afforded us by our options. The key resource in engineering practice is information. No resource is infinite, however, and as a result scarcity is a fact of life. According to Simon, "… it is a task of rationality to allocate scarce things. Performing that task is the focal concern of economics" [221]. Much of economics is concerned with human behavior or, more precisely, *rational* human behavior. Rationality is commonly defined as *the state of having good sense and sound judgment* or *the quality of being consistent* *with or based on logic* [185]. Simon asserts that economics "…exhibits in purest form the artificial component in human behavior…the outer environment is defined by the behavior of other individuals…the inner environment is defined by an individual's goals and capabilities for rational, adaptive behavior" [221]. Economics thus illustrates quite well the interactions among inner and outer environments, in particular "…how an intelligent system's adjustment to its outer environment (its *substantiative rationality*) is limited by its ability, through knowledge and computation, to discover appropriate adaptive behavior (its *procedural rationality*)" [221]. This line of reasoning, aptly describes the circumstances faced by stakeholders engaged in decentralized design – individual objectives and preference structures, subject to shared control and limited, common resources. Increasing the realism in modeling a given situation forces a shift in solution strategy from *substantiative rationality* (choosing the right course of action) to *procedural rationality* (finding approximately the specifics of a good course of action). A logical consequence of this shift is increased reliance on estimation under uncertainty and computational load.

In this dissertation the dimension with regard to which it is the author's prime goal to increase the amount of realism is that of interactions in engineering design processes. With this in mind, the focus is on supporting both the *substantiative* and *procedural rationality* of collaborating decision-makers. This objective is accomplished by drawing on principles from a number of different fields, ranging from engineering science to social science, specifically that branch of social science that deals with the production, distribution, and consumption of goods and services as well as their management [185], namely *economics*. With this in mind, the discussion turns to the role of *decision theory* and *utility theory* (Section 9.6.3), as well as *game theory* (Section 9.6.4) in modeling the rational aspects of interactions in engineering design.

9.6.3 On Decision Theory and Utility Theory

Decision theory is defined as an interdisciplinary area of study, related and of interest to practitioners in mathematics, statistics, economics, philosophy, management, psychology [and engineering design]. It is concerned with the optimal decisions to be taken under particular circumstances [8]. Although there are a good number of social scientists focusing on the manner in which people actually make decisions (i.e., a *positive* or *descriptive* discipline), most decision theory is *prescriptive* or *normative* in nature. Associated goals center on the identification of optimal decisions for given scenarios. In order to support the development of a *normative* thesis, certain assumptions regarding optimal behavior are required. Often these posits center on the concept of *rationality*. Such is the case in *utility theory*, where decision-maker rationale is governed by sets of axioms, such as those later on in this Section. Other assumptions, commonly made, include perfect knowledge (complete information) and total accuracy. Considering that optimal decisions (resulting from *normative* behavior) often result in hypotheses that are tested against actual behavior, the *descriptive* and *prescriptive* aspects of decision theory are necessarily closely linked. With this in mind, it is a fundamental goal of this research to reconcile both notions by creating a *normative* means of decision support that is nevertheless reflective of human behavior and practical considerations in anticipation of future organizational trends.

There are certain archetypes of decisions that have been historically considered to require a theory. Exemplars include *inter-temporal choice* (i.e., different actions leading to different outcomes, realized at different points in time) and *complex choice*. Two archetypes are of primary importance in this dissertation. The first is *choice among incommensurable quantities* – the subject of microeconomics. Although it is seldom considered under the heading of decision theory, it is nevertheless the subject of many of the issues considered within decision theory. In engineering design, examples include any tradeoffs made between competing objectives (i.e., quantities measured on different scales and not always comparable using a common monetary denominator). The second archetype is that *choice under uncertainty*. This subject comprises the central matter of decision theory. The most common application in engineering design, center on the challenge of evaluating tradeoffs among alternatives, characterized by differences in performance as well as variability associated with that performance. Such *choice under uncertainty* is addressed predominantly through the use of *utility theory*. Although it is noted that uncertainty, despite its importance on the subject at hand, is not treated explicitly in this dissertation. Nevertheless, in the event that risk can be numerically bounded, it is readily incorporated into the decision-making process via the calculation of *expected utility* based on assessed preferences.

The concept of *utility* is generally defined as a measure of satisfaction or happiness associated with a particular outcome. A central concept in the treatment of utility is that of uncertainty. The utility of different alternatives to a particular decision-maker is then evaluated in light of the risk associated with pursuing those options. Mitigation of risk, however, requires the ability to quantify that risk, traditionally treated through *probability theory*. In more recent years, the proponents of *Dempster-Shafer theory, possibility theory*, and *fuzzy logic* have maintained that *probability* comprises only one of many possible alternatives for the expression of stochastic uncertainty. It is important to note that the roots, nature, and most appropriate means of quantification of uncertainty in engineering design are not focused upon in this dissertation, although its prevalence is recognized.

One of the main distinctions between different measures of utility in the study of economics is whether they are *ordinal* or *cardinal* in nature. *Ordinal utilities* describe an individual's preferences clearly, but not uniquely. That is to say that they can be subjected to any monotonically increasing function, while still describing the same preferences [8]. The quantitative comparison of one person's preferences to those of another or the amalgamation of preferences is thus not possible. Ordinal utilities do allow for the listing of alternatives in order of preference, however. *Cardinal utilities*, on the other hand, are in line with the original view of utility (discussed later on) as a measurable quantity that can be aggregated across individuals. A drawback is that cardinal utility lacks an objective means of reconciling different values attributed to the same commodity by different individuals. It is for this reason that utility was abandoned as a foundation for analyzing economic behavior in *neoclassical economics* and its focus was shifted to the study of indifference curves (which serve as a basis for determining the ordinal utility of market baskets; only the relative ordering of preferences is considered). Any numerical values in this context are only used for the establishment of said order.

Another critical distinction, usually made in the treatment of utility theory, is based on whether *objective* and *subjective* interpretations of probability are adopted. The *objectivist* (or frequentist as it is more commonly known) perspective considers events to be strictly impersonal and repetitive. Consequently, probabilities are assigned (according to their relative frequencies of occurrence) only to those events that are considered to be random. The *subjectivist* (or Bayesian) school of thought is based on the assignment of probabilities to uncertain events based upon degrees of belief (either personal or logically justifiable). In the context of engineering design, we must consider that both of these perspectives, despite their virtually diametrical opposition, play a key role. The efforts of engineers are fundamentally scientific in nature. Nevertheless, in the absence of sufficient data to establish long-run frequency of occurrence, a significant amount of insight is required. This is usually referred to as engineering judgment and constitutes the fundamental premise behind engaging and deferring to the acumen of domain experts. It is also this element of inference that distinguishing engineering from pure (and less applied) science. Savage [196] espoused a more *subjective* view of the concept of probability that takes into consideration vagueness and interpersonal differences. This stands in marked contrast to the *frequentist* interpretation of the concept, advocated by von Neumann and Morgenstern [252] in their treatment of utility. Other terms considered for the concept of *subjective probability* by Savage were *personal probability*, *psychological probability*, and *degree of conviction*.

Savage defines a utility as follows: "A utility is a function U associating real numbers with consequences in such a way that, if $f = \sum p_i f_i$ and $g = \sum \sigma_j g_j$; then $f \leq g$, if and only if $\sum p_i U(f_i) = \sum \sigma_j U(g_j)$" or, rewritten, $U[f] \leq U[g]$. The reader is referred to Table 9-1 for the Savage Axioms of Utility.

Table 9-1- Savage's Postulates of a Personalistic Theory of Decision

Postulates of a Personalistic Theory of Decision [196]

P1	The relation $\leq$ is a simple ordering.
D1	$f \leq g$ given B, if and only if $f' \leq g'$ for every f' and g' that agree with f and g, respectively, on B and with each other on $\sim B$ and $g' \leq f'$ either for all such pairs or for none.
P2	For every f, g, and B, $f \leq g$ given B or $g \leq f$ given B.
D2	$g \leq g'$; if and only if $f \leq f'$, when $f(s) = g$, $f'(s) = g'$ for every $s \in S$.
D3	B is null, if and only if $f \leq g$ given B for every f, g.
P3	If $f(s) = g$, $f'(s) = g'$ for every $s \in B$, and B is not null; then $f \leq f'$ given B, if and only if $g \leq g'$.
D4	$A \leq B$; if and only if $f_A \leq f_B$ or $g \leq g'$ for every f_A, f_B, g, g' such that: $f_A(s) = g$ for $s \in A$, $f_A(s) = g'$ for $s \in\sim A$, $f_B(s) = g$, for $s \in B$, $f_B(s) = g'$ for $s \in\sim B$.
P4	For every A, B, $A \leq B$ or $B \leq A$.
P5	It is false that, for every f, f', $f \leq f'$.
P6	Suppose it false that $g \leq h$; then, for every f, there is a (finite) partition of S such that, if g' agrees with g and h' agrees with h except on an arbitrary element of the partition, g' and h' being equal to f there, then it will be false that $g' \leq h$ or $g \leq h'$.
D5	$f \leq g$ given B ($g \leq f$ given B); if and only if $f \leq h$ given B ($h \leq f$ given B), when $h(s) = g$ for every s.
P7	If $f \leq g(s)$ given B ($g(s) \leq f$ given B) for every $s \in B$, then $f \leq g$ given B ($g \leq f$ given B).

An alternate view is offered by von Neumann and Morgenstern in their classic text *Theory of Games and Economic Behavior* [252]. In this book, von Neumann and Morgenstern investigate the foundations of the study of economic behavior, rooted in the concept of rational individuals who act to maximize their individual utilities. The focus in the text is on finding "the mathematically complete principles which define 'rational behavior' for the participants in a social economy, and to derive from them the general characteristics of that behavior." In other words, the authors sought a set of rules for each participant telling him/her how he/she ought to behave in social economic situations in which participants must enter into relations of exchange with others, and thus, each participant attempts to maximize a function (i.e., the result of the exchange, or utility) of which he/she does not control all of the variables. The result was the underpinnings of modern *game theory*. Along the way, the authors needed to quantify the notion of preference beyond that of their contemporaries. At the time, 'utility' as a measure of the preference of one object or aggregate of objects over another was limited to ordinal scales in practice although it was originally conceived as a cardinal quantitative measure (see below). In other words, utility (in the form of indifference curves) permitted economists to indicate *whether* a single person's utility for one object was greater than his/her utility for another, but there was no basis for numerical comparison of utilities to indicate *by how much* an object was preferred over another. However, in developing a theory of games and economic exchange and interaction, von Neumann and Morgenstern were concerned with determining *how much* an individual participant could get if he/she behaved rationally so that what the rational individual in an interactive situation strives for could be described fully in one numerical datum (or utility). They wished to develop *cardinal* utility measures.

To suggest the possibility of developing cardinal utility functions, von Neumann and Morgenstern described two assumptions that lead to the possibility of numerically measurable utilities. First, assume that an individual has a complete set of preferences. In other words, given any two outcomes, an individual should be able to tell which of the two outcomes he/she prefers. For example, given three outcomes A, B, and C, an individual should be able to state whether he/she prefers A over B over C or A over C over B, etc. Second, assume that the individual can compare not only individual events but also events combined with stated probabilities. A 50%-50% combination of outcomes B and C, for example, would be the prospect of seeing B occur with a probability of 50% and C occur with a probability of 50% (with B and C mutually exclusive events). Thus, we assume that an individual can state whether he/she prefers the event A to the 50%-50% combination of B and C or vise versa. If the individual prefers A to B to C, then he/she will prefer A to the combination of B and C. If, on the other hand, he/she prefers C to A to B, then an assessment of his/her preferences for A against the combination of B and C contains new information. For example, if he/she prefers A to the combination of B and C, then his/her preference for A over B is greater than his/her preference for C over A. In this manner, utilities (or differences of utilities) can be measured.

A fundamental assumption behind von Neumann and Morgenstern's argument is that if events can be combined with probabilities, then the same must be true for the utilities attached to them. Thus, von Neumann and Morgenstern assert that there are two requirements for a correspondence between measures of outcomes and a numerical valuation of utility (u): $b \succ c$ implies $u(b) > u(c)$, where $\succ$ denotes 'is preferred to' and $u(\alpha b + (1-\alpha)c) = \alpha u(b) + (1-\alpha)u(c)$, where $\succ$ denotes 'is preferred to', b and c are potential outcomes of a decision, and α is a numerical probability. If these two properties hold for a *utility function*, then *utility* is determined up to a linear transformation. In loose terms, *utility* is then a *cardinal* rather than an *ordinal* function.

In order to demonstrate that *utility functions* do indeed exist, it is necessary to postulate a set of axioms (see Table 9-2 or

Table 9-1) that in effect define the "rationality" of the individual. That is to say that adherence of ones preferences to the rules set by the axioms, guarantees the existence of a utility function. This utility function then has the favorable property of assigning numerical utilities to all possible outcomes, such that the best course of action for the individual is the one with the highest expected utility.

The power of utility theory as a guide to consistent decision making thus rests in the ***expected utility theorem***. Slightly different versions of the expected utility theorem may be found throughout the literature (e.g., [130], [114]). It is described by Keeney and Raiffa as follows: "If an appropriate utility is assigned to each possible consequence and the expected utility of each alternative is calculated, then the best course of action is the alternative with the highest *expected utility*." By assigning appropriate utilities to all possible consequences using an appropriate numerical utility function, alternatives can be rank ordered by expected utility, and a decision maker's preferred course of action is the one corresponding to the highest expected utility.

When making a decision, the first step is to develop a value or utility function that assigns appropriate utilities to all possible consequences. If consequences are described in terms of probability distributions, then the expected utility of each consequence should be calculated based on the utility function and the probability distributions. If the outcome of an alternative, $\underline{X}_i$, can be described by a single attribute A_1, with probability density function $f_p(A_1(\underline{X}_i)$ as described in Equation 2.1, its expected utility may be calculated as:

$$E[u(A_1(\underline{X}_i))] = \int u(A_1(\underline{X}_i))f_p(A_1(\underline{X}_i))dA_1 \qquad (9.1)$$

If an alternative leads to a discrete set of *b* possible outcomes, again described by a single attribute A_1 with probability density described in Equation 2.2, the expected utility may be calculated as:

$$E[u(A_1(\underline{X}_i))] = \sum_{k=1}^{b} p_k u_k (A_1(\underline{X}_i)_k) \tag{9.2}$$

The challenge here is in assigning *appropriate* utilities and a corresponding *appropriate* utility function. Other frameworks, implying the existence of utilities with the desirable property that expected utility might be employed as a guide for preference consistent decision-making, have been proposed by Luce and Raiffa [130] and Fishburn [83].

Table 9-2 - The Von Neumann and Morgenstern Axioms of Utility [252]

The system **X** of entities, $X_1, X_2, X_3, \ldots, X_n$ with α and β on the open interval (0,1).	
Axiom 1	
$X_i \succ X_j$ is a complete ordering of **X**. This means write $X_j \prec X_i$ when $X_i \succ X_j$.	
Axiom 1:a	Then for any two X_i, X_j one and only one of the three following relations holds: $X_i \sim X_j$, $X_i \succ X_j$, $X_i \prec X_j$.
Axiom 1:b	If $X_i \succ X_j$ and $X_j \succ X_k$ then $X_i \succ X_k$.
Axiom 2	
Axiom 2:a	$X_i \prec X_j$ implies that $X_i \prec \alpha X_i + (1-\alpha) X_j$.
Axiom 2:b	$X_i \succ X_j$ implies that $X_i \succ \alpha X_i + (1-\alpha) X_j$.
Axiom 2:c	$X_i \prec X_j \prec X_k$ implies the existence of an α with $\alpha X_i + (1-\alpha) X_k \prec X_j$.
Axiom 2:d	$X_i \succ X_j \succ X_k$ implies the existence of an α with $\alpha X_i + (1-\alpha) X_k \succ X_j$.
Axiom 3	
Axiom 3:a	$\alpha X_i + (1-\alpha) X_k \sim (1-\alpha) X_k + \alpha X_i$.
Axiom 3:b	$\alpha(\beta X_i + (1-\beta) X_k + (1-\alpha) X_k \sim \gamma X_i + (1-\gamma) X_k$ where $\gamma = \alpha\beta$.

It is important to note that it is only the quantification of risk (either *objectively* or *subjectively*) that allows for the determination of an action's *expected value*. The expectation of a (random) action is ascertained via the summation of the probability of each possible outcome of that action, multiplied by its corresponding *payoff*. The assertion that this payoff is determined by an individual considering the likelihood of each such state constitutes the *expected utility hypothesis* in economics, as discussed above. Von Neumann and Morgenstern proved that any *normal* preference relation assessed over a finite set of states can be written as an *expected utility* (also called von-Neumann Morgenstern utility). The concept of *Subjective Expected Utility* (SEU), brought forth by Savage, combines two distinct *subjective* concepts – (1) a personal utility function and (2) a personal probability analysis based on Bayesian (rather than a frequentist) probability theory. Some of the fundamental criticisms for the application of utility as descriptors of preference are the difficulties inherent in estimating utility payoffs. In the context of *behavioral economics* it has been shown that consumers have a higher degree of loss aversion than they have for an equivalent gain. This discrepancy is supported more closely through adherence to Savage's axioms, given in Table 9-1.

It is important to note that, although the calculation of *expected utility* remains essentially the same regardless of whether the uncertainty associated with disparate acts is modeled *objectively* or *subjectively*, the underlying philosophy is fundamentally different. Thus, while a more *objective* view of utility makes sense in the realm of economics where most consequences can be reduced in terms of monetary gains (i.e., *payoffs*), the preferences of collaborating designers, each assigned responsibility for a coupled design sub-problem based on domain expertise, can benefit from a more personalized or *subjective* interpretation, depending on the amount and fidelity of data at their disposal. Additionally, many experiments involving lottery questions have shown individuals to have inconsistent preferences in the face of risk. This is a significant consideration in engineering design where the notion of risk translates not solely to monetary gains, but the potential loss of human life. Further compelling reasons for the adoption of such a *subjective* interpretation follow in Section 9.6.4, regarding the implementation of *game theoretic principles*, where *utility* is usually presented as a function, correlating a player's anticipated *payoff* to his or her *strategy*. Daniel Bernoulli showed that the concept of personal utility provides a more realistic measure of worth by reflecting the variation of a person's risk aversion with that person's initial wealth. It is this basis that is built upon by Savage in his proposition of the concept of *Subjective Expected Utility* (SEU) in 1954. The notion of initial wealth is correlated with the overall performance potential in this dissertation.

9.6.4 On Game Theory and its Application in Engineering Design

Game theory is a branch of applied mathematics that makes use of models to study interactions with formalized incentive structures [8]. More commonly, it is defined as *a theory of competition stated in terms of gains and losses among opposing players* [185] or *a mathematical method of decision-making in which a competitive situation is analyzed to determine the optimal course of action for an interested party* [2]. Von Neumann and Morgenstern are credited with introducing the subject of game theory in their book *The Theory of Games and Economic Behavior* [252] in which they also provide their treatment on the subject of decision theory in terms of *utility*, as discussed in Section 9.6.3. Mostly as a result of their drastically distinct mode of analysis in the first and second parts of their book, the most notable line drawn in game theory persists between *cooperative* and *non-cooperative* behavior. *Non-cooperative* game theory is characterized by the explicit and complete description of rules and close examination of strategies espoused by interacting players. The goal is to find solutions comprised of suitable pairs of equilibrium strategies. It is considered to be the more fundamental of the two branches [29]. *Cooperative* game theory takes a less blueprinted approach and focuses on situations where players are able to negotiate and assess their respective tradeoffs *a priori*. Often it is assumed that negotiations can be concluded through the use of *binding agreements*. In this case, the nature of precise *strategies* available does not matter much and it is the underlying *preference* structure that comes to bear [29].

According to von Neumann and Morgenstern, the most a game theorist can state about the outcome of a *cooperative* game is that the result will lie somewhere in the *bargaining set*, defined to be the set of all individually rational, *Pareto efficient* payoff pairs in a cooperative payoff region. The idea of a *bargaining set* is closely related to the notion of a contract curve introduced by the economist Edgeworth. It is also closely related to the two-player case of the *core* as defined in *cooperative game theory* [29]. The definition of *Pareto efficiency* is as follows: A change that can make at least one individual better off, without making any other individual worse off is called a *Pareto improvement*: an allocation of resources is *Pareto efficient* when no further Pareto improvements can be made [8]. Often *Pareto efficiency* is also referred to as *Pareto optimality*. This is unfortunate as pointed out by Binder, since this suggests that a Pareto optimal point cannot be improved upon [29]. In terms of the balanced solutions sought in this dissertation, this translates to the avoidance of those points along the *Pareto frontier* which are strongly biased towards the achievement of one stakeholder's objectives. A good example is that of a two player *zero sum game*, where stakeholder interests are diametrically opposed and one player's gain is another's loss (i.e., the sum of player payoffs is consistently zero). Mathematically, *Pareto efficiency* is defined as follows: An outcome $s^* \in S$ is said to be Pareto optimal (or Pareto Efficient) if there is no other outcome $s \in S$ satisfying

1. $u_1(s) \geq u_1(s^*)$ and $u_2(s) \geq u_2(s^*)$, and
2. $u_i(s) > u_i(s^*)$ for at least one player *i* [9] .

A *Nash equilibrium*, on the other hand, is a kind of optimal strategy for games involving two or more players, whereby the players reach an outcome to mutual advantage. If there is a set of strategies for a game with the property that no player can benefit by changing his strategy while the other players keep their strategies unchanged, then that set of strategies and the corresponding payoffs constitute a *Nash equilibrium*…A game may have many *Nash equilibria*, or none [8]. Mathematically, a *Nash Equilibrium* of a strategic form game $G = \{S_1,...,S_n,u_i,...,u_n\}$ is a strategy profile $(s_1^*,s_2^*,...,s_n^*)$ such that for each player *i* we have $u_i(s_1^*,...,s_{i-1}^*,s_i^*,s_{i+1}^*,...,s_n^*) \geq u_i(s_1^*,...,s_{i-1}^*,s,s_{i+1}^*,...,s_n^*)$ for all $s \in S_i$ [9].

Another important distinction in *game theory* is typically made between games of *strategic* and *extensive* form. The *strategic* (or *normal*) *form* of a game is a compact representation where players simultaneously choose their strategies. So called *payoff matrices* are often used to present the various strategies among which the players can choose, where each cell corresponds to a possible strategy combination or result of the game. Mathematically, a *strategic form game* (or a *game in normal form*) is simply a set of n persons labeled $1, 2, \ldots, n$ (and referred to as the *players* of the game) such that each player *i* has:

1. A choice set S_i (also known the *strategy set* of player *i;* its elements are called the *strategies* of player *i*), and
2. A *payoff function* $u_i : S_1 \times S_2 \times \cdots \times S_n \longrightarrow \mathbb{R}$ [9].

A classic game that is used to explain game theoretic principles is the *Cournot* duopoly game, where two competing firms, producing identical products, are faced with having to determine their optimal output quantity in order to maximize profits. An interesting outcome of this game is that its *Nash equilibrium* also constitutes the market equilibrium of the duopoly [9].

An *extensive form game* (or a *multistage or sequential game*) is usually defined as any games requiring the sequential actions of multiple players. This stands in marked contrast to the *strategic form* games where interacting parties move concurrently. In *extensive form* games the level of knowledge or awareness of each of the players becomes a distinguishing characteristic. *Sequential games* are games of *perfect information* when every information set is a singleton. Otherwise, they are games of *imperfect information*. "A sequential game of perfect information, therefore, is a sequential game in which a player knows exactly what choices have been made in the game at the time she has to make a choice" [9].

In an n-player sequential game (with perfect or imperfect information) a strategy profile $(s_1^*, s_2^*, \ldots, s_n^*)$ is said to be a *Nash Equilibrium* (or simply and equilibrium) if for each player i we have $u_i(s_1^*,...,s_{i-1}^*,s_i^*,s_{i+1}^*,...,s_n^*) \geq \max_{s \in S_i} u_i(s_1^*,...,s_{i-1}^*,s,s_{i+1}^*,...,s_n^*)$ [9]. A special form of the extensive form non-cooperative game is that resulting from the *Cournot* duopoly model first analyzed by Heinrich von Stackelberg. In the *von Stackelberg* formulation of the duopoly game, published in his 1934 *Marktform und Gleichgewicht*, the quantity chosen by the first firm is now given to the second in making its decision. Interacting parties thus move in sequence, rather than simultaneously as in the *Cournot* duopoly, thereby transforming the game into a *sequential game* with *perfect information*. It seems intuitive that making the first move provides an inherent, strategic advantage. In fact, this often turns out to be the case and has been dubbed the *first mover advantage*. The strategic assignment of this advantage is one of the central themes in this dissertation and explored in great detail. It is noted, that whether moving first is an advantage or a disadvantage depends on whether the "goods" in question are *strategic substitutes* or *strategic complements*. When dealing with *strategic complements* reactions of stakeholders match. That is to say that the reaction to a competitor raising his or her price would be raising ones own price. In the case of *strategic substitutes*, opposite reactions are to be expected. For example, an increase in a competitors preferred quantity would be countered by a decrease in one's own preferred quantity. Overall, competition tends to be more aggressive when dealing with *strategic complements* (i.e., price), rather than with *strategic substitutes* (i.e., quantity). The point worth noting in this regard is that game theory allows for the analysis of interdependencies among stakeholders, where Nash Equilibria constitute the best any stakeholder can do, given actions undertaken by other stakeholders. In sequential interactions (e.g., Stackelberg games), the notion of commitment is an extremely important one since it effectively changes the rules of the game. The consequence is the potential emergence of a first mover's advantage. In this regard it is often helpful to consider second order derivatives. Due to the number of design variables considered in this dissertation and the complexity of the associated paths, traced out in any of the associated design spaces, only absolute magnitudes of first order derivatives are considered in forecasting the nod for any *first mover's advantage*.

Extensive form games are usually analyzed through the use of *game trees*. A primary characteristic of these game trees is that each (decision) node clearly reflects the order in which decisions are made and the information that is available to the player making the decision at that particular node. In the case of *compromise decisions* (over continuous design spaces) the notion of decision points is somewhat altered. Rather than discreet decision points that can be represented effectively in decision trees and game matrices, the corresponding designer strategies are often represented in the form of BRCs or RRSs, as is the practice for games in *strategic form*. The reader will recall that it is compromise decisions that are focused upon primarily in this dissertation.

Ideal games assume the rational behavior of individuals who have significant and mutual knowledge of (1) each other's rationality, (2) personal preferences, and the game they are playing (i.e., the strategic structure of their interactions). *Non-Ideal* games do not meet one or more of these criteria. A *Nash Equilibrium* of an ideal game is an outcome in which each stakeholder adopts a best reply to the others. There are two distinct interpretations of this standard. The *subjective* interpretation states the standard in terms of stakeholder preferences. An outcome thus constitutes a *Nash Equilibrium* if on and only if, given the outcome, no stakeholder prefers another outcome that can be reached through a *unilateral* change in strategy. The *objective* view, on the other hand, states the standard in terms of payoff increases. Consequently, a Nash Equilibrium is reached only when no single stakeholder's change in strategy can produce an increase in that stakeholder's payoff. Although the objective *Nash Equilibrium* is the canonical one, the subjective interpretation constitutes an outcome that is incentive-proof, or free of *subjective* impetuses to changes in strategy [257]. Idealizations in games often result in payoff increases and incentives coinciding, ensuring the agreement of *objective* and *subjective* interpretations.

The situations for which game theoretic protocols are employed in this dissertation, however, though idealized, nevertheless benefit from a *subjective* interpretation of the matter. To emphasize this point, the reader is urged to consider Bernoulli's assertion that the cash value of a person's wealth is not its true, or moral, worth to him or her. "Thus, according to Bernoulli, the dollar that might be precious to a pauper would be nearly worthless to a millionaire – or better, to the pauper himself were he to become a millionaire. Bernoulli then postulates that people do seek to maximize the expected value of moral worth, or what has been called moral expectation" [196]. To put it another way, *everything is relative*. The notion of payoff alone is not sufficient in weighing worth and a more personalistic or subjective interpretation is required. This realization is extremely important in engineering design, where tradeoffs are crucial. It is with a more balanced means of making such interdependent choices that we concern ourselves in this dissertation. Bernoulli developed the example of the pauper and the millionaire further into what has come to be known as the ***law of marginal utility*** in the literature of economics, namely that fixed values of cash wealth typically produce smaller increments of moral wealth as the net cash wealth to which said increment is applied increases. Mathematically speaking, according to Savage [196], this law states that utility as a function of money is a concave function. A rational individual will thus always (1) prefer the status quo to any *fair gamble* (i.e., any random act producing a zero change in net wealth) and (2) be willing to pay a premium in excess of *expected value* as insurance against a loss. The implication here is (1) a *natural risk averseness* that is quite representative of engineering design (as embodied for example in factors of safety, redundancy, and failsafe measures) and (2) a tendency for stakeholders to pursue and fend for the satisfaction of their objectives. Furthermore, Bernoulli postulated as a rule of thumb that the slope of utility as a function of wealth could be considered to be inversely proportional to a person's wealth, specifically that a person's utility is equal to the logarithm (to any base) of that person's cash value, resulting in *Everyman's Utility Function*. The notion of wealth in this discussion translates to the degree to which the design objectives of a particular stakeholder are already being met (i.e., the current value of expected utility). Cash value, on the other hand, corresponds to the net increase in expected utility that results from a given action.

With this in mind, it is noted that Savage asserts that the ***law of marginal utility*** "…plays no fundamental role in the von Neumann-Morgenstern theory of utility, viewed either empirically or normatively. Therefore the possibility is left open that utility as a function of wealth may not be concave, at least in some intervals of wealth" [196]. Since it is a fundamental aim of this work to seek more balanced solutions to coupled design problems, the Savage Axioms of Utility (see Table 9-1) are rendered more appropriate. Furthermore, Savage stresses that "…all theological questions aside, there are no acts of infinite (or minus infinite) utility, and that one might reasonably so postulate, which would amount to assuming utility to be bounded" [196]. This line of reasoning also lends itself to a more physically meaningful interpretation of the consequences of acts associated with engineering design. Non-espousal of the ***law of marginal utility*** is in line with the optimizer's line of reasoning, continuously seeking higher payoffs. Since this dissertation is written in the context of *bounded rationality* and the quest for *satisficing* solutions, the *relative* or *personal* context of utilities is considered to have a significant bearing on stakeholder interactions. This is an especially important point considering that a fundamental aim is that of seeking solutions that are balanced from the systems perspective.

9.6.5 Adding Perspective

Thus, the solution strategy, pursued in this dissertation, is subject to arguments rooted in the concept of *bounded rationality* [221] and stakeholders are well informed about the game in which they participate. Although, there is no critical distinction between *objective* and *subjective* interpretations of the (*Nash*) *Equilibrium*, balanced satisfaction of stakeholder objectives in collaborative design spaces requires consideration of *wealth* (as captured in level of satisfaction of stakeholder preferences) rather than *cash payoffs* (as embodied in unilateral improvements in stakeholder objectives).

In consideration of this, the concept of *small worlds*, emphasized by Savage [196], constitutes a useful analogy to the consideration of design sub-problems given in this dissertation and falls in line with the notion of *bounded rationality*. For Savage, *small worlds* $\overline{S}$ serve the purpose of satisfying the quasi practical necessity of isolating or confining attention to relatively simple or idealized situations (i.e., decisions), the sum total of which constitute the corresponding *grand world* S. To put it another way, the partition of the *grand world* into subsets results in the sum total of *small world* ***states*** $\bar{s}$. Although these are not necessarily finite in number, supposing so is mathematically simpler. *Small world* **acts** $\bar{f}$ are functions, relating *small world* **states** $\bar{s}$ to *small world* **consequences** $\bar{f}$, in turn considered to be equivalent to *grand world* **acts** $\bar{F}$. A set of *grand world* ***acts*** is thus part of the definition of any given *small world*. This relation is quite representative of the manner in which design problems and design sub-problems are related in decentralized design. In this analogy, design sub-problems correspond to small worlds, the decisions related to which result in *small world* ***consequences***, thereby constituting *grand world* ***acts***. *Small world* decisions are functions from states of a sub-problem design space to the corresponding solution space. Since many of the design sub-problem system descriptors are derived from the overarching design problem, these are invariably linked. Clearly, decisions made at the sub-problem level factor into system level performance. This relationship between small and grand worlds and design sub-problems and design problems was illustrated in Figure 1-16. A special kind of small world, (1) satisfying completely the postulates given in Table 9-1, (2) agreeing with a probability $\bar{P}$ such that $\bar{P}(\bar{B}) = \bar{P}([\bar{B}])$ for all $\bar{B} \subset \bar{S}$, and having utility $\bar{U}$ such that $\bar{U}(\bar{f}) = E(\bar{f})$ for all $\bar{f} \in \bar{F}$ is called a *microcosm*. Those that satisfy the postulates but neither admit $\bar{P}$ as their associated probability of occurrence nor $\bar{U}$ as a utility are referred to as *pseudo-microcosms*.

With this in mind, engineering design sub-problems and their reintegration into the overarching design sub-problems, from which they were derived, are focused upon both because this mechanism (1) ensures the continuous alignment of stakeholders with their domains of expertise and (2) closely reflects the dynamics of decentralized design. The general principles behind reliance on *expected utility*, nevertheless apply, however. Decision-makers will tend to favor those acts the *expected utility* of which is as large as possible. In the case of individual decision-makers acting as stakeholders in a problem over which they share responsibility, it is reasonable to assume that the number of acts open to them is finite. Considering that not all interacting stakeholders have complete knowledge of each other's considerations rationality is also relative. The term *considerations* as used in this dissertation implies all the sum of all technical restrictions, constraints, performance targets, objectives, preferences, etc. particular to a stakeholder engaged in the design of an artifact.

9.6.6 Closure

Often, speed, bottleneck avoidance and reliability are identified as motives for distributed problem solving. Design coordination is considered to involve organization and control, integration, and modeling [38] as well as communication, negotiation, and the use of knowledge from practical applications [259]. The importance of coordination in engineering design is emphasized by Coates et al. who state that "…the concurrent engineering perspective does not recognize that the key to achieving optimal design performance is the effective coordination of the design process" and emphasize that "… activities should not necessarily be performed in parallel but rather organized to achieve optimum performance" [56]. This aim is pursued through the strategic sequencing of stakeholders, based on indicators of responsiveness evaluated in the context performance potential. The goal is to avoid wasting shared resources. In the arena of Artificial intelligence, "resource monitoring is identified as an integral requirement of coordination [54,55]. The need to continuously assess the status of available resources, and subsequently act on the information when necessary, is seen as imperative if the resources are to be used in the most effective manner [56]. Andreasen and co-authors [15] cite trends focused on moving away from isolated towards concurrent design process implementations, made increasingly easy through improvement of computational resources, suggesting, however, that:

> "A major shortcoming of the Concurrent Engineering view is the failure to recognize that what is truly required is not for activities to be carried out in parallel but for resources to be effectively utilized in order to carry out tasks for the right reasons, at the right time, to meet the right requirements and give the right results. That is: the key to achieving optimal design performance, and hence design productivity is the effective coordination of the design process" [15].

Another scenario is focused on the distribution of control and required information, thereby providing each agent with a certain degree of autonomy. This is view is "…perhaps more representative of the control mechanisms involved within actual organizations" [259]. A shortcoming of this distribution is that each agent only has a partial perspective of the overarching (global) problem being addressed. Consequently, it is a key concept to empower collaborating entities to amount to more than the sum of their collective parts through structured synergism. This is line with the notion of Cooperative Distributed Problem Solving (CDPS) [62] develops ideas from distributed computing and artificial intelligence, focusing on how multiple intelligent systems collectively solve problems, beyond their individual capabilities. Durfee and Lesser [62] further hypothesize that coordination is not a separate phase in group activity, but rather an integral aspect of decision-making, arising out of local planning and not the provision of a protocol or language to allow entities to communicate. Making collaboration an integral part of stakeholder activities throughout the duration of the resulting relationships promotes this end. As asserted by Jennings, all coordination approaches should ensure that:

> "…that all necessary portions of the overall problem are included in the activities of at least one agent, that agents interact in a manner which permits their activities to be developed and integrated into an overall solution, that team members act in a purposeful and consistent manner, and that all of these objectives are achievable within available computational and resource limitations" [108].

Associated coordination technologies take many forms, ranging from process and conflict management to rationale capture [116]. "Coordination and cooperation are two major concerns in systems involving distributed computers, termed intelligent decisions-making agents, sharing information and resources in order to solve a common set of tasks" [82]. One conclusion in the quest to automate the control mechanisms that once governed how an artifact progressed through its lifecycle however is "…that the control, like the agents, should be distributed" [259]. Consequently, agents in a distributed environment need to be able to adjust to changing circumstances, adapting their roles and responsibilities as required. A certain degree of autonomy is essential for dynamic adaptation and maintaining enterprise agility. It is asserted in this dissertation that although agents are defined to be a resource that is human, software, or hardware, the ultimate decision power should always rest with the human. Retaining stakeholder dominion allows these to manage risks associated with their design sub-problems more effectively and make any required interpretations. System level risk management, however, is not addressed explicitly in this work.

The AI research community recognizes the need for flexibility in process structuring, focusing on continuous monitoring and updating of models based on the evolution of information content. Smith [227] specifies reliability, speed, the ability to handle applications that are characterized by natural spatial distribution, and extensibility as reasons for espousing a distributed approach to problem solving. From a logistic standpoint centralized design suffers from communication bottlenecks and increased potential for complete failure. Scheduling is often viewed as the basis for coordination; in some cases it is considered to be coordination. This is an inherent feature of the sequencing aspect of the decentralized design approach pursued here.

Bullinger and Warschat [35] note that merely increasing concurrency in design by allowing succeeding processes to be started prior to the completion of those processes preceding them increases the amount of uncertain and incomplete information. Additionally, Petrie [181] notices that people loose their ability to maintain a comprehensive picture of design decision-, constraint-, and rationale- history and interplay for even small projects. It is in light of these concerns that PDM solutions have made their debut. Often described as providing the right data, to the right people, at the right points in time, the effective means of leveraging that information into decentralized decision-making has thus far been lacking. It is true that research in coordination has been conducted in a number of fields, the most notable of which are computer science, organization theory, and engineering design. “In reality, a plethora of approaches and computer-aided systems now exist which generally only address individual aspects of coordination in isolation" [56]. Few, however, deal with more than a single aspect simultaneously. Whitfield and co-authors note that domain independent coordination mechanisms must be augmented with domain specific ones to successfully facilitate coordination [259]. Considering that the central focus in this dissertation is on distributed decision-making, coordination mechanisms, and essential rationality, principles originating from the field of economics are drawn upon quite heavily.

The laws of supply and demand are not limited to the realm of economics, but transcend to engineering design as well. Conflict is a closely related notion, typically lax when supply is ample and tense when supply is scant. This is especially true when limited resources are shared among various parties with diverse and likely conflicting interests. In this dissertation, the primary shared resource considered is the design space or, more specifically, the manner in which the corresponding design freedom is allocated among designers, acting as stakeholder in a common design process. The common (system level) design space is defined by shared as well as individual constraints. Stakeholder interests correspond to design sub-problem objectives, which are derived from system level aspirations. Naturally, there is a certain level of trade-off inherent in the solution of coupled design sub-problems. The resulting allocation problem is addressed through the development of a means of agile goal-oriented conflict resolution.

Though many interesting challenges lie in the manner in which systems are best partitioned among interacting stakeholders, *a priori* decomposition is taken as a point of departure in this dissertation. With this in mind, the central issue addressed is that of decentralized resolution of engineering design problems in collaborative, distributed environments. The focus is on structuring designer interactions such that a more balanced resolution of system level tradeoffs is possible. Doing so requires a closer level of cooperation. While this increases the burden placed on the decision-maker in part, stakeholders are no longer required to formulate their responses for every conceivable outcome. Instead their efforts are focalized via the communication of decision critical information content only. This is done in an effort to increase both the efficiency and effectiveness of interactions and stands in marked contrast to the elicitation of *pure (un-randomized) strategies* relied upon traditionally. Since these by definition clearly define actions for each conceivably reachable decision node (point) at which a stakeholder would be required to make a decision if that node were actually to be reached, even games without chance are determined entirely only if all stakeholders select and follow *pure strategies*. In design, such *pure strategies* are often defined in terms of Best Reply Correspondences (BRC) or Rational Reaction Sets (RRS) as implemented in non-cooperative game theoretic resolutions of coupled design problems. Rather than focusing on a potentially endless array of what if scenarios, the chosen approach is centered on identifying mutually acceptable regions of collaborative design spaces, taking as the nexi of stakeholder considerations. The primary means of quantifying and evaluating the suitability of these regions it through consistent reliance on utility functions.

Although always a subject of contention in the field of engineering design there are many undeniable advantages to reliance utility functions in practice. In general, the constructs of utility theory, as used within this research, constitute compromise between absolute mathematical rigor and practical tractability. Their application is rooted in the notion of *bounded rationality* and the attainment of *satisficing* solutions to complex systems, purported by Herbert Simon. Other more recent viewpoints of relevance include those of Yakov Ben-Haim [27], who focuses on representing uncertainty using information gaps rather than probability distributions and reliance on ranged sets of specifications in engineering design, based on the views purported by Simon. In a strict sense, the application of utility theory dictates that a design process should be driven only by preference and consequently negates the existence of bounds, constraints, or other "artificial" restrictions on design freedom, other than those posing clear violations of natural laws. Only implicit bounding of a design space is possible through the use of decision-maker utilities. That is to say that expected utility should be used as a means of filtering out solutions that lie outside of the practical bounds of a problem. In this dissertation, utilities are used as a means of filtering out solutions that do not meet minimum designer requirements. In fact, solutions that are considered to be feasible must meet the minimal requirements of all stakeholder involved in a given design process. However, utilities are formulated in a resource conscious manner. That is to say that although they are regarded as absolute, they are assessed in the context of what is realistically achievable. As such, utilities also serve as a neutral, stakeholder specific means of normalization that personalizes the contributions of shared parameters on objective value achievement. Utilities implemented in this fashion constitute a quantitative basis amalgamating preferences in the spirit of individual stakeholders acting as "benevolent dictators". As defined by Savage, utilities are thus considered as functions **U** that arithmetize the relation of preference among acts [196].

Success is relative. It is what we can make of the mess we have made of things.

T. S. Eliot

A good discussion increases the dimensions of everyone who takes part.

Randolph Bourne, American Author (1886–1918)

The wise man is he who knows the relative value of things.

William Ralph Inge

I not only use all of the brains I have, but all I can borrow.

Woodrow Wilson, 28th President of the United States (1856-1924)

The nature of work is fundamentally changing for today's information workers. We've moved from an era of personal productivity to one of joint productivity. From tightly coupled systems and organizations, to loosely-coupled interconnections between people, business processes and work groups.

- Ray Ozzie, CTO of Microsoft, March 10, 2005

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