INTEGRATING DESIGN AND MANUFACTURING FOR A HIGH SPEED CIVIL TRANSPORT WING

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Abstract

The aerospace industry is currently addressing the problem of integrating design and manufacturing. Because of the difficulties associated with using conventional, procedural techniques and algorithms, it is the authors' belief that the only feasible way to integrate the two concepts is with the development of an appropriate Knowledge-Based System (KBS). The authors propose a methodology for an aircraft producibility assessment, including a KBS, that addresses both procedural and heuristic aspects of integrating design and manufacturing of a High Speed Civil Transport (HSCT) wing. The HSCT was chosen as the focus of this investigation since it is a current NASA/aerospace industry initiative full of technological challenges involving many disciplines. The paper gives a brief background of selected previous supersonic transport studies followed by descriptions of key relevant design and manufacturing methodologies. Georgia Tech's Concurrent Engineering / Integrated Product and Process Development methodology is discussed with reference to this proposed conceptual producibility assessment. Evaluation criteria are presented that relate pertinent product and process parameters to overall product producibility. In addition, the authors' integration methodology and reasons for selecting a KBS to integrate design and manufacturing are presented in this paper. Finally, a proposed KBS is given, as well as statements of future work and overall investigation objectives.

List of Acronyms

ASDL	Aerospace Systems Design Laboratory
ASTROS	Automated STRuctural Optimization System
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CATIA™	Computer-graphics Aided Three-dimensional Interactive Application system
CE	Concurrent Engineering
CLIPS	C Language Integrated Production System
DFM/DFA	Design for Manufacture and Assembly
FLOPS	FLight OPtimization System
HiSAIR	High-Speed Airframe Integration Research
HSCT	High Speed Civil Transport
HSR	High Speed Research
IPPD	Integrated Product and Process Development
KBS	Knowledge Based System
LCC	Life Cycle Cost
MDO	Multidisciplinary Design Optimization
PI	Productivity Index
QFD	Quality Function Deployment
ROI	Return On Investment
Tk/tcl	Toolkit / tool command language
TQM	Total Quality Management
UI	Utilization Index
UPC	Unit Production Cost

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Background

During the mid-1970s, a supersonic transport (SST) preliminary study conducted by the Lockheed-California Company (1) assessed wing tip structural design refinements necessary to meet flutter speed requirements. Several approaches were considered to solve the problem. The principal approach was to provide additional stiffening to the wing tip over and above that provided for strength design. This stiffening was provided primarily by increasing the thickness of the surface structure in the wing tip region, and resulted in a significant mass penalty. An alternate approach for improving the aeroelastic behavior of the wing tip, thereby reducing the mass penalty, was to increase the depth of the wing tip structural box, with due consideration to the associated aerodynamic performance degradation due to increased wave drag. However, results from analysis showed that if the baseline use of titanium for the wing tip structure was retained, an increase in wing tip thickness afforded no significant benefits since the wave drag penalties offset the savings resulting from the reduced surface panel thickness. Another approach to improving the aeroelastic behavior was to change the structural material. It was found that the most significant improvement in performance was achieved with the application of boron-aluminum composite material on the unmodified baseline wing tip. However, the cost and maturity of manufacturing processes for boron-aluminum was considered high-risk. Because advanced materials can be tailored to the various requirements of a particular engineering component, the key to optimizing cost and performance is a fully integrated design process capable of balancing all of the relevant design and manufacturing variables. [2]

Design and Manufacturing Methodologies

Integrated Product and Process Development (IPPD) techniques aimed at assessing producibility can help aircraft designers perform the necessary trade-off studies to design the strongest, lightest, least expensive wing structure that meets the static and dynamic load-carrying requirements for a specified mission. Such a concurrent design requires an integration of design and manufacturing and an optimization process that will consider design trade-offs related to product performance (productivity), utilization, producibility, and support. Design and manufacturing guidelines and constraints are established using the principles and techniques of Concurrent Engineering (CE) to assess the relative importance of parameters related to design and manufacturing processes. The life cycle of aerospace products includes the design phases before production, namely the conceptual, the preliminary, and detail design phases. It is well known that the freedom to alter designs decreases substantially as the design matures from a conceptual level to full scale production. In addition, evidence indicates that the greatest opportunities to influence producibility are in the early design phases. Hence, there is a definite need to incorporate producibility concepts early in a product's design cycle. The High Speed Civil Transport was chosen as the focus of this investigation since it is a current NASA/aerospace industry initiative full of technological challenges involving many disciplines.

Many techniques exist in industry today for product and process quality control that are relevant to the concept of producibility. In addition, several new philosophies have been developed for the purpose of integrating manufacturing [and assembly] considerations into the early design stages. A few of these techniques are discussed here.

Concurrent Engineering / Integrated Product and Process Development

As industries and governments around the world restructure to achieve major quality improvements in order to become more competitive in the world marketplace, the term Concurrent Engineering, or Integrated Product and Process Development, is being used to express the desired environment. CE has been defined as "a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support".[3] CE can be viewed as the implementation arm of the Total Quality Management (TQM) strategy. It can be described as a modern treatment of systems engineering which combines quality engineering methods in a computer integrated environment.

Figure 1 shows a flow diagram for Integrated Product and Process Development during the various design phases. It illustrates in a clockwise flow on the outer circle the hierarchical decomposition activities from the conceptual design system to major component/sub-system, to part/sub-component to manufacturing process. The inner small loops on the right half represent the product design trade iterations. The left half shows the process recomposition activities and the inner loops represent the process design trades. The long outer loop iteration represents what has usually been done in the past since redesign was often required due to product design incompatibilities with manufacturing processes. It is desired to have the ability to make parallel product-process design trades at the system level, as well as the component and part level. This will require filling in the IPPD center box in Figure 1 with methods, tools, knowledge and capabilities necessary for assessing both product and process. The procedure for integrating design and manufacturing entails both product and process design trade iterations. The lowest box in Figure 1, namely Manufacturing Processes, has traditionally been a costly bottleneck in terms of both dollars and schedules. Hence, this constitutes the motivation for the authors' work in this area.

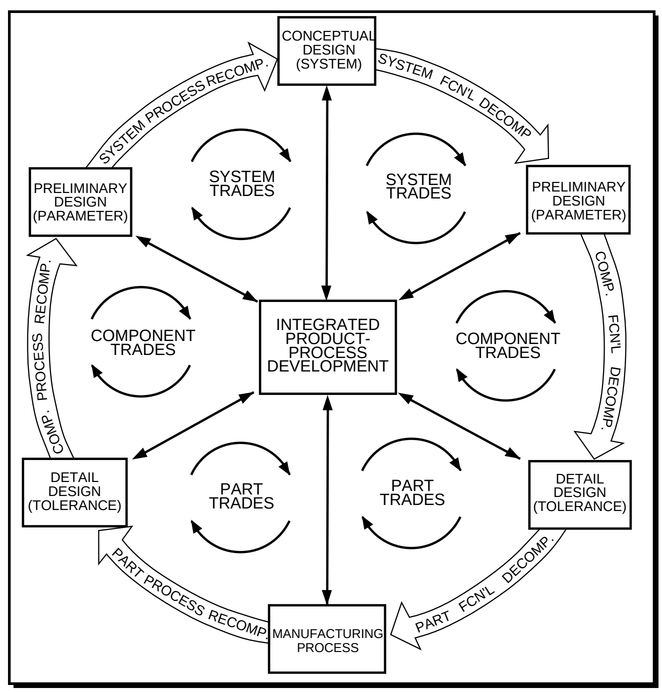

Figure 1: Integrated Product and Process Development

While Figure 1 represents the flow process desired for IPPD, it does not provide the methodology required to implement IPPD. The methodology being developed and utilized at Georgia Tech is illustrated in Figure 2. The methodology in Figure 2 illustrates the interaction of the

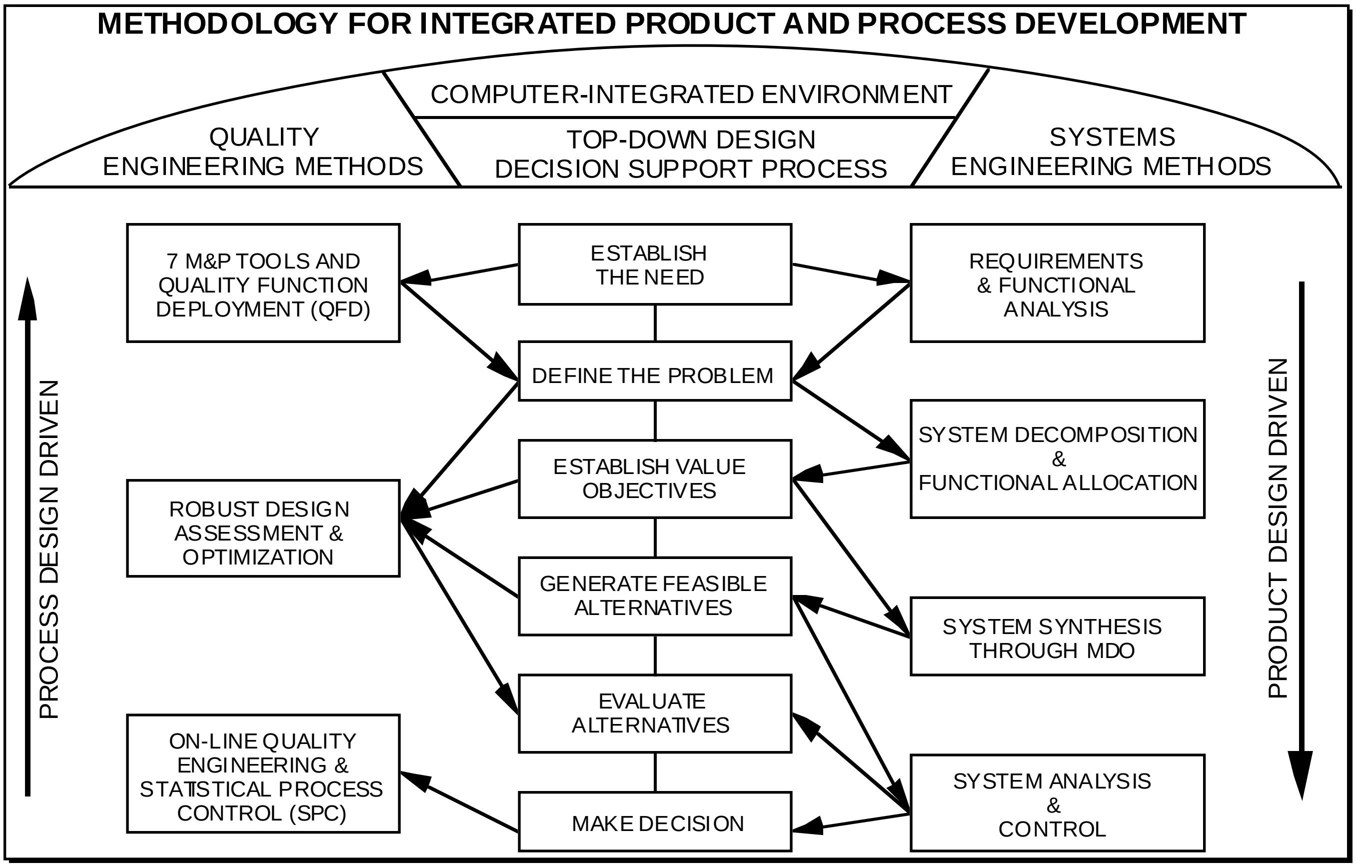

Figure 2: IPPD Methodology at Georgia Tech

four key elements necessary such that parallel product and process trades can be made at the appropriate level of system decomposition and recomposition. Depicted is an "umbrella" with the four key elements: systems engineering methods, quality engineering methods, top down design decision support process, and computer integrated environment. Beneath the umbrella are the interactions necessary for making parallel product and process design trades. The methodology takes advantages of successful methods and tools for both product and process. It should be noted that system synthesis is achieved through the use of MDO to generate feasible alternatives. These feasible alternatives are then evaluated for process robustness using quality engineering methods and a decision made on selecting the best alternative based on the criteria established from the value objectives.

The heart of the CE methodology being used at Georgia Tech is a Top Down Design Decision Support Process. Decision support is an essential element, particularly for management, that is used to focus efforts on the design goals. It supplies a logical, rational means for including factors that must be considered when making a decision. In this case, manufacturing factors must be considered throughout the entire wing design process. The structure is not designed to restrict thinking, but to organize it and ensure its completeness. Since design can be viewed as an iterative decision making process, it can be described as a sequence of steps. Trades at the *system and component level* using information from *component and part level* trades are considered essential if an integrated design and manufacturing approach is to take place.

Design for Manufacture / Design for Assembly

Design for Assembly (DFA) evolved from the need to consider assembly problems in the early design stages. DFM/DFA is a method for simplifying a design so that a part [or component] can be manufactured in the most efficient manner. The technique is also based on selection of the best assembly method (manual, flexible, or automatic) and reducing the total number of parts. The DFA characteristics of a component have a direct relationship to the product's overall producibility.

Quality Function Deployment

Quality Function Deployment (QFD) is a product [and process] development technique that emphasizes customer requirements in engineering system design. It is a rational, sequential system for translating customer requirements into company requirements for all stages of the product from research and development to full-scale production and marketing/distribution. QFD is a philosophy that helps ensure that the important objectives of quality, cost, and timeliness are retained and translated through product development.

Evaluation Criteria

Several criteria can be used to relate pertinent product and process parameters to overall product producibility. Also, the criteria can be used to make trade-offs in evaluating alternative HSCT wing structural designs.

Productivity Index

The first criterion is called the Productivity Index (PI); it relates design parameters to economic feasibility elements and is defined as:

$$PI = \frac{pl \times V_{block}}{W_{empty} + W_{fuel}} \tag{1}$$

where:
- pl payload
- V_{block} block speed
- W_{empty} aircraft empty weight
- W_{fuel} fuel weight

Traditionally, productivity by itself has been just a measure of a commercial aircraft's performance capability. The limiting case for the PI, i.e. when the block speed and payload are constant, is essentially equivalent to the gross weight. The PI has been applied as an objective function, as opposed to gross weight, for the conceptual design refinement of an HSCT. [4]

Designer's non-recurring production cost trade-off tool

The cost to manufacture a product is a function of the mass of the material used and the efforts required to process, fabricate, and assemble it. While manufacturing costs are inherently related to the cost of materials, they are more strongly dependent upon other factors such as the difficulty of machining a part, the specified precision, the number of parts in a component, and the difficulty in assembling those parts.

The production cost trade-off tool models relative production costs based on general relationships between the principal manufacturing parameters and manufacturing effort.[5] The tool allows designers to evaluate different [structural] concepts for their relative costs, thereby enabling them to make rational cost-related trade-offs for materials, material quantity, manufacturing methods, precision, and quantity of parts. The designer's non-recurring production cost trade-off equation is given by:

$$COST_{nr} = weight^{a} \times b + \frac{weight \times c}{Q} \tag{2}$$

where:
- $COST_{nr}$ non-recurring cost in notional \$
- a material cost for each material type and manufacturing method
- b manufacturing complexity for the appropriate material type, mfg. method, specified precision, and number of fabricated parts in a component
- c tooling cost based on material density and fabrication technique
- Q the quantity of a given part produced for the first 500 units.

This production cost analysis tool calculates only the *relative* costs of competing structural designs. Because it does not account for economic or business factors, the tool does not produce valid, *calibrated* cost estimates. The designer's non-recurring production cost trade-off tool has been used to determine three relative production costs of a given wing structural concept fabricated from titanium, aluminum, and composites. [4] The results indicated that the structural concept fabricated from aluminum was the least expensive, despite requiring additional weight to meet the load-carrying requirements.

Conventional programming of the designer's non-recurring production cost trade-off tool and the required database (in the form of tables) in a standard algorithmic language (FORTRAN or C) presents many problems. This is because of the difficulty associated with using *procedural* techniques to determine the best materials, structural concepts, manufacturing and fabrication processes, and if applicable, precision required for machining. These parameters are typically determined from rules, guidelines, and constraints related to manufacturing, fabrication, and assembly. Thus, this cost trade-off tool may be better utilized within the domain of Knowledge-Based Systems. One of the authors is currently involved with the development of a specialized KBS aimed at using the cost trade-off tool to determine the non-recurring (production) costs for different wing structural concepts.

Utilization Index

Another criterion used to relate economics to design parameters is called the Utilization Index (UI) and was used by Hiller Helicopters in the 1950s. It is defined as:

$$UI = \frac{A}{1 + \left(\frac{K \times pl \times V_{block}}{R} \right)} \tag{3}$$

where:
- pl payload
- UI Utilization Index
- A operational availability
- K loading rate
- R range
- V_{block} block speed

The UI can serve as an objective function when optimizing a given configuration at the system level. Since the research performed by the authors focused on producibility at the major component level, the UI was not used as an objective function.

Producibility Ratio

The producibility ratio has been defined as the rate at which a part can be fabricated from a given material compared with the rate at which the same part can be fabricated from a selected baseline material with all other pertinent variable factors held constant. The machining-time ratio is the reciprocal of the producibility ratio; it represents the relative number of production hours required to fabricate a part from a given material compared with the time required to fabricate a part from a baseline material.

The producibility ratio as stated above has not been included in this research. However, a broader assessment of producibility for the HSCT, including both procedural and heuristic components, is discussed in a later section of this paper.

Integration Methodology

In a recent assessment of cycle time for a preliminary design, it was estimated that an aeroelastic design cycle for an HSCT could range from 6 to 12 months with current technology. [6] Such an estimate substantiates the need to develop technology and systems that can reduce aeroelastic and structural design cycle time. The steps of a proposed solution that may shorten the design cycle time are given in the following paragraphs.

The first step is a reduction in model generation time and efforts. The authors have attempted this with the development of an integration system linking FLOPS, CATIA, and ASTROS. FLOPS, or FLight OPtimization System, is a NASA Langley-developed multidisciplinary system of computer programs for conceptual and preliminary design and evaluation of advanced aircraft concepts. CATIA, developed by Dassault Systemes, has become an industry standard throughout much of the aerospace community for creating three-dimensional geometric models using wireframe, surface, and solid modeling constructions. ASTROS, or Automated STRuctural Optimization System, is a system developed by the USAF that is capable of performing structural analysis, static aeroelastic and flutter analysis, as well as automated structural design while considering a multiplicity of design conditions.

The current system includes a Tk/tcl (Toolkit / tool command language) script that parses a FLOPS input file for aircraft geometrical parameters and then interactively sends commands to CATIA to draw the aircraft as a 3-D solid model.[7] The script also contains procedures that read a previously generated points file (of the finite element model nodes) and then draws a finite element wireframe model. The finite element model of the wing is drawn *inside* the 3-D solid model of the wing. This allows for excellent visualization of the aircraft itself as well as the wing finite element model. The model(s) can then be rotated, translated, scaled, colored, and/or shaded in innumerable combinations with CATIA.

One objective of this research is similar to that of NASA Langley's High-Speed Airframe Integration Research (HiSAIR) program: "to consolidate the aircraft geometry definition into a single tool that can output the various required representations from a common model."[8] While the system executive software for NASA's HiSAIR system is written in the UNIX command language [9], the integration system under development for this research is coded using an interpretive shell system called Tk/tcl.[10] Tk/tcl combines an interpretive language core with an X11 windowing system to produce a powerful run-time executive. This permits the users to easily customize and/or extend existing applications *without having to recompile them*. A preliminary system linking FLOPS, CATIA, and ASTROS has been implemented on the IBM RS/6000. Figure 3 shows a representative HSCT solid model generated using this system. Figure 3 includes a wireframe ASTROS wing finite element model. The shaded areas represent various point structural design locations on the HSCT wing. The locations of the critical point design areas will need to be determined from an in-depth structural analysis of the wing finite element model. Preliminary industry studies indicate the critical design regions may be near the wing tip, near the intersection of the inboard and outboard wing, and by the engine mounts. For academic purposes, only the critical regions will be analyzed; in industry, all of the components and parts of the structure would be analyzed in great detail. The basic design regions represent forward, middle, and outboard aft sections of the wing. Given the geometrical locations, the dimensions, thicknesses, and weights for spars, ribs, skin panels, and spar caps in these regions will be calculated using ASTROS. Using manufacturing guidelines and constraints, assumptions can be made regarding material choices for the particular regions, part complexity factors, and tooling complexities. The previously mentioned designer's production cost trade-off tool can then be used to make product (and process) design trade iterations for the different structural regions of the wing planform. Alternative wing structural concepts can be evaluated using areal weight as the metric (in pounds per square foot). This process flow is shown in Figure 4.

The second step in reducing aeroelastic design cycle time would be the development and introduction of a Knowledge-Based System. This KBS can be used for combining the synthesis code, FLOPS, and the FEM package, ASTROS, with heuristic components of producibility. The knowledge base of heuristic issues can be developed into expert systems that may be used to advise the designer and incorporates manufacturing guidelines and constraints into the heuristic module of producibility. The KBS will include the manufacturing rules-of-thumb that can help to determine parameters related to material selection, tooling complexities, fabrication limits, and overall manufacturing complexities.

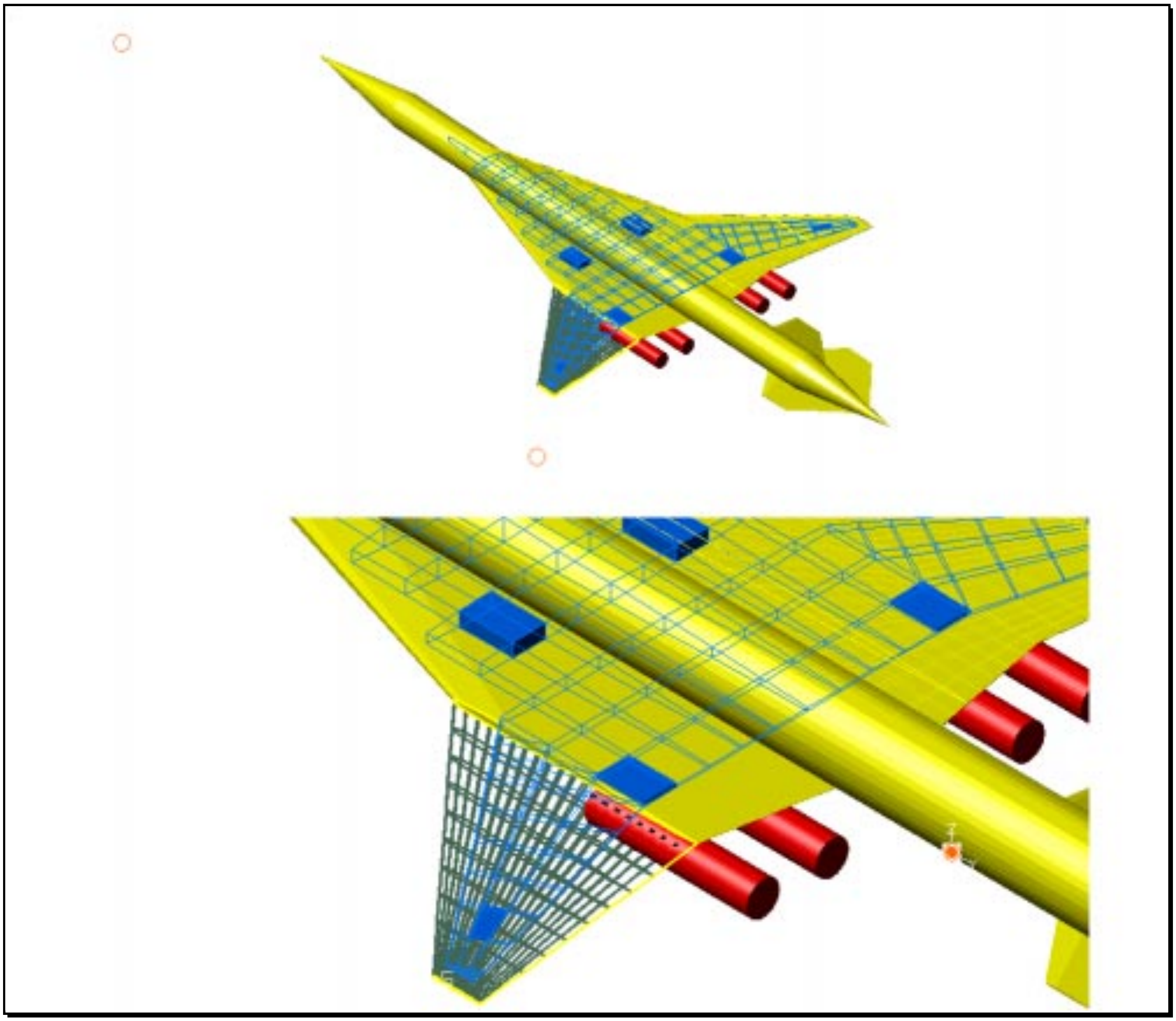

Figure 3: CATIA HSCT Solid Model With Critical Design Areas

Why Use a Knowledge-Based System?

Today's aerospace industry is faced with the same problem that this paper addresses: how can manufacturing considerations be integrated into the aircraft design process in order to reduce design cycle time and iterations? Preliminary studies at Boeing [6] have led to their belief that it is feasible to automate most, if not all, of the structural finite element modeling process for a given type of configuration utilizing one of the commercially available knowledge-based or object-oriented systems. They are convinced that a practical system can be created that will automate much of the model generation, execution of fairly sophisticated multidisciplinary processes, and preparation of preformatted results for engineering review.

The need for a KBS must be translated into benefits relevant to the user management. Knowledge-Based Systems can provide seven types of benefits: [11]

- reduced costs,
- improved quality,
- increased revenues,
- captured expertise,
- easily distributed expertise,
- raised barriers to market entry, and
- a training effect on users.

It is not difficult to see why a KBS that integrates design and manufacturing would be of interest and value to today's aerospace industry. The KBS must be constructed from a source of expertise, which can consist of formal, written knowledge (i.e., textbooks) or informal heuristics (guidelines or rules-of-thumb) not documented elsewhere. Heuristic expertise is crucial to the success of expert systems. Because of Georgia Tech's frequent interactions with industry, government, and other academic institutions, it will be possible for the authors to obtain the necessary heuristics by interviewing domain (manufacturing) experts or by observing their actions.

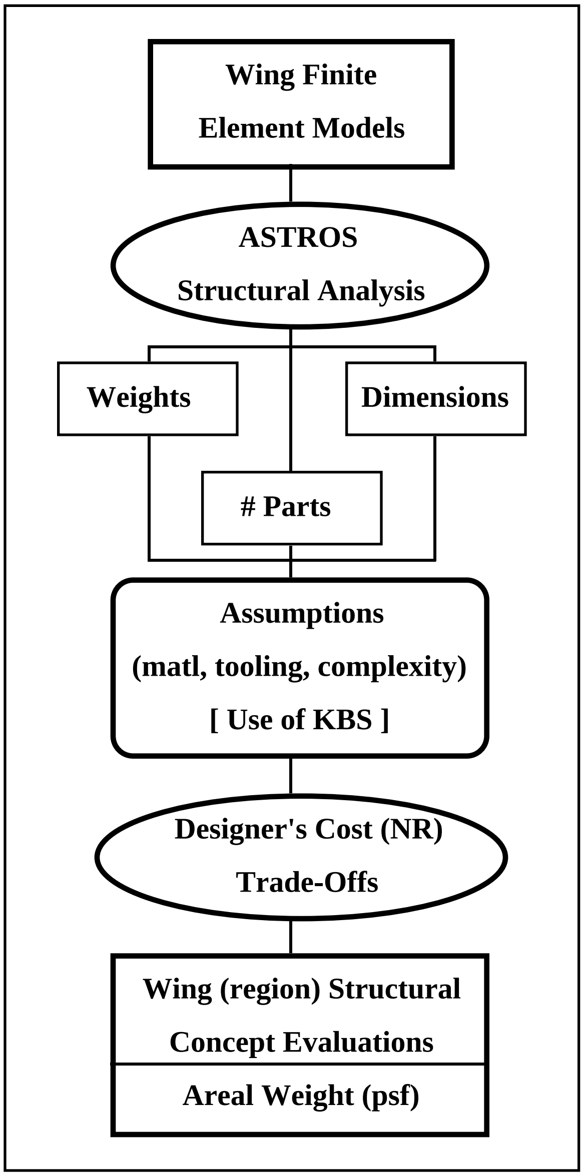

Figure 4: A Procedure for Performing Product and Process Trades at the Major Component Level

As all system designers know, there are certain information-processing problems that do not yield well to traditional computing methods. The concept of integrating design and manufacturing is a prime example of such a problem. To evaluate the potential of possible application domains for Knowledge-Based Systems, a set of desired attributes for good KBS domains have been developed as part of a major expert system development project at GTE Laboratories. (12) These attributes are related to basic system requirements, the type of problem, the "experts", problem bounds, and domain personnel. Many of these attributes are general enough to be applicable to all expert systems; several are easily inferred to be appropriate to the domain of the integration of design and manufacturing.

For example, some of the attributes associated with the system basic requirements are:

- *The domain is characterized by the use of expert knowledge, judgment, and experience.* Domain experts in the field of manufacturing exist within the aerospace industrial contacts of Georgia Tech. The experience of these people will help provide the heuristics for the KBS.
- *Conventional programming (algorithmic) approaches to the task are not satisfactory.* The designer's non-recurring production cost trade-off tool is an example of this.
- *The completed system is expected to have a significant payoff for the corporation.* A reduction in design cycle time would constitute a very significant payoff for any aerospace corporation that utilized such a KBS.

An attribute related to the problem type is:

- *The task requires the use of heuristics (rules-of-thumb, strategies, etc.). It may require consideration of an extremely large number of possibilities.* Many of the complexities associated with the selection of structural concepts and the manufacturing of an aircraft wing are best addressed by heuristics.

Another general feature is:

- *The need for the task is projected to continue for several years. The need must exist enough beyond the period of system development to generate the payoff.* NASA's High Speed Research (HSR) program is currently in its fifth year (Phase II) and is projected to last through the year 2001.

The aforementioned attributes are the reasons why the authors are investigating the use of a KBS for the integration of design and manufacturing of an HSCT wing.

Proposed Knowledge-Based System

As related to the overall concept of product affordability, cost can be considered as a key element of producibility. Therefore, the utilization of a cost model as a procedural module within a synthesis model is a valid method to assess producibility in design. (13) FLOPS has an economics model developed by Johnson(14), that is capable of performing LCC analyses for aircraft conceptual designs. This integration of an LCC model into the synthesis model FLOPS is an example of the utilization of procedural knowledge to determine the producibility of an aircraft concept at the earliest design levels.

The combination of FLOPS and ASTROS with heuristic components of producibility constitutes the authors' attempt for an integration of design and manufacturing for aerospace systems designers. Aircraft development at the conceptual level will be addressed by the procedural model, while the heuristic module would apply a suitable cost module during the preliminary design. Figure 5 shows the relationships within the procedural and heuristic components for an HSCT producibility assessment. The procedural model consists of optimizations performed by both FLOPS and ASTROS, but with different objective functions for each. This may require the introduction of multiobjective optimization trade-offs. Heuristic producibility issues are those that require the knowledge of experts to resolve. Design and manufacturing experts from academia, industry, and government are used in conjunction with design and manufacturing oriented textbooks to develop checklists, lists of guidelines, or design rules. These checklists and rules pertain to constraints associated with materials, fabrication, assembly, and processes. These issues can be developed as a KBS.

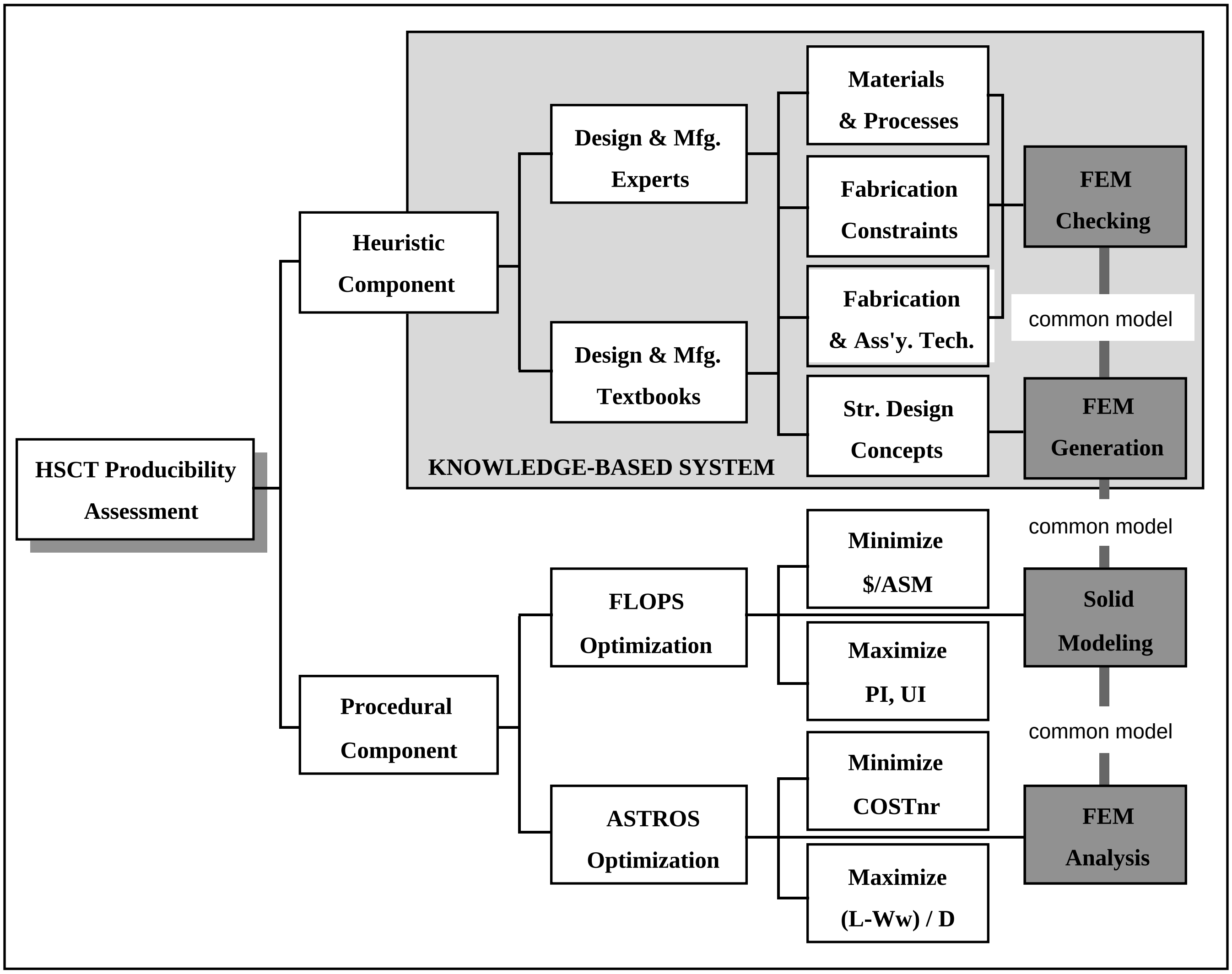

Figure 5: Procedural and Heuristic Components of Producibility

Several examples of heuristic issues related to manufacturing processes that are suitable for incorporation into such a KBS are provided here. All manufacturing processes are subject to limitations in terms of shape complexity, minimum and maximum dimensions, tolerances, and surface finishes. [15] These limitations are highly dependent upon workpiece material. The maximum size of a part or component that can be produced by any one technique is often limited by the availability of large equipment. There are also limitations due to process conditions themselves. More often, the limitation is on the minimum size that can be produced or on wall thickness. There are both practical and fundamental thickness limitations. Unnecessarily tight tolerances and surface finish specifications are a major cause of excessive manufacturing costs. Each manufacturing process is capable or producing a part to a certain surface finish and tolerance range without extra expenditure. The specified tolerances should, if possible, be within the range obtainable by the intended manufacturing processes to avoid separate finishing operations.

The aircraft designers and manufacturers must know the production rate and the total quantity to be produced to select the appropriate method of production. The part or item can be produced in any of three general ways. It can be produced manually, with a flexible manufacturing system (FMS), or with fixed automation. [11] All three methods can be used on individual workstations or throughout the factory. The method of manufacturing is ultimately determined economically; the approach that yields the highest return on investment (ROI) and the lowest unit production cost (UPC) is used. [16]

A life cycle KBS model that has been used successfully in many expert systems is shown in Figure 6. [17] The figure shows the stages from Planning to System Evaluation and describes the development of the system to some point at which its functional capabilities will be evaluated. The life cycle follows an iterative pattern until the system is delivered for routine use. The life cycle is subsequently used for KBS system maintenance, enhancement, and evolution.

Because of its availability at Georgia Tech, CLIPS will be used as the expert system language. CLIPS is a multiparadigm programming language that provides support for rule-based, object-oriented, and procedural programming. [17] The procedural programming language provided by CLIPS has features similar to languages such as C, Ada, and Pascal and is syntactically very similar to LISP. CLIPS was developed at NASA Johnson Space Center with the specific purpose of providing high portability, low cost, and easy integration with external systems. CLIPS is written using the C programming language to facilitate these objectives. CLIPS is an acronym for *C Language Integrated Production System*.

Figure 6: Possible Linear Model of Expert System Development Life Cycle

Future Work

The integration of design and manufacturing is a monumental task that is only beginning to be addressed by the aerospace industry, government and academia. While much research and formulation has been done, the overall goal of the integration of design and manufacturing is a long way from completion. Several significant steps need to be executed in order to develop just a simple system for assessing product producibility. These steps include:

- research and formulation of a suitable knowledge base of manufacturing guidelines and rules-of-thumb
- development of a specialized prototype KBS aimed at using an expanded model for production costs incorporating the designer's non-recurring production cost trade-off tool
- research and development of a more general KBS to incorporate heuristics into the assessment of producibility as a major part of integrating design and manufacturing
- the combination of FLOPS and ASTROS (in a procedural sense) with heuristic issues of producibility
- verification of the knowledge by experts from the industry, and
- perform an overall producibility assessment and system evaluation.

The development and growth of suitable Knowledge-Based Systems may present an opportunity for the aerospace industry to replace the trend of increasing manpower with increasing computational power.

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