Technology for Rotorcraft Affordability Through Integrated Product/Process Development (IPPD)*

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Abstract

This 1999 Alexander A. Nikolsky Lecture is a presentation on an approach to identify, evaluate, and select technologies (both product and process) that can make rotorcraft more affordable for both civil and military applications. It has evolved over the 15 years that I have been a professor at the Georgia Institute of Technology in the school of Aerospace Engineering and the Director for the Center of Excellence in Rotorcraft Technology. It is based, however, on much of the previous 15 years of experience I had as an Army Aviator and as an engineer, manager, and senior executive with the U.S. Army Aviation Systems Command and the U.S. Army Aviation Research and Development Command. Recent Nikolsky lectures have identified challenges and opportunities for rotorcraft to play a broader, more sustained role, especially for commercial applications. A sense of frustration has been voiced by these previous lecturers that rotorcraft *have not reached their potential*, especially as personal use, public service, commuter and mass produced systems. I also have experienced this frustration and have spent more or less the last 15 years since coming to Georgia Tech trying to better understand the affordability dilemma of rotorcraft, as well as other aircraft systems. One of my goals has been to develop an approach that will help rotorcraft *reach their potential*. I hope this paper will help shed some light on where we have been and where we need to go.

Background

My background in rotorcraft covers thirty years, beginning with helicopter flight training while becoming an Army aviator enroute to a tour in South Vietnam. Actually, my appreciation for the air-mobility that vertical flight/lift could provide on the battlefield was garnered a year earlier in Germany. As a Field Artillery Battery Commander in the first REturn of FORces to GERmany (REFORGER) exercise in 1968, I saw battalion upon battalion of Army vehicles (tanks, trucks, howitzers, and jeeps) lined up behind each other on the narrow German roads as a January thaw left movement over land next to impossible. The year I spent in Southeast Asia (mostly South Vietnam, but some time in Cambodia) was filled with experiences that reinforced my belief that the helicopter was revolutionizing the battlefield. As a lift ship platoon leader and air-mobile operations commander in the 162nd Assault Helicopter Company, I saw on a daily basis the benefits of quickly moving fresh troops from remote locations to anywhere on the battlefield; and as a gunship platoon leader I saw the great potential of the helicopter as an airborne weapon system. When I became the S-3 Operations Officer for the 13th Combat Aviation Battalion I helped plan and execute much bigger air-mobile operations, including the largest air-mobile operation in history (the single lift of the 7th ARVN Division with ~ 150 helicopters in one operation from South Vietnam up the Mekong River into Cambodia to free up the Highway 1 Mekong River Crossing which had been taken over by the Khmer Rouge and North Vietnamese forces).

After getting a master's degree (M.S.) in Aerospace Engineering (specializing in aeroelasticity and dynamics) from Georgia Tech in 1974, I arrived in St. Louis, MO, as the vibration and dynamics engineer in the Airworthiness Qualification Division of the Army Aviation Systems Command (AVSCOM). This was a very opportune time, as two of the Army's "Big Five" development programs, the Utility Tactical Transport Aircraft System (UTTAS) and Advanced Attack Helicopter (AAH) programs, had just been contracted to the four prime U.S. helicopter manufacturers (Bell, Boeing, Hughes, and Sikorsky). Over the next four years (1974-1978), as AVSCOM's vibration and dynamics "troubleshooter"

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and source selection evaluation board (SSEB) evaluator, I had the opportunity to be involved with and learn more about real world helicopter engineering than could ever be taught in a life time in the classroom. Leaving active military duty as an Army Major in 1978 for civil service (I did stay in the Reserves and currently am a Colonel) I served the next four years at the Aviation Research and Development Command (AVRADCOM); first as Chief of the Aeromechanics Branch, and then as Chief of the Structures and Aeromechanics Division. During this time I helped with the engineering transition of the UH-60A Black Hawk, the AH-64A Apache, and the CH-47D Chinook helicopters from engineering development into production. I also led the Army Helicopter Improvement Program (AHIP) technical development effort, including serving as the Technical Area Chief on the AHIP SSEB, which led to the development of the OH-58D Kiowa, the Army's first truly integrated cockpit/MEP helicopter. The last two years at AVRADCOM I served as the Director for Advanced Systems, which included coordinating most of the command's technology base program, and led the Concept Exploration for the Light Helicopter Experimental (LHX), which has led to the development of the RAH-66 Comanche. I also had members of my Advanced Concepts Branch support the Joint Vertical Lift Experimental (JVX) assessment which has led to the V-22 Osprey tilt rotor aircraft. During this period I also served for six months in 1983 as the Acting Chief Scientist for the Army's Combined Arms Center (CAC) and gained an appreciation for the role that rotorcraft play in combined arms operations. I left the government senior executive service at the beginning of 1984 to accept a position as a professor in the School of Aerospace Engineering, Georgia Institute of Technology, and serve as the Rotorcraft Design Professor for the newly formed Army Center of Excellence in Rotorcraft Technology (CERT).

Since arriving at Georgia Tech, I've had an opportunity to digest the experiences I encountered over the previous decade, as well as pursue a number of endeavors (advisory boards: Army Science Board, Air Force Studies Board and NASA Aeronautics subcommittees; consultant: aerospace industry, Institute for Defense Analyses (IDA), National Center for Advanced Technologies (NCAT)). In addition, by serving as the Director of CERT since 1986 and teaching rotorcraft design for the past 15 years I've had a chance to keep abreast of and help to advance rotorcraft technology. Beginning in the middle 1980's I became involved with the "Quality Revolution", including Concurrent Engineering, which was causing substantial changes in the commercial sector. In the early 1990's, through my involvement with the NCAT Industry Affordability Task Force, as a member of the Executive Committee, I helped to define and implement the concept of Integrated Product/Process Development (IPPD) for the defense sector - an enabling process for world class competitiveness in the commercial sector. While being exposed to this changing environment in the commercial and defense sectors I took the opportunity to introduce these concepts in academia through the development of a graduate program in Aerospace Systems Design. These concepts have served as a testbed for teaching and developing a generic IPPD methodology which has led to the development of Robust Design Simulation (RDS). It is this generic IPPD methodology that has also served as a catalyst for the Technology Identification, Evaluation and Selection (TIES) approach that will be presented in this Nikolsky lecture - *Technology for Rotorcraft Affordability through IPPD*. A detailed example of the TIES approach for identifying and evaluating technologies for a civil tiltrotor is included in the Design Session of the Forum and is entitled: "Implementation of a Technology Impact Forecast Technique on a Civil Tiltrotor".

Introduction

As industries and governments around the world refocused in the early 1980's to achieve major quality improvements to become more competitive in the world marketplace, the terms Total Quality Management (TQM) and Concurrent Engineering (CE) were identified with management and engineering changes that were necessary to achieve the desired environment. TQM was defined as an integrated strategy, formulated in government and industry, to make quality a driving consideration at each step of a product's life cycle. CE was defined as a systematic approach to the integrated, concurrent design of products and related processes, including manufacture and support.[1]

Through these efforts one soon realized that it was during product development and with cross-disciplinary teams that the greatest opportunities existed to implement quality initiatives. This led to the identification of Integrated Product Development (IPD) and Integrated Product Teams (IPTs) in the late 1980's. However, it soon became evident, especially in the commercial sector, that integrated product development without integrated process development would not lead to world class quality, affordable systems, and reduced development and manufacturing cycle times. Integrated Product/Process Development (IPPD) was first identified in the NCAT Technology for Affordability White Paper[2] in 1994 as *a management methodology that incorporates a systematic approach to the early integration and concurrent application of all the disciplines that play a part throughout a system's life cycle*. The need for IPPD in the commercial sector was based on the continuation of the Quality Revolution as illustrated in Figure 1. As shown, the Cost Advantage in the 1960's was Cheap Labor, High Volume, and Low Mix Production. Beginning in the 1970's the Japanese re-educated the world on the use of both on-line and off-line Statistical Process Control (SPC) and Variability Reduction, off-line being during the design or development phase. They also raised the ante on Customer Satisfaction, something that was lost on those industries not facing world class competition. The automotive industry was one of the first industries (the electronics industry quickly followed) that felt the urgent need for change due to the strong competition from Japan, beginning in earnest in the early 1980's. As an example, a timeline comparison of where design changes were taking place during the development of a Japanese automobile with those for a U.S. automobile are illustrated in Figure 2[3]. As can be seen the Japanese automobile company made design changes earlier and thus could produce a car with higher quality in a shorter period of time. This direct comparison served as part of a "wake-up call" for the U.S. automotive industry and the race for improved quality and reduced cycle times continues today.

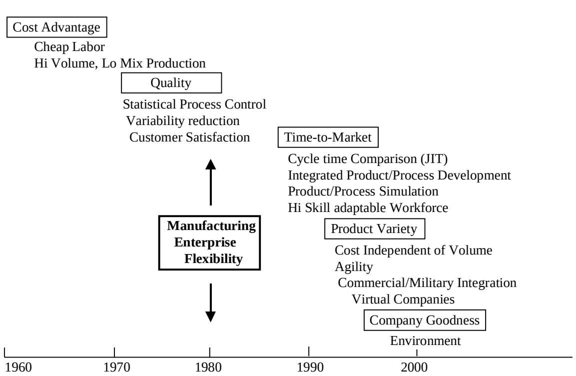


Figure 1. Quality Revolution

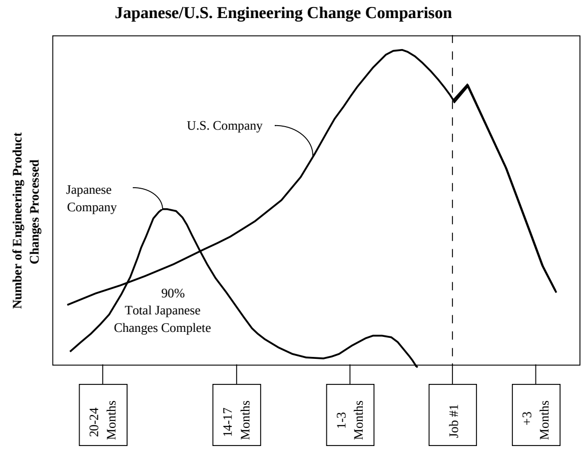


Figure 2. Japanese/U.S. Automotive Engineering Change Comparison

As can be seen in Figure 1, the 1990's have seen the emphasis shift to Time-to-Market and Product Variety. Time-to-Market has resulted in an emphasis on Cycle Time Comparison (JIT), IPPD, Product/Process Simulation, and a High Skill Adaptable Workforce; while Product Variety has emphasized Cost Independent of Volume, Agility, Commercial/Military Integration, and Virtual Companies. As we move into the next millennium, Company Goodness with respect to the Environment will undoubtedly receive increased emphasis.

IPPD at Georgia Tech

The cultural change taking place in industry and government due to the Quality Revolution identified the need for education and training, as well as new systems approach methodologies that captured the essence of IPPD and Product/Process Simulation. Something like the Systems Engineering methodology that was developed in the late 1950's and early 1960's for designing and building large scale complex systems, such as ballistic missiles and manned space flight systems, was needed. When I came to Georgia Tech in 1984 to teach rotorcraft design I knew of the difficulties of transitioning from development to production, since I had witnessed these difficulties for the UH-60 Black Hawk and the AH-64 Apache programs. I also knew that the design freedom and cost leverage was greatest at the front end of the development program, as I experienced when helping to direct the OH-58D Kiowa and the LHX development efforts. As I became involved with the Quality Revolution in the 1980's (through consulting with industry and government) and the emergence of TQM and CE, I began to introduce more of these concepts into the rotorcraft design courses. In addition, through being a member of the Georgia Tech Computer Integrated Manufacturing Systems (CIMS) program and seeing the need for a cross-disciplinary course addressing CE, I introduced such a course, called "Introduction to Concurrent Engineering" in 1989. This course has been taught every year since then and now includes an emphasis on IPPD. Another course I introduced in 1989 was "Design for Life Cycle Cost", which not only familiarizes engineering students with parametric cost estimating, but also introduces the students to statistical methods and approaches, such as Taguchi's Parameter Design Optimization Method [4] and in later years elements of Robust Design Simulation (RDS).

In 1992 the Aerospace Systems Design Laboratory (ASDL) and a graduate program in Aerospace Systems Design in the School of Aerospace Engineering were initiated to support both education and research programs in both fixed wing and rotorcraft design. The catalyst for the initiation of ASDL was a grant from NASA Ames Research Center to address *Integration of Design and Manufacturing for the High Speed Civil Transport (HSCT)* under the NASA USRA Advanced Design Program (ADP). The graduate synthesis courses in fixed wing and rotorcraft design have become the testbeds for developing the new systems approach methodologies that capture the essence of IPPD and Product/Process Simulation. In 1994 the Georgia Tech ASDL won two three-year NASA contracts which further helped in the development of ASDL and the new systems approach methodologies. One of these NASA contracts was a *Multidisciplinary Design &Analysis (MDA) Fellowship* program from NASA Headquarters which also involved placing students in industry as summer interns, thus getting industry more involved along with their feedback. The second contract was a program for *New Approaches to Multidisciplinary Design Optimization (MDO)* from NASA Langley Research Center and served to take the generic IPPD methodology being used in the graduate design courses to include System Synthesis through MDO as a means for implementation of higher fidelity physics-based analysis tools. These two contracts also helped to justify the hiring of two junior design faculty so that three parallel sets of graduate design courses are now taught - rotorcraft, fixed wing aircraft, and space launch vehicles. Research contracts over the past few years for the Office of Naval Research (ONR) has focused on developing an Affordability Science that could support ONR's Affordability Measurement and Prediction program. Thus, the generic IPPD Methodology has evolved into System Synthesis through MDO that is now being extended through RDS for affordability measurement and prediction.

The Generic IPPD Methodology that has been taught at Georgia Tech over the past five years, and used as the education and training approach for the Navy's Acquisition Reform effort is illustrated in Figure 3. The Methodology consists of four key elements, illustrated at the top in "umbrella" form. These four elements are Systems Engineering (SE) methods and tools, Quality Engineering (QE) methods and tools, a Top Down Design Decision Support (TD3S) process, and a Computer Integrated Environment (CIE). Below the "umbrella" are the sub-elements of each key element. As illustrated by the downward arrow, the SE methods and tools flow is product design and decomposition driven, while the QE methods and tools flow is process design and recomposition driven. The arrows from the SE and QE methods and tools feeding into the TD3S process, the heart of the methodology for tradeoff assessment, represent the information flow, which for timely integration, cycle time reduction and decision making requires a CIE. *The primary design/synthesis iteration illustrated is between the SE method; System Synthesis through Multidisciplinary Design Optimization (MDO), to "Generate Feasible Alternatives" and the QE method, Robust Design Assessment & Optimization, to "Evaluate Alternatives" and finally to update the System Synthesis*. It will be shown later how the iterative process is exercised through RDS and can be used for Technology Identification, Evaluation and Selection (TIES).

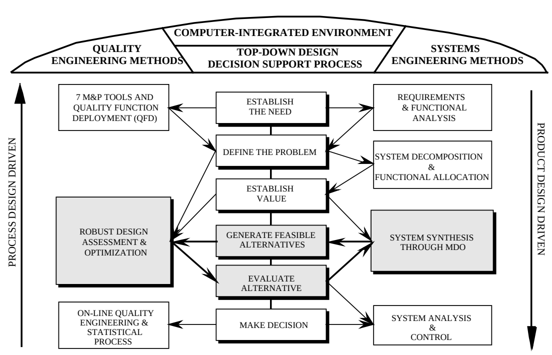


Figure 3. Georgia Tech Generic IPPD Methodology

The Methodology illustrated in Figure 3 is considered as a *procedural* approach to design, but also encompasses an *analytical* approach in the SE method, "Systems Synthesis through MDO", and an *experimental* approach in the QE method, "Robust Design Assessment and Optimization"[5]. The *procedural* approach is a trade-off process where the objective is modified as the design proceeds. The solution that results is the solution that satisfies all the design objectives in the *best manner*. The *analytical* approach is a function of the problem attributes that are precisely defined - much of engineering optimization, especially in academia, have followed an *analytical* approach. The *experimental* approach to design relies on a matching of design attributes to the objective of the design process - use of Design of Experiment methods characterize the *experimental* approach (Ref. 5). The procedural approach illustrated in Figure 3 has also been called a Design Justification approach. Design Justification is a term used to describe a design process where the economic ramifications of design decisions are considered concurrently with design development and are used to guide the design process so as to result in the most economical criteria satisfying design (Ref. 5). This is the basis for the Roadmap to Affordability using RDS that will be discussed later.

For large-scale integration of complex systems the IPPD methodology provides the centerpiece in the hierarchical tradeoff process flow illustrated in Figure 4. The right half of the figure represents the SE decompositon from system (conceptual design) to component (preliminary design) to part (detail design) to the on-line manufacturing process; while the left half represents the QE recomposition from the manufacturing process back to the system. Inside the circle are parallel trades at the system, component, and part levels. A methodology (the center box), such as that in Figure 3, is necessary if true IPPD is to be exercised. The hierarchical process flow in Figure 4 is also useful in understanding why the Japanese were able to make design changes earlier (Figure 2) and shorten the development cycle time. This is further illustrated, in a more generic way, in Figure 5, which illustrates a traditional serial approach versus a CE approach. As can be seen the IPPD focus should be in design and development. The traditional serial approach is illustrated in Figure 6 and is based on a SE decomposition and also shows the wall that has often separated design and manufacturing in many companies. While SE decomposition has served its purpose in producing high performing large-scale systems, such as aerospace, it has also served to lock in life cycle cost early as illustrated in Figure 7. This figure has been used often as a general trend for large-scale complex systems (as illustrated in the top left schematic), but was actually developed for a Boeing ballistic missile system. Ballistic missile systems served as the basis and major reason for developing the SE methodology. Therefore, for IPPD SE methods and tools are considered *necessary*, but *not sufficient.*

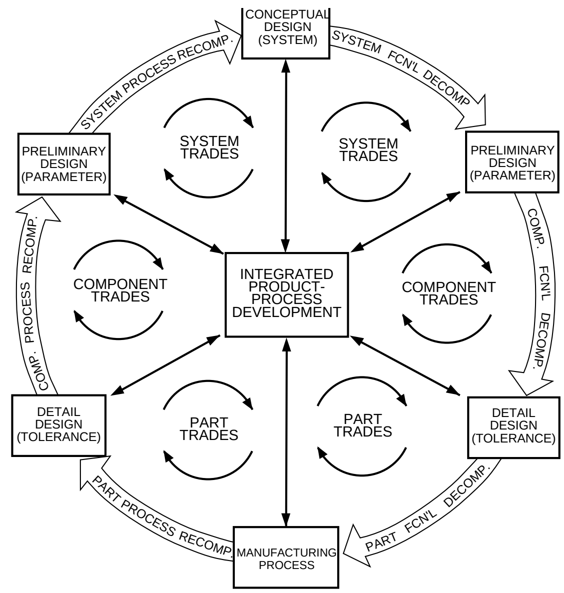


Figure 4. Hierarchical IPPD Process Flow

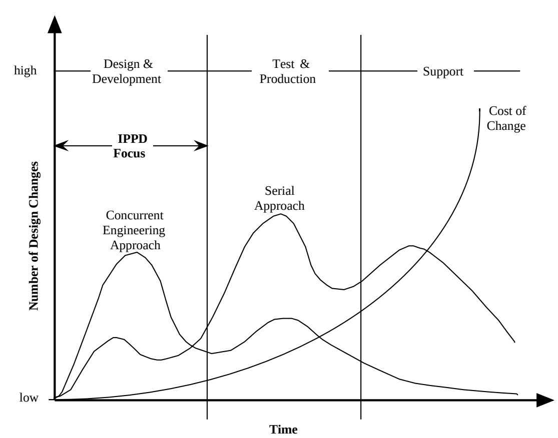


Figure 5. Traditional Serial Approach versus CE Approach

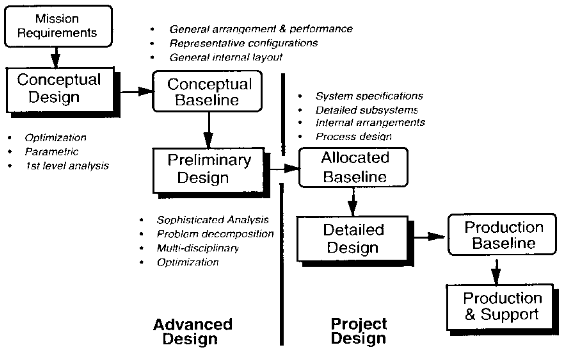


Figure 6. Traditional Development Process (Using Systems Engineering Only)

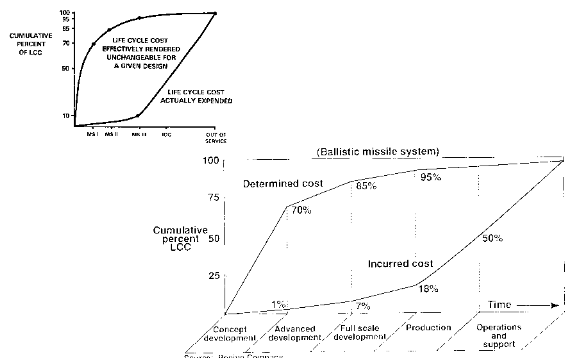
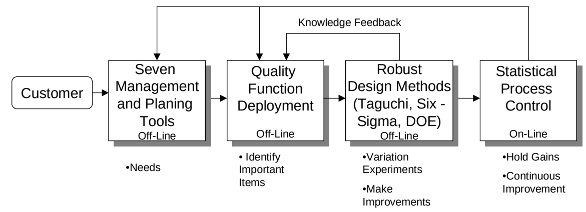


Figure 7. Life-Cycle Cost Gets Locked In Early

Quality Engineering methods and tools have evolved out of the "Quality Revolution", and provide the means of bringing downstream manufacturing process information back into the design process, thus emphasizing a recomposition rather than a decomposition approach. They basically consist of the flow illustrated in Figure 8. Quality Function Deployment (QFD) is used to transform the "Voice of the Customer" and prioritize where improvements are needed. Robust Design Assessment and Optimization methods, such as Taguchi, then provides the mechanism for identifying the process improvements. Statistical Process Control (SPC), an on-line manufacturing process, provides the means to hold these gains as well as to insure continuing quality improvement, through variability reduction. The emphasis on achieving a "Six Sigma" process capability has been evident in the electronics and propulsion industry for at least the past five years and is now being emphasized for large scale complex systems, such as aerospace[6].

To better understand the Hierarchical IPPD Process Flow illustrated in Figure 4, the identification of product/process *metrics* for design trade-offs at various levels of decomposition and recomposition is provided in Figure 9. The right half product metrics, such as speed, power, weight, range, volume, productivity are familiar to most engineers, while the left half process metrics, such as life cycle cost, return on investment, etc. are not as familiar.



Having heard the "voice of the customer", QFD prioritizes where improvements are needed; Taguchi provides the mechanism for identifying these improvements

Figure 8. Quality Engineering Flow

All of the process metrics involve cost/time relationships, as illustrated in Figure 10 for theoretical production[7]. The relationships in Figure 10 can be used to discuss some of the recent manufacturing initiatives, such as *lean manufacturing* and *just-in-time (JIT) manufacturing*. As can be seen there is a split in the cost/time relationship depending on whether it is the "largest" or "smallest" production run. The intersection with the Cost/Time curve, in essence the learning curve from Theoretical First Unit Cost (TFUC or T1), shows that the "largest run" takes more time but has the lowest cost/unit while the "smallest run" takes an opposite path. Reducing the TFUC and flattening out the learning curve are the essence of "lean manufacturing". By the same token the relationship between "Setup time" and "Setup cost" is what Toyota Production Systems attacked with JIT[8]. In most manufacturing industries "Setup time" was considered relatively fixed to handle cyclic variations in orders and to achieve Economic Batch Quantities (EBQs). Along with this assumption was that inventory was considered an asset, in order to be able to ramp up when necessary. Under the Toyota system, with its suppliers as an integral part of the production process, "Setup times" and the related "Setup costs" were driven toward zero and inventory became a liability, rather than an asset. Finally, Figure 11 illustrates how the Cost/Time curve can become a constraint curve for candidate manufacturing processes for use in design tradeoffs. As can be seen Process E lies outside the constraint curve, while Processes A - D fall within the constraint curve. Thus if the product technology warrants the benefits in reduced weight, volume, etc. and can only

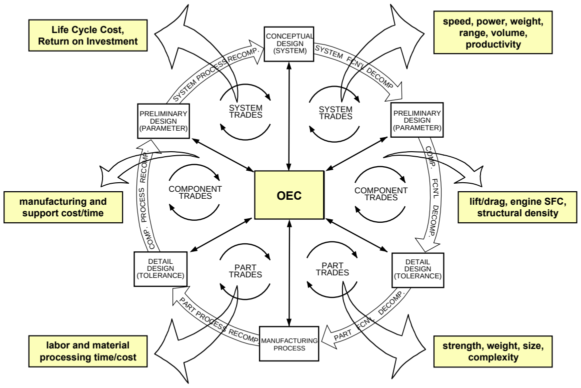


Figure 9. Product/Process Metrics for Design Trade-Offs

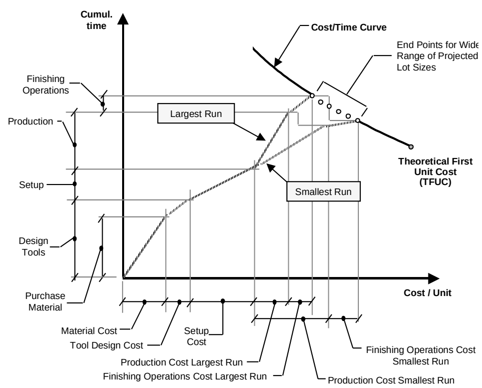


Figure 10. Cost/Time Analysis for Theoretical Production

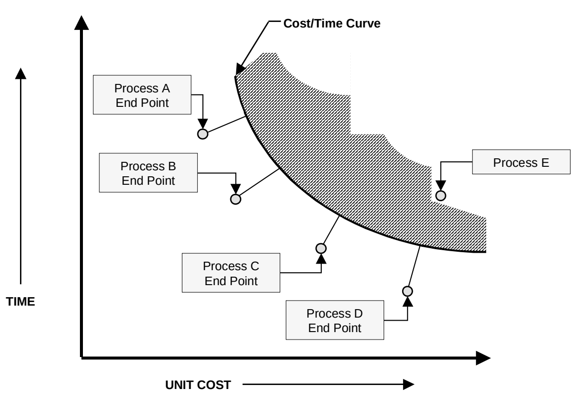


Figure 11. Cost/Time Constraint Curve

be used with Process E, then a parallel manufacturing technology development program must be initiated to bring the manufacturing process into the feasible design space (Ref. 7)

An approach to modeling the Hierarchical IPPD Process Flow in Figure 4 and to evaluate the metrics and the Overall Evaluation Criterion (OEC) shown in Figure 9 is depicted in Figure 12. Illustrated are typical decomposition models, i.e. Aircraft Synthesis (Sizing), Finite Element Analysis (FEA), and recomposition process models, i.e. knowledge based system (KBS), component cost models, and a Top-Down Aircraft LCC model. These models were developed and exercised in a Ph.D. thesis, *Integration of Design and Manufacturing for a HSCT*[9], and highlighted in several journal papers and conference proceedings (References 10,11,12).

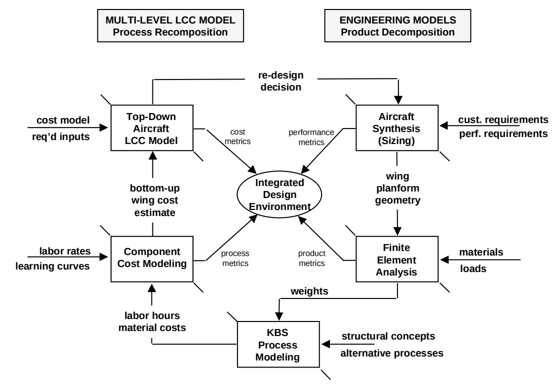


Figure 12. Typical Models Used for Decomposition and Recomposition

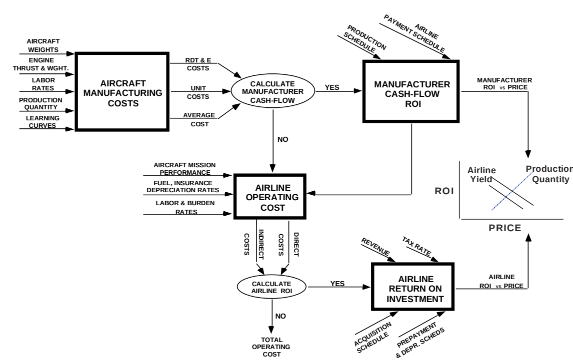


Figure 13. ALCCA Flowchart

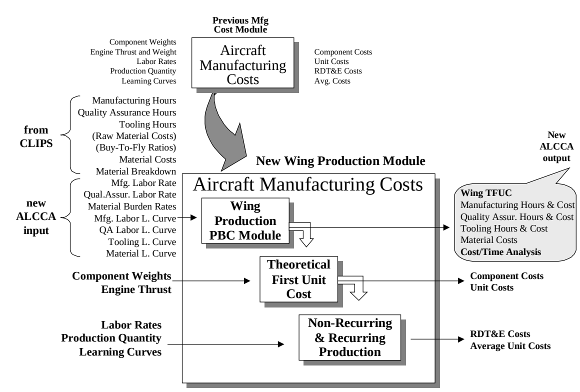


Figure 14. New ALCCA Wing Manufacturing Cost Module

A key element of this research was to convert the NASA/Georgia Tech Aircraft Life Cycle Cost Analysis (ALCCA), Figure 13, into a more process-based cost model, as illustrated in Figure 14. As can be seen in Figure 14 the weight-based Aircraft Manufacturing Costs module was replaced with a New Wing Production Module which included the capability to establish the cost/time relationships illustrated in Figure 10, using the NASA KBS, CLIPS, to generate manufacturing heuristic input. It is noted that the ALCCA model in Figure 13 is more than a LCC model as it includes the capability to assess cash flow analysis and the ability to assess price as well as cost - something that will be addressed in the next section.

In summary it can be seen that the Generic IPPD Methodology developed at Georgia Tech has helped create an education and research graduate program in Aerospace Systems Design. This Generic IPPD Methodology has also been used, over the past three years, by the Navy in their acquisition reform effort through short courses, video-based education, and an interactive training CD: *An Interactive Training Program For IPPD Awareness.*

The Roadmap to Affordability through Robust Design Simulation (RDS)

Before beginning the discussion in this section the terms "affordability" and "robust design" should be defined. Affordability, as we use it, is associated with the *benefit-cost ratio* (BCR), which is used in economic analysis when economic resources are constrained and relates the desired benefits to the capital investment required to produce the benefits. This method of selecting alternatives is most commonly used by governmental agencies for determining the desirability of public works projects.[13] A project is considered viable when the net benefits associated with its implementation exceed its associated costs. For the assessment and the selection of new aircraft or technologies for insertion into existing aircraft, the ratio may be more appropriately considered the *system effectiveness to the system cost ratio* or *operational effectiveness to operational cost ratio*, which has been often used in the military for Cost & Operational Effectiveness Analyses (COEA's). The term system effectiveness can be considered a function of the capability, dependability, and availability of the system; while the system cost should be the life cycle cost of the system[14]. Robust design is defined in Reference 13 as the systematic approach to finding optimum values of design factors which result in economical designs with low variability. A slightly modified version of this definition is being used in the ASDL Affordability Science research and has been defined as the *systematic approach to finding optimum values of design factors which results in economical designs which maximize the probability of success.*

Over the past several years the Georgia Tech ASDL has been supporting the Office of Naval Research (ONR) Affordability Measurement and Prediction (AMPP) program. The AMPP Objectives are to enhance affordability of Navy weapons systems by development of a generic (non-program specific) set of methodologies and tools to:

- Facilitate Science and Technology (S&T) resource allocation decisions
- Enable early definition/assessment of weapons system design trade spaces
- Assess impact of technology insertion
- Perform LCC prediction for early stage weapons systems; focus on Operations and Support (O&S) cost research
- Define affordability metrics
- Predict system affordability

The impact of the AMPP program is to provide more bang for the Navy buck at all stages of the acquisition process. The ASDL has been providing Affordability Science research on four tasks in support of the Navy AMPP program. These are:

Task 1: Affordability Measurements and Prediction via Joint N-Variant Distributions and the Fast Probability Integration (FPI) Technique

Task 2: Fuzzy Situational Tree Networks for Knowledge Retention and Decision Making in Affordability Science

Task 3: Advances in Soft Computing and Mathematical Sciences

Task 4: A Method for the Identification and Measurement of Critical Technologies Needed to Enhance Affordability

In addition, the results of this basic Affordability Science research are being transferred to industry and government through an ONR Phase II SBIR project on Affordability Measurement & Prediction

Technologies with a small business, Global Technology Connections, Inc. In partnership with the Rolls Royce - Allison Engine Company and the V-22 Program Office, the Georgia Tech ASDL and GTC, Inc. are assessing, for this SBIR project, T406 propulsion system technologies for V-22/T406 Affordability. Also, through a task under the National Rotorcraft Technology Center (NRTC) Georgia Tech Center of Excellence in Rotorcraft Technology (CERT) entitled: *Basic IPPD for Rotorcraft Affordability* we are addressing affordability with a focus on NASA's Short Haul Civil Tiltrotor (SHCT) aircraft. As a result of these research efforts a Roadmap for Affordability is being implemented through the use of Robust Design Simulation (RDS) as illustrated in Figure 15. In the center box is the linkage between Synthesis & Sizing and Economic Life-Cycle Analysis, which has evolved from the primary iteration in the Generic IPPD Methodology illustrated in Figure 3 and discussed earlier. As this linkage has been developed Simulation and the Operational Environment have been included to address additional life cycle issues and constraints in the affordability assessment. Inputs into this center box come from three areas that will now be addressed.

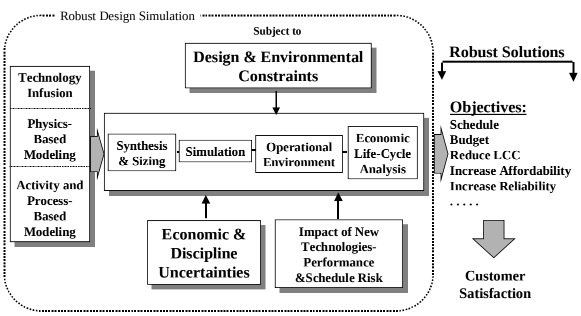


Figure 15. Roadmap to Affordability through RDS

From the left side comes *Technology Infusion* which must be handled through the use of improved modeling since most current Synthesis & Sizing models and Economic Life-Cycle Cost Analysis models are based on historical data and linear regression of this data, i.e. weight equations, drag polars, cost estimating relationships, etc. If the new aircraft or system is to be similar to the existing database then the current models are sufficient for synthesis and economic analysis. However, if new technologies, either product or process, are required for innovative or out-of-the-box designs then these historical databases must be replaced with more relevant data. Physics-Based Modeling is a way of bringing higher fidelity analysis (CFD, FEA, etc.), or experimental results, into the synthesis & sizing models and directly links disciplinary analysis and the S&T program into advanced design. Physics-Based Modeling is more applicable to product technologies in today's environment than it is to process technologies. Therefore, Activity and Process-Based Modeling based on heuristic type models, such as knowledge based systems (KBSs), must be developed to establish and provide the cost/time analysis discussed earlier and depicted in Figure 12.

Synthesis and sizing for aerospace systems have always been multidisciplinary as illustrated in Figure 16. Given a mission description and performance requirements the disciplines of aerodynamics, propulsion, and weight control are coupled together through common design parameters to provide a fuel and thrust/power balance. Geometric, performance and operational constraints are then used to define a feasible design space and size the vehicle. The sized vehicle is then sent for cost analysis and optimization takes place through the variation of a small number of design variables, i.e.

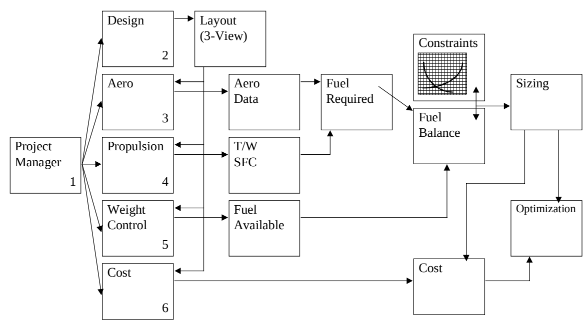


Figure 16. Aerospace Conceptual Design Synthesis and Optimization

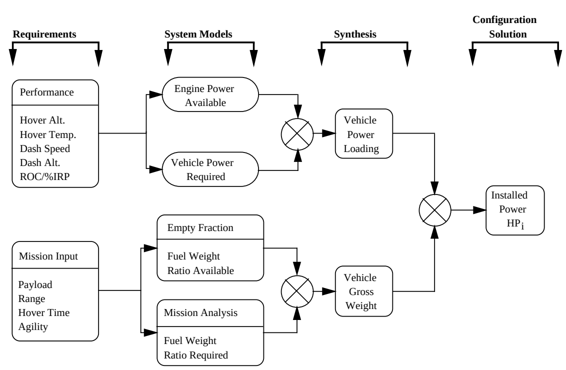


Figure 17. Obtaining Installed Power through Vehicle Design Synthesis

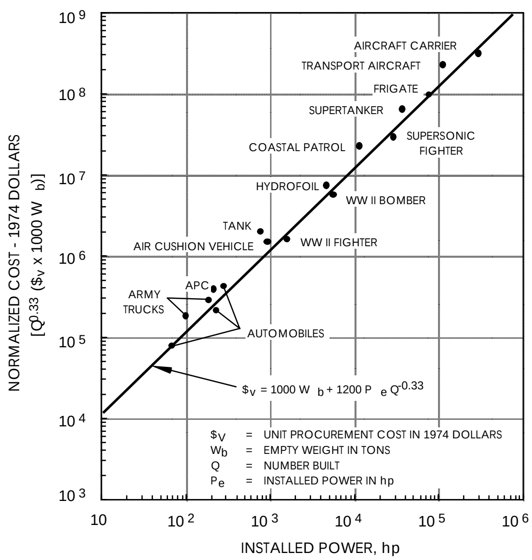


Figure 18. Normalized Cost of Bare Vehicles

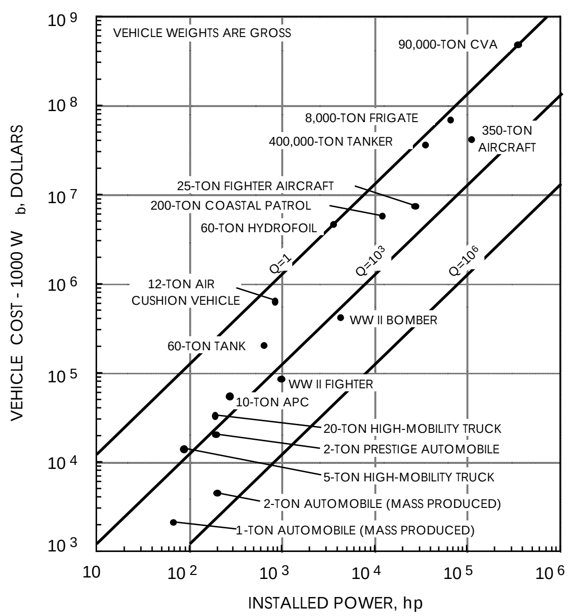


Figure 19. Vehicle Cost in Terms of Installed Power, Empty Weight, and Number Built

wing aspect ratio for fixed wing aircraft, and disk loading for rotorcraft, to obtain, in most cases, the minimum gross weight. The output of the vehicle synthesis process is the configuration solution (installed power) as illustrated in Figure 17 for rotorcraft[15]. It has been shown by Dix and Riddell[16] that the normalized cost of bare vehicles can be compared principally on the basis of installed power as illustrated in Figure 18. Furthermore, the trend curve shifts with the number built, as illustrated in Figure 19, thus indicating the benefits of mass production and today's emphasis on cost independent of volume.

The evolution of synthesis and sizing methods for rotorcraft has probably been documented best by Hiller Aircraft Corporation[17]. Illustrated in Figure 20 is the final design solution for the teetering rotor system in the Hiller Army Proposal for the Light Observation Helicopter (LOH) in the early 1960's. The Model 1100 design solution resulted in a design gross weight of 2410 lbs for a disk loading of 2.5 lbs/sq.ft. Five constraints are depicted on Figure 20 At the top of the constrained design space is a gross weight limit of 2450 lbs; on the left side is a rotor diameter size limitation of 35.2 ft; on the bottom is an effective blade aspect ratio of 21 representative of the lower limit on rotor solidity imposed by structural and dynamic considerations; and on the right side is a hard and soft constraint for forward flight performance. The first is a definite boundary based on the 110 knot forward speed requirement and is defined as the maximum values of design mean lift coefficients compatible with an equivalent parasite flat plate drag area of 5.0 sq. ft. and appropriate tip speeds. The second is the desired (but not required) boundary that the rotor limit (V_{RL}) on forward speed at sea level is equal to or greater than the speed obtainable at Military Rated Power (MRP).

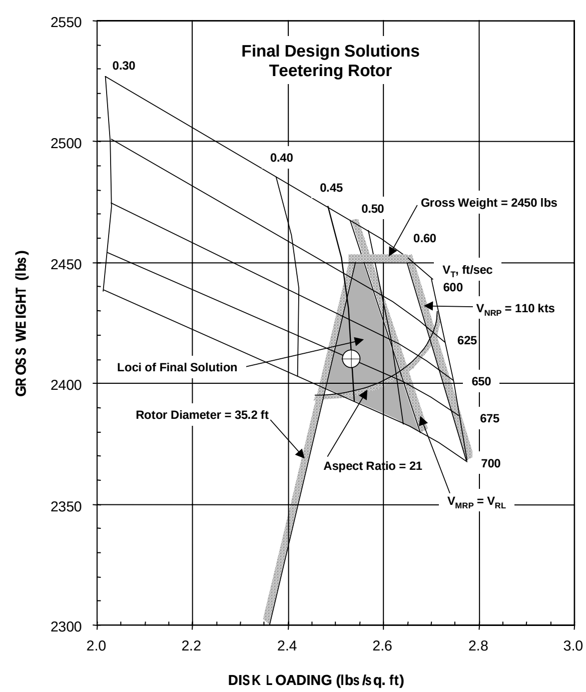


Figure 20. Hiller Model 1100 LOH Solution

Synthesis, in today's environment; however, requires early consideration of additional life cycle, environmental, and economic constraints. As stated by William A. Wulf, President of the National Academy of Engineering[18]:

> "My favorite quick definition of what engineers do is design under constraint. We design things to solve real problems, but not just any solution will do. Our solutions must satisfy constraints of cost, weight, size, ergonomic factors, environmental impact, reliability, safety, manufacturability, repairability, and so on. Finding a solution that elegantly satisfies all these constraints is one of the most difficult and profoundly creative activities I can imagine."

To provide these creative activities in today's environment we need to start with current vehicle synthesis models that are multidisciplinary in nature and provide the hooks to translate mission and performance requirements into configuration solutions. At the same time, however, we must provide a means for expanding the disciplines and replacing the historical databases with more realistic and current data, based on physics-based and process-based models. The approach that the ASDL has been following for rotorcraft is illustrated in Figure 21. At the center is the conceptual design synthesis and sizing programs commonly used in ASDL for rotorcraft, i.e. VASCOMP[19], HESCOMP[20], and GTPDP[21]. Around the outer loop are the disciplines that must be brought into the synthesis process, either as constraints or as active design parameters for optimization. The term, RSE, stands for Response Surface Equation, which can be considered an on-line regression analysis where the design parameters from higher fidelity analysis, based on physics-based models or experimental data, are passed to the synthesis and sizing code and replace the historical data. These RSEs can be linear or nonlinear, and usually a quadratic relationship suffices. The ASDL has been working with RSEs for the past six years and has considerable experience in selecting them[22].

Getting back to the Roadmap to Affordability through RDS in Figure 15 the bottom entries are Economic & Discipline Uncertainties and Impact of New Technologies - Performance & Schedule Risk. Before discussing uncertainties in economic analysis it is important to understand the relationships and differences between economics, engineering economy, and accounting. *Economics*

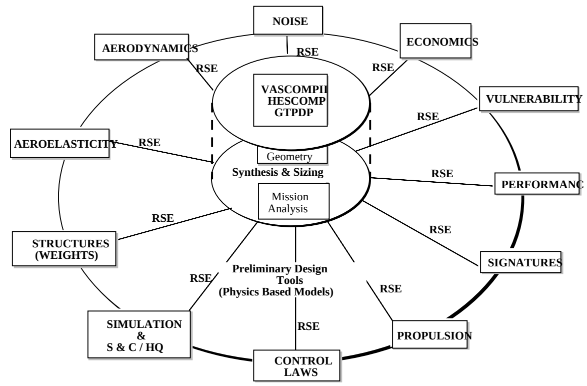


Figure 21. Synthesis & Sizing Relationships with Physics-Based Models

generally deals with broader and more global issues than engineering economy, such as the forces that control the money supply and trade between nations. *Engineering economy* uses the interest rate established by the economic forces to solve a more specific and detailed problem. However, it usually is a problem concerning alternative costs in the future. The accountant is more concerned with determining exactly, and often in great detail, what costs have been in the past. One might say that the economist is an oracle, the engineering economist is a fortune teller, and the accountant is a historian (Ref. 13)

We have seen that the Quality Revolution has introduced statistical and probabilistic methods for manufacturing processes off-line into the design and development phase. Yet most designers and engineers still use deterministic methods and for a while, probability and statistics have been removed from many undergraduate engineering curricula. There is no doubt that risk and uncertainty are the greatest at the front end of the system life cycle process as illustrated in Figure 22[23]. As can be seen both the Known-Unknowns (risk) and the Unknown-Unknowns (uncertainty) are the greatest during concept development and validation; therefore, a probabilistic approach to design is necessary in a Roadmap to Affordability. The risk and uncertainty is with respect to cost, schedule and performance and requires the use of forecasting techniques. For new products most of the detailed forecasting activity is likely to be devoted to the development of products whereby the strategy of the company is realized. In doing this there are a number of inter-related considerations which must be taken into account[24]

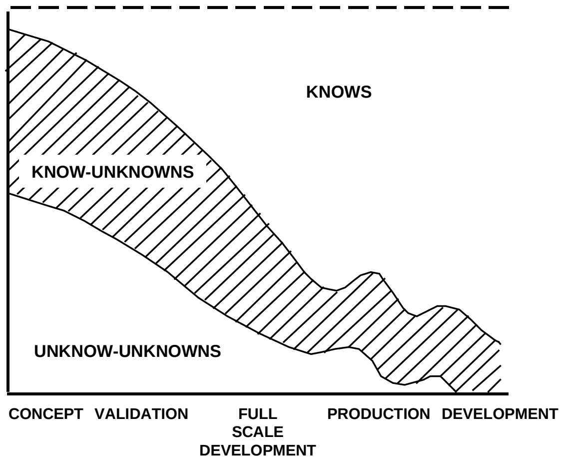


Figure 22. Risk and Uncertainty Greatest at the Front End

The technical specification must ensure that the new product exploits the potential of the technology to the maximum extent. If the performance specification is too low the product will not be competitive, if too high it is unlikely to be realized in practice. A technology forecast can assist in establishing the appropriate level to aim for. The design of the product must be related to the likely growth rate and ultimate size of the market. The design and choice of materials for a product to satisfy a low volume market may be very different from those for a mass market. These decisions must be taken several years before the product is launched. These considerations will also affect the methods of production which in turn have important implications for the product design. The extent to which this matching is achieved will manifest itself in the eventual unit cost for the product and its profitability. In order to achieve this, forecasts are required not only for the ultimate size of the market but also for the rate of its growth following its introduction. This will also affect plant capacity decisions and the choice of manufacturing processes. This is a situation where choices have to be made, often irreversible, with respect to the detailed nature of the product and how it will be made. Market forecasts are essential if the most technological choice is to be made. (Ref. 24)

To address this risk and uncertainty more than a LCC analysis is required and is why an economic analysis, such as in the ALCCA displayed in Figure 13, is included in the Robust Design Simulation (RDS). This is further justified by reviewing the cash flow analysis curve in Figure 23. As can be seen the cumulative cash flow and desired Return On Investment (ROI) are highly dependent on the R&D slopes and why cost and risk sharing partners are usually required on new aircraft programs. The uncertainties in technologies and markets are further illustrated in Figure 24 and also in a sample manufacturer's program cash for a military aircraft, a derivative commercial aircraft, and a new commercial aircraft in Figure 25. Thus it can be seen that for a new commercial aircraft to be launched much more knowledge must be brought forward to the front end of the life cycle process and a probabilistic approach utilized.

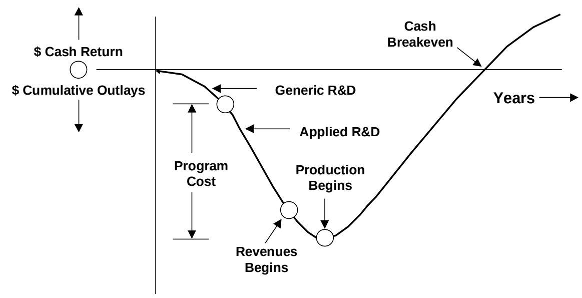


Figure 23. Cumulative Cash Flow and Desired ROI

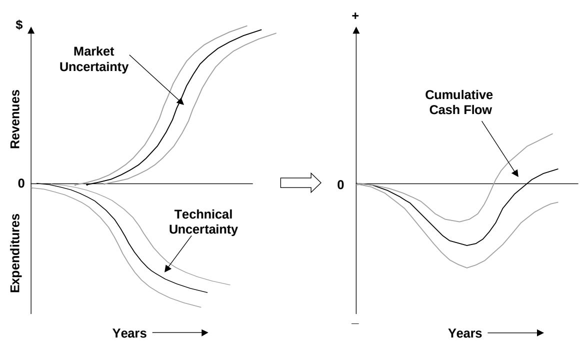


Figure 24. Cumulative Cash Flow for Complex Engineered Systems

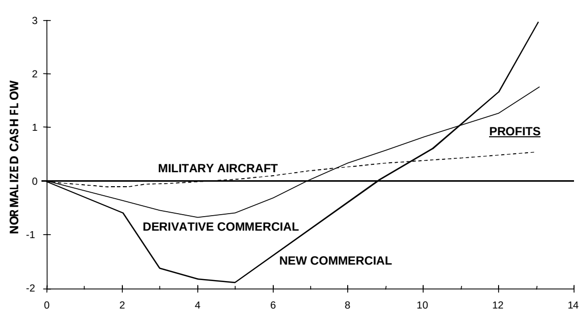


Figure 25. Sample Manufacturer's Program Cash Flow

To address the risk and uncertainty in economic analysis a probabilistic approach in which Monte Carlo simulation is often employed as illustrated in Figure 26. Each variable in the analysis is assigned a cumulative probability distribution. The probability distributions are constructed from historical data, econometric analysis or any theoretical models that might be applicable. Once the probability distributions have been constructed, the next step is to establish a value for each variable by the use of a random number generator in association with these distributions. After all variables have been assigned values in this way, they are substituted into the economic model of the problem to determine cash flow and calculate the profitability criterion, such as Distributed Cumulative Function (DCF) ROI. The procedure is repeated hundreds of times so that a probability distribution of the profitability criteria can be developed. (Ref. 13)

For engineering analysis, especially using higher level, more physics-based models, new methods for probabilistic analysis than just the brute force of Monte Carlo simulation are required. As part of its ONR Affordability Science research the Georgia Tech ASDL has developed new options for probabilistic design as illustrated in Figure 27.

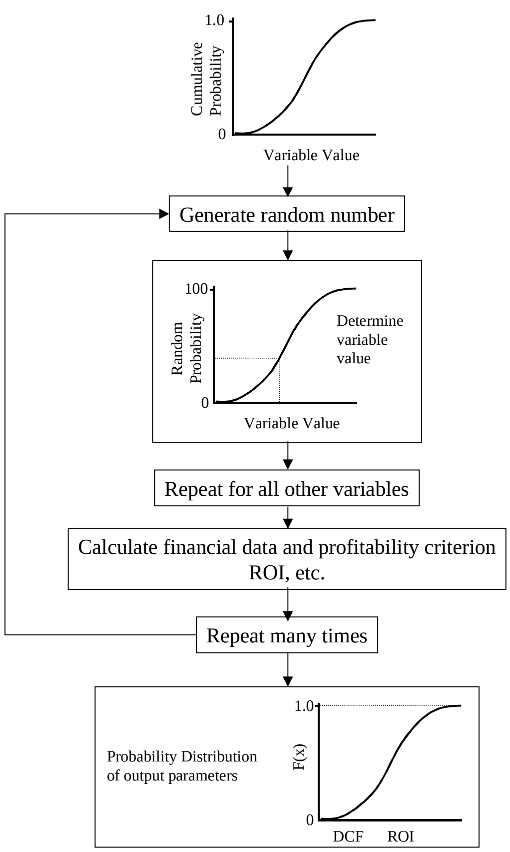


Figure 26. Steps in Economic Risk Analysis

Option I is the straight forward application of Monte Carlo simulation to the sophisticated analysis code which is the most exact probabilistic design approach but is also the most time-consuming and computationally intense. The second option, Option II, consists of using a "metamodel" seen as a RSE representation or approximation of the sophisticated analysis code. While much faster than Option I the approximation of the analysis may not be accurate enough, as only approximately 15 design variables can be included in the "metamodel". The third option, Option III, allows use of the sophisticated analysis code and approximates the Monte Carlo simulation through the use of Fast Probability Integration (FPI). FPI was developed for conducting probabilistic design of turbomachinery to insure high reliability using finite element analysis (FEA).[25]

Once a probabilistic approach to address economic uncertainties is incorporated directly into the RDS (Figure 15), discipline uncertainty and the impact of new technologies on performance and schedule risk can also be accommodated. To incorporate the pertinent design and environmental constraints, the top input in Figure 15, requires sophisticated or approximate analysis models which then can be handled by the options in Figure 27. The Robust Solutions that are the output of the RDS satisfy multiple objectives which result in Customer Satisfaction.

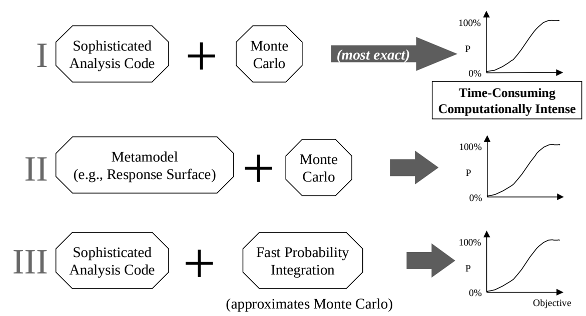


Figure 27. Options for Probabilistic Design

Technology Identification, Evaluation and Selection (TIES) Approach

The evolution of Georgia Tech's Aerospace Systems Design program is illustrated in Figure 28. As can be seen, the introduction of graduate rotorcraft design courses in 1984 initiated the evolution. In 1989 courses in "Introduction to Concurrent Engineering" and "Design for LCC" broadened the program to address quality and affordability issues. In 1992 the graduate design program was expanded to include fixed wing aircraft design courses and the ASDL was initiated based on a grant from NASA Ames Research Center on “Integration of Design and Manufacturing for the HSCT” under the NASA USRA ADP program. In 1994 NASA grants for the *Multidisciplinary Design and Analysis (MDA) Fellowship* program and the *New Approaches to MDO* were awarded to ASDL. These programs led to ASDL’s pioneering research in the use of Response Surface Equations (RSE) as approximations of higher fidelity, more physics-based disciplinary analysis tools for incorporation into the synthesis process at the system level. In 1995 the Aerospace Systems Design graduate program was expanded to include spacecraft design, particularly launch vehicle design. In 1996 the development of the RDS approach was initiated and also the Space Systems Design Laboratory (SSDL) was established. Also beginning in 1996 was the initiation of the Affordability Sciences effort with the Office of Naval Research (ONR) under their Affordability Measurement and Prediction Program. In 1997 the identification of Fast Probability Integration (FPI) was first introduced into RDS as an enabling technology for efficient

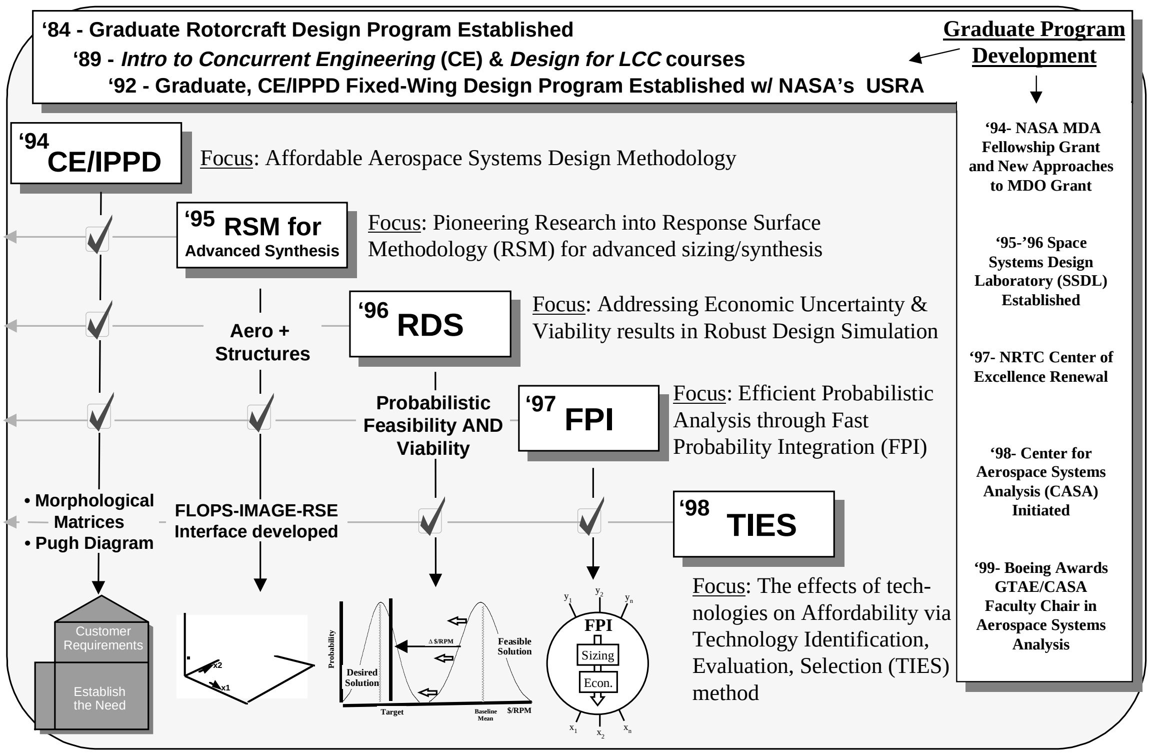


Figure 28. Evolution of Georgia Tech’s Graduate Program in Aerospace Systems Design

probabilistic analysis. In 1998 the Center for Aerospace Systems Analysis (CASA) was initiated, as an overarching center for the ASDL and SSDL efforts, based on government and industry support to address the affordability, safety, environmental and information technology issues facing the aerospace community. The TIES approach was also initiated in 1998 as a means for technology impact forecasting for both new and legacy systems.

The evolution described in the previous paragraph and illustrated in Figure 28 is based on using more of a *systems analysis* rather than *systems engineering* approach, thus the name for CASA. Systems analysis generally includes:

1. Breaking the system down into its component parts
2. Gaining an understanding of each of the individual parts
3. Knowing how the different parts interact
4. Recognizing the contribution of each part to the system
5. Putting the system back together based upon what was learned

Steps 1 and 2 are usually achieved without any major difficulty using traditional SE approaches, but steps 3 and 4 are seldom considered or receive only cursory attention. Discounting the importance of steps 3 and 4 when related to process or product results in dismantling of the system, redesigning and rebuilding parts or, more often, complete subassemblies, followed by assembly and retest of the total system. When related to management, continuous reorganization is the result. Each new reorganization is expected to achieve what the preceding ones failed to accomplish. Step 5 is really synthesis, but only if steps 1,2,3, and 4 were performed diligently and in depth. "In depth" does not mean excessive amounts of study. It does mean concentrating on the major factors that affect the system's performance.

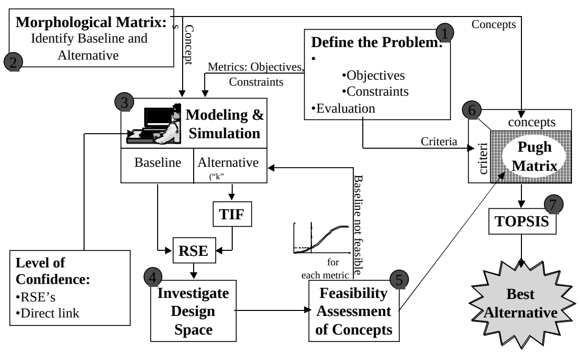


Figure 29. Technology Identification, Evaluation and Selection (TIES) Methodology

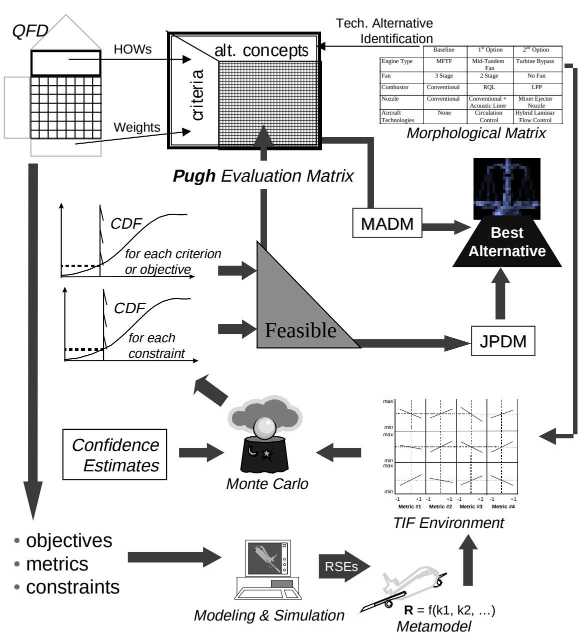


Figure 30. Pictorial Representation of TIES

Synthesis is no more than a fusion of all the known elements into a coherent whole. It requires bringing information together from many different sources and disciplines, evaluating that information in the context of the interactions, and putting that information together in such a way that the inter-dependencies of all the parts are satisfied. It means capitalizing on the total knowledge and expertise available in the system.[26]

The generic IPPD methodology illustrated in Figure 3 attempts to provide the systems analysis framework to address all of the five steps discussed above. This will then provide the necessary balance between synthesis and analysis. An example of how it is used for Technology Identification, Evaluation, and Selection (TIES) will now be presented. It outlines a comprehensive, structured, and robust methodology for decision making in the early phases of design of a new system or for the upgrade of an existing system. It will be introduced as an implementation approach for the generic IPPD methodology (Figure 3) and the RDS (Figure 15). Each of the seven steps illustrated in Figure 29 will now be briefly discussed as they set the framework for the detailed example that will be given in the Design Session at this AHS Forum: "Implementation of a Technology Impact Forecast Technique on a Civil Tiltrotor". A more pictorial representation of the TIES Methodology is illustrated in Figure 30.

1. *Problem Definition*: Once the need for a new or modified product/system is established, the Integrated Product Team (IPT) must translate the "voice of the customer" into the "voice of the engineer/ manufacturer/supporter" which entails the mapping of qualitative needs/requirements into system product and process parameters. A very efficient and organized method for accomplishing this translation is through "brainstorming" using the Seven Management and Planning Tools[27] and Quality Function Deployment[28](QFD). From QFD and the brainstorming techniques, system level metrics such as objectives, constraints, and evaluation criteria are established. As indicated in Figure 29, the evaluation criteria are used in the Pugh Evaluation Matrix[29] and the objectives and constraints are used in the Modeling and Simulation step. The brevity of this explanation should in no way diminish the importance of this step. On the contrary, any IPT will concur that formulating the problem properly is a key to its successful resolution. Also, engineering universities have often been criticized by industry for not spending enough time on problem formulation and too much time on problem analysis.

2. *Baseline and Alternative Concepts Identification*: When designing a complex system, such as an aerospace vehicle, there exists a multitude of combinations of subsystems or attributes that may satisfy the problem definition. A functional and structured means of decomposing the system is through the use of a Morphological Matrix (Ref. 24) and a Design Structure Matrix[30] (DSM). The Morphological Matrix aids the decision maker/designer/IPT in identifying possible new combinations of subsystems/attributes to meet the customer needs. Typically, a conventional configuration (one which contains present day technology) is chosen as a datum point to begin the feasibility investigation. Other combinations of attributes constitute the alternatives. All of these concepts are supplied to the Pugh matrix and are then evaluated in alternate steps. A Design Structure Matrix (DSM) is used to display the sequence of processes that are shown as numbered boxes on a diagonal. Feedforward and Feedback loops between the boxes are then evaluated to assess the couplings between functions and activities. DSM is therefore an excellent process development tool to accompany the Morphological Matrix product development tool. James L. Rogers at NASA LaRC has developed an excellent Design Manager's Aid for Intelligent Decompositon (DeMAID), which is a user-friendly tool based on the DSM and has been used in our graduate program in Aerospace Systems Design for the past five years, as well as at Boeing.

3. *Modeling and Simulation*: A modeling and simulation environment is needed to quantitatively assess the metrics being tracked for the concepts identified from the Morphological Matrix. These concepts can be subjected to qualitative assessment and this is what has been done in the Introduction to Concurrent Engineering/IPPD course and is illustrated in Figure 31. To facilitate the evaluation of many design alternatives and support sensitivity studies, conceptual design is most often performed with the use of monolithic or legacy vehicle synthesis/sizing codes. For robust design and assessment of new technologies these synthesis/sizing codes must be incorporated into a probabilistic design environment. The vehicle synthesis/sizing codes are, by nature, multi-disciplinary tools (aerodynamics, propulsion, and weights); however, the level of fidelity in each disciplinary area and the applicability of the historical database (in-the-box versus out-of-the-box designs) are the pertinent issues. When the chosen vehicle synthesis/sizing code is deficient, the appropriate analysis capability is introduced in the form of more physics-based higher fidelity tools. This has been the essence of much of the Multidisciplinary Design Optimization (MDO) work to date and is why the SE box in Figure 3 is identified as "System Synthesis through MDO".

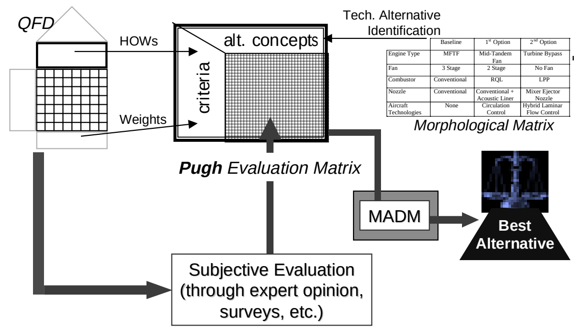


Figure 31. TIES without Modeling and Simulation

4. *Investigate Design Space*: This step provides for the establishment of the probabilistic design environment and the creation of the design space. The design space is created based on the design variables (and their ranges) defined in Step 1. In probabilistic design, the outcome sought is either a cumulative distribution function (CDF) or a probability density function (PDF) for each design objective or constraint. These distributions represent the outcomes of every possible combination of synthesized designs so it is a representation of the feasible design space against which the decision maker can now compare a desired target value. Based on these results, decisions concerning active constraints, relaxation of targets, relaxation of constraints or infusion of new technologies can be made. This approach has been the essence of parametric sensitivity in aerospace vehicle system design for the past 50 years, as illustrated in Figure 32[31]. However, in today's environment more than a few vehicle performance design variables must be varied; minimizing vehicle gross weight may not be the right objective function; and deterministic point designs don't adequately account for the risk and uncertainty in cost, schedule, and performance. Therefore, a probabilistic approach and the use of multi-objective functions must be included.

5. *Determination of System Feasibility and Probability of Success*: Once the target value for a specific metric is identified, concept feasibility is evaluated via the appropriate CDF by overlaying the target value. For example, if a metric has an 80% chance of achieving the target, the decision-maker

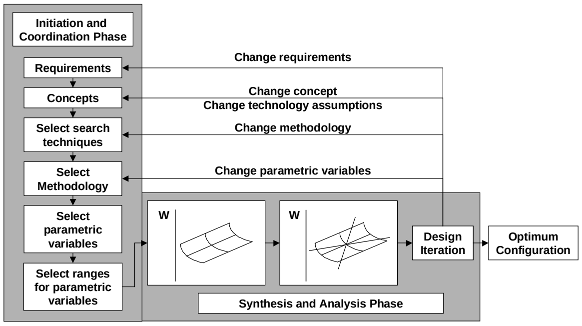


Figure 32. Vehicle Synthesis and Parametric Sensitivity

may assume that it is no longer a constraint and does not warrant further investigation. Yet, a low probability value (or small confidence) of achieving a probability value (or small confidence) of achieving a solution that satisfies the constraints implies that a means of improvement must be identified. This includes, but is not limited to, the infusion of new technologies. The need for the infusion of a technology is required when the manipulation of the variable ranges has been exhausted, optimization is ineffective, constraints are relaxed to a limit, and the maximum performance attainable from a given level of technology is achieved. The maximum level of a given technology is essentially the natural limit of the benefit. This implies that the maturation variation with time remains constant. When this limit is reached, there is no other alternative but to infuse a new technology. Formulation of new technologies in terms of elementary variables does not lend itself to disciplinary or multidisciplinary technology assessment. Hence, the assessment of new technologies must be addressed through the metrics they affect since synthesis/sizing tools are typically based on regressed historical data, limiting or removing their applicability to exotic concepts or technologies. The solution is to model and define technology metrics for the new technologies as a delta with respect to current technology based on subjective experience. In practical terms, technology metric “k” factors are introduced into the analysis or sizing tool to infuse a hypothetical enhancement or degradation associated with the new technology. In effect, the “k” factors simulate the discontinuity in benefits or penalties associated with the addition of a new technology.

6. *Population of the Pugh Evaluation Matrix*: The Pugh Evaluation Matrix is a method where concept formulation and evaluation is performed in an organized manner. The concepts identified in Step 2 form the columns, and the evaluation criteria (or important metrics) in Step 1 form the rows. The elements of the matrix are populated from the feasibility assessment for each concept and criteria. Since the metrics are in the form of CDFs, the decision maker has the ability to select a confidence level associated with a given metric. The confidence level is also related to the risk of uncertainty associated with a particular technology and the selection of these levels is purely subjective. The corresponding value of the metric (for a fixed confidence level) is then inserted into the appropriate cell of the matrix. This process is repeated for each metric and concept. It should be noted that the Pugh Evaluation Matrix, as originally conceived, was aimed at decision making under subjective terms when numerical data was unavailable. The matrix was populated based on a subjective scale determined by experts in the system (e.g., IPT).

7. *Best Alternative Concept Determination*: Once the Pugh Matrix is populated, the next step is to determine the best alternative concept. This decision making process is facilitated through the use of Multiple Attribute Decision Making (MADM) techniques. For the purpose of the TIES methodology, a Technique for Order Preference by Similarity to Ideal Solution[32] (TOPSIS) is utilized. TOPSIS provides an indisputable preference order of the solutions obtained in the Pugh Matrix with the end result being the best alternative concept.

Summary and Conclusions

An attempt has been made to document an evolution of methods and techniques that have evolved in the Georgia Tech ASDL over the past 7-9 years that are aimed at assisting the aerospace community in general, and the rotorcraft community in particular, in addressing Technology for Affordability through IPPD. The end product of this effort is the interactive “carpet/contour plot” illustrated in Figure 33. In this plot the blade loading, Ct/Sigma, is plotted versus wing loading for a notional Civil Tiltrotor. The constraints that are listed on this plot are from left to right: Sideline Noise, Direct Operating Cost (DOC), Installed Power, Gross Weight, and DOC plus Interest. Above the contour plot are the twelve design parameters (aspect ratio, wing loading, etc) and their current values along with a bar chart depicting the range of values for the parameters. Listed below the design parameters are the criteria/metrics that are used in an Overall

Evaluation Criterion (OEC) to evaluate the best solution for the impact of technology. Next to these criteria/metrics are bar charts indicating whether the constraints are active or not. The shaded area gives an indication of the probability of the constraint being satisfied. A completely shaded bar chart indicates that there is no probability that the constraint can be satisfied. The interdependencies of these constraints are captured in the contour plot. Since the contour plot is completely shaded gray, with no white spaces, there is no feasible solution for the combination of design parameters and constraints identified. This indicates that either the constraints have to be relaxed or a new technology incorporated to identify a feasible design space. The parametric evaluation of new technologies is provided in the referenced Design Session paper at this AHS Forum. This interactive environment, which we call Robust Design Simulation (RDS) provides a Roadmap to Affordability and can be used to assess technologies for rotorcraft affordability through Integrated Product/Process Development (IPPD).

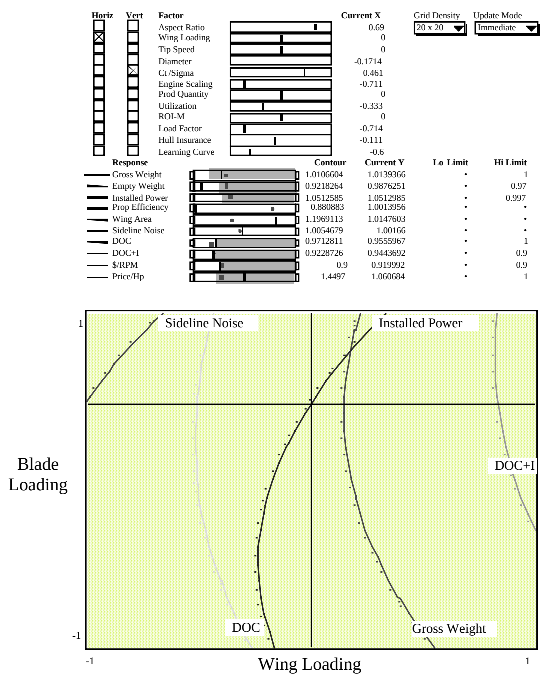


Figure 33. Contour Plot for Civil Tiltrotor

The importance of the contour plot in Figure 32 versus the one in Figure 19 for the Hiller Model 1100 LOH solution is that affordability and environmental constraints are included in Figure 32, while only performance, geometric, and operational constraints are included in Figure 19. This is a significant breakthrough for addressing affordability early in the design process; for conducting technology impact forecasting for new and modified systems; and does it using a probabilistic design approach. The research is far from being complete, but a RDS environment has been created that can be used by the rotorcraft community. Georgia Tech, in the Center of Excellence in Rotorcraft Technology (CERT) and the Center for Aerospace Systems Analysis (CASA), along with its supporting laboratories, ASDL and SSDL, look forward to working with industry and government in addressing real problems facing the aerospace community.

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