A Stochastic Approach to Designing Affordable, Environmentally Acceptable Systems

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Abstract

The objective of this paper is to give an overview of current research thrusts focused on meeting the challenges associated with designing complex systems. Such systems must be capable of simultaneously meeting future needs for affordable, environmentally acceptable systems. These requirements for increased environmental compatibility, increased performance, and decreased cost are all fundamentally contradictory, and there is consequently a need for new design philosophies and methods capable of synthesizing acceptable solutions from a landscape of innumerable possibilities. In 1997, researchers at the Georgia Institute of Technology began responding to this need by exploring new methods for systems design under a base of funding provided by the NSF, ONR, and others. Many of these initiatives have since shown outstanding promise as stepping stones in the path to development of comprehensive methods to design affordable, environmentally acceptable systems. This paper describes five of these research thrusts in detail and illustrates opportunities for transition of these methods into industrial practice and educational curricula.

1. INTRODUCTION

There is a revolution happening today in the way complex systems are designed and built. This revolution was provoked by the simultaneous convergence of several trends. First, tomorrow's systems will be more complex than ever before, so much so that no *single* person will be able to *fully* understand and master the details of every subsystem and synthesize them all into a coherent, functional whole. This is particularly evident when it is necessary to continually make trades amongst various subsystems using "apples to oranges" comparisons between options. A framework is needed which can provide a "universal currency" for evaluating the merit of design trades, particularly where overall system affordability is concerned.

This further implies several more needs: in order to evaluate various design trades, one must have detailed, physics-based modeling and simulation (M&S) tools available. One must further recognize that even the best M&S tools cannot capture every possible factor impacting the performance of a complex system. It is therefore essential to have the capability of making these design trades in the presence of uncertainty. Moreover, this uncertainty is not static but varies with time (i.e. it is stochastic), and this must be factored into the design process. The design must be robust with respect to external uncertainties. Finally, one must be able to assess the feasibility and viability of the overall system in the context of the environment in which it is to operate. Each of these five needs is addressed in turn and various research thrusts focused on meeting these needs are described.

2. AFFORDABILITY PROBLEM FORMULATION

The subject of how best to define affordability for complex systems, particularly that pertaining to vehicles, has been a point of debate for many years. This is because of the complexity in defining accurate and logical definitions of cost and developing accounting systems to track it. However, research in the fields of thermodynamics, systems design, economic theory, and others have begun to see integration and application to a degree never before seen. The results have enabled a detailed understanding of all elements contributing to vehicle cost using a single figure of merit based on *fundamental thermodynamic principles*.[1,2,3,4,5,6,7,8] An example of the results obtainable from this process is shown in Figure 1, which gives cost breakdown for a typical Boeing 737 airliner. The left-most pie chart shows total cost breakdown. The fuel cost is then broken down by major subsystem, and the propulsion system fuel cost is further broken down by engine component. The latter two portions of this figure are results that *cannot be obtained by conventional analysis*. The methods developed under this NSF-funded research initiative are now capturing the interest of various entities within industry (GEAE, Boeing) and government (NASA, Army) and are also beginning to be taught in graduate level propulsion design courses at GT. This research was possible because the NSF provided "seed money" to pioneer research that was initially deemed to "academic" to warrant industrial support.

3. PHYSICS-BASED MODELING AND SIMULATION

As engineered systems become more complex and subject to increasingly stringent requirements, the task of modeling these systems becomes more costly and time-consuming. This is particularly the case during the early stages of the design process where there is little knowledge available to use in building a product model, yet the design decisions made at this stage will have far-reaching impact. A striking example of this is the technology selection process common to the initial phases of all high-capital design projects. For instance, in the design of a new jet aircraft, one of the first steps is to select the basic technologies to be used in the vehicle. There are typically many technology concepts "on the drawing board" at any given time, and not all of these technologies will necessarily be useful in helping to meet a particular set of design objectives. Even if they were, there are never enough resources to develop them all into production-ready concepts at the same time. Therefore, one must select technologies quickly and judiciously while simultaneously factoring in the risk and resources required for each.

This is a daunting problem and one that has no easy solution. However, considerable progress towards a viable method to meet these needs has been made over the past several years, thanks to support from the NSF and the Office of Naval Research (ONR). This has resulted in the development of the Technology Identification, Evaluation, and Selection (TIES) method, the basic elements of which are shown in Figure 2.[9,10,11,12,13] TIES is a method for selecting technologies, beginning with identifying a need, developing a physics-based metamodel to represent generic technologies, evaluating technology concepts, and selecting those that are the most beneficial to a given set of design objectives. These methods are today being funded through government entities such as ONR and NASA.

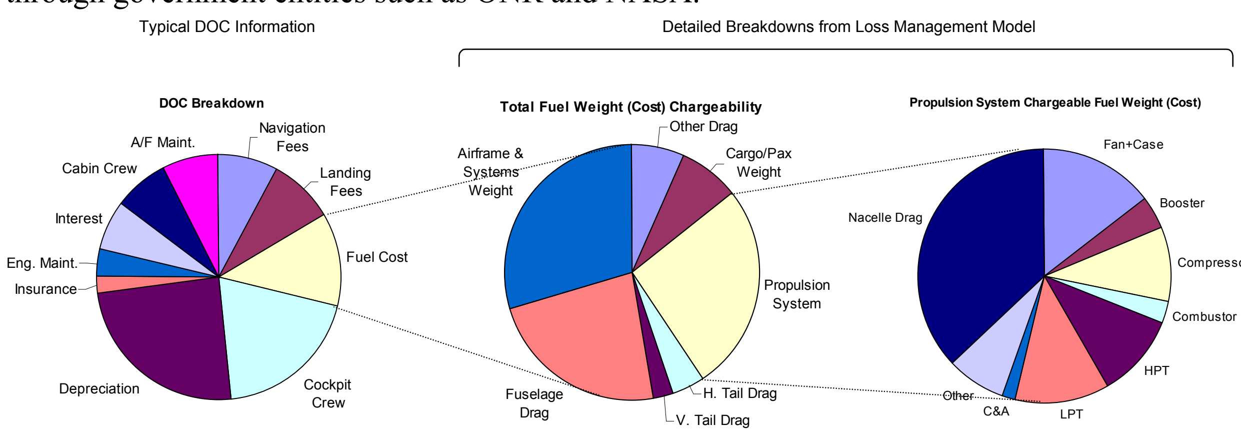

Figure 1: Typical Operating Cost Breakdown (Engine Component Level).

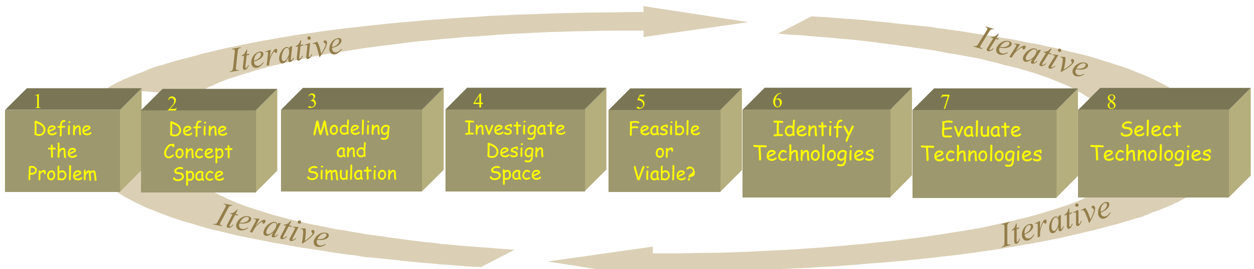

Figure 2: Steps in the TIES Analysis Process.

4. UNCERTAINTY MODELING

A third element required for comprehensive design of affordable, environmentally acceptable systems is a means of accounting for the uncertainty that is an integral part of complex systems. Considerable research and development has been done on methods for analyzing this type of uncertainty, particularly as it pertains to complex systems design. Probabilistic analysis algorithms have proven useful as "wrappers" around deterministic analysis codes, and this approach has proven highly effective in understanding uncertainty associated with external factors that are beyond the designer's control.[14,15,16] An example of such an analysis is given in Figure 3, which shows how uncertainty in aircraft mission requirements can impact the thrust requirement for a propulsion system. The left side of this figure shows distribution on mission parameters such as range, payload, and maneuver requirements. The right side shows a probability distribution of required thrust. This type of information can be used to assist designers in selecting the best thrust class for an engine to ensure the highest probability of meeting the ultimate thrust requirement without over-designing the engine. The methods developed under this research initiative sponsored by NSF support are now seeing application with several of our industrial sponsors, most notably GE Aircraft Engines. They are also seeing considerable use in government, notably at NASA Glenn Research Center, and are also being taught in the graduate aircraft design course sequence at Georgia Tech.

5. ROBUST DESIGN SIMULATION

A topic closely related to uncertainty modeling is robust design simulation. This is essentially an extension of uncertainty modeling wherein the objective is to not only model uncertainty, but also manipulate the design so that it is as insensitive to uncertainty as possible. A typical example of this is probabilistic engine cycle design, as described in reference 17. Ref. 17 describes how the engine thermodynamic cycle for a large commercial turbofan engine can be selected so as to minimize the impact of design and external uncertainties on system performance. This study was conducted in conjunction with our industrial partner, GE Aircraft Engines, and is described in further detail in reference 18. Moreover, these methods are also being taught in the graduate design sequence of courses at Georgia Tech.

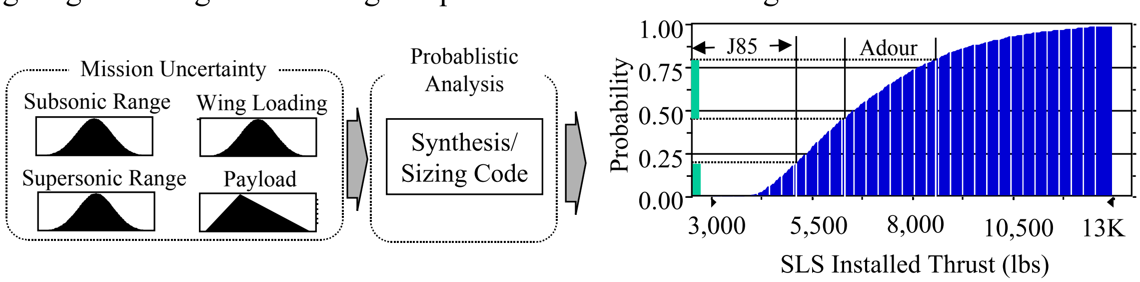

Figure 3: Typical Probabilistic Engine Thrust Sizing Results.

6. FEASIBILITY/VIABILITY ASSESSMENT METHOD

The last research effort that will be mentioned in connection with stochastic design of affordable, environmentally compatible systems is the role of system feasibility/viability evaluation methods in determining overall system merit.[19] To understand what this means, consider Figure 4, which shows a global business modeling and simulation environment for the aircraft engine industry. The previous discussion focused on the internal and external uncertainties and how one could design for uncertainty using robust design techniques, as shown at the upper and lower right of Figure 4.

One must capture this uncertainty in the context of an affordability problem formulation using physics-based modeling and simulation tools (right center) that will allow examination and visualization of all salient features regarding how these factors impact the engine design. However, all of these decisions must be made in the context not only of how close the engine design and technologies come to meeting requirements, but must also include the entire business environment. In effect, one must consider how engineering design decisions interplay with optimal business strategy. Thus, some of the newest research efforts are focusing on applying mathematical concepts such as game theory in conjunction with engineering analysis methods, physics-based models, and business environment models to find analytical answers to questions such as "when is it optimal to partner with another company?", and "what is the optimal core engine size to ensure maximum flexibility to respond to market demand?" In fact, our industrial partners are already expending considerable resources to develop the engineering and business models necessary to make the boxes depicted in Figure 4 a reality. Georgia Tech is working to develop the underlying theory that will be needed to sort through the innumerable competitive scenarios to find the handful that provide the most robust strategy in a competitive business environment. It is anticipated that results obtained from this research initiative will ultimately be folded into the curriculum at Georgia Tech.

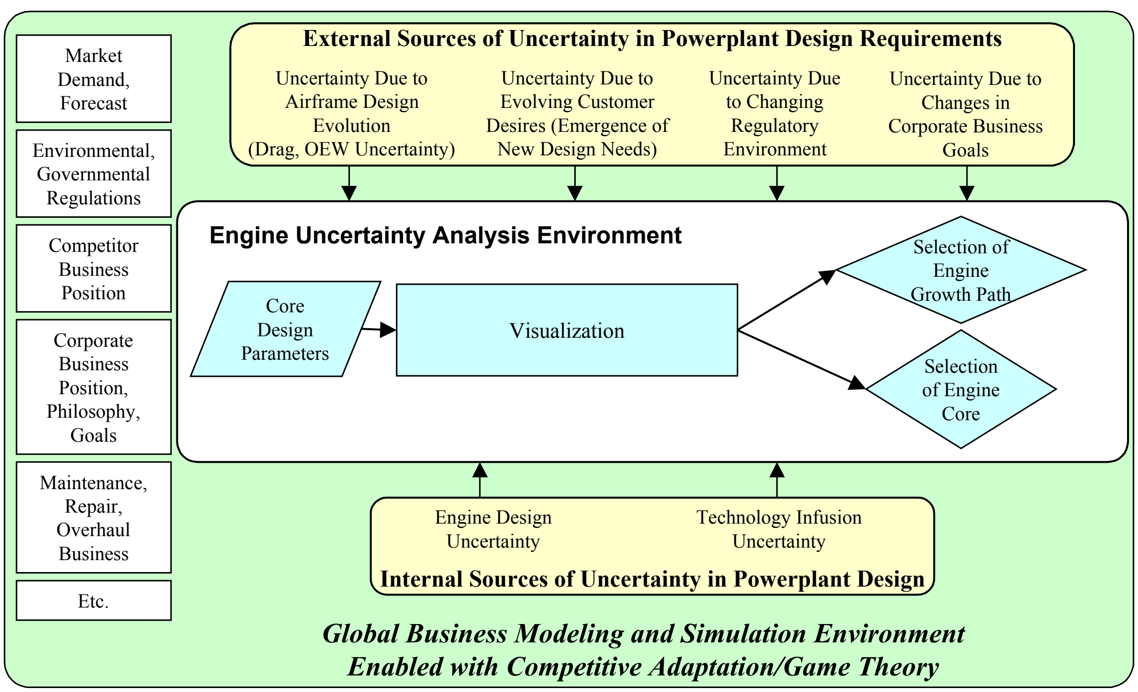

Figure 4: Research Vision Linking Design Uncertainty, Requirements Uncertainty, and Engine Design.

7. CONCLUSIONS

It is evident that there is considerable need for a new paradigm in the way complex systems are designed and built. This is need is particularly poignant in light of the increasingly stringent (and mutually exclusive) requirements on performance, cost, and environmental compatibility. Researchers at Georgia Tech, in conjunction with NSF support, set out in 1997 to find means of addressing this need. This ultimately led to the initiation of several new and innovative lines of research, a few of which are described briefly herein. Each of these lines has been developed to the point of maturity as to be ready for transition into government-sponsored development or even industrial practice. Thus, the seed money initially provided by the NSF for this work has not only advanced the state of the art in complex systems design, but it has also spawned *several* self-sustaining areas of new research that will ultimately yield benefits manifold greater than the initial investment. The references listed below are all part and parcel of the research sponsored under this grant.

8. REFERENCES

1 Roth, B.A., Mavris, D.N., "A Comparison of Thermodynamic Loss Models Suitable for Gas Turbine Propulsion," J. of Propulsion and Power, Mar-Apr 2001, Vol 17, No. 2, PP324-332.

2 Roth, B.A., Mavris, D.N., "A Generalized Model for Vehicle Thermodynamic Loss Management and Technology Concept Evaluation," presented at the World Aviation Congress and Exposition, San Diego, CA, Oct. 2000, SAE2000-01-5562.

3 Roth, B.A., Mavris, D.N., "A Work Availability Perspective of Turbofan Engine Performance," presented at the AIAA Aerospace Sciences Meeting, Reno, NV, Jan 2001, AIAA2001-0391.

4 Roth, B.A., and Mavris, D.N., "A Generalized Work Potential Perspective of Engine Component Performance," Presented at the 2001 AIAA/ASME/SAE Joint Propulsion Conference, Salt Lake City, UT, 8-11July, 2001, AIAA2001-3301.

5 Roth, B.A., and Mavris, D.N., "A Comparison of Propulsion Loss Decks for the J85-GE-21 Turbojet Engine," Presented at the 2001 AIAA/ASME/SAE Joint Propulsion Conference, Salt Lake City, UT, 8-11July, 2001, AIAA2001-3300.

6 Roth, B.A., Mavris, D.N., "Technology Evaluation via Loss Management Models Formulated in Terms of Vehicle Weight," Presented at the 59th International Conference of the Society of Allied Weight Engineers, St. Louis, June, 2000. SAWE paper number 3001.

7 Roth, B.A., Mavris, D.N., "A Comparison of Thermodynamic Loss Models Suitable for Gas Turbine Propulsion: Theory and Taxonomy," Presented at the 36th Joint Propulsion Conference and Exhibit, Huntsville, AL, July 2000, AIAA2000-3714.

8 Roth, B.A., Mavris, D.N., "A Comparison of Thermodynamic Loss Models Applied to the J-79 Turbojet Engine," Presented at the 36th Joint Propulsion Conference and Exhibit, Huntsville, AL, July 2000, AIAA2000-3715.

9 Roth, B.A., German, B.J., Mavris, D.N., "Adaptive Selection of Engine Technology Solution Sets from a Large Combinatorial Space," Submitted to the 2001 AIAA/ASME/SAE Joint Propulsion Conference, Salt Lake City, UT, 8-11July, 2001.

10 Roth, B.A., Mavris, D.N., Macsotai, N.I., "Adaptive Selection of Pareto-Optimal Engine Technology Solution Sets," Submitted to the 23rd Congress of the International Aeronautical Sciences, Toronto, 8-13 Sept. 2002.

11 Kirby, M.R., Mavris, D.N., "A Technique for Selecting Emerging Technologies for a Fleet of Commercial Aircraft to Maximize R&D Investment," Presented at the SAE Aerospace Congress and Exhibition, Seattle, WA, September 10-13, 2001.

12 Kirby, M.R., Mavris, D.N., "A Method for Technology Selection Based on Benefit, Available Schedule and Budget Resources," Presented at the 5th World Aviation Congress and Exposition, San Diego, CA, October 10-12, 2000.

13 Roth, B.A., Graham, M., Mavris, D.N., "Adaptive Selection of Aircraft Engine Technologies in the Presence of Risk," 2002 ASME Turbo Expo, Netherlands, June, 2002.

14 Mavris, D.N., Roth, B.A., and Macsotai, N.I., "A Method for Probabilistic Sensitivity Analysis of Commercial Aircraft Engines," Presented at the 14th ISABE, Florence, Italy, Sept. 1999.

15 Roth, B., Mavris, D., and Elliott, D., "A Probabilistic Approach to UCAV Engine Sizing," 34th Joint Propulsion Conference, July 13-15, 1998, Cleveland, OH, AIAA98-3264.

16 Mavris, D.N., Roth, B., "A Methodology for Robust Design of Impingement cooled HSCT Combustion Liners," 35th Annual Aerospace Sciences Meeting and Exhibit, Reno, NV, January 6-9, 1997. AIAA-97-0288.

17 Mavris, D.N., Macsotai, N.I., Roth, B.A., "A Probabilistic Design Methodology for Commercial Aircraft Engine Cycle Selection," 1998 World Aviation Congress and Exposition, Anaheim, CA, September 28-30, 1998. SAE-985510.

18 Roth, B., Mavris, D., "A Stochastic Approach to Designing Affordable, Environmentally Acceptable Systems," Presented at the 1999 NSF Grantees Conference, Long Beach, CA, Jan. 1999.

19 Roth, B.A., Mavris, D.N., "Commercial Engine Architecture Selection in the Presence of Uncertainty and Evolving Requirements," Presented at the 14th ISABE, Bengalore, India, Sept. 2001.

20 Roth, B.A., Mavris, D.N., "Commercial Engine Architecture Selection in the Presence of Uncertainty and Evolving Requirements," Presented at the 14th ISABE, Bengalore, India, Sept. 2001.