ROTORCRAFT SYSTEM DESIGN
FOR
AFFORDABILITY THROUGH
INTEGRATED PRODUCT/PROCESS DEVELOPMENT
(IPPD)

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Abstract

It is well known that the Life Cycle Cost (LCC) for complex systems, such as rotorcraft, gets locked in early during the design and development process. One reason for this situation is that many early product design decision s are made by the aircraft manufacturer/designer during conceptual design, before they are passed on to subcontractors/ suppliers/vendors for design at the component/sub component/part level. This approach results in a time lag for conceptual design being conducted by the various participants. This serial, product decomposition approach has resulted in high performance and capable systems, but not always the most affordable or competitive system. This traditional approach assumes that minimizing weight reduces cost, even LCC. Integrated Product /Process Development (IPPD) is being tauted as a new approach, where parallel product/process (performance/cost) design tradeoffs are conducted. This paper will present how system design for affordability through IPPD, including rotorcraft, is being development in the Georgia Tech Aerospace Systems Design Laboratory (ASDL).

Introduction

A popular figure that has been used over and over, again to depict how LCC gets locked in early for complex systems is provided in Figure 1. Two curves are illustrated: one generic in nature and the other based on the Boeing ballistic missile system for which data was generated in developing the generic curve. If these curves are correct, and most people believe they are, especially for aerospace systems, then it is during conceptual design and concept development phase where most of the leverage is available to impact LCC.

The traditional development process that has been used for aerospace systems is illustrated in Figure 2. As can be seen, mission requirements drive conceptual design and a performance based, optimized design is achieved through parametric sensitivities using first level analysis. This Vehicle Design Synthesis approach is illustrated for rotorcraft in Figure 3. It is unique for aeronautical systems and has provided a multidisciplinary design optimization (MDO) approach from the outset. Four columns are shown: Requirements, Systems Models, Synthesis, and Configuration Solution. Requirements are performance and/or mission oriented, thus product dominated and do not reflect life cycle downstream process considerations, such as how the system will be produced or manufactured, maintained or supported, and upgraded or retired. Four System Models are identified in Figure 3: two to balance the performance requirements and two to balance the mission requirements. All of these models can be first level or of higher fidelity, although sophisticated analysis has traditionally been conducted in Preliminary Design, as illustrated in Figure 2, when more knowledge and time are available. The multiple disciplines involved in conceptual design have been propulsion, aerodynamics and weights engineering. A major portion of the MDO research effort in the U.S. and Europe has been aimed at bringing more sophisticated, product-oriented disciplinary analysis (aerodynamics, propulsion, structures, and controls) into conceptual and preliminary design, using emerging mathematical and information based technologies.

As illustrated in Figure 3, the balance between engine power available and vehicle power required determines the critical vehicle power loading, whether it be for hover, forward flight or maneuver. By the same token, the balance between fuel weight ratio *available* (from empty weight fraction and known useful load) and fuel weight ration *required* (from mission analysis) determines the vehicle gross weight. Synthesis is achieved through the balance of vehicle power gross weight which results in an installed power and a Configuration Solution. A clear understanding of vehicle-design synthesis is necessary when understanding rotorcraft affordability, as will be addressed in a later section.

An excellent discussion of how the approach illustrated in Figure 3 has been used in a multidisciplinary manner to improve the performance/capability of rotorcraft has been provided by Carlson (Ref.1). figure 4 (Figure 7 from Ref. 1) portrays the mission segments that must be considered, in addition to range, to exploit rotorcraft capability. Vertical Take-off and Landing (VTOL) must be available over a large range of altitudes and ambient temperatures. The installed power (power loading, l_{po}) required to achieve this VTOL capability is a function of rotor efficiency (figure of merit M_f), rotor disk loading (w, a design parameter) and engine lapse rate characteristics. Many rotorcraft missions (e.g., military, rescue, logging) require that significant time be spent in hover and the fuel required for this flight mode is, as with power loading, a function of rotor efficiency and disk loading and, as in the range segment, a function of fuel and weight efficiency. Weight efficiency is expressed in terms of W_E and W_p, which are empty weight ($_E$) and payload ($_p$) fractions of gross weight (W_g), respectively.

It can be seen that the traditional development process, illustrated in Figure 2, based on the vehicle-design synthesis in Figure 3, has greatly enhanced the performance/capabilities of rotorcraft and other aeronautical systems. However, the emphasis today is on producing more affordable aircraft to gain and/or retain world market share and new design methods and tools are required. This is especially true for rotorcraft, if they are to fulfill their potential in the commercial marketplace. "System Design for Affordability through IPPD" is the new design methodology being developed in the Georgia Tech ASDL and will be discussed in a later section. First, a review of rotorcraft economics will be presented.

Rotorcraft Economics

Success of rotorcraft as commercial transportation systems has been very spotty over the past forty years. Numerous enterprising commercial efforts have been initiated, only to end in bankruptcy. While rotorcraft have proven to be a very formidable weapon systems for the military, their affordability is also often questioned in view of the large cost, both acquisition and support, that they incur. In the U.S., NASA recently hosted an Economics Workshop (Ref. 2), with objectives to identify the key cost drivers, develop strategies for minimizing costs, and for improving cost prediction capabilities. Several presentations where made which addressed the inaccuracy and fallacy of using weight-only based cost estimating relationships. In a presentation entitled: "Helicopters Cost Too Much" by Frank Harris, he concluded that the price is driven quite differently between fixed and rotary wing aircraft. He provided the following estimated purchasing price relationships:

For Rotorcraft:
$$ Driven by (Weight Empty)$^{0.4638}$ x (Total Eng(s)). HP)$^{0.6238}$

For Fixed Wing (Propeller Driven):
$$ Driven by (Weight Empty)$^{0.8649}$ x (Total Eng(s). HP)$^{0.2786}$

Mr. Harris concluded that rotorcraft $'s per pound of weigh empty is roughly twice as sensitive to power loading (i.e., HP/GW) as a prop drive airplane. To make matters worse, providing VTOL capability has required doubling HP/GW. Therefore, he concludes that the real problem is power and its high price in the VTOL world.

Using a more detailed Rotorcraft base price estimating relationship, provided in Figure 5, (Ref. 2), Mr. Harris was able to get correlation for a database of 121 helicopters and one tilt rotor aircraft with an average error of +/- 10.2%. Note that this relationship not only includes design factors, but also the country in which the rotorcraft is produced. Note that the most affordable light commercial helicopter should be a single piston powered, single main rotor helicopter with fixed landing gear, built in Russia or some other country with extremely low labor rates.

Mr. Harris' insights are very worthwhile and they are particularly enlightening if the Vehicle-Design Synthesis process in Figure 3 is understood. As can be seen in Figure 3, vehicle power loading is at least an equal partner with vehicle gross weight in Synthesis. Since the hover power loading is usually critical, especially at high altitude and hot temperature conditions, the price of VTOL capability through increased installed power can be readily appreciated.

One of the first insightful looks at rotorcraft economics was provided in a paper by two Hiller Helicopters engineers, F. David Schnebly and Richard M. Carlson, at the Tenth Annual Forum of the American Helicopter Society (AHS), June 24-25, 1954 (Ref. 3). Their paper (1) outlined costs trends in present rotorcraft designs; (2) suggested a basis for determining revenue potentials, and (3) presented a method of tabulating cost figures for complete economic analysis of any transport helicopter operation. Among their conclusions, based on three hypothetical helicopter designs capable of carrying 10, 20 and 35 passengers, respectively, were the following:

> Minimum direct costs would result from a 35-passenger design, and little would be gained from this standpoint by increasing the rotorcraft's size to carry more passengers.

Higher utilization drives costs down rapidly; 3000 hours per year was cited as an "ultimate goal".

Costs are lowest at design ranges: helicopters designed for 200-mile ranges will be relatively expensive to operate on shorter hauls; limited seat capacities in such operations will not allow operator to take advantage of full gross weights.

Costs per passenger-mile minimize at about fifty cents (50 cents pr ton-mile) for the 35-passenger design, assuming 75% load factor. This is closest to twice the fixed-wing transport figure.

It was concluded by the authors that whether this cost is too high depends upon the time saving involved, as well as upon what other forms of transportation with which the helicopter is competing. With trip lengths around 30 miles, overall time needed for trip by helicopter is calculated as roughly one-third the time required for the same trip by airplane. On this basis, according to Schnebly and Carlson, passengers might well be willing to pay a fare three times as high. (Ref. 3).

Another insightful look at rotorcraft economics was provided by Michael K. Hynes, former President of Brantly-Hynes Helicopter, Inc. (Ref. 4). He states "to design, produce, and bring to market any helicopter is not the result of some secret process. At its simplest level, it takes some well-known ingredients, namely: capital, engineering, material, fabrication man-hours, supervision and overhead". He emphasizes that "Time is the enemy" and illustrates it by reviewing the time required to obtain an FAA helicopter Type Certificate. He concludes that for some of the best and most capable companies in the world, it takes an average of 32 months - and all the while the costs continue to mount. Another important point made by Mr. Hynes is that the future of the commercial light helicopter industry is dependent upon their ability to improve what they already have and to continue to gain public acceptance. One step that he advocated was to make it easier for interested parties to obtain their helicopter ratings by establishing highly qualified and innovative helicopter flight schools. The airplane industry realized this fact long ago and set up numerous learn-to-fly centers.

System Design for Affordability

The totality of the "System" must be considered from the outset if affordability for complex systems are going to be impacted where the design freedom and LCC leverage are available, Figure 1. This focus, along with the life cycle time line, is illustrated in Figure 6. Everyone of the elements along the time line, e.g., design, develop, etc., can be considered process based and should be subjected to cost/time analysis as early in the design process as possible. In addressing LCC, it should be realized that a re required tradeoff between acquisition and operations and support cost must occur. An excellent example is provided by Mr. Hynes (Ref. 4) concerning the replacement of piston engines with turbines in light helicopters. He states:

> "To put a jet into a low-cost helicopter is an exercise in economic futility. Even the newest and smallest turboshaft engine, recently certificated by an East Coast firm, will have a price tag of $35,000. The FAA approval for installation in a helicopter would run into the $250,000 area. Putting it as simply as possible, it doesn't matter how cheap these engines are to run; if you can't afford to buy one, you'll never receive the benefits of its low operating costs."

Affordability is where competition is determined today, largely as a result of emerging economic powers around the world which are providing increased competition, as well as the quality revolution that has swept the industrialized world. The continuing to evolve elements of quality evolution are illustrated in Figure 7 (Ref. 5). This evolution is from *Cost Advantage*, through the use of cheap labor and high volume, low mix production; to *Quality*, through SPC, variability reduction and customer satisfaction; to today's emphasis on *Time-to-Market* and *Product Variety*. The sub-elements under today's emphasis are all affordability directed and require new design methodologies which can be applied as early in the design/development process as possible.

While many, but not all, companies in the commercial sector have adopted, it not completely accepted, the changing environment in Figure 7, the Department of Defense (DoD) in the U.S.A. is just beginning to adopt this change and now emphasizes the use of Integrated Product/Process Development (IPPD) and the use of Integrated Product Teams (IPTs) in all of its DoD activities (Refs. 6&7). The DoD acquisition process and its interfaces are illustrated in Figure 8. An extremely complex process involving numerous players in government and industry, a complete "culture change" will be required to accommodate in defense the necessary transitions taking place in the commercial sector. At the bottom of Figure 8 are two aspects of Industry Design Phases which reflect the need for an IPPD design/development methodology. While the Product Design Phases encompass a *decomposition flow* from Conceptual to Preliminary to Detailed design; the Process Design States reflect a *recomposition flow* from On

Line Quality methods from Tolerance to Parameter to System design (Ref. 8). System Design is the earliest design phase and involves:

- Development of a system with intended function.
- Requires technical knowledge from science and engineering.
- Originality/invention/marketing strategy
- Design Concept

Since this phase/stage is where the most design freedom exists and the LCC can be leveraged, it has been the focus for the Georgia Tech IPPD affordable design methodology effort. By using the term "System Design", it also avoids the confusion of the term "Conceptual Design" which is product design oriented and occurs at different times in the design life cycle for the different participants in the development of complex, aeronautical systems.

Georgia Tech IPPD Approach

Georgia Tech is one of the few universities in the world that has a graduate research and education program in Aerospace Systems Design. Graduate courses were initiated in Rotorcraft Design in 1985 to provide an interdisciplinary experience for graduate students in the School of Aerospace Engineering involved in the Center of Excellence in Rotorcraft Technology (CERT), an ongoing rotorcraft center of excellence since 1984 with principal sponsorship coming from the Army, industry and now, NASA. Concurrent Engineering methods and tools were introduced in 1989, along with a Design for LCC course. A formal graduate degree program was approved in 1992, when fixed wing, as well as rotary wing aircraft design courses were introduced and the Aerospace Systems Design Laboratory was formed to support the program. The current emphasis is on "System Design for Affordability through IPPD" and stresses the use of Robust Design Simulation. Robust design is becoming an overused word and the definition used in our Aerospace Systems Design program is:

> "the systematic approach to finding *optimum values of design factors* which result in *economical* designs with *low variability*.

Taguchi (Ref.. 8) achieves this goal by first performing Parameter Design, and then, if the conditions still are not optimum, by performing Tolerance Design. Georgia Tech in its ASDL is addressing System Design, where science and engineering along with innovativeness and creativity are used to achieve synthesis and determine optimum values of design *control factors*, not just their variability to *noise factors*.

Understanding the IPPD process flow for parallel cost/performance tradeoffs and system decomposition/recomposition is a prerequisite for implementing the Georgia Tech IPPD design methodology. This process flow is illustrated in Figure 9. It illustrates both the product and process design phases/stages discussed previously in boxes located round the outer circle. Starting at the top (conceptual Design (System)) box the clockwise flow around the right half of the circle represents the decomposition flow through the product design phases. This flow corresponds to the traditional development process illustrated in Figure 2. The small inner circle trades represent the various trades made during conceptual, preliminary and tolerance design, respectively. while this approach has resulted in high performing and capable aeronautical systems, it doesn't reflect the affordability emphasis in today's environment. The fallacy with this traditional development approach has been that numerous design changes were required when the Manufacturing Process box at the bottom of Figure 9 is encountered. These changes are reflected by the "humps" in the serial approach illustrated in Figure 10. Also illustrated in Figure 10 is a Concurrent Engineering approach which illustrates a higher "hump" earlier in the life cycle, the design and development phase, where the cost of change is substantially lower, and substantially lower "humps" in the latter phases. It is during this early phase that the IPPD focus must be applied.

This IPPD focus is presented in Figure 9 by the recomposition left half flow from the bottom Manufacturing Process box around to the top Conceptual Design (System) box. The small inner circle trades represent process design trades and, as mentioned earlier, Taguchi methods have usually been applied in making component trades during the Parameter and Tolerance phases/stages, while the emphasis with the Georgia Tech approach is during the System Design phase/stage. A major purpose of the flow in Figure 9 is to illustrate that numerous, parallel product/process design trades are necessary at different levels. For critical (high risk) product/process technologies an IPPD design methodology must allow for the incorporation of detailed (tolerance) based design information in the System level design trades. The emergence of robust design methods and information-based technologies can allow this capability.

Product/process metrics for design tradeoffs at various levels of the decomposition/recomposition flow in Figure 9 must be identified early in the design/development process. Figure 11 illustrates examples of these metrics for aeronautical systems, with an Overall Evaluation Criterion (OEC) identified in the center box. Most of the metrics are readily recognizable, especially on the right half, product design side.

The process metrics, however, are cost and time oriented and are not as familiar, especially to design and product technology engineers. Any process during the life cycle of a complex product must be measured in terms of time and cost. Cycle time reductions and comparison are of utmost importance in the changing environment, Figure 7. Cost/time analysis for theoretical production is illustrated in Figure 12 (Ref. 10). Cumulative time for manufacturing/production is illustrated on the vertical axis, while cost/unit is on the horizontal axis. Emanating from the origin is a line defining the relationship between time and cost. Its intersection with Cost/Time (Learning Curve) is highly dependent on the projected lot size. The thrust for "Just-In-Time manufacturing" can readily be explained using such a curve, as the drive to reduce setup time can be directly related to reducing setup cost (inventory, etc.) This type of curve can also be used to assess critical processes during system Design candidate election, as illustrated in Figure 13. Various processes can be plotted from historical data and technology (both product/process) demonstration programs (in the case of new concepts & materials) and evaluated in a "carpet plot" like format, similar to product technology constraint curves. If the use of large thermoplastic materials in aircraft structural concepts would have been evaluated using such a cost/time analysis in conceptual/system design, numerous later design changes, and the cost and performance changes associated with them could have been avoided on past aircraft development programs.

While the example of cost/time analysis illustrated in Figure 12 has been representative of manufacturing/production, a similar cost/time analysis should be conducted for each of the critical life cycle elements/ processes identified on the bottom of Figure 6, e.g., design, develop, etc.

Typical models used for the decomposition and recomposition activities illustrated in Figure 9, to address the metrics in Figure 11 are illustrated in Figure 14. Both engineering and multi-level LCC models are required. The use of a Knowledge Based System (KBS) for process modeling is required to adequately address the heuristics involved with process cost/time analysis. The integration framework for engineering and multi-level LCC models has been developed by a recent Ph.D. student at Georgia Tech using various wing structural/material concepts for the High Speed Civil Transport (HSCT) (Ref. 11). It has also been introduced into the fixed wing aircraft design course curriculum during the past year.

Georgia Tech IPPD Design Methodology

A generic IPPD methodology has been developed at Georgia Tech and has been used in its aerospace systems design education and research programs. It is illustrated in Figure 15 and consists of four elements in the form of an umbrella at the top of the chart with the interaction of these four elements underneath the umbrella. This methodology is used to allow the parallel product/process design trades at the different levels illustrated in the IPPD flow of Figure 9. The four key elements are: System Engineering methods, Quality Engineering methods, a Top-Down Design Decision Support process, and a Computer-Integrated Environment. Each of these elements are *necessary*, but not *sufficient*, for the execution of IPPD. Systems Engineering methods have been a powerful contributor to designing and developing complex systems for the past forty years, but have been predominantly *product design driven*. Quality Engineering methods reflect the quality revolution that has taken place over the past twenty years, but are predominantly *process design driven*. The decision support process is at the heart of all design trades and should be at the center of any design methodology. However, decision made without the necessary information, gained from appropriate methods/tools, are at best a hit or miss proposition. The emergence of information-based technologies allows the creation of decision-based architectures and the Computer-Integrated Environment. This capability not only allows the interaction between the other key elements, illustrated in Figure 15, but also allows progress toward the "Virtual Companies", identified as the next phase in the Quality evolution, Figure 7.

Much of the development of the Georgia Tech IPPD methodology has been focused on the High Speed Civil Transport, based on grants received to support this effort, as well as the economic challenges facing the introduction of Second-generation Supersonic Transport (SST). However, under the National Rotorcraft Technology Center (NRTC) Rotorcraft Center of Excellence (RCOE) program the Georgia Tech CERT has received funding for a task: "Basic IPPD Research for Affordable Rotorcraft Design". This task falls under the NRTC category: Affordability: Integrated Product and Process Development (IPPD)-Supported by Virtual Prototyping (VP) and Advanced Distributed Simulation (ADS). The Georgia Tech plan for this task is to collaborate closely with industry and government (NASA/Army) by focusing the basic IPPD research for affordable rotorcraft design on a Civil Tilt Rotor (CTR) aircraft and air vehicle technology insertion for an existing military helicopter.

There is much to be learned for all aeronautical system affordability (both civil and military) from the unique relationship and interface that must exist between the aircraft manufacturer and the operator, as well as regulatory authorities, for commercial transport aircraft development.

The aircraft and engine manufacturers, along with the operators, are the principal participants with respect to identifying a key product and process characteristics, based on customer requirements, principally the passengers. This unique relationship between participants is based on early aircraft economic assessment as illustrated in Figure 16. As can be seen strong interactions and communications must take place early in the program to understand the bottom line relationship between ROI and Price, and the sensitivity to overall success metrics for each: production quantity (manufacturer) and required yield (airline). With deregulation of the airline industry and the introduction of numerous low cost, no frills airlines, airline yield, as measured in required average yield Revenue Passenger Miles, \$/RPM has become the overall criterion driving the airline industry, as well as aircraft manufacturers. An Aircraft Life Cycle Cost Analysis (ALCCA) has been developed by NASA over the years to provide simulation of this environment and its flow of operations is illustrated in Figure 17. It provides a very useful tool for understanding how the key product and process characteristics are brought together for cost-performance trades between the aircraft manufacturers and airlines.

At the NASA Rotorcraft Economics Workshop (Ref.. 2), Mr. Tom Galloway, NASA Ames Systems Analysis Branch suggested a similar approach to be applied for the Civil Tilt Rotor (CTR) economic Assessment. The Georgia Tech plan is to research the application of Robust Design Simulation (RDS) for further development of the Georgia Tech generic IPPD design methodology illustrated in Figure 15.

Georgia Tech Robust Design Simulation

As illustrated in Figure 15, much of the interaction of the three elements below the umbrella involves robust design assessment and optimization. It is also illustrated in Figure 7 that Product/Process Simulation is a key element of Time-To-Market. As stated in the definition of Robust Design variability is a key element, therefore, the idea of Robust Design Simulation is key to the execution of IPPD. The RDS that has been developed and executed for fixed wing aircraft is illustrated in Figure 18. It has been called by both students and faculty, "the inverted pyramid". It involves starting with key discipline design variables (both product & process), determined from screening using a two-level Design of Experiment (DOE) screening process in conjunction with Pareto charts. Using these key design variables and Response Surface Methodology (RSM) recomposition takes place by generating Response Surface Equations (RSEs) at the technology metric level. Point design optimization can then take place; however, by introducing uncertainty analysis using Monte Carlo simulation, robust solutions can be generated for an Overall Evaluation Criterion (OEC). The OEC can be solely based on an economic metric, such as \$/RPM, or a weighted set of criteria, which may be more applicable for military systems. The outer arrows and feedback loops illustrate the iterative nature of RDS and how it can be utilized in a design decision process.

Summary and Conclusions

To be competitive in the work marketplace industry has realized that for complex systems, such as rotorcraft, affordability must be considered as early as possible in the design/development process. New design methodologies that allow Integrated Product/Process Development (IPPD) are required. Over the past five years, Georgia Tech, in its Aerospace Systems Design Laboratory has been developing a new IPPD design methodology based on Robust Design Simulation. While much of the focus has been on fixed wing aircraft, and specifically the High Speed Civil Transport, a new task under the NRTC RCOE will allow Georgia Tech to conduct research and develop this methodology for rotorcraft. Rotorcraft System Design for Affordability through IPPD is the thrust of this effort and this paper has focused on the need and the approach to be followed.

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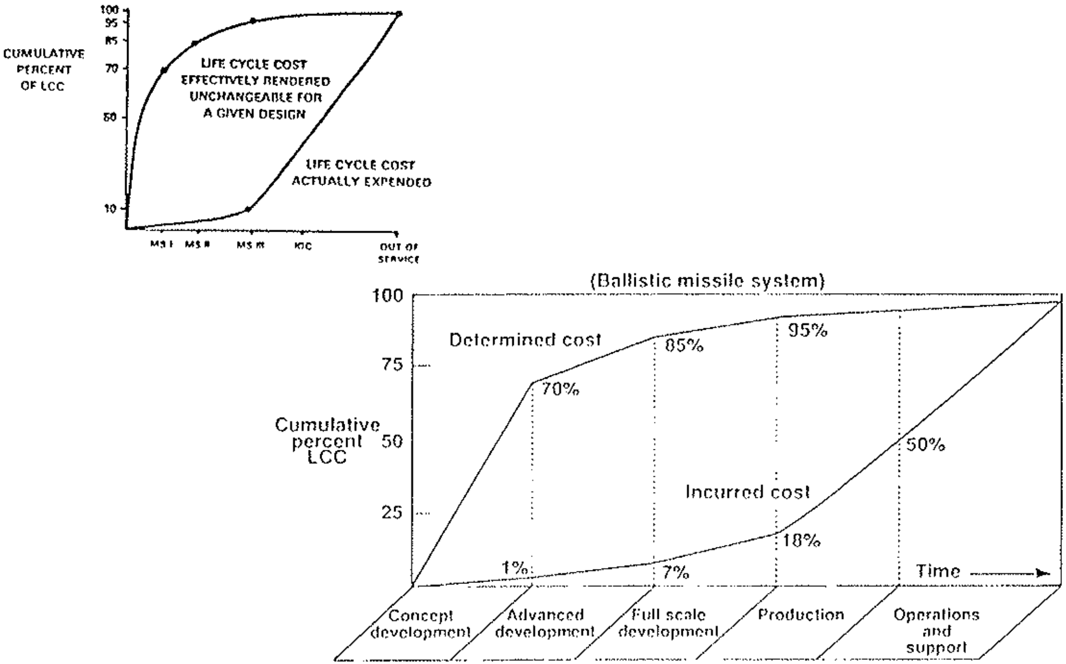

Source: Boeing Company

Figure 1: Life Cycle Costs Gets Locked In Early for Complex Systems

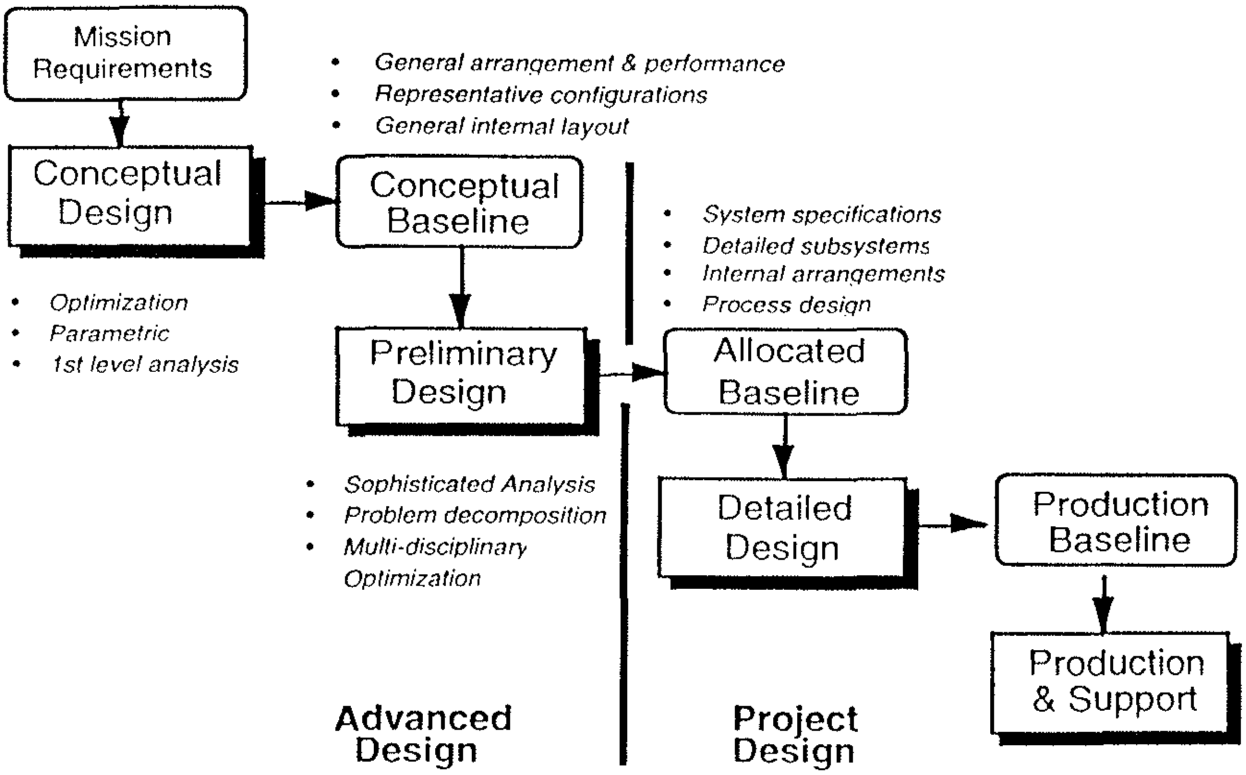

Figure 2: Traditional Development Process

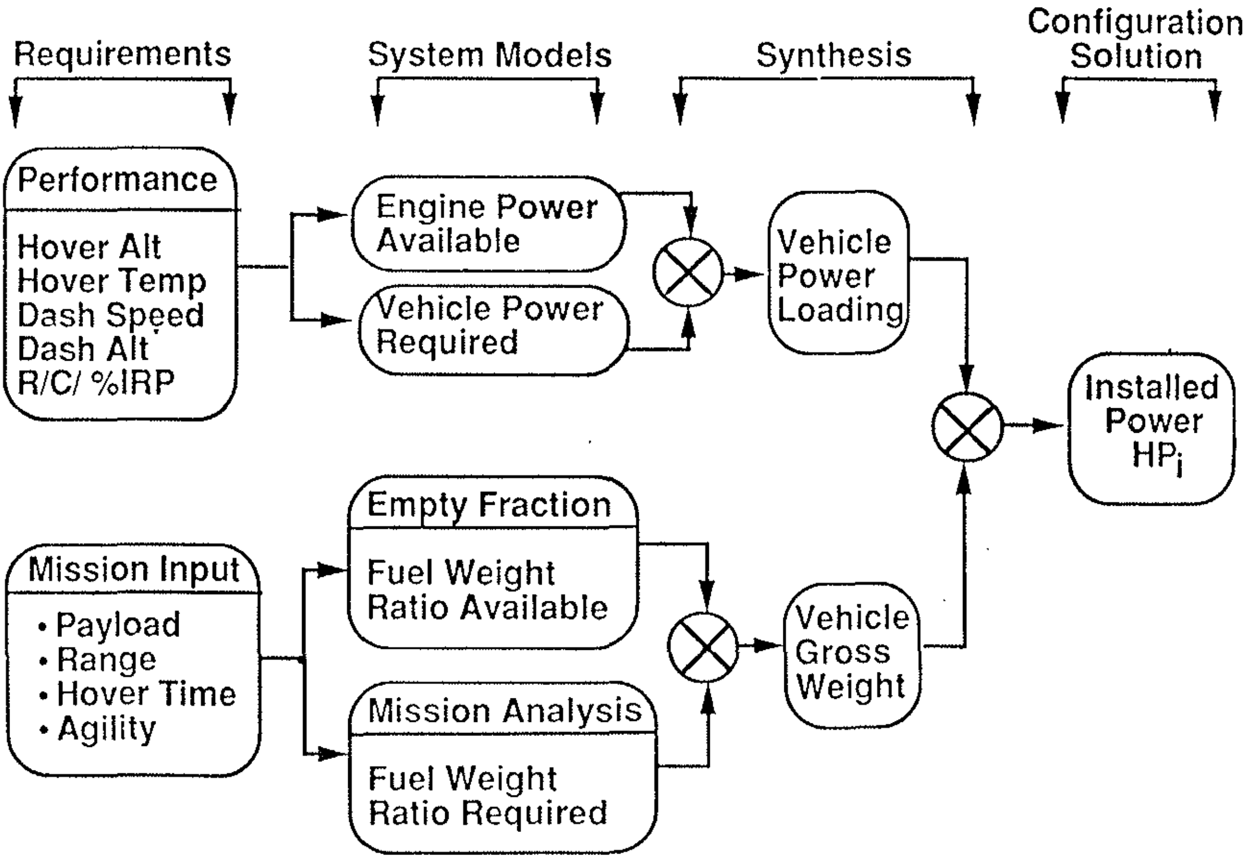

Figure 3: Vehicle Design Synthesis

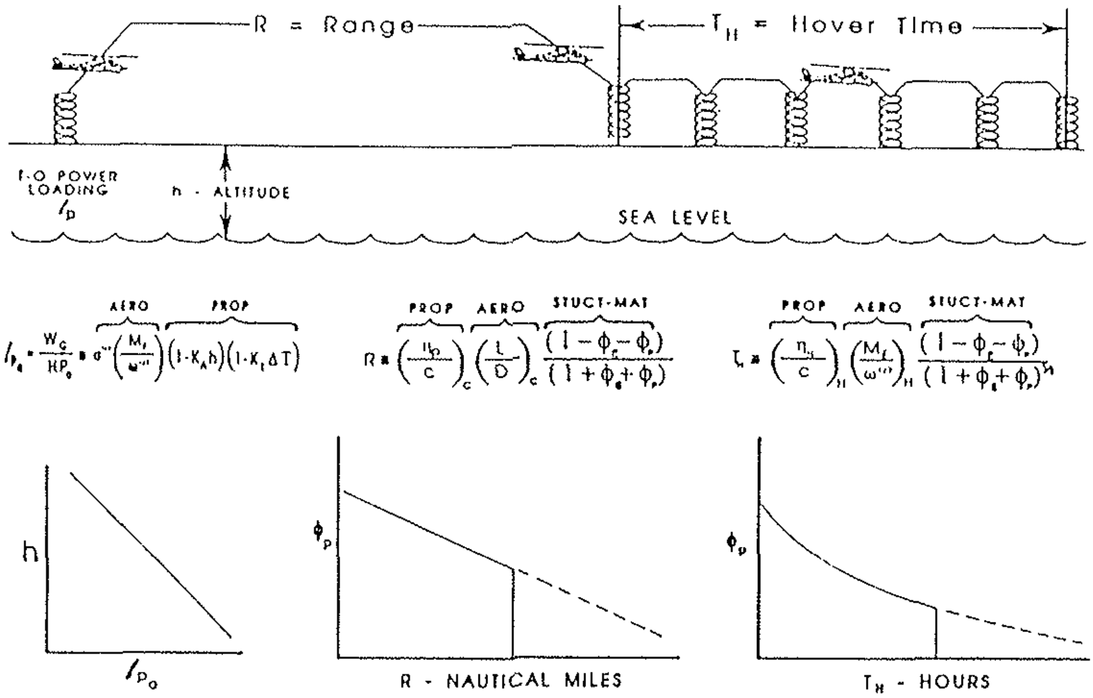

Figure 4: Altitude-Range-Hover Mixed Mode Missions

Note: Found From 121 Helicopters & 1 Tiltrotor

In 1994 Dollars,

$$\text{Base Price} = \$227 \times H \times (\text{Wgt. Empty})^{0.4638} \times (\text{Total Eng (s). HP})^{0.6238} \times (\text{Blades Per Rotor})^{0.1750}$$

Where H is the product of 5 factors:

$$H = \text{Eng. Type} \times \text{Eng. No.} \times \text{Country} \times \text{Rotors} \times \text{Ldg. Gear}$$

The Factors Are:

Engine Type	
Piston	1.000
Piston (Supercharged)	1.330
Piston (Converted to Turbine)	1.175
Gas Turbine	1.750

Engine Number	
Single	1.000
Multi	1.328

Country	
U. S. Commercial	1.000
Russia	0.337
Fr/Ger	0.879
Italy	1.042
U. S. Military	0.804

No. of Main Rotors	
Single	1.000
Twin	1.084

Landing Gear	
Fixed	1.000
Retractable	1.104

Figure 5: A Rotorcraft Base Price Estimating Relationship (With An Average of 10.2%)

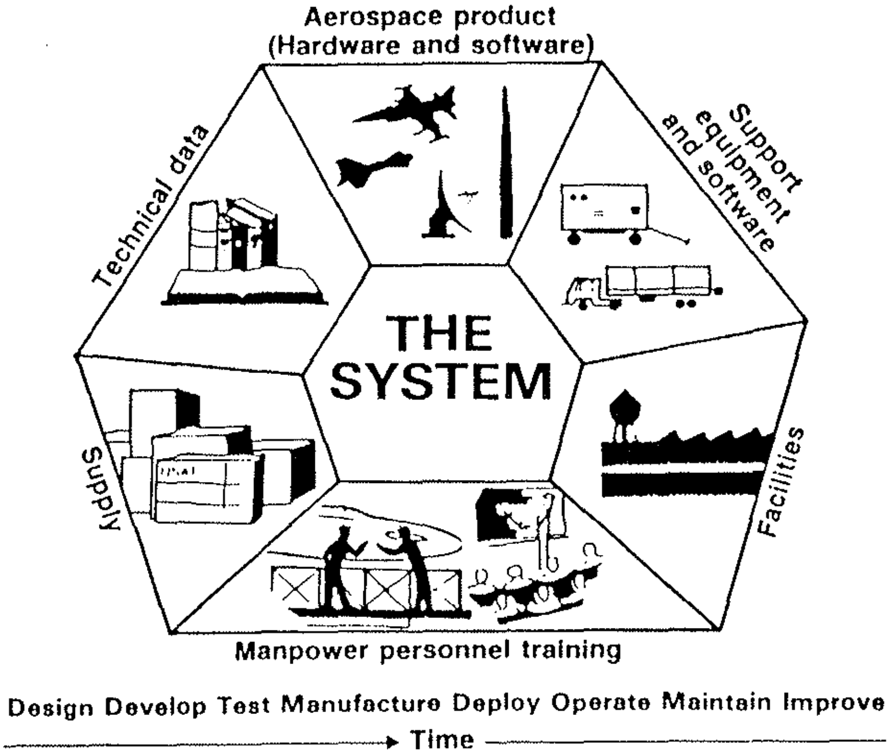

Figure 6: The Totality of the System

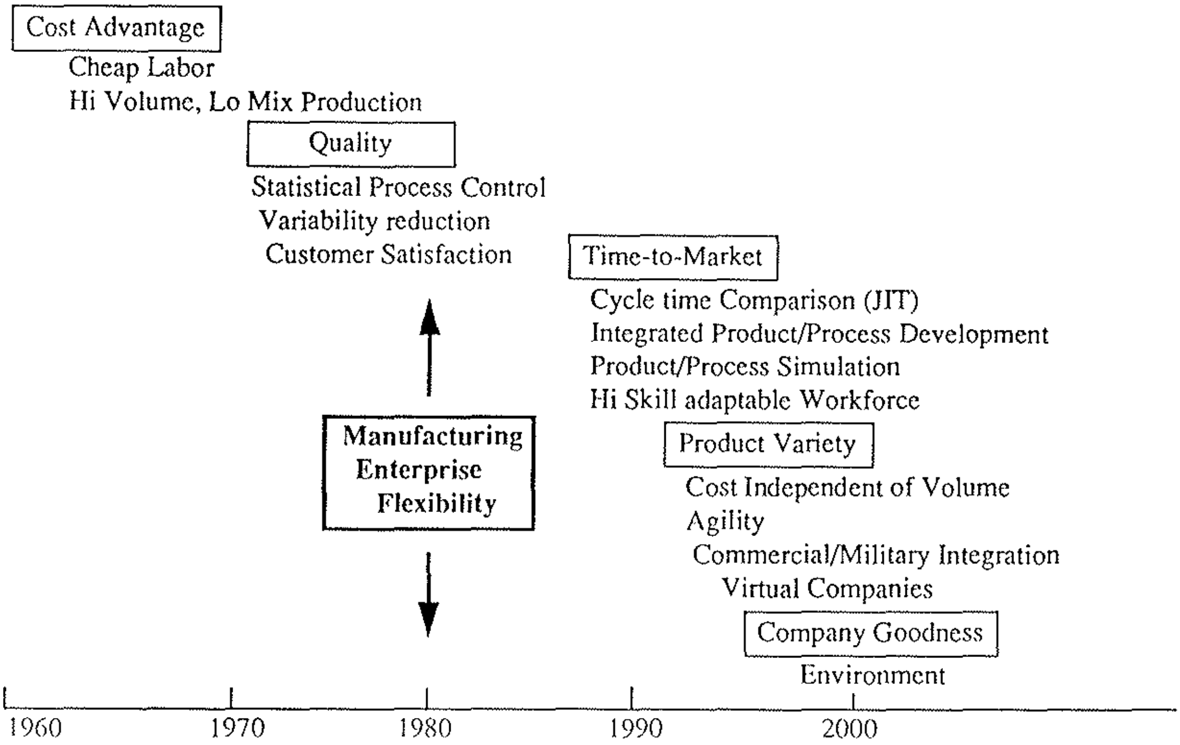

Figure 7: Where Competition is Determined Today

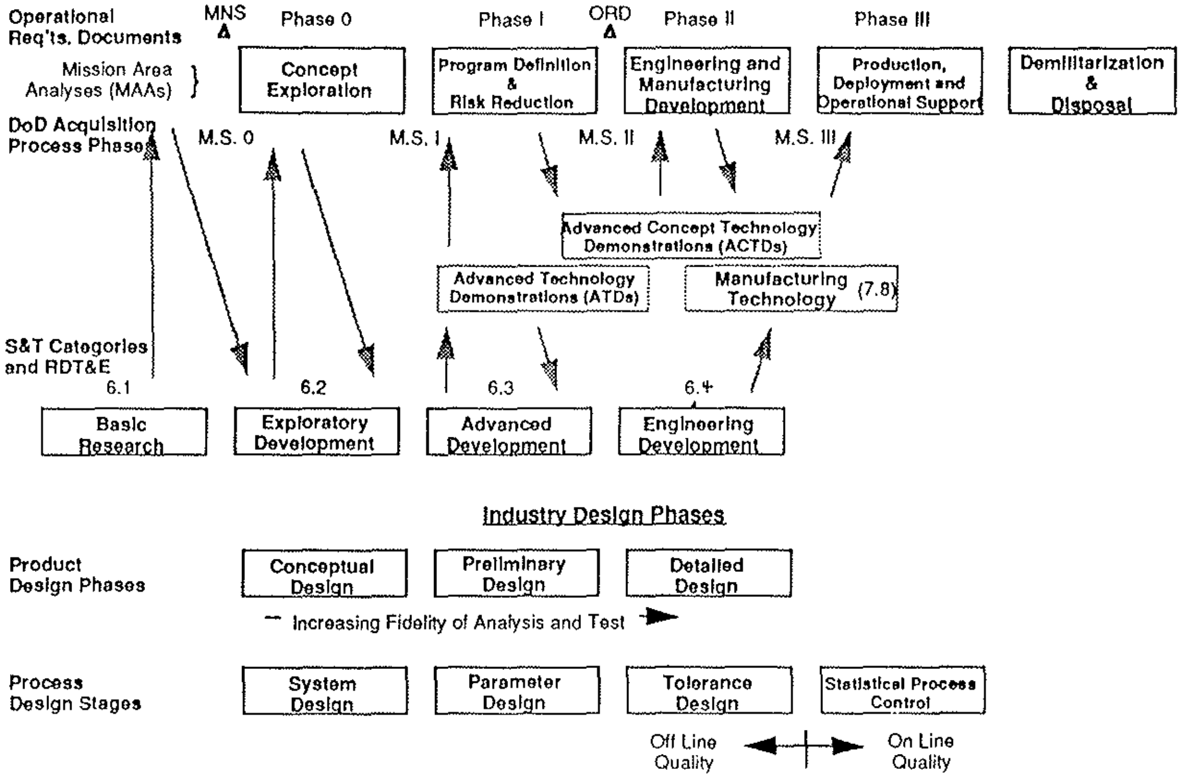

Figure 8: The DoD Acquisition Process and Its Interfaces

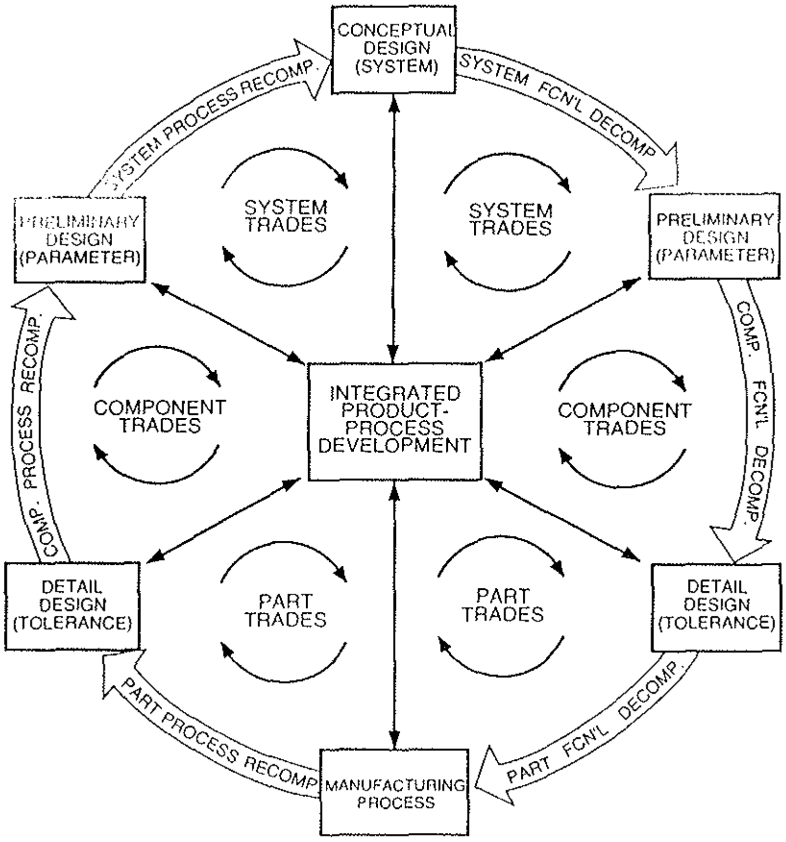

Figure 9: IPPD Process Flow for Parallel Cost/Performance Tradeoffs and System Decomposition/Recomposition

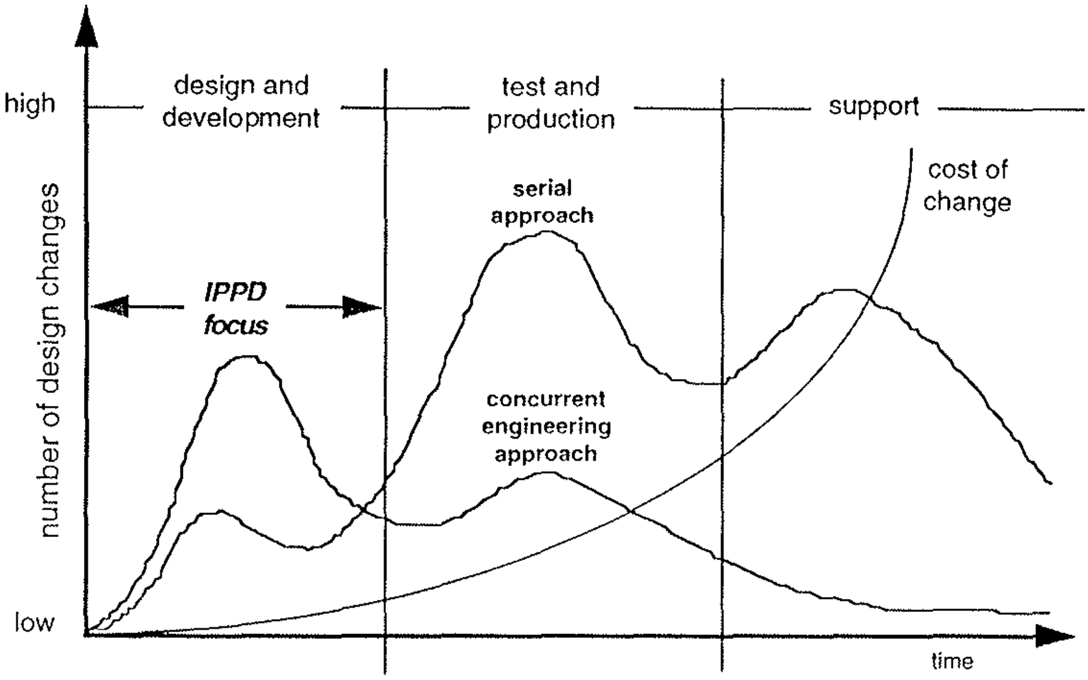

Figure 10: A Traditional Serial Approach Versus A Concurrent Engineering Approach

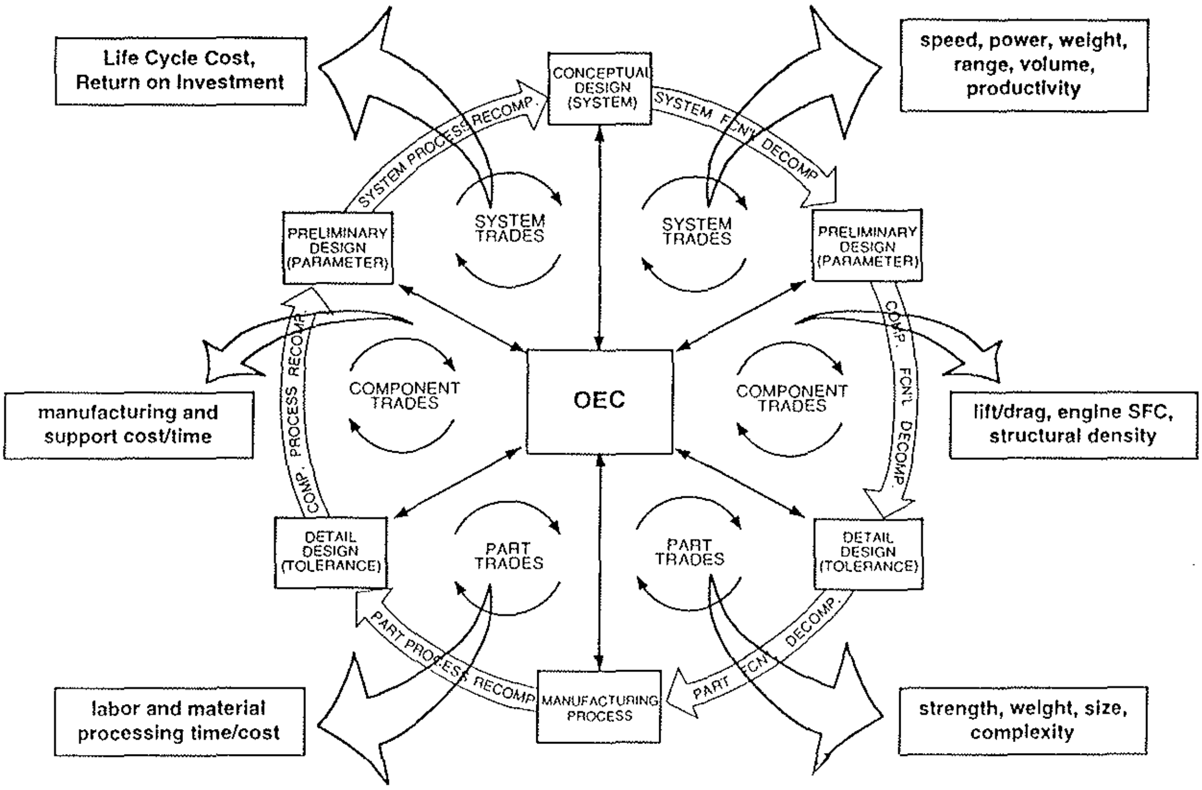

Figure 11: Product/Process Metrics for Design Trade-offs at Various Levels of Decomposition and Recomposition

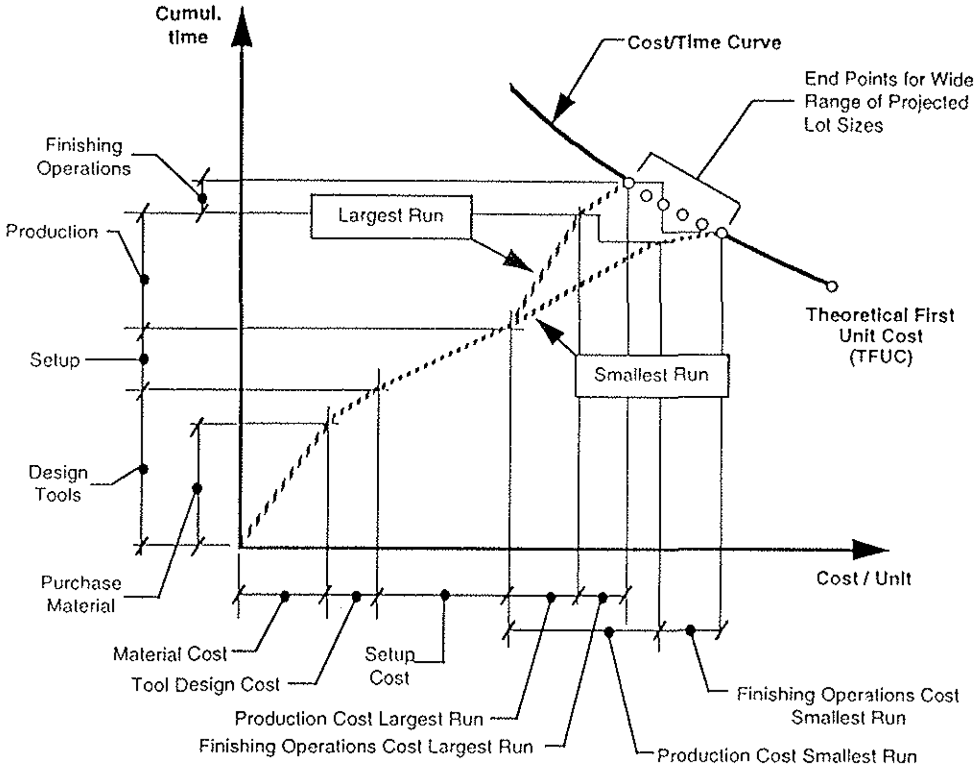

Figure 12: Cost/Time Analysis for Theoretical Production

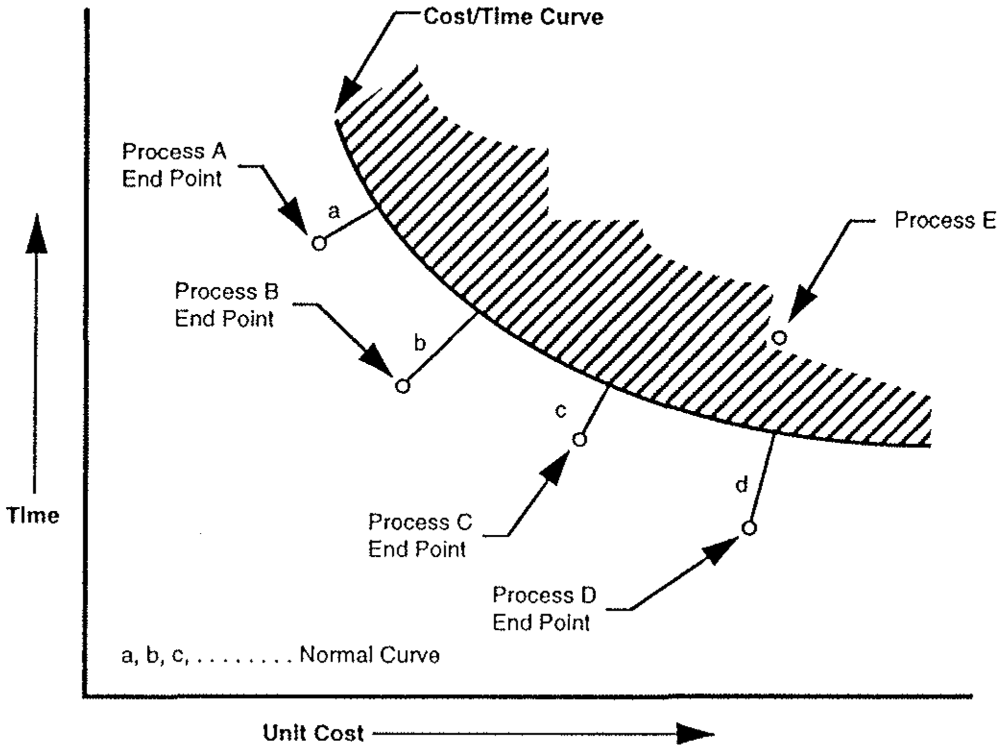

Figure 13: Cost/Time Constraint Curve for Candidate Selection

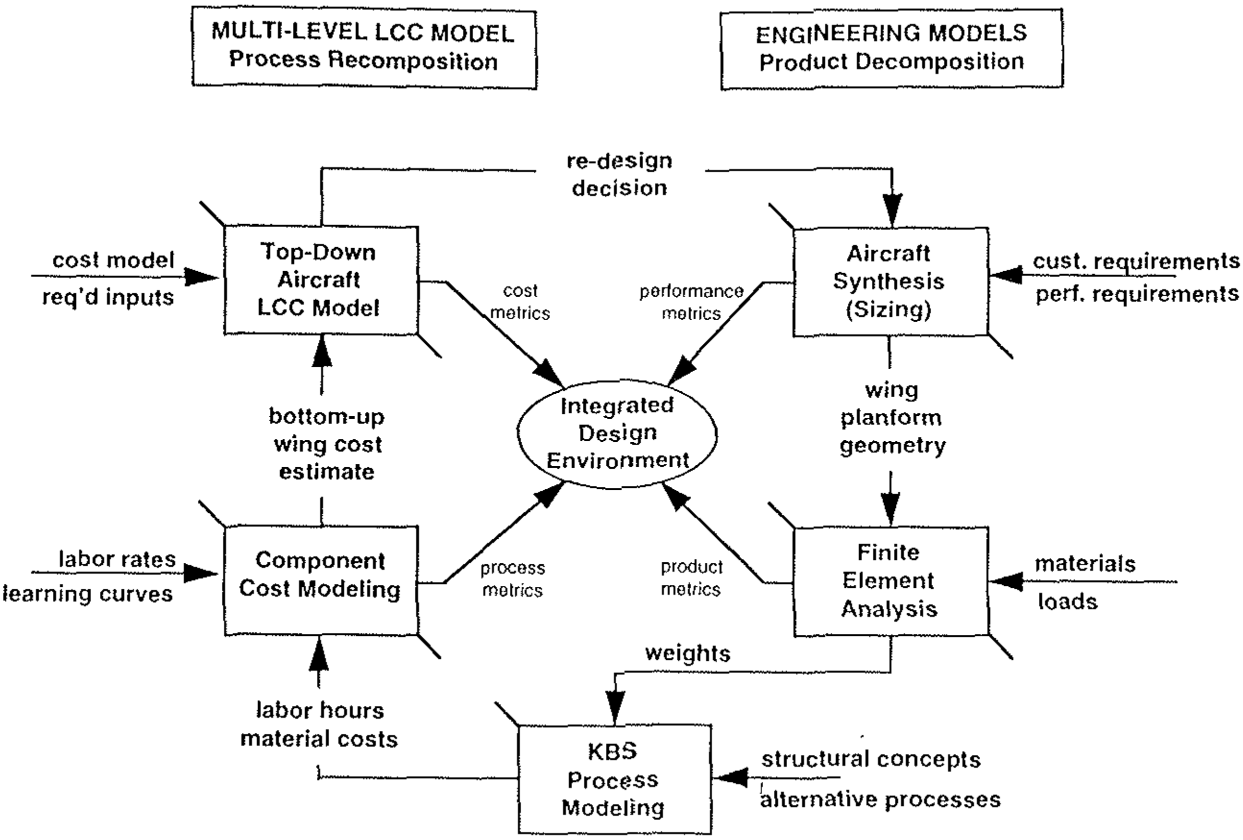

Figure 14: Typical Models Used for Decomposition and Recomposition Activities: An Aircraft Example

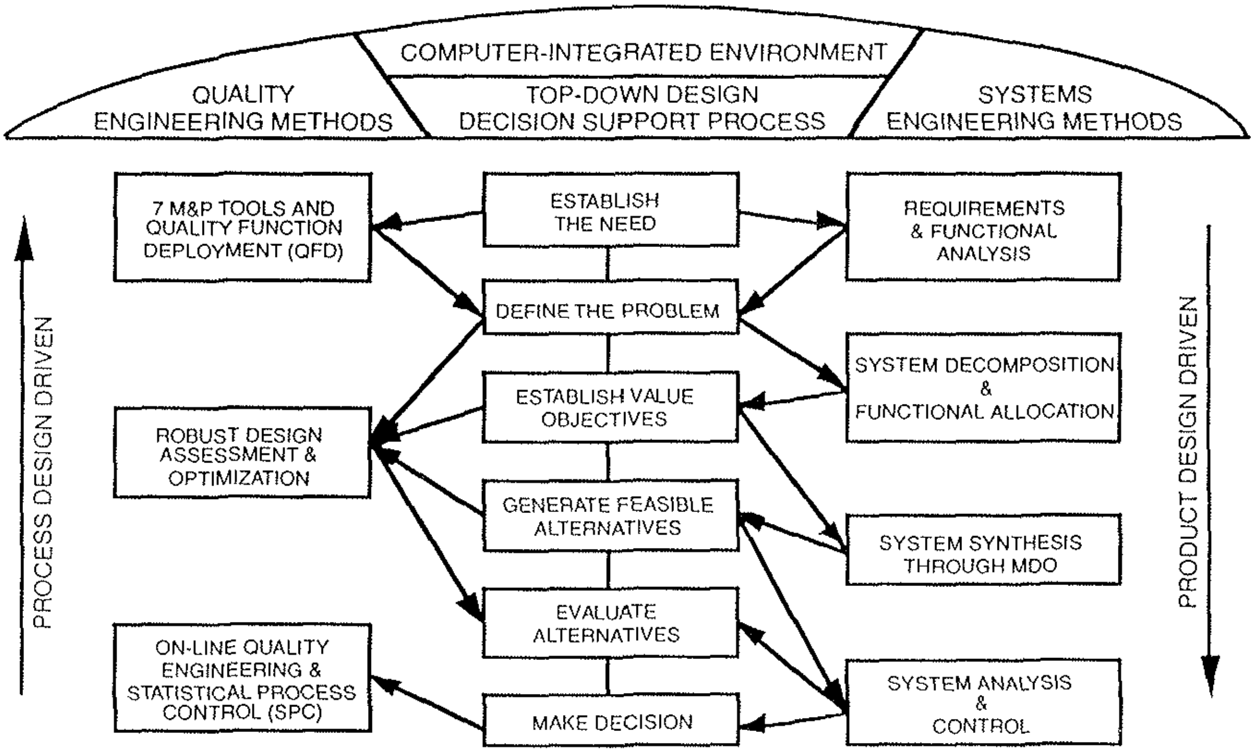

Figure 15: A Generic IPPD Methodology for Cost/Performance Trades

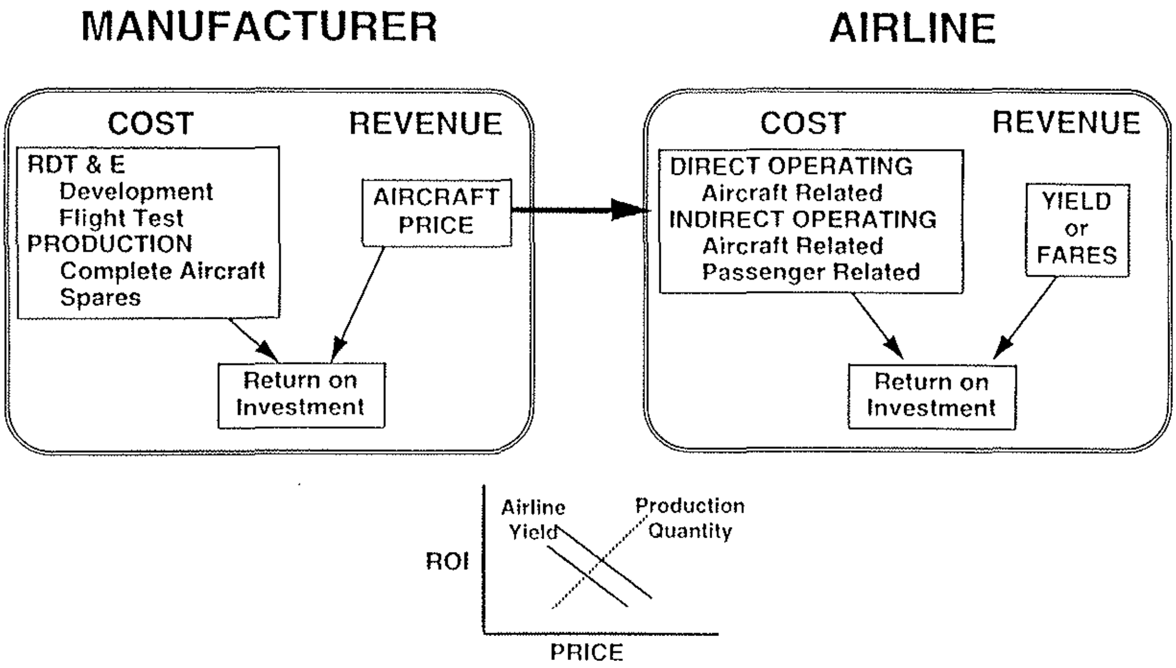

Figure 16: Aircraft Economic Assessment

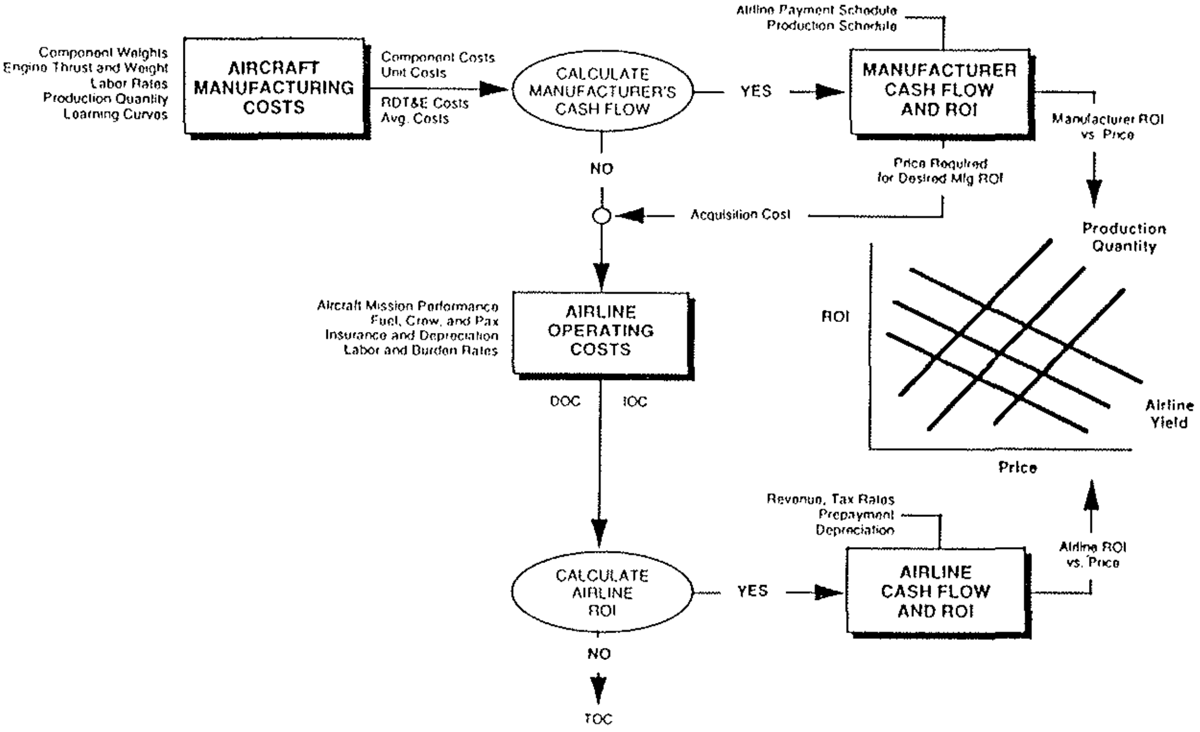

Figure 17: ALCCA: Analysis Schedule

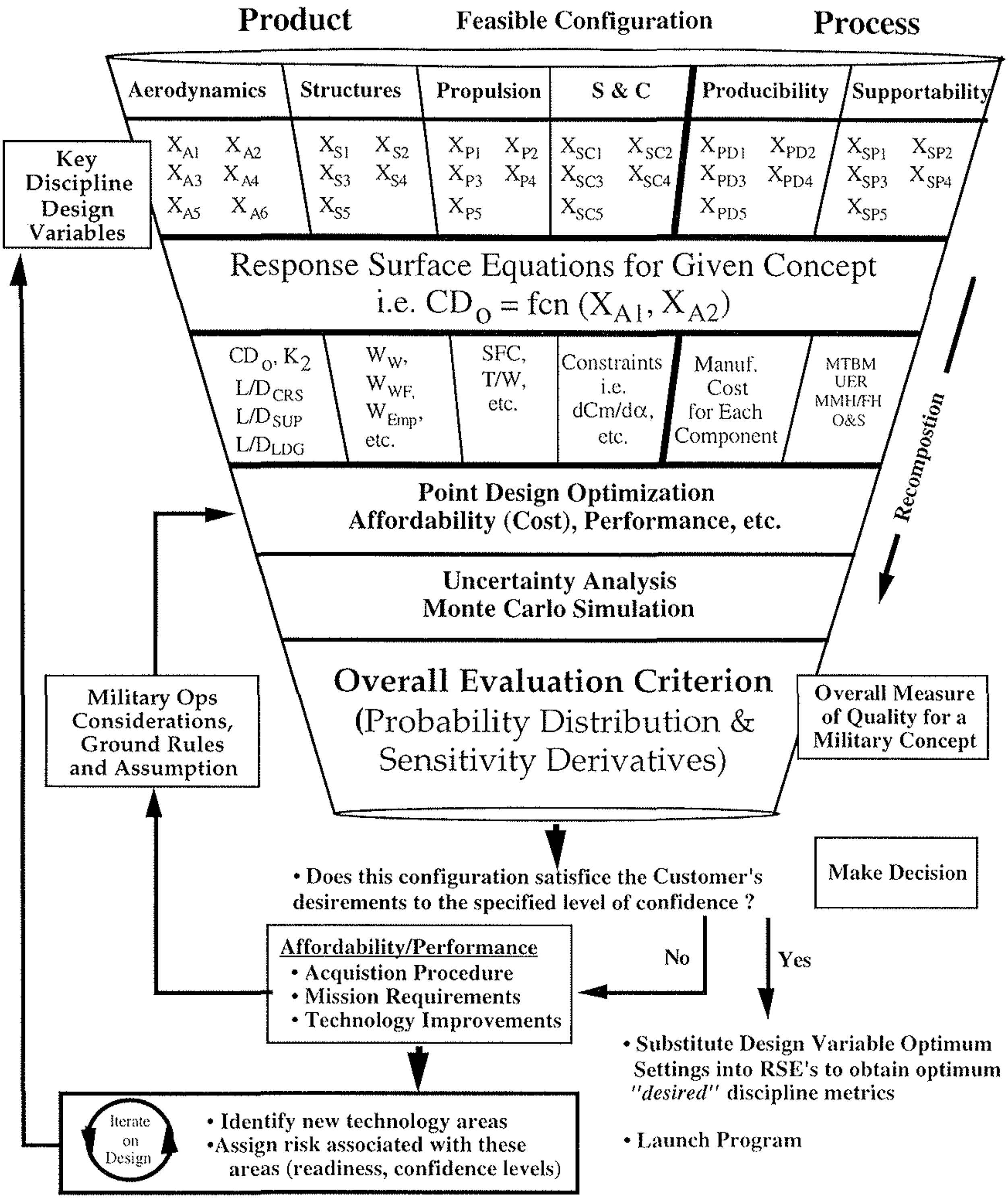

Figure 18: IPPD Funnel Chart