INTEGRATED PRODUCT DEVELOPMENT FOR THE WING STRUCTURAL DESIGN OF THE HIGH SPEED CIVIL TRANSPORT

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Abstract

The extent of knowledge required to perform the task of integrating manufacturing with aircraft design is beyond the expertise of a single engineer. This defines the need for a decision support system, or Knowledge-Based System, to aid the engineer in performing parallel product and process trades. This paper describes a research effort that includes development and integration of a manufacturing knowledge base and a rule-based reasoning system. NASA interests in the research discussed in this paper are directly related to their High Speed Research program. According to the program, NASA and this country's aerospace industry have undertaken the challenge of designing and building a 2nd generation supersonic commercial transport by the early 21st century. The proposed aircraft, called the High Speed Civil Transport, is envisioned to cruise at Mach 2.4 and carry 300 passengers to destinations in excess of 5,000 nautical miles. In addition, this aircraft must be economically viable and affordable, while being environmentally friendly and abiding by all appropriate FAR and EPA requirements. Integrated Product Development techniques aimed at assessing producibility can help designers perform the necessary trade-off studies to design the strongest, lightest possible structure at the least cost that meets the load-carrying requirement for a specified aircraft range. This concurrent design requires an integration of design with manufacturing and an optimization process that will consider design trade-offs related to product performance, producibility, and support. This integrated design and manufacturing approach can be used to develop low cost, producible structural design concepts. This approach involves encoding the knowledge of human experts concerning aircraft manufacturing and design into an appropriate representation. The seamless integration of a manufacturing Knowledge-Based System with aircraft preliminary design and analysis tools will yield a concurrent engineering system that will assist aerospace systems designers in performing parallel product and process design trades.

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Acronyms

ACE	Assistant Cost Estimator
AI	Artificial Intelligence
ASDL	Aerospace Systems Design Laboratory
ASTROS	Automated STRuctural Optimization System
CAD	Computer Aided Design
CAPE	Computer Aided Parametric Estimating
CATIA™	Computer-graphics Aided Three-dimensional Interactive Application system
CBA	Cost Benefits Analysis model
CDA	Composites Design Assistant
CDMA	Composites Design and Manufacturing Assistant
CE	Concurrent Engineering
CLIPS	C Language Integrated Production System
DTC	Design-to-Cost
$/RPM	Dollars per Revenue Passenger Mile
EDCE	Engine Development Cost Estimator
EPA	Environmental Protection Agency
FAR	Federal Aviation Regulation
FLOPS	FLight OPtimization System
GSRP	Graduate Student Researchers Program
HiSAIR	High-Speed Airframe Integration Research
HSCT	High Speed Civil Transport
HSR	High Speed Research
IPD	Integrated Product Development
IPPD	Integrated Product and Process Development
KB	Knowledge Base
KBD	Knowledge-Based Design
KBE	Knowledge-Based Engineering
KBS	Knowledge-Based System
KMCE	Knowledge-based Manufacturing Cost Estimator
MDO	Multidisciplinary Design Optimization
PRICE H	Programmed Review of Information for Costing and Evaluation, the H stands for Hardware development and production, recurring and non-recurring
ROI	Return on Investment
Tk/tcl	Toolkit / tool command language
TQM	Total Quality Management
UPC	Unit Production Cost

Purpose and Scope

This paper describes research, development, and integration of a manufacturing knowledge base with a rule-based reasoning system. A Knowledge-Based System (KBS) is under development for integration of design and manufacturing for the High Speed Civil Transport (HSCT) wing. The extent of knowledge required to perform the task of integrating manufacturing with aircraft design is beyond the expertise of a single engineer. This defines the need for a decision support system, or KBS, to aid the engineer in performing parallel product and process trades.

Today's aerospace industry is faced with the same problem that this paper addresses: how can manufacturing considerations be integrated into the aircraft design process in order to reduce design cycle time and iterations? Preliminary studies at Boeing[1] have led to a belief that it is feasible to automate most, if not all, of the structural finite element modeling process for a given type of configuration utilizing one of the commercially available knowledge-based or object-oriented systems. The engineers at Boeing are convinced that a practical system can be created that will automate much of the model generation, execution of fairly sophisticated multidisciplinary processes, and preparation of preformatted results for engineering review.

The need for a Knowledge-Based System (KBS) must be translated into benefits relevant to the user management. Beckman[2] describes seven types of benefits that can be realized with the use of Knowledge-Based Systems:

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

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

There are certain information-processing problems that do not yield well to traditional computing methods. The concept of integrating design and manufacturing is a prime example of such a problem. To evaluate potential application domains for Knowledge-Based Systems, a set of desired attributes for good KBS domains have been developed as part of a major expert system development project at GTE Laboratories.[3] These attributes are related to basic system requirements, problem type and bounds, "experts", and domain personnel. Many of these attributes are general enough to be applicable to all expert systems; several are easily inferred to be appropriate to the domain of the integration of design and manufacturing.

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

- *The domain is characterized by the use of expert knowledge, judgment, and experience.* Domain experts in the field of manufacturing exist within the aerospace industrial contacts of Georgia Tech. The experience of these people will help provide the heuristics for the KBS.
- *Conventional programming (algorithmic) approaches to the task are not satisfactory.* Many of the characteristics inherent to manufacturing are governed by rules-of-thumb and guidelines that are not easily encoded in an algorithmic language.
- *The completed system is expected to have a significant payoff for the corporation.* A reduction in design cycle time would constitute a very significant payoff for any aerospace corporation that utilized such a KBS.

An attribute related to the problem type is:

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

Another general feature is:

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

The aforementioned attributes are the reasons why the authors are developing a manufacturing KBS that, when integrated with current preliminary design and analysis tools, will assist aerospace engineers in performing parallel product *and* process trades. This approach involves encoding the knowledge of human experts concerning aircraft manufacturing and design into an appropriate representation.

Background

Several related research efforts are also addressing the need for Knowledge-Based Engineering (KBE). Messimer and Henshaw[4] describe a materials and processing knowledge base and a model-based reasoning system developed to aid an engineer in the selection and critique of composite materials and processes. The system is known as Composites Design and Manufacturing Assistant (CDMA). The system was designed for composites producibility analysis. Other references[5,6,7] describe the Composites Design Assistant (CDA) developed at Lockheed Missiles and Space Company. Like the CDMA, the Lockheed CDA system functions as an assistant to an engineer for design and analysis of composite structures.

Through discussions with aerospace engineers at Lockheed Aeronautical Systems Company (LASC) in Marietta, GA, the authors have been informed that LASC is also pursuing Knowledge-Based Design (KBD). The objectives of their efforts are: the distribution of design knowledge in interactive advisory systems, the automation of multidisciplinary aspects of design, and the facilitation of IPD. The work includes use of a CAD system, a knowledge-based tool, a relational database, and a CAD/KB interface.

General Electric Aircraft Engines (GEAE) has also investigated the uses and applications of KBE.[8] Their Knowledge-based Manufacturing Cost Estimator (KMCE) was applicable only to a limited class of compressors. The Assistant Cost Estimator (ACE) was applicable to the entire engine system. The Engine Development Cost Estimator (EDCE) was another GEAE initiative developed to predict engine development costs quickly and accurately to facilitate development cost trade studies.

The Cost Benefits Analysis (CBA) model was developed by McDonnell Douglas with the help of Arthur Anderson & Company. The CBA system is a PC-based model that estimates fabrication costs using an expert system. The expert system is used with a spreadsheet, a database, and a natural language interface. The database includes data for both metal and composite structures cost information. Studies were conducted at McDonnell Douglas using CBA to support HSCT design efforts to determine and analyze relevant cost issues.

The KBS under development at Georgia Tech's Aerospace Systems Design Laboratory (ASDL) is easily identified as a relevant research project that will contribute to this country's aerospace industry. The development and growth of this KBS may present an opportunity for the aerospace industry to replace the trend of increasing manpower with increasing computational power.

System Requirements

Design and manufacturing decisions are tightly coupled; decisions made about manufacturing processes or material selections are rarely independent of the decisions made during the aircraft preliminary design process. The material selection and the choice of a processing method are closely related decisions affecting part producibility. As illustrated in Figure 1, the producibility of an aircraft part is governed by three factors: product design, process design, and economics. Product design requires the satisficing of performance and geometry specifications. Process design is governed by manufacturing heuristics and necessitates a product decomposition and process recomposition, which is characteristic of Integrated Product and Process Development (IPPD). Design-to-Cost (DTC) and parallel product and process trades are essential parts of the economics associated with aircraft system producibility.

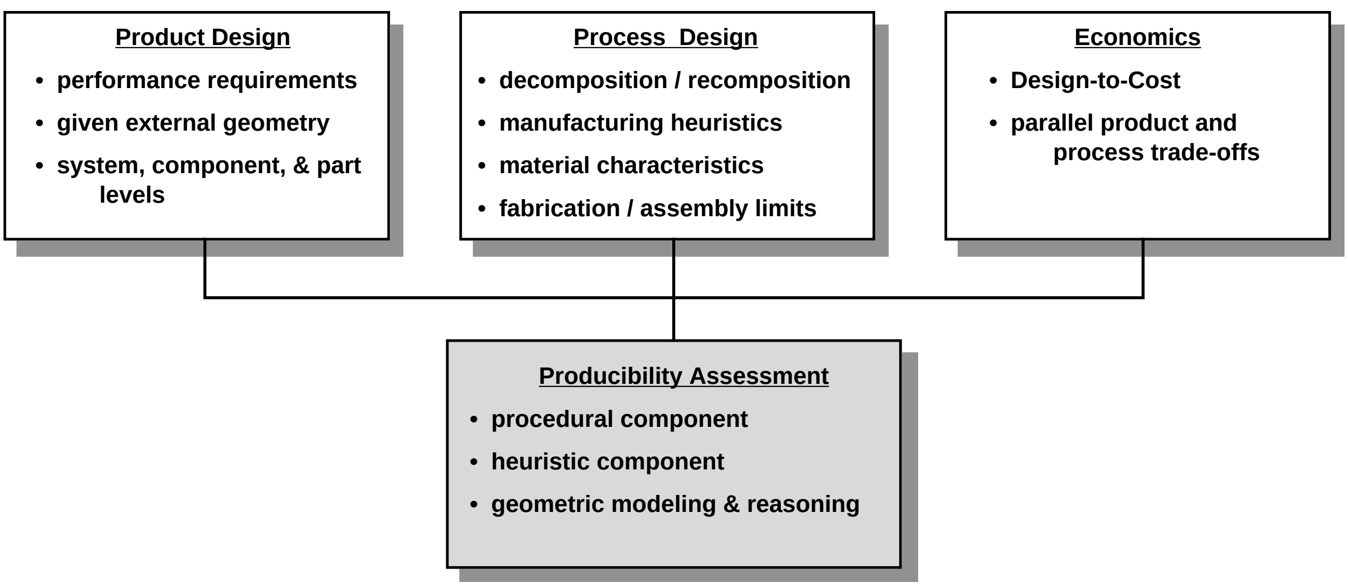

Figure 1: Aircraft Producibility

To perform a producibility assessment for the HSCT, both procedural and heuristic components must be analyzed. Figure 2 shows a breakdown of the procedural and heuristic components of an HSCT producibility assessment.

The combination of FLOPS[9] and ASTROS[10] with heuristic components of producibility constitutes the authors' attempt for an integration of design and manufacturing for aerospace systems designers. FLOPS, or FLight OPtimization System, is a NASA Langley-developed multidisciplinary system of computer programs for conceptual and preliminary design and evaluation of advanced aircraft concepts. ASTROS, or Automated STRuctural Optimization System, is a system developed by/for the USAF that is capable of performing structural analysis, static aeroelastic and flutter analysis, as well as automated structural design while considering a multiplicity of design conditions. Aircraft development at the conceptual level is addressed by the procedural model, while the heuristic module applies a suitable cost model during preliminary design. The procedural model consists of

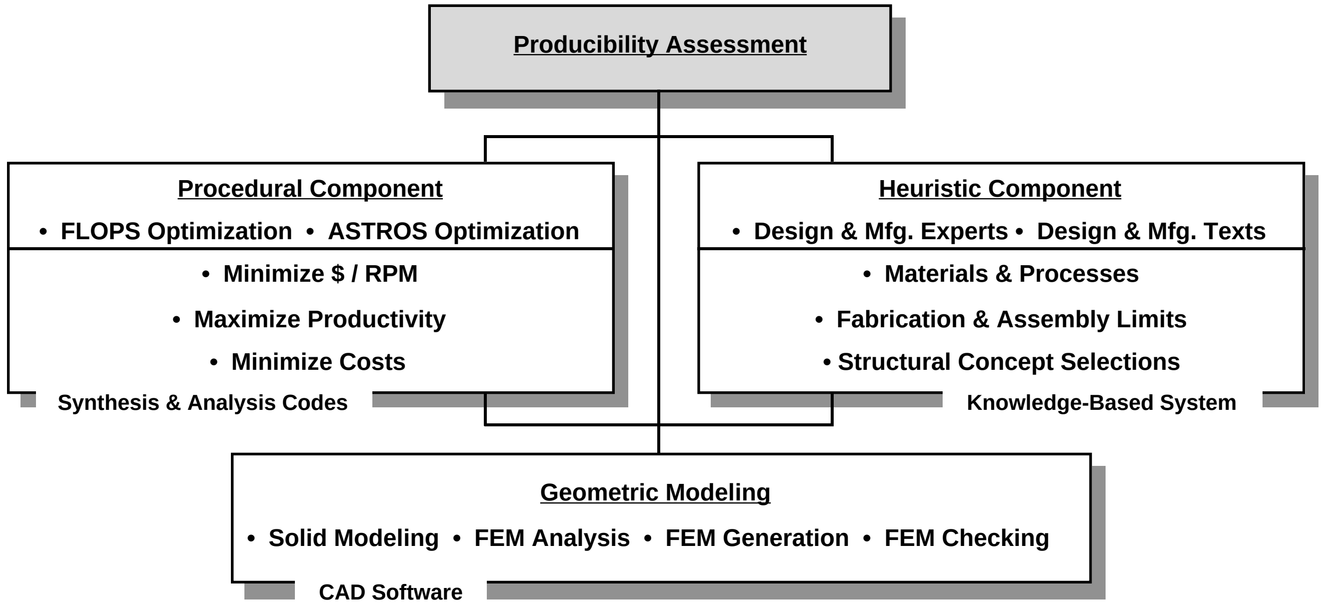

Figure 2: Procedural and Heuristic Components of Aircraft Producibility

optimizations performed by both FLOPS and ASTROS. CATIA, or Computer-graphics Aided Three-dimensional Interactive Application system, will be the Computer Assisted Design (CAD) package used in this research.

Heuristic producibility issues are those that require the knowledge of experts to resolve. The knowledge of design and manufacturing experts from academia, industry, and government is used in conjunction with design and manufacturing oriented textbooks to develop checklists, lists of guidelines, or design rules. These checklists and rules pertain to constraints associated with materials, fabrication, assembly, and processes. These issues can be developed as a KBS. The design and development of a producibility assessment system appears appropriate for Artificial Intelligence (AI) methods since the solution procedure is governed by a complex reasoning process not well suited for algorithmic solutions. By definition then, the producibility assessment may be best handled by a KBS. Procedural design and analyses lead to *product* trades, while the heuristics related to manufacturing can yield *process* trades. A revolutionary way to perform these trades in *parallel* is called Integrated Product and Process Development (IPPD).

Integrated Product and Process Development

IPPD techniques aimed at assessing producibility can help aircraft designers perform the necessary trade-off studies to design the strongest, lightest, least expensive wing structure that meets the static and dynamic load-carrying requirements for a specified mission. Such a concurrent design requires an integration of design and manufacturing and an optimization process that will consider design trade-offs related to product performance (productivity), utilization, producibility, and support. Design and manufacturing guidelines and constraints are established using the principles and techniques of Concurrent Engineering (CE). The life-cycle of aerospace products includes the design phases before production, namely the conceptual, the preliminary, and detail design phases. It is well known that the freedom to alter designs decreases substantially as a design matures from a conceptual level to full scale production. In addition, evidence indicates that the greatest opportunities to influence producibility are in the early design phases. Hence, there is a definite need to incorporate producibility concepts early in a product's design cycle.

As industries and governments around the world restructure to achieve major quality improvements in order to become more competitive in the world marketplace, the term Concurrent Engineering, or IPPD, is being used to express the desired environment. CE has been defined as "a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support".[11] CE can be viewed as the implementation arm of the Total Quality Management (TQM) strategy. It can be described as a modern treatment of systems engineering which combines quality engineering methods in a computer integrated environment.

Figure 3 shows a flow diagram for Integrated Product and Process Development during the various design phases. On the outer circle it illustrates in a clockwise flow the hierarchical decomposition activities from the conceptual level to major component (sub-system) level, to part (sub-component) level to manufacturing process level. The small inner loops on the right half represent the *product* design trade iterations. The left half of the outer circle shows the process recomposition activities while the inner loops represent the *process* design trades. The long outer loop iteration represents what has traditionally been done in past aerospace systems design. Redesign was often required due to product design incompatibilities with manufacturing processes. It is desired to have the ability to make parallel *product & process* design trades at the system level, as well as at the component and part levels. This will require formalizing the IPPD environment shown in the center of

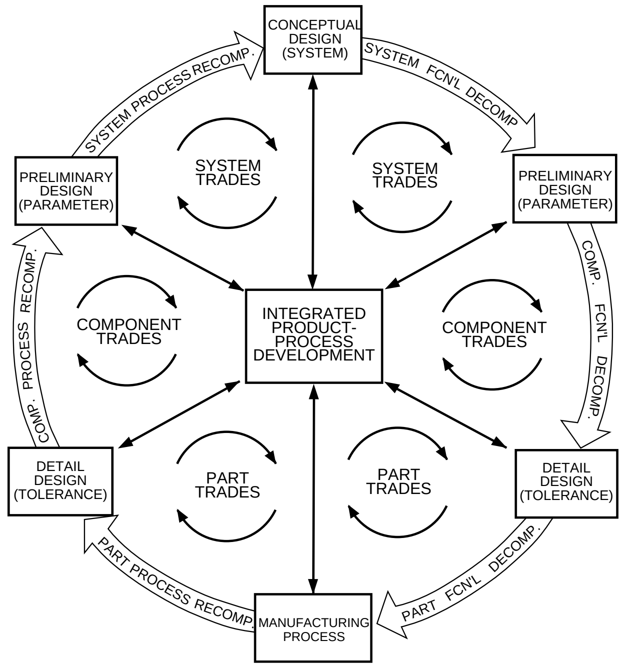

Figure 3: Integrated Product and Process Development

Figure 3 with the appropriate methods, tools, knowledge, and capabilities necessary for assessing both product and process. The procedure for integrating design and manufacturing requires both product and process design trade iterations. The lowest component in Figure 3, Manufacturing Processes, has traditionally been a costly bottleneck in terms of both dollars and schedules.

While Figure 3 represents the flow processes desired for IPPD, it does not provide the methodology required to implement IPPD. The methodology being developed and utilized to implement IPPD at Georgia Tech is illustrated in Figure 4. The methodology in Figure 4 illustrates the interaction of the four elements necessary for parallel product and process trades to be made at the appropriate level of system decomposition and recomposition. Depicted are four key elements: systems engineering methods, quality engineering methods, a top down design decision support process, and a computer integrated environment. Beneath the top level are the interactions necessary for making parallel product and process design trades. The methodology takes advantage of successful methods and tools for both products and processes. It should be noted that system synthesis is achieved through the use of Multidisciplinary Design Optimization (MDO) to generate feasible alternatives. These feasible alternatives are then evaluated for process robustness using quality engineering methods and a decision is made based on selection of the best alternative concept.

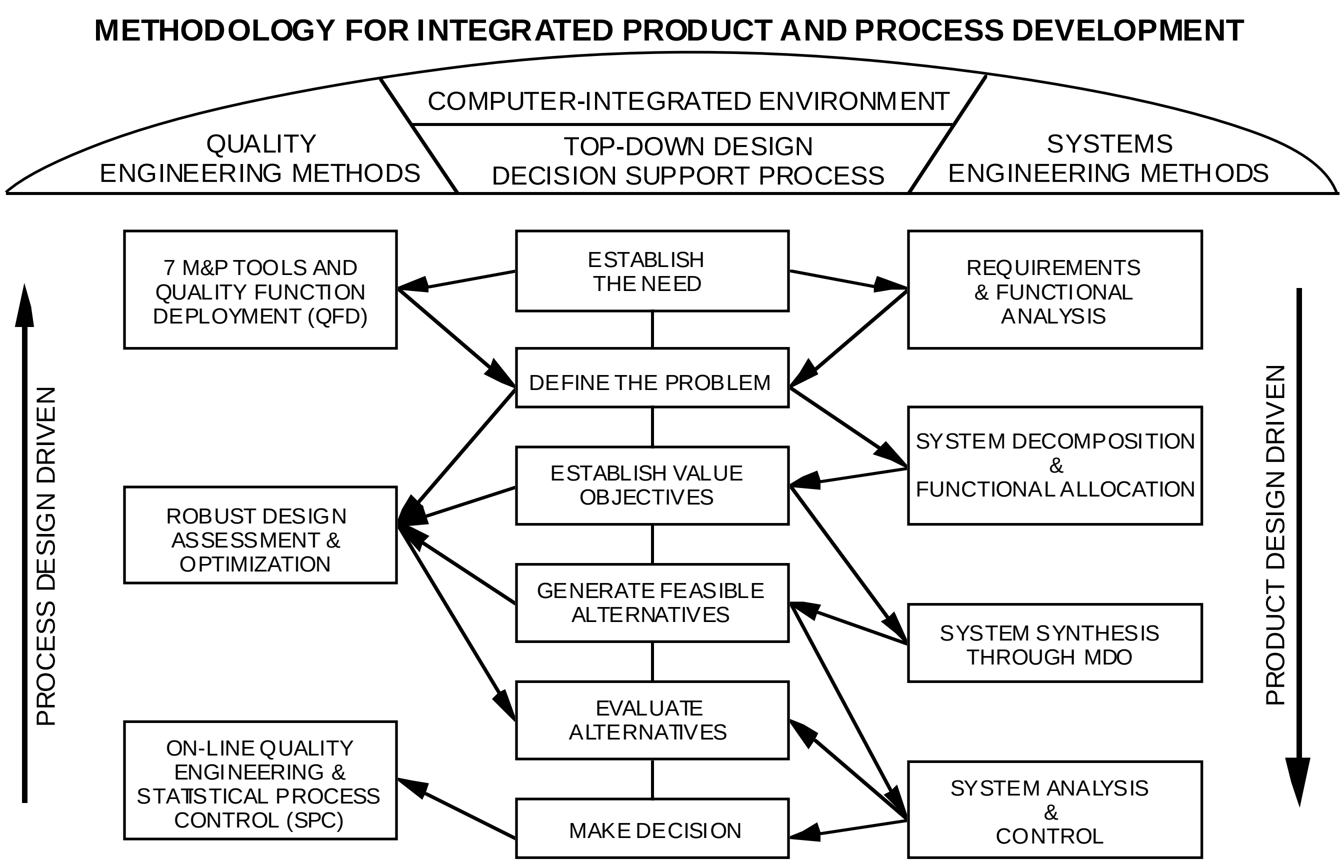

Figure 4: IPPD Methodology at Georgia Tech

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

System Development

The objectives of this research include the formulation of a model that will predict wing structure production costs. The model should allow evaluation and prioritization of structural concept candidates during typical *procedural* conceptual and preliminary design analyses. It should also be able to predict [wing] structural costs quickly and accurately to facilitate parallel product and process trade studies. The research will ultimately demonstrate closure between heuristic and procedural components of producibility.

In a recent assessment of cycle time for a preliminary design, it was estimated that an aeroelastic design cycle for an HSCT could range from 6 to 12 months with current technology.[1] Such an estimate substantiates the need to develop technology and systems that can reduce aeroelastic and structural design cycle time in addition to satisfying the above stated project objectives. The proposed research and system development has been divided into two parts: Phase I--a reduction in model generation time and efforts; and Phase II--the research, development, and introduction of the manufacturing-oriented KBS.

Phase I: Reduction in Model Generation Time and Efforts

A preliminary integration system linking FLOPS, CATIA, and ASTROS has been developed. CATIA, developed by Dassault Systemes, has become an industry standard throughout much of the aerospace community for creating three-dimensional geometric models using wireframe, surface, and solid modeling constructions. The current system uses a Tk/tcl[12] (Toolkit / tool command language) script to parse a FLOPS input file for aircraft geometrical parameters. The system then utilizes a CATIA wrap[13] to automatically send commands to CATIA to model the aircraft as a 3-D solid model. Tk/tcl was used for the wrap embodiment. Therefore, the wrap has capabilities for an interactive shell as well as a graphical user-interface. The CATIA wrap permits access to all 1500 CATIA GEOmetry (CATGEO) functions through a single user-procedure. Collectively, the CATGEO calls can be used to develop any geometric model definition that a user could normally do interactively. This provides a *substantial* reduction in model generation efforts.

The script also contains procedures that read a previously generated points file of the finite element model nodes and then draw a wireframe representation of the finite element model. The finite element model of the wing is drawn *inside* the 3-D solid model of the wing. This allows for excellent visualization of the aircraft as well as the wing finite element model. The model(s) can then be rotated, translated, scaled, colored, and/or shaded in innumerable combinations with CATIA.

One objective of this research is similar to that of NASA Langley's High-Speed Airframe Integration Research (HiSAIR) program: "to consolidate the aircraft geometry definition into a single tool that can output the various required representations from a common model."[14] While the system executive software for NASA's HiSAIR system is written in the UNIX command language[15], the prototype system developed for this research is coded using the interpretive shell system called Tk/tcl. Tk/tcl combines an interpretive language core with an X11 windowing system to produce a powerful run-time executive. This permits the users to easily customize and/or extend existing applications *without having to recompile them*. The prototype system linking FLOPS, CATIA, and ASTROS has been implemented on the IBM RS/6000.

Figure 5 shows a representative HSCT solid model generated using this system. The figure includes a wireframe ASTROS wing finite element model. The shaded

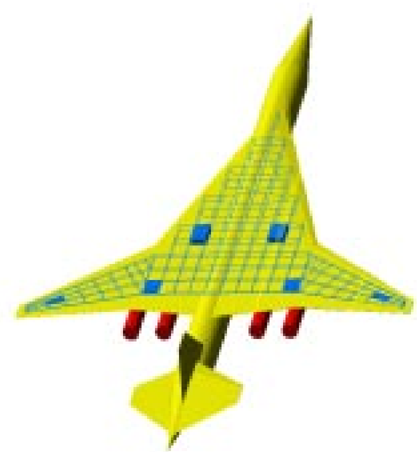

Figure 5: CATIA HSCT Solid Model

areas represent various point structural design locations on the HSCT wing. The locations of the critical point design areas will need to be determined from an in-depth structural analysis of the wing finite element model. Preliminary industry studies indicate the critical design regions may be near the wing tip, near the intersection of the inboard and outboard wing, and by the engine mounts. For academic purposes, only the critical regions will be analyzed; in industry, all of the components and parts of the structure would be analyzed in great detail. The basic design regions represent forward, middle, and outboard aft sections of the wing. The dimensions, thicknesses, and weights for spars, ribs, skin panels, and spar caps in these regions will be calculated by ASTROS. Using manufacturing guidelines and constraints, assumptions can be made regarding material choices for the particular regions, part complexity factors, and tooling complexities. Alternative wing structural concepts can be evaluated using areal weight as the metric (in pounds per square foot). This process flow is shown in Figure 6.

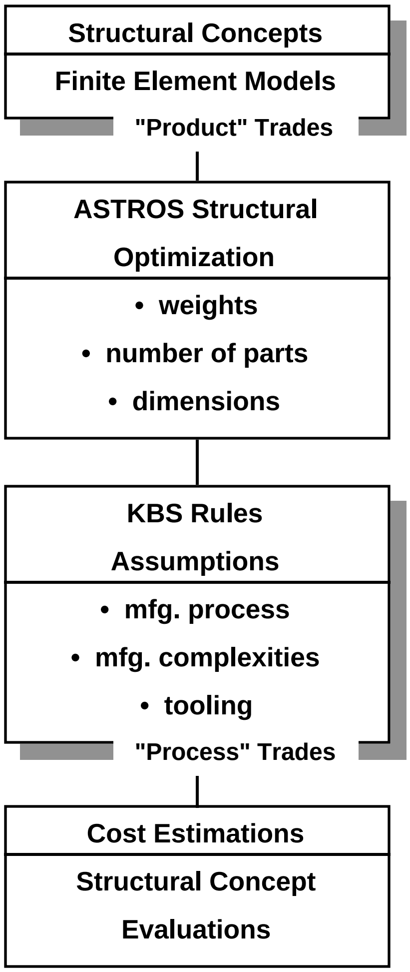

Figure 6: Product and Process Trades

Phase II: KBS Development

This research phase consists of the development of a manufacturing KBS. The KBS can be used in conjunction with the synthesis code, FLOPS, and the structural optimization package, ASTROS, and the heuristic components of producibility. The knowledge base of heuristic issues can be developed into expert systems that may be used to advise the designer and incorporates manufacturing guidelines and constraints into the heuristic module of producibility. The KBS will include the manufacturing rules-of-thumb that can help to determine parameters related to material selection, tooling complexities, fabrication limits, and overall manufacturing complexities.

As related to the overall concept of product affordability, cost can be viewed as a key element of producibility. Hence, the utilization of a cost model as a procedural module within a synthesis model is a valid method to assess producibility in design.[16] FLOPS has an economics model developed by Johnson[17], that is capable of performing LCC analyses for aircraft conceptual designs. This integration of an LCC model into the synthesis model FLOPS provides an example showing the utilization of procedural knowledge to determine the producibility of an aircraft concept at the earliest design levels. The LCC model that may be used for this research is called the Aircraft Life Cycle Cost Analysis (ALCCA)[18]. ALCCA, unlike Johnson's LCC model, is capable of performing economic sensitivity studies for both subsonic *and* supersonic aircraft.

There are many heuristic issues related to manufacturing processes that are suitable for incorporation into a manufacturing-oriented KBS. For example, all manufacturing processes are subject to limitations in terms of shape, complexity, minimum and maximum dimensions, tolerances, and surface finishes.[19] These limitations are highly dependent upon workpiece material. In the aerospace industry, the maximum size of a part or component that can be produced by any one technique is often limited by the availability of large equipment. There are also limitations due to process conditions. More often, however, the limitation is on the minimum size that can be produced or on wall thickness. There are both practical and fundamental thickness limitations. Unnecessarily tight tolerances and surface finish specifications are a major cause of excessive manufacturing costs. Each manufacturing process is capable or producing a part to a certain surface finish and tolerance range without extra expenditure. The specified tolerances should, if possible, be within the range obtainable by the intended manufacturing processes to avoid separate finishing operations.

The following are examples of heuristics related to manufacturing constraints and fabrication limits. They are specific to the HSCT.[20] These are examples of the types of heuristics that will be included in an extended version of the KBS that can access detailed part data from a finite element analysis.

- 20" fuselage frame spacing
- 40" wing spar / rib spacing
- 400" maximum length wing panels
- 125" maximum width wing panels
- 100" maximum width fuselage panels

The aircraft designers and manufacturers must know the production rate and the total quantity to be produced to select the appropriate method of production. The part or item can be produced in any of three general ways. It can be produced manually, with a Flexible Manufacturing System (FMS), or with fixed automation.[2] All three methods can be used on individual workstations or throughout a factory. The manufacturing method is ultimately determined economically; the approach that yields the highest return on investment (ROI) and the lowest unit production cost (UPC) is used [DTC].

Because of its availability at Georgia Tech, CLIPS will be used as the expert system language. CLIPS is an acronym for *C Language Integrated Production System*. CLIPS is a multiparadigm programming language that provides support for rule-based, object-oriented, and procedural programming.[21] The procedural programming language provided by CLIPS has features similar to languages such as C, Ada, and Pascal. CLIPS was developed at NASA Johnson Space Center with the specific purpose of providing high portability, low cost, and easy integration with external systems.

A prototype KBS has been developed, using CLIPS, that estimates production costs for structural assemblies fabricated from either aluminum, titanium, or graphite/epoxy members. Currently, the system reads the data describing the structural members (member type, number of parts, part weight, etc.) and then based on this information, matches the member characteristics to data tables to determine the appropriate coefficients for each member for use in a designer's production cost trade-off tool equation.[22] Eventually, geometric models of the candidate aircraft, such as those developed using the FLOPS/CATIA integration system, may be received directly from CATIA, while knowledge of the preferred material and manufacturing process required by that material will be retrieved from a manufacturing process and materials database, respectively.

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

The production cost trade-off tool models relative production costs based on general relationships between the principal manufacturing parameters and manufacturing effort. The tool is based on relationships from the reference manual for the GE PRICE H parametric cost model, specifically, those used to generate PRICE H manufacturing complexities. It allows designers to evaluate different structural concepts for their relative costs, thereby enabling them to make rational cost-related trade-offs for materials, material quantity, manufacturing methods, precision, and quantity of parts. The designer's production cost trade-off equation is given by:

$$COST = weight^{a} \times b + \frac{weight \times c}{Q} \tag{1}$$

where:

where:	*COST*	production cost in notional dollars
	a	material cost for each material type and manufacturing method
	b	manufacturing complexity for the appropriate material type, mfg. method, specified precision, and number of fabricated parts in a component
	c	tooling cost based on material density and fabrication technique
	Q	the quantity of a given part produced for the first 500 units.

This production cost analysis tool calculates only the *relative* costs of competing structural designs. Because it does not account for economic or business factors, the tool does not produce valid, *calibrated* cost estimates. The designer's production cost trade-off tool has been used to determine three relative production costs of a given wing structural concept fabricated from titanium, aluminum, and composites.[23] The results indicated that the structural concept fabricated from aluminum was the least expensive, despite requiring additional weight to meet the load-carrying requirements.

Conventional programming of the designer's production cost trade-off tool and the required database (in the form of tables) in a standard algorithmic language (FORTRAN or C) presents many problems. This is because of the difficulty associated with using *procedural* techniques to determine the best materials, structural concepts, manufacturing and fabrication processes, and if applicable, precision required for machining. These parameters are typically determined from rules, guidelines, and constraints related to manufacturing, fabrication, and assembly.

The objects and attributes describing the parts in a structural assembly are input to CLIPS. The objects are the `part_types`, while the attributes are the `material_type`, `unit_weight`, `quantity`, and `manufacturing_method`. The objects and their associated attributes are used to determine the appropriate

material cost coefficient, a
based on
```
part_type
material_type
manufacturing_method
```

manufacturing complexity coefficient, b
based on
```
part_type
material_type
quantity
manufacturing_method
specified_precision
```

and

tooling cost coefficient, c
based on
```
material_type
fabrication_technique
```

Selected entries from the tables of coefficients for the different materials, number of parts, part weights, etc., were asserted into working memory. A series of rules assigns the appropriate coefficients for material cost, manufacturing complexity, and tooling cost based on matches with the asserted facts about the elements and their associated attributes. The system writes the element ID number, the coefficients a, b, and c, the number of parts, and the part weights to an output file in column format. These columns of data can be used in a spreadsheet to calculate the assembly production costs based on the designer's production cost trade-off tool equation. This allows the designer to perform production cost trade-offs based on process (selected by the KBS) and product (the structure itself).

Future Work

The preliminary integration system linking FLOPS, CATIA, and ASTROS will be modified and improved in future work. Though it reduces model generation times and efforts, there are still many ways in which the system can be made more robust.

The research and formulation of a suitable knowledge base of manufacturing guidelines and rules-of-thumb must be completed. The prototype KBS is relatively small since it will only handle simple example cases. The KBS will be modified and extended. It is hoped to eventually have the CLIPS KBS automatically access the ASTROS database to get the data it needs to determine the production coefficients and to write the output file to be used to calculate the production costs. Once the KBS collects the information related to element type (membrane, shear panel, or rod -- corresponding to skin panels, ribs, and spar caps), material type, weight, and dimensions, it can begin processing the information. Some ideas to be executed by an extended version of the KBS include:

- check panel dimensions, i.e. compare them with fabrication limits based on maximum size that can be produced by an aircraft manufacturer.
- compare the thicknesses of the panels with minimum [or maximum] thickness requirements.
- possibly make suggestions for alternative material types that could, or have previously been, used in the particular section of the wing in which the element is located. For example, substitution of composites or titanium for aluminum components.

A flow diagram illustrating an extended version of the KBS and the tasks to be performed is shown in Figure 7.

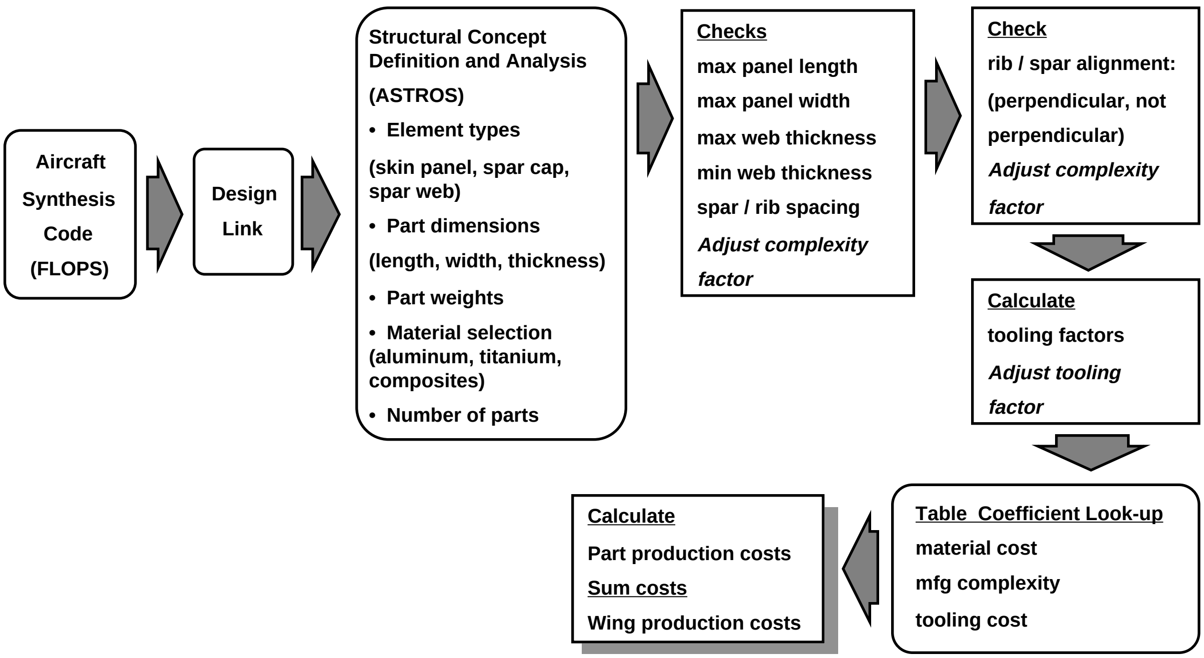

Figure 7: Extended KBS Execution

The authors are also investigating the use and appropriateness of Computer Aided Parametric Estimating (CAPE) tools for this research. As mentioned in the previous section, the production cost trade-off tool used for cost estimation is based on relationships from the GE PRICE H parametric cost model. PRICE H is the acronym for Programmed Review of Information for Costing and Evaluation. H signifies Hardware development and production, recurring and non-recurring. The PRICE H models are currently used by many U. S. aerospace industries. PRICE H has been applied to Design-to-Cost activities.[24]

Conclusions

The integration of manufacturing heuristics with design is a concept that is only beginning to be addressed by today's aerospace industry. As outlined in this paper, much research and formulation has been done in this area. However, several significant steps need to be completed before a useful and accurate system is completed that will enable designers to perform parallel product and process trades in a reasonable amount of time. When such a system is complete, it will be invaluable for modern aerospace systems designers.

Conventional programming of the designer's production cost trade-off tool and the required database (in the form of tables) in a standard algorithmic language presents many problems. This is because of the difficulty associated with using procedural techniques to determine the best materials, structural concepts, manufacturing and fabrication processes, and if applicable, precision required for machining. These parameters are typically determined from rules, guidelines, and constraints related to manufacturing, fabrication, and assembly. Thus, the cost trade-off tool, or any other similar appropriate manufacturing costing algorithm, appears to be better implemented with a Knowledge-Based System.

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