GC 2012-5608: AN INNOVATIVE APPROACH TO AN INTEGRATED DESIGN AND MANUFACTURING MULTI-SITE ”CLOUD-BASED” CAPSTONE PROJECT

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Michael Richey is an Associate Technical Fellow currently assigned to support technology and innovation research at the Boeing Company. Michael is responsible for leading a team conducting research projects to improve the learning experience for engineers and technicians. His research encompasses, Complex Adaptive Systems, Learning Curves, Learning Sciences and Engineering Education Research focusing on understanding the interplay between knowledge spillovers, innovation, wealth creation, and economies of scale as they are manifested in questions of growth, evolvability, adaptability and sustainability. Additional responsibilities include providing business leadership for engineering technical and professional educational programs. This includes development of engineering programs in advanced aircraft construction, composites structures and product lifecycle management. Michael is responsible for leading cross-organizational teams from academic, government focusing on how engineering education must acknowledge and incorporate this new information and knowledge to build new methodologies and paradigms that engage these developments in practice. Michael holds a PhD in Strategy, Programme and Project Management, with a focus on Engineering Education Research from Skema Business School, and a Stanford Certified Project Manager (SCPM) certificate from Stanford Center for Professional Development. Michael often represents Boeing internationally and domestically as a speaker - presenter and has authored multiple patents on Computer-Aided Design and Computer-Aided Manufacturing and has published a book on nano science and multiple papers in lead journals addressing topics in large scale system integration and learning sciences.

Mr. Fabian Zender, Georgia Institute of Technology

Fabian Zender obtained his Undergraduate degree in Aerospace Engineering from the Georgia Institute of Technology in May of 2012. He is currently working towards completing the requirements for a PhD in Aerospace Engineering which he hopes to complete by 2015. Fabian has been working in the Integrated Product Lifecycle Engineering (IPLE) Laboratory and has been involved in a variety of research as an undergraduate. Some of his research includes leading a team of undergraduate students from three universities, testing multi-user CAx tools developed under a NSF grant. Fabian has also been involved in the MENTOR project funded by DARPA which is designed to engage and interest high school students in the STEM areas. Fabians research interests include fixed-wing and rotorcraft design as well as the inclusion of Computer Aided Engineering (CAE) tools in the systems engineering process. He is also studying the impact of global collaboration on design.

Dr. Daniel P. Schrage, Georgia Institute of Technology

Dr. Schrage is a professor in the School of Aerospace Engineering and Director of the U.S. Army Vertical Lift Research Center of Excellence (VLRCOE), a position he has held since 1986. Prior to coming to Georgia Tech in 1984, Dr. Schrage served as an Army aviator, engineer, manager and senior executive servant with the U.S. Army Aviation Systems Command (AVSCOM) for ten years. As a dynamics, vibrations and aeroelasticity engineer he served as the Army’s expert in these areas during the design and development of all the Army’s major aviation systems, including the UH-60 Black Hawk, the AH-64 Apache, the CH-47D Chinook, and the OH-58D Kiowa Warrior helicopters, as well as major upgrades to Army Aviation fixed wing aircraft, such as the RU-21D, and OV-1D Mohawk. In addition, he served as the dynamics evaluator and technical area chief on Army Aviation major Source Selection Evaluation Boards (SSEBs), that led to the development of these systems. As the Chief of the Structures and Aeromechanics Division, AVSCOM Dr. Schrage oversaw the airworthiness qualification and engineering development efforts for all new and upgraded Army aviation systems and provided engineering support to the program managers for these systems. As the Director for Advanced Systems and the Associate Technical Director at SES Level 3, Dr. Schrage oversaw the Command’s Science and Technology program, a joint program with NASA which was the largest in the Army, and also led the concept development for new systems, such as the LHX, which led to the development of the RAH-66 Comanche helicopter. Dr. Schrage also served on a temporary assignment as the Chief Scientist for the Army’s Combined Arms Center (CAC) and was an active duty Army aviator/commander and field artillery battery commander with combat experience in Southeast Asia. Also, during the 1980s and 1990s, Dr. Schrage served as a consultant for the Army (Army Science Board twice), Air Force (Air Force Studies Board), the Institute for Defense Analysis (IDA), NASA and industry. As a member of the National Center for Advanced Technologies (NCAT) Executive Committee in the 1990s, Dr. Schrage defined the Integrated Product/Process Development (IPPD) methodology that was taught by NCAT through short courses and video based instruction for the Army, Navy and industry as part of the DoD acquisition reform effort. Dr Schrage has written a number of book chapters and has over 100 refereed publications and is a Fellow of both the AHS and AIAA.

Dr. Greg Jensen, NSF Center for e-Design BYU Site

C. Greg Jensen joined the faculty at BYU in 1983. He received both his BS and MS at BYU. In 1993 he completed his dissertation, ”Analysis and Synthesis of Multi-axis Sculptured Surface Machining” at Purdue University. He is currently the BYU site director of the NSF IUCRC Center for e-Design that is focused on the development of next generation multiuser collaborative cloud-based CAx tools and methods. Dr. Jensen was chosen as the first Fulton College Professorship of Global Engineering, a position he held from 2007 -2009. Under the direction of Dr. Jensen, BYU's mechanical engineering students have participated in six PACE global collaborative design projects. From 2006-2010 he directed a PACE Project that spanned 19 time zones and involved 26 national and international schools in the modeling, analysis and manufacturing of four working Formula-1 type racecar. Dr. Jensen has also conducted research in Engineering Design and Modeling found in the specific areas of Computer Aided Geometric Design, Parametric CAx Modeling, and Multi-discipline CAD-centric Design Optimization. He is currently involved in the development next generation CAx tools, curvature matched machining methods, parametrics and customization of CAx tools for industries like Boeing, GM, Pratt & Whitney, ATK, Ford, Belcan, etc.

Mr. Barry McPherson, The Boeing Company
James Fehr, The Boeing Company

James Fehr is currently the Learning, Training and Development (LTD) Senior Manager responsible for Engineering Learning support across The Boeing Company Enterprise. He started his career in aviation in the United States Air Force and in 1988 joined the Boeing team. After holding various production positions supporting Boeing Commercial Airplanes, James joined the Boeing Training and Development Team as an Employee Development Specialist. Expanding on this experience, James accepted a position with Boeing Commercial Aviation Services (CAS) in 1997 where he was responsible for developing technical publications and learning courseware for Boeing Customer Airlines. James accepted management responsibility for the Boeing 737 maintenance training group in 1998 where he assisted in establishing the global maintenance training network to support Customer Airlines worldwide. In 2004, James rejoined the Boeing Learning, Training and Development team to help launch the new Boeing 787 program. In 2010, James led the LTD team in providing preparatory support and learning strategies that led to Boeing's success in capturing and launching the KC-46 Tanker program. James is now the Learning, Training and Development (LTD) Senior Manager responsible for engineering learning support to the Boeing Enterprise. James has a Masters in Business Administration and a Masters Certificate in Project Management from the Keller Graduate School of Management, and a Bachelors of Science degree in Technical Management from DeVry University.

James has a wonderful wife Angela and three great kids, Krista (18), Monica (16) and Anthony (14). As a family, they enjoy road trips in the RV, quad & dirt bike riding and water sports. James and family currently live in Granite Falls, Washington.

Matthew M. Symmonds, The Boeing Company
Mr. David E French, The Boeing Company

Biography David French,

David French is an engineer and learning science researcher at the Boeing Company in Everett, Washington, where he is currently working with a team conducting research projects to improve the learning experience for Boeing engineers. His current research focus is directed at studying the integration of social networking tools to improve online education and training courses, and examining the communication behaviors of informal groups of learners. He has 25 years experience teaching engineering courses in the workplace, designing assessment tools, and developing courseware and curricula used in training engineers in the commercial and defense product lines. Dave is also committed to helping improve Science, Technology, Engineering, and Math education for K-12 students to grow the supply pipeline of our future technical workforce. Recent projects include development of engineering programs in advanced aircraft design and construction, composites structures and product lifecycle management. He works in the Technology and Innovation group within the Boeing Learning, Training, and Development organization.

Mr. French holds a BS degree in Mechanical Engineering and has completed extensive coursework in adult and industrial education. He has co-authored several research papers pertaining to education in the workplace and product lifecycle management.

Mr. Barry McPherson, The Boeing Company

Barry McPherson is currently the leader of the Education Programs group in LTD (Learning, Training & Development) responsible for building learning solutions that address critical skills in Boeing Commercial Airplanes (BCA) division at The Boeing Company.

Over his 26 year Boeing career he has worked on various defense programs in many different engineering groups; starting as an NC Programmer on the B-2 program to F-22 in structures, systems, tooling and many other manufacturing related groups. This is where his composites experience originated and then onto developing and teaching programming, relational design and composite modeling.

In the last ten years, Barry's focus has been on the ”supply pipeline” of our future technical workforce, where he and a colleague partnered to build several composite certificate programs with the University of Washington (UW) through their Aero and Astro department. Two of the largest programs are: Aircraft Composite Structural Analysis and Design (ACSAD) and Aircraft Composite Materials and Manufacturing (ACMM). Over a thousand Boeing employees have taken advantage of these programs to date. Most notably, we created a Masters in Aerospace Engineering program Composite Materials and Structures.

In addition to the composites programs we also collaborated with Purdue University and the Georgia Institute of Technology on Product Lifecycle Management (PLM) certificate programs through the Boeing Learning Together program.

During this time he has co-authored several research papers pertaining to education in the workplace and product lifecycle management.

He is also the PLM Technical expert for the LTD engineering group where he provides the strategy and vision for all the PLM services the group provides around the world.

An Innovative Approach to an Integrated Design and Manufacturing Multi-Site “Cloud-based” Capstone Project

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Abstract

This paper will detail an innovative engineering capstone collaboration between students at Brigham Young University (BYU), Georgia Tech (GT) and the University of Puerto Rico – Mayagüez Campus (UPRM) with industry mentors and learning requirements provided by The Boeing Company. While this is not the first multi-university capstone engineering, design and prototyping effort undertaken, it is the first multisite effort to employ CAx tools that have been modified to allow more than one designer, engineer or manufacturing personnel to concurrently access the same part or assembly cloud-based model file. Single-user CAx applications of the past three decades are not being modernized by implementing Massive Multiplayer Online Role-Playing Games (MMORPG) techniques, methods and servers to bring dispersed team members together to more rapidly model, analyze and prototype the most challenging designs. Allowing more engineers, a global digital-brain paradigm, to simultaneously enter the cloud-based CAD model has also shown improved designs, i.e. more innovative solutions than a single designer would generate. It also leads to more reliable and reusable contextual geometry, topology and constraints for downstream analyses and manufacturing. The modification of these traditional engineering tools is suggesting a major restructuring of undergraduate laboratories, curriculum changes to design, engineering and manufacturing classes and in particular the existing approaches to capstone using antiquated CAx tools couched in single-user architectures.

Introduction

The Boeing model for design and manufacture of a new airplane program is among the most advanced aircraft programs in existence. The approach includes a complex database of physical and functional characteristics, sub-system design/build plans, and other shared information that supports the broader project. In the same way that a new design criterion affects the mechanical properties and engineering knowledge domains for aircraft structures i.e., metals to composites, suppose university programs adopted courses that required emerging, interdependent relationships between physical product constraints and multidisciplinary, multicultural globally dispersed members of a design team? Could geographically dispersed teams of students complete a design assignment, with subgroups leveraging distributive expertise independently contributing and collectively impacting the design plan? What if the design-build teams partnering with industry were enrolled in courses across multiple universities, time zones, and functional disciplines in university departments? This project details a cyber-infrastructure platform (from the cloud) and distributive expertise within the students, faculty and industry advisory board members where learning was coordinated across multiple contexts within an immersive graphical environment and dispersed geographically, all working together to optimize a multidisciplinary aerospace problem within a dynamical complex learning ecology. This academic–industry learning model is not a trivial task to achieve in a cooperative environment and particularly where grades are an important factor to consider. This concept, when overlaid against personal agency and social structure specifically, the user community, models and rules, could serve as an effective guide for constructing a framework for managing and capturing complex patterns of social behavior, closing the industry/university “knowing-doing” gap that persists in undergraduate engineering education.

To examine the viability and readiness of the BYU multi-user CAx tools and leverage GT’s world-class Integrated Design and Manufacturing (IDM) curriculum and UPRM’s analysis capabilities, Boeing funded and mentored a six month capstone project to redesign the F-86 Sabre Jet metal wing with a monolithic composite wing. This paper discusses the IDM and multi-user curriculum and multi-user code development efforts leading up to the launch of the BYU/GT/UPRM project. Next the paper discusses the selection and organization of the team. The paper highlights student lectures and the design and analysis work accomplished as well as lessons learned from using cloud-based CAx tools to bring dispersed team members together. It also discusses how the mentoring from industry experts and specialists helped to direct and accelerated the team learning.

Case Study Approach

To assess the performance of the multi-user CAx tool NX Connect built by Brigham Young University, students from three universities were selected to test the design and collaboration capabilities of the program. Brigham Young University students in Provo, UT; Georgia Institute of Technology students in Atlanta, GA and students from the University of Puerto Rico-Mayagüez Campus, Mayagüez, PR participated in a Capstone project to be evaluated by The Boeing Company requiring the redesign of the F-86 Sabre wing. Short courses were provided to the undergraduate and graduate students to familiarize them with both the capabilities of the multi-user CAx tool and the IDM methodology. Similarly, the students took an online course on composites from the University of Washington titled Aircraft Composites Overview for Engineers and Technicians. Both the composite and the IDM courses were based on Certificate programs taught to Boeing engineers at the respective schools. Building on each other's area of expertise and knowledge, the students made use of the newly acquired knowledge to refine their design criteria and create a large assembly using the CAx tool.

Once the selection was made, the undergraduate students, under the mentorship of the graduate students, began the design of the F-86 Sabre wing utilizing NX Connect, allowing students at each university to collaborate and design instantaneously across multiple time zones, bringing in expertise from self-organized teams with backgrounds in aerospace, mechanical, and manufacturing engineering. The team was divided into two main groups, one directing the design for multiple spars while the other team focused on the ribs. Each week the teams met with the graduate students, faculty, and Boeing advisory board to review and advice on the design of the wing.

Keeping in scope the evaluation of the collaborate aspect of the project the students also made use of multi-user pre-processing software Cubit Connect to generate the mesh to be used for the structural analysis of the assembly. As the project moved forward, developers worked on new functionality that was added to the multi-user tools on a continuous basis to provide the necessary functionality to ensure that the undergraduates would be able to complete the design.

Background

Because the project integrates two new complex methodologies to create a new concurrent design paradigm utilizing new cloud-based CAx tools and a virtual manufacturing cost analysis, some background information is presented on these methodologies to familiarize the reader with information on what these methodologies are.

What is IDM?

Critical to any successful product development process is having the right knowledge at the right time to make the right decision. Early knowledge about product design and produceability facilitates informed decision-making about when and how to proceed and reduce the risk of costly design changes later in the product lifecycle when they become more and more expensive.[1]

Programs that follow a knowledge-based process have a higher probability of meeting cost and schedule estimates. Problems occur when knowledge builds more slowly than commitments to proceed. If a decision is made to commit to manufacture a product before critical technology, design, and manufacturing knowledge are captured, problems cascade and may become unmanageable, cost increases, schedules are delayed, and performance and quality may be degraded.

Figure 1 shows how changes become more costly and have greater impact later on in the lifecycle, and how by using a knowledge-based concurrent engineering approach, constraints are known early on when redesigns are less costly.[2]

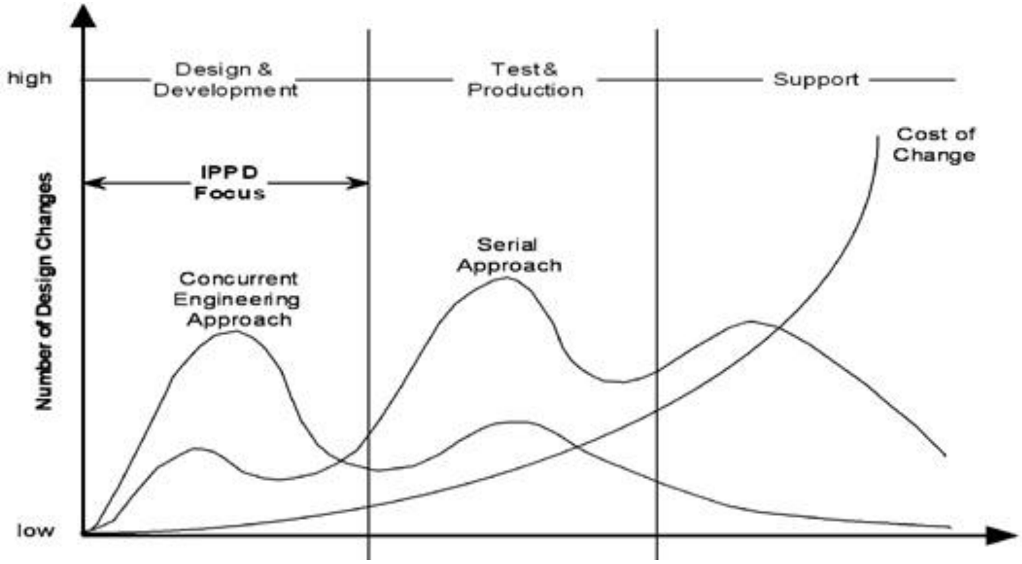


Figure 1. Cost of Redesign throughout the Lifecycle

A report by the Government Accountability Office found that successful government and commercial enterprises separate technology development from product development.[3] They insist that the technologies and resources necessary to satisfy customer requirements be mature and available *before* the onset of product development. They then employ a knowledge-based product development tradeoff process to capture specific design and manufacturing information about a product that corporate-level executives use to decide when and whether to proceed.[1]

The integrated design and manufacturing (IDM) methodology developed at Georgia Tech[2] seeks to develop a product through collaborating trade studies early on with both designers and manufacturers from a variety of all relevant disciplines. A designer can come up with a design with excellent performance, but if it cannot be manufactured the design is irrelevant. Georgia Tech uses a knowledge-based design process, integrating both design methodologies with manufacturing processes to create a complete design. Trade studies on product and process characteristics are conducted in an iterative fashion to form an integrated product and process development (IPPD) approach[4], as shown in Figure 2. The design progresses from the system level objectives to being decomposed into components and then parts.

These parts are then recomposed into components and back into the system.[4]

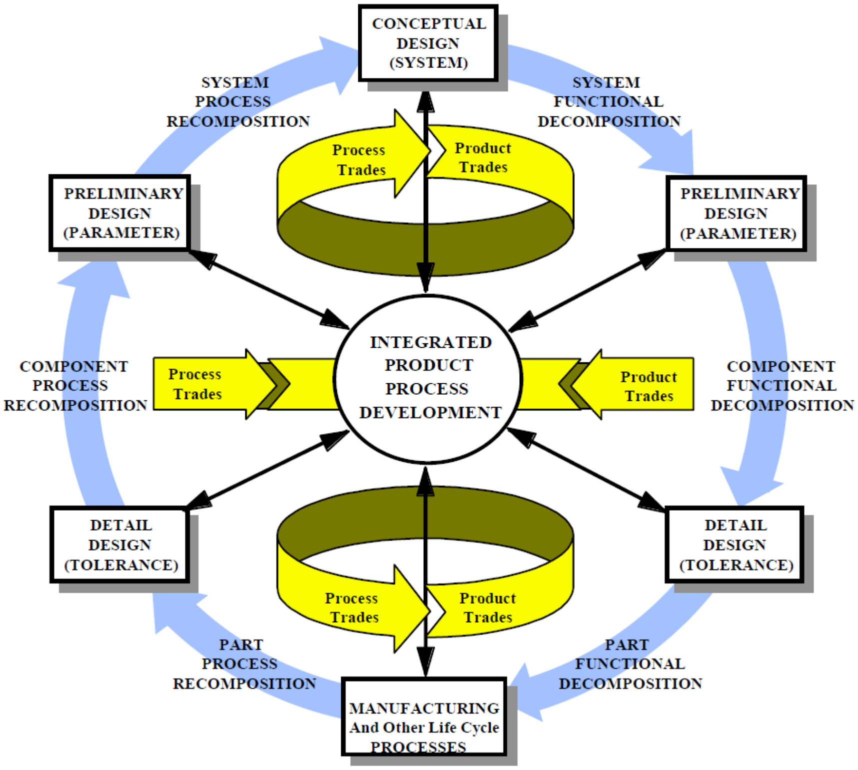


Figure 2. IPPD Iterative Process

A suite of systems engineering, management and planning tools are used to understand the requirements, objectives and customer importance before the start of the design process. Often the engineer knows what the customer requires and desires, but must quantify their characteristics importance to the customer. The customer's requirements and desires can be compared against each other in a prioritization matrix to quantify how important each is to the customer. Once the system level requirements are understood, the quality function deployment (QFD) tool is used to translate the customer requirements to key product and process characteristics. This provides an understanding of which requirements carry the most cost and risk, which engineering metrics relate to most of the requirements, and what constraints and tradeoffs are inherent in the design. The QFD translates the customer importance to the engineering characteristics of the system, and these are then deployed to the subsystem level and then the component level if required. The QFD results translate into a set of weighted characteristics which can be rolled into an Overall Evaluation Criterion (OEC) as a set of weighted criteria, as illustrated in Figure 3.

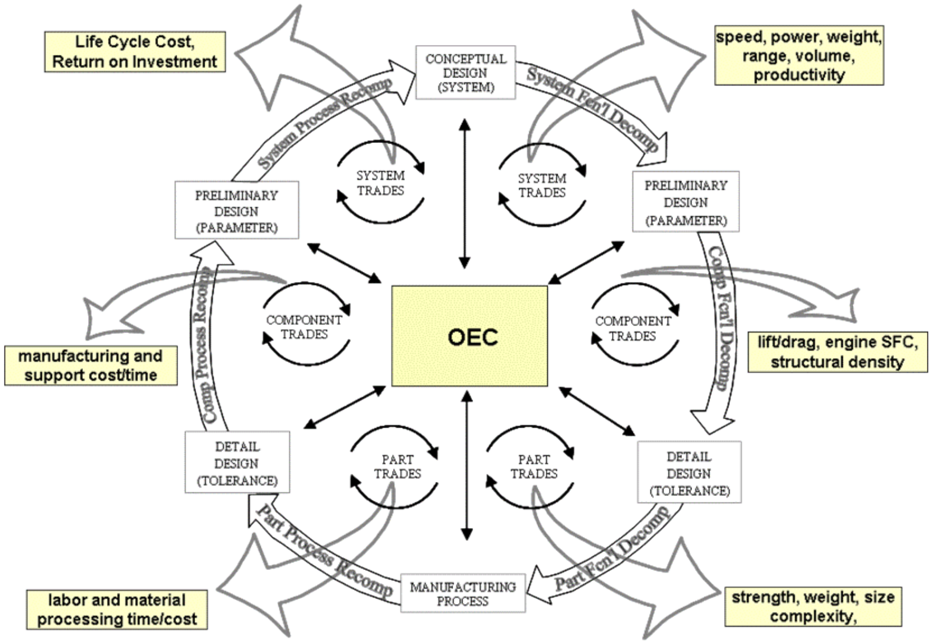
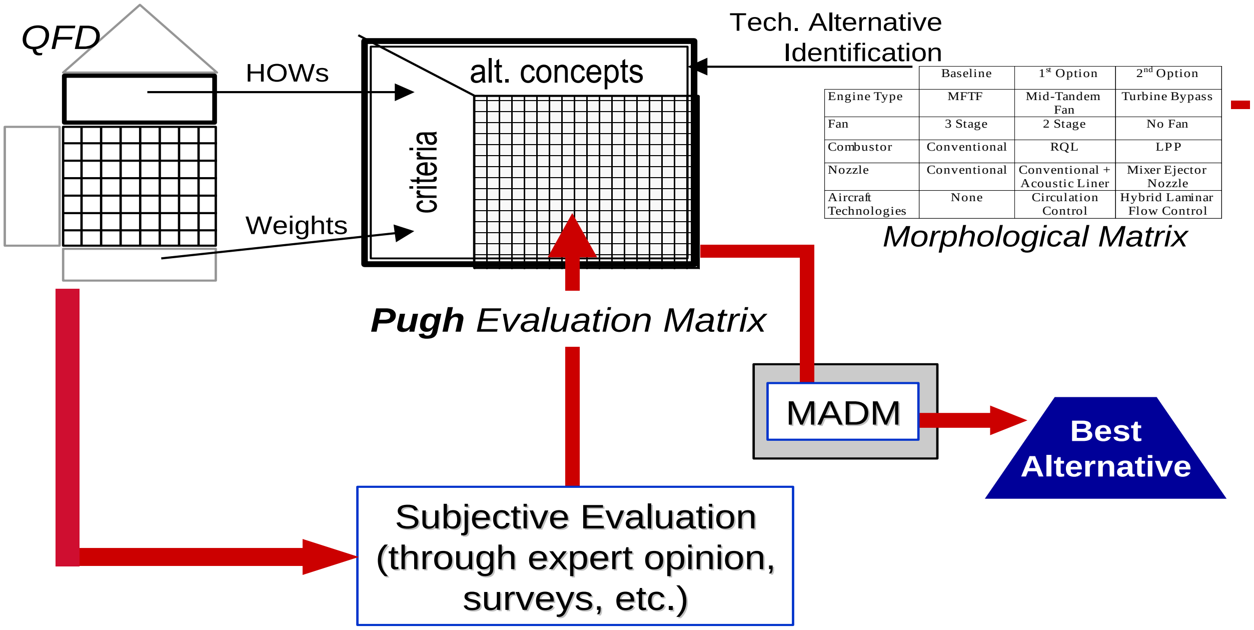


Figure 3. Product and Process Criteria for OEC at Different Levels[12]

From the design space, several of the most promising candidate concepts are selected using a morphological matrix to be evaluated and compared to the baseline using a Pugh matrix. The Pugh matrix evaluates each concept subjectively against the baseline for all the criteria selected. The overall evaluation criterion (OEC) is created to compare a baseline product with any new concepts to determine the overall benefit to cost value of a concept, therefore providing a more detailed differentiation of the design space.

If there are several candidates that score similarly, then further investigation and trade studies are needed to down select. The use of a quantitative multi-attribute decision method (MADM) can be used as illustrated in Figure 4. Probabilistic models are often used to consider the uncertainty of the requirements and engineering characteristics and typically can lead to the selection of a more robust design solution when considering aerospace systems. The design work then progresses to detailed design, by investigating how to create the product using computer aided engineering tools, and virtual testing of the product among others.



	Baseline	1st Option	2nd Option
Engine Type	MFTF	Mid-Tandem Fan	Turbine Bypass
Fan	3 Stage	2 Stage	No Fan
Combustor	Conventional	RQL	LPP
Nozzle	Conventional	Conventional + Acoustic Liner	Mixer Ejector Nozzle
Aircraft Technologies	None	Circulation Control	Hybrid Laminar Flow Control

Figure 4. Integrated Set of Visual IPPD Tools

What are Multi-user CAx Tools?

Difficulty in implementing the previously described integrated design process can be traced back to a common source, CAx software capabilities. The serial design sequence is a direct result of the single user applications, which allow only a single user into a single part file at a time resulting in longer design times even when using the IPPD process for initial design selection. Multi-user applications have been developed to change the serial design process to a parallel design process, pushing the design process into a multi-user paradigm. Tools like ROCCAD[5], CADDAC[6], and CoAutoCad[7] have been developed for use in engineering but provide asynchronous modeling capabilities, where multiple users can visualize a model but only a single user can modify that model at a time.

Research is conducted at Brigham Young University to adapt single user CAD/CAM tools to allow multi-user synchronous capabilities. One such tool, NX Connect, is an adaption of UG NX developed by Siemens PLM. This tool provides multi-user capabilities and allows users to model, assemble, and draft concurrently, allowing users across time zones to collaborate instantaneously without passing control of the model to other users, allowing real time collaboration. NX Connect utilizes a fully distributed client-server technology utilized by Massive Multi-player Online Role-Playing Games (MMORPG), allowing large numbers of users to collaborate while reducing bandwidth consumption and providing a scalable architecture. The NX Connect tool was utilized for this case study by students from all participating institutions to allow multi-location, real time collaboration to occur.

Similarly, Cubit, a finite element preprocessor developed at Sandia National Laboratories, was modified at Brigham Young University to create a multi-user finite element tool named Cubit Connect, which in real time allows collaborative mesh generation and repair. Once the geometry was completed, students at each university were able to simultaneously mesh different portions of the wing and prepare the design for analysis. The tool utilizes source code donated by Sandia and allows simultaneous transfer of mesh data through a peer to peer architecture.

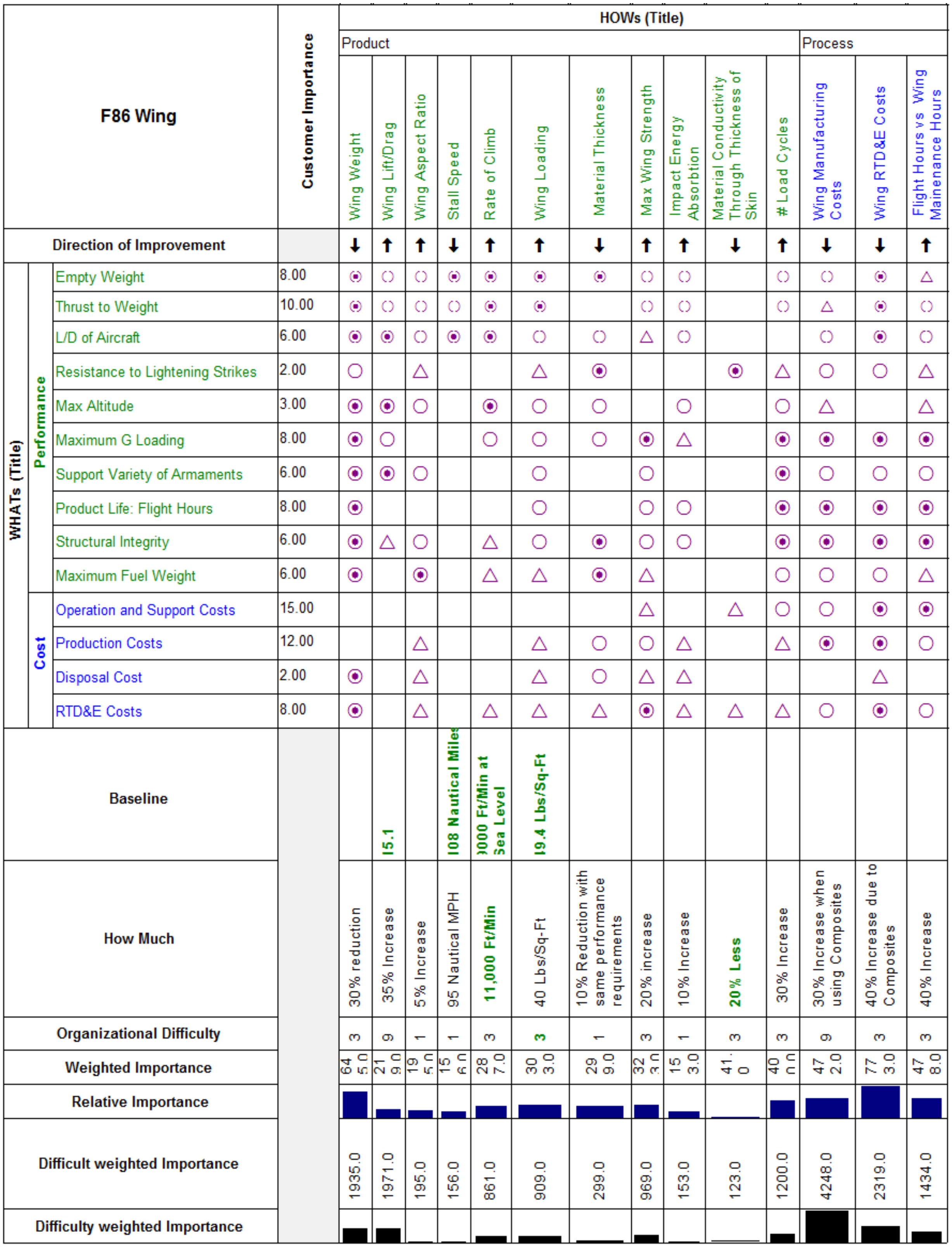
Introduction to Case Study Findings

This project was a six month collaborative effort between Brigham Young University (BYU), Georgia Tech (GT), and University of Puerto Rico Mayagüez (UPRM), sponsored by The Boeing LTD Engineering Group, to illustrate the collaborative nature required for modern aerospace product development and to validate how the necessary IDM trade studies can be accomplished with innovative CAx tools now being developed. This evaluation was to be carried out by having a team of undergraduates from the three universities redesign the wingbox for the F-86 fighter jet and document the impact of the new design methodologies. In following the findings are presented and their impact on closing the learning/doing gap is evaluated.

Finding 1: IDM

The students at Brigham Young University, the Georgia Institute of Technology, and the University of Puerto Rico Mayaguez used the IDM methodology to collaboratively work through the systems engineering, management and planning tools to better understand the problem and determine the best alternative wing concept given the constraints and scope of the project.

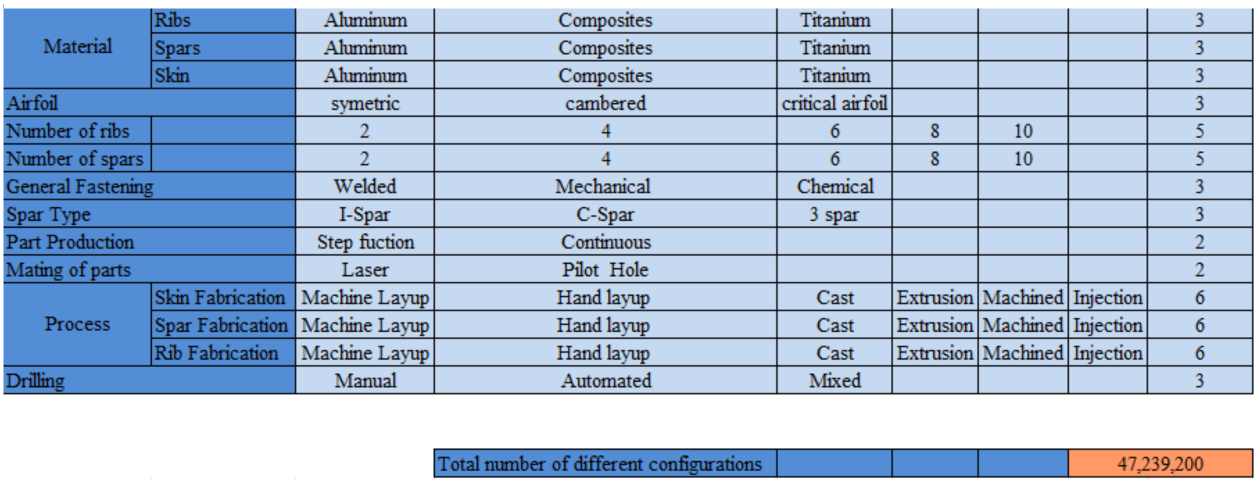
The first step in understanding the problem was to assess the customer requirements for the system level. Since this project was concerned with the development of the wing box only, the wing was treated as the main system although it is usually only a sub-system in an aerospace vehicle. Since no formal request for proposal (RFP) existed the customer requirements and weightings were based on performance and cost targets common to fighter jets. These customer's requirements were used to develop the QFD which is shown in Figure 5. Engineering means as well as processes to achieve the customer requirements were determined and their impact on customer requirements recorded. After assigning difficulty ratings matrix multiplication was used to identify the most important engineering characteristics, which was the wing manufacturing cost, with several other metrics having secondary importance. In working with the QFD, the group felt that it was important to consider these factors in the design and in doing so moved to the next phase, determining plausible concepts.



F86 Wing			Customer Importance	HOWs (Title)													
				Product											Process		
				Wing Weight	Wing Lift/Drag	Wing Aspect Ratio	Stall Speed	Rate of Climb	Wing Loading	Material Thickness	Max Wing Strength	Impact Energy Absorbtion	Material Conductivity Through Thickness of Skin	# Load Cycles	Wing Manufacturing Costs	Wing RTD&E Costs	Flight Hours vs Wing Mainenance Hours
Direction of Improvement				↓	↑	↑	↓	↑	↑	↓	↑	↑	↓	↑	↓	↓	↑
WHATs (Title)	Performance	Empty Weight	8.00	◉	○	○	◉	◉	◉	◉	○	○		○	○	◉	△
		Thrust to Weight	10.00	◉	○	○	○	◉	◉		○	○		○	△	◉	○
		L/D of Aircraft	6.00	◉	◉	○	◉	◉	○	○	△	○			○	◉	○
		Resistance to Lightening Strikes	2.00	○		△			△	◉			◉	△	○	○	△
		Max Altitude	3.00	◉	◉	○		◉	○	○		○		○	△		△
		Maximum G Loading	8.00	◉	○			○	○	○	◉	△		◉	◉	◉	◉
		Support Variety of Armaments	6.00	◉	◉	○			○		○			◉	○	○	○
		Product Life: Flight Hours	8.00	◉					○		○	○		◉	◉	◉	◉
		Structural Integrity	6.00	◉	△	○		△	○	◉	○	○		◉	◉	◉	◉
		Maximum Fuel Weight	6.00	◉		◉		△	△	◉	△			○	○	○	△
	Cost	Operation and Support Costs	15.00								△		△	○	○	◉	◉
		Production Costs	12.00			△			△	○	○	△		△	◉	◉	○
		Disposal Cost	2.00	◉		△			△	○	△	△				△	
		RTD&E Costs	8.00	◉		△		△	△	△	◉	△	△	△	○	◉	○
Baseline					15.1		108 Nautical Miles	000 Ft/Min at Sea Level	19.4 Lbs/Sq-Ft								
How Much				30% reduction	35% Increase	5% Increase	95 Nautical MPH	11,000 Ft/Min	40 Lbs/Sq-Ft	10% Reduction with same performance requirements	20% increase	10% Increase	20% Less	30% Increase	30% Increase when using Composites	40% Increase due to Composites	40% Increase
Organizational Difficulty				3	9	1	1	3	3	1	3	1	3	3	9	3	3
Weighted Importance				645.0	219.0	195.0	156.0	287.0	303.0	299.0	323.0	153.0	41.0	400.0	472.0	773.0	478.0
Relative Importance																	
Difficult weighted Importance				1935.0	1971.0	195.0	156.0	861.0	909.0	299.0	969.0	153.0	123.0	1200.0	4248.0	2319.0	1434.0
Difficulty weighted Importance																	

Figure 5. Wing Level QFD

Table I. Morphological Matrix



Material	Ribs	Aluminum	Composites	Titanium				3
	Spars	Aluminum	Composites	Titanium				3
	Skin	Aluminum	Composites	Titanium				3
Airfoil		symetric	cambered	critical airfoil				3
Number of ribs		2	4	6	8	10		5
Number of spars		2	4	6	8	10		5
General Fastening		Welded	Mechanical	Chemical				3
Spar Type		I-Spar	C-Spar	3 spar				3
Part Production		Step fuction	Continuous					2
Mating of parts		Laser	Pilot Hole					2
Process	Skin Fabrication	Machine Layup	Hand layup	Cast	Extrusion	Machined	Injection	6
	Spar Fabrication	Machine Layup	Hand layup	Cast	Extrusion	Machined	Injection	6
	Rib Fabrication	Machine Layup	Hand layup	Cast	Extrusion	Machined	Injection	6
Drilling		Manual	Automated	Mixed				3
			Total number of different configurations				47,239,200	

A table of engineering characteristics available for change and the options for each was compiled. Since the scope of the project was to strengthen the inner structure of the wing cost effectively using composites, the engineering characteristics fall into the categories of rib, spar and skin material and manufacturing processes. Table I shows the morphological matrix of the wing.

The number of different configurations totals more than 47 million. It is not possible to evaluate each option so it is necessary to reduce the number of choices. Several different concepts were selected from the morphological matrix. The team wanted to compare both composite as well as hybrid configurations, so four total design concepts were selected: metallic, composite, hybrid multi-rib and hybrid multi-spar. These concepts are shown in Table II.

Table II. Selection of Metallic, Composite and two Hybrid Concepts

	Skin	**Aluminum**	Composites	Titanium			
Airfoil		symetric	**cambered**	critical airfoil			
Number of ribs		2	4	6	8	**10**	
Number of spars		**2**	4	6	8	10	
General Fastening		Welded	**Mechanical**	Chemical			
Spar Type		**I-Spar**	C-Spar	3 spar			
Part Production		**Step fuction**	Continuous				
Mating of parts		Laser	**Pilot Hole**				
Process	Skin Fabrication	Machine Layup	Hand layup	Cast	Extrusion	**Machined**	Injection
	Spar Fabrication	Machine Layup	Hand layup	Cast	**Extrusion**	Machined	Injection
	Rib Fabrication	Machine Layup	Hand layup	**Cast**	Extrusion	Machined	Injection
Drilling		Manual	**Machined**	Mixed			

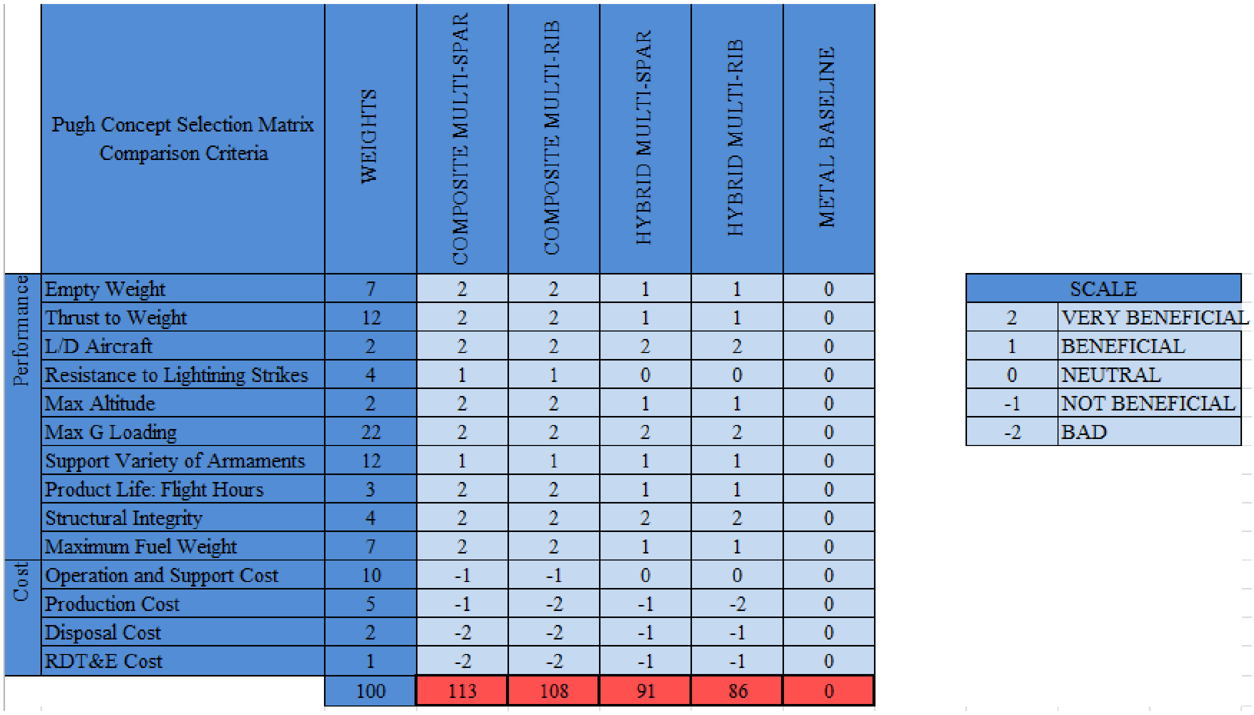
	Skin	Aluminum	**Composites**	Titanium			
Airfoil		symetric	**cambered**	critical airfoil			
Number of ribs		2	4	6	**8**	10	
Number of spars		**2**	4	6	8	10	
General Fastening		Welded	**Mechanical**	Chemical			
Spar Type		**I-Spar**	C-Spar	3 spar			
Part Production		**Step fuction**	Continuous				
Mating of parts		Laser	**Pilot Hole**				
Process	Skin Fabrication	Machine Layup	**Hand layup**	Cast	Extrusion	Machined	Injection
	Spar Fabrication	Machine Layup	Hand layup	Cast	**Extrusion**	Machined	Injection
	Rib Fabrication	**Machine Layup**	Hand layup	Cast	Extrusion	Machined	Injection
Drilling		Manual	**Automated**	Mixed			

Composite							
Material	Ribs	Aluminum	**Composites**	Titanium			
	Spars	Aluminum	**Composites**	Titanium			
	Skin	Aluminum	**Composites**	Titanium			
Airfoil		symetric	**cambered**	critical airfoil			
Number of ribs		**2**	4	6	8	10	
Number of spars		2	4	6	**8**	10	
General Fastening		Welded	**Mechanical**	Chemical			
Spar Type		**I-Spar**	C-Spar	3 spar			
Part Production		**Step fuction**	Continuous				
Mating of parts		Laser	**Pilot Hole**				
Process	Skin Fabrication	Machine Layup	**Hand layup**	Cast	Extrusion	Machined	Injection
	Spar Fabrication	Machine Layup	Hand layup	Cast	**Extrusion**	Machined	Injection
	Rib Fabrication	**Machine Layup**	Hand layup	Cast	Extrusion	Machined	Injection
Drilling		Manual	**Automated**	Mixed			

Hybrid Multi-Spar							
Material	Ribs	**Aluminum**	Composites	Titanium			
	Spars	Aluminum	**Composites**	Titanium			
	Skin	Aluminum	**Composites**	Titanium			
Airfoil		symetric	**cambered**	critical airfoil			
Number of ribs		**2**	4	6	8	10	
Number of spars		2	4	6	**8**	10	
General Fastening		Welded	**Mechanical**	Chemical			
Spar Type		**I-Spar**	C-Spar	3 spar			
Part Production		**Step fuction**	Continuous				
Mating of parts		Laser	**Pilot Hole**				
Process	Skin Fabrication	Machine Layup	**Hand layup**	Cast	Extrusion	Machined	Injection
	Spar Fabrication	Machine Layup	Hand layup	Cast	**Extrusion**	Machined	Injection
	Rib Fabrication	Machine Layup	Hand layup	**Cast**	Extrusion	Machined	Injection
Drilling		Manual	**8**	Mixed			

In order to compare these designs to each other, a Pugh matrix is used. The Pugh matrix compares the weighted performance and cost characteristics for each concept against the baseline metallic wing using a scale of -2 to +2 representing bad (-2) to very beneficial (+2). The Pugh matrix is shown in Table III. The concept that scored highest was the composite multi-spar design, consequently this concept was chosen by the team to move forward with to the next phase of the project. It should be noted that the uncommon multi-spar design was selected over the commonly used multi-rib design due the fact that composites were used and manufacturing of constant cross-section spars was considered to be more economical than forming complex shaped ribs using composites. This validates the IPPD process over the more common serial approach to design which would not have found this deficiency until much later in the design process.

Table III. Pugh Matrix Comparison

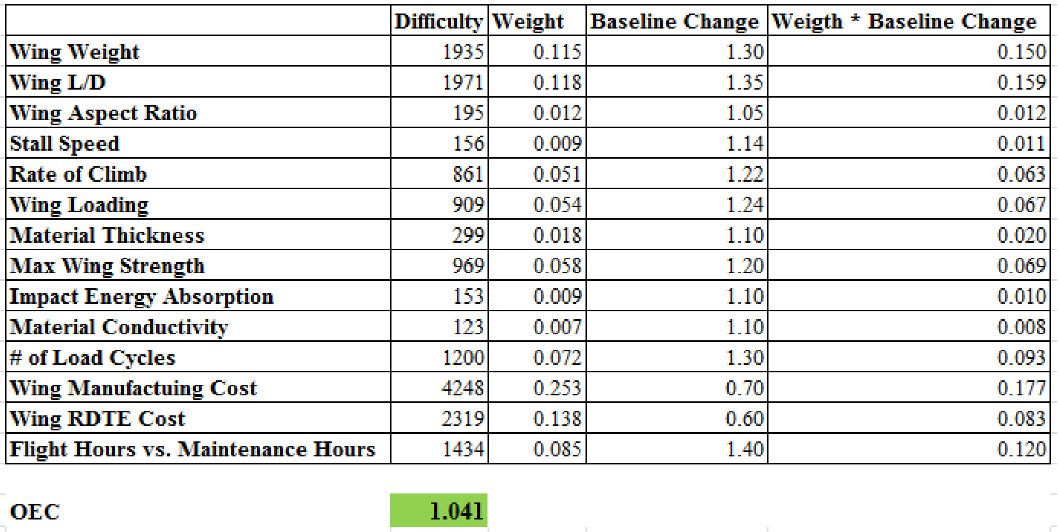


	Pugh Concept Selection Matrix Comparison Criteria	WEIGHTS	COMPOSITE MULTI-SPAR	COMPOSITE MULTI-RIB	HYBRID MULTI-SPAR	HYBRID MULTI-RIB	METAL BASELINE
Performance	Empty Weight	7	2	2	1	1	0
	Thrust to Weight	12	2	2	1	1	0
	L/D Aircraft	2	2	2	2	2	0
	Resistance to Lightining Strikes	4	1	1	0	0	0
	Max Altitude	2	2	2	1	1	0
	Max G Loading	22	2	2	2	2	0
	Support Variety of Armaments	12	1	1	1	1	0
	Product Life: Flight Hours	3	2	2	1	1	0
	Structural Integrity	4	2	2	2	2	0
	Maximum Fuel Weight	7	2	2	1	1	0
Cost	Operation and Support Cost	10	-1	-1	0	0	0
	Production Cost	5	-1	-2	-1	-2	0
	Disposal Cost	2	-2	-2	-1	-1	0
	RDT&E Cost	1	-2	-2	-1	-1	0
		100	113	108	91	86	0

SCALE	
2	VERY BENEFICIAL
1	BENEFICIAL
0	NEUTRAL
-1	NOT BENEFICIAL
-2	BAD

In order to evaluate the composite multi-spar concept against the baseline, the overall evaluation criterion (OEC) was used. The OEC uses the difficulty weighted values from the QFD to predict how much improvement the new concept will have over the baseline. Using the chosen concept, the OEC is calculated to be 1.041 which represents a 4.1% improvement compared to the baseline. Table IV shows the OEC criteria, weighting factors and OEC value. Baseline changes were based on research available[8] and engineering judgment. It is important to note at this point that it proved invaluable to have students from all backgrounds to properly evaluate each criterion. In a real design, the engineering team would need to assess whether this amount of improvement is worth the effort to redesign an existing product. Within the scope of this project, it was assumed that the improvement is substantial enough to move forward.

Table IV. Overall Evaluation Criterion for the Hybrid Multi-spar Concept



	Difficulty	Weight	Baseline Change	Weigth * Baseline Change
Wing Weight	1935	0.115	1.30	0.150
Wing L/D	1971	0.118	1.35	0.159
Wing Aspect Ratio	195	0.012	1.05	0.012
Stall Speed	156	0.009	1.14	0.011
Rate of Climb	861	0.051	1.22	0.063
Wing Loading	909	0.054	1.24	0.067
Material Thickness	299	0.018	1.10	0.020
Max Wing Strength	969	0.058	1.20	0.069
Impact Energy Absorption	153	0.009	1.10	0.010
Material Conductivity	123	0.007	1.10	0.008
# of Load Cycles	1200	0.072	1.30	0.093
Wing Manufactuing Cost	4248	0.253	0.70	0.177
Wing RDTE Cost	2319	0.138	0.60	0.083
Flight Hours vs. Maintenance Hours	1434	0.085	1.40	0.120
OEC	**1.041**			

Using the IDM process enabled the students to understand the problem, customer requirements, and the relationship they have with the engineering characteristics. The team was able to look at the available options that could be changed to redesign the wing and down selected the 47 million possible configurations to 4 concepts: metallic, fully composite, hybrid multi-spar and hybrid multi-rib. After comparing the concepts it was determined that the composite multi-spar was most beneficial and gives an overall benefit to cost increase of 4.1% over the baseline. Using the IDM process resulted in a viable concept that was worth pursuing to the next stages in development and also highlighted that early collaboration of all disciplines prevented a bad design choice from being made (Multi-rib Design) which would have led to costly corrections later.

Finding 2: Collaboration

For modern complex aerospace systems collaboration is imperative. Evermore complex systems require engineers from different backgrounds to work together to solve a common problem. This project was only concerned with the development of one sub-system, nonetheless engineering students from multiple backgrounds were required. The participating universities and students were selected based on their skills and knowledge to further this project with backgrounds in aerospace, mechanical and manufacturing engineering.

It is important to note that “individual members of a team do not require complete overlap of all information within a problem space in order to possess a congruent and accurate team mental model of a defined problem."[9] An integral part of successful collaboration is therefore the availability of the right people at the right time. This allows for the formation of self-organizing teams.

In order to establish the mental model for this project the capabilities of each student had to be determined first, so that sub-teams with sufficient overlap could be created.

Table V shows how concurrent sub-teams were formed, "X" representing the ribs team and "Y" representing the spars team. It can be seen that teams were formed such that there was some overlap in capabilities, but also some clear separation between the social and educational backgrounds of team members.

Table V: Team Capabilities

		Modeling				**Major**		**Other Knowledge**			
		Catia	**NX**	**Inventor**	**ProE**	**Aerospace**	**Mechanical**	**Composites**	**FEA**	**Structures**	**Cubit**
GT	Juan Pablo Afman	X		X	X	X				X	
	Sam Slaughter					Y					
	Fabian Zender	X		X	X	X		X	X		
BYU	Catalina Sanchez	X	X	X	X		X		X		
	Shelby Ward	X	X		X		X		X		
	Tim Bright	Y			Y		Y	Y	Y	Y	
	James Wu	Y	Y				Y	Y			Y
UPRM	Juan Cordero		Y				Y		Y		
	Michael Cruz	Y	Y				Y		Y		
	Luis Mercado					Y	Y		Y		

This project highlighted the importance of collaboration early in the design process. Utilizing the IPPD process enabled the team to include manufacturing considerations before spending too much time on a design that could possibly never be manufactured. It also allowed for the inclusion of preliminary aerodynamics analysis before continuing with the detailed structural design. The IPPD process as well as the collaboration between varying socio-educational backgrounds enabled the team to early on select the design best for all downstream disciplines.

While collaboration provides great benefits, allowing multiple users to participate also introduces some complications unknown to single user applications. Inherently, if there is a problem with the design it will most likely be noticed by multiple engineers at the same time. When working in a multi-user environment it is of utmost importance to communicate well to ensure that multiple people do not edit the same feature at the same time resulting in interference and wasting costly engineering hours.

Furthermore during initial design decisions, assumptions have to be made according to the information available at the time. While the cultural and professional differences can be helpful to consider different viewpoints, they also have the potential to cause gridlock when opinions are contrary. This can be resolved but requires a select number of leaders or power users that can make the final decision. Design teams should determine who these people should be before the beginning of the design process, should they not be subject to a predefined management structure. This will become ever more important when increasing the number of people involved in the design process and relying on crowdsourcing for conceptual design. Subject matter experts should be selected to have the decision making positions.

Finding 3: Multi-User Tools

Students were able to collaborate using the previously described software developed at BYU. The software clients were deployed at each university with the MMORPG server located at Brigham Young University. Students were able to connect to the server and utilize the local installation of UG NX and the NX Connect plugin. No files were stored locally instead the server maintained a database of all sketches, points, and features and propagated them to all connected users. As students worked collaboratively at the boundary of the capabilities of the current multi-user plugin, the software was updated continuously to fix encountered errors and add capabilities while the students continued to develop their models. NX Connect utilizes the UG NX Open Application Programming Interface (API) which allows for modification of the UG NX environment for automation and parametric purposes. Since the API is utilized, every feature must be integrated into the MMORPG technology and as the API is updated, so must the MMORPG client-server architecture be updated.

Some of the additions to the NX Connect capabilities added during the case study include: multi-user assembly part trees, expressions (allowing parametric modeling), sketch modification, constraints, ruled surfaces, offset curves, Boolean operations, splines, and points, as well as adjustments to the previously developed features including extrudes, revolves, mirror curves, and sketches. These features were implemented to allow ribs and spars with tapers and twists to be generated for the modeling of the F-86 Sabre wing. As the project progressed, the students identified lacking capabilities and worked with the software development team to find the best ways to achieve the required functionality.

The students were able to develop components of the wing faster utilizing the developed multi-user CAD tool, however some of the required capabilities (in particular for the assembly process) could not be added in time for the conclusion of this project, requiring some of the work to be completed in UG NX 6.0 package in order to finalize the assembly for subsequent analysis.

Finding 4: How Working in a Multi-User Environment Changes Design for Users

When working in a multi-user environment, special care must be taken to avoid friction between the users. Similarly to Clausewitz description of “friction of war”[10] there is an absence of clear information in the multi-user environment. To minimize this, prior to the start of each design session a brief organizational meeting was required to discuss what parameters were to be used, what geometry to create, and who was working on what part to assure the associativity of the features created were kept well-structured in case some of the dependencies needed to be edited later. Size and scope of the organizational meetings are dependent on the complexity of the components to be created, the flexibility of the parametric model to be used and the number of users to be working in the same design session. The more users, variables and general complexity the more time should be used to organize the sessions and avoid unwanted changes or deviations to be made and to ensure that an overall cohesive model is created.

For the spars model, shown in Figure 6, the students from each university were assigned particular sections to sketch so that they could all be joined accordingly using the Ruled Feature Operation. Before the sketches could be started the parameters needed to be determined and entered into NX so that every user had access to them. Coordinate systems were created using those parameters so that the sketches could be associated to each particular coordinate system. In this case the Spars team was split between the root and tip sections of the wing and the station number of the spar. Usually the first or last three from the leading or trailing edge were then assigned to a particular user.

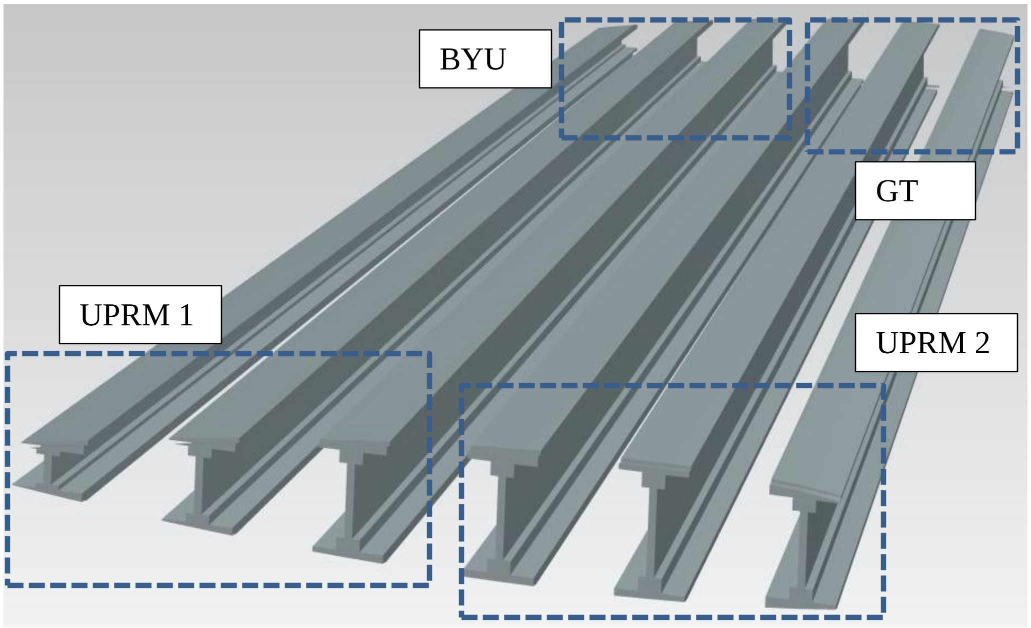


Figure 6. Spars Model Sub Division Structure

Having all users be assigned particular areas of the model exclusively serves to eliminate the occurrence of accidental changes to be made to the component as well as avoiding errors due to multiple requests to the server. The same component area sub division method could be applied to single piece components with a high number of features such as an engine block. Having each user work with the dependencies of the features in his area of the model avoids the occurrence of associativity errors due to the lack of familiarization with the geometry that another user whom did not create the geometry might have, primarily in the case that one of the dependencies needed to be modified. Once each user starts working on his area of the model the design time is ideally shortened to 1/n, where n is the number of users.

In the case that further revisions are needed, they can be made by any user; however care must be taken not to disrupt the dependencies of other models. Some research is being conducted at Brigham Young University to decompose models and workspaces to deal with feature access.

For the FEA model using Cubit Connect a similar task subdivision based on areas of the model was found to be effective to eliminate double meshing of any features. The users were also assigned to inspect the mesh and ensure satisfactory mesh properties for their part. Overall, when comparing the advantages and disadvantages of using the multi-user tools it was found that even for simple models the need for initial set-up and organization time is outweighed by the time reduction from the multi-user paradigm. These benefits will be much enhanced when considering the creation of large scale, complex geometries.

Future Work

While the IDM process allows for quick down selection of designs and encourages the inclusion of collaboration early in the design process, tools used in the process such as QFD still have a single-user architecture. Similarly Morph and Pugh matrices, as well as OEC calculations had to be carried out by a single user. Future work should focus on combining all tools in a collaborative, multi-user product lifecycle management (PLM) architecture.

Such a tool should be based on a social-networking architecture enabling students to work in an environment natural to them and also much more efficient in creating self-organizing design teams than formation by traditional means of communication. Such self-organizing teams should then be able to utilize the PLM infrastructure to engage in all required design work collaboratively, including but not limited to: IDM tools, meshing for computational fluid dynamics (CFD) as well as finite element analysis (FEA), and solving computer aided engineering (CAE) problems.

Furthermore the design process utilizing the global-brain paradigm should be further investigated and optimized. Expanding the size of the design teams towards a mass collaboration environment will lead to problems during design selection. Future work should find a process or algorithm for down selection of the final design that could be based on experience, knowledge, and previous inputs from each user. Additionally the idea of open-innovation and its application in complex aerospace systems should be investigated.

Conclusions

Nothing within the corporate environment is static, design-manufacturing processes and methods, business models and product differentiation are constantly evolving. In this partnership, students, professors, industry experts, technologists and scientists work together to develop innovative educational model, a new culture with shared artifacts, practices, and behaviors, and common frameworks that will help advance personalized learning[11].

The cap stone project enabled students to transfer knowledge within a social network, mentored by peers, industry workplace experts and professors through both face-to-face and leverage a cyber infrastructure. Through this translational framework the students developed strong outcomes in critical thinking, creativity and innovation. Our intent was to push the multi-user technology and to test a distributive industry design experience for the students. Education and Technology were at the center of this partnership.

The cloud-based collaborative multi-user tools and the IDM methodology both proved to be effective tools during this study. The IDM process allowed a set of designs to be generated and let the user select a design that can meet customer functional specifications. Through early collaboration of students from different social-educational backgrounds manufacturing design choices could be made before deciding on the conceptual design and thus eliminated costly design iterations. The study proved that the multi-user tools are an effective way to bring cross functional teams together to collaborate instantaneously across space and time, generating and evaluating designs much faster than a single user environment could provide, reducing design time up to 1/n, where n users are collaborating in the multi-user environment. These tools can also enable project managers, vendors, suppliers, and engineering personnel to instantaneously collaborate on projects, drastically reducing the time and cost to market providing a better final product to the customer.

The study also indicated that, should these multi-user tools be developed into full commercial applications and combined with the IDM process, better designs could be achieved and concurrent product design could be compressed dramatically. This indicates that a shift in design processes is needed, as current collaborative work is changed from a follow the sun paradigm to a “emergent product design” real time 7/24/365 global design paradigm. The study also showed that the curriculum for students can be modified so that students can begin to work virtually with engineers from partner companies on future products while being located in their classroom environments. Incorporating what we know about how people learn including, learning models, the educational system and the activities required to develop student outcomes in critical thinking, creativity, innovation and knowledge to fill the jobs in the areas of science, technology, engineering and mathematics (STEM) in the future.

The study proved that industry and academia can effectively collaborate to ensure students are exposed to the industry principles of collaborative distributed digital and have an opportunity to learn experientially thru hands-on environment, effectively closing the learning-doing gap.

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