A NON-WEIGHT BASED, MANUFACTURING INFLUENCED DESIGN (MIND) METHODOLOGY FOR PRELIMINARY DESIGN

Johanna Ceisel*, Philipp Witte*, Tim Carr*, Satya Pogaru*, and Dimitri N. Mavris*
***Aerospace Systems Design Laboratory (ASDL),**
Georgia Institute of Technology, Atlanta, GA, USA
jceisel@asdl.gatech.edu

Keywords: *Aircraft Design, Cost Abstraction, Design for Manufacturing, Surrogate Modeling*

Abstract

Manufacturing has traditionally focused on the late stages of aircraft design when the structure is already well defined. But advanced materials, new manufacturing processes, and globalization necessitate that manufacturing and design trade-offs be conducted earlier in the design process. This paper defines a new design methodology that incorporates appropriate, non-weight based manufacturing criteria during preliminary design to enable performance, structures, and manufacturing cost trade-offs. This methodology integrates a non-proprietary manufacturing tool, SEER-MFG, with design codes written in MATLAB into a multi-disciplinary environment using ModelCenter. The main cost drivers for manufacturing, such as ply and fastener count, are extracted from detailed designs and fed to SEER-MFG enabling preliminary design modeling and analysis. Surrogate modeling techniques are then used to visualize the data and facilitate multi-attribute decisions between different concepts.

1 Introduction

Performance at any cost days are over for the aerospace and defense industries due to the economic downturn and global competition. Customers now demand more performance at lower cost and risk. In order to stay competitive, manufacturers are addressing this shift to affordability through innovative designs enabled by advanced materials, manufacturing processes, and technologies. These advanced materials, such as composites, lead to a higher design freedom and reduced weight, but typically increased cost [1]. Furthermore, the manufacturing tooling and redesign costs that support advanced materials are much larger contributors to cost than in the past. As a result of these changes, cost is no longer proportional to weight, but to material and the respective manufacturing processes as well [2]. A new non-weight based design methodology is needed that allows design for manufacturability trades earlier in design to better balance performance, time, and cost, when design freedom is greatest and cost commitment least.

In order to model design and manufacturing within preliminary design without using a weight based approach, there are four main challenges to overcome: 1) Need a non-proprietary, non-weight based manufacturing cost modeling tool 2) Lack of knowledge about the internal structure, causing disconnect between the necessary fidelity of data between design and manufacturing 3) Integrated multi-disciplinary model to generate data for trades 4) Rapid data visualization to enable multi-attribute decision making.

2 MInD Approach

The first challenge outlined above is a heavy reliance on proprietary, historical data in the form of weight-based cost models, which limits the design space to a manufacturer's existing family of aircraft and manufacturing capabilities. This prevents advanced concepts from moving forward since there is a lack of historical data. Due to a lack of modeling tools and design standards, composites are currently mainly being used in “aluminum structural designs”, which provide limited performance benefits at a high cost compared to “true composite structural designs” [3]. Furthermore, emerging global suppliers and their advanced manufacturing capabilities are considered too late due to the difficulty in modeling them. As a result, a non-proprietary, configurable process based costing tool is needed instead of weight-based methods in order to accurately represent manufacturing cost, open the design space, and maximize the potential benefits these advanced materials and processes via in-house or outsourced offer. In contrast to weight based models, activity based models break down a process into a series of steps or activities. The cost for each process is generally found using time and motion studies of each activity which is then multiplied by appropriate labor rates. Since the data is at the activity level and non-aggregated, activity based models are configurable and relevant, enabling the modeling of advanced concepts. There are several commercially-available process-based cost tools such as NASA’s P-BEAT and SEER-MFG by Galorath. SEER-MFG was ultimately selected as the most suitable cost tool for integration into the multidisciplinary model. SEER-MFG is the direct result of the government’s Composite Affordability Initiative (CAI), resulting in a large breadth and depth of current industry data from many aerospace manufacturers. Since the tool is activity based, it is highly configurable and is not limited to a certain set of manufacturing processes.

Another main issue in the design process is incorporating manufacturing at the early stages of design due to the significant disconnect in the fidelity of data between preliminary-level design and manufacturing. Traditional cost tools used at the early stages of design use weight as the surrogate for cost and are appropriately called weight-based costing tools [4]. Weight-based costing tools are convenient for traditional aluminum aircraft because an approximation of the aircraft weight is readily available throughout design as it is a crucial parameter for assessing aircraft performance. However, as mentioned earlier and as Rais-Rohani and Dean point out in their survey of cost models, the accuracy of a weight-based cost model depends on the accuracy and relevancy of the historical data, making them useless for new designs, materials, or processes [5]. But the input parameters needed for process based cost tool are often not available in conceptual or even preliminary design phases. Therefore, an approach is needed to generate the appropriate geometry data for the detailed cost model. In order to overcome this challenge, the MInD approach developed a structure to manufacturing translator or mathematical relationships to define the internal structure based on the OML of the aircraft instead of drafting the geometry in a CAD tool. For example, the wing aspect ratio, wing area, wing taper, wing sweep, wing thickness, rib orientation, and rib spacing is sufficient information to determine the size and quantity of every rib in a wing using simple geometry and scaling. Then these relationships were supplemented with additional “rules of thumb” to estimate the number of parts and fasteners in every rib. The entire process of creating and applying such equations is shown in Fig. 1.

A critical component of the MInD methodology is the multi-disciplinary model, which generates the data for analysis. As discussed earlier, the MInD model encompasses a structure to manufacturing translator in MATLAB that feeds the high-fidelity manufacturing cost model. The manufacturing data is then fed into a parametric production scheduling model and cash flow model. In parallel, the weight of the aircraft from the geometry model is used by the performance and sustainment model to generate performance and sustainment data. Integration software is used to connect the models and respective information flow. Once integration is complete, the multi-disciplinary model can be run for various designs and analyzed.

However, these run times can take up to 5 or more minutes for each concept. Even with limitless computation power, the data is difficult to visualize in a way that various stakeholders can make quick, informative decisions. A method is needed to overcome the time and data visualization challenge. One method pioneered by Mavris and Schrage is to use Surrogate Modeling [6]. This technique involves running cases in a Design of Experiments (DOE) to maximize the information and minimize the number of required runs. This data is then used to generate Response Surface Equations (RSE) using least squares regression. The result of the surrogate modeling process is a set of 2nd order polynomial equations that approximate the code regressed. The surrogate modeling technique has several advantages. The equations do not contain the proprietary data that the software requires, they do not require a license to be used, and the inputs can be varied at near instantaneous runtimes. Instantaneous runtimes makes RSEs a key enabler for rapid and interactive multidisciplinary tradeoffs. Whereas the process-based cost model takes several minutes to run for one design point, the RSE that fully captures the model across a specific design range takes less than a second. After the RSEs are created, they are then incorporated into an excel-based trade-off tool that dynamically feed graphs, such as Pareto frontier charts, wing geometry, engineering diagrams, production schedule, and cost break-outs for different, parametric concepts. This approach is then repeated to build a library of concepts for different designs, materials, and manufacturing processes. Once different concepts are loaded into the tool, important design space trade-offs can be made early in the design process. For example, an aluminum design with an automated process can be compared to an advanced composite design with a manual process. The trade-off tool serves as a common portal for engineering, manufacturing, finance, and marketing, to conduct dynamic concept trades. Critical key questions can now be answered, such as: What design, material, and manufacturing process best meets performance at a reduced cost? Outsource or keep in-house? And what critical production quantity justifies the capital investment cost for automation? The MInD approach is summarized in Fig. 2.

3 Manufacturing Cost Model

There are several different cost models that can be broadly categorized as parametric, bottom-up, analogous, and analytical [7]. Parametric cost models link cost to technical parameters through mathematical expressions called Cost Estimating Relationships. Bottom-up cost models involve extensive data gathering of all information related to the cost of the final product. Analogous models look at the differences between the new product and an existing product of which the cost is known to estimate the cost of the new product. Analytical models use independent variables that directly

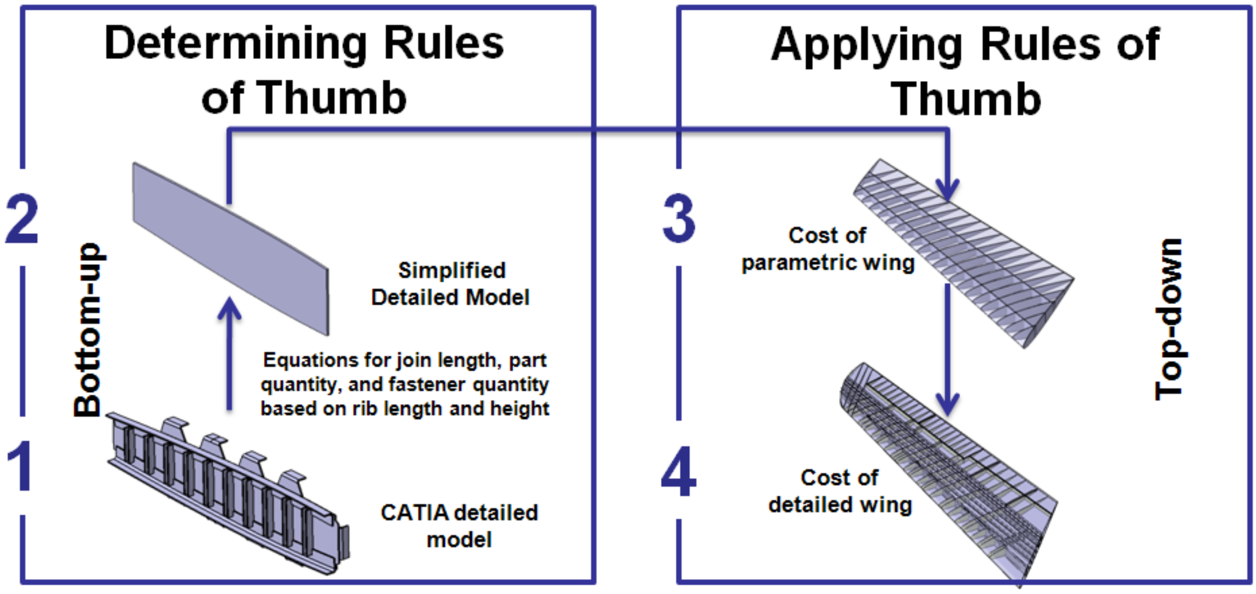

Fig. 1. Manufacturing Data Generation Process

relate to the cost through labor time, material cost, equipment, etc. This last category of cost models includes activity based costing models. As explained earlier, activity based models were chosen due to their detail and ability to support advanced designs and processes.

SEER-MFG was ultimately selected as the most suitable cost tool for integration into the multidisciplinary model. It contains a large breadth and depth of current industry data collected from the government's Composite Affordability Initiative. SEER-MFG advances the work done by Morris and Gantois, because it has a large collection of cost models for various processes instead of one equation for material, detailed manufacturing and assembly [8]. SEER-MFG is able to provide different cost equations for various fabrication and assembly processes, such as machining, sheet-metal forming and welding, riveting, and adhesive bonding respectively. SEER has enough cost drivers to capture new production plans. Instead of just using weight, surface area and complexity as the cost drivers, SEER has preliminary level drivers such as thickness, number of parts, pocket quantity, and fastener quantity. So the cost benefit of even just integrating two parts on the entire airframe can be realized. Further, various production plans can be configured and evaluated. For instance, one could evaluate the cost benefit of using different curing, trimming, or fastening/bonding operations. For a specific process, such as machining, one can trade number of setups, loads/unloads, types of material removal, sequence of material removal, process speed, time, and cost. The cost model can be used to determine the material, labor, and tooling cost.

The cost models must be made at the level at which cost data is to be extracted. To extract the cost data at the subassembly level, there must be individual cost models for each subassembly. If on the other hand the cost data is to be extracted at the part level, there must be separate cost models for each part. Research or expert opinion is needed to select the appropriate processes and determine the correct process inputs for each part or subassembly for a certain material. Typical processes for parts fabricated out of aluminum include stretch

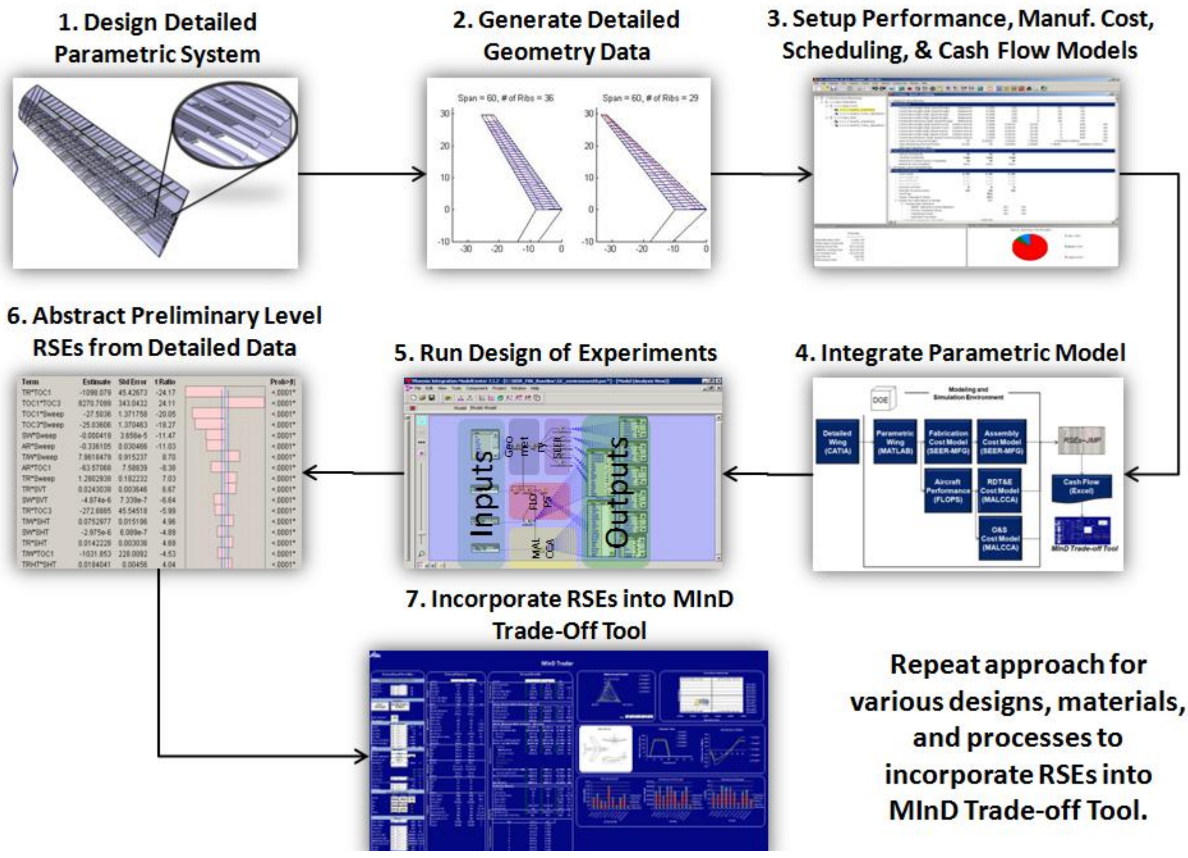

Fig. 2. MInD Approach

forming, rolling, bending, and machining [9]. Typical processes for parts fabricated out of carbon or fiberglass composites include hand-layup, automated fiber placement, and Resin Transfer Molding (RTM) [10]. Similarly, SEER-MFG models need to be created for the major assembly steps. Fit-up, drill, fastening, welding, and bonding are all examples of process models that can be configured to represent the assembly process.

Each of the SEER-MFG models can be run in server mode. In this mode, SEER-MFG can be run from the command prompt. By using the batch mode within SEER-MFG, several inputs in the model can be varied sequentially.

4 Manufacturing Translator

As mentioned earlier, a manufacturing translator tool of the aircraft Outer Mold Line (OML) and internal structure is required to feed the detailed cost model. The geometry model must be parametric in order to determine the effects of design changes on cost. Since a detailed cost model typically contains cost drivers such as part width, length, joint length and fastener quantity, the parametric geometry tool must be sufficiently detailed. Several Computer Aided Design (CAD) tools exist for this task. There are two distinct categories for CAD tools: non-parametric and parametric. Non-parametric CAD tools only store the endpoints of the vectors that describe the part, which makes editing the part difficult. AutoCAD is an example of a commonly-used 3D CAD program that is non-parametric. On the other hand, parametric CAD tools define solids by a set of parameters and constraints. By storing the steps taken to generate solids or surfaces, parametric CAD tools allow the user to easily make changes to the geometries [11]. If the dimensions of the parts are updated by the user, the geometry will automatically update.

The issue with creating geometries in detailed software packages such as CATIA is that they require substantial experience in drafting, require a lot of experience in structural design, and are difficult to parameterize. The difficulties in making a parametric model lie in unforeseen constraints. When a rib is defined using the OML and a plane offset from the centerline, the rib will automatically update in size when the OML is changed. But when the plane is offset past the tip of the wing, the geometry will cause an error because the intersection between the rib and OML is ill-defined. To avoid such issues, parametric geometry model was created using mathematical relationships to define the internal structure based on the OML of the aircraft instead of drafting the geometry in a CAD tool.

For example, a sheet metal rib contains many individual parts that are all riveted together to form the rib, shown in Fig. 3. These components include the rib web which holds together the rib. These components include the rib web which holds together the rib. Caps are attached to the top and bottom of the rib web to increase its bending stiffness. Shear-ties are attached to the rib in order to attach it to the wing skins. Vertical stiffeners are mounted on the rib web to prevent the rib from buckling under wing bending. One shear-tie is generally attached between each set of stringers. Vertical stiffeners are usually attached at each shear-tie and stringer.

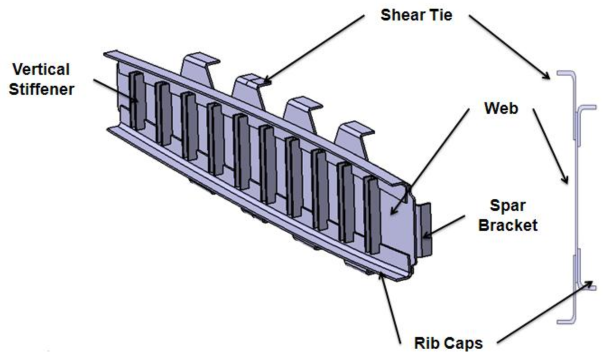

Fig. 3. Sheet Metal Rib Diagram

From these design conventions, an equation can be developed that relates the number of parts of a rib to the stringer spacing. Furthermore, the number of fasteners can be calculated from the fastener diameter, fastener pitch, and fastener edge distance. Structural designers generally adhere to a set of structural standards that are established by their company. But all of the standards are generally very similar because they are based on historic experience and structural tests. Most of these structural standards use a 4 or 5 diameter pitch and 2 diameter edge distance. Such equations as shown below for part quantity and fastener quantity as a function of the overall rib dimensions can be generated for all components in the aircraft structure and provide the necessary level of detail for the preliminary level manufacturing cost model.

Length of Cap = Rib Length (1)

*Height of V-stiffener = Rib height – 2 * Stringer web length* (2)

*VStiffener Qty = 2 * (Rib Length / Stringer Spacing)* (3)

Sheartie Qty = VStiffener Qty (4)

*Part Quantity = 1(web) + 2(caps) + Vstiffener Qty + Sheartie Qty + 2 * (Spar Joints)*

*= 5 + 4 * (Avg Dist Betw Spars / Stringer Spacing)* (5)

*Join Length = 2 * Length of Cap + Qty of VStiffener * Avg Height of V - Stiffener*

*=2 * Length of Rib + 2 * (Avg Dist Betw Spars / Stringer Spacing) * (Height or rib – 2 * Stringer web length)* (6)

*Fastener Pitch = 4 * Fastener Diameter* (7)

Fastener Qty = Join Length / Fastener Pitch (8)

5 MInD Multidisciplinary Model

5.1 Overall Information Flow

A critical component of the MInD methodology is the multi-disciplinary model, which generates the detailed data for abstraction. A parametric geometry, structures to manufacturing translator, and manufacturing cost model are integrated into a multidisciplinary model along with performance, production, and cash flow. Basic OML geometry parameters are fed to the geometry model. For a fuselage, these parameters would be the fuselage length, fuselage width, nose length, and tail taper angle. For the wing, these parameters would be its area, sweep, aspect ratio, and taper. The geometry model then feeds the dimensions of all of the internal structure parts to manufacturing translator, which then feeds the manufacturing cost model. The manufacturing cycle time and production quantity are then fed into a low fidelity capacity model. In the capacity model, the number of lines, shifts, and tooling required to meet a minimum production rate is determined. Once the capacity is determined, then the production schedule is generated using the capacity and average time per unit. The production schedule with the manufacturing labor, material, tooling, and equipment costs are then used to generate the cash flow model.

Concurrently, the geometry model also feeds the weight of the aircraft to the performance model to generate performance data, such as thrust to weight, wing loading, and climb rate. Weight and performance data were also fed into the operations and sustainment cost model to generate operations costs for a particular mission profile and load.

All of the outputs are collected into a data table for abstraction. These relationships between all of the individual models are visually depicted in Fig. 4.

5.2 Physics Based Performance Model

As the term implies, physics-based tools are high fidelity tools that model the physics behind a process rather than generalizing the behavior through simple equations. For instance instead of creating a relationship of jet engine horsepower using jet engine weight based on a set of existing engines, a physics-based model would model the stages of the jet engine to determine the engine thrust and efficiency. This allowed the modeling of new engines that would not be part of the historical data set. The parametric geometry tool feeds the OML dimensions to NASA's Flight Optimization System (FLOPS) aircraft analysis and conceptual design code. The wing OML data is combined with basic size assumptions based on the F-86F fuselage and control surfaces to calculate key performance parameters. FLOPS calculates a weight breakdown for the aircraft at various mission stages, aerodynamic data, fuel consumption, and basic performance parameters such as takeoff field length and approach velocity. The weight breakdown from FLOPS was compared against the F-86F weight breakdown to validate the FLOPS model. Using the data generated by FLOPS, other key performance parameters were calculated such as max climb rate, minimum turning radius, combat radius, wing loading, thrust to weight ratio, and stall speed. These performance calculations were based on a widely-used aircraft performance reference [12]. A mission constraint plot was also created based on the work of Mattingly, Heiser, and Daley which shows thrust to weight ratio vs. wing loading for various mission segments [13].

5.3 Model Integration

Several integration tools exist to aid in stitching together the individual codes into a single multidisciplinary model. ModelCenter by Phoenix Integration is one such tool. A screenshot of ModelCenter is shown in Fig. 5, in which the inputs are listed to the left, individual codes are represented by gray icons, links between codes are indicated by black lines, and the outputs are listed to the right. ModelCenter contains a library of plug-ins called wrappers to link software such as Matlab, SEER-MFG, and excel together. For software that ModelCenter doesn't already contain, custom wrappers can easily be created.

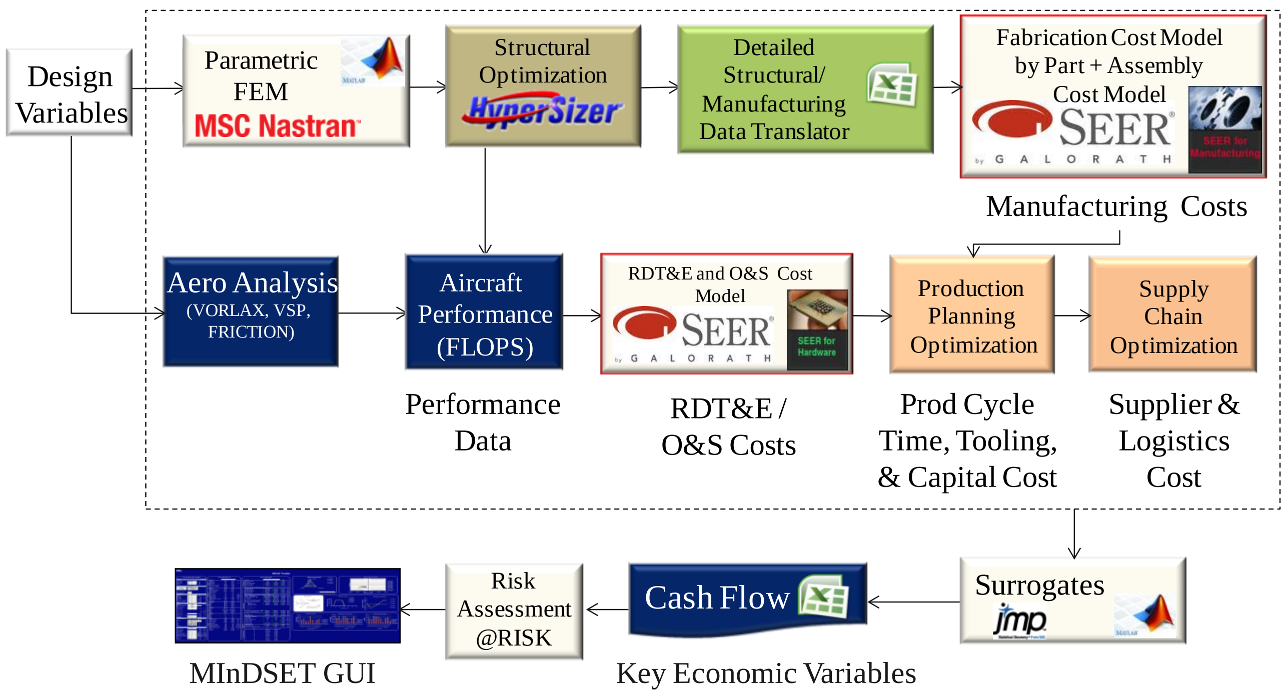

Fig. 4. MInD Multidisciplinary Model

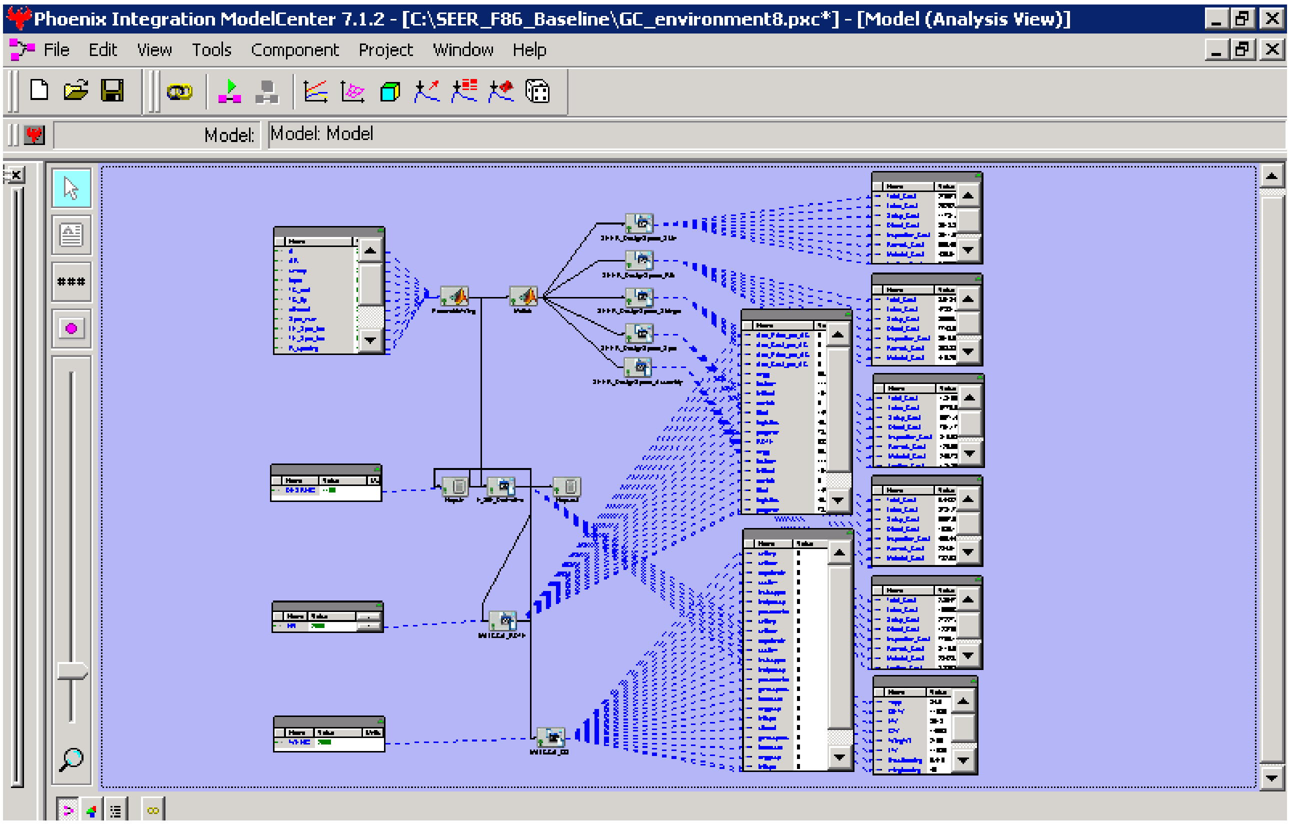

Fig. 5. Screenshot of ModelCenter Environment

5.4 Concurrent and Future Work

One of the shortcomings of this project was the lack of structural sizing due to limited resources and time. The skin thickness was included as a Design of Experiment (DOE) input instead of being sized based on loads on the wing. Another shortcoming was an unconstrained capacity per line was assumed to determine a rough order production rate. Production rate currently reflects aggregated man hours per process versus true cycle time. Since the time this paper was written, a high fidelity structural optimization and production planning tool were developed an integrated into the MInD framework. The Nastran, HyperSizer, and Production Planning icons shown in Fig. 4 shows how this work was integrated into MInD. Please refer to reference [14] and [15] for further information. For information on the risk assessment tool, please refer to reference [16]. Future work encompasses replacing the rigid body aerodynamics model with a higher fidelity model and potentially incorporating stability and control.

6 MInD Tradeoff Tool

After running the design of experiments through the multidisciplinary model, the response surface equations (RSEs) were extracted and integrated into a tradeoff tool. The real-time tradeoff tool enabled by RSEs allows for instantaneous key metrics tradeoffs between the major stakeholders in the design process, namely the Customer, Finance, Engineering, and Manufacturing. A Microsoft Excel spreadsheet provides a convenient platform for such a tradeoff tool since it is portable and easily accessible to many users. The response surface equations can be stored as VBA scripts so that they can be called up anywhere in the spreadsheet similar to existing function within Excel.

The tool is organized into three tabs: 1) Executive Summary 2) Engineering and 3) Manufacturing. Each tab has a concept input, information, and results section. There are also diagrams to visually depict the numbers contained in each of the sections. The executive summary section shows data from all four stakeholders. The engineering and manufacturing tabs show the same data, but at a more detailed level. For instance, a dynamic constraint plot diagram, V-n diagram, and drag polar plots are shown on the engineering tab, while key performance metrics and overall performance scoring by concept are shown on the executive summary. On the manufacturing tab, key metrics at the process level by sub-component are shown, such as cycle time, labor, material, and tooling cost per part, while manufacturing costs are rolled into an income statement on the executive summary tab.

A new concept can be added or deleted within minutes. Parameters, such as design, manufacturing, and economic variables, are set and saved to store a concept. An optimization technique called Technically Ordered Preference by Similarity to Ideal Solution (TOPSIS) [17] was used with individual weighting factors for each stakeholder for concept selection. This technique selects the design that is closest to the theoretical ideal in all metrics and furthest from the theoretical worst design in all metrics. The visual display section of the executive summary tab for an aluminum sheet metal and machined, fighter wing (data is only for a wing) is shown in Fig. 6. Since all the loaded concepts shown are aluminum, all the concepts fall into the low performance and cost quadrant. Composites and advanced concepts fall in the other quadrants, such as high performance and cost (top right). A concept ranking, structures, operations, and risk tab were added as follow-on work to this phase along with composite concepts.

7 Conclusion

This research outlines a manufacturing influenced design (MInD) methodology that incorporates appropriate performance, structures, and manufacturing criteria for

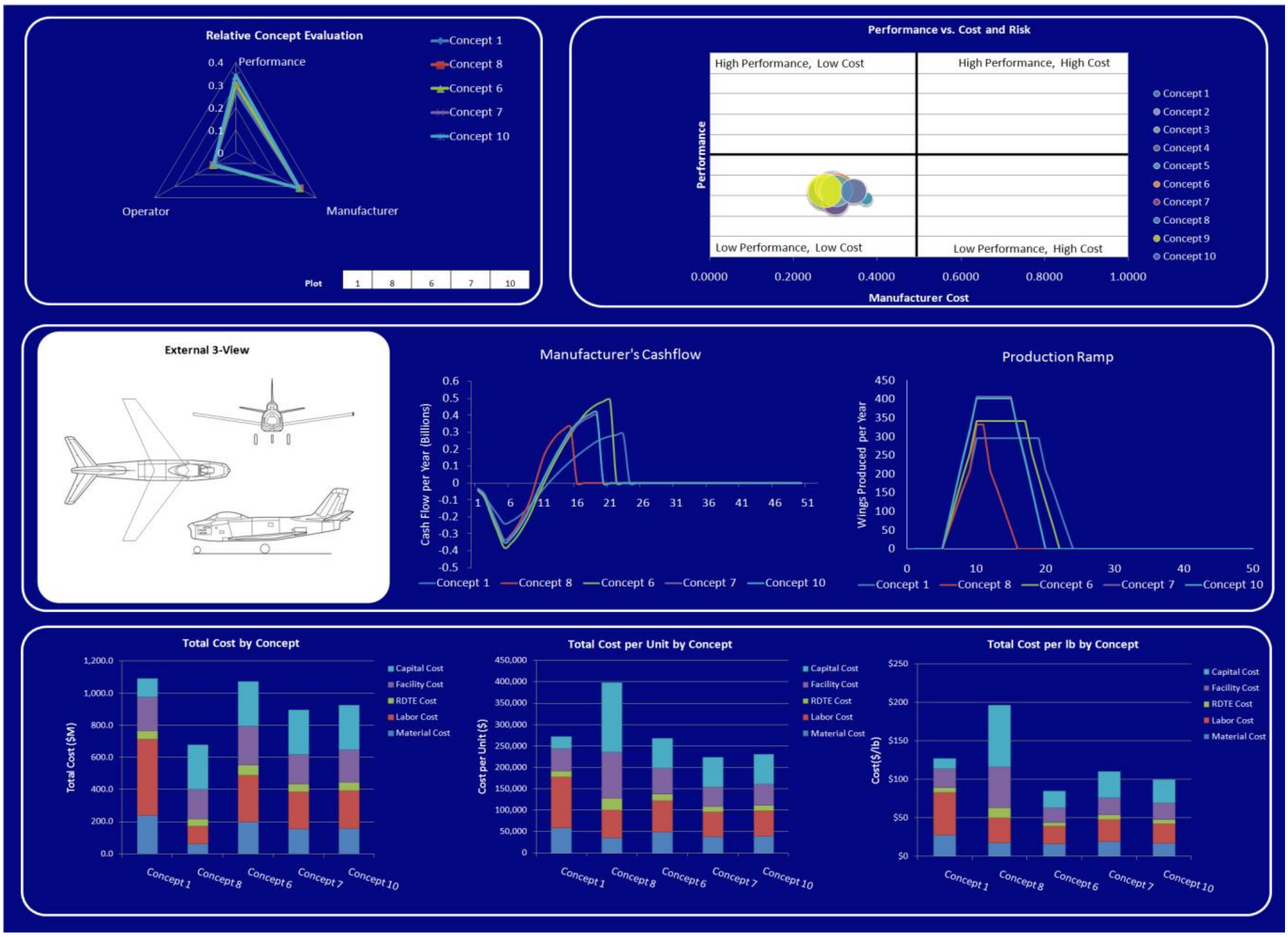

Fig. 6. MInD Trade-Off Tool - Executive Summary Tab

preliminary design without the reliance on weight based data. The MInD methodology provides the approach, model, and tool for multi-disciplinary trade-offs, enabled by activity-based costing, manufacturing translator, and the response surface methodology. By allowing early design and manufacturing trade-offs, the MInD methodology hopes to accelerate innovation through increased design freedom and knowledge sharing at a reduced cost and risk.

Acknowledgements

This work would have not been possible without the valuable guidance and contributions from our advisor, Dr. Zhimin Liu from ASDL, and sponsors, John Griffith and Charley Saff from the Boeing Company. We would also like to thank Joe Falque and Brian Glauser of Galorath Incorporated for their advice and support of the SEER-MFG tool. Finally, we thank Hsin-Hsiao (Jim) Ma, an undergraduate research assistant, for writing the parametric wing, MATLAB code.

References

[1] Stickler P. Composite materials for commercial transport – issues and future research direction. *American Society for Composites (ASC) 17th Technical Conference*, W. Lafayette, IN, 2002.

[2] Gutowski T, Henderson R and Shipp C. Manufacturing costs for advanced composites aerospace parts. *SAMPE Journal*, Vol. 27, No. 3, 1991.

[3] Mason K. *Compression molding technology adapts to meet new composite material processing requirements*. Composite Technology, June 2004.

[4] Curran R, Gilmour M, McAlleenan C and Kelly P. Aerospace product cost management at the early concept operations phase. *The 26h Congress of International Council of the Aeronautical Sciences (ICAS)*, Anchorage, Alaska, September 14-19, AIAA Paper No. 2008-094, 2008.

[5] Rais-Rohani M and Dean E B. Toward manufacturing and cost consideration in multidisciplinary aircraft design. *37th AIAA/ASME/ASCE/AHS/ASC Structures, Dynamics and Materials Conference and Exhibit*, Salt Lake City, UT, pp. 2606-2612, April 15 – 17, 1996.

[6] Schrage D P and Mavris D N. Integrated product/process design/development (IPPD) through robust design simulation. *The 1st AIAA Aircraft Engineering, Technology and Operations Congress*, Los Angeles, CA, AIAA Paper No. 95-3892, September 19-21, 1995.

[7] Crosby S, Kundu A K, Curran R and Raghunathan S. Fabrication and assembly cost drivers for aircraft manufacturing. *The 3rd Annual Aviation Technology Integration, and Operations Conference (ATIO)*, Denver, Colorado, AIAA Paper No. 2003-6827, November 17-19, 2003.

[8] Gantois K and Morris A J. The multi-disciplinary design of a large-scale civil aircraft wing taking account of manufacturing costs. *Structural and Multidisciplinary Optimization*, Vol. 28, No. 1, pp 31-46, August, 2001, .

[9] Tlusty G. *Manufacturing Processes and Equipment*. Prentice Hall, 2000.

[10] Mallick P K. *Fiber-reinforced composites, materials, manufacturing and design*. 3rd ed, CRC Press, 2008.

[11] Farin G, Hoschek J and Kim M S. *Handbook of computer aided geometric design*. Elsevier Science, pp. 519-520, 2002.

[12] Anderson J D. *Aircraft performance and design*. McGraw-Hill, 1999.

[13] Mattingly J D, Heiser W H and Daley G H. *Aircraft engine design*. 2nd edition, AIAA, 1987.

[14] Lee M, Ceisel J, Liu Z, and Mavris D., "A Parametric, Preliminary Structural Analysis and Optimization Approach with Manufacturing Cost Considerations", 53rd Structures, Structural Dynamics, and Materials and Co-located Conferences, Honolulu, Hawaii, April 17, 2012.

[15] C. Sundaresan, Z. Tang, J. Ceisel, D. Mavris, "Parametric Production Planning and Scheduling Optimization for Preliminary Design," 28th Congress, ICAS, Brisbane, Australia, September 2012.

[16] R. Combier, J. Ceisel, Z. Liu, D. Mavris, "A Probabilistic Risk-Based Methodology for Manufacturing Influenced Aircraft Design", SAMPE 2011 Conference, Long Beach, CA, May 23, 2011.

[17] G. Jahanshahloo, F. Lotfi, M. Izadikhah, "Extension of the TOPSIS method for decision-making problems with fuzzy data", Applied Mathematics and Computation, 181 (2006) 1544-1551.

Copyright Statement