A METHODOLOGY FOR PARAMETRIC PRODUCTION PLANNING IN PRELIMINARY AIRCRAFT DESIGN

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Abstract

As advanced composite materials are increasingly utilized in the aerospace industry, production planning has become a critical factor to be considered earlier in the design process. This paper introduces a methodology that integrates aircraft design and production planning into a parametric multi-disciplinary model in order to conduct design and producibility trades during preliminary phase. The methodology consists of two main parts. The first part is a parametric equipment and tooling model which provides various production process scenarios and estimates recurring and nonrecurring tooling costs, number of tools, and tooling capacity for each scenario. The second part is a production planning optimization model which optimizes the aircraft manufacturing flow by minimizing the total cost to meet demand under different constraints. Moreover, design of experiments and surrogate modeling techniques are applied to parameterize the models. A case study of an advanced composite fighter wing box design serves as a proof of concept for this methodology.

1 Introduction

As a survey of forty aerospace executives indicated, innovative products such as the Boeing 787 which consists of 50% composite material [1] serve the basis of competitive advantage in the market [2]. The advanced composite materials used in aircraft design result in performance increase and fuel burn reduction. However, they require advanced manufacturing processes which are costly and risky for original equipment manufacturers (OEMs). The aerospace OEMs need to be able to balance manufacturing cost, schedule, and risk to ensure the success of aircraft programs.

In an attempt to solve this problem in recent years, there has been a paradigm shift in the overall approach to bring design knowledge forward, to unlock the design freedom, and to reduce the committed cost throughout the process as illustrated in Fig. 1 [3]. With the paradigm shift, new methodology and tools need to be developed to facilitate the engineers to capture the knowledge from not just aerospace, but also manufacturing disciplines.

Advanced composite materials also pose unique challenges in production planning. Due to the mechanical and thermal properties of advanced composites, they cannot be machined or formed like sheet metal, but require advanced manufacturing processes and expansive tooling and equipment. Engineering design changes may warrant completely new tooling and different processes [4], and potentially result in higher production costs because the advanced composite manufacturing processes require expensive equipment such as non-destructive inspection (NDI) with a price tag of about 2.4 million USD each based on industry expert's quote or an autoclave worth 1.6 million USD [5]. These equipment may also become production bottlenecks which reduce efficiency and flexibility, thus leading to increase in production cost. In addition, the tooling required to manufacture composite components has to be replaced at regular intervals due to wear and tear caused by numerous curing cycles. Furthermore, an interview conducted by Sehdev et al (1995) with 25 companies in USA and Europe concluded that “[t]he key problem identified is the effective use of material and process knowledge at the early design stages” [6]. Therefore, it is essential to include production planning in early design phases to reduce risk and cost.

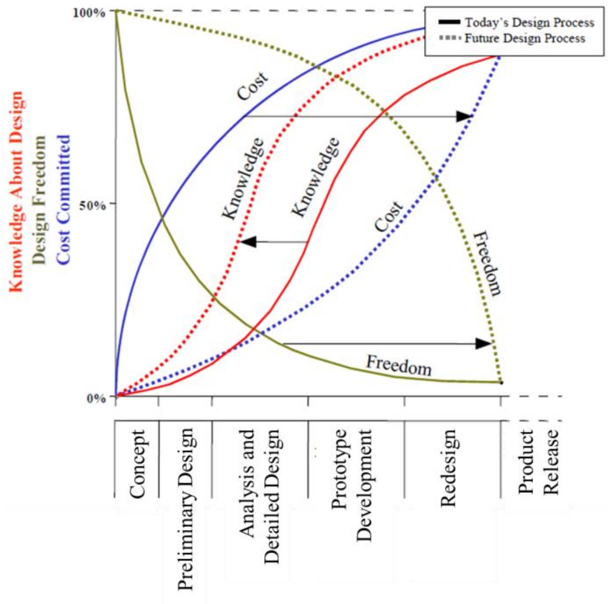

Fig. 1. Paradigm Shift in Design Process [3]

All these aforementioned factors coupled with the ever present need to reduce capital investment, identify resource conflicts, reduce material handling time and inventory costs, estimate accurate delivery times, and account for possible schedule revisions justify the need for a parametric production planning environment. Due to the complex nature of composite manufacturing, we can no longer look at it only as a combinatorial optimization problem. With the help of a parametric modeling environment, production planning can be incorporated earlier in the design process, where smart design choices can be made to minimize cycle time, cost, and risk while maximizing performance and production rate.

The paper starts off introducing the current needs in the aerospace manufacturing industry, and a brief description of aircraft and production planning design phases, followed by a background on the Manufacturing-Influenced Design (MInD) research framework. Section 2 proposes a methodology for parametric production planning at the preliminary aircraft design phase. Section 3 presents a case study of an advanced composite fighter wing box design using the methodology. Finally, Section 4 summarizes the findings and concludes with directions for future research.

1.1 Aircraft and Production Planning Design Phases

With the needs in aerospace manufacturing in mind, the design practice is first examined in order to define the scope and fidelity of analysis within each design phase and identify the gap between the phases. The commonly accepted aircraft design process is categorized into three major phases from conceptual, preliminary to detailed design [7]. The level of detail in configuration increases through each design phase. Conceptual design produces attributes on high-level configuration arrangement, performance, material selection, and size and weight estimation. In the preliminary design phase, more internal structures are added to the configuration and advanced analysis such as computational fluid dynamics (CFD) and finite element analysis (FEA) are performed. It is followed by the detailed design phase where all the features of the aircraft are defined. Traditionally, the aircraft manufacturing process has been separate from the aircraft design. Manufacturers develop production plans after the design concept is chosen using a serial process with an “over the wall” mentality [8]. Manufacturers would attempt to make the product only to discover it may or may not be feasible. This would result in costly, unwanted design changes as illustrated in Fig. 2 [9]. In recent years, there have been efforts to change that mentality with integrated product teams (IPT), and the methodology of Integrated Product and Process Design (IPPD) is becoming more widely accepted and practiced.

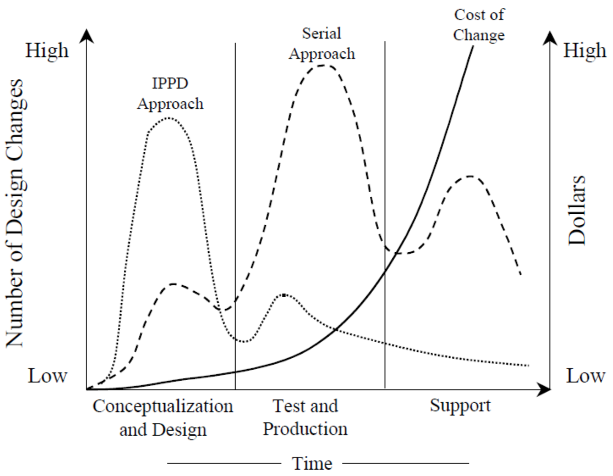

Fig. 2. Serial versus IPPD Approach to Design [9]

To better integrate production planning information with aircraft design as indicated in IPPD, there should be an improved alignment in design process between the two disciplines. Therefore, this research proposes three design phases (conceptual, preliminary, and detailed) of production planning corresponding the phases of aircraft design. In conceptual planning phase, the attributes can be production rate, cost, production capacity, number of lines and number of shifts in the time period of years. In preliminary phase, a more thorough production plan can be defined at work-station level based on the design and material, thus providing higher-fidelity cost and production rate estimation. The time period considered at this phase is shorter as in months or days. Furthermore, the detailed phase of planning provides a detailed work plan in the time period of days or hours that can be distributed amongst the workers onto the factory floor. The design phases for the two disciplines are summarized in Table 1.

Now with the proposed new production planning phases, gaps between the two disciplines can be exposed. First, there is a lack of formal methods or tools to design production flow at conceptual or preliminary phases. Second, the existing manufacturing design tools are mostly at the detailed phase, which leads to difficulties in integrating production planning with aircraft design. A framework named MInD is developed to be able to bring manufacturing information earlier into the aircraft design phases, thus enabling trade-off studies with higher fidelity between design alternatives. This paper focuses on the conceptual and preliminary design, and production planning phases.

Table 1. Design Phases and the Corresponding Key Outputs for Aircraft Design and Production Planning

	Aircraft Design	**Production Planning**
Conceptual (Strategic)	– Configuration arrangement – Performance – Material selection – Size and weight estimation	– Production rate – Production cost – Production capacity – Number of lines and number of shifts – Time period: *years*
Preliminary (Tactical)	– Internal structures arrangement – CFD – FEA	– Preliminary production plan at work-station level – Higher-fidelity cost and production rate estimation. – Time period: *months or days*
Detailed (Operational)	– All features in aircraft	– Detailed work plan onto the factory floor – Time period: *days or hours*

1.2 MInD Multi-disciplinary Framework

Analyzing the traditional design progression, it is apparent that some disciplines are not given the importance they should be given, earlier on, in the process, especially Structures and Manufacturing trades because of their significant impact on overall program costs. There is a need for a framework to abstract these considerations up from the detailed phases into conceptual and preliminary design to facilitate more knowledge and design freedom. The Manufacturing-Influenced Design (MInD) framework developed by Aerospace Systems Design Laboratory (ASDL) at Georgia Institute of Technology incorporates design, manufacturing, structures, performance, and operations into one multi-disciplinary model to enable product and process based trade studies at the preliminary design phase [10].

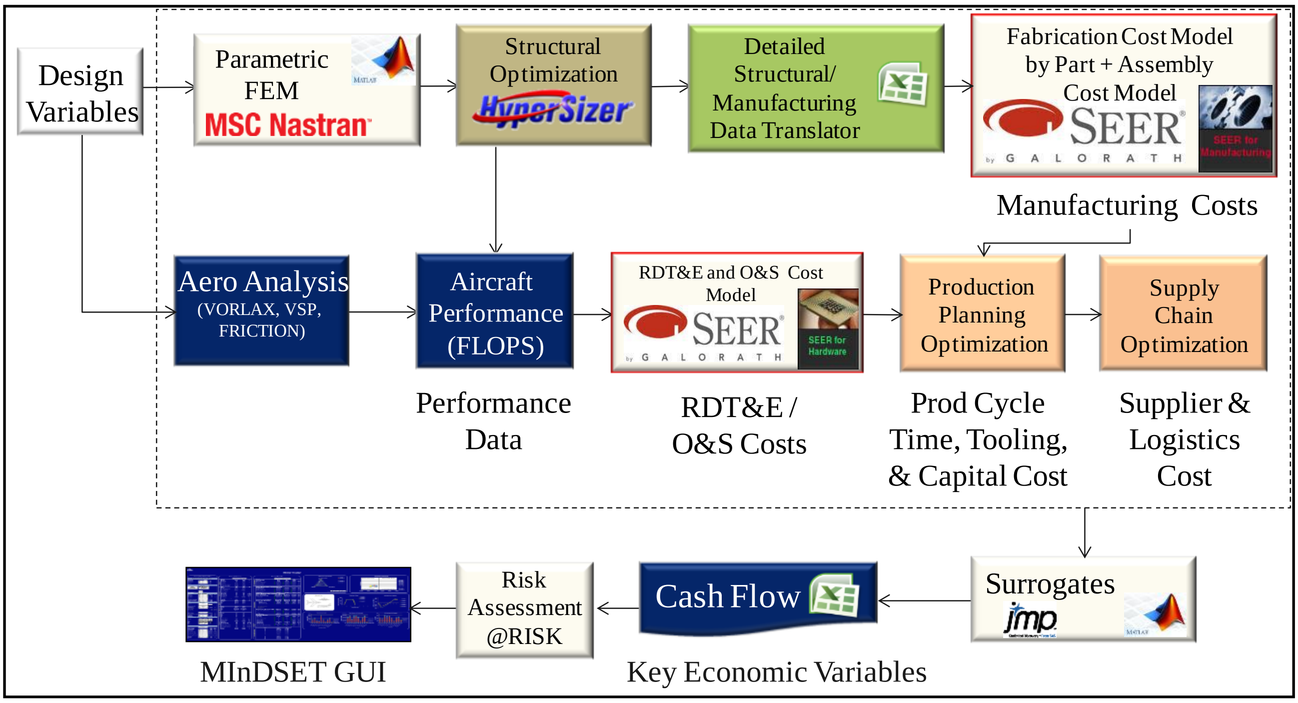

Fig. 3. MInD Multi-disciplinary Framework

As seen in Fig. 3, the disciplines involved in MInD are structures, aerodynamics, manufacturing cost estimation, production planning, supply chain, and risk analysis. They are linked together with the aircraft design variables in a modeling and simulation (M&S) environment. MInD takes in top level inputs such as outer mold line (OML) variables and production quantity. With the help of a parametric structural optimization tool, rules of thumb (simple equations that relate detailed part dimensions and quantities to OML dimensions), and a high fidelity manufacturing cost model, it calculates outputs involving performance metrics, internal structure parameters, total number of parts required, part thicknesses, labor times and costs per part for fabrication, sub-assembly, and final assembly. Design of experiments and surrogate modeling are applied to provide the back-end data in order to construct the front-end graphical user interface (GUI) called Manufacturing-Influenced Design Space Exploration Tool (MInDSET).

The production planning research discussed in this paper serves a critical part of the framework. Production planning has not traditionally been taken into consideration until after the detailed design phase when a design concept is finalized. The MInD framework helps abstract the effects of manufacturing and design choices on production planning earlier on in the design process.

2 Research Methodology

The objective of the proposed methodology for parametric production planning is to integrate aircraft design and production planning into a parametric multi-disciplinary model in order to conduct design and producibility trades during preliminary phase. The methodology consists of two main parts. The first part is a parametric equipment and tooling model which provides various production process scenarios and estimates recurring and nonrecurring tooling costs, number of tools, and tooling capacity for each design. The second part consists of a production planning optimization model which optimizes the aircraft manufacturing flow by minimizing total cost to meet demand under different constraints. Moreover, design of experiments and surrogate modeling techniques are applied to parameterize the models. The complete data flow through the models is shown in Fig. 4. The three key enablers to this methodology are SEER-MFG, IBM ILOG LogicNet Plus XE (LNP), and surrogate modeling. In the following sections, each part of the methodology will be described in further detail.

2.1 Definitions and Assumptions

Several key terms used in this methodology are defined here. They are important in scoping the models in Section 2.2.

- Equipment: It includes all general purpose machinery such as autoclaves, non-destructive inspection equipment, milling machines, presses, routers, etc. The parametric equipment and tooling model accounts for the acquisition and installation costs for all equipment [11].
- Non-Recurring Tooling: It refers to the tools designed solely for use on a particular airframe program. It includes layup tools, autoclave tools, assembly tools, dies, jigs, fixtures, etc. Nonrecurring tooling hours are those required to plan fabrication and assembly operations and to design, fabricate, assemble, and install the initial set of tools required for the planned production rate [11].
- Recurring Tooling: It refers to all of the labor and tooling costs associated with tooling replacement, modifications, repair, and maintenance [11].

This methodology is designed to aid enterprise level decision making for innovative designs, so it is focused at late conceptual and early preliminary phases of aircraft design and production planning when the program is still in its formative stages and majority of the costs are not committed. The manufacturing facility is assumed to be unconstrained. At the time of the publication, the demand is modeled as a uniform distribution, i.e., constant demand for every production year from the start to the end. Variable demand will be considered in future research as explained in the conclusion section. For labor hours available, it is assumed that there are 250 working days in a year and three shifts of eight hours a day. The production planning time period is on yearly basis. Labor times for the manufacturing processes are calculated from empirical data in SEER-MFG, which is a commercially available tool that was created under the U.S. government's Composites Affordability Initiative (CAI) and contains a large product and process knowledge base attained from many major aerospace manufacturers [12].

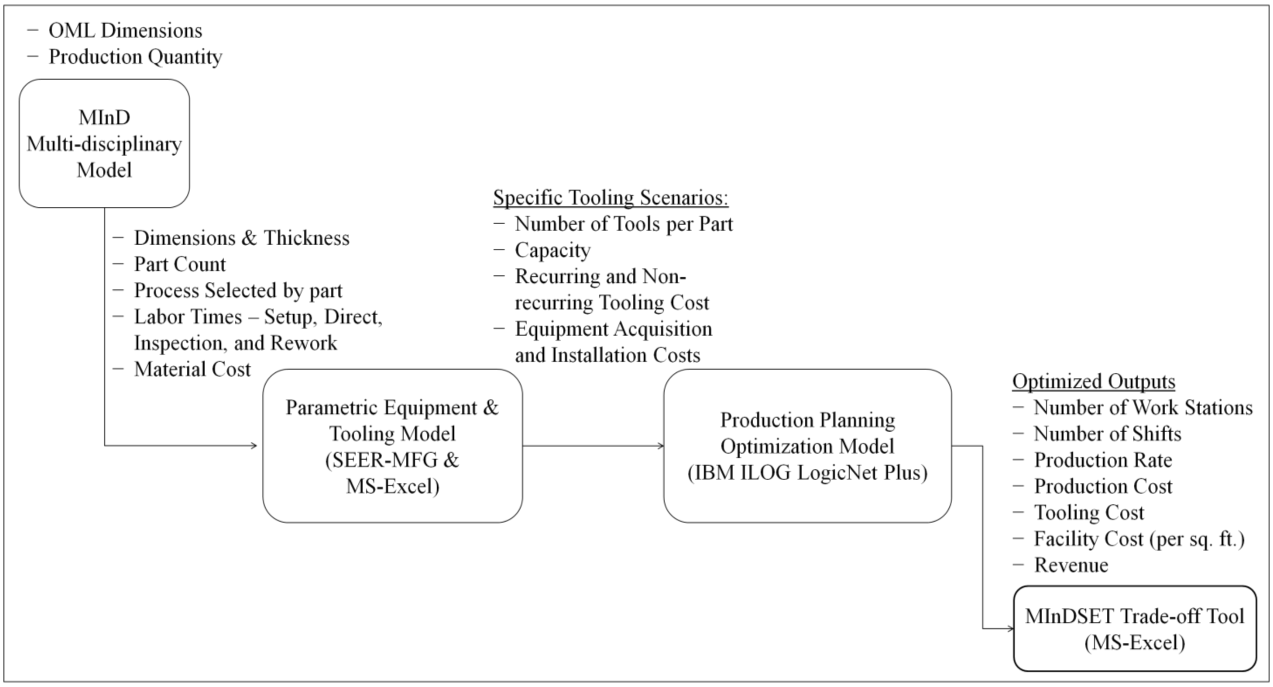

Fig. 4. The Data Flow Through Each Model in the Parametric Production Planning Methodology

2.2 Parametric Production Planning Methodology

2.2.1 Parametric Equipment and Tooling Model

As mentioned in previous sections, the first part of the methodology is a parametric equipment and tooling model. Its function is to provide critical inputs to the production planning optimization model in the form of recurring & non-recurring tooling costs, equipment acquisition and installation costs, and tooling capacity. The model is designed to parametrically select appropriate tooling and equipment required for a particular manufacturing process selected using Microsoft Excel. The model consists of four major steps explained as follows.

The first step consists of reviewing the design. This step allows the user to set the design concept by entering specifications such as part dimensions, material type, ply count, number of fasteners, part thickness, number of stiffeners, along with certain manufacturing and production cost levers such as learning curves, labor rates for assembly and fabrication, production quantity, and material costs. Besides part fabrication specifications, this step also outlines the design assembly definition. The Excel front-end also has a visual representation of each component of the design being evaluated. The purpose of this step is to provide a section where the user can review the design concept.

The second step is to determine equipment and tool set scenarios. The objective of this step is to select appropriate tooling and equipment scenarios per design concept for a particular combination of manufacturing process and material. Tooling and equipment selection depends on a number of different factors such as fabrication, sub-assembly, final assembly process, and for composite designs, resin type, thermal conductivity, thermal coefficient of expansion, and heat resistance. Another major factor that affects tooling selection is production quantity. A small production quantity usually will not justify the acquisition of more expensive advanced tooling and equipment. On the other hand, the advanced tooling and machinery can be advantageous for a large production quantity. The scenarios are based on an equipment and tooling library set up in the back-end of the model.

The third step is to determine capacity and costs. The objective of this step is to compute all the costs and labor hours depending on the design, manufacturing process, tooling, and equipment. Equipment cost data is sourced from actual aerospace equipment vendors in the industry. Along with acquisition cost, the Excel tool also accounts for equipment installation costs by allowing the user (or a subject matter expert) to enter an equipment installation cost to acquisition cost ratio. The tool uses this ratio to calculate the installation costs and adds it up to the acquisition cost to give an aggregate equipment cost figure for each part. Non-recurring tooling costs are calculated by using Response Surface Equations (RSE) built around empirical data in SEER-MFG. In composite manufacturing, the tooling used in the layup and cure processes needs to be replaced every so often because of damage caused by the numerous high pressure and temperature cycles it is made to go through [4]. In most instances, the cost for replacing a tool or changing a few parts will not be the same as that for initial tooling procurement. This is accounted for in the model by the replacement cost ratio which is the ratio of the replacement cost to initial procurement cost. Recurring tooling costs or replacement costs are calculated within the Excel tool as a function of tooling replacement rate, replacement cost ratio and production quantity desired.

The final step is to feed manufacturing scenarios to the production optimization model. The objective of this step is to bring together all the critical metrics calculated by the model and display them in a format that can be input to the production planning optimization model which is described in the next section.

2.2.2 Production Planning Optimization Model

The production planning optimization model optimizes the aircraft manufacturing flow by minimizing total cost incurred to meet demand under different constraints. It is modeled using

IBM ILOG LogicNet Plus XE (LNP) [13]. ILOG LNP is a commercial software package for production planning and supply chain network optimization. The model built in LNP accepts inputs in the format of databases consisting of various forms, and performs optimization routines to obtain the optimized configuration of the manufacturing systems.

Once the manufacturing scenario has been finalized and the related equipment and tooling information are generated by the parametric equipment and tooling model, the work stations required to manufacture the designed parts are modeled in LNP. Relevant information about the design and manufacturing processes are entered into data forms. Information about the design being manufactured is fed to the Product Details form. The Bill of Materials form translates the work breakdown structure of the design to all the components that need to be produced through the manufacturing systems. For example, this form is where the number of spars (2), ribs (20) and skin-stringer panels (2) required to assemble a single wing box is modeled. Specifics about the corresponding work stations derived from BoM are entered in the Line Details form respectively. Production capacity and costs are modeled for each combination of components and assigned work station in the Production Information form and Overall Capacity form. The model is setup in such a way that there is a penalty factor of 1.5 associated with production costs incurred in the third shift compared to the first and second shifts, respectively. The oven curing work station is modeled in the Tanks form with inputs including cycle time and number of components that can be cured simultaneously based on industry subject matter experts' opinion.

After the inputs are entered into the database forms, the model performs the optimization routine and generates the optimized production facility configuration with outputs including number of work stations, number of shifts, production rate, total cost, total profit, capital costs, production costs, labor costs, and facility costs.

2.2.3 Parameterization

For parameterization of the models described above, a design of experiments (DoE) needs to be first set up to model the design space so that a surrogate model can be ensured to represent the complicated outputs of LNP. Table 4 lists the input variables with their ranges that were varied in the DoE. The main advantage of using a DoE is that a maximum amount of knowledge is gained with a minimum expenditure of experimental effort such as runs or computation time. DoE has different designs such as full factorial, Latin Hypercube Sampling (LHS), Box-Behnken, and Central Composite Design as shown in Fig. 5. For this research, LHS is chosen for the DoE based on its space-filling characteristics [14]. Commercially available software ModelCenter by Phoenix Integration [15] is used to set up the M&S environment where the inputs, LNP, and outputs are linked in order to automatically run all the cases generated by LHS.

After the DoE is generated, surrogate models use various techniques such as polynomial response surface methods, neural network, and Gaussian process models to capture the relationships between the input variables and the responses or metrics of interests. Table 5 lists the responses that are of this research's interests. Due to the complex nature of the data generated from the LHS DoE, the surrogate modeling technique that is best applied to this research is yet to be determined at the time of publication of this paper, as stated below as a part of future research in Section 4.

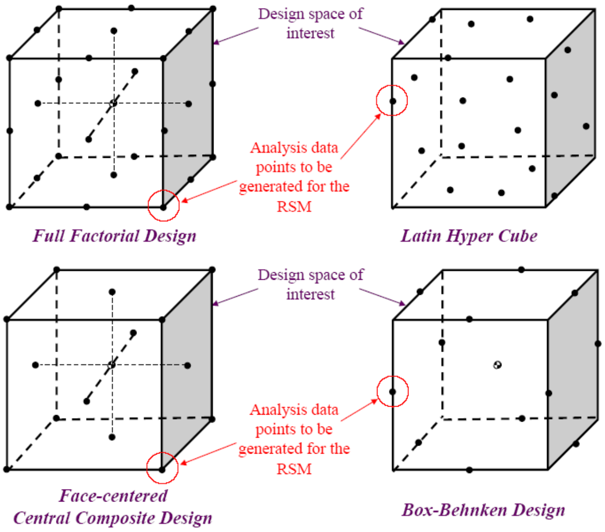

Fig. 5. Graphical Representations of Common DoE's

3 Case Study

This methodology was applied to the F-86F fighter aircraft as seen in Fig. 6 [16]. The F-86F wing box was chosen due to the variety of structural shapes and choice of manufacturing processes seen within the wing box, and its strong relation with overall aircraft performance. The associated data is non-proprietary for research purposes. The scope of the case study is limited to the primary wing box components comprising of spars, ribs and skin-stringer panels. Table 2 lists the baseline design characteristics of the F-86F wing box in this case study. The design is an advanced composite wing box that exhibits a high level of integration realized through the use of co-bonding and paste-bonding manufacturing methods along with hand layup techniques. The baseline manufacturing process is illustrated in Fig. 7.

According to the steps stated in Section 2.2.1, RSEs created using SEER-MFG were used to compute non-recurring tooling, labor and material costs; and labor times for the wing box baseline design. Equipment and tooling selection was made based on the manufacturing process. Non-recurring tooling costs were calculated as a function of a tooling replacement rate of 100 units. Costing information for equipment that consisted of manual trimming devices, ovens, and laser ultrasonic testing and manual hand-held devices for NDI was sourced from aerospace grade equipment vendors from industry.

Table 2. The Baseline Design Characteristics of the F-86F Wing Box

Parameter	**Baseline Value**
Wing Area (ft^2)	313.3
Aspect Ratio	4.88
Sweep (deg)	35
Taper Ratio	0.514
Range (nm)	804
Rib Spacing (in)	12

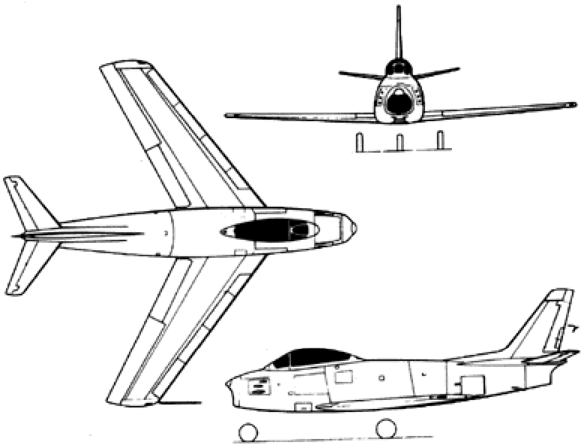

Fig. 6. F-86F Sabre 3-view Engineering Diagram [16]

Table 3. The Optimized Outputs Over Different Production Periods

Production Period	10 Years	15 Years (Baseline)	20 Years
No. of work stations	13	11	11
No. of Shifts for all work stations	28	21	17
Production Cost ($/yr)	46,380,500	28,673,300	21,315,200

After the outputs from the parametric equipment and tooling model were generated, the production planning optimization model was set up in LNP. The production of the wing box structure was modeled as a 4 stage manufacturing process in LNP as shown in Fig. 8. They are defined as work stations which are component layup, oven curing, NDI, and wing box final assembly. As shown in Fig. 8, the Bill of Materials (BOM) is visualized for the advanced composite wing box case study design which constrains the LNP model by setting a minimum lot increment size for each wing box final assembly. A total production quantity of 4000 wing boxes was considered over a production life of 15 years as the baseline production scenario for the case study.

Table 3 shows the optimized outputs for number of work stations, number of shifts for all work stations, and production cost for the baseline wing box design over different production period scenarios. These key outputs give the engineer insight into the implications of top level design and management decisions. A shorter production period implies that more units would have to be produced each year causing the optimization model to open more work stations to keep up with the demand. This is why we see an increase in the number of work stations, shifts, and the associated production costs as the production period reduces. In future work, optimal production rate for profitability and robust design to demand variability will be investigated.

3.1 Sensitivity Analysis

A sensitivity analysis was carried out on LNP to identify the significant input variables in the production planning optimization model. LHS DoE is performed in the M&S environment

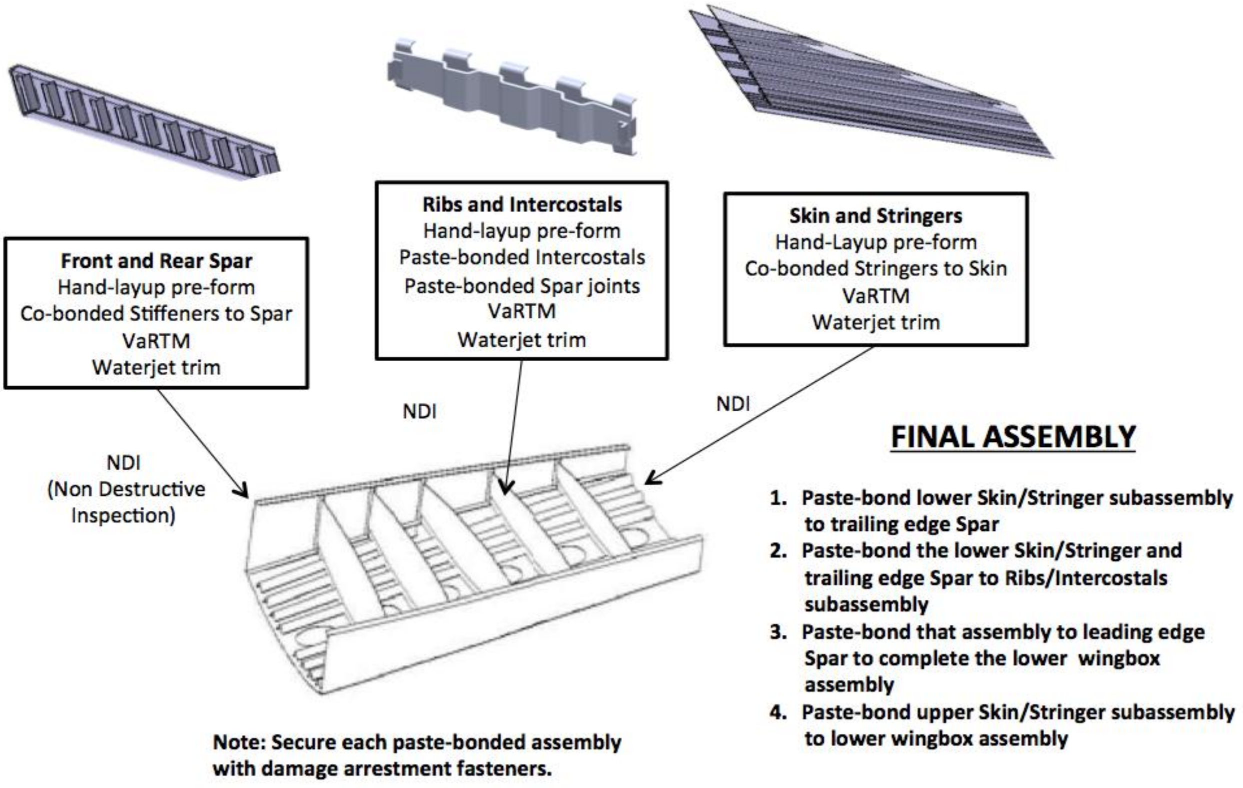

Fig. 7. The Baseline Manufacturing Process for the Advanced Composite Wing Box Design

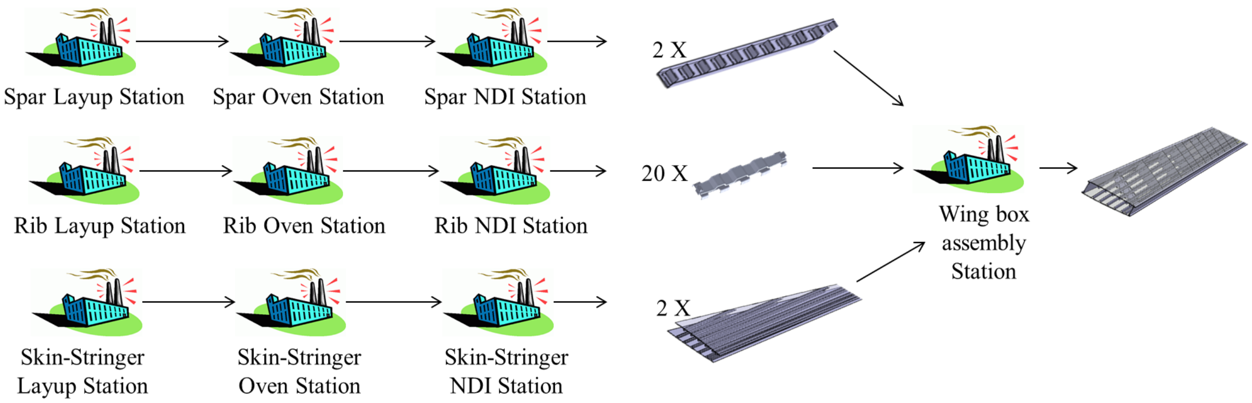

Fig. 8. Bill of Materials and the Corresponding Work Stations in Production Planning

involving LNP. The results of the analysis are shown in Pareto plots (Fig. 9 – Fig.14) that identify the contribution from the inputs to the response's variability. A Pareto plot is a statistical tool that "displays the severity (frequency) of variables and is ordered from top to bottom in decreasing order" [17], allowing the designer to understand which variables have significant impact on the response variability in the model. It is based on Pareto's Law which states that "80% of the total of any group will come from 20% of the components of that group" [18].

The input variables and ranges are enlisted in Table 4 for the baseline wing box design. The demand range was selected to explore production period from 10-20 years. The ranges for profit margin and facility cost per square foot were picked based on industry subject matter expert opinion. Labor hour available ranges were chosen to study the effect of varying the number of workers at each work station. Each worker contributes 2000 hours per shift at each work station in one year based on the assumption of 250 working days each year. Based on number of inputs, 1400 cases for the DoE were generated, and LNP was run within the ModelCenter M&S environment in batch mode with each case taking 2-3 minutes on an average. Table 5 shows the responses and their significant variable drivers.

As expected, market demand was noted to be the most significant driver in this study. From the BOM data, it is apparent that the rib is the most constraining product. This is confirmed by Pareto plots in Fig. 10 and 12 which show the effect of rib labor hours available on tooling and equipment costs incurred, and facility area required for new work stations in the case study scenario. The study helps us realize that, for the particular case study being considered, having a wing box design with lesser number of ribs will relax the constraint rib manufacturing imposes on the overall production plan which in turn will help meet higher demand and reduce overall costs. This result seems intuitive since a lower number of ribs would require a reduced amount of time for final assembly operations. The optimization objective within LNP was set to minimize total cost incurred and as a result, the model minimizes the number of work stations it opens in order to keep the facility costs low. Hence, facility cost per square foot area emerged as another significant driver. Further, the trends seen in Fig. 11 and Fig. 13 depict the effect demand has on production cost and revenue generated thus verifying logical behavior of the model. For future work, the production levers shown will be incorporated into design. For instance, a wing at preliminary level could be constrained by a maximum rib quantity and facility square footage in order to maximize production rate and minimize cost, while maximizing performance.

Table 4. DoE Input Variables

Input Variable	Min. Value	Max. Value
Demand (No. of Wing Boxes/year)	200	400
Profit Margin (%)	5	10
Facility Cost per Sq. Ft. ($/year)	800	1000
Rib Labor Hours Available (Per year)	14000	18000
Spar Labor Hours Available (Per year)	14000	18000
Skin-Stringer Labor Hours Available (Per year)	14000	18000
Final Assembly Labor Hours Available (Per year)	8000	12000

Table 5. DoE Output Variables and the Corresponding Significant Drivers from the Sensitivity Analysis

Output Response	Significant Drivers
Demand Satisfied	– Demand – Final Assembly Labor Hours Available – Facility Cost Per Sq. Ft.
Number of Work Stations	– Demand – Rib Labor Hours Available
Production Cost	– Demand – Facility Cost Per Sq. Ft.
Tooling & Equipment Cost	– Demand – Rib Labor Hours Available
Revenue	– Demand – Profit Margin
Final Assembly Number of Shifts	– Demand – Final Assembly Labor Hours Available

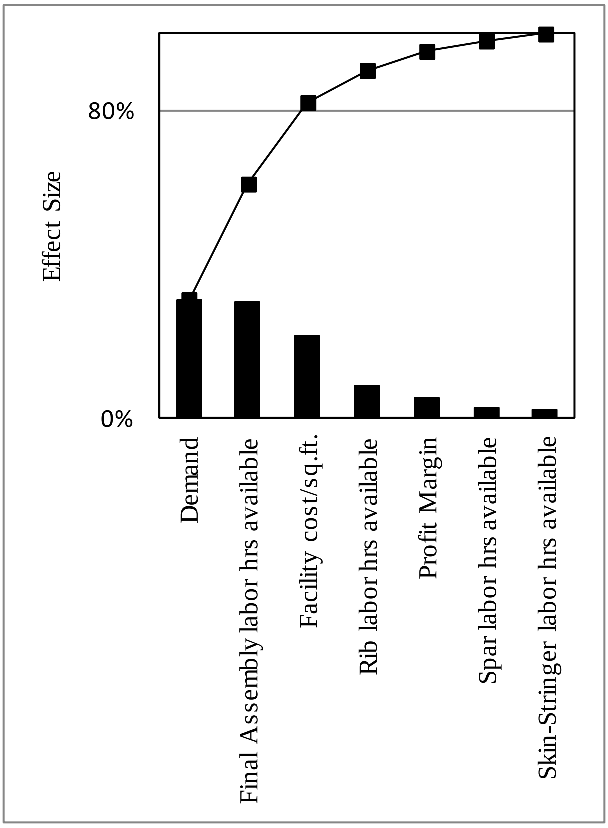

Fig. 9. Pareto Plot for the Output Demand Satisfied

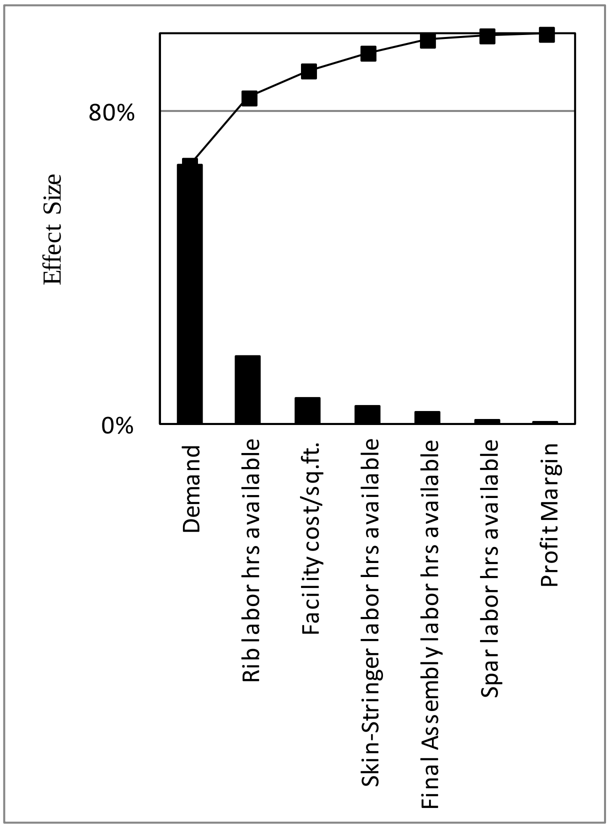

Fig. 10. Pareto Plot for the Output Number of Work Stations

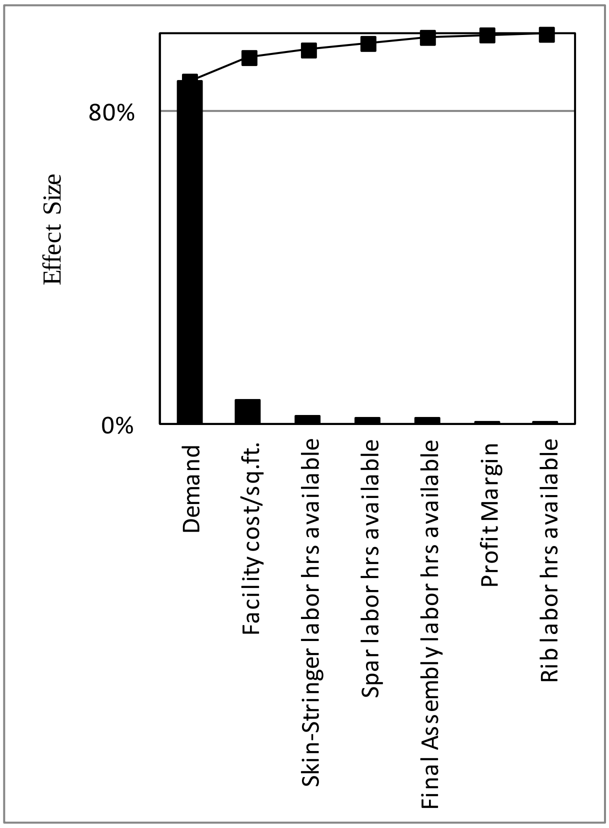

Fig. 11. Pareto Plot for the Output Production Cost

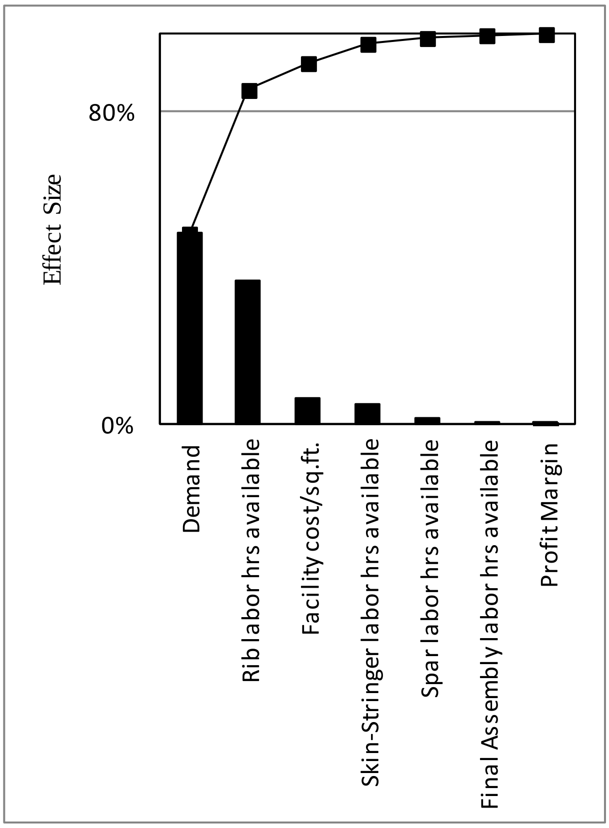

Fig. 12. Pareto Plot for the Output Tooling and Equipment Cost

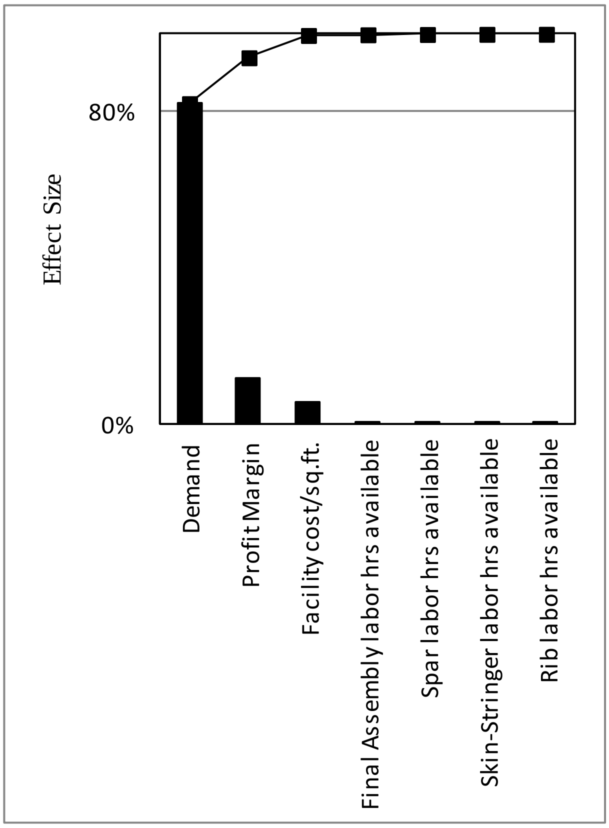

Fig. 13. Pareto Plot for the Output Revenue

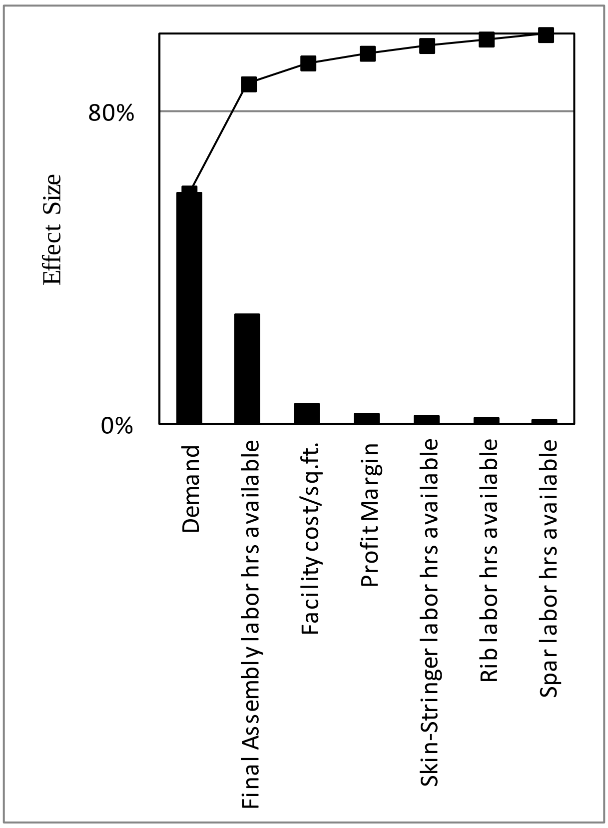

Fig. 14. Pareto Plot for the Output Final Assembly Number of Shifts

4 Conclusions and Future Research

The methodology for parametric production planning enables stake holders to conduct performance, and production trades by leveraging high fidelity manufacturing models and knowledge about the manufacturing processes in conceptual and preliminary design. The main parts of the methodology are parametric equipment and tooling model, and production planning optimization model. Design of experiments and surrogate modeling techniques are applied to parameterize the models.

A case study of the F-86F wing box design using advanced composite material and advanced manufacturing process is presented. It demonstrates the capability of the methodology to generate equipment and tooling knowledge as well as the optimized production plans given different labor and capacity constraints. A sensitivity analysis was performed using DoE and the M&S environment, and the significant input variables in the optimization model are identified to facilitate constructing surrogate models in the next steps.

This methodology breaks new grounds in integrating production planning with aircraft design in the early design stages, and in enabling us to minimize cycle time, cost, and risk while maximizing performance and production rate. Another important value is the application of surrogate modeling techniques to production planning.

Future research involves running a DOE to explore the aircraft wing box design space to find a design point that is most robust to demand variability through a Monte Carlo analysis. Surrogate models for production planning will be created and integrated in order to enable rapid design and manufacturing trades within the MInD Framework.

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