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Modeling-based Design of Strategic Supply Chain Networks for Aircraft Manufacturing

Zilin "Elizabeth" Tang[a,*], Marc Goetschalckx[b], Leon McGinnis[b]

[a] The Daniel Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA, 30332-0150, USA
[b] H. Milton Stewart School of Industrial & Systems Engineering, Georgia Institute of Technology, Atlanta, GA, 30332-0205, USA

Abstract

The aerospace supply chain network has evolved and become more complex over the years. New methods are needed to design and analyze the system, and to establish the interactions between aircraft (product) design and supply chain (process) design. This paper aims to introduce a strategic multi-product, multi-period design model for the manufacturing of an aircraft wing-box with a planning horizon of the full program duration. The supply chain systems consist of a number of external suppliers, candidate manufacturing sites, and a number of customers at fixed locations. The design model is a mixed-integer linear programming optimization routine that minimizes the total time-discounted network cost. The model generates a system configuration that specifies the location and capacity of the manufacturing sites, the material flow, and the transportation routes within the network. The model is implemented using open-source tools, and has a comprehensive and flexible data structure to support the decision-making process during the early aircraft design stages.

Keywords: *Aerospace manufacturing; supply chain design; mixed-integer linear programming.*

1. Introduction

In recent years, the impact of an efficient supply chain has become more and more important on the overall competitiveness of the aerospace companies. During the early planning phase for an aircraft program, the supply chain design is one of the crucial elements among all the planning efforts, which include market research and aircraft design, to ensure technical feasibility and economic viability of the long-term program strategy. The parts and services provided by the suppliers make up 65% to 80% of the final cost of aerospace products [1]. Major aerospace companies such as Boeing and Airbus both experienced challenges posed by the global joint venture supply chain strategy in their newest B787 and A380 programs [2]. The joint venture strategy benefited the companies with risk-sharing partnerships all over the world. At the same time, this strategy exposed the problems in supply chain management which partially contributed to the heavy delays in both airplane deliveries [1, 3]. Strategic

* Corresponding author. Tel.: +01-678-538-8522; *E-mail address*: ztang@asdl.gatech.edu.

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decisions in the aerospace supply chain in the case of B787 and A380 impose risks, and demand quick responses [4]. Therefore, the business cases for aerospace products such as the B787 and A380 need to take into account global manufacturing process development with information including manufacturing cost, schedule, risks, and trade-offs between domestic production and outsourcing. A strategic supply chain design model implemented in this paper focuses on the aerospace manufacturing sector. A generic representation of a supply chain in Fig. 1 serves as a baseline configuration and consists of the entities in the network (external suppliers, intermediate processing domestically and overseas facilities, final assembly and customers) as well as the flow between these entities. For this research, which is illustrated with a generic fighter wing-box, the high-level work breakdown structure (WBS) of wing-box at the conceptual design phase includes skins, stringers, ribs and spars. These components make up the bill of material (BOM) for the manufacturing system, which are then translated based on Fig. 1 into the notional supply chain network for the wing-box as illustrated in Fig. 2. In the current research, the external suppliers are defined to be raw material suppliers for aluminum, but this can be expanded in the future to include additional raw materials. Fabrication and subassembly can be performed in company owned (in-house) facilities that are located both domestically and/or overseas. In wing-box case, skins and stringers do not require subassembly processes and thus are directly transported from fabrication facilities to final assembly. Final assemblies are assumed to be always produced in in-house domestic facilities. The material flows include raw materials from the external suppliers, lower-level components produced in fabrication, major WBS components produced in subassembly, and finished wing-boxes produced in final assembly. All materials enter the supply chain system from external suppliers, and all finished products (fully-assembled wing-boxes) leave the system to the external customers, which are the assembly facilities for the whole aircraft.

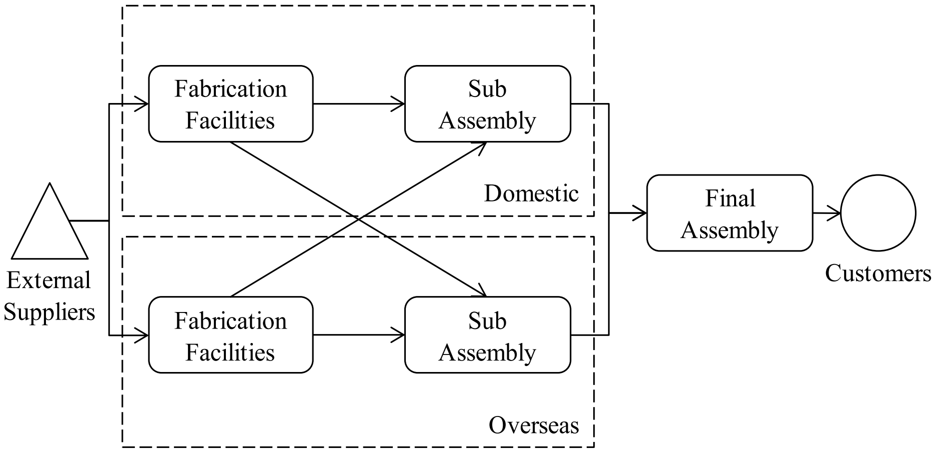


Fig. 1. Generic notional supply chain network configuration

The optimization model uses a mixed-integer linear programming formulation. The objective of the model is to determine the minimum cost configuration of the supply chain network to satisfy a given demand pattern for the wing-box. Microsoft Access, MathProg [5] and GLPK [6] are the software applications used in this research.

Section 2 of this paper presents a literature review of the aerospace supply chain history and development as well as the past work on strategic supply chain models. Section 3 briefly describes the content and the implementation of the supply chain model. Section 4 focuses on data collection and preliminary experimental results. Section 5 summarizes the current research and proposes future work.

2. Literature Review

2.1. Aerospace supply chain history

Many papers have been published about supply chain modeling in general, but only a few have focused specifically on supply chains in aerospace industry. Rose-Anderssen et al. (2008) presented a detailed history and evolution of the aerospace supply chain by borrowing the cladistic classification used in biology [2]. The aircraft manufacturing industry started around 1910 when there were only simple material transactions between an aircraft builder and material suppliers. As the aircraft designs, technologies, production techniques, as well as the political environment (the occurrence of the first and second world wars) evolved, the aircraft manufacturing industry changed between 1910s and 1960s.

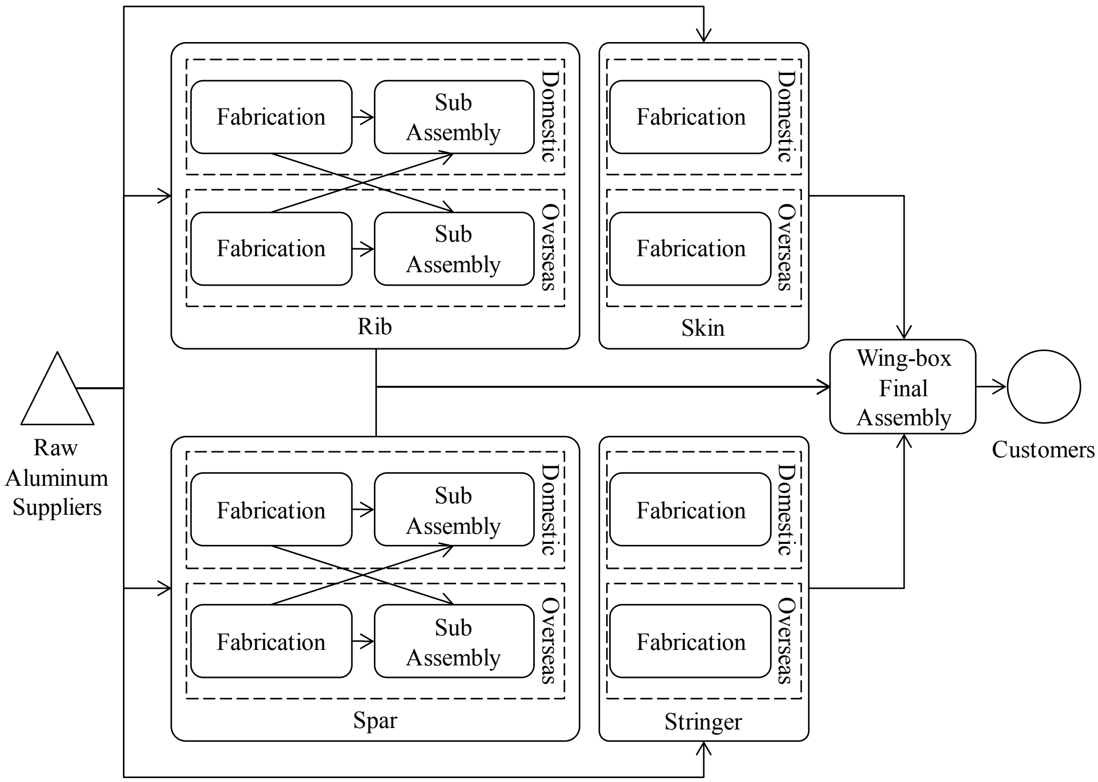


Fig. 2. Notional supply chain network for a generic fighter wing-box

Around 1975, a major bifurcation point in the industry occurred when Airbus was formed to compete with companies in North America. The companies such as Boeing were operating using original equipment manufacturer (OEM) dominated supply chains. Airbus started the joint venture supply chains. This is the start of modern aerospace supply chains. In the OEM dominated supply chains, there is a high level of buyer dominance over suppliers, and the suppliers had to commit to cost reduction in order to create a long-term relationship with the buyer. On the other hand, the decisions in the joint venture supply chains are not buyer-dominated, but decentralized across the buyers and the suppliers. While Boeing and Airbus based their supply chains on two very different business philosophies, they still shared many common improvements as the time went on. The total quality management (TQM) movement made the supply chain a part of the corporate strategy as well as the overall risk assessment for market, financial and technological risks.

In the 1990s, the commercial aircraft manufacturers were faced with a drop in market demands and shifted focus to the airline's profitability. There was an urgent need to reduce cost, thus the practice of lean supply chains was widely implemented. In the mid-1990s, programs like the Boeing 777 and A340 were launched with new characteristics in their supply chains. They incorporated the suppliers specifically from the customer countries hoping to gain more overseas market share. To this point, the supply chains have truly evolved from single material transactions to global supply chains. With the increase in use of advanced materials such as composites for primary airframe structures over the last decade [7], Boeing took a radical innovative step and also started to implement the joint venture strategy that Airbus has been practicing for years. The latest airplane program in Boeing Commercial is the Boeing 787 which is a pioneering concept that uses 50% of composite material [8], so the firm needed to gain knowledge from both inside and outside the company, as well as build risk-sharing partnerships with suppliers all over the world. Therefore, supply chain design became even more critical for the success of the program.

2.2. Strategic supply chain modeling

Geoffrion and Powers (1995) provided a detailed review of the strategic distribution systems design over 20 years from 1970s to the 1990s. They presented the evolution of the designs in six areas: logistics as a corporate function, computer technology, algorithms, data development tools, software capabilities, and how software is utilized by the companies during the design process [9]. Vidal and Goetschalckx (1997) provided a comprehensive review on strategic production-distribution models by presenting them in a tabular format that listed characteristics of the models for global and domestic supply chains [10]. Other research focused on other industries such as the global automotive industry [11]. Other aspects of the supply chain such as the global transfer prices were also investigated in Vidal and Goetschalckx (2001) [12]. However, there is not much literature focusing on aerospace supply chain design, and even less on the research for the strategic planning stage in an aircraft program.

Even though few papers exist on aerospace strategic supply chain design, many common definitions and methods used in the general supply chain designs can be applied in this context. Supply chain design problem involves three design levels: 1) strategic planning based on network design, 2) tactical planning based on design and management of a fulfillment system, 3) operational planning based on dynamic network management [13]. The focus of this work is at the first level, the strategic planning. At the strategic level, the planning horizon is long term and expressed in years instead of weeks or days, and the high-level objectives are network definition, cost minimization, and profit maximization [13]. The decisions involved at this level deal with the number of facilities, associated locations, manufacturing capacity, and the allocation of customer demand. The supply chain can be simply defined as the integration of flow of material and information between manufacturers, suppliers and customers [14].

As mentioned in the previous section, the aerospace supply chain has evolved into a global joint venture system. Given the nature of the aerospace industry with products (i.e., aircrafts) generally having a lifespan of 15 years or more, the supply chain design becomes more complicated and needs to generate a network configuration that has multiple periods, multiple scenarios, multiple countries, and multiple facilities for different echelons of the supply chain [15]. Therefore, it is required to enlist computer models to help the decision makers to design an optimized strategic supply chain with desired performance.

The outputs (results) of the optimization models include the number, location, capacity and type of manufacturing facilities; the suppliers set; the transportations to use, the quantity of material to transport and produce throughout the system; and lastly the inventory information [10]. Most of the data for these supply chain models for the aerospace industry is proprietary and difficult to obtain access to. Therefore, due to limited access to data and for the simplicity of the experiment, the inventory part of the supply chain is not modeled in the current work and will be incorporated in the next steps. The objectives of the strategic model are the standard financial measures in the corporation such as minimization of net present value (NPV) of the total cost or maximization of the NPV of the total profit.

3. The Strategic Supply Chain Networks Model

In this section, the summary of the mathematical model and its implementation are described. There are six types of constraints in the model: 1) BOM-based material conversion equations, 2) capacity restrictions, 3) demand satisfaction constraints, 4) internal consistency constraints between decision variables, 5) constraints to calculate intermediate values, 6) additional configuration constraints. At the strategic supply chain design stage, the objective function is to minimize total network cost, which is the sum of purchase, transportation (channel), fabrication, assembly, and capital costs of opening manufacturing facilities. The NPV of total cost is obtained by summing the total cost per year with applied discount rate over the production years. Due to the page restriction of the paper, the details of the model are not included here. Goetschalckx (2011) provides a comprehensive explanation to the models similar to the one used here [16].

As mentioned in the introduction section, the strategic supply chain model uses the mixed-integer linear programming technique to generate an optimized configuration that has the minimum total network cost for a generic fighter wing-box production. The implementation of the model requires various sub-models within the corresponding software to work together. Microsoft Access is used to store all the instance data as well as the outputs at the end of the optimization. GNU MathProg is a modeling language for the mathematical representation of the model [5]. It provides us a way to express the algebraic relationships and the value for the parameters through a model file and a data file, respectively. MathProg reads the data files and model files, and translates them into a format that the solver understands. The solver used in this work is GNU Linear Programming Kit (GLPK) which is for solving linear programming, mixed integer programming and other related problems [6].

4. Experimental Results

4.1. Assumptions and data collection

In aerospace industry, most aircraft designs and its related manufacturing costs are proprietary. In order to make this research available for academic publication, all the data of the generic fighter wing-box were extrapolated from the F-86F aircraft model which is available in the open literature. In this model, the baseline production quantity was assumed to meet the demand of 2000 units of wing-boxes over 15 production years. The discounted factor was assumed to be 5.8% [17]. The labor rate was benchmarked against the data obtained from Bureau of Labor Statistics (BLS) in United States Department of labor. Based on BLS database, the employer costs for employee compensation for aircraft manufacturing in the US was $63.02 (FY 2010 Q3) [18]. Transportation related data was based on internet searches as well as experts opinions. For example, the ocean container rate from China to USA was estimated to be about $5000 USD for a 40 ft container [19]. The product information, in this case, the wing-box geometry and weight, was generously provided by a research team in the Aerospace Systems Design Laboratory (ASDL) in the School of Aerospace Engineering at Georgia Tech. As the baseline, the wing-box weighed 2143 lb and consisted of 18 ribs, 12 stringers, 2 spars and 2 skins (upper and lower skin). The majority of production labor hours and cost data were also generated by the ASDL team [20].

The following sections summarize the preliminary experimental results. It is important to keep in mind that the results aim to demonstrate the capabilities of the supply chain design model rather than to provide actual observations and action plans due to the lack of real data. If there were more and more accurate data available, the mathematical model would be able to generate results with higher accuracy and fidelity. The experiments are also designed to examine the behaviors of the model. After performing the following experiments, the model is proven to behave in the reasonable ways and to be flexible enough to accommodate various changes in data.

4.2. Experiment 1: change in labor rate

In this experiment, the impact of change in labor rate in the model was investigated. Labor rate changes dramatically around the world ranging from $63.02 in the US to only $2.2 in China [18]. The overseas labor cost per hour in this experiment was increased from 10% to 200% of the domestic labor rate with a step size of 10%, while all the other parameters remained the same. The resulting NPV of the total network cost as the main output from the objective function in the model is plotted in Fig. 3.

As the overseas labor rate increased, the total network cost increased to the point where the overseas labor rate was at 100%, i.e. the same as the domestic labor rate. For rates lower than 100%, more overseas facilities were selected as the cheaper options to be part of the system instead of the domestic ones. Beyond the 100% point, the total network cost stabilized even when the overseas labor rate continued to increase. Under the premise of the labor rate being the only parameter allow to change, the optimization model as the minimization of the cost generated supply chain configurations establishing primarily domestic facilities and less or none of the overseas facilities. The resulting trend produced by the model was correct and the behavior of the model was as predicted.

4.3. Experiment 2: change in demand profiles

This experiment examined the model by changing the demand profiles to uniform, trapezoidal, and triangular distributions, respectively. The production time span varied from 10 years, 15 years, to 20 years. The distributions of the 2000 units over these years are shown in Fig. 4 (a)-(c). The results for NPV are illustrated in Fig. 4 (d).

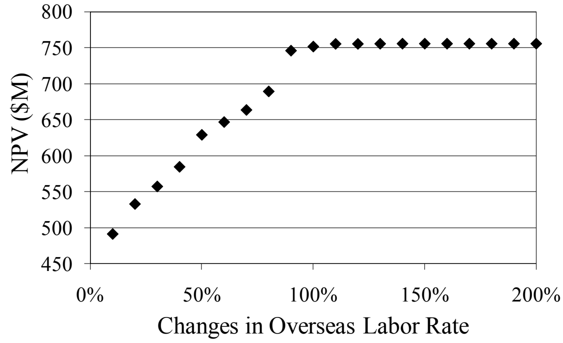


Fig. 3. The NPV of total network cost based on the labor rate changes

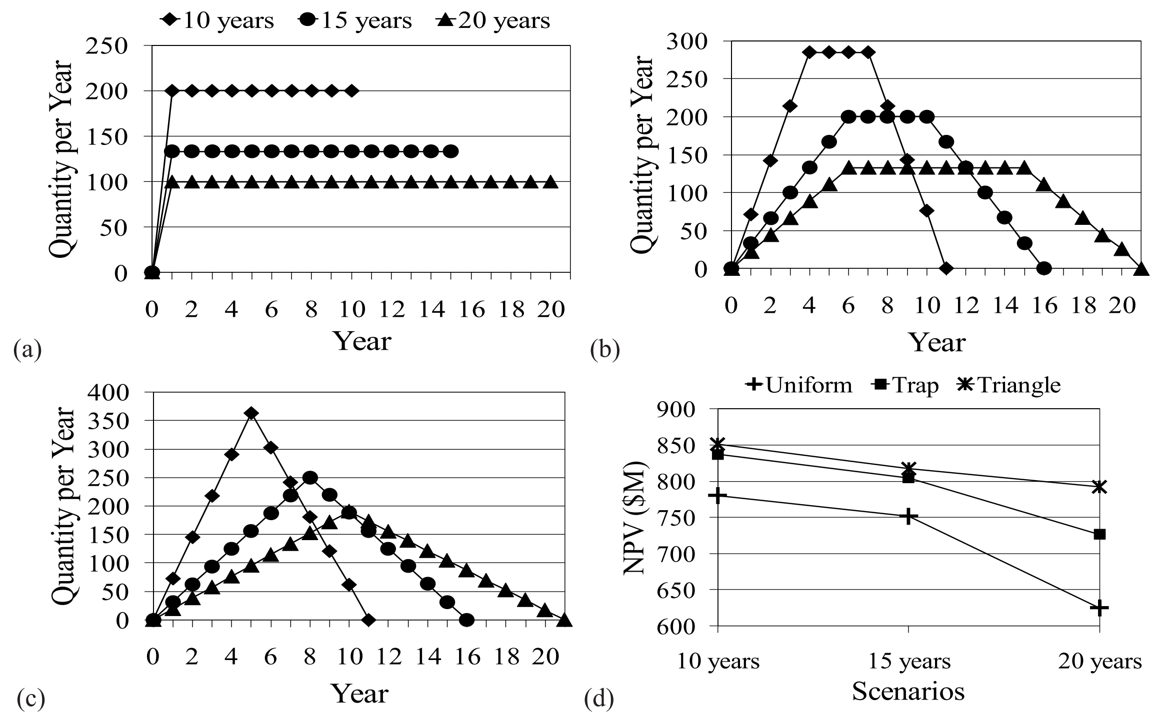


Fig. 4. (a) Uniform demand profile; (b) trapezoidal demand profile; (c) triangular demand profile; (d) the NPV of total network cost based on the changes in demand profile and the production years

The NPV's of the total network cost is decreasing as the production period shifted from 10, 15 to 20 years. In this experiment, for a given demand profile and discount rate, the only parameter changed was the number of production years. For the same discount rate and total number of aircraft manufactured, but while using more production years, the supply chain would need to install less manufacturing capacity early on and as a consequence the model resulted in lower NPV cost values. Therefore, the NPV was at the highest for the 10 production years case, and the lowest for the 20 production years case.

As for the changes in demand profile, the triangular distributions had the highest costs comparing to the other two profiles. The uniform demand profile incurred the least cost, and the trapezoid distribution was in between. This was because the peaked quantities at the middle of the production periods were the highest for triangular demand profile. The supply chain configurations were required to open additional facilities when the capacities of the baseline facilities were overwhelmed, and in turn, adding more capital costs and transportation costs to the overall system.

4.4. Experiment 3: make vs. buy trade studies

In this experiment, make vs. buy trades were studied using the model. Unlike the previous two experiments which were based on the baseline notional supply chain network shown in Fig. 2, the notional supply chain in this experiment is shown in Fig. 5. It included external fabricated and sub-assembled component suppliers being injected into the system at the intermediate manufacturing steps. This modification enabled us to study the make vs. buy trades that are of interest to the decision makers in aerospace companies. Depending on the purchase price offered by the external part suppliers, the decision makers could decide whether a WBS component would be made within the company's facilities or be bought straight from the external suppliers, i.e. outsourced. Thus, the changes in purchase prices were important in the make vs. buy decisions. Another important factor was the capital cost associated with the domestic or overseas facilities owned by the company. For instance, if a component was to be bought from a fabrication supplier, then the corresponding domestic fabrication facility could be eliminated in the supply chain, in turn implying capital cost savings for the company. Moreover, the discount rate the company implements also had a significant impact on the cost distribution during the production period and the supply chain configuration. Therefore, with all the other parameters fixed, the three changing parameters in this experiment were the purchase price from the external suppliers, the capital cost, and discount rate.

The purchase price from external suppliers was set at levels from 20% to 200% of the baseline total manufacturing cost. The capital cost of each company-owned manufacturing facility was varied by factors of 0.5 to 2. The factor of 2, for example, indicated the capital costs were twice as much as the baseline ones, 0.5 meaning half of the baseline ones. The discount rate was set at levels of 0% to12%, where 5.8% was the baseline value [17]. 3-D graphs were generated for the different cases based on these parameter changes to reflect the total cost NPV results. In order to better illustrate the behaviors of the results, the 3-D graphs are "sliced" and the corresponding 2-D "slices" are presented and explained in the following paragraphs.

4.4.1. Case 1: discount rate vs. purchase price at the baseline capital cost

As the discount rate was fixed at the baseline 5.8% and the capital cost was also set at the baseline value, the only varying parameter was the purchase price. The resulting 2-D graph for the total cost NPV is as shown in Fig. 6 (a), which resembles a step-function. The solid line is for Case 1 and the dotted line is for Case 2 which is presented in the next section. This behavior can be explained by examining the status (open or closed) of the facilities under the various purchase price settings. As the purchase prices were low (only 20% or 40% of the baseline manufacturing cost), all the WBS components were purchased from external part suppliers. As the purchase price increased, more and more in-house facilities (domestic or overseas) were open in order to minimize the total system cost. When the purchase price reached 200% of the baseline manufacturing cost, the model decided to have all parts produced in-house facilities instead of buying from any of the external suppliers.

The plot in Fig. 6 (b) shows the expected downward trend by varying discount rate for a fixed purchase price of 100% of the baseline total manufacturing cost and at baseline capital cost. The NPV of the total cost decreased as the discount rate increased.

With Fig. 6 (a) and (b) in mind, a 3-D surface plot combining the two parameters (purchase price change and discount rate) effect on the NPV of the total cost is illustrated in Fig. 7 (a). The lighter-colored the area on the surface plot was, the higher the NPV of the total cost was. It is important to examine the supply chain systems during the strategic planning stage from the 3-D perspective in order to take into account effects from multiple parameters on the final result, and to perform balanced trade studies during the make vs. buy decision making process.

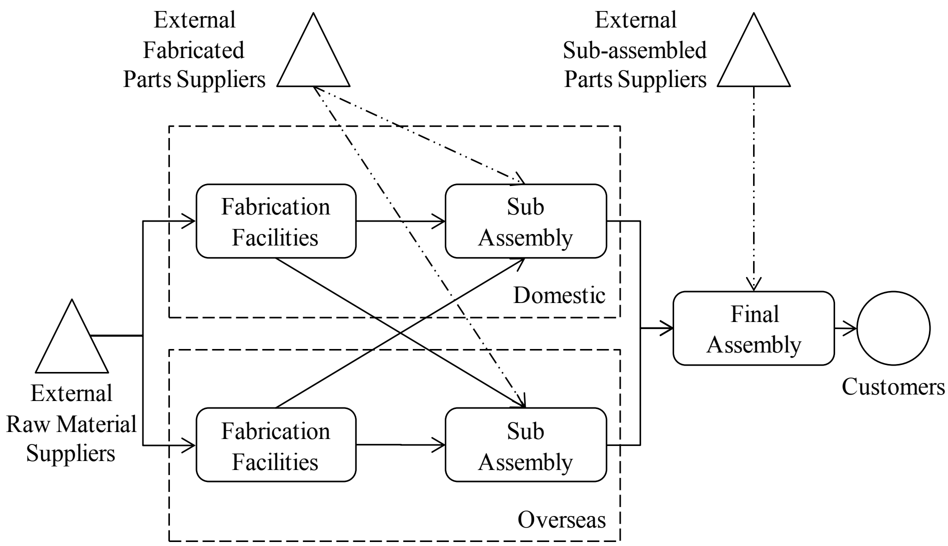
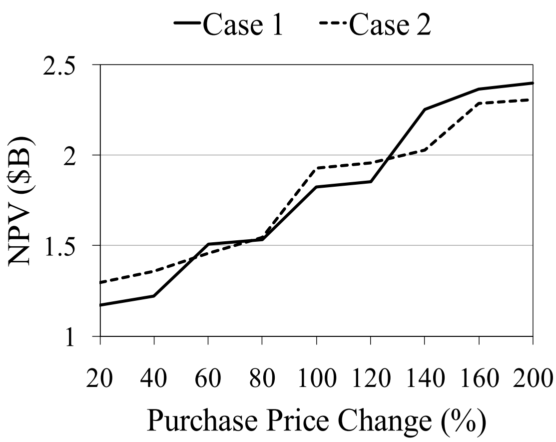


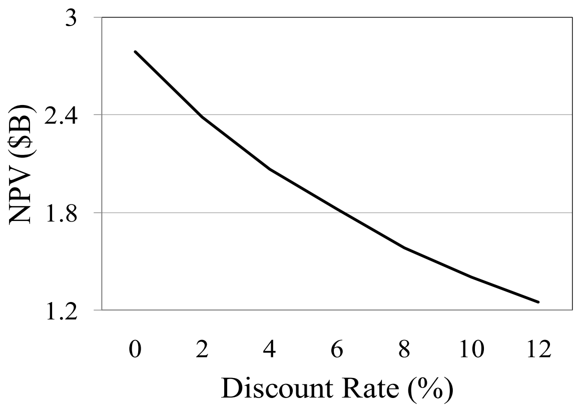
Fig. 5. The notional supply chain configuration with external part suppliers for Experiment 3

4.4.2. Case 2: discount rate vs. purchase price at the capital cost with factor 1.1

The capital costs were varied by factors from 0.5 to 2, but factor value of 1.1 was chosen to be included in this paper because it demonstrated the sensitivity of the model to these parameter changes. As seen in Fig. 6 (a), the dotted line represented the NPV of the total cost that increased as the purchase price changes became higher. It also appeared to have a slightly different step-function like behavior comparing to Case 1, which reflected the different supply chain configurations. More parts were being outsourced to external suppliers at each purchase price change than they were in Case 1. Likewise, the 3-D plot was generated for this case as shown in Fig. 7 (b) which had similar trend but different slops and curvature comparing to Case 1.



(a)



(b)

Fig. 6. (a) the NPV of total network cost with respect to the purchase price changes at a fixed discount rate 5.8% in Case 1 and Case 2; (b) the total cost NPV with respect to the changes in discount rate with purchase price fixed at 100% of the baseline total manufacturing cost and with baseline capital cost in Case 1

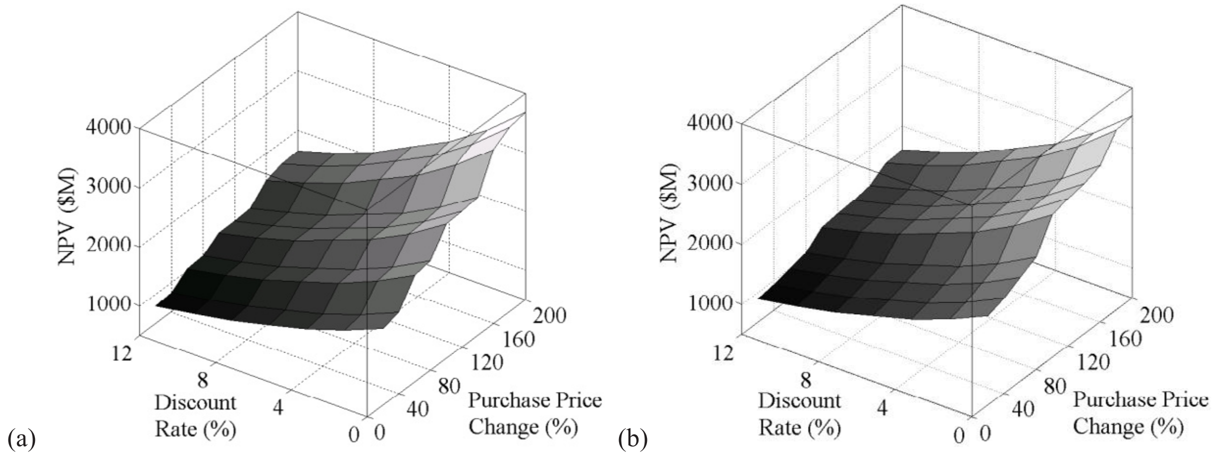


Fig. 7. (a) the NPV of total network cost with respect to changes in discount rate and purchase price levels at the baseline capital cost in Case 1; (b) the NPV of total network cost with respect to changes in discount rate and purchase price levels at the capital cost by factor of 1.1 in Case 2

5. Conclusion and Future Research

The strategic design of a supply chain network is a challenging task for any organization, particularly for the aerospace companies as the innovative aircraft products evolve and the network becomes more global and complex. To meet this challenge from the system engineering perspective, a formal method to model the supply chain is essential for the companies' competitiveness and success. This research breaks new ground in bridging the aerospace and supply chain disciplines at the early design phase via translating aircraft design data into supply chain information.

In summary, a strategic supply chain design model is introduced in this paper to help answer the high-level questions such as make or buy decisions, the allocation and location of the manufacturing facilities, and manufacturing capacity. The mathematical model utilizes the mixed-integer linear programming to optimize for minimization of the total network cost. The paper explains the content and structure of the model that is flexible and comprehensive. The case study using the model is constructed to design the supply chain networks for a generic fighter wing-box, and can be expanded to include more data as well as to study different new scenarios. Several experiments are performed to examine the behavior of the model. By changing the inputs, the resulting NPVs of the total network cost provide insight on the parameter impact on the supply chain system configurations.

As emphasized in Section 3, the availability of the data in the model would impact the fidelity of the results. One of the future improvements involves obtaining more realistic data by more interviews with the industry experts and open literature search. The current model is deterministic, but the long-term goal is to construct probabilistic model based on the current one that can better analyze different scenarios and risk assessment. Ultimately, the vision for the research effort in strategic aerospace supply chain design is to build a framework that incorporates surrogate modeling techniques to enhance the integration with aircraft design. The framework will be able to provide more information at the early product design stages and consequently assist the aircraft design selection as well as other strategic decisions.

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