Cost Analysis for Manufacturing of Composite Aerospace Products with Uncertainties

Xudong Liu

A Thesis

in

The Department

of

Mechanical and Industrial Engineering

Presented in Partial Fulfillment of the Requirements
for the Degree of Master of Applied Science (Industrial Engineering) at
Concordia University
Montreal, Quebec, Canada

July 2009

Your file Votre référence
ISBN: 978-0-494-63065-5
Our file Notre référence
ISBN: 978-0-494-63065-5

ABSTRACT

Cost Analysis for Manufacturing of Composite Aerospace Products with Uncertainties

Xudong Liu

Applications of composite materials in manufactured products are experiencing fast growth in recent years due to many of their property advantages over traditional materials in manufacturing industry. The success of using composite materials in producing automotive, aerospace or other products also depends, to large extent, on the competitiveness of their manufacturing and production costs. In this research, a cost analysis model is developed for aerospace product manufacturing using composites. Based on cost breakdowns for each step of the manufacturing process, an aggregate production plan was obtained to determine optimal production quantity and required workforce level. Sensitivity analysis was conducted to investigate the behavior of the model with varying parameter values. We also incorporated a stochastic programming model in the cost analysis procedure in dealing with uncertainty factors such as demands and raw material costs. An example of the model for the development and the analysis is based on the production of an aircraft wing box skin. This can be extended to production of other similar aerospace products.

Keywords: *Cost Analysis; Composites manufacturing; Aggregate Production Planning*

ACKOWNLEGEMENTS

I am honored to express my sincere gratitude to my supervisors, Dr. Mingyuan Chen and Dr. Suong Van Hoa, for their invaluable support and guidance through all the phases of my graduate study and the preparation of this thesis. Their encouragement, insight, and patience made this entire effort possible.

I would like to appreciate my colleagues for their precious comments and critiques in fulfillment of my thesis.

I am appreciative of financial assistance received from the Faculty of Engineering and Computer Science, Concordia University, Concordia Centre for Composites, CRIAQ, NSERC, Bell Helicopter, and Bombardier Aerospace.

Finally, I would like to thank my parents, and numerous friends who have supported me technically and spiritually. Without their help and encouragement, I would not have been able to work out the difficulties I encountered and finish this thesis successfully.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter One

Introduction

1.1 Foreword

As introduced in Mazumdar (2002), industrial applications of composite materials began in the 1940s primarily for military purposes. They have had rapid growth in recent years due to technological advances and much improved manufacturing processes. Composite materials possess a variety of excellent features such as light weight, high mechanical properties and these factors have made them widely used in modern product structures. They are used in different types of industries including: aerospace, automotive, marine, boating, sporting goods, among others. Although the great variety for styling and high finished surface quality of composite structures have made them preferred choices for many industry sectors, one of the widest applications of composite materials to date has been in the aerospace industry (Mazumdar, 2002). To some extent, improved manufacturing technologies and lower material costs have reduced the cost of composites materials in aerospace industry. However, their costs in general are still higher than the equivalent metal materials in most applications (Mazumdar, 2002). In order to further reduce manufacturing cost, many researchers have made significant effort in developing cost analysis models and production planning tools for producing composite materials and products.

To build cost analysis models for composites manufacturing, a detailed analysis of cost breakdowns for each step of composites manufacturing processes is presented. We also proposed an aggregate production planning model for composites manufacturing. Aggregate production planning helps the manufacturer to provide adequate production capacity to satisfy market demands while keeping the production costs low. This is necessary to the survival and success of the manufacturer.

1.2 Introduction of Composite Materials

This section provides a general introduction of constituents, advantages, manufacturing techniques, and applications of composite materials.

1.2.1 Constituents of Composite Materials

Composite materials are made by combining two or more constituent materials to provide a unique combination of properties of the products. The properties of composite materials are usually better than the constituent material properties (Mazumdar, 2002). As described in Hoa (2009), advanced composite materials normally contain three main components: fibers, a matrix, and an interface between fibers and matrix.

- Fibers: fibers can be glass, carbon or Kevlar. They provide stiffness, strength stability, and other structural properties to composite materials.
- Matrix: matrix can be polymer, metal, or ceramic, all of which have several functions in the composite structure. Most of their functions are very important for satisfactory performance of the structure.
- Interface: the bond between the fibers and the matrix.

1.2.2 Advantages of Composite Materials

The greatest advantage of composite materials for most applications is light weight (Mazumdar, 2002). Jones (1999) identified that the "strength to weight ratios" of composite materials are high, consequently they can support a heavier load than the equivalent metal materials of the same weight. For a given structure, the material used must be strong enough to bear the required load. Otherwise, the weight and size must be increased. In this regard, composite materials can provide significant weight savings for many mechanical structures.

Another advantage of composite materials is the design flexibility (Mazumdar, 2002). By combining appropriate fibers and matrix, composite materials can provide precise properties of a particular structure according to the requirement of a specific purpose. Moreover, compared with its equivalent materials such as steal, composite structures can be molded into different shapes economically.

Composite materials also have good heat, fatigue and corrosion resistance (Hoa, 2009). These features make them durable when they are exposed to rugged environments when they are used to make boats, certain chemical devices, and spacecrafts.

1.2.3 Applications of Composite Materials

In the past few decades, application of composite materials has been experiencing rapid growth. They are widely applied in many industries such as aerospace, automotive, marine, and sporting goods.

As composite materials can save the weight of structures, they are usually used as bumper beam, load floor, radiator support or hood in automobiles. Composite materials are also widely used in marine applications such as passenger ferries, fishing and recreational boats, because of corrosion resistance and light weight. Sporting goods such as golf shafts, tennis rackets, ice skates, and hockey sticks are generally nowadays made by composite materials.

1.2.4 Applications of Composite Materials in Aerospace Industry

As pointed out in Mazumdar (2002), aerospace industry has been the main user of composite materials. Composite materials have been used in making many different aerospace products of various sizes. Major benefits of using composite materials for aerospace products include lighter weight, less corrosion, and hence easier for maintenance. In aerospace industry, carbon fiber composites are primarily used because of their high properties such as high tensile strength, low weight, and low thermal expansion (Mazumdar, 2002). Aircraft flaps, ailerons, rudder, and many other components of flat shape are nowadays mostly made by composite materials and autoclave molding technique is frequently used in the production of these structures (Hoa, 2009). Major aerospace companies such as Boeing and Airbus are using composite materials for producing major airplane components such as fuselage and wings of very large commercial airplanes: Boeing 787 and Airbus A350XWB.

1.2.5 Composites Manufacturing Technology

Modern composites manufacturing techniques include autoclave molding, filament winding, pultrusion, liquid composite molding, and thermoplastic composites (Hoa, 2009). In this study, we focus on the autoclave molding technique. It is the most commonly used composites manufacturing technique in aerospace industry (Mazumdar, 2002). It can provide good quality composite products, but the manufacturing cost is relatively higher than using other modeling techniques. The main steps of autoclave molding are prepregs cutting, tool preparation, laying up prepregs, bagging preparation, curing in autoclave, removal of the part from the tool, inspection, and finishing (Hoa, 2009). The material used in this manufacturing process is commonly graphite/epoxy prepregs.

Although some companies have recently started to use automated machines to make prepregs cutting and to perform lay-ups, these operations are normally done manually (Mazumdar, 2002). Hence, it is a labor intensive manufacturing procedure and labor cost is the most significant component of the total production cost.

1.2.6 Production Cost Analysis with Composite Materials

Despite the numerous advantages of composite materials as they are applied in various industries, metal based materials are still dominant in manufacturing mechanical products. One of the critical factors limiting composite materials applications is their high production cost. Composite materials are usually more expensive than traditional metal materials mainly due to the higher cost of raw materials and extensive labor costs involved in composite manufacturing (Mazumdar, 2002).

In the last few decades, many researchers and manufacturers have made great efforts to reduce production cost of composite structures at the design stage. For example, one of the good methods to reduce production cost is to integrate several pieces of composite parts into one integrated molded structure so that the cost associated with the assembly processes can be eliminated.

Moreover, cost analysis tools and techniques have been developed and used to reduce production cost of composites in the manufacturing stage. Examples are Advanced Composites Cost Estimating Manual (ACCEM), technical cost model, analogy approach, and methods engineering (Mazumdar, 2002).

In this research, we developed an aggregate production planning model to analyze and optimize the production cost for certain type of process of composite materials manufacturing.

1.3 Aggregate Production Planning

Gaither (1986) defined aggregate production planning as the process of designing a production scheme to meet the medium to long term forecasted demands. Its purpose is to allocate different manufacturing resources in satisfying the demands and to minimize production costs in the planning time horizon.

In developing an aggregate production planning model, production variables such as work force level and inventory level are determined to accommodate production capacity in each period (usually weeks, months, or seasons) over the planning time horizon (usually 6 months to 18 months) (Leung *et al* 2006). A company may change the work force level by hiring or laying off operators. It may also change the production rate by using overtime production or reducing regular work hours. To decide the inventory level, a trade-off between changing production rate and holding the inventory is required.

One major difficulty in composites production planning and cost analysis is the uncertainties associated with customer demands and purchasing prices of raw materials. Since composite materials are more expensive and material properties are specific for certain applications, the risk due to uncertain demands and material prices is much higher comparing to that in traditional manufacturing business. Production planning and cost analysis models should be able to handle such uncertainties. In this research, we apply the two-stage linear programming model, which is a typical model of stochastic programming approach, to address the uncertainties involved in production planning of composite manufacturing.

1.4 Scope of the Thesis

In this thesis, we present a detailed cost analysis of composite manufacturing process and develop an aggregate production planning model. A stochastic programming approach is used to address uncertainties which are customer demands and raw material prices in the production planning and cost analysis. An optimal production plan with the minimized production cost is obtained. The production plan contains inventory policy of raw material, work force level, inventory level, and production rate in each period. The production of wing box upper skin for an aircraft using composite materials is analyzed as a numerical example. We apply both the deterministic and stochastic model to solve this problem and the results are analyzed and compared. Finally, a sensitivity analysis is performed for the solutions of stochastic model.

1.5 Research Contribution

In this research, an integrated production planning model is proposed for cost analysis for a certain type of aerospace composite products. The developed model presents a detailed analysis of cost breakdowns of the production process. In addition, a stochastic programming model is developed to obtain optimal solution of the production planning problem with uncertain demands and raw material prices. This is a significant extension to that presented in Leung *et al* (2006).

The developed model is for comprehensive cost analysis of composite manufacturing for aerospace products considering various scenarios due to economic uncertainties. The model can be easily modified for cost analysis on similar products manufactured by composite materials in aerospace or other industries. The main purpose of this thesis is to develop a scientific and integral cost analysis approach for composites manufacturing.

1.6 Organization of the Thesis

This thesis is organized into six chapters. Following the introductory Chapter 1, Chapter 2 provides a review of the literature in cost analysis models, composites manufacturing, aggregate production under uncertainty environment and aggregate production planning. Chapter 3 presents an introduction of composites manufacturing process focusing on aerospace products. Problem description, model formulation and solution methods are presented in Chapter 4. Example problem and result analysis are presented in Chapter 5. Chapter 6 presents concluding remarks and discusses possible future research topics in this area.

Chapter Two

Literature Review

2.1 Introduction

In the last several decades, many academic and industry researchers made significant efforts in developing different composites manufacturing processes to improve product performance and to reduce production cost. In this research, we develop a cost analysis model and an aggregate production planning model for composite manufacturing of aerospace products, subject to demand and resource uncertainties. Relevant research articles are reviewed and summarized in the following sub-areas:

- Cost analysis techniques in composites manufacturing.
- Manufacturing cost estimation and optimization models.
- Manufacturing cost models with uncertainties.
- Aggregate production planning with uncertainties.

2.2 Cost Analysis Techniques in Composites Manufacturing

Northrop Corporation (1976) developed an "Advanced Composite Cost Estimating Manual" (ACCEM) for the U.S Air Force. In this approach, the production processes were described in a collection of basic or primitive steps. For instance, in lay-up process, laying up a single prepreg sheet is a primitive step. All the primitive steps are written in forms to calculate the total production time of each operation. After that, the primitive time is plotted against various parameters, such as the dimensions of the product, in the best-fit curve. According to the best-fit curve, the equation of the production time of each primitive step can be derived as $t = Ay^B$, where A and B are constants obtained from the best-fit curve, and y is the plotted parameter. In each primitive step, the cost can be obtained by multiplying the production time by the cost factor. Finally, standard sub-processes with associated time estimation standards of some typical composites structures are listed.

Gutowski *et al* (1994) developed a theoretical cost analysis model for advanced composites fabrication. After reviewing considerable data regarding composites manufacturing processes, the authors concluded that composites manufacturing processes follow a first-order velocity response so they can be modeled as having first-order dynamics. Moreover, the manufacturing processes are divided into many sub-processes. Each of them can be modeled as $y = v_0\{t - \tau(1 - e^{-t/\tau})\}$, where y is an extensive variable such as length or weight of the identified task, t is sub-process time, and τ is the dynamic time constant with the unit of time. The production cost of a sub-process can be obtained by multiplying sub-process time by a cost factor. Finally, a comparison between the traditional cost model ACCEM and the proposed model were conducted. It showed that the proposed model is more practical and has a great correlation with the ACCEM model.

Kassapoglou (1999) presented an optimization method to optimize both the production cost and weight of a composite fuselage frame simultaneously. The structural requirement and manufacturing constraints were combined and considered in the optimization model. The purpose is to find the lowest weight and cost point. The author used a near-optimal Pareto set of design to select the overall optimum configuration. The author also applied this approach to different manufacturing options of the fuselage frame such as: a sheet metal frame, a frame made by high-speed machining, a frame made by hand layup, and a frame made by resin transfer molding. The results showed that the resin transfer molding option is in the lowest cost and weight point when the frames are lightly loaded, and the high-speed machining option is in the lowest cost and weight point when the frames are highly loaded.

Bernet *et al* (2000) developed an integrated and consolidation cost model for commingle yarn based composites. The model can be applied to production of different composites structures. The authors compared different cost estimate methods of composites manufacturing. They categorized them as comparative techniques, process-oriented cost models, parametric cost models and process flow simulations. In the model proposed by the authors, the total manufacturing cost are divided into material cost, labor cost, and overhead cost. Furthermore, they divided the processing time of each operation into setup time, run time, move time, and wait time. In doing so, the model can be used for a wide range of manufacturing processes and makes it possible to obtain the minimum production cost in a relatively simple cost model.

Mazumdar (2002) categorized composites production costs as nonrecurring and recurring costs. The nonrecurring costs can be divided into equipment, tooling, facility development, and engineering development costs. Recurring costs are also called operating costs consisting of direct materials costs, indirect material costs, direct labor costs, indirect labor costs, cost of running equipment, packaging and shipping costs, scrap handling costs, and loss costs. He also analyzed several composite manufacturing processes such as lay-up technique, filament winding, and compression molded sheet-molding compound using the proposed cost scheme of production costs.

Wang *et al* (2002) developed a method to optimize both production cost and weight of composite structures at the same time. They developed two algorithms using cost and weight increment ratio to keep the balance between cost and weight. One of them incorporates the parameter ($\Delta\$/\Delta kg$) directly to the balance between cost and weight. Two examples problems were presented to illustrate the application of the proposed methods. It was shown that they are effective in balancing the production cost and the weight of the studied composite structures.

Kaufman *et al* (2008) studied cost optimization of composite aircraft structures considering quality levels of laminates. The authors developed a cost model to optimize manufacturing cost, inspection cost and weight of the structure. The laminate quality was considered as a design variable. The production cost of a general composite structure – composites skin element – was analyzed as a case study. The authors used a standard flaw size and examined the effects of laminate quality on the direct operating cost. The optimal flaw size can be obtained when the sum of non-destructive testing cost, manufacturing cost and weight penalty is minimized.

Ye *et al* (2009) presented a cost estimation model for manufacturing composite waved beams. The objective function of this model is to minimize material, labor, tools, and equipment costs. Since all of these cost components are directly related to the process time, the authors also proposed a method to determine the processing time of making composites waved beam using autoclave. The proposed optimization model includes a working procedure model and divides the total cost into different cost components. The objective function of the optimization model is directly expressed by the process time.

The model can be revised for solving different cost analysis problems of composites manufacturing.

2.3 Manufacturing Cost Estimation and Optimization Models

Park and Kim (1995) presented cost estimation model for advanced manufacturing in an activity-based costing system. They compared activity-based cost system with traditional cost accounting system. They noted that these two cost systems are different in dealing with overhead cost and estimating cash flows. They showed that the activity-based cost system is a more reasonable approach using a real word example. The authors then incorporated the proposed cost system into an investment decision model. One of the major features of the proposed cost system is the activity utilization. This feature improved the investment decision model and provides more accurate information for investment decisions.

Chibesakunda (2000) presents the parametric cost estimating model for deburring processes in metal cutting. In the parametric model, different processes can be compared and their parameters can be determined. Total cost were categorized as variable cost and fixed cost for the deburring processes. The variable cost is further divided into material, direct labor, and energy costs. The fixed cost has 7 elements: main machine, auxiliary equipment, tool, building cost, overhead, maintenance, and capital costs. He also provided a breakdown of the cost for each element. This information can be used for cost reduction proposes and sensitivity analyses.

Yamashina (2002) presented an approach called "manufacturing cost deployment" for manufacturing cost reduction. It involves four basic steps. First, examining different production losses and categorizing them into causal losses and resultant losses; second, searching for the relationship of processes' losses and cost factors related to them; third, clarifying available and unavailable loss reductions; and forth, removing the identified losses and obtaining the total reduction cost. The author also presented an algorithm consisting of four matrices developed following the basic steps. A case study was examined and it demonstrates that the proposed manufacturing cost deployment approach can lead to reduced manufacturing cost and improvement activity.

Niazi and Dai (2006) presented a review of several methodologies for manufacturing cost estimation. They classified them as qualitative and quantitative techniques. The qualitative techniques consist of intuitive and analogical techniques, and the quantitative techniques include both parametric and analytical techniques. The intuitive cost estimation techniques are experience based and cost estimation may be drawn from a domain experts' knowledge. The knowledge can be componentized and stored in the forms of rules, decision trees, judgments, and so on. The analogical cost estimation techniques, such as regression analysis models and back-propagation neural-network models, use the information drawn from historical cost data. The parametric cost estimation techniques based on statistical tools. The cost is considered as a function of constituent variables. The analytical techniques separate one product into units, operations and activities, and the total cost is the sum of all these elements. The analytical cost estimation techniques can also be categorized as operation-based approach, breakdown approach, tolerance-based cost models, feature-based cost estimation, and activity based costing system.

2.4 Manufacturing Cost Models with Uncertainties

Jha (1996) developed a stochastic model for production planning and cost optimization. The objective function of this model is to minimize the sum of set-up, tools, machining, in-process inventory, and penalty costs. Instead of calculating the exact optimized total cost by the two-stage stochastic programming, the author used a stochastic geometric approach to estimate the probable range of the total cost. Hence the problem can be solved with relatively less computational efforts. Using the upper bound and lower bound of the total production cost, the manufacturer can decide if the production of a particular product is worth the cost of production.

Shahi *et al* (1999) developed a cost estimation model for manufacturing flat plate products using fuzzy sets. In this paper, the authors applied fuzzy sets and probability approaches to address the uncertainty of cost estimation in flat plate processing industry. The estimation model is based on activity-based costing system. The authors noted that processing activities in the manufacturing system can be divided into three groups: work preparation activities such as drawing and nesting, manufacturing activities like set-up and cutting, and material handling activities akin to uploading and packing the materials. Each of the activities is a variable and is uncertain. Hence, it may be desirable to incorporate the fuzzy sets and probability distributions into the cost estimation model.

Shehab and Abdalla (2002) presented a knowledge-based system for production cost modeling. The proposed system can be used to develop a cost model for machining and injection molded products at the design stage. The proposed system consists of two key modules, machining module and injection molding module. After analyzing the two main modules, a computerized cost model was presented. This model integrates the relationship of cost factors, product development activities, and product geometry. The objective function of the cost model is to minimize the cost of material, mould, and processing. Fuzzy logic-based knowledge was applied to deal with the uncertainties in the cost model. Finally, a case study was used to validate the proposed system.

Eklin *et al* (2007) presented a cost estimation model of shop floor production. Instead of considering a limited capacity, they proposed a model under a stochastic environment. Moreover, the model improved an existing iterative cost estimating heuristic, and the improvement was derived from the integration of simulation and optimization. They used the data generated from the simulation as input to the optimization model. Setup and process time of the machine were considered as random variables following certain distributions. They also showed the advantage of the cost estimation model developed over the existing deterministic model by conducting a computational study.

2.5 Aggregate Production Planning under Uncertainty Environment

Günter (1982) presented a comparison of two types of aggregate production planning methods: linear programming models and parametric linear decision rules. The author used a multi-stage and multi-item production system as a case study to compare these two approaches. The same stochastic demand processes, demand forecasts, and rolling schedules were used in the two approaches. The results show that the linear decision rules are better than linear programming models under highly stochastic environment.

Leung *et al* (2006) proposed a stochastic model for multi-site aggregate production planning with uncertain customer demands. Production quantity and workforce level at different production plants are two key decision variables. They were determined by minimizing the total cost composed of production, labor, inventory, subcontracting, hiring and laying off and shortage costs. A two-sage stochastic programming approach was used. The authors also considered the production planning problem with additional constraints such as production capacity and production plant site selection. Real-world problem data were used to examine the effectiveness and efficiency of this model. Sensitivity analysis was performed for different probability distributions and economic scenarios.

Zhao *et al* (2006) developed an aggregate planning model with uncertain customer demands. The objective function of the model is to maximize the profits considering the trade-offs of service level and producer risk. In the end, a sensitivity analysis was performed. It showed that the reproduction point has the greatest affect on the manufacturing profit. It also concluded that the production cycle and standard deviation of product demand are two significant factors of the reproduction point.

Hsieh and Wu (2000) presented a demand and cost forecast method in aggregate production planning using possibilistic linear programming models. They performed a comparison between possibilistic model and a classic aggregate production planning problem model. Results showed that the possiblistic linear model could accept a wider range of imprecise demands and give a lower production cost than the deterministic model. Finally, a sensitivity analysis was conducted to examine the effectiveness of the possiblistic model in accommodating demand and cost variations of a real production system.

Moghaddam *et al* (2007) presented an aggregate production planning model using fuzzy approach and a fuzzy mixed-integer mathematical model was developed. The objective function is to minimize the sum of inventory, regular time labor, over time labor, outsourcing, and shortage costs. A typical linear programming approach with fuzzy technological coefficient was applied to the mathematical model. The authors also indicated that fuzzy approach and stochastic programming are two main methods to deal with uncertainties in production planning. The fuzzy approach is more accurate when no historical data are available.

Wang and Fang (1999) presented a fuzzy linear programming model of aggregate production planning. The variables are product price, subcontract cost, workforce level, production capacity, and demand. They are determined based on the fuzziness assumption. The solution procedure contains two steps: first, formulating the problem as a fuzzy linear programming model; second, modeling the fuzzy data. The authors developed an interactive system which makes it possible for the decision maker to modify the objective and constraint functions until a satisfactory solution is found. The authors also compared the proposed model with a traditional deterministic model in aggregate production planning and the comparison revealed that the proposed model is more accurate for real-world applications.

2.6 Summary

The literature discussed in this chapter covers the research work carried out in the area of manufacturing cost analysis and aggregate production planning. Research work has been conducted by several authors in cost modeling and analysis for composites manufacturing.

However, the existing work is either limited to certain productions or too complicated for solving practical problems. One of the purposes of this research is to build a simple and accurate cost estimation model for composites manufacturing which can be extended to analyze other similar composites products in aerospace industry. We also found several recent research articles presenting cost analysis models of composites manufacturing with uncertainties or aggregate production planning with uncertainties. In this research, we present a detailed mathematical model to perform the cost analysis and combined it with aggregate production planning as an optimization model. Moreover, the uncertainties are addressed by the stochastic programming approach.

In the next chapter, the considered composites manufacturing process are described in details. Then production steps of autoclave processing are introduced. Finally, the raw materials of composite structures and equipments involved in the autoclave processing are discussed.

Chapter Three

Composites Manufacturing Process

In this chapter, a description of composites manufacturing process based on autoclave processing is presented.

3.1 Production Steps of Autoclave Processing

In this section, we introduce the production steps involved in the autoclave processing. The main production steps are prepregs reparation and cutting, tools preparation, laying up prepregs, curing in the autoclave, removal of the part from the mold, inspection, and finishing steps. Figure 3.1 shows the typical steps of the autoclave manufacturing process (Hoa, 2009).

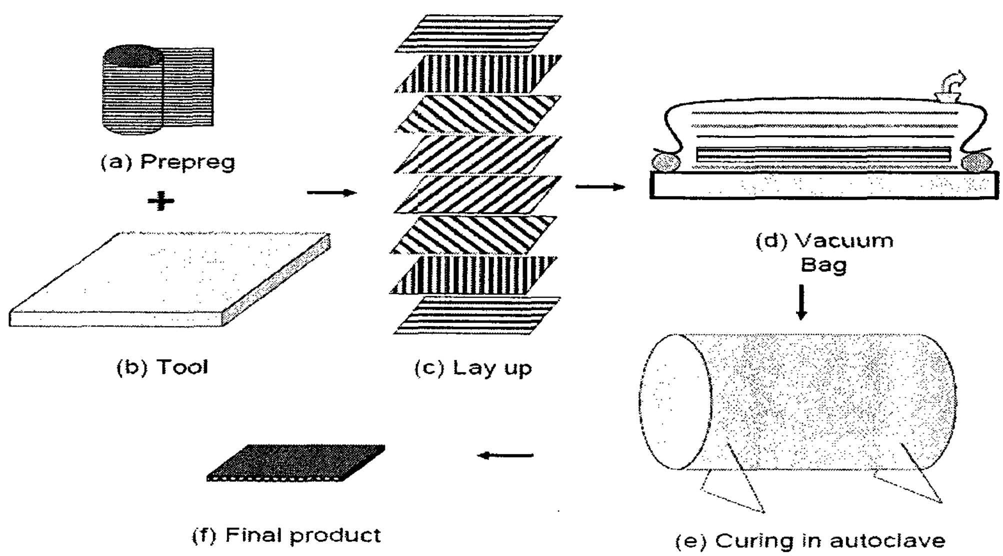

Figure 3.1. Main Steps in Autoclave Manufacturing Process (Hoa, 2009)

3.1.1 Prepregs Preparation and Cutting

In order to slow down the reaction of the resin in the prepregs and prevent the resin becoming hard, one needs to store the prepregs inside a freezer at about -5 °C once they are received. When laminates are to be made to prepregs, they must be taken out from the freezer and left in the room temperature for several hours. This allows the temperature of the prepregs to be increased to room temperature and the viscosity of the resin can be reduced. In the prepregs cutting stage, a well designed cutting method can help to reduce the scrap of prepregs and to reduce the total production cost.

3.1.2 Tools Preparation

The mold (also called tool) is used to provide the shape and surface finish for the composite part. It is designed according the dimensions of the part. The part must be cured in an autoclave with high temperature and pressure. The autoclave is usually made up of metal or graphite/epoxy. A good mold surface can result in a final part with good surface quality. The sticking of the product to the model can cause damage to both of the mold and the product, so mold cleaning fluid is needed to clean the mold before laying up the prepregs to the mold. Release agent and films are also needed to be placed on the mold to obtain a good surface of the composite part.

3.1.3 Laying up the Prepregs

After the release agent and films are applied, prepregs are placed by hands (Hand-Lay-Up). The orientations of the layers of the prepregs are usually following the stacking sequence for angle [0/90/+45/-45/-45/+45/90/0]. Figure 3.2 shows the schematic of the [0/90/+45/-45/-45/+45/90/0] Hand-Lay-Up process (Hoa, 2009). To assure the laminates to align with straight fibers, layers of the prepregs have to be well packed, and the operating process "debulking" needs to be performed after a certain number of layers have been laid. For example, for a total of 20 layers of prepregs to be laid up, one needs "debulking" after laying up every 5 layers. Hence, we perform totally 4 "debulking processes" in laying up the prepregs. In each "debulking", the breather material and vacuum bag are placed around the mold. Then vacuum is applied using a vacuum pump. After laying up all layers of prepregs, we need to place the bleeder materials and breather materials again. Finally another vacuum bag is placed, the vacuum needs to be kept during the autoclaving process. Figure 3.3 shows the assembly of all layers (Hoa, 2009).

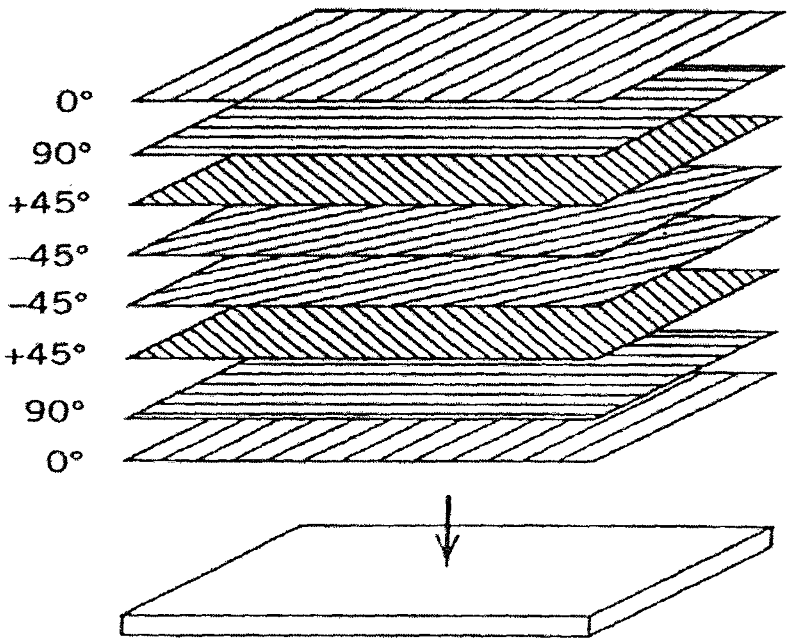

Figure 3.2. Schematic of [0/90/+45/-45/-45/+45/90/0] Hand-Lay-Up Process (Hoa, 2009)

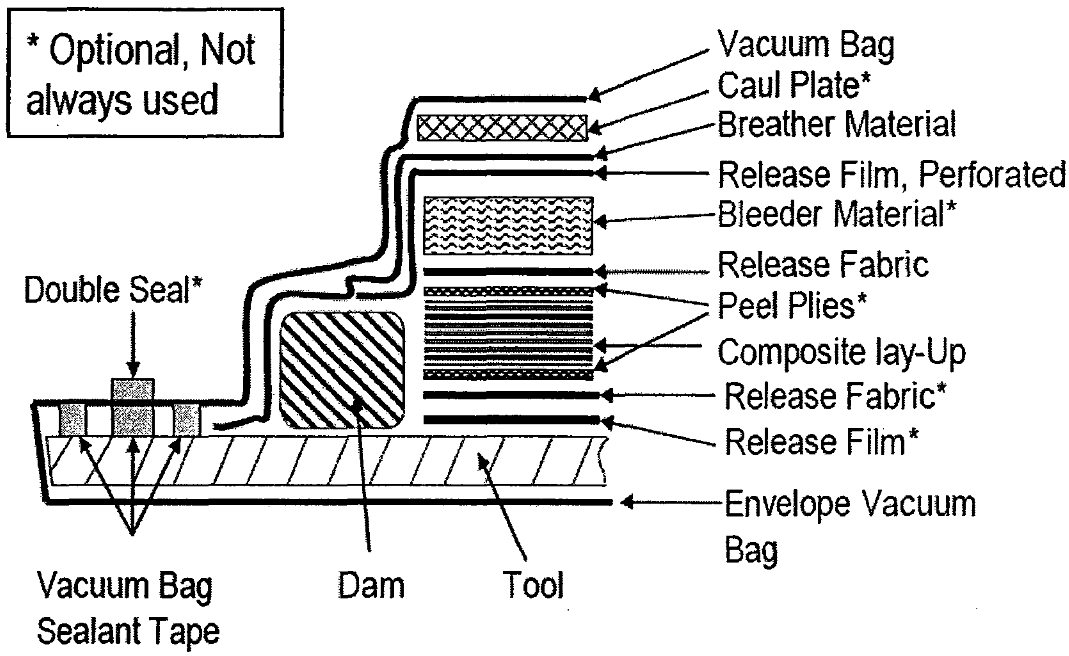

Figure 3.3. The Assembly of all Layers (Hoa, 2009)

3.1.4 Curing in the Autoclave

To bond the adjacent layers strongly, high pressure and heat must be provided by the autoclave. The curing cycle is decided by considering the heat transfer and energy balance, resin flow and consolidation, and void suppression. The composite part needs to be cured in the autoclave for several hours, and the temperature and pressure are usually about 180 °C and 600KPa.

3.1.5 Removing the Part from the Mold, Inspection, and Finishing

After the part is cured in the autoclave, the vacuum bag, bleeder materials, breather materials and rubber molds are removed, and then the composite part is removed from the mold. Inspection and trimming are essential to make the surface of the composite part smooth and with good quality. Finally the finished part needs to be moved to the storage place.

3.2 Raw Materials

To manufacture composite structures, eight types of major raw materials are required.

- A prepreg is an abbreviated term of "pre-impregnated" composite fiber, fabric, or mat in flat form. Prepregs have a certain amount of matrix to bond fibers together. They can be unidirectional tape, woven fabric prepregs, or rovings.
- Mold cleaning fluid is used to clean the surface of the mold before placing release agent and films.
- Release agent and films are applied on the surface of the mold to prevent sticking between the mold and part.
- Bleeder materials are used to absorb the resin that leaks out during the curing process in the autoclave. Normally, bleeder materials are polyester mat, fibreglass, and cotton.
- Breather materials allow the escaping of volatiles and gases during the curing process in the autoclave. Commonly, Breather materials are polymer films and they can resist high temperature and pressure.
- Vacuum bag is sealed on the mold with sealant tape. A vacuum pump is then applied to create a consistent compression across the structure.
- Sealant tape is used to seal the periphery of the mold and vacuum bag.

3.3 Tools and Equipment in Autoclave Processing

Major tools and equipment used in autoclave processing are autoclave, molds, and vacuum pump.

- An autoclave can be considered as a vessel with a heating facility and can provide high pressure. To provide high pressure, the autoclave is usually manufactured as a large cylindrical tube. A door is set up at the end of the tube, so the mold can be taken in and out of it. Since high temperature must be supplied during the curing process, the autoclave is usually made of welded steel. Commonly, autoclaves are very expensive and their capacities are limited. Figure 3.4 and Figure 3.5 show the schematic drawing and photo of an autoclave (Hoa, 2009).

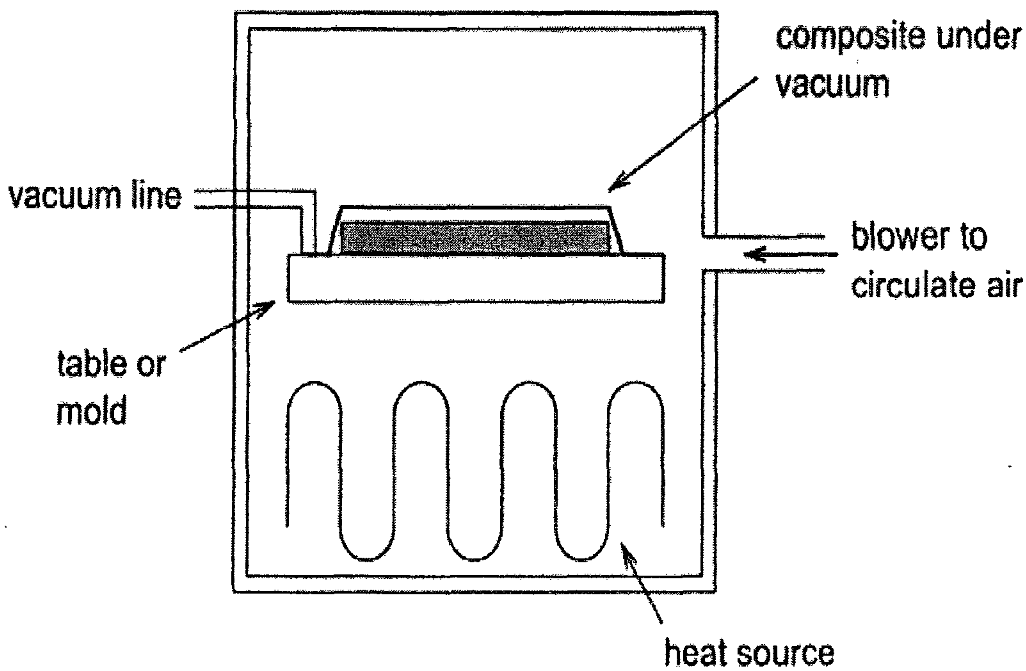

Figure 3.4. Schematic of an Autoclave (Hoa, 2009)

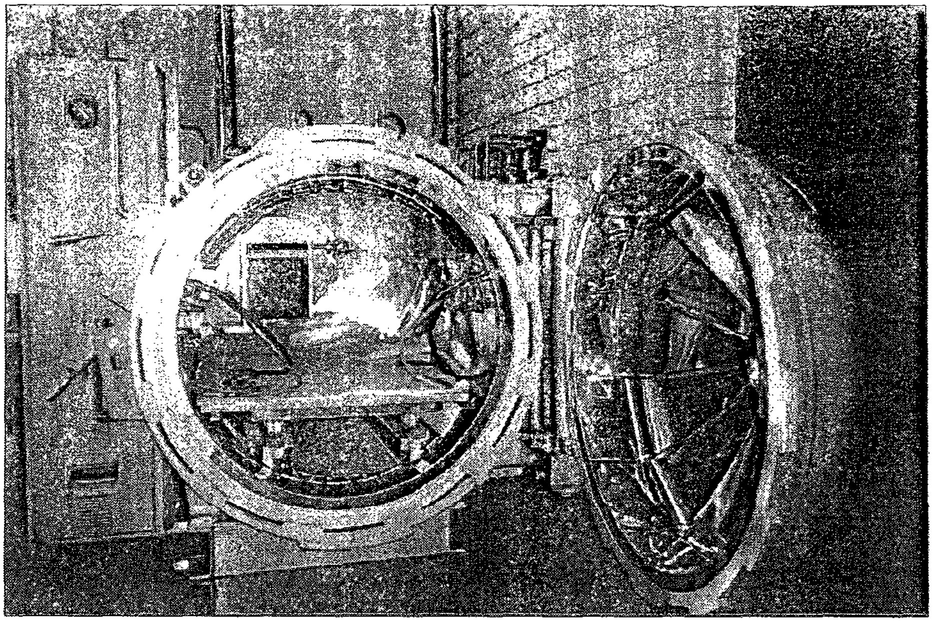

Figure 3.5. Photo of an Autoclave (Hoa, 2009)

- Molds used in autoclave processing are usually made up of stainless steel or aluminum. To design the mold, the expansion and contraction of the mold and the part shrinkage must be considered.
- A vacuum pump is used to create a vacuum during the debulking process.

3.4 Summary

The costs of making composite products are incurred at each step of the process and are associated with the required raw materials and tools. The labor cost can be obtained based on cost breakdowns for each step of the manufacturing process.

In the next chapter, a mathematical model formulation for cost analysis and aggregate production planning in composites manufacturing is developed. The cost breakdowns for each step of the manufacturing process are presented along with the formulation of the model. The uncertainty environment is considered in cost analysis and aggregate production planning.

Chapter Four

Model Formulation and Solution Approach

In this chapter, we first present an analytical model of production cost analysis for a certain type of composite structure. We also propose an aggregate production planning model for composites manufacturing. The stochastic programming approach will be used to address uncertainties due to different economic environments, such as customer demands and raw material prices.

The production cost model developed in this section only considers the production process with one group of operators and no overtime work allowed. Its purpose is to identify the factors affecting the production cost. The model developed can be used for cost analysis for a small-scale composite manufacturing system.

The developed aggregate production planning model can be used to design a production planning scheme for forecasted medium-term demands. It deals with the allocation of production resources to satisfy the demands and to minimize production costs in a time planning horizon.

Stochastic programming is a methodology for solving optimization problems with uncertainties. A typical stochastic programming model with recourse can be solved with a two-stage linear programming model. It is the most widely used stochastic programming model and it is applied in this research to deal with the aggregate production planning in composite manufacturing.

Before the production cost analysis model and the aggregate production planning model are presented, notations to be used in the rest of the chapter are presented.

4.1 Notations

4.1.1 Index Sets

I	$= \{1, \ldots, N_m\}$	Set of types of materials;
J	$= \{1, \ldots, N_e\}$	Set of types of machine and equipments;
K	$= \{1, \ldots, N_k\}$	Set of tools;
L	$= \{1, \ldots, N_p\}$	Set of time periods;
O	$= \{1, \ldots, N_o\}$	Set of operation steps;
S	$= \{1, \ldots, N_s\}$	Set of economic growth scenarios;

4.1.2 Parameters

AM_i Ordering cost of material i; $i \epsilon I$

CB Unit shortage cost at the end of each period;

CH Cost of hiring one group of operators;

CI Unit inventory cost to hold product at the end of each period;

CL Cost of laying off one group of operators;

CLO Overtime wage of one group of operators;

CLR Regular time wage of one group of operators;

CRA Cost of energy consumption per hour of operating autoclave;

CRE_j Cost of energy consumption per hour (electricity, compressed air,...) of equipment j; $j \epsilon J$

CRP Cost of energy consumption per hour of operating the pump;

D Annual customer demand;

D_l Customer demand during period l used in the deterministic model;

D_l^s Customer demand during period l under scenario s in the stochastic model; $s \in S$, $l \in L$;

FEC_j Fraction of equipment j time capacity available for overtime use; $j \in J$

FEP Fraction of pump time capacity available for overtime use; $j \in J$

FM_j Maintenance factor of equipment j; $j \epsilon J$

FO Overhead cost factor;

FSM_i Scrap factor of material i; $i \epsilon I$

FOW Fraction of the available workforce for overtime in each period;

FOA Fraction of the available autoclave processing time capacity available for overtime use in each period;

HM_i Holding cost of material i; $i \epsilon I$

IRE_j Interest rate on cost of equipment j; $j \epsilon J$

IRT_k Interest rate of tool cost k; $k \epsilon K$

NE_j Lifetime of equipment j; $j \epsilon J$

NT_k Lifetime of tool k; $k \epsilon K$

NW_0 Initial number of groups of operators;

P^s Probabilities of economic growth scenario s in the stochastic model; $s \in S$

PE_j Purchasing price of equipment j; $j \epsilon J$

PM_i Unit purchasing price of material i; $i \epsilon I$

PM_i^s Unit purchasing price of material i under scenario s in the stochastic model; $s \in S, i \in I$

PT_k Purchasing price of tool k; $k \epsilon K$

QU_i Order unit of material i; $i \epsilon I$

QM_i Order quantity of material i; $i \in I$

RM_i Amount of material i required for one product; $i \epsilon I$

SE_j Salvage of equipment j; $j \epsilon J$

ST_k Salvage of tool k; $k \epsilon K$

TEA Processing time capacity of curing in the autoclave during one period;

TPA Processing time of curing in the autoclave for one final product;

TPE_j Processing time of equipment j; $j \epsilon J$

TS_o Processing time of operators in each production step o; $o \epsilon O$

TW Total regular time labor hours in each period;

U Reciprocal value of N;

W Wage of one group of operator used in the production cost model;

4.1.3 Decision Variables

B_l Under-fulfillment in period l used in deterministic model; $l \in L$

B_l^s Under-fulfillment in period l under scenario s in stochastic model; $l \in L$ $s \in S$

N Number of composite parts curing in the autoclave at the same time, which equals to the number of molds and sets of rubber molds;

NH_l Number of group of operators hired during period l; $l \in L$

NL_l Number of group of operators laid off during period l; $l \in L$

Number of group of operators required during period ;

Order quantity of material during period ;

Overtime production quantity during period ;

Regular time production quantity of in period ;

Reciprocal value of ;

Inventory level of products at the end of period used in deterministic model

Inventory level of products at the end of period under scenario ;

4.2 Production Cost Analysis Model

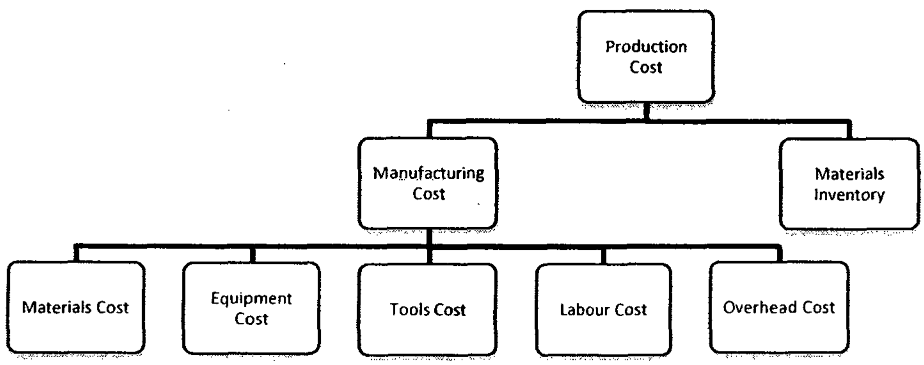

Figure 4.1. Breakdown of Production Cost

The considered production cost components in the production cost model are summarized in Figure 4.1 and they are formulated by the equations 4.1~4.10 (Bernet *et al*, 2000). The production cost consists of manufacturing and inventory cost. The manufacturing cost is composed of material cost , equipment cost , labor cost and overhead cost .

Material Cost

(4.1)

In the considered composite manufacturing process, raw material cost is the purchasing cost of all raw materials such as prepregs, release agent, release film and so on. To produce one piece of the product, many operations must be operated on these materials and scraps are unavoidable. For example, when operators trim the final products, the scrap of prepregs is generated at the same time. Therefore, materials cost is formulated as in equation (4.1) with the scrap factor FSM_i.

Labor Cost

$$CL = \sum_{o\in O} D \times W \times TS_o \tag{4.2}$$

The labor cost CL can be obtained by multiplying the labor cost of manufacturing one final product and annual customer demand D. $\sum_{o\in O} TS_o$ means the total operating time in fishing one final product.

Equipment Cost

$$CE = \sum_{j\in J}[\frac{(PE_j - SE_j)}{NE_j} + IRE_j \times PE_j + FM_j \times PE_j + D \times TPE_j \times CRE_j] \tag{4.3}$$

The first term of equation (4.3) is equipment depreciation cost. The value of equipment decreases over the years, and the equipment has salvage value at the end of its usage. "Straight-line" method (Bernet *et al*, 2000) is used to calculate the equipment depreciation cost in this model. The second term is the interest on cost of equipment, such as the interest of the loan required to purchase the autoclave. The third term is annual equipment maintenance cost. The annual equipment maintenance cost is considered as a certain percentage of its purchasing price. The fourth term is energy consumption cost (electricity, cooling water, compressed air and so on) of using the equipment. It can be obtained by multiplying the energy consumption rate and processing time of the autoclave, for example.

Tools Cost

$$CT = \sum_{k\in K}[\frac{(PT_k - ST_k)}{NT_k} + IRT_k \times PT_k] \quad (4.4)$$

Tools or molds cost CT consists of the depreciation cost and interest cost.

Inventory Cost of Materials

$$CI = \sum_{l\in L}\sum_{i\in l}[AM_i \times D \times RM_i(1 + FSM_i)/QM_i + HM_i \times QM_i/2] \quad (4.5)$$

Inventory cost of materials CI consists of ordering and holding costs. Ordering cost can be the cost of personnel order forms, postage, telephone calls, authorization, typing of orders and so on. Holding cost includes opportunity cost of funds tied up in inventory, storage costs such as rent, heating, lighting, depreciation, obsolescence, deterioration, breakage, and so on. We can formulate the inventory cost of materials as equation (4.5). According to the EOQ (Economic Order Quantity) model, the minimized inventory cost of materials can be obtained when letting the derivative of the ordering quantity QM_i to be 0 in equation (4.5) as shown in equations (4.6) and (4.7). We can obtain EOQ_i from equation (4.8) and the minimized inventory cost of materials CI^* is given in equation (4.9).

$$\frac{d(CI)}{d(QM_i)} = \frac{HM_i}{2} - \frac{AM_i \times D \times RM_i(1+FSM_i)}{{QM_i}^2} \quad (4.6)$$

$$\frac{d(CI)}{d(EOQ_i)} = \frac{HM_i}{2} - \frac{AM_i \times D \times RM_i(1+FSM_i)}{{EOQ_i}^2} = 0 \quad (4.7)$$

$$\Longrightarrow EOQ_i = \sqrt{\frac{2 * AM_i \times D \times RM_i(1+FSM_i)}{HM_i}} \quad (4.8)$$

$$CI^* = \sum_{i \in I} \sqrt{2 \times AM_i \times D \times HM_i \times RM_i(1 + FSM_i)} \tag{4.9}$$

Overhead Cost

Overhead cost usually includes the cost of supervision, payroll, inspection and testing, rent and so on. This group of expenses is necessary for the business, but do not directly generate profit. It can be calculated by multiplying an overhead factor Fo by the summary of all the other costs (Bernet *et al*, 2002).

Production Cost

The production cost is the summation of the material cost CM, equipment cost CE, tools cost CT, labor cost CL, inventory cost CI^* and overhead costs FO.

$$CP = (1 + FO) \times \{\sum_{i \in I} D \times RM_i \times PM_i \times (1 + FSM_i)$$

$$+ \sum_{o \in O} D \times W \times TS_o$$

$$+ \sum_{j \in J} [\frac{(PE_j - SE_j)}{NE_j} + IRE_j \times PE_j + FM_j \times PE_j$$

$$+ D \times TPE_j \times CRE_j]$$

$$+ \sum_{k \in K} [\frac{(PT_k - ST_k)}{NT_k} + IRT_k \times PT_k]$$

$$+ \sum_{i \in I} \sqrt{2 \times AM_i \times D \times HM_i \times RM_i(1 + FSM_i)}\} \tag{4.10}$$

4.3 Aggregate Production Planning Model

The production cost analysis and calculation presented in the previous section has several limitations for large scale composite manufacturing. For instance, if customer demand is high, more operators will be needed. To address such limitations, an aggregate production planning approach is introduced in this section.

Aggregate production planning can be used to generate a medium term (6 months to 18 months) production plan with optimized production quantity, inventory level and workforce level. For optimal production planning, we assume that the work force level can be varied by hiring or laying off operators and the production rate can be varied by using production overtime or reducing regular work hours. A trade-off between production rate and the inventory level is required. The breakdown of production cost for the aggregate production planning is shown in Figure 4.2.

We first introduce the assumptions in formulating the aggregate production planning model.

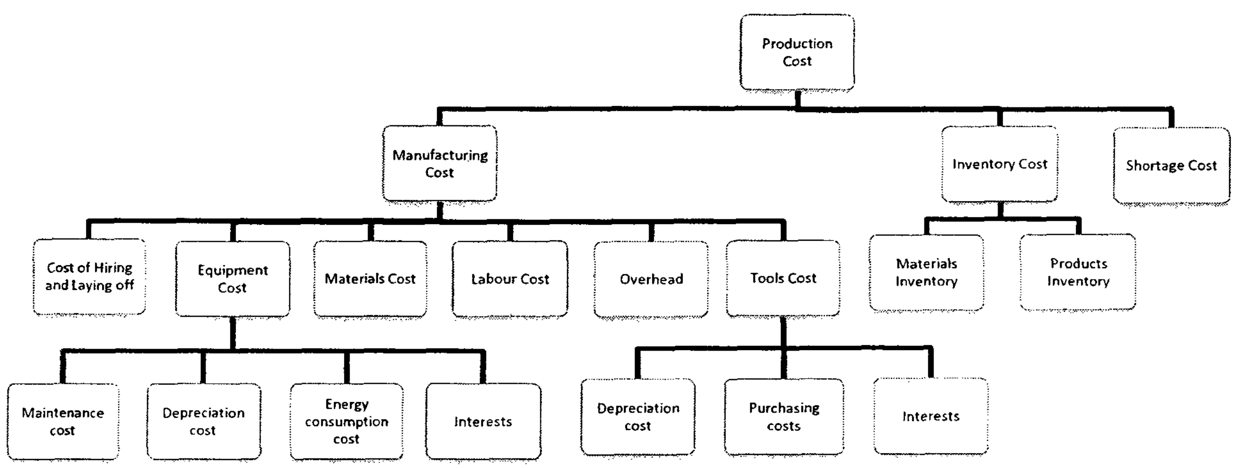

Figure 4.2. Costs Breakdown in Aggregate Production Planning

4.3.1 Model Assumptions

The following assumptions are used in formulating the production planning model for the considered composite manufacturing process.

1. Customer demand can be different for different time periods.
2. Customers can only place one order at the beginning of each period.
3. The ordered products are delivered at the end of each period.
4. The manufacturer can place more than one order of materials in each period.
5. The ordered raw materials will be received with delay.
6. Late delivery of products is not allowed.
7. The manufacturer has one autoclave and one vacuum pump already.
8. The number of molds and sets of rubber molds need to be decided.
9. Operators may be hired or laid off by units of groups at the beginning of each period.

4.3.2 Deterministic Model Formulation

In addition to the cost components discussed in the previous sections , the aggregate production planning model also includes the cost of hiring and laying off operators, products inventory cost, products shortage cost, regular time and overtime labor cost are introduced.

Cost of Hiring and Laying off

Equation 4.11 gives the cost of hiring or laying off operators in different periods

$$CHL = \sum_{l \in L}(NH_l \times CH + NL_l \times CL) \qquad (4.11)$$

Labor Cost

In the aggregate production planning, labor cost is the total cost of all labor related activities in the production. Since the overtime is allowed, the number of finished products can be divided into the number of overtime products and the number of regular-time products. Hence, we calculate the total labor cost using equation (4.12). It is the sum of the regular-time labor cost and overtime labor cost.

$$CL = \sum_{l\in L}\sum_{o\in O}(CLR \times NW_l \times TW + CLO \times QO_l \times TS_o) \tag{4.12}$$

Products Inventory Cost

$$CIP = \sum_{l\in L} I_l \times CI \tag{4.13}$$

The product inventory cost is the cost associated with the storage of products in the warehouse for each period. It equals to the number of products in inventory at the end of each period multiplying by the unit inventory cost.

Products Shortage Cost

$$CIB = \sum_{l\in L} B_l \times CB \tag{4.14}$$

The product shortage cost is the penalty cost associated with under-fulfillment of customer demand. It equals to the under-fulfillment of product multiply the unit shortage cost.

In summary, the objective function of production cost is formulated as follows:

Objective Function

$$Min = (1 + Fo) \times \{\sum_{l\in L}\sum_{i\in I} D_l \times RM_i \times PM_i(1 + FSM_i)$$

$$+ \sum_{l\in L}\sum_{o\in O}(CLR \times NW_l \times TW + CLO \times QO_l \times TS_o)$$

$$+\sum_{l\in L}(NH_l \times CH + NL_l \times CL)$$

$$+\sum_{l\in L}\sum_{j\in J}[\frac{(PE_j - SE_j)}{NE_j} + IR_j \times PE_j + FM_j \times PE_j$$

$$+\frac{D_l \times TPA \times CRA}{N} + D_l \times TPP \times CRP$$

$$+\sum_{k\in K}[\frac{(PT_k - ST_k)}{NT_k} + N \times IR_k \times PT_k + N \times PT_k]$$

$$+\sum_{l\in L}\sum_{i\in I}[AM_i \times D_l \times RM_i(1 + FSM_i) \times Y_{il}$$

$$+HM_i \times \ QM_{il}/2] \ + \ \sum_{l\in L}(I_l \times CI) + \sum_{l\in L} B_l \times CB\} \tag{4.15}$$

The objective function is to be minimized subject to the following constraints functions.

Constraints

$$NW_l = NW_{l-1} + NH_l - NL_l \qquad \forall l \in L \tag{4.16}$$

$$\sum_{o\in O} TS_o \times QR_l \le NW_l \times TW \qquad \forall l \in L \tag{4.17}$$

$$\sum_{o\in O} TS_o \times QO_l \le FOW \times NW_l \times TW \qquad \forall l \in L \tag{4.18}$$

$$TPA \times QR_l \le N \times TEA \qquad \forall l \in L \tag{4.19}$$

$$TPA \times QO_l \le FOA \times N \times TEA \qquad \forall l \in L \tag{4.20}$$

$$I_{l-1} + QR_l + QO_l - I_l = D_l - B_l \qquad \forall l \in L \tag{4.21}$$

$$QU_i \times \sum_{n\in N} 2^{2n-1} \times w_{iln} = 1 \qquad \forall i \in I, l \in L \tag{4.22}$$

$$QM_{il} = QU_i \times \sum_{n\in N} 2^{2n-1} \times x_{iln} \qquad \forall i \in I, l \in L \tag{4.23}$$

$$(x_{iln} - 1) \times M + Y_{il} \le w_{iln} \le Y_{il} \qquad \forall i \in I, l \in L, n \in N \tag{4.24}$$

$$0 \le w_{iln} \le x_{iln} \qquad \forall i \in I, l \in L, n \in N \tag{4.25}$$

$$N = \sum_{n\in N} 2^{2n-1} \times z_n \qquad \forall j \in J \tag{4.26}$$

$$\sum_{n\in N} 2^{2n-1} \times v_n = 1 \qquad \forall j \in J \tag{4.27}$$

$$(z_n - 1) \times M + U \le v_n \le U \qquad \forall j \in J, n \in N \tag{4.28}$$

$0 \le v_n \le z_n$ $\forall j \in J, n \in N$ (4.29)

$NH_l, NL_l, NW_l, QO_l, QR_l, I_l \in R_0^+$ $\forall\, l \in L$ (4.30)

$x_{iln}, z_n, w_{iln}, v_n \in \{0,1\}$ $\forall i \in I, j \in J, n \in N$ (4.31)

Constraint (4.16) ensures that the labor force level in any period equals to the previous period labor force level plus or minus the change of labor force caused by hiring or laying off operators. Constraint (4.17) defines the regular time working hours. Constraint (4.18) defines the overtime working hours limit. Constraints (4.19) and (4.20) show that regular time and overtime production are also subject to the capacity of autoclave. Constraint (4.21) ensures that the total production of regular-time and overtime plus the inventory at the end of the previous period is equal to the demand plus the inventory level and minus the under-fulfillment. Constraints (4.22)~(4.25) are the constraints used to decide the order quantity of materials and linearize the mathematical terms of material inventory cost (Chang, 2006). The mathematical terms of equipment energy consumption cost is linearized by constraint (4.26)~(4.29) (Chang, 2006). Constraints (4.30) and (4.31) determine the domain of the variables.

4.3.3 Stochastic Programming Formulation

The deterministic approach is widely used in optimization of production planning. However, the real word problems always contain uncertainties. For instance, in the production planning system, parameters are usually uncertain and changeable such as customer demand, it is impossible to estimate it exactly in advance and it changes depending on the economic environments. So uncertainty factors should be considered if we attempt to obtain more accurate production plan.

For this purpose, stochastic programming approach is used in this research to address the uncertainties involved in composites manufacturing. When parameters are not certain, we usually assume those parameters fit in some given set of possible values with associated probabilities or probability distributions in the stochastic programming approach. As mentioned earlier in this thesis, we used the two stage linear programming to solve the stochastic programming problem. In the two-stage linear programming model of this research, customer demands and purchasing prices of raw materials are assumed to be at different levels with associated probabilities under different economic growth scenarios: "Good", "Normal" or "Down". We assume that future economic situation can be placed in one of these economic growth scenarios with the assumed probabilities.

At the first stage of the two-stage programming modeling, decisions on production quantity, workforce level, and materials ordering quantity are made without considering different economic growth scenarios. Economic growth scenarios are brought into this model at the second stage to address the risk factors of the first stage decisions, and the second stage decisions are then decided (Leung *et al*, 2006).

Objective Function at the First Stage

$$Min = (1 + FO) \times \{\sum_{l \in L} \sum_{o \in O} (CLR \times NW_l \times TW + CLO \times QO_l \times TS_o)$$

$$+ \sum_{l \in L} (NH_l \times CH + NL_l \times CL)\} \tag{4.32}$$

The components of the objective function at the first stage are the labor costs, hiring and laying off cost and overhead cost. The first stage decision variables are production quantity, workforce level, and raw material ordering quantities.

Objective Function at the Second Stage

$$Min = \sum_{s \in S} P^S \times \{\sum_{l \in L} \sum_{i \in I} D_l^s \times RM_i \times PM_i^s \times (1 + FSM_i)$$

$$+ \sum_{l \in L} \sum_{j \in J} [\frac{(PE_j - SE_j)}{NE_j} + IE_j \times PE_j + FM_j \times PE_j \times CRP$$

$$+ \frac{D_l^s \times TPA \times CRA}{N} + D_l \times TPP]$$

$$+ \sum_{k \in K} [\frac{(PT_k - ST_k) \times N}{NT_k} + N \times PT_k + N \times IT_k \times PT_k]$$

$$+ \sum_{l \in L} \sum_{i \in I} [AM_i \times D_l^s \times RM_i (1 + FSM_i) \times Y_{il}$$

$$+ HM_i \times QM_{il}/2]$$

$$+ \sum_{l \in L} I_l^s \times CI + \sum_{l \in L} B_l{}^s \times CB\}(1 + FO) \qquad (4.33)$$

We index the second stage bdecision variables by the index of economic growth scenarios $S = \{Good, Normal, Down\}$, with associated probabilities P^s. The costs of raw materials, equipment, tools, inventory of materials and products, shortage of products, and overhead associated with these scenarios are taken into account at the second stage. The objective function can be obtained by multiplying the costs and the associated probabilities P^S in equation (4.33). In this model, the second stage decision variable is inventory level of products I_l^s, and the under-fulfillment of products B_l^s. The inventory level and under-fulfillment of products depends on the customer demands and production quantity. Production quantity can be determined at the first stage, but customer demands are different under different economic growth scenarios. Hence, the inventory level and under-fulfillment of products are second-stage decision variables.

Constraints

Constraints at the first stage are the same as the constraints in the deterministic model discussed in the previous section. But at the second stage, constraint (4.34) is applied to replace constraint (4.21) in the deterministic model. Recourse parameters CI^s, and D_l^s, and second stage decision variables I_l^s are used

$$I_{l-1}^s + QR_l + QO_l - I_l^s = D_l^s - B_l^s \qquad \forall l \in L, s \in S \qquad (4.34)$$

Chapter Five

Numerical Examples and Analysis

In this chapter, a numerical example is presented to validate and illustrate the mathematical models developed in the previous chapter. The numerical example used in this chapter is hypothetical with realistic assumptions. We present the production cost model and aggregate production planning models to solve this problem. We also perform sensitivity analysis on the outputs of them. The problem is solved by LINGO optimization software, version 10, on a PC platform with 2.53GHZ and 4.0 GB RAM.

5.1 Problem Description

The upper skin of a wing box is a typical aerospace structure and it is more often manufactured by composite materials in aerospace industry. In this problem, we assume that an aggregate production planning is required for a manufacturer of the upper skins in the coming 12 months.

Figure 5.1 shows the configuration of a wing box. The upper and lower skins are manufactured using autoclave modeling process. The ribs are manufactured using Resin Transfer Molding (RTM) process. Bonding is required to bond the ribs and skins. The configuration of the upper skin of the wing box is shown in Figure 5.2. The dimensions of the upper skin are 6 × 12 feet, and it has three ribs and five stringers, which can be produced using rubber molds.

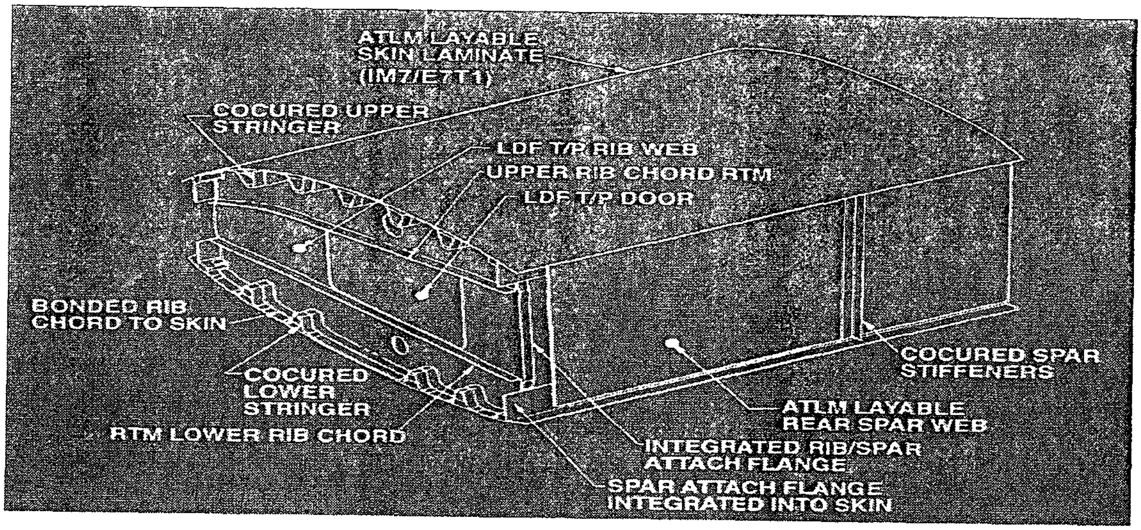

Figure 5.1. Configuration of an Aircraft Wing Box

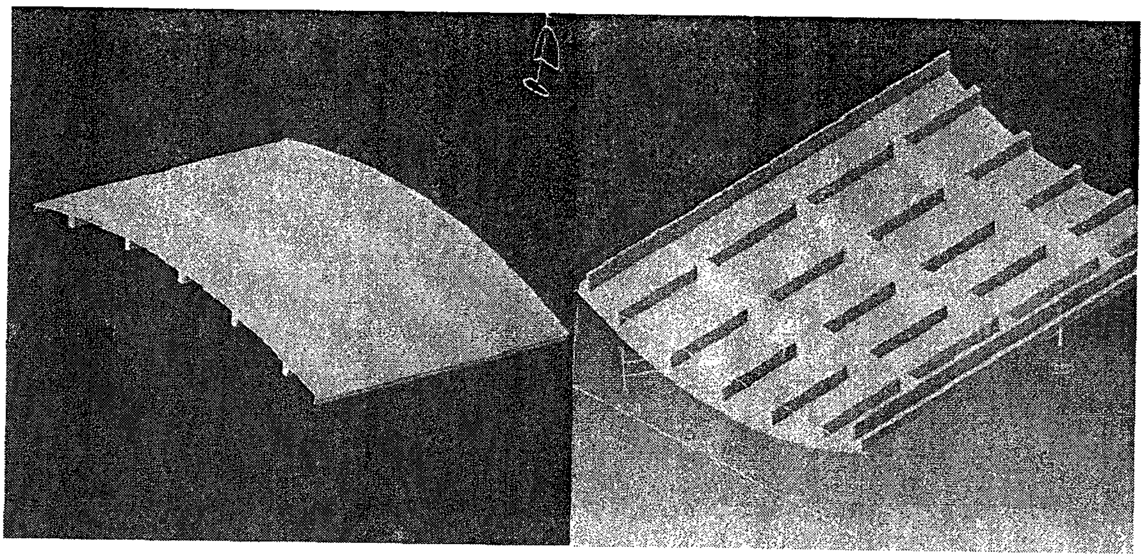

Figure 5.2. Configuration of the Upper Skin of an Aircraft Wing Box

5.2 Numerical Example of Production Cost Analysis

The production steps of manufacturing the upper skins with associated operating time of operators and processing of equipments are summarized in Table 5.1. Amount consumed for one product, unit purchasing price, scrap factor, and purchasing cost of each type of material for one product are shown in Table 5.2.

The production cost can be estimated by applying equation (4.10) with the expected value of the input parameters. It is essential for manufacturers to identify which variables are most influential and sensitive to change the production (Berthelot *et al*, 1996). For this purpose, a sensitivity analysis is performed using the software Microsoft Excel in this study.

Table 5.1. Manufacture Process of the Upper Skin

Production Step	**Processing Time by 2 operators TS_0 (hours)**	**Process Time on Equipment(s) TPE_j (hour)**
Preparation of the mold surface	1	N/A
Laying up 5 layers of Prepregs	0.5	N/A
Debulking	0.5	0.33(vacuum pump)
Placement of rubber molds	0.33	N/A
Laying up 5 layers of prepregs	0.5	N/A
Debulking	0.5	0. 33(vacuum pump)
Laying up 5 layers of prepregs	0.5	N/A
Debulking	0.5	0.33(vacuum pump)
Laying up 5 layers of prepregs	0.5	N/A
Debulking	0.5	0.33 (vacuum pump)
Placement of bleeder materials	0.167	N/A
Placement of breather materials	0.167	N/A
Placement of vacuum bag	0.5	N/A
Moving to autoclave machine	0.33	N/A
Setting up the autoclave	0.2	2(autoclave)
Curing in the autoclave	0.8	8(autoclave)
Removal of the part	0.5	N/A
Inspection	0.5	N/A
Trimming	1	N/A
Moving to Storage	0.33	N/A

Table 5.2. Bill of Materials

Material	Amount	Unit Price	Scrap Factor	Purchasing Cost ($)
Prepregs	49.1 pound	60 $/pound	0.02	3745
Release Agent	0.7065 L	23.38$/ L	0.03	1701
Mold Cleaning Fluid	0.7065 L	4$/ L	0.014	286
Release Film	14.1312 m²	5.036 $/m²	0.021	7265
Breather Material	14.1312 m²	4.7 $/m²	0.015	6741
Bleeder Material	7.0656 m²	5.2 $/m²	0.012	3718
Vacuum Bag	14.1312 m²	1.96 $/m²	0.02	2825
Sealant Tape	44.8 m²	0.671 $/m²	0.009	3033

Table 5.3. Production Cost Analysis Input

Production cost variables	Units	Low	Average	High
Annual Customer Demand	Piece	50	100	150
Overhead factor FO	N/A	0.25	0.5	0.75
Purchasing cost of prepregs per product	$/piece	1872.72	3745.44	5618.16
Purchasing cost of release agent per product	$/piece	8.50	17.011	25.52
Purchasing cost of cleaning fluid per product	$/piece	1.43	2.86	4.29
Purchasing cost of release film per product	$/piece	36.32	72.65	108.98
Purchasing cost of breather per product	$/piece	33.70	67.41	101.11
Purchasing cost of bleeder per product	$/piece	18.59	37.18	55.77
Purchasing cost of Vacuum bag	$/piece	14.12	28.25	42.37
Purchasing cost of Sealant tape	$/piece	15.16	30.33	45.49
Wage of one group of operator	$/piece	18	36	54
Total operating time of one product	Hour	4.91	9.82	14.73
Purchasing price of autoclave	$	500000	1,000,000	1500000
Purchasing price of vacuum pump	$	1000	2000	3000
Salvage of autoclave	$	50000	100,000	150000
Salvage of vacuum pump	$	100	200	300
Lifetime of autoclave	Year	15	30	45
Lifetime of vacuum pump	Year	5	10	15
Interest rate of autoclave	$/year	0.025	0.05	0.075

Table 5.3. Production Cost Analysis Input (Continued)

Interest rate of vacuum pump	$/year	0.025	0.05	0.075
Maintenance factor of autoclave	N/A	0.004	0.008	0.012
Maintenance factor of vacuum pump	N/A	0.0075	0.015	0.0225
Processing time of autoclave	Hour	4	8	12
Processing time of vacuum pump	Hour	0.66	1.32	1.98
Cost of energy consumption of autoclave	$/hour	2	4	6
Cost of energy consumption of vacuum pump	$/hour	0.5	1	1.5
Purchasing price of molds	$	50000	100,000	150000
Purchasing price of rubber molds	$	5000	10,000	15000
Salvage of mold	$	5000	10,000	15000
Salvage of rubber molds	$	500	1,000	1500
Lifetime of modle	Year	10	20	30
Lifetime of frubber molds	Year	10	20	30
Interest rate of modle	N/A	0.005	0.01	0.015
Interest rate of rubber molds	N/A	0.005	0.01	0.015
Ordering cost of prepreg	$	142.5	285	427.5
Ordering cost of release agent	$	85	170	255
Ordering cost of mold cleaning fluid	$	65	130	195
Ordering cost of release film	$	95	190	285
Ordering cost of breather Material	$	55	110	165
Ordering cost of bleeder materials	$	80	160	240
Ordering cost of vacuum bag	$	37.5	75	112.5
Ordering cost of sealant tape	N/A	40	80	120
Holding cost of prepregs	$/pond/year	1.85	3.7	5.55
Holding cost of release agent	$/L/year	0.58	1.16	1.74
Holding cost of mold cleaning fluid	$/L/year	0.6	1.2	1.8
Holding cost of release film	$/ m²/year	0.7	1.4	2.1
Holding cost of breather materials	$/ m²/year	0.8	1.6	2.4
Holding cost of bleeder materials	$/ m²/year	0.85	1.7	2.55
Holding cost of vacuum bag	$/ m²/year	0.35	0.7	1.05
Holding cost of sealant tape	$/m/year	0.1	0.2	0.3

The production cost model is firstly formulated in Microsoft Excel. Different parameter values are then inputted into the production cost model, so different values of production cost output can be obtained. Table 5.3 summarizes the ranges of values of production cost parameters used in equation (4.10). Figure 5.3 shows the schematic of the sensitivity analysis output of the production cost model. Take the annual customer demand for example, we input the values 51, 52,...,150 to the model, and the corresponding output of

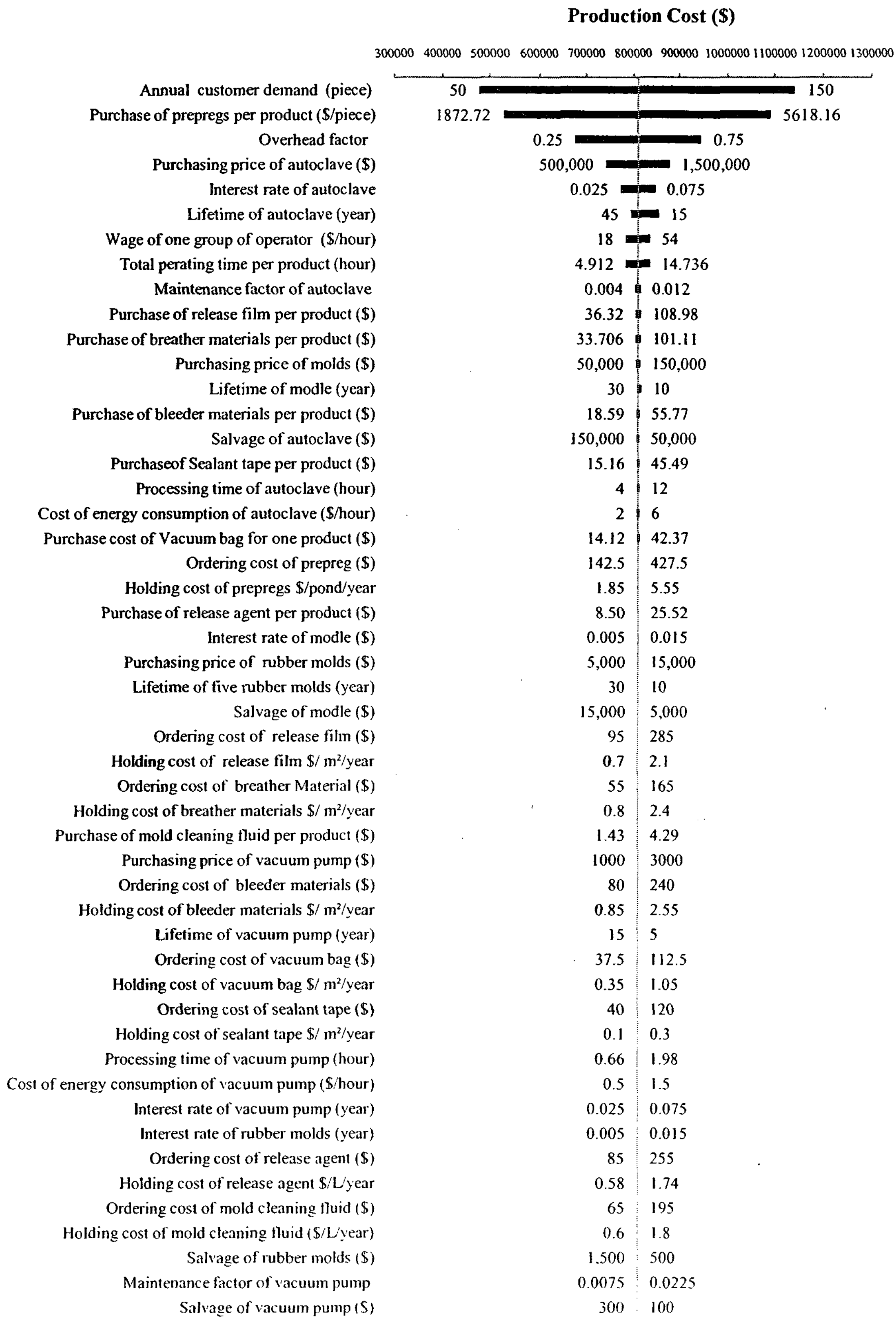

Figure 5.3. Production Cost Sensitivity Analysis Output

production costs are $484653, $491307,..., $1141597, respectively. The results of the sensitivity analysis indicate that the uncertainties in estimating the annual customer demand and purchasing price of prepregs have the greatest effects on the output of production cost. So considerable attentions should be paid to these variables.

5.3 Numerical Example of Aggregate Production Planning

The upper skin of the wing box used for the production cost analysis model is also considered to illustrate aggregate production planning model.

5.3.1 Problem data

Based on the different economic scenarios, period customer demands in different growth scenarios D_l^s are shown in Table 5.4. Equipment cost and tool cost data are shown in Table 5.5 and Table 5.6. Labor, hiring and laying off cost data are shown in Table 5.7. Unit purchasing prices of raw materials PM_i^s are shown in Table 5.8. Data used for inventory cost of materials are summarized in Table 5.9. The other data used in this model are: the overhead factor $Fo = 0.5$, the products unit inventory cost CI = $300, and the products unit shortage cost CB = $20000.

Table 5.4. Customer Demands

Scenario s	**Probabilities** P^s	**Period Demand** D_l			
		1	**2**	**3**	**4**
Good	0.2	50	80	100	80
Normal	0.6	40	70	80	60
Down	0.2	30	50	60	40

Table 5.5. Equipment Cost Data

Equipment j	Processing Time TPE_j (hours)	Lifetime NE_j (years)	Purchase PE_j ($)	Salvage SE_j ($)	Energy Cost CRE_j ($/hour)	Maintenance Factor FM_j	Interest IRE_j
Autoclave	10	20	1,000,000	100,000	10	0.011	0.06
Pump	1.32	10	2,000	200	5	0.05	0.06

Table 5.6. Tool Cost Data

Tools k	Lifetime NT_k (year)	Purchase PT_k ($)	Salvage ST_k ($)	Interest IRT_k
Mold	10	100,000	10,000	0.01
Rubber Molds	5	10,000	1,000	0.02

Table 5.7. Labor Cost and Hiring and Laying off Cost Data

Regular Time Hours TW (h)	Regular Time Wage CLR ($)	Overtime Wage CLO ($)	Hiring Cost CH($)	Laying off Cost CL ($)
420	30	45	500	4000

Table 5.8. Material Cost Data

Material i	Unit Purchasing Price PM_i^s		
	Scenario s		
	Good	Normal	Down
Prepregs	100$/pound	60$/pound	50$/pound
Release Agent	36.38$/L	33.38$/L	30.38$/L

Table 5.8. Material Cost Data (Continued)

Mold cleaning Fluid	6$/L	4$/L	2$/L
Release Film	7.2$/ m²	5.036$/ m²	3.2$/ m²
Breather Material	5.5$/ m²	4.7$/ m²	3.5$/ m²
Bleeder Materials	7.2$/ m²	5.2$/ m²	3.2$/ m²
Vacuum Bag	3.3$/ m²	1.96$/ m²	1.5$/ m²
Sealant Tape	0.9$/m	0.671$/m	0.3$/m

Table 5.9. Material Inventory Cost Data

Material	**Ordering Cost** AM_i(\$)	**Holding Cost** HM_i	**Order Units** QU_i
Prepregs	285	3.7$/pond/period	100 pound
Release Agent	170	1.16 $/L/period	10 L
Mold cleaning Fluid	130	1.2$/L/period	10 L
Release Film	190	1.4$/ m²/period	50 m²
Breather Material	110	1.6$/ m²/period	50 m²
Bleeder Materials	160	1.7$/ m²/period	10 m²
Vacuum Bag	75	0.7$/ m²/period	50 m²
Sealant Tape	80	0.2$/m/period	50 m²

5.3.2 Solution of Deterministic Model

The example problem is solved using optimization software LINGO and the code is shown in Appendix A. We run the deterministic model three times based on the data of economic growth scenario "Good", "Normal", and "Down". Tables 5.10~5.12 show the optimized production plans in economic growth scenario "Good", "Normal", and "Down". For instance, we can see that the majority of products are produced by regular time production from Table 5.10. Only 2, 6, and 6 products are produced by overtime production in periods 1, 2, and 3, respectively. One group of operators is hired in period 1, and another group is hired in period 2. The number of groups remains at 2 in periods 3 and 4.

We also show the cost breakdowns of the optimized production plan in "Normal", and "Down" economic growth scenarios in Tables 5.13. Taking the costs breakdown of "Normal" economic growth scenario as an illustrate example, we can note that the total production cost is $2,642,203. The major expenses are material cost and overhead cost, which are $1,250,680 and $ 880,734, respectively.

Table 5.10. Optimized Production Plan in "Good" Economic Scenario

Period l	**Regular Time Production Quantity QR_l**	**Over Time Production Quantity Qo_l**	**Number of Groups Hired NH_l**	**Number of Groups Laid off NL_l**	**Number of Groups**	**Products Inventory I_l**
Period 1	48	2	1	0	1	0
Period 2	84	6	1	0	2	8
Period 3	84	6	0	0	2	0
Period 4	80	0	0	0	2	0

Table 5.11. Optimized Production Plan in "Normal" Economic Scenario

Period l	**Regular Time Production Quantity QR_l**	**Over Time Production Quantity Qo_l**	**Number of Groups Hired NH_l**	**Number of Groups Laid off NL_l**	**Number of Groups**	**Products Inventory I_l**
Period 1	40	0	1	0	1	0
Period 2	74	0	1	0	2	4
Period 3	84	0	0	0	2	8
Period 4	48	4	0	1	1	0

Table 5.12. Optimized Production Plan in "Down" Economic Scenario

Period l	**Regular Time Production Quantity QR_l**	**Over Time Production Quantity Qo_l**	**Number of Groups Hired NH_l**	**Number of Groups Laid off NL_l**	**Number of Groups Required**	**Products Inventory I_l**
Period 1	42	4	1	0	1	16
Period 2	42	4	0	0	1	12
Period 3	42	4	0	0	1	0
Period 4	40	0	0	0	1	0

Table 5.13. Costs Breakdowns in Different Economic Scenarios

Cost	**Economic Growth Scenario**		
	Good	**Normal**	**Down**
Material ($)	1,250,680	679,278	400,153
Labor ($)	94,290	77,340	55,620
Hiring and Laying Off ($)	1,000	5,000	500
Equipment ($)	136,492	129,700	139,776

Table 5.13. Costs Breakdowns in Different Economic Scenarios (Continued)

Tool ($)	254,800	254,800	127,400
Materials Inventory ($)	21,807	19,577	16,612
Shortage ($)	0	0	40,000
Products Inventory ($)	2,400	3,600	8,400
Overhead ($)	880,734	584,647	394,230
Total ($)	2,642,203	1753,943	1,182,693

5.3.3 Solution of Stochastic Model

We also solved the problem using the stochastic programming model and the code of LINGO is shown in Appendix B. The production plan based on the stochastic model and costs breakdown are shown in Table 5.14 and Table 5.15.

Table 5.14. Optimized Production Plan Based on the Stochastic Model

Period l	**Regular Time Production Quantity QR_l**	**Over Time Production Quantity Qo_l**	**Number of Groups Hired NH_l**	**Number of Groups Laid off NL_l**	**Number of Groups Required**
Period 1	48	2	1	0	1
Period 2	84	4	1	0	2
Period 3	84	8	0	0	2
Period 4	80	0	0	0	2

Table 5.15. Costs Breakdown Based on the Stochastic Model

Material ($)	737,733
Labor ($)	94,290
Hiring and Laying Off ($)	1,000
Equipment ($)	129,473
Tool ($)	254,800
Material Inventory ($)	19,502
Shortage ($)	0
Products Inventory ($)	23,000
Overhead ($)	629,900
Total ($)	1,889,700

5.3.4 Solution Analysis

As presented in section 5.3.2, the optimal production costs based on "Good", "Normal", and "Down" economic growth scenarios are $2,642,203, $1,753,943, and $1,182,693, respectively. So we can obtain the expected optimal production cost:

$$\$2{,}642{,}203 \times 0.2 + \$1{,}753{,}943 \times 0.6 + \$1{,}182{,}693 \times 0.2 = \$1{,}817{,}345$$

The expected optimal production cost can be obtained if we can have the prior information. But as we know, several uncertainties are involved in composites manufacturing such as customer demands and raw materials prices. The stochastic model is used to balance or hedge against the uncertainties and at the same time it has impacts on the expected optimal production cost. The difference between the expected optimal production cost $1,817,345 and the optimal production cost obtained from the stochastic model $1,889,700 is $72355. It is called the expected value of perfect information (EVPI). The EVPI measures the maximum amount a decision maker would be ready to pay in return for complete and accurate information about the future (Birge, 1997). In this problem, we can see that the difference $ 72355 is the cost that the manufacturer should be ready to pay each year due to the uncertainties of customer demand and raw material purchasing cost.

5.3.5 Sensitivity Analysis Based on Stochastic Model

Sensitivity analysis of production cost for different probability distribution of economic scenarios is presented in this section. Three assumptions of analysis are shown in Table 5.16. In assumption 1, "Down" economic growth scenario is considered more likely to happen than other two economic growth scenarios. In assumption 2, "Normal" economical growth scenario is considered most likely to happen. And in assumption 3, "Good" economic growth scenario is considered far more likely to happen than others.

Table 5.16. Probability Assumptions in Different Economic Growth Scenarios

Assumption	Good	Normal	Down
1	0.1	0.1	0.8
2	0.1	0.8	0.1
3	0.8	0.1	0.1

The cost breakdowns of the optimized production plans obtained from the three assumed situations are given in Table 5.17. As in assumption 1, when the highest probability is associated with the smallest customer demand, all the costs except the products inventory cost are smaller than those in the other assumptions. In contrast, the smallest products inventory cost is observed when the highest probability is associated with the highest customer demand in assumption 3. This means the higher customer demand is expected in the assumption, the more operators, overtime production are needed to avoid products inventory.

Table 5.17. Sensitivity Analysis for Different Probability Distributions of Scenarios

Cost	**Assumption**		
	1	**2**	**3**
Material ($)	513,118	708,505	110,8487
Labor ($)	94,290	98,290	101,725
Hiring and Laying Off ($)	1,000	2,000	5,000
Equipment ($)	124,040	129,586	134,341
Tool ($)	254,800	254,800	254,800
Materials Inventory ($)	17,526	19,540	21,155
Shortage ($)	0	0	20,000
Products Inventory ($)	26,840	7,660	5,800
Overhead ($)	515,807	607,691	810,154
Total ($)	1,547,423	1,828,074	2,463,570

It can also be seen that more raw materials, labor hours, processing time of equipments and tools, materials inventory, and overhead are needed, when the customer demand is higher. The tool costs are the same in these three assumptions. It means the manufacturer doesn't need to buy more molds and sets of rubber molds in this type of production scale. Moreover, the shortage cost occurs only when the customer demand is very high in this problem.

5.4 Summary

A numerical example problem is presented based on the hypothetical data. Sensitivity analysis is conducted on the production cost model. It shows the impact of different parameters on the production cost. Aggregate production planning approach is used in this numerical example when the customer demand is high. Both the deterministic and stochastic models are used to obtain the optimal production plans. The comparison of their solutions shows that the penalty cost occurs because of the uncertainties. Sensitivity analysis is also conducted on the stochastic model. The results show that with higher customer demand, all component costs of product cost except product inventory cost increase.

Chapter Six

Conclusions and Future Research

In this chapter we present a summary of the research carried out in this thesis. It also includes several concluding remarks based on the problem modeling. Future research directions in this area are also discussed.

6.1 Conclusion

In this study, we proposed a production cost model to analyze the costs of composites manufacturing based on the autoclave modeling technique. The components of the total production cost were identified and analyzed using the production cost model. The production of upper skins of an aircraft wing box was used as an illustrate example in this study. A sensitivity analysis was also performed on the results of production cost model. The variables that have the greatest effects on the production cost were then identified.

In addition, an aggregate production planning model was used for large scale production of composites manufacturing. More cost factors such as hiring and laying off, and in product inventory costs were considered in the production planning model. A stochastic programming model was used to address the uncertainties of demands and raw material prices in the production process. We used the production of upper skins of the wing box as an illustrate example. Optimal production plans were obtained by using the deterministic and stochastic models developed in this research. Sensitivity analysis was also performed on the stochastic model and it shows that if the higher probability is associated with the higher customer demand, the manufacturer needs to increase the cost of hiring operators and overtime production to avoid products inventory.

Both the production cost and aggregate production planning model developed in this study can be easily modified for cost analysis on similar products manufactured by composite materials in aerospace or other industries.

6.2 Remarks

This research can be conducted as an extension and combination of the research in Bernet *et al* (2000) and the one in Leung *et al* (2006). Comparing to the cost estimation model of composite manufacturing presented by Bernet *et al* (2000), the model we developed in this research is more practical with the detailed analysis of cost breakdowns of each production process. Additional uncertainty factors were considered in our research compared with stochastic model in Leung *et al* (2006), and the models developed in this research are more reasonable and practical for composite manufacturing.

6.3 Future Research

The research presented in this thesis can also be extended in several aspects. Our suggestions for the future research in this field are:

- Considering more uncertainties involved in composites manufacturing in the model.
- Incorporating cost analysis at the product design stage to the production cost model.
- Considering other composites manufacturing techniques in addiction to autoclave molding.

- Developing cost analysis model which can be used for manufacturing different composite structures at the same time.

REFERENCES

1. Bernet, N, Wakema, M.D, Bourban, P.E., and Manson, J., 2002. "An Integrated Cost and Consolidation Model for Commmingled Yarn Based on Composites," Journal of Composites, **33**, 495-506.
2. Berthelot, C. F., Sparks, G. A., Blomme, T., Kajner, L., and Nickeson. M., 1996. "Mechanistic-Probabilistic Vehicle Operating Cost Model," Journal of Transportation, **122**, 337-341.
3. Birge, J., and Louveaux, F., 1997. Introduction to Stochastic Programming: Springer Series in Operations Research, Springer-Verlag, New York, NY.
4. Chang, C.T., 2006. "An Acquisition Policy for A Single Item Multi-supplier System with Real-World Constraints," Applied Mathematical Modelling, **20**, 1-9.
5. Chibesakunda, E., 2000. "Parametric Cost Model for Deburring Processes," Laboratory for Manufacturing Automation, CRC Press.
6. Eklin, M., Arzi, Y., and Shtub, A., 2007. "Model for Cost Estimation in A Finite-Capacity Stochastic Environment Cased on Shop Floor Optimization Combined with Simulation," European Journal of Operational Research, **194**, 294-306.
7. Gaither, N., 1986. Production and Operations Management: A problem-Solving and Decision-Making Approach, The Dryden Press.
8. Gay, D., Hoa, S.V., and Tsai, S.W., 2003. Composite Materials Design and Applications, CRC Press.
9. Gutowski, T., Hoult, D., Dillon, G., Neoh, E., Muter, S., Kim, E., and Tse, M., 1994. "Development of A Theoretical Cost Model for Advanced Composites Fabrication," Composites Manufacturing, **5**, 231-239.

10. Günter, H.O. 1982. "A Comparison of Two Classes of Aggregate Production Planning Models under Stochastic Demand," Second International Working Seminar on Production Economics, Innsbruck, February, 16–20.

11. Hsieh, S., and Wu, M.S., 2000. "Demand and Cost Forecast Error Sensitivity Analyses in Aggregate Production Planning by Possibilistic Linear Programming Models," Journal of Intelligent Manufacturing, **11**, 355-364.

12. Hoa, S.V., 2009. Principles of the Manufacturing of Composite Materials, Destech Publications.

13. Jha, N.K., 1996. "Probabilistic Cost Estimation in Advance of Production in A Computerized Manufacturing System through Stochastic Geometric Programming," Computer and Industry Engineering, **30**, 809-821.

14. Kassapoglou, C., 1999. "Minimum Cost and Weight Design of Fuselage Frames Part B: Cost Considerations, Optimization, and Results," Composites, **30**, 895-904.

15. Kaufmann, M., Zenker, D., and Mattei, C., 2008. "Cost Optimization of Composite Aircraft Structures Including Variable Laminate Qualities," Composites Science and Technology, **68**, 2748-2754.

16. Leung, S., Wu, Y., and Lai, K.K., 2006. "A Stochastic Programming Approach for Multi-site Aggregate Production Planning," Journal of the Operational Research Society, **57**, 123-132.

17. Li, H., Foschi, R., Vaziri, R., and Fernlund, G., 2002. "A Probability Based Modeling of Composites Manufacturing and Its Application to Optimal Process Design," Journal of Composite Materials, **36**, 1967.

18. Mazumdar, S.K., 2002. Composites Manufacturing: Materials, Product and Process Engineering, CRC Press.

19. Moghaddam, T., Rabbani, R., Gharehgozli, M., and Zaerpour, A.H., 2007. "A Fuzzy Aggregate Production Planning Model for Make-to-Stock Environments. Industrial Engineering and Engineering Management," Proceedings of IEEE International Conference, 1609-1613.

20. Nam, S.J., and Logendran, R., 1992. "Aggregate Production Planning– A Survey of Models and Methodologies," European Journal of Operation Research, **61**, 255-272.

21. Niazi, A., and Dai, S., 2006. "Product cost estimation: Technique classification and Methodology Review," Journal of Manufacturing Science and Engineering, **128**, 563–575.

22. Northrop Corporation., 1976. Advanced Composite Cost Estimating Manual (ACCEM), AFFDL-TR-76-87.

23. Osteryoung, J.S., Eldon, N., MacCarty, D.E., and Reinhart, W.J., 1986. "Use of the EOQ Model for Inventory Analysis," Production and Inventory Management, **27**, 39 – 46.

24. Park, C.S., and Kim, G.T., 1995. "An Economic Evaluation Model for Advanced Manufacturing Systems Using Activity-Based Costing," International Journal of Manufacturing Systems, **14**, 439–451.

25. Shahi, H.J., Shayan, E., and Masood, S., 1999. "Cost estimation in flat plate processing using fuzzy sets," Computers & Industrial Engineering, **37**, 485-488.

26. Shehab, E., and Abdalla, H., 2002. "An Intelligent Knowledge-Based System for Product Cost Modelling," The International Journal of Advanced Manufacturing Technology, **19**, 49-65.

27. Wang, K., Kelly, D., and Dutton, S., 2002. "Multi-Objective Optimisation of Composite Aerospace Structures," Composite Structures, **57**, 141-148.

28. Wang, R.C., and Fang H.H., 1999. "Aggregate Production Planning with Multiple Objectives in A Fuzzy Environment," European Journal of Operational Research, **133**, 521-536.

29. Young, K.S., 1991. "A Cost Estimation Model for Advanced Manufacturing Systems," International Journal of Production Research, **29**, 441 – 452.

30. Ye, J., Zhang, B., and Qi, H., 2009. "Cost Estimates to Guide Manufacturing of Composite Waved Beam," Materials & Design, **30**, 452-458.

31. Yamashina, H., 2002. "Manufacturing cost deployment", International Journal of Production Research, **40**, 4077-4091.

32. Zaloom, V., and Miller, C., 1982. "A review of Cost Estimating for Advanced Composite Materials Applications," Engineering Costs and Production Economics, **7**, 81-86.

33. Zhao, Y., Lu, L., and Fang, S., 2006. "Stochastic Linear Optimization for Modeling Uncertainty in Aggregate Production Planning," Proceedings of the International Conference on Autonomic and Autonomous Systems (ICAS'06), 31.

APPENDIX A

Lingo Code of Deterministic Model

```
SETS:

Material/M1..M8/:FSM, RM,PM,AM,HM,QU;                                    !I;
Equipment/E1..E2/:NE,PE,SE,IE,FM,CRE,Tp,TEC,FEC,TPB,TPI;                 !J;
Tool/T1..T2/:PT,ST,NT,IT;                                                !K;
Operationstep/S1..S20/:TS;                                               !O;
Period/P1..P4/:D,B,TW,FW,QR,QO,NW,NH,NL, NPS, Io,NWo,I;                  !L;
Order(Period,Material):QM,Y,X1,X2,X3,X4,X5,X6,W1,W2,W3,W4,W5,W6;         !M;

ENDSETS

!********************************** Data *******************************;
DATA:
CB=20000;
FOW=0.1;
FOA=0.1;
Fo=0.5;
CH=500;
CI=300;
CL=4000;
TEA=420;
Io=0;
TW=420;
NWo=0;
M=10000000000;

AM=@ole('F:\model\Compostes manufacturing4.XLSX','Material_Fixedcost');
CLO=@ole('F:\model\Compostes manufacturing4.XLSX','overtime_wage');
CLR=@ole('F:\model\Compostes manufacturing4.XLSX','regulartime_wage');
CRA=@ole('F:\model\Compostes manufacturing4.XLSX','Autoclave_energycost');
CRP=@ole('F:\model\Compostes manufacturing4.XLSX','Pump_energycost');
D=@ole('F:\model\Compostes manufacturing4.XLSX','Period_demand');
FSM=@ole('F:\model\Compostes manufacturing4.XLSX','Material_ScarpFactor');
FM=@ole('F:\model\Compostes manufacturing4.XLSX','Equipment_MaintenaceFactor');
HM=@ole('F:\model\Compostes manufacturing4.XLSX','Material_Hodlingcost');
NE=@ole('F:\model\Compostes manufacturing4.XLSX','Equipment_timelife');
NT=@ole('F:\model\Compostes manufacturing4.XLSX','tool_timelife');
PM=@ole('F:\model\Compostes manufacturing4.XLSX','Material_UnitPrice');
PE=@ole('F:\model\Compostes manufacturing4.XLSX','Equipment_purchaseprice');
PT=@ole('F:\model\Compostes manufacturing4.XLSX','tool_purchaseprice');
```

```
QU=@ole('F:\model\Compostes manufacturing4.XLSX','Order_units');
RM=@ole('F:\model\Compostes manufacturing4.XLSX','Material_Required');
SE=@ole('F:\model\Compostes manufacturing4.XLSX','Equipment_Salvage');
ST=@ole('F:\model\Compostes manufacturing4.XLSX','tool_Salvage');
TS=@ole('F:\model\Compostes manufacturing4.XLSX','Labour_workinghours');
TPA=@ole('F:\model\Compostes manufacturing4.XLSX','autoclave_processtime');
TPP=@ole('F:\model\Compostes manufacturing4.XLSX','pump_processtime');
IE=@ole('F:\model\Compostes manufacturing4.XLSX','Equipment_InterestRate');
IT=@ole('F:\model\Compostes manufacturing4.XLSX','tool_InterestRate');
@ole('F:\model\Compostes manufacturing4.XLSX','Quantity_Regular')=QR;
@ole('F:\model\Compostes manufacturing4.XLSX','Quantity_overtime')=QO;
@ole('F:\model\Compostes manufacturing4.XLSX','Workers_hired')=NH;
@ole('F:\model\Compostes manufacturing4.XLSX','Workers_laid_off')=NL;
@ole('F:\model\Compostes manufacturing4.XLSX','workers_required')=NW;
@ole('F:\model\Compostes manufacturing4.XLSX','Order_Quantity')=QM;

ENDDATA

!***************************Objective Function***************************;

MIN=Materials+Labor+MaterialsInventory+ProductsInventory+HiringandLayingoff+Eq
uipments+Tools+Shortage+OverheadCost;

!************************* **** Contraints *****************************;

! SUBJECT TO;

Materials=@SUM(Period(L): @SUM(Material(I) : D(L)*RM(I)*PM(I)*(1+FSM(I))));

Labor=@SUM(Period(L):NW(L)*CLR*TW+QO(L)*CLO*@SUM(Operationstep(O):T
S(O)));

MaterialsInventory=@SUM(Period(L):@SUM(Material(I):D(L)*AM(I)*(1+FSM(I))*R
M(I)*Y(L,I)+HM(I)*QM(L,I)/2));

ProductsInventory= @SUM (Period(L): CI*I(L));

HiringandLayingoff=@SUM (Period(L):(NH(L)*CH+NL(L)*CL));

Equipments=@SUM(Equipment(J):(PE(J)-SE(J))/NE(J)+IE(J)*PE(J)+FM(J)*PE(J)
+@SUM(Period(L):D(L)*TPA*CRA*Z)+@SUM(Period(L):D(L)*TPP*CRP));

Tools=@SUM (Tool(K): (PT(K)-ST(K))*N/NT(K)+N*IT(K)*PT(K)+N*PT(K));
Shortage=@SUM(Period(L):CB*B(L));
```

```
OverheadCost=FO*(Materials+Labor+MaterialsInventory+ProductsInventory+Equipmen
ts+Tools+HiringandLayingoff+Shortage);

@FOR (Period (L) | L #EQ#1: NW(L)=NWo+NH(L)-NL(L));
@FOR (Period (L) | L #GT# 1:NW(L)=NW(L-1)+NH(L)-NL(L));
@FOR (Period (L) | L #EQ#1:Io+QR(L)+QO(L)-I(L)=D(L)-B(L));
@FOR (Period (L) | L #GT#1:I(L-1)+QR(L)+QO(L)-I(L)=D(L)-B(L));
@FOR (Period (L):QR(L)*@SUM(Operationstep(O): TS(O))<=NW(L)*TW);
@FOR (Period (L):QO(L)*@SUM(Operationstep(O): TS(O))<=FOW*NW(L)*TW);
@FOR (Period (L):QR(L)*TPA<=N*TEA);
@FOR (Period (L):QO(L)*TPA<=N*FOA*TEA);
N = (u1+2*u2+4*u3+8*u4+16*u5);
v1+2*v2+4*v3+8*v4+16*v5=1;
(u1-1)*M+Z<=v1;
v1<=Z;
 0<=v1;
v1<=u1;
(u2-1)*M+Z<=v2;
 v2<=Z;
0<=v2;
v2<=u2;
(u3-1)*M+Z<=v3;
v3<=Z;
0<=v3;
v3<=u3;
(u4-1)*M+Z<=v4;
 v4<=Z;
 0<=v4;
v4<=u4;
(u5-1)*M+Z<=v5;
v5<=Z;
0<=v5;
v5<=u5;

@FOR(Period(L):@FOR(Material(I):QM(L,I)=QU(I)*(x1(L,I)+2*x2(L,I)+4*x3(L,I)+8*
x4(L,I)+16*x5(L,I)+32*x6(L,I))));
@FOR(Period(L):@FOR(Material(I):QU(I)*(W1(L,I)+2*W2(L,I)+4*W3(L,I)+8*W4(L,
I)+16*W5(L,I)+32*W6(L,I))=1));
@FOR(Period(L):@FOR(Material(I):(x1(L,I)-1)*M+Y(L,I)<=W1(L,I)));
@FOR(Period(L):@FOR(Material(I):W1(L,I)<=Y(L,I)));
@FOR(Period(L):@FOR(Material(I):0<=W1(L,I)));
@FOR(Period(L):@FOR(Material(I):W1(L,I)<=x1(L,I)));
@FOR(Period(L):@FOR(Material(I):(x2(L,I)-1)*M+Y(L,I)<=w2(L,I)));
@FOR(Period(L):@FOR(Material(I):w2(L,I)<=Y(L,I)));
@FOR(Period(L):@FOR(Material(I):0<=W2(L,I)));
@FOR(Period(L):@FOR(Material(I):W2(L,I)<=X2(L,I)));
```

```
@FOR(Period(L):@FOR(Material(I):(x3(L,I)-1)*M+Y(L,I)<=w3(L,I)));
@FOR(Period(L):@FOR(Material(I):w3(L,I)<=Y(L,I)));
@FOR(Period(L):@FOR(Material(I):0<=W3(L,I)));
@FOR(Period(L):@FOR(Material(I):W3(L,I)<=X3(L,I)));
@FOR(Period(L):@FOR(Material(I):(x4(L,I)-1)*M+Y(L,I)<=W4(L,I)));
@FOR(Period(L):@FOR(Material(I):W4(L,I)<=Y(L,I)));
@FOR(Period(L):@FOR(Material(I):0<=W4(L,I)));
@FOR(Period(L):@FOR(Material(I):W4(L,I)<=x4(L,I)));
@FOR(Period(L):@FOR(Material(I):(x5(L,I)-1)*M+Y(L,I)<=W5(L,I)));
@FOR(Period(L):@FOR(Material(I):W5(L,I)<=Y(L,I)));
@FOR(Period(L):@FOR(Material(I):0<=W5(L,I)));
@FOR(Period(L):@FOR(Material(I):W5(L,I)<=x5(L,I)));
@FOR(Period(L):@FOR(Material(I):(x6(L,I)-1)*M+Y(L,I)<=W6(L,I)));
@FOR(Period(L):@FOR(Material(I):W6(L,I)<=Y(L,I)));
@FOR(Period(L):@FOR(Material(I):0<=W6(L,I)));
@FOR(Period(L):@FOR(Material(I):W6(L,I)<=x6(L,I)));
@FOR(Period(L):@FOR(Material(I):@BIN(X1(L,I))));
@FOR(Period(L):@FOR(Material(I):@BIN(X2(L,I))));
@FOR(Period(L):@FOR(Material(I):@BIN(X3(L,I))));
@FOR(Period(L):@FOR(Material(I):@BIN(X4(L,I))));
@FOR(Period(L):@FOR(Material(I):@BIN(X5(L,I))));
@FOR(Period(L):@FOR(Material(I):@BIN(X6(L,I))));
@BIN(u1);
@BIN(u2);
@BIN(u3);
@BIN(u4);
@BIN(u5);
@BIN(c11);
@BIN(c12);
@BIN(c21);
@BIN(c22);
@BIN(c31);
@BIN(c32);
@FOR(Period(L):@GIN(NH(L)));
@FOR(Period(L):@GIN(NL(L)));
@FOR(Period(L):@GIN(NW(L)));
@FOR(Period(L):@GIN(QR(L)));
@FOR(Period(L):@GIN(QO(L)));
@FOR(Period(L):@GIN(I(L)));
@FOR(Equipment(J):@GIN(N));

END
```

APPENDIX B

Lingo Code of Stochastic Model

```
SETS:

Material/M1..M8/:FSM,RM,PMG,PMN,PMD,AM,HM,QU;                                  !I;
Equipment/E1..E2/:NE,PE,SE,IE,FM,CRE,Tp,TEC,FEC,TPB,TPI;                        !J;
Tool/T1..T2/:PT,ST,NT,IT;                                                        !K;
Operationstep/S1..S20/:TS;                                                       !O;
Period/P1..P4/:DG,DN,DD,TW,FW,QR,QO,NW,NH,NL,NPS,Io,NWo,IG,IN,ID;                !L;
Order(Period,Material):QM,Y,X1,X2,X3,X4,X5,X6,W1,W2,W3,W4,W5,W6;                 !M;

ENDSETS

!********************************** Data ********************************;

DATA:

FOW=0.1;
FOA=0.1;
Fo=0.5;
CH=500;
CL=4000;
TEA=420;
Io=0;
TW=420;
NWo=0;
M=10000000000;

AM=@ole('F:\model\Compostes manufacturing3.XLSX','Material_Fixedcost');
CLO=@ole('F:\model\Compostes manufacturing3.XLSX','overtime_wage');
CLR=@ole('F:\model\Compostes manufacturing3.XLSX','regulartime_wage');
CRA=@ole('F:\model\Compostes manufacturing3.XLSX','Autoclave_energycost');
CRP=@ole('F:\model\Compostes manufacturing3.XLSX','Pump_energycost');
CIG=@ole('F:\model\Compostes manufacturing3.XLSX','Inventory_unit_cost_Good');
CIN=@ole('F:\model\Compostes manufacturing3.XLSX','Inventory_unit_cost_Normal');
CID=@ole('F:\model\Compostes manufacturing3.XLSX','Inventory_unit_cost_Down');
DD=@ole('F:\model\Compostes manufacturing3.XLSX','Period_demand_Down');
DN=@ole('F:\model\Compostes manufacturing3.XLSX','Period_demand_Normal');
DG=@ole('F:\model\Compostes manufacturing3.XLSX','Period_demand_Good');
FSM=@ole('F:\model\Compostes manufacturing3.XLSX','Material_ScarpFactor');
FM=@ole('F:\model\Compostes manufacturing3.XLSX','Equipment_MaintenaceFactor');
HM=@ole('F:\model\Compostes manufacturing3.XLSX','Material_Hodlingcost');
NE=@ole('F:\model\Compostes manufacturing3.XLSX','Equipment_timelife');
```

```
NT=@ole('F:\model\Compostes manufacturing3.XLSX','tool_timelife');
PMD=@ole('F:\model\Compostes manufacturing3.XLSX','Material_UnitPrice_down');
PE=@ole('F:\model\Compostes manufacturing3.XLSX','Equipment_purchaseprice');
PT=@ole('F:\model\Compostes manufacturing3.XLSX','tool_purchaseprice');
QU=@ole('F:\model\Compostes manufacturing3.XLSX','Order_units');
RM=@ole('F:\model\Compostes manufacturing3.XLSX','Material_Required');
SE=@ole('F:\model\Compostes manufacturing3.XLSX','Equipment_Salvage');
ST=@ole('F:\model\Compostes manufacturing3.XLSX','tool_Salvage');
SPG=@ole('F:\model\Compostes manufacturing3.XLSX','Scenarios_proportion_Good');
SPN=@ole('F:\model\Compostesmanufacturing3.XLSX','Scenarios_proportion_Normal';
SPD=@ole('F:\model\Compostes manufacturing3.XLSX','Scenarios_proportion_Down');
TS=@ole('F:\model\Compostes manufacturing3.XLSX','Labour_workinghours');
TPA=@ole('F:\model\Compostes manufacturing3.XLSX','autoclave_processtime');
TPP=@ole('F:\model\Compostes manufacturing3.XLSX','pump_processtime');
IE=@ole('F:\model\Compostes manufacturing3.XLSX','Equipment_InterestRate');
IT=@ole('F:\model\Compostes manufacturing3.XLSX','tool_InterestRate');
@ole('F:\model\Compostes manufacturing3.XLSX','Quantity_Regular')=QR;
@ole('F:\model\Compostes manufacturing3.XLSX','Quantity_overtime')=QO;
@ole('F:\model\Compostes manufacturing3.XLSX','Workers_hired')=NH;
@ole('F:\model\Compostes manufacturing3.XLSX','Workers_laid_off')=NL;
@ole('F:\model\Compostes manufacturing3.XLSX','workers_required')=NW;
@ole('F:\model\Compostes manufacturing3.XLSX','Order_Quantity')=QM;

ENDDATA

!****************************Objective Function***************************;

MIN=Materials+Labor+MaterialsInventory+ProductsInventory+HiringandLayingoff+Eq
uipments+Tools+OverheadCost;

!************************* **** Contraints ******************************;

! SUBJECT TO;

Materials=0.6*(@SUM(Period(L):@SUM(Material(I):DN(L)*RM(I)*PMN(I)*(1+FSM(
I)))))+0.2*(@SUM(Period(L):@SUM(Material(I):DG(L)*RM(I)*PMG(I)*(1+FSM(I)))))
+0.2*(@SUM(Period(L): @SUM(Material(I) : DD(L)*RM(I)*PMD(I)*(1+FSM(I)))));

Labor=@SUM(Period(L):NW(L)*CLR*TW+QO(L)*CLO*@SUM(Operationstep(O):T
S(O)));

MaterialsInventory=0.6*@SUM(Period(L):@SUM(Material(I):DN(L)*AM(I)*(1+FSM(
I))*RM(I)*Y(L,I)+HM(I)*QM(L,I)/2))+0.2*@SUM(Period(L):@SUM(Material(I):DG(
L)*AM(I)*(1+FSM(I))*RM(I)*Y(L,I)+HM(I)*QM(L,I)/2))+0.2*@SUM(Period(L):@S
UM(Material(I) : DD(L)*AM(I)*(1+FSM(I))*RM(I)*Y(L,I)+HM(I)*QM(L,I)/2));

ProductsInventory=0.6*@SUM(Period(L):CIN*IN(L))+0.2*@SUM(Period(L):CIG*IG(
L))+0.2*@SUM(Period(L): CID*ID(L));
```

```
HiringandLayingoff=@SUM(Period(L):(NH(L)*CH+NL(L)*CL));

Equipments=0.6*@SUM(Equipment(J):(PE(J)-SE(J))/NE(J)+IE(J)*PE(J)+FM(J)*PE(J)
+@SUM(Period(L):DN(L)*TPA*CRA*Z)+@SUM(Period(L):DN(L)*TPP*CRP))+0.2*
@SUM(Equipment(J):(PE(J)-SE(J))/NE(J)+IE(J)*PE(J)+FM(J)*PE(J)
+@SUM(Period(L):DG(L)*TPA*CRA*Z)+@SUM(Period(L):DG(L)*TPP*CRP))
+0.2*@SUM(Equipment(J):(PE(J)-SE(J))/NE(J)+IE(J)*PE(J)+FM(J)*PE(J)
+@SUM(Period(L):DD(L)*TPA*CRA*Z)+@SUM(Period(L):DD(L)*TPP*CRP));

Tools=0.6*@SUM(Tool(K): (PT(K)-ST(K))*N/NT(K)+N*IT(K)*PT(K)+N*PT(K))
+0.2*@SUM(Tool(K): (PT(K)-ST(K))*N/NT(K)+N*IT(K)*PT(K)+N*PT(K))
+0.2*@SUM(Tool(K): (PT(K)-ST(K))*N/NT(K)+N*IT(K)*PT(K)+N*PT(K));

OverheadCost=FO*(Materials+Labor+MaterialsInventory+ProductsInventory+Equipmen
ts+Tools+HiringandLayingoff);

@FOR(Period(L) | L #EQ#1:NW(L)=NWo+NH(L)-NL(L));
@FOR(Period(L) | L #GT# 1:NW(L)=NW(L-1)+NH(L)-NL(L));
@FOR(Period(L) | L #EQ#1:Io+QR(L)+QO(L)-IG(L)=DG(L));
@FOR(Period(L) | L #GT#1:IG(L-1)+QR(L)+QO(L)-IG(L)=DG(L));
@FOR(Period(L) | L #EQ#1:Io+QR(L)+QO(L)-IN(L)=DN(L));
@FOR(Period(L) | L #GT#1:IN(L-1)+QR(L)+QO(L)-IN(L)=DN(L));
@FOR(Period(L) | L #EQ#1:Io+QR(L)+QO(L)-ID(L)=DD(L));
@FOR(Period(L) | L #GT#1:ID(L-1)+QR(L)+QO(L)-ID(L)=DD(L));
@FOR(Period(L):QR(L)*@SUM(Operationstep(O):TS(O))<=NW(L)*TW);
@FOR(Period(L):QO(L)*@SUM(Operationstep(O):TS(O))<=FOW*NW(L)*TW);
@FOR(Period(L): QR(L)*TPA<=N*TEA);
@FOR(Period(L): QO(L)*TPA<=N*FOA*TEA);

N=(u1+2*u2+4*u3+8*u4+16*u5);
v1+2*v2+4*v3+8*v4+16*v5=1;
(u1-1)*M+Z<=v1;
v1<=Z;
0<=v1;
v1<=u1;
(u2-1)*M+Z<=v2;
v2<=Z;
0<=v2;
v2<=u2;
(u3-1)*M+Z<=v3;
v3<=Z;
 0<=v3;
v3<=u3;
(u4-1)*M+Z<=v4;
v4<=Z;
0<=v4;
v4<=u4;
```

```
(u5-1)*M+Z<=v5;
v5<=Z;
0<=v5;
v5<=u5;

@FOR(Period(L):@FOR(Material(I):QM(L,I)=QU(I)*(x1(L,I)+2*x2(L,I)+4*x3(L,I)+8*
x4(L,I)+16*x5(L,I)+32*x6(L,I))));

@FOR(Period(L):@FOR(Material(I):QU(I)*(W1(L,I)+2*W2(L,I)+4*W3(L,I)+8*W4(L,
I)+16*W5(L,I)+32*W6(L,I))=1));

@FOR(Period(L):@FOR(Material(I) :(x1(L,I)-1)*M+Y(L,I)<=W1(L,I)));
@FOR(Period(L):@FOR(Material(I) :W1(L,I)<=Y(L,I)));
@FOR(Period(L):@FOR(Material(I) :0<=W1(L,I)));
@FOR(Period(L):@FOR(Material(I) :W1(L,I)<=x1(L,I)));
@FOR(Period(L):@FOR(Material(I) :(x2(L,I)-1)*M+Y(L,I)<=w2(L,I)));
@FOR(Period(L):@FOR(Material(I) :w2(L,I)<=Y(L,I)));
@FOR(Period(L):@FOR(Material(I) :0<=W2(L,I)));
@FOR(Period(L):@FOR(Material(I) :W2(L,I)<=X2(L,I)));
@FOR(Period(L):@FOR(Material(I) :(x3(L,I)-1)*M+Y(L,I)<=w3(L,I)));
@FOR(Period(L):@FOR(Material(I) :w3(L,I)<=Y(L,I)));
@FOR(Period(L):@FOR(Material(I) :0<=W3(L,I)));
@FOR(Period(L):@FOR(Material(I) :W3(L,I)<=X3(L,I)));
@FOR(Period(L):@FOR(Material(I) :(x4(L,I)-1)*M+Y(L,I)<=W4(L,I)));
@FOR(Period(L):@FOR(Material(I) :W4(L,I)<=Y(L,I)));
@FOR(Period(L):@FOR(Material(I) :0<=W4(L,I)));
@FOR(Period(L):@FOR(Material(I) :W4(L,I)<=x4(L,I)));
@FOR(Period(L):@FOR(Material(I) :(x5(L,I)-1)*M+Y(L,I)<=W5(L,I)));
@FOR(Period(L):@FOR(Material(I) :W5(L,I)<=Y(L,I)));
@FOR(Period(L):@FOR(Material(I) :0<=W5(L,I)));
@FOR(Period(L):@FOR(Material(I) :W5(L,I)<=x5(L,I)));
@FOR(Period(L):@FOR(Material(I) :(x6(L,I)-1)*M+Y(L,I)<=W6(L,I)));
@FOR(Period(L):@FOR(Material(I) :W6(L,I)<=Y(L,I)));
@FOR(Period(L):@FOR(Material(I) :0<=W6(L,I)));
@FOR(Period(L):@FOR(Material(I) :W6(L,I)<=x6(L,I)));
@FOR(Period(L):@FOR(Material(I):@BIN(X1(L,I))));
@FOR(Period(L):@FOR(Material(I):@BIN(X2(L,I))));
@FOR(Period(L):@FOR(Material(I):@BIN(X3(L,I))));
@FOR(Period(L):@FOR(Material(I):@BIN(X4(L,I))));
@FOR(Period(L):@FOR(Material(I):@BIN(X5(L,I))));
@FOR(Period(L):@FOR(Material(I):@BIN(X6(L,I))));
@BIN(u1);
@BIN(u2);
@BIN(u3);
@BIN(u4);
@BIN(u5);
```

```
@BIN(c11);
@BIN(c12);
@BIN(c21);
@BIN(c22);
@BIN(c31);
@BIN(c32);
@FOR(Period(L):@GIN(NH(L)));
@FOR(Period(L):@GIN(NL(L)));
@FOR(Period(L):@GIN(NW(L)));
@FOR(Period(L):@GIN(QR(L)));
@FOR(Period(L):@GIN(QO(L)));
@FOR(Period(L):@GIN(IG(L)));
@FOR(Period(L):@GIN(IN(L)));
@FOR(Period(L):@GIN(ID(L)));
@FOR(Equipment(J):@GIN(N));

END
```