An Optimization Model for Composite Wind Turbine Blade Production Planning

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Abstract

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Composite wind turbine blades are major components of wind towers and they constitute a significant proportion of the cost of building wind towers. It has been a common practice that wind turbine blade manufacturing companies extend production to multiple sites. This thesis will apply an integrated production planning model to multi-site composite wind turbine blade manufacturing for improved operations performance and minimized supply chain cost. The model is formulated by mixed integer linear programming (MILP) and contains three modules: raw material inventory module, production module and finished product distribution module. It covers the operations of a whole supply chain including raw materials procurement and inventory control, production planning, manpower planning, finished products warehousing and transportation. A numerical example is given to illustrate the model and to examine computational efficiency of it. Sensitivity analysis is conducted to identify important cost factors and to provide directions for managerial operations in cost reduction.

Key words: composite, wind turbine blades, multi-site, production planning, supply chain cost, MILP, cost reduction.

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Chapter One

Introduction

1.1 Motivation

Wind power, a clean and renewable energy, is one of the solutions to the world growing need of energy. Nowadays, wind power has become one of the world's fastest growing sectors of energy market, and the fast growing wind energy market requires future wind turbine to be more efficient and less costly (Joselin Herbert et al., 2007).

Wind turbine blades are major components of wind towers and they constitute about 15%-20% of the cost of building wind towers (Jureczko et al, 2005). The improvement of composite manufacturing technology enables manufacturers to make larger wind turbine blades which can give more power output. For example, the current wind turbines have reached the size of 80 to 120 meters in diameter with output of 2-5MW (Griffin and Ashwill, 2003). The world's largest wind turbine has a rotor diameter of 124 meters with a swiping area larger than a football court when mounted on a wind tower (Bonnet and Dutton, 2007). As the size of blades grows, the manufacturing and transportation costs increase significantly.

Many researchers have conducted research on materials, structural design, and engineering analysis on composite wind turbine blades to improve product properties such as stiffness to weight ratio, strength to weight ratio, and fatigue performance. Research has also been conducted aiming at lowering blades manufacturing cost. However, studies on blades supply chain and logistics are very limited and even more so on production planning of wind turbine blade manufacturing. This is one of the reasons motivating the research of this thesis.

It has been a common practice that wind turbine blade manufacturing companies extend production to multiple sites in order to efficiently utilize global resources and reduce overall supply chain cost. This requires production planners to coordinate production in all of production locations with consideration of operations throughout the whole supply chain. Multi-site manufacturing environment adds complexity to production planning problems. Local planning may not be capable of giving an optimal solution to achieving best global performance. With global planning, relationship between individual production sites becomes both competition and cooperation. They compete for local cost and capacity, and cooperate for overall performance of the company. This thesis is aiming at providing a tool for production planning in a multi-site manufacturing environment, which incorporates operations of every major aspect of a supply chain for wind turbine blade manufacturing.

1.2 Objectives of the Thesis

The purpose of this thesis is to apply an integrated production planning model to multi-site composite wind turbine blade manufacturing for improved operations performance and minimized supply chain cost. The specific objectives are as follows.

(1) To review and study composite wind turbine blade manufacturing technologies, analyze cost structure of wind turbine blade manufacturing for possible supply chain cost reduction.

(2) To develop a mathematical model which integrates planning for raw materials procurement, production, workforce, finished products transportation for multi-site composite wind turbine blade manufacturing.

(3) To analyze controllable factors which may affect the operation costs and to identify important factors for wind turbine blade manufacturing cost reduction.

1.3 Research Methodology

In this research, an MILP model is developed to search for the optimal production plan to minimize the supply chain cost of a composite wind turbine blades production. The model is built based on the environment of a multi-site blade manufacturer supplying products to multiple customers. It covers the operations of a whole supply chain including raw materials procurement and inventory control, production planning, manpower planning, finished products warehousing and transportation. The idea of aggregate production planning is applied to the model development in which customers' demands, production capacities, and finished products transportation capacities are treated integratively. Modular approach is used in model formulation. The model consists of three modules: raw material inventory module, production module, finished products distribution module. The production module is the core of the model by interacting with the other two modules.

1.4 Organization of This Thesis

Chapter 2 investigates composite wind turbine blade manufacturing technologies and related issues. In Chapter 3, a mathematical optimization model for production planning, materials procurement and finished products transportation is presented. A numerical example is given in Chapter 4 to illustrate the model. Then sensitivity analysis is carried out to identify important factors affecting total supply chain cost. Chapter 5 gives the conclusion and possible future research topics in this area.

Chapter Two

Composite Wind Turbine Blade Manufacturing and Cost Reduction Issues

This chapter introduces composite wind turbine blades manufacturing technologies and issues regarding blade production, transportation and cost reduction which need to be considered in production planning decision. The aspects to be studied and discussed in this chapter are geometry of wind turbine blades, composite materials, blades manufacturing techniques, production processes, facilities layout, and blades transportation.

2.1 Wind Turbine Blade Dimension

The most common structure of wind turbine is three blades mounted on a tower in a vertical plane. Wind turbine converts wind energy into electricity which can be stored and transmitted. Based on Betz's Elementary Momentum Theory, the power converted by wind turbine can be calculated with the equation below.

$$P = \alpha \rho A v^3 \tag{2.1}$$

where α is the aerodynamic efficiency constant, ρ is the air density, A is the area of rotor plane, and v is the velocity of wind. The rotor plane area $A = \pi r^2$. r, the radius of the rotor plane, is approximately the length of the wind turbine blades. The aerodynamic efficiency constant α is related to the rotor blade design.

As pointed out in Griffin (2002), the rate of power output to rotor plane area of the commercial turbines ranges between 0.36 KW/m^2 and 0.50 KW/m^2. The representative dimensions for rotors between 750 KW and 5 MW are listed in Table 2.1.

Table 2.1 Power output vs dimensions of wind turbines (source: Griffin, 2002)

Power Output (KW)	Diameter (m)	Blade Length (m)	Maximum Chord (m)
750	49.6	23.6	2.0
1500	70.0	33.2	2.8
2000	81.0	38.5	3.2
3000	99.2	47.1	4.0
4000	114.5	54.4	4.6
5000	128.0	60.8	5.1

The sketch of a typical wind turbine blade is shown in Figure 2.1. The blade root where there are bolted joints connecting the blade and the hub is usually circular, and the blade transitions to pure airfoil at the point of the maximum chord.

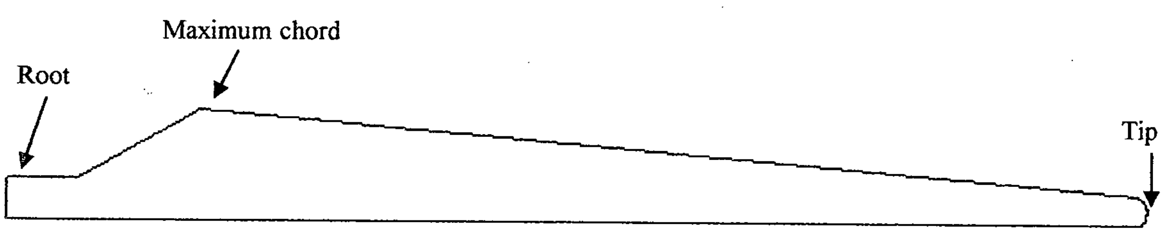

Figure 2.1 Typical Blade Planform

2.2 Wind Turbine Blade Design

Wind turbine blade design is to have good aerodynamic efficiency and high strength to weight ratio. Since wind turbine blades are very large and are mounted on high towers, they are exposed to great loads from wind, gravity of their own mass, and centrifugal forces during rotation. They must be strong and have light weight. The shape of a wind turbine blade affects its aerodynamic efficiency, weight and strength.

Study on traditional blades design indicates that the weight of blades has cubic growth rate to the length. Recently, Veers et al. (2003) reviewed the design and manufacturing processes of different wind turbine blades. It shows that the recent design has a lower weight growth rate which is of a power of 2.3 to the length. They pointed out that "this is primarily attributed to two causes, namely the materials/manufacturing approach and the design criteria for the blades". Shape and materials selection are major factors to be considered for wind turbine blades design. Many institutions and manufacturers are carrying out blades design studies aiming at good strength and aerodynamic properties and light materials. Besides physical properties, cost is another important issue. Wind turbine blade structure design can affect its manufacturing complexity, assembling costs, and transportation costs. Some different structure designs are proposed by researchers.

obvious advantages of the sandwich structure are high bending stiffness, high strength and low weight. Therefore, as the size of wind turbine blades is growing, the sandwich structure will be likely used more widely in the future in order to enhance buckling resistance of the structure (Berggreen et al., 2007). However, some difficulties and disadvantages of applying sandwich structure must be overcome. First, the commonly used non-destructive inspection (NDI) method may not always detect the defects and damages of the sandwich structure. Second, core materials are relatively soft and light. They have very different stiffness and strength compared to the adjacent fibre reinforced hard skins. As a result, sandwich structure is more prone to delamination and failure because of the weak interface between core materials and hard skins.

As the mass of wind turbine blades grows, thick inboard section is required. Generally known by the wind turbine blade industry, the higher thickness to chord ratio (t/c) contributes to the lower mass growth rate with length. However, thick airfoils tend to cause poor aerodynamic efficiency. Flat trailing edge of inboard section was proposed to improve the aerodynamic performance characteristics. Traditionally, airfoils are simply truncated to get the flat trailing edge. Standish et al. (2003) did aerodynamic analysis on the blunt trailing edge airfoils and modified the approach of truncating the trailing edge of inboard blade region by adding the trailing edge thickness while maintaining the airfoil's maximum thickness and camber constant. This approach improved both structural and aerodynamic performances of large wind turbine blades.

Integrated structures have been commonly used by blade manufacturers, and most of the studies of blade design focus on this type of structure. The integrated structures can provide the rotor blades good static and fatigue performance, and require limited joints and bonds, hence lower the complexity of the design process. However, high transportation cost is a major problem of the blades with this type of structure. Griffin (2002) estimated transportation costs of blades of different sizes and pointed out that "a sharp increase in transportation costs occurs for blade structure with length exceeding 46 m, and at lengths greater than 61 m the cost of long-haul ground transportation may become prohibitive". They investigated many design concepts, such as jointed designs, multi-piece blade assemblies, and decoupled skins. They found that the multi-piece structure is either not cost effective or not structurally efficient. Although the chance of having defects in smaller pieces is lower than in larger pieces, the blade with the multi-piece structure may have lower fatigue and structure performance due to joints. Design complexity and assembling effort of the multi-piece structure added to the manufacturing costs and counters the savings from transportation costs.

2.2.2 Composite Materials for Wind Turbine Blade

Physical requirements for the materials of wind turbine blades are high stiffness, low density, and long fatigue life. Figure 2.3 compares the physical properties of some candidate materials. Wood, composites and ceramics have better performance of stiffness versus density than all the other materials. Among them, wood has the lowest density, but the relatively low stiffness makes it hard to support the structure of large wind turbine blades. Ceramics has the best stiffness, but its density is too high. Comparatively, composite materials have moderate density and high stiffness, so they are the ideal materials for large wind turbine blades. Composite materials are made of reinforcements (fibres) and matrix materials. The properties of fibres and matrices, and interface between them affect the performance of the composite materials.

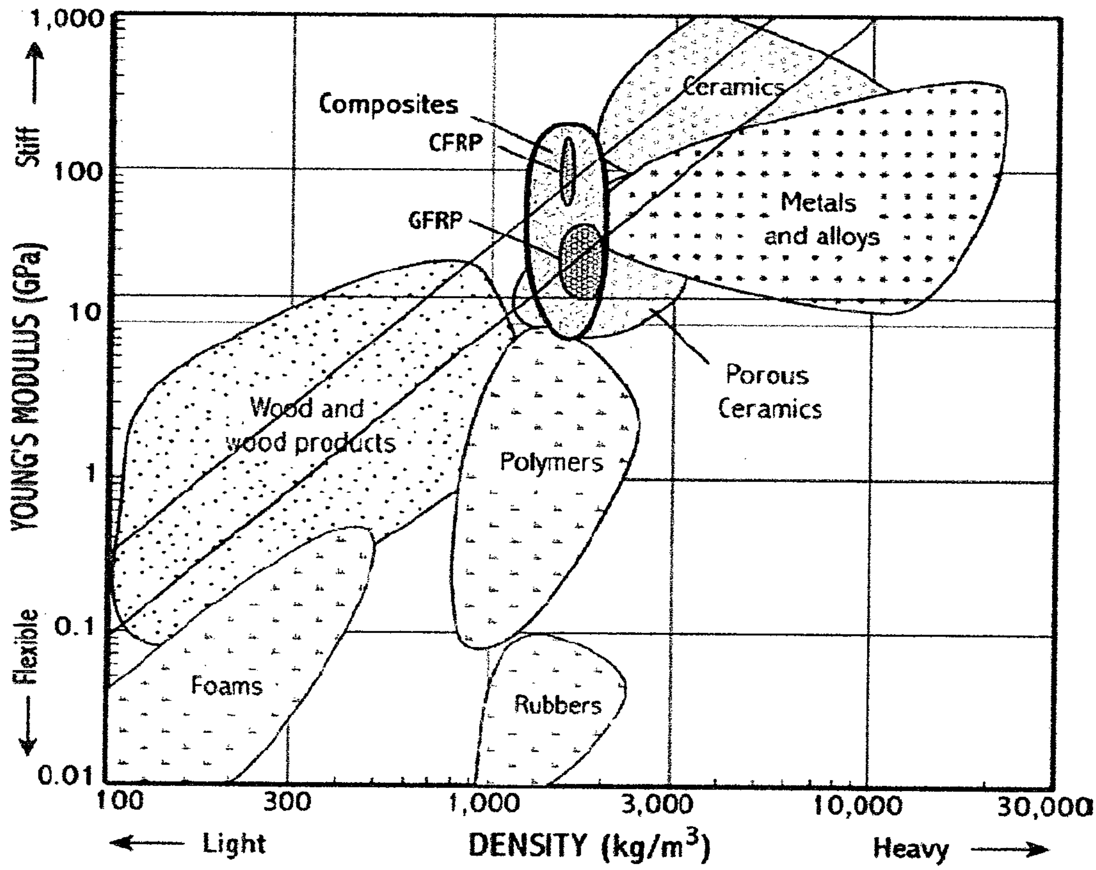

Figure 2.3 Stiffness vs density of candidate materials (adapted from Brøndsted, 2005)

According to the cost study of TPI (2003), materials used in blade production are in the following groups.

1. Gelcoat
2. Continuous strand mat
3. Biaxial E-glass fabric
4. Uniaxial E-glass fabric
5. Core

6. Resin
7. Promotor
8. Catalyst
9. Bonding adhesive
10. Root attachment system

Among all these materials, fibre, resin and core materials account for the majority of the total materials cost. In this study, we will mainly consider these three major materials.

2.2.2.1 Fibre reinforcement

Fibre materials are the most important components in composite products because they bear the majority of the load of the composite structure. The most commonly used fibre reinforcement for wind turbine blade is glass fibre. In recent years, carbon fibres have been increasingly used in wind turbine blade manufacturing because of their superior properties and decreasing price. Composites with some other fibre materials which have moderate mechanical properties and low densities are also under study and development. Table 2.2 shows properties of some candidate fibre materials and their composites. Discussion of fibre materials will focus on glass fibres and carbon fibres.

Table 2.2 Physical properties of candidate fibre materials and their composites (adapted from Brøndsted et al., 2005)

Type	Fibres			Composites			
	Stiffness E_f (Gpa)	Tensile Strength σ_f (Mpa)	Density ρ_f (g/cm^3)	Orientation θ	Stiffness E_c (Gpa)	Tensile Strength σ_c (Mpa)	Density ρ_c (g/cm^3)
E-Glass	72	3500	2.54	0°	38	1800	1.87
				Random	9.3	420	1.6
Carbon	350	4000	1.77	0°	176	2050	1.49
				Random	37	470	1.37
Aramid	120	3600	1.45	0°	61	1850	1.33
				Random	14.1	430	1.27
Polyethylene	117	2600	0.97	0°	60	1350	1.09
				Random	13.8	330	1.13
Cellulose	80	1000	1.5	0°	41	550	1.35
				Random	10.1	170	1.29

Composite materials are based on the fibers listed and a polymer matrix with properties E_m = 3 GPa, σ_m = 100 MPa, and ρ_m = 1.2 g/cm3. The composite properties are calculated from the simple composite theory (law of mixtures); the orientation factor is 1 for aligned composites and 1/3 for random composites.

Glass Fibre

There are two types of glass fibres, E-glass and S-glass. S-glass has better stiffness and strength than E-glass. However, due to higher property to price ratio, E-glass is chosen to be used in most commercial wind turbine blade production. The E-glass fibre for composite production is coated by silane coupling agent which can provide environmental resistance and also facilitate bounding between fibres and matrix materials.

Glass fibres can be woven or stitched into different kinds of fabrics, such as randomly oriented fibre mats, unidirectional fibres and differently oriented fibre layers stitched together. The form of fabrics can affect porosity of the fabrics, fibre-volume fraction of the composite materials, and the strength of the composite structure in different orientations. Take the LM wind turbine blades for example. The most important glass fibre fabrics used in production are continuous filament mat (CFM), non-crimp uniaxial fabric, non-crimp biaxial fabric, and non-crimp multiaxial fabric (Koefoed, 2003).

CFM is made of randomly oriented fibre strands. It is used to hold the main fabrics in place during lay-up process. However, due to its properties of high porosity and low fibre volume fraction after compressed, its major function is to enhance the resin flow in the preforms during injection, and therefore reduce injection time. Figure 2.4 shows a picture of the CFM.

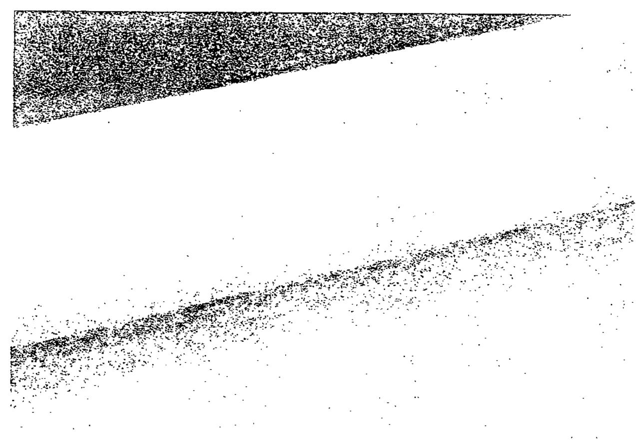

Figure 2.4 Picture of continuous filament mat

The main glass fibre reinforcements are non-crimp uniaxial, biaxial and multiaxial fabrics. The little deformation of non-crimp fabrics during lay-up can ensure fibres uniformly arrayed in composite materials, and resin rich areas can be reduced due to zero crimp. The uniformly dispersed non-crimp glass fibre fabrics have better tensile fatigue resistance than many woven fabrics (Mandell, 1991). Therefore the non-crimp fabrics have better structure performance compared to the woven fabrics. However, resin flow through the non-crimp fabrics is very slow due to the fine alignment of fibres leaving very small flow channels. The flow in the thickness direction is even slower than that along the fibre direction. This causes difficulty during resin injection. As a result, the randomly oriented mats are used in wind turbine blade preforms to provide resin flow channels and shorten the flow distance through the non-crimp fabrics.

Different orientation of fibres provides different strength performances in different structural orientations. The uniaxial fabric constitutes of the major part of reinforcement. It only contains one direction of bundles of glass fibres which are stitched together to form a fabric as Figure 2.5.

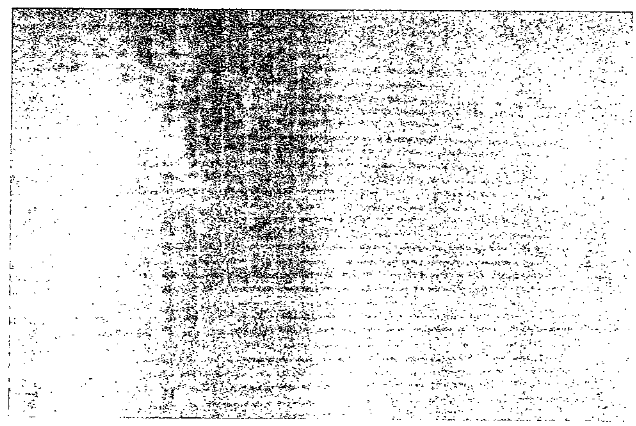

Figure 2.5 Picture of uniaxial fabric

The non-crimp biaxial fabric contains two layers in different orientations, $+45^{\circ}$ and -45° stitched together by polyester threads. Figure 2.6 shows an example of the biaxial glass fibre fabric.

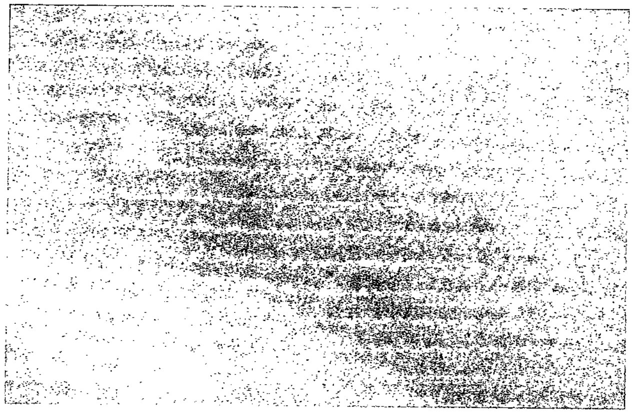

Figure 2.6 Picture of biaxial fabric

The multiaxial glass fibre fabric contains several layers with different orientations, such as 0°, $+45^\circ$, -45°, and 90°. This kind of layup can provide almost isotropic resin flow and strength properties. An example of multiaxial glass fibre fabric is shown in Figure 2.7.

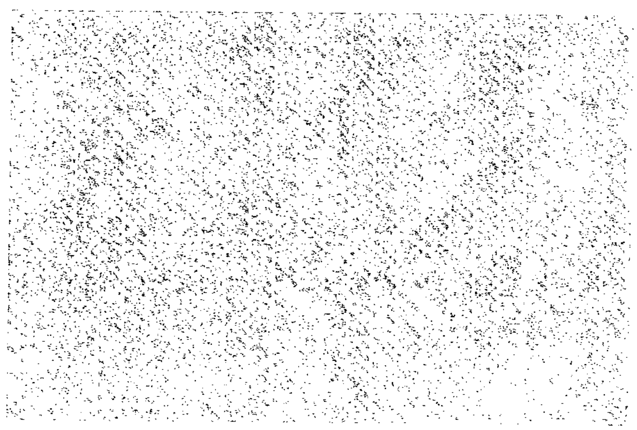

Figure 2.7 Picture of multiaxial fabric

Carbon fibre

Carbon fibres have several apparent advantages over glass fibres in blade applications: higher modulus, lower density, higher tensile strength and reduced fatigue sensitivity (Mandell et al., 2003). Therefore, carbon fibres have become of increasing interest in blade design and manufacturing. There are three fundamental ways that carbon fibres may be used in wind turbine blade designs, such as bulk replacement of load-bearing fibreglass materials, selective reinforcement; and new total blade designs (Veers et al., 2003). Recent studies show that applying carbon fibre or hybrid of carbon fibre and glass fibre can result in blades with higher structural and load performance. Currently, the major challenge of using carbon fibres is the high cost. Tests on some lower cost varieties of carbon composites with larger tow sizes and thinner plies show that this type of carbon fibre materials have poorer compressive strength (Veers et al., 2003). Another challenge of using carbon fibres is production efficiency. The crystallographic structure of carbon fibre gives it highly anisotropic mechanical and thermal expansion properties. Carbon fibres have strong strength along the fibre direction, while they have poor strength upright to the fibre direction. Therefore, during production, small misalignments of carbon fibres can produce a dramatic reduction in fatigue strength. Thus manufacturing processes are critical to the introduction of carbon fibres into blade designs (Veers et al. 2003).

2.2.2.2 Resin

As matrix material, the main function of resin is to bind fibres together, absorb energy, and protect fibres. Resins are categorized based on thermal properties into two groups, thermoset and thermoplastic.

Thermoset

The majority of wind turbine blade manufacturers use thermoset polymers of which epoxies, polyesters and vinylesters are popularly used. Generally, the thermoset resins are liquid and have low viscosities which make them easy to process and to wet the fibres. This property of thermoset resins gains their popularity in composite production. When reacting with curing agent or catalyst at certain temperatures, the molecules of the resin start an irreversible cross-link process and form a rigid 3D network structure. Temperature control is important during resin injection and curing process. The higher is the temperature, the lower the viscosity of the resin tends to be, and the more easily the resin flows through and wets the fibre preform. However, raising temperature can cause faster resin cross-link and solidification which in turn can be accelerated by the heat generated from the chemical reaction. This process increases the resin viscosity in a very short time and makes the resin hard enough to stop the flow. This phenomenon is usually the cause of incomplete fill and poor fibre wetting during production.

Thermoplastic

In recent years, there has been increasing interest in thermoplastic resins with use temperatures up to 170℃ (Gultowski, 1997). Compared to thermoset, one of the most important advantages of thermoplastic is that it has high toughness and failure strain. Thermoplastic matrix has better energy absorption especially on the interface between fibre and matrix and thus gives the composites a higher resistance to failure. Short processing cycle time is another advantage of thermoplastic. Compared to the curing process of thermoset, melting and solidification of thermoplastic is faster. Additionally, thermoplastic can be remelted and thus recyclable. Furthermore, thermoplastic is usually solid at room temperature, so it is much easier to store it than thermoset resin which is liquid and has certain shelf life. However, there are some disadvantages preventing the wide use of thermoplastics in wind turbine blades manufacturing. The major challenge is that thermoplastics are highly viscous even heated to a relatively high temperature. This makes resin transfer molding (RTM) of thermoplastics a hard process, especially for large structures like wind turbine blades. In addition, thermoplastics usually require higher processing temperature than thermosets, which leads to higher production cost and higher requirements for moulds and equipment. In spite of their negative aspects, there are no apparent reasons to prevent the use of thermoplastic composites for wind turbine blade structures (van Rijswijk et al., 2005). Specific properties of thermosetting and thermoplastic resins are shown in Table 2.3.

Table 2.3 Resin properties (data adapted from Gultowski, 1997)

Materials	E (GPa)	σ Failure (MPa)	Maximum Strain(%)	Density (g/cm^3)	T_g (℃)	$T_{process}$ (℃)
			Thermosetting			
Epoxy (Hecules 3501-6)	3.4	59	3.3	1.2	170	177
Polyester (orthopthalic)	3.4	69	1.5	1.3	75-100	25-100
			Thermoplastic			
Polypropylene	1.4	34	200	0.9	-20	200-280
Nylon 6.6	2.8	76	100	1.2	57	270-290
Polycarbonate	2.4	66	110	1.1	157	260

2.2.2.3 Core materials

Core materials act as inserts in the sandwich structure. The commonly used core materials in wind turbine blades are enclosed PVC foam and coated balsa wood. The application of sandwich structure is driven by the growing size of wind turbine blades and the needs to reduce blade weight and load. The advantages and disadvantages of using this structure have been listed previously in the blade structure part. As discussed, weak interface between soft core material and hard fibre reinforced shell can lead to delamination which causes local buckling and jeopardizes wind turbine blade damage tolerance. Recently, some new core materials are under development. The concepts of developing new core materials include: 1) to have structural elements in forms of pins, stitches, or plates extending through the thickness of the soft and light weight core materials, 2) to have stiff and strong surface to provide good connection to hard shell and to distribute load. ***X-Cor***™ sandwich material system developed by Aztex, Inc., USA is an example of this kind of core material (Thomsen, 2006).

2.3 Wind Turbine Blade Manufacturing Techniques

In the early years, smaller wind turbine blades were manufactured using wet hand-lay-up technique in open moulds. Production with this method causes high emission of harmful chemicals into the air. Currently, production method is moving toward the process with lower emissions such as RTM and vacuum assisted resin transfer molding (VARTM). The majority of blade manufacturers use a ''wet'' process, either VARTM or an open mould lay-up and impregnation. Dry lay-up of preforms and subsequent infusion remain a process of high interest for the wind industry (Griffin and Ashwill, 2003). Some other manufacturers use a different process with prepreg materials. For instance, Vesta produce wind turbine blade using prepreg fibreglass. Both VARTM and prepreg materials have particular design challenges for manufacturing large wind turbine blades. For VARTM processes, the permeability of the dry preform determines the rate and degree of the wetting process. For prepreg materials, sufficient bleeding is required to avoid resin-rich areas and to eliminate voids because of trapped gasses (Griffin and Ashwill, 2003). The post-cure temperatures for perpreg materials and VARTM process are different. Prepreg materials usually require a higher cure temperature (90℃-110℃), while VARTM process generally requires only 60℃-65℃. Therefore, prepreg materials have higher mould and tooling requirement. Raw materials storage conditions for these two production processes are quite different. For VARTM, dry fibres can be stored under normal conditions with infinite shelf life. Most thermosetting resins can be stored under room temperature with shelf life ranging from several months to infinite. In contrast, Prepreg materials are typically stored at -18℃ with a shelf life from 6 months to 12 months. The comparison of the two processes well explains the preference of VARTM to prepreg. The study of this thesis will mainly consider VARTM method. Data and assumptions will be based on this process.

The development of VARTM can be dated back to the Macro method in the 1950's. The recently developed Seemann composites resin infusion molding process (SCRIMP) is a promising VARTM process. VARTM differs from RTM mainly in that only one sided mould is used with the other side covered by the flexible vacuum bag, and resin flow is driven by vacuum. The advantages of VARTM make it an attractive method of making large wind turbine blades. First, only one sided mould is needed, hence it lowers the mould and tooling cost (William et al., 1996). Second, it eliminates the need of precisely mould matching so it requires shorter set-up time compared to the two sided mould for RTM. Furthermore, it operates under low pressure, which eliminates the use of equipment exerting high pressure, and makes it suitable for producing products of large dimension. The typical VARTM process is demonstrated in Figure 2.8.

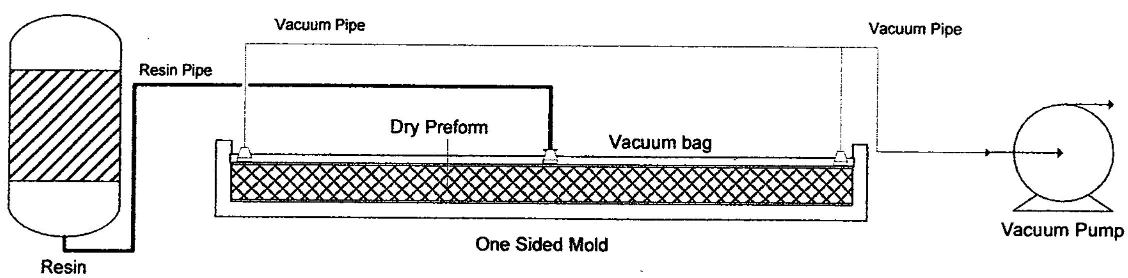

Figure 2.8 Diagram of a typical VARTM setup

Mould design and selection can affect composite production and cost. The traditional and mostly used moulds are metal moulds made of steel or aluminium. One of the advantages of metal moulds is that they can be repeatedly used for many production cycles, usually hundreds of times, therefore they are suitable for large volume production. Furthermore, metal moulds can be used under high temperature and high pressure. However, cost for metal moulds is high and production time for them is usually long. In addition, metal moulds have high thermal expansion coefficient which is quite different from that of the composite materials processed in the moulds. This may cause high internal stress or even deformation of the final products. Nowadays, composite moulds are increasingly used for production of composite products. Usually, composite moulds are made using the same materials as to be processed in them. It can eliminate the problems caused by different thermal expansion coefficient. Another advantage of composite moulds is that the cost is low and production time is short. However, short life cycles, low processing pressure and temperature, and limited choices of resins to be processed are the disadvantages of composite moulds.

For VARTM, resin injection and cure processes are two critical steps which need to be carefully designed and controlled. A proper selection of parameters for injection and cure processes is crucial to yield successful molding results and to obtain an appropriately cured part with minimum defects (Ruiz et al., 2006). Poor injection can result in incomplete mould filling, voids, resin rich areas and preform deformation. Improper curing temperature and time control can cause incomplete cure (resin polymerization) and excessive internal stress. All these defects are well known causes leading to failure or short life of wind turbine blades. Besides affecting mechanical performance, the design and control of both processes also affect production cycle time.

Resin injection

Figure 2.9 demonstrates the resin flow through a channel during injection process.

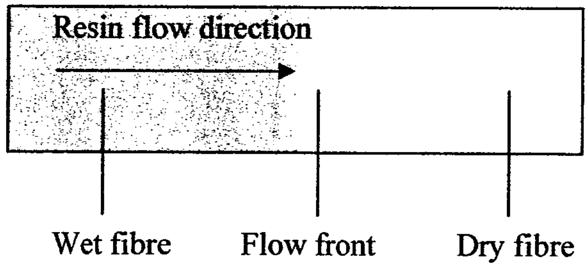

Figure 2.9 Demonstration of one dimension resin flow during injection

Resin flow rate during injection can be calculated by Darcy's law.

$$v = -\frac{K \times \Delta P}{\eta} \tag{2.2}$$

Where v is fluid velocity, K is the permeability tensor of the porous media, ΔP is the pressure difference, and η is the viscosity of the resin fluid. The equation indicates that preform permeability, viscosity of injected resin, and exerted pressure difference are major factors affecting the resin flow velocity. Resin injection is a complex process in which many factors interact with each other, so interaction and effects of all the factors should be systematically considered. The feasibility of an injection of very large structures with the VARTM process is mainly determined by four aspects, namely, the geometry of the product, the materials used in the product, injection tooling, and the injection strategy (Brouwer et al., 2003). The first three aspects have been mostly determined during a product design stage leaving injection strategy the most workable and controllable aspect to be worked on for resin injection process. Figure 2.10 shows an injection process for a wind turbine blade halve.

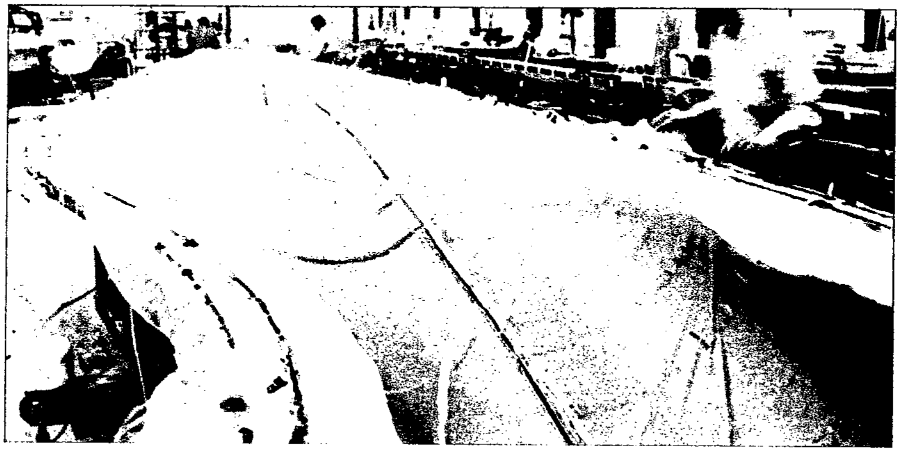

Figure 2.10 Resin injection for a wind turbine blade halve (source: Brouwer et al., 2003)

One major aspect of injection strategy is the selection of placement of resin inlets and the location of vacuum outlets which determines the resin flow direction and distance. For injecting wind turbine blade, the resin inlets are along a resin pipe placed at the lowest position in the longitude direction of blade preform while vacuum outlets are located along the edge of the mould. Once injection starts, resin flows from the inlets toward the edge to wet the preform. With the proper lay-up of high permeable media as flow channels, this strategy can achieve the ideal perpendicular resin flow to the inlet pipe, so flow fronts can maintain almost straight and parallel to the inlet pipe. Air traps and dry spots can be avoided with this injection strategy.

Vacuum pressure is another important factor to be carefully controlled during the injection process. Lower vacuum pressure can drive resin flow faster, which can shorten injection time. However, it is not always the case that the lower the pressure the better is the injection. First, too fast resin flow can distort fibre alignment thus affect strength performance of the final products. Second, low vacuum pressure can cause high compressive stress on preform which will reduce permeability of some parts of the preform and cause poor wetting of those parts. Additionally, low pressure leads to over-saturation of gas in the resin and evaporation of volatile components which causes bubbles and voids. Therefore, proper vacuum pressure should be applied to an injection process.

Cure

Mould temperature and time control are important factors during the resin curing process. For thick composites, an optimal choice of curing process parameters results in a minimum number of defects, such as micro-cracks, delamination, warpage or spring-in (Ruiz et al., 2006). In addition, proper choices of process conditions can reduce cycle time and energy consumption in a molding cycle (Yu et al., 1997). The research on curing process optimization can be found in numerous literatures. Chen et al. (1993) analyzed the effect of humidity upon residual stresses of composite laminates after the termination of cool down. Yu et al. (1997) used a generic algorithm (GA) to search for optimal or near optimal molding cycle which can reduce the cycle time and improve property uniformity of a composite part. Michaud et al. (2002) developed a simulation based optimization procedure to identify conditions resulting optimal part quality and processing time for a thick RTM part. Ruiz et al. (2006) divided the temperature profile of a liquid composite molding (LCM) process into a series of heating/cooling ramps and dwell times as shown in figure 2.11. They proposed a numeric optimization model consisting of seven objectives: the minimum cycle time, maximum extent of cure, minimum exothermic temperature, minimum cure gradients and minimum curing and cooling stresses.

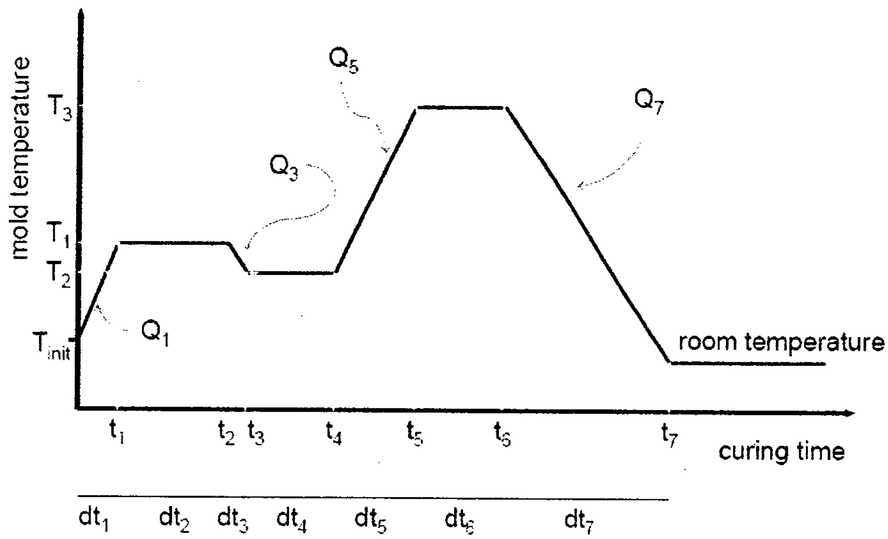

Figure 2.11 Discretization of temperature profile of an LCM process (adapted from Ruiz et al., 2006)

The development of curing process optimization methods and software has provided useful tools and become complement to the often used experience based process design and control of LCM.

2.4 Wind Turbine Blades Production Process

Koefoed (2002) listed five steps of VARTM manufacturing process for wind turbine blades. TPI (2003) divided the blade manufacturing process into 12 major steps in terms of labour tasks. We generalize that the typical production process for wind turbine blade includes the following steps.

1. Preparing materials and moulds.

In this step, different types of glass fibre fabrics and core materials are cut into required shapes to facilitate lay-up. Gel coat material is sprayed into blade skin moulds to form a layer of protector on blade surface.

2. Materials lay-up into moulds.

Pre-cut fibre reinforcements, fabrics in roll and core materials are laid up in designed sequence into a mould. On top of the preform, there is a layer of peel ply making it possible to separate cured composite structure from the vacuum bag. The final layer is the vacuum bag which is sealed at the edge of a mould.

3. VARTM process.

4. Assembly preparation.

Some components and sub-parts such as shear webs and lightning conductor are installed in this step.

5. Bonding.

Adhesive is applied to joint the blade halves and shear webs. The integral wind turbine blade is formed after this step.

6. Removed from moulds.

7. Finishing (cutting and grinding).

8. Inspection.

9. Testing.

During the whole production process, steps 1, 2, 4, 5 and 7 are more labour intensive and require the most of worker hours, while the other steps are mainly machine work.

2.5 Facilities Layout

Facilities layout design influences production efficiency, capacity, flexibility, product quality, work environment safety, and eventually influences a company's operation performance and cost. Production process required for producing a product is the basic factor to determine production facilities layout. Production process can be categorized into job shop, batch, assembly line, and continuous flow. The most suitable production process for wind turbine is job shop for which similar job tasks are grouped together to form different job centers performing different tasks. Then the whole process of the wind turbine blade production can be carried out by four job centers, shear webs, low pressure and high pressure skins, bonding and finishing, and inspection. Minimizing materials transportation distance and effort is a major objective of optimizing facilities layout. For wind turbine blade, the length constrains the movements within a plant. With this concern, TPI (2003) reviewed a number of conceptual designs of plant layout in their cost study of wind turbine blade manufacturing. They concluded that linear flow arrangement can simplify movement of blades through the facility. Besides minimizing effort on materials and products flow, minimizing changeover time and effort is another objective of plant layout design. Changeover of production of blades requires at least movement of moulds which have similar sizes or even bigger sizes than blades.

Obviously, linear flow arrangement also provides ease of changeover thus lower changeover time and cost. The concept of linear flow wind turbine blade plant layout is shown in figure 2.12.

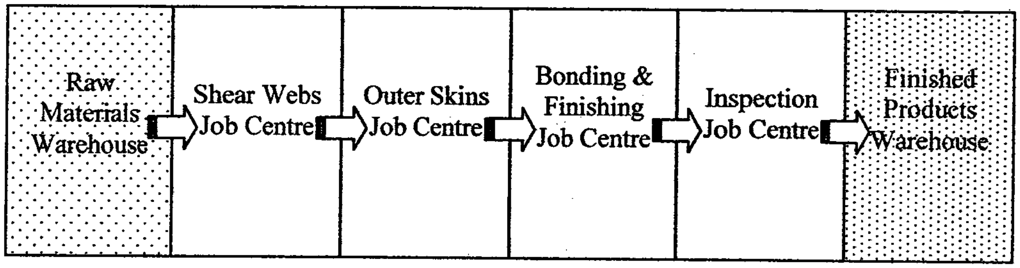

Figure 2.12 Linear flow blade plant layout concept

2.6 Transportation

Transportation of wind turbine blades becomes a critical issue as the size of blade is growing. With the increase of wind turbine blades size, the transportation cost increases significantly and may be prohibitive for long-haul ground transportation when the length is over 61m (Griffin, 2002). Wind turbine blades transportation studies can be found in the research works of Smith (2001) and TPI (2003). According to their study, the following aspects of blade transportation are major issues affecting transportation cost.

Transportation method.

The common wind turbine blades transportation modes are tractor-trailer, railroad, steerable dolly, barge and chartered ocean or lake vessels. Capacity and freight are different for different transportation methods. The selection of transportation methods is determined by the location of a plant and its access to transportation channels such as road, railway and water.

Number of wind turbine blades to be transported.

The long term disruption of traffic and inconvenience to local populations would be considered intrusive. Furthermore, the cyclical stress of multiple over-dimensioned loads could significantly increase the possibility of failure. These two reasons make it difficult to obtain permits for large numbers of shipments (Smith, 2001).

Loaded height.

Overhead clearance is a major constraint for transportation through old urban or rural areas. In spite of careful route selection, it is probable that such areas can be encountered in the route of blades transportation. In order to pass the low utility areas, some utility lines may be required to be temporarily disconnected. Transportation cost will be very high because of the charges for service disruption, activity planning, etc.

Seasonal transportation limit for overweight and oversized objects.

In some roads, transportation of overweight objects are highly limited or prohibited during some seasons, e.g. spring when frozen ground is thawing. In some agricultural areas, transporting oversized objects is limited during busy agricultural seasons such as spring and autumn. In congested urban areas, it is prohibited to transport oversized goods during rush hours. These limitations must be respected for wind turbine blades transportation.

2.7 Composite Manufacturing Cost Studies

Cost studies on composite manufacturing can be found in many literatures. Eaglesham (1998) studied the cost for aerospace composite manufacturing using activity-based costing methodology and developed a decision support system for advanced composite manufacturing cost estimation. The purpose of the system is to provide more accurate product cost estimation at the product design phase and to help to achieve design and manufacturing cost reduction. In his work, the assumption is that operations are in computer integrated manufacturing (CIM) environment in which computer aided process planning and production scheduling is one of the essential conditions.

Schubel (2009) conducted technical cost analysis on manufacturing process of 45-metre wind turbine blades using vacuum infusion to identify important cost factors on overall production cost. Effects of factors were studied by varying the values of variables, such as labour cost, programme life time, component area, deposition time, cure time and reinforcement price.

Joosse et al. (2002) investigated cost effective application of carbon fibres in large wind turbine blades manufacturing. They did experiments with a variety of material combinations and tested mechanical performances of the samples. They concluded that the application of carbon fibres in T-bolt joint and spar can result in high fatigue performance and reduced cost of making large blades.

Jureczko et al. (2005) developed a numerical wind turbine blade optimization model. The cost study was mainly focused on minimizing material cost through optimal blade design.

Barlow et al. (2002) developed a procedure to estimate the cost of manufacturing aircraft composite components using RTM and VARTM. The study examined each production step of RTM and VARTM, and assigned cost equations to all the production process steps. Manufacturing cost was estimated based on processing time and labour hours required for production steps.

Veldsman and Basson (1998) discussed the importance of cost estimation models for low to medium volume RTM production, and pointed out that the application of cost estimation models can facilitate composite product design process and lower the overall product cost. They suggested that estimation for tooling cost, labour and consumable cost and material cost should be included in the model.

TPI (2003) conducted a thorough cost study for large wind turbine blades. They categorized blade cost into direct manufacturing cost, indirect manufacturing cost and transportation cost. Direct manufacturing cost was estimated by studying detailed bill of material and blade manufacturing labour tasks. Overhead, development and facility capacity and conceptual design were considered to estimate indirect manufacturing cost. Transportation costs were studied by comparing different transportation scenarios and identifying transportation constraints.

Verrey et al. (2006) compared manufacturing cost of thermoset and thermoplastic RTM processes for a composite automotive component. A technical cost model was used to analyze the cost of the two different manufacturing processes. Costs for materials, direct labour, overheads, equipment, energy, consumables, tooling, transportation and subcontract parts were compared respectively. Sensitivity analysis was conducted to identify main cost drivers and potential cost reduction directions. Their cost study established a way of selecting proper production strategies for economic production.

Most cost studies on composite manufacturing focus on product design, material selection and production technologies. However, researches on supply chain management and production planning of composite manufacturing are very limited. According to Ferreirinha et al. (1993), 27% of a product cost is determined by the decisions on production planning, work preparation, purchasing and material management, and 76% of a company's accounted expenditure is on these activities. Optimizing production plan, material purchasing plan, and finished product transportation plan will potentially contribute to wind turbine blade cost reduction. Chapter 3 will present a mathematical optimization model.

Chapter Three

Mathematical Model to Optimize Turbine Blade Supply Chain Cost

In this chapter, an MILP model of optimizing wind turbine blade supply chain cost is proposed with discussions on the following aspects.

- Description of the multi-site wind turbine blade manufacturing supply chain problem,
- Cost structure,
- Assumptions for the model,
- Notations and explanations, and
- Model formulation

3.1 Problem Description

It has been a common practice that manufacturers use multi-site production facilities and supply products to customers in different regions. In this thesis, the problem to be studied is based on the environment of multi-site wind energy turbine blades manufacturing. The follows are the description of the considered problem. The manufacturer uses multiple production sites. Each production site can produce different types of wind turbine blade. During the period under study, the company supplies products to several wind farms. Each plant can ship products to every customer as required. Figure 3.1 shows an example relationship network with two production sites and three customers.

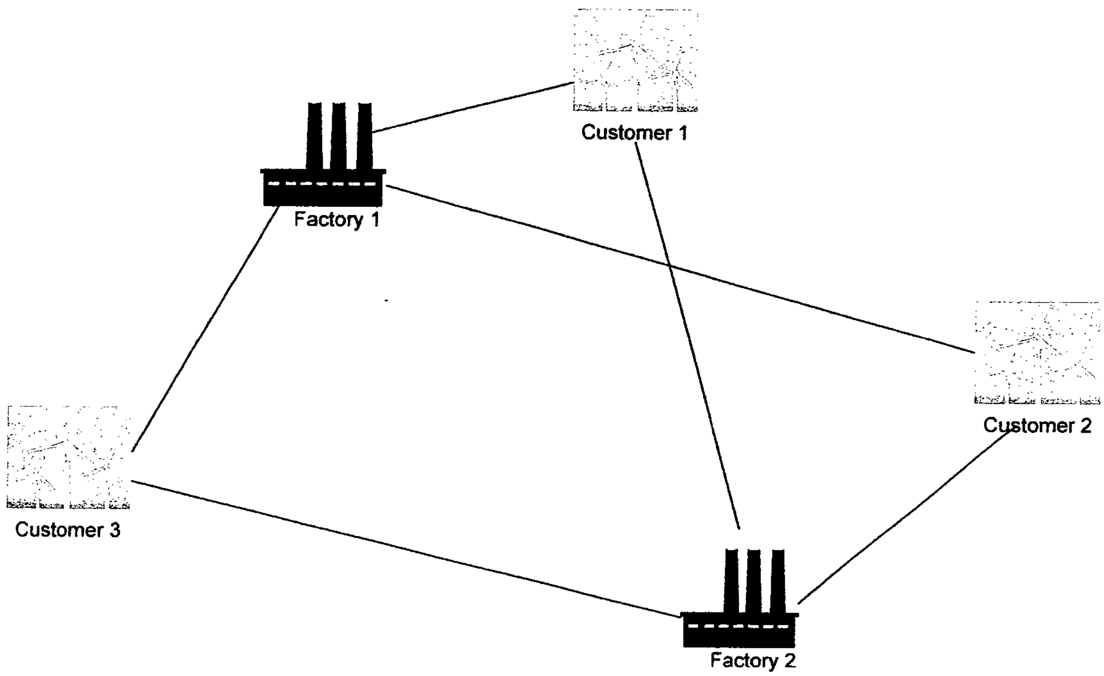

Figure 3.1 An example of relationship between products sites and customers

Customers place orders over certain period of time before they need the wind turbine blades to be delivered. Due to the seasonal feature of the demands, the company may encounter labour and equipment shortage or excessiveness, warehouse capacity limit and finished goods transportation limit problem. Orders for raw materials should be placed in order that each material arrives at the factory when its inventory level goes down to the safety stock. Order quantity is determined by production consumption and minimum order quantity. Finished goods production quantities may vary in different months, therefore, material requirements may be different in different months correspondingly.

We assume that the demands for wind turbine blades are seasonal. As a result, production can also be seasonal. Capacity planning is therefore critical. The facility capacity is determined by the maximum number of moulds that can be placed on production floor. Labour capacity is determined by number of workers at work. In slow seasons, workers can be laid off. In busy seasons, the plants will hire them back and recruit new workers if necessary. However, the change of work force level will cause costs of layoff and recruitment. Therefore the trade-off between keeping work force level and changing it need to be considered.

The size and weight of the wind turbine blade raise some special problems in wind turbine blades transportation, such as overweight, and over dimension which cause more difficulty in shipping them to customers. Government regulations require that overweight and over dimensional goods can only be transported under limited conditions. Therefore, transportation cost is a considerable factor and also a main cost driver composing the total supply chain cost of wind turbine blades manufacturing.

An MILP model is formulated to solve these problems by minimizing the relevant costs, and thus optimizing the total profit of the company. The objective of the model is to minimize the relevant operation costs including raw material purchasing and inventory cost, production cost, and finished product inventory and transportation cost. The model is consisted with the logic of an MRP system. First, the global shipping plan should meet customers' needs by their deadlines. Production plan then should satisfy the shipping plan, and raw materials should be ready before planned production. At the same time, other constraints such as facility capacity, manpower capacity, warehouse capacity, and transportation capacity also need to be satisfied.

3.2 Cost Structure

The costs considered in developing the model are raw materials purchasing and inventory cost, production cost, and finished products inventory and transportation cost.

3.2.1 Raw Materials Purchasing and Inventory Cost

The cost for raw materials can be categorized into two parts: fixed cost and variable cost. Fixed cost here is the ordering cost which happens when a purchase order is placed. It is independent of the quantity or amount in the order but related to the times of orders placed. Variable inventory cost includes materials cost and inventory carrying cost. Materials cost is the major inventory cost which is directly related to the amount or quantity of the orders. Inventory carrying cost is the cost for storing and handling materials inventory. It is directly proportional to the level of inventory kept in stock. Combining small orders into fewer big orders may lower total ordering cost. However, doing this may increase inventory carrying cost. The model will consider the trade-offs between fixed ordering cost and variable inventory cost.

3.2.2 Production Cost

Production cost includes direct costs and indirect costs. Direct costs consist of labour cost, and unit production cost such as electricity cost, and the cost of resources consumed in production. All the direct costs are variable costs. Indirect costs include overhead costs and other costs not directly related to production of individual blades. They also include development costs which are involved in products design, documentation, etc. The overhead costs and development costs are fixed costs. Other indirect costs are facilities costs which are the costs of building the plants, purchasing and installing equipment, and mould tooling costs. The plant and equipment costs are fixed costs but mould tooling costs are variable costs as the moulds may be used for producing a certain number of blades. There are also other costs related to production, such as changeover cost, hiring cost and layoff cost. Setup cost occurs when production changes from one type of blade to another. Setup includes obtaining tools, positioning work in process material, returning tooling, cleanup, setting the required jigs and fixtures adjusting tools, and inspecting material (Allahverdi et al., 1999). Changeover cost is the cost involved in these activities. More changeovers can increase total production cost and reduce production capacity. Hiring cost reflects training new workers, and the low productivity when a worker is new. Layoff cost is the compensation paid to the laid off workers.

3.2.3 Finished Product Inventory and Transportation Cost

Finished products inventory cost is mainly caused by storing and handling the finished products. Since wind turbine blades have very large dimensions, they require large or open space for storage. Because of their large size and mass, handling them takes more effort, and may even require special equipment. Obviously, it is desirable to have little or even no inventory of finished products in order to minimize the finished products inventory cost. However, keeping inventory may be inevitable due to limited production capacity and varying customers' demands. The level of inventory kept in each period at each production site should be considered together with other factors so that all the demands are met on time with the lowest total supply chain cost.

The large size of wind turbine blades makes transporting them special. TPI Composites Inc. (2003) categorized the wind turbine blades transportation cost into five parts: freight, over-dimension charge, escort charges, permit, and return freight. In this study, we assume that only land transportation by tractor trailer (truck) is used. Using the TPI transportation cost categories, we consider that permit is a fixed cost which is charged by a state or province in the route of the transportation. All the other costs are variable costs which are relevant to transportation distances and the types of product transported. In our model formulation, we use an aggregate freight cost to represent the combination of the five costs. The calculation procedure will try to ship products to a customer from the closest production site so that transportation cost can keep as low as possible. However, due to production capacity, finished products warehousing capacity, transportation limit, or other factors, we may have to ship products to a customer from other production sites.

3.3 Assumptions

The following assumptions are made for the model development.

Demand

(1) Demands from all customers are known and fixed 12 months prior to the products require dates.

(2) All customer demands must be satisfied by their deadlines.

Raw materials

(3) Raw material purchasing lead-time is known.

(4) Ordered raw materials should arrive at the plant when the inventory level reaches the safety stock.

Production

(5) At one time, only one type of product can be produced in any plant.

(6) Similar to the planning model developed by Timpe and Kallrath (2000), there is only one possible production changeover at any plant within each period.

Finished products warehousing and transportation

(7) At the beginning of the first month, finished products inventory is 0 at each plant.

(8) Finished products are shipped out before or in the month when they are needed by customers.

3.4 Mixed Integer Linear Programming Model Formulation

The development of a mixed integer linear programming model will be discussed below.

3.4.1 Notations and Explanations

Indices:

i = index of product types, $i \in \{1,...I\}$.

j = index of customers, $j \in \{1,...J\}$.

f = index of plants, $f \in \{1,...F\}$.

u = index of raw materials, $u \in \{1,2,3\}$.

m = index of months, $m = \{1,...,12\}$.

Parameters and variables:

(1) Demand

D_{ijm} = demand, $\forall i, j, m$

(2) Raw materials

FC_u = fixed ordering cost, $\forall u$

UC_u = unit material cost, $\forall u$

IC_u = unit inventory carrying cost, $\forall u$

R_{ui} = usage of raw material, $\forall u, i$

MOQ_u = minimum order quantity of raw material, $\forall u$

OQ_{um} = raw material order quantity, $\forall u, m$

RB_{ufm} = beginning stock of raw material, $\forall u, f, m$

SF_u = safety stock of raw material, $\forall u$

$$O_{ufm} = \begin{cases} 1 & \text{order placed} \\ 0 & \text{otherwise} \end{cases}, \forall u, f, m$$

(3) Production

PQ_{ifm} = production quantity, $\forall i, f, m$

FEC_f = fixed monthly equipment cost, $\forall f$

UEC_{if} = unit equipment cost for producing one product, $\forall i, f$

PR_i = mould production rate, $\forall i$

LR_i = worker hours required per unit of product, $\forall i$

NP_{ifm} = number of days of product production, $\forall i, f, m$

NM_{if} = number of moulds available, $\forall i, f$

L_{fm} = number of workers, $\forall f, m$

LC_f = unit labour cost, $\forall f$

LW_{fm} = number of workers laid off, $\forall f, m$

$$LO_{fm} = \begin{cases} 1 & \text{layoff occurs} \\ 0 & \text{otherwise} \end{cases}, \quad \forall f, m$$

LOC_f = unit layoff cost, $\forall f$

RW_{fm} = number of new workers recruited, $\forall f, m$

$$EM_{fm} = \begin{cases} 1 & \text{recruiting occurs} \\ 0 & \text{otherwise} \end{cases}, \quad \forall f, m$$

EMC_f = unit recruiting cost, $\forall f$

CC_f = changeover cost, $\forall f$

CT_f = changeover time, $\forall f$

$$\alpha_{ifm} = \begin{cases} 1 & \text{product in production at the beginning of a month} \\ 0 & \text{otherwise} \end{cases}, \quad \forall i, f, m$$

$$\beta_{ifm} = \begin{cases} 1 & \text{product in production in the end of a month} \\ 0 & \text{otherwise} \end{cases}, \quad \forall i, f, m$$

$$\gamma_{ifm} = \begin{cases} 1 & \text{product in production in a month} \\ 0 & \text{otherwise} \end{cases}, \forall i, f, m$$

$$\delta_{ifm} = \begin{cases} 1 & \text{production state change between month } m\text{-1 and month } m \\ 0 & \text{otherwise} \end{cases}, m = 2,\ldots,12, \forall i, f,$$

$$\sigma_{ifm} = \begin{cases} 1 & \text{production state change within a month} \\ 0 & \text{otherwise} \end{cases}, \forall i, f, m$$

(4) Finished products inventory and transportation

DF_i = size of finished product, $\forall i$

DL_f = finished product storing capacity, $\forall f$

HC_i = finished product unit monthly storage cost, $\forall i$

FB_{ifm} = beginning stock of finished product, $\forall i, f, m$

UTC_i = unit product transportation cost, $\forall i$

S_{fj} = distance between plant and customer, $\forall f, j$

PC_{ifj} = oversize and overweight permit charge, $\forall i, f, j$

TL_{ifjm} = product monthly transportation limit, $\forall i, f, j, m$

TQ_{ifjm} = transportation quantity, $\forall i, f, j, m$

3.4.2 Mathematical Model

The structure of the model is shown in Figure 3.2. It contains three modules: raw material, production, finished product distribution. Production module is the core of the model and it interacts with the other two modules and links them together to form an integrated model.

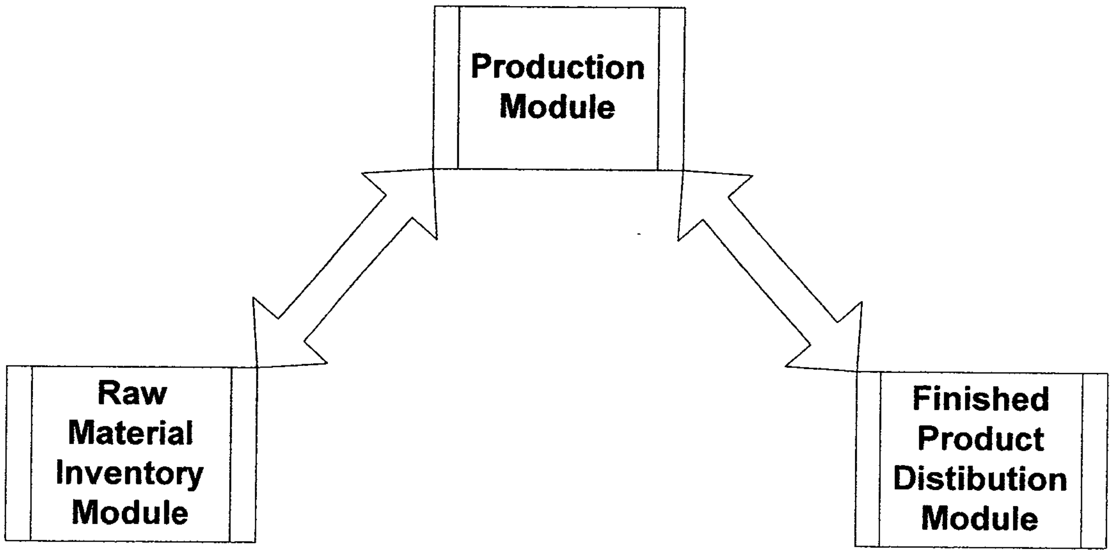

Figure 3.2 Model structure

3.4.2.1 Formulating costs of each module

Raw materials inventory cost

As discussed before, demands for finished products are not constant. As a result, production quantity and material requirement at a production site may be different in different periods. Clearly, the traditional EOQ model does not apply to this situation. Wagner and Whitin (1958) proposed a dynamic economic lot size model for the inventory control problem with demands varying over N periods. The idea of the algorithm is to enumerate all the alternatives of placing an order in period n_1 ($n_1 = 1, \ldots N$) to cover the demand from period n_1 to n_2 ($n_2 \geq n_1$) by this order. An order policy is a combination of alternatives so that orders are placed in certain periods and fills demands of certain periods from the order periods on. Inventory carrying cost and fixed ordering cost are considered for each order policy and the one with the lowest total inventory cost is the optimal solution. We implement this algorithm to the raw material module. Our inventory cost problem can be visualized as a shortest path problem in a network shown in Figure 3.3. Each node represents a period, and the arch connecting two nodes n_1 and n_2 represents that order quantity of period n_1 covers materials requirements from period n_1 to period n_2.

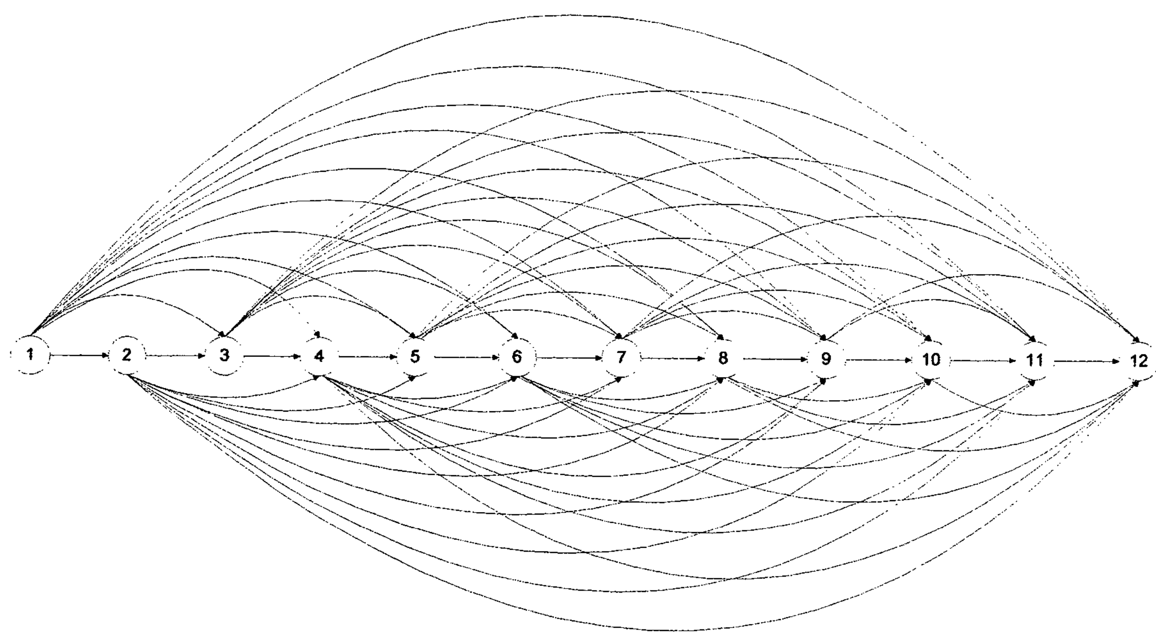

Figure 3.3 A network demonstrating all of path possibilities from node 1 to node 12

Then the raw materials inventory cost can be formulated as:

$$RIC = \sum_{m=1}^{12} \sum_{f=1}^{F} \sum_{u=1}^{U} (O_{ufm} \times FC_u + OQ_{ufm} \times UC_u + RB_{u,f,m+1} \times IC_u) \qquad (3.1)$$

Production cost

Production cost includes fixed facility cost, variable equipment cost, labour cost, layoff cost, recruiting cost and production changeover cost.

- Fixed facility cost:

$$FFC = \sum_{m=1}^{12} \sum_{f=1}^{F} FEC_f \tag{3.2}$$

- Variable equipment cost:

$$VEC = \sum_{f=1}^{F} \sum_{m=1}^{12} \sum_{i=1}^{I} PQ_{ifm} \times UEC_{if} \tag{3.3}$$

- Labour cost:

$$LBC = \sum_{f=1}^{F} \sum_{m=1}^{12} L_{fm} \times LC_f \tag{3.4}$$

- Layoff cost:

$$LFC = \sum_{f=1}^{F} \sum_{m=2}^{12} LW_{fm} \times LOC_f \tag{3.5}$$

- Recruiting cost:

$$REC = \sum_{f=1}^{F} \sum_{m=2}^{12} RW_{fm} \times EMC_f \tag{3.6}$$

- Changeover cost:

$$CHC = \frac{1}{2} \sum_{m=1}^{12} \sum_{f=1}^{F} \sum_{i=1}^{I} (\delta_{ifm} + \sigma_{ifm}) \times CC_f \tag{3.7}$$

Finished product inventory and transportation cost

Finished product inventory cost is formulated as:

$$FPIC = \frac{1}{2}\sum_{m=1}^{12}\sum_{f=1}^{F}\sum_{i=1}^{I}(FB_{ifm} + FB_{i,f,m+1}) \times HC_i \tag{3.8}$$

Finished product transportation cost contains freight and permit charge.

$$FPTRC = \sum_{m=1}^{12}\sum_{i=1}^{I}\sum_{f=1}^{F}\sum_{j=1}^{J} TQ_{ifjm} \times (UTC_{ifj} \times S_{fj} + PC_{ifj}) \tag{3.9}$$

3.4.2.2 The Objective Function

The objective function of the model is given below.

Minimize:

Z = Raw Material Inventory Cost

+ Production Cost

+ Finished Products Inventory and Transportation Cost

Then the objective function can be written as

Minimize:

$$Z = RIC + FFC + VEC + LBC + LFC + REC + CHC + FPIC + FPTRC$$

$$= \sum_{m=1}^{12}\sum_{f=1}^{F}\sum_{u=1}^{U}(O_{ufm} \times FC_u + OQ_{ufm} \times UC_u + RB_{u,f,m+1} \times IC_u) +$$

$$\sum_{m=1}^{12}\sum_{f=1}^{F} FEC_f + \sum_{f=1}^{F}\sum_{m=1}^{12}\sum_{i=1}^{I} PQ_{ifm} \times UEC_{if} + \sum_{f=1}^{F}\sum_{m=1}^{12} L_{fm} \times LC_f +$$

$$\sum_{f=1}^{F}\sum_{m=2}^{12} LW_{fm} \times LOC_f + \sum_{f=1}^{F}\sum_{m=2}^{12} RW_{fm} \times EMC_f + \frac{1}{2}\sum_{m=1}^{12}\sum_{f=1}^{F}\sum_{i=1}^{I}(\delta_{ifm} + \sigma_{ifm}) \times CC_f +$$

$$\frac{1}{2}\sum_{m=1}^{12}\sum_{f=1}^{F}\sum_{i=1}^{I}(FB_{ifm} + FB_{i,f,m+1}) * HC_i + \sum_{m=1}^{12}\sum_{i=1}^{I}\sum_{f=1}^{F}\sum_{j=1}^{J} TQ_{ifjm} \times (UTC_{ifj} \times S_{fj} + PC_{ifj})$$

3.4.2.3 Constraints

The minimization of the objective function is subject to the following constraints.

Constraints of Raw Materials Module

Material orders should satisfy material requirements by production, and ensure materials stock above safety stock at any time.

$$RB_{ufm} + OQ_{ufm} \geq \sum_{i=1}^{I} PQ_{uifm} \times R_{ui} + SF_u, \ \forall u, f, m \qquad (3.10)$$

Constraint (3.10) also acts as a link between raw materials module and production module.

The beginning stock of raw materials in each month is calculated as follows:

$$RB_{u,f,m+1} = RB_{ufm} + OQ_{ufm} - \sum_{i=1}^{I} PQ_{uifm} \times R_{ui}\text{, } \forall u,f,m \tag{3.11}$$

Order quantity of each order should not be less than the minimum ordering quantity.

$$OQ_{ufm} \times O_{ufm} \geq MOQ_u\text{, } \forall u,f,m \tag{3.12}$$

O_{ufm} is a binary decision variable to indicate if an order should be placed for material u in month m for plant f. The value of O_{ufm} can be determined by the inequalities (3.13) and (3.14).

$$OQ_{ufm} \geq O_{ufm}\text{, } \forall u,f,m \tag{3.13}$$

$$O_{ufm} \times G \geq OQ_{ufm}\text{, } \forall u,f,m \tag{3.14}$$

where G is a very large number.

Constraints of production module

The total production quantity is limited by the total demands. The total production quantity of each product at all the plants should not exceed the total demand of that product by all the customers for the whole planning horizon.

$$\sum_{m=1}^{12}\sum_{f=1}^{F} PQ_{ifm} \leq \sum_{m=1}^{12}\sum_{j=1}^{J} D_{ijm}\text{, } \forall i \tag{3.15}$$

Production quantity is limited by facility capacity in terms of available number of sets of moulds used for production on the shop floor.

$$PQ_{ifm} \leq NM_{ifm} \times NP_{ifm} \times PR_i\text{, } \forall i,f,m \tag{3.16}$$

For composite wind turbine blade manufacturing, manpower has both functional flexibility and numerical flexibility. Functional flexibility allows workers to perform a variety of tasks throughout the entire production process. Therefore, labour capacities can be considered aggregately. The total number of workers in a month at a plant L_{fm} is used to determine the labour capacity in this model, which reflects the functional labour flexibility. The number of workers should satisfy production quantity based on worker hours required per product. We assume 22 working days per month and 8 working hours per day. Then,

$$22 \times 8 \times L_{fm} \geq \sum_{i=1}^{I} (PQ_{ifm} \times LR_i), \ \forall f, m \tag{3.17}$$

Numerical flexibility is the degree of workforce level change. Due to seasonal variation of customers' demands, production varies in response. Consequently requirement for workers changes seasonally. Constraints (3.18) ~ (3.26) are developed to formulate the workforce level change. If the number of workers exceeds what is needed, some workers may be laid off at a plant. Number of workers laid off LW_{fm} can be formulated with the inequalities (3.18), (3.19), (3.20) and (3.21).

A decision variable LO_{fm} is introduced to indicate if layoff happens.

$$L_{fm} - L_{f,m+1} \leq G \times LO_{f,m+1}, \ \forall f, m \tag{3.18}$$

$$L_{f,m+1} - L_{fm} < G \times (1 - LO_{f,m+1}), \ \forall f, m \tag{3.19}$$

The two inequalities above make sure that LO_{fm} is 1 when the number of workers in the previous month is larger than that in the current month, otherwise, it is 0. Then,

$$LW_{f,m+1} \leq G \times LO_{f,m+1}, \ \forall f, m \tag{3.20}$$

$$LW_{f,m+1} \geq L_{fm} - L_{f,m+1} + G \times (LO_{f,m+1} - 1), \ \forall f, m \tag{3.21}$$

Inequalities (3.20) and (3.21) ensure that LW_{fm} is a positive number when the number of workers in the previous month is larger than that in the current month, otherwise, it is 0.

If workers are not enough in any month, the company will recruit new workers. Number of workers recruited RW_{fm} is governed by the following relations where EM_{fm} is the decision variable indicating if new workers are recruited.

$$L_{f,m+1} - L_{fm} \leq G \times EM_{f,m+1},\ \forall f,m \tag{3.22}$$

$$L_{fm} - L_{f,m-1} < G \times (1 - EM_{f,m+1}),\ \forall f,m \tag{3.23}$$

$$RW_{f,m+1} \leq G \times EM_{f,m+1},\ \forall f,m \tag{3.24}$$

$$RW_{f,m+1} \geq L_{f,m+1} - L_{fm} + G \times (EM_{f,m+1} - 1),\ \forall f,m \tag{3.25}$$

At a plant, in any month, layoff and recruiting cannot happen at the same time. Then,

$$LO_{fm} + EM_{fm} \leq 1,\ \forall f,m \tag{3.26}$$

Changeover is a significant factor for wind turbine blade manufacturing. There are considerable setup time and setup cost when changeover takes place. Production sequence affects the number of changeovers. Constraints (3.27) ~ (3.41) are specifically to formulate production changeover and sequence in this model. Production state variables α_{ifm} and β_{ifm} indicate what product plant f is in the state of at the beginning and the end of month m. As discussed, one plant can only be in the state of one product at one time. Therefore,

$$\sum_{i=1}^{I} \alpha_{ifm} = 1,\ \forall f,m \tag{3.27}$$

$$\sum_{i=1}^{I} \beta_{ifm} = 1,\ \forall f,m \tag{3.28}$$

State variable γ_{ifm} indicates if plant f is in the state of product i within the month m. α_{ifm}, β_{ifm} and γ_{ifm} can mutually affect each other, and the relationship among them is,

$$\alpha_{ifm} + \beta_{ifm} \geq \gamma_{ifm}, \ \forall i, f, m \tag{3.29}$$

γ_{ifm} is also determined by the production quantity of a product.

$$PQ_{ifm} \geq \gamma_{ifm}, \ \forall i, f, m \tag{3.30}$$

$$PQ_{ifm} \leq G * \gamma_{ifm}, \ \forall i, f, m \tag{3.31}$$

There are two production state change variables. δ_{ifm} represents production state change between month *m-1* and month *m*. σ_{ifm} represents state change within month *m*.

$$\alpha_{i,f,m+1} - \beta_{ifm} \leq \delta_{i,f,m+1}, \ \forall i, f, m \tag{3.32}$$

$$\beta_{ifm} - \alpha_{i,f,m+1} \leq \delta_{i,f,m+1}, \ \forall i, f, m \tag{3.33}$$

$$\beta_{ifm} + \alpha_{i,f,m+1} \geq \delta_{i,f,m+1}, \ \forall i, f, m \tag{3.34}$$

$$\alpha_{i,f,m+1} + \beta_{ifm} + \delta_{i,f,m+1} \leq 2, \ \forall i, f, m \tag{3.35}$$

The four inequalities above ensure that δ_{ifm} is 1 if $\beta_{ifm} \neq \alpha_{i,f,m+1}$, and δ_{ifm} is 0 if $\beta_{ifm} = \alpha_{i,f,m+1}$. Similarly, for σ_{ifm}, we have,

$$\alpha_{ifm} - \beta_{ifm} \leq \sigma_{ifm}, \ \forall i, f, m \tag{3.36}$$

$$\beta_{ifm} - \alpha_{ifm} \leq \sigma_{ifm}, \ \forall i, f, m \tag{3.37}$$

$$\alpha_{ifm} + \beta_{ifm} \geq \sigma_{ifm}, \ \forall i, f, m \tag{3.38}$$

$$\alpha_{ifm} + \beta_{ifm} + \sigma_{ifm} \leq 2, \ \forall i, f, m \tag{3.39}$$

As assumed, only one time of changeover is possible in each month. Then,

$$\sum_{i=1}^{I} \gamma_{ifm} - 1 \leq \frac{1}{2} \sum_{i=1}^{I} \sigma_{ifm}, \ \forall f, m \tag{3.40}$$

and,

$$\sum_{i=1}^{I} \gamma_{ifm} \geq \sum_{i=1}^{I} \sigma_{ifm}, \; \forall f, m \tag{3.41}$$

In each month, the total number of production days plus the changeover time cannot exceed 22 days.

$$\sum_{i=1}^{I} NP_{ifm} + \frac{1}{2} \sum_{i=1}^{I} (\delta_{ifm} + \sigma_{ifm}) \times CT_f \leq 22, \; \forall f, m \tag{3.42}$$

<u>*Constraints of finished product distribution module*</u>

Beginning stock of finished product of the first month is assumed to be 0.

$$FB_{i,f,1} = 0, \; \forall i, f \tag{3.43}$$

The inventory of finished product at the beginning of each month can be calculated as below.

$$FB_{i,f,m+1} = FB_{ifm} + PQ_{ifm} - \sum_{j=1}^{J} TQ_{ijfm}, \; \forall i, f, m \tag{3.44}$$

Because customers' demands should be satisfied by the deadlines, the cumulative shipped quantity of finished products from the first month to any month should not be less than the cumulative customers' demands.

$$\sum_{m=1}^{M} \sum_{f=1}^{F} TQ_{ijfm} \geq \sum_{m=1}^{M} D_{im}, \text{ for } M\text{=1, …, 12, } \forall i, j \tag{3.45}$$

There are transportation limits for shipping wind turbine blades inland, which makes transporting this product a special problem. Due to overweight and over-dimension regulation, blade transportation quantity of any month from plants to customers should not exceed the limit of that month. Constraint (3.46) only applies to the transportation problems considering oversized and overweight products.

$$TQ_{ifjm} \le TL_{ifjm},\ \forall i,f,j,m \tag{3.46}$$

Total space occupied by finished product in any month should not exceed the capacity of finished product warehouse.

$$\sum_{i=1}^{I}(FB_{ifm} + PQ_{ifm} - \sum_{j=1}^{J} TQ_{ifjm}) \times DF_i \le DL_f,\ \forall f,m \tag{3.47}$$

For each plant, the cumulative shipped finished products quantity from the first month to any month can not be larger than the cumulative production quantity from the first month to any month.

$$\sum_{m=1}^{M}\sum_{j=1}^{J} TQ_{ifjm} \le \sum_{m=1}^{M} PQ_{ifm},\ M=1, \ldots, 12,\ \forall i,f \tag{3.48}$$

(3.47) and (3.48) are common constraints between production module and finished product distribution module.

3.4.2.4 Specialities of Composite Wind Turbine Blade Manufacturing

The special features of wind turbine blade manufacturing are labour flexibility, production changeover and transportation limits. How these specialities are reflected in the mathematical model is discussed below.

Labour flexibility

In the considered wind turbine blade manufacturing process, workforce planning can be more flexible comparing to that in other production systems such as computer aided machining. The labour flexibility can be fulfilled with multi-skilled workers. A team of trained workers are likely able to work through the entire turbine blade manufacturing process with a variety of tasks. For example, during resin injection and curing process, workers who lay up preform fabrics can, with proper training, work satisfactorily in assembling, bonding, finishing and inspection job stations. This feature makes manpower planning for wind turbine blade production different from that of many other types of production, e.g. automobile production, electronics production and steel production in which each worker can only perform limited types of tasks. Training multiple skilled workers in those industries is normally very expensive. Wijngaard (1983) categorized production manpower in two dimensions, level and function. He pointed out that both horizontal (function) and vertical (level) flexibilities can determine the extent of aggregation of manpower planning. Due to the functional labour flexibility of wind turbine blade production, manpower can be planned in an integrative way. In the production planning model presented in this section, constraint (3.17) limits the production capacity by the total number of available workers instead of the number of workers working on each single production step. Functional flexibility provides an alternative form of coping with variance to numerical flexibility (Riley and Lockwood, 1997). Then the change on workforce level is formulated with the aggregate number of workers by constraints (3.18) ~ (3.26). The aggregate workforce planning is a more realistic feature for wind turbine blade production comparing to that in other production systems. One of the advantages of production with labour flexibility is that it allows adjustment to temporary overloads in shop (Felan III et al., 1993). It also enables a company to utilize labours efficiently especially during the production slow season. In spite of the cost for providing cross-training to workers, increasing labour flexibility may improve production performance (Felan III et al., 1993).

Production changeover

Since each plant can produce more than one type of wind turbine blade, facilities layout has to be flexible so that production can change from one type to another. However, due to the fact that the sizes of wind turbine blades and their moulds are very large, it takes longer time and more effort to setup the production line for a different product. Additionally, the size of wind turbine blades determines the way of facilities layout. Therefore, the floor layout may be different for the products with different sizes. This makes production sequence and changeover a considerable issue for wind turbine blade manufacturing. Minimizing changeover cost and time is one of the major objectives of the model. Constraints (3.27) to (3.46) of the production module in the math model were developed to formulate production sequence and changeover as they significantly affect the production capacity.

Transportation limits

Transportation limit is the special problem encountered for shipping wind turbine blades because their sizes are very large. Inequality (3.46) is assigned to constrain the transportation quantities with transportation limits.

This MILP model has limited number of binary integer variables and can be solved directly using off-shelf optimization software package on common platforms such as a PC. In this research we used LINGO to obtain optimal solutions for different cases of an example problem. Details are presented in the next chapter.

Chapter Four

Numerical Example and Analysis

In this chapter, the solution of a numerical example with the developed model is presented. The mathematical model is programmed in LINGO and solved on a PC with AMD Turion dual core processor of 1.8GHz and 1982MB memory (RAM). The optimal solution with a reasonable tolerance 0.1% was obtained. In the later part of the chapter, sensitivity analysis is carried out to show how cost factors affect production and transportation planning decisions and the total supply chain cost, and to identify the most important cost drivers.

4.1 Example problem

In the considered example problem, a composite wind turbine blade manufacturer has two plants ($f = 2$) producing two types of wind turbine blades ($i = 2$) of 30-meter and 50-meter lengths respectively. Both plants can produce these two types of products. During the planning horizon which is 12 months, the two plants supply their products to 3 wind farms ($j = 3$). Due to confidentiality of the composite industry, it is difficult to obtain and use the real data of any wind turbine blade manufacturing company. The data used in this example problem are mostly adapted or derived from published literatures with some slight adjustments but still reflect the nature of composite wind turbine blade manufacturing. The data and the discussion about their rationality are given below.

According to WWEA (2009), in year 2008, the worldwide total installed wind power capacity had reached 121,188 mW with the newly installed capacity of 27,261 mW. It is forecasted that the total installed capacity will reach 152,000 mW in 2009 and 190,000 mW in 2010. By 2020, the global capacity will be more than 1,500,000 mG based on the forecasted growth rate. Obviously, the demand for wind turbine blades keeps growing every year. If we convert installed capacity to the numbers of wind turbines with 30 meter blades or 50 meter blades, in 2010, 95,000 units of 30 meter blades or 32,600 units of 50 meter blades will probably be needed to build wind farms globally. The scale of current wind farms ranges from a few to several hundreds of wind towers (Wikipedia 1). We believe that larger wind farms will be built in the future. In the example problem of our study, the customers are 3 hypothetical to-be-built large wind farms with turbine blade demands as shown in Table 4.1.

Table 4.1 Finished product demand matrix

Month	1	2	3	4	5	6	7	8	9	10	11	12
30m Blade												
Customer 1	0	0	0	45	60	54	54	45	0	0	0	0
Customer 2	0	0	0	0	0	0	0	0	0	0	0	0
Customer 3	0	0	45	60	60	60	60	60	60	0	0	0
50m Blade												
Customer 1	0	0	0	0	0	0	0	0	0	0	0	0
Customer 2	0	0	0	0	90	90	108	150	120	90	81	90
Customer 3	30	54	0	0	0	0	0	0	0	0	0	0

The assumed distances between the plants and the customers are listed in Table 4.2.

Table 4.2 Distances between plants and customers

	Customer 1	Customer 2	Customer 3
Plant 1	90	550	960
Plant 2	1080	720	180

For blade transportation cost, detailed studies can be found in Smith (2001) and TPI (2003). Smith (2001) studied logistic costs of major components of wind turbines in the United States. South Dakota was the considered destination, turbine blades were assumed to be delivered through short haul and long haul distances. Different inland transportation methods for shipping blades were examined. It was proposed that truck be used for blades of 750-kW to 2500-kW turbines, and rear-steering equipment be added for blades of turbines over 3500 kW. Oversized load permit of the States on the assumed shipping routes were considered in the study. It was estimated that the transportation cost per load for 750-kW to 2500-kW blades ranges from \$4.74 to \$5.50 per mile, and the cost for moving 3500-kW blades is about \$9.50 per mile. Considering cost effective factors and the constraints of oversize and overweight limits, Smith (2001) assumed that two 2500-kW blades or one 3500-kW blade can be transported per load. To convert the power ratings to blades sizes, we can use the data in Table 2.1 and interpolate for particular sizes. Then 30 meter blades correspond to power rating about 1200 kW, and 50 meter blades correspond to 3500 kW power output. We assume that two 30 meter blades can be put on one load while a single 50 meter blade consists of one load.

The blade transportation cost study in TPI (2003) was based on the assumption that an existing manufacturing facility and the other two evaluated plant locations supply blades to wind farms in different regions of the United States. 30 meter, 50 meter and 70 meter blades were the objects of the study. The authors of the study considered tractor trailer size and weight limits and blade size and weight constraints for different States. The transportation cost was categorized into freight, overdimension charge, escort charges, permits and return freight. Their estimated blade transportation cost fell in a similar range as shown in Smith (2001). We adapted the TPI transportation cost category in this thesis. Since the available blade transportation data are limited, our transportation costs are generated by slightly adjusting the data from those reported in these two study reports. The transportation cost data used in this thesis research are shown in Tables 4.3, 4.4 and 4.5.

Table 4.3 Freight cost (dollar/blade·km)

	Freight	Overdimension Charge	Escort Charge	Return Freight	Total
30m Blade	0.60	0.45	0.53	0.42	2.00
50m Blade	1.92	1.50	1.74	0.84	6.00

Table 4.4 Permit charge for 30m blade (dollars/blade)

	Customer 1	Customer 2	Customer 3
Plant 1	50	150	200
Plant 2	200	150	50

Table 4.5 Permit charge for 50m blade (dollars/blade)

	Customer 1	Customer 2	Customer 3
Plant 1	75	225	300
Plant 2	300	225	75

Smith (2001) stated that "state officials are generally more accepting of one or a few oversized/overweight transport loads as opposed to 50 or 150 shipments". In certain seasons, transportation for overdimension goods is prohibited on some roads. Based on this information, we generated the transportation limits given in Tables 4.6 and 4.7.

Table 4.6 Transportation limits for 30m blade

Month		1	2	3	4	5	6	7	8	9	10	11	12
Plant 1	Customer 1	90	90	30	30	90	90	90	45	30	30	90	90
	Customer 2	90	90	0	0	90	90	90	90	60	60	60	60
	Customer 3	30	30	0	0	30	30	30	30	0	0	30	30
Plant 2	Customer 1	60	60	0	0	60	60	60	60	0	0	60	60
	Customer 2	60	60	30	30	90	90	90	90	30	30	60	60
	Customer 3	90	90	0	0	90	90	90	45	30	30	90	90

Table 4.7 Transportation limits for 50m blade

Month		1	2	3	4	5	6	7	8	9	10	11	12
Plant 1	Customer 1	60	60	20	20	60	60	60	30	20	20	60	60
	Customer 2	60	60	0	0	60	60	60	60	40	40	40	40
	Customer 3	20	20	0	0	20	20	20	20	0	0	20	20
Plant 2	Customer 1	40	40	0	0	40	40	40	40	0	0	40	40
	Customer 2	40	40	20	20	60	60	60	60	20	20	40	40
	Customer 3	60	60	0	0	60	60	60	30	20	20	60	60

We estimate the storage space occupation of the two types of blades by their dimensions. We assume that the finished product inventory carrying rate is 2% per month. The discussion about inventory carrying cost will be presented in the part of raw material inventory data. The finished products storage data are listed in Table 4.8. We also assume that the finished product storage capacity is 9,000 m^3 at plant *1*, and 15,200 m^3 at plant *2*.

Table 4.8 Finished product sizes and storage costs

	Space Occupation (m^3)	Storage Cost (dollars/month)	
		Plant 1	Plant 2
30m Blade	86	550	540
50m Blade	380	2500	2300

TPI (2003) estimated blade manufacturing plant cost using floor area based on their conceptual floor layout design. Their designed 30 meter blade plant has 6 tooling sets and the 50 meter blade plant has 4 sets. The numerical example of our study considers two plants with larger capacities and plant layout is flexible to adapt to the production for different types of blades, which is assumed to require 20% more floor area to allow layout change. When estimating the fixed facility cost, we also consider finished product storing area, parking area, and shipping area which doubles the total plant area. TPI (2003) also estimated initial tooling cost for the three types of blades that they studied. We derived the unit equipment cost based on their tooling cost data and the assumption of 400 cycles of mould lifetime. Required worker hours are directly adapted from the TPI report, and mould rates were derived from the capacity of conceptually designed facility layout. There is a wide variation on worker's salary around the world. Even in a same country, people on similar positions may have very different salaries in different regions. Since most of the data are based on manufacturing in the U.S., we generated labour cost data based on the same consideration. The current minimum wage in the U.S. ranges between \$5.15 and \$8.56 by States, and the federal minimum wage is \$7.25 (Wikipedia 2). In our example, we assume that the workers' hourly salaries are about 35% to 133% above the minimum wages. For lay-off cost, we assume that the company need to pay for 4% of the workers working hours of the current year. Recruiting cost is assumed with the consideration of costs involved in hiring or calling back workers, training, and low productivity due to new workers.

Changeover significantly affects wind turbine blade production capacity and cost. Allahverdi et al. (1999) pointed out that setup cost is directly proportional to setup time when concern is only limited to machine idle time, and the cost is relatively high when other factors have to be considered. For wind turbine blade production, setup includes returning moulds, obtaining moulds, rearranging floor layout, adjusting tooling, material preparation, etc. Therefore setup cost cannot be estimated based on setup time only. In the example problems, setup time and cost are considered explicitly so that their significance can be reflected in the model. Data of production costs, time, and production rates are listed in Table 4.9 and Table 4.10.

Table 4.9 Production capacity and related costs

	Fixed Facility Cost (dollars/mth)	Unit Labour Cost (dollars/hr)	Unit Layoff Cost (dollars)	Unit Recruiting Cost (dollars)	Change - over Cost (dollars)	Change - over Time (days)
Plant 1	800000	12	300	672	8000	2
Plant 2	1100000	11.5	265	644	15000	3

Table 4.10 Production rates

	Unit equipment cost (dollars/product)		Mould rate (products/ mould·day)	Worker hours per product	Number of Moulds	
	Plant 1	Plant 2			Plant 1	Plant 2
30m Blade	600	620	0.91	450	10	15
50m Blade	1650	1700	0.46	1201	6	9

The usages of glass fibre fabrics, resin and core materials are adapted from the TPI blade bill of materials (BOM) whose calculation is based on known glass-to-resin ratios. Minimum order quantity and safety stock are determined by the inventory policy of each company. In our study, we assume that both plants keep sufficient safety stocks to produce 16 units of 30 meter blades or 8 units of 50 meter blades. There are numerous studies on inventory carrying cost. Richardson (1995) summarized that the average annual inventory carrying cost can be estimated by 25% to 55% of inventory value depending on the types of products and business. Some logistic experts use 18% to 75%

per year as the inventory carrying rate in practice. Fibre glass and core materials can be easily stored under normal conditions, hence their inventory carrying costs are relatively low. Thermosetting resins require higher storing conditions, and there is a chance to become obsolete because of their shelf life, so their inventory carrying cost is higher. We assume 2% per month as the inventory carrying rate for fibre glass, 4% for resin and 1.5% for core material. Material cost data are estimated by comparing the data in Griffin (2002) and TPI (2003). The data of raw material purchasing and inventory are shown in Table 4.11 and 4.12.

Table 4.11 Raw material inventory data

Material	Mininum Order Quantity (kg)	Safety Stock (kg)		Usage (kg/product)	
		Plant 1	Plant 2	30m Blade	50m Blade
Fiberglass	5000	20000	20000	2500	12000
Resin	10000	8000	8000	1250	5800
Core	2000	1000	1000	190	865

Table 4.12 Material inventory costs

Material	Fixed Ordering Cost (dollars/order)	Unit Cost (dollars/kg)	Monthly Inventory Carrying Cost (dollars/kg)
Fiberglass	900	4.2	0.08
Resin	1500	4.5	0.18
Core	700	6	0.09

4.2 Optimal Production Plan

The problem is formulated as an MILP model which has 501 continuous variables, 352 integer variables and 1642 constraints. The result of the optimal production plan includes production quantity, production sequence and workforce plan.

Production Quantity

The optimal monthly production quantities solved by the model are shown in Table 4.13.

Table 4.13 Optimal production plan

Month		1	2	3	4	5	6	7	8	9	10	11	12
Plant 1	30m blade	0	82	82	79	0	0	0	0	0	0	0	0
	50m blade	19	0	0	1	59	60	60	60	47	47	47	19
Plant 2	30m blade	0	79	88	88	0	0	90	45	30	0	0	0
	50m blade	29	55	20	20	60	77	43	60	23	34	34	29

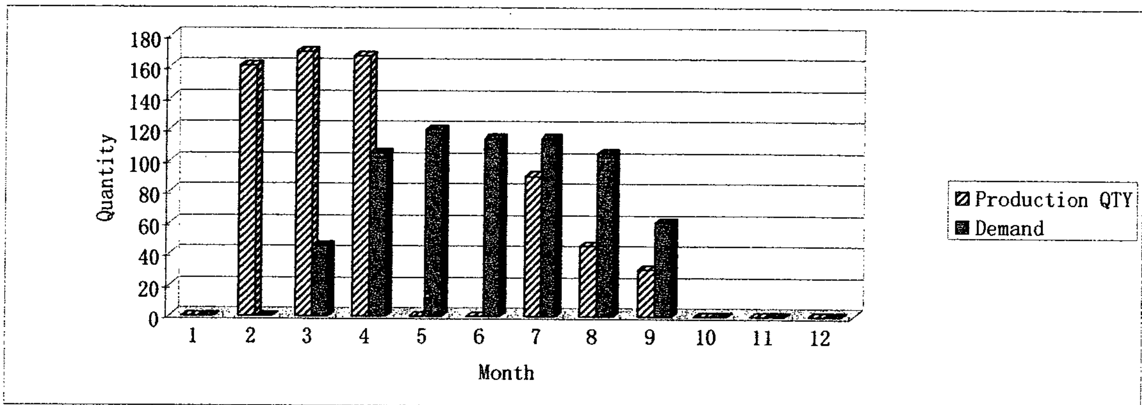

Figure 4.1 Production quantity vs demand for 30m blade

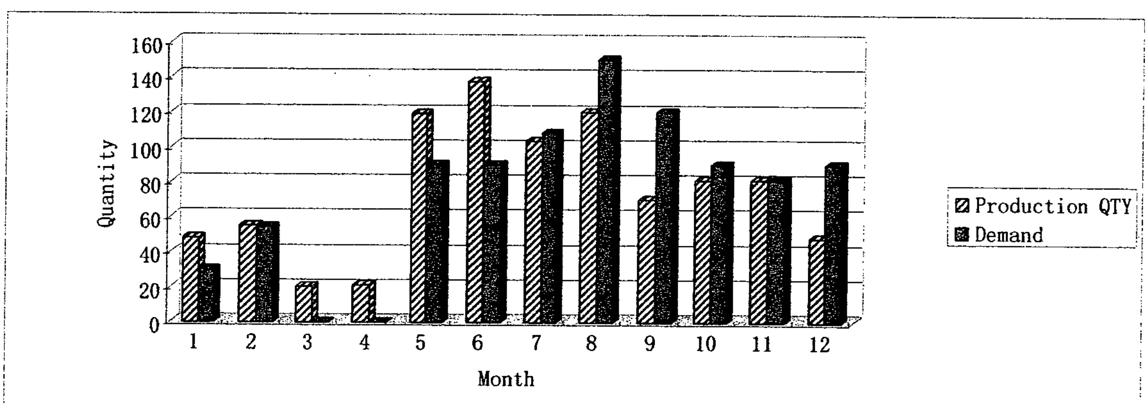

Figure 4.2 Production quantity vs demand for 50m blade

For the 30-meter blade, unit inventory carrying cost is relatively low. Therefore, inventory cost is not the priority to be considered for the production plan. In the contrary, the unit inventory carrying cost for the 50-meter blade is high, so its inventory cost is a major factor to be considered. Figure 4.1 shows that production quantity of the 30-meter blade is very different from its demand in each month. Inventory level of this product is high in some months. Figure 4.2 indicates that production quantity of the 50-meter blade is close to its demand and its inventory is relatively low.

Production Sequence

Sequence of the products in production at each plant in every month is shown in Table 4.14. '1' represents that production state is on for the product at that time. Since both two factories need to produce more than one type of blade, changeover is inevitable. However, the sequence generated by the optimized production plan tries to minimize the total number of changeovers.

Table 4.14 Production state

Month			1	2	3	4	5	6	7	8	9	10	11	12
Plant 1	**30m Blade**	**Begin**		1	1	1								
		End		1	1									
	50m Blade	**Begin**	1				1	1	1	1	1	1	1	1
		End	1			1	1	1	1	1	1	1	1	1
Plant 2	**30m Blade**	**Begin**			1					1				
		End		1		1			1		1			
	50m Blade	**Begin**	1	1		1	1	1	1		1	1	1	1
		End	1		1		1	1		1		1	1	1

With the schedule above, the total changeover cost for the whole planning horizon is $136,000.

Workforce Plan

Number of workers is another factor to be considered for production planning. Table 4.15 shows the solution for number of workers at the two plants in different months given by the model.

Table 4.15 Workforce level

Month	1	2	3	4	5	6	7	8	9	10	11	12
Plant 1	130	209	208	208	403	409	409	409	321	321	321	130
Plant 2	200	575	362	362	409	524	524	524	232	232	232	200

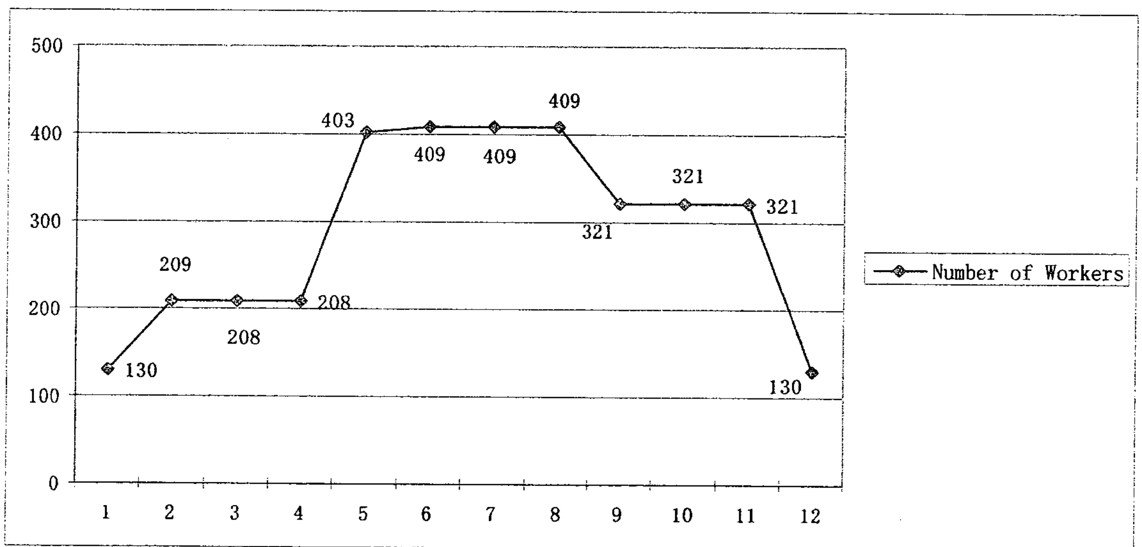

Figure 4.3 Workforce level at plant 1

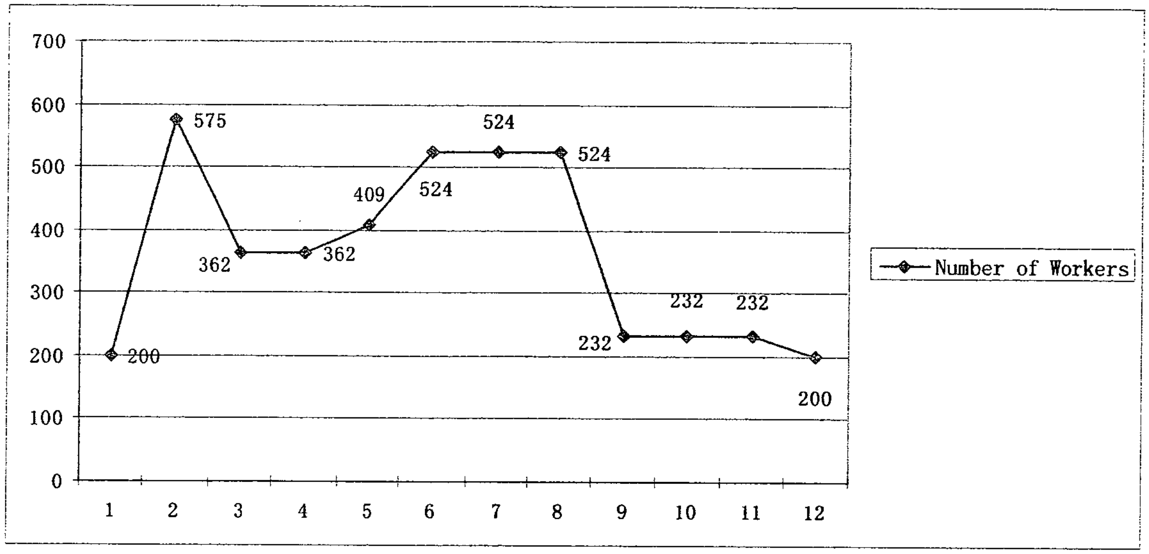

Figure 4.4 Workforce level at plant 2

As we know, customers' demands are seasonal, and production follows a seasonal pattern consequently. As a result, the number of workers needed in different months will be different. However, drastic change of workforce level should be avoided in order to minimize the recruiting and layoff costs. Figures 4.3 and 4.4 show that workforce level follows a seasonal pattern in both plants. In the same season the numbers do not fluctuate significantly. Although laying off and recruiting workers cannot be avoided, the costs on them are kept as low as possible. The total recruiting cost is \$534,516, and the total layoff cost is \$226,531. The total production cost is \$41,826,330.

4.3 Optimal Finished Product Transportation Plan

The optimal finished products transportation plan solved by the model is shown in Table 4.16. From the result, we can see that the demand of customer *1* is mostly supplied by plant *1*, and demand of customer *3* is mainly shipped from plant *2*. It can be explained by that the optimal finished product transportation plan gives priority to the nearest plant to ship products to a customer so that transportation cost is maintained as low as possible. Customer *2* is neither close to plant *1* or plant *2*, so both plants have similar priority to ship products to fulfill its demand.

Table 4.16 Finished product transportation plan

Month			1	2	3	4	5	6	7	8	9	10	11	12
Plant 1	Customer 1	30m Blade		56	30	30	90	10						
		50m Blade												
	Customer 2	30m Blade												
		50m Blade	18				60	60	60	60	40	40	40	40
	Customer 3	30m Blade		26										
		50m Blade	1											
Plant 2	Customer 1	30m Blade					42							
		50m Blade												
	Customer 2	30m Blade												
		50m Blade		1	20	20	60	60	60	60	20	20	40	40
	Customer 3	30m Blade		79			90	45	90	45	30			
		50m Blade	29	54										

The total finished products transportation cost is \$3,354,469. Based on the finished products shipping plan above, the ending inventory of each month is given in Table 4.17, and the total finished products inventory cost is \$471,868.

Table 4.17 Finished product ending inventory

Month		1	2	3	4	5	6	7	8	9	10	11	12
Plant 1	30m Blade			51	100	10							
	50m Blade				1					7	14	21	
Plant 2	30m Blade			88	177	45							
	50m Blade						17			3	17	11	

4.4 Optimal Raw Materials Purchasing Plan

The raw materials purchasing plan and the inventory costs are shown in Tables 4.18, 4.19 and 4.20.

Table 4.18 Fibre glass purchasing plan and inventory

Month	Plant 1			Plant 2		
	Order Qty (kg)	Beginning Inv. (kg)	Ending Inv. (kg)	Order Qty (kg)	Beginning Inv. (kg)	Ending Inv. (kg)
1	228609.5	20000	20000	351706.9	20000	20000
2	204569.7	20000	20000	853672.1	20000	20000
3	203626.8	20000	20000	460930.2	20000	20000
4	208954.6	20000	20000	460930.2	20000	20000
5	708000	20000	20000	720000	20000	20000
6	720000	20000	20000	922331.4	20000	20000
7	720000	20000	20000	742668.6	20000	20000
8	720000	20000	20000	832500	20000	20000
9	563796.8	20000	20000	347839.3	20000	20000
10	563796.8	20000	20000	407726.9	20000	20000
11	563796.8	20000	20000	407726.9	20000	20000
12	228609.5	20000	20000	351706.9	20000	20000

Table 4.19 Resin purchasing plan and inventory

Month	Plant 1			Plant 2		
	Order Qty (kg)	Beginning Inv. (kg)	Ending Inv. (kg)	Order Qty (kg)	Beginning Inv. (kg)	Ending Inv. (kg)
1	110494.6	8000	8000	169991.7	8000	8000
2	102284.8	8000	8000	415908	8000	8000
3	101813.4	8000	8000	226465.1	8000	8000
4	104277.3	8000	8000	226465.1	8000	8000
5	342200	8000	8000	348000	8000	8000
6	348000	8000	8000	445793.5	8000	8000
7	348000	8000	8000	362706.5	8000	8000
8	348000	8000	8000	404250	8000	8000
9	272501.8	8000	8000	169372.3	8000	8000
10	272501.8	8000	8000	197068	8000	8000
11	272501.8	8000	8000	197068	8000	8000
12	110494.6	8000	8000	169991.7	8000	8000

Table 4.20 Core material purchasing plan and inventory

Month	Plant 1			Plant 2		
	Order Qty (kg)	Beginning Inv. (kg)	Ending Inv. (kg)	Order Qty (kg)	Beginning Inv. (kg)	Ending Inv. (kg)
1	16478.94	1000	1000	25352.21	1000	1000
2	15547.29	1000	1000	62310.98	1000	1000
3	15475.64	1000	1000	34090.7	1000	1000
4	15833.55	1000	1000	34090.7	1000	1000
5	51035	1000	1000	51900	1000	1000
6	51900	1000	1000	66484.72	1000	1000
7	51900	1000	1000	54415.28	1000	1000
8	51900	1000	1000	60450	1000	1000
9	40640.35	1000	1000	25367.17	1000	1000
10	40640.36	1000	1000	29390.31	1000	1000
11	40640.36	1000	1000	29390.31	1000	1000
12	16478.93	1000	1000	25352.21	1000	1000

The results above show that with the optimal material purchasing plan, the ending inventories of fibre glass, resin and core materials remain at the lowest level, the safety stock. The total raw materials purchasing and inventory cost is $85,367,520.

4.5 Supply Chain Cost Composition

With the optimal production, material purchasing and finished product shipping plan, the total supply chain cost is $131,420,200. The composition of the supply chain cost is shown in figure 4.5. With the optimal plan, material inventory cost contributes to the majority (64.96%) of the total supply chain cost. However, more than 99% of the materials inventory cost is from the material cost. Material cost is determined by product design, material selection, and market price. Inventory carrying cost and fixed ordering cost can be almost negligible, which can be explained by that material inventory cost is minimized with the optimal material purchasing plan. The second major cost is production cost which composes 31.83% of the total supply chain cost. It is followed by transportation cost which takes 2.86%. The finished product inventory cost stands at the last place with only 0.36%.

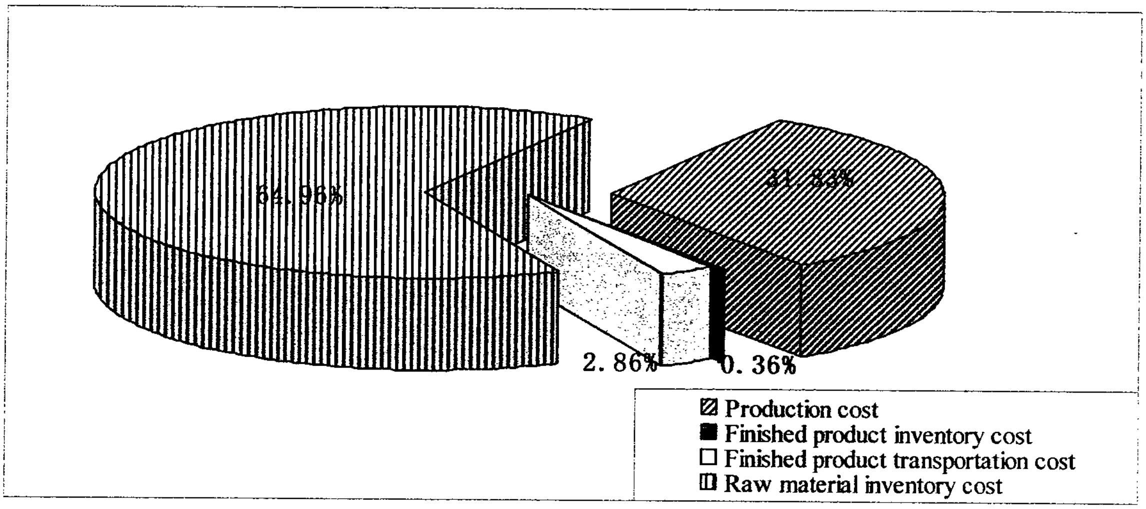

Figure 4.5 Supply chain cost composition by the optimal production plan

4.6 Sensitivity Analysis

Besides generating optimal production plan, we also used the model to perform sensitivity analysis. Through sensitivity analysis, we can identify which factors have important impacts on raw material purchasing, production planning and transportation planning as well as the total supply chain cost of composite wind turbine blade manufacturing. In practice, it can help a company to make decisions on improvements of its operations. The assumption on sensitivity analysis is that when the value of a factor or certain factors changes, all the other conditions stay the same.

4.6.1 Analysis on factors

There are two criteria on selecting factors for sensitivity analysis. The first is that the factors must be controllable. The second is that the factors will potentially affect production plan decisions. We carry out sensitivity analysis on the following factors.

- fixed ordering cost
- raw materials inventory carrying cost
- production efficiency
- finished products inventory cost
- freight for transporting finished products

4.6.1.1 Analysis on Fixed Ordering Cost

Table 4.21 Sensitivity analysis on fixed ordering cost

Scale of Change	Total RM Inv. Cost	Total SC Cost	% of Change on SC Cost
-50%	85,330,330	131,346,600	-0.056%
-40%	85,339,480	131,393,400	-0.020%
-30%	85,345,930	131,391,700	-0.022%
-20%	85,353,060	131,426,000	0.004%
-10%	85,360,290	131,434,100	0.011%
0%	85,367,520	131,420,200	0.000%
10%	85,422,490	131,452,400	0.025%
20%	85,381,580	131,452,200	0.024%
30%	85,389,880	131,446,500	0.020%
40%	85,397,100	131,450,500	0.023%
50%	85,403,600	131,417,400	-0.002%

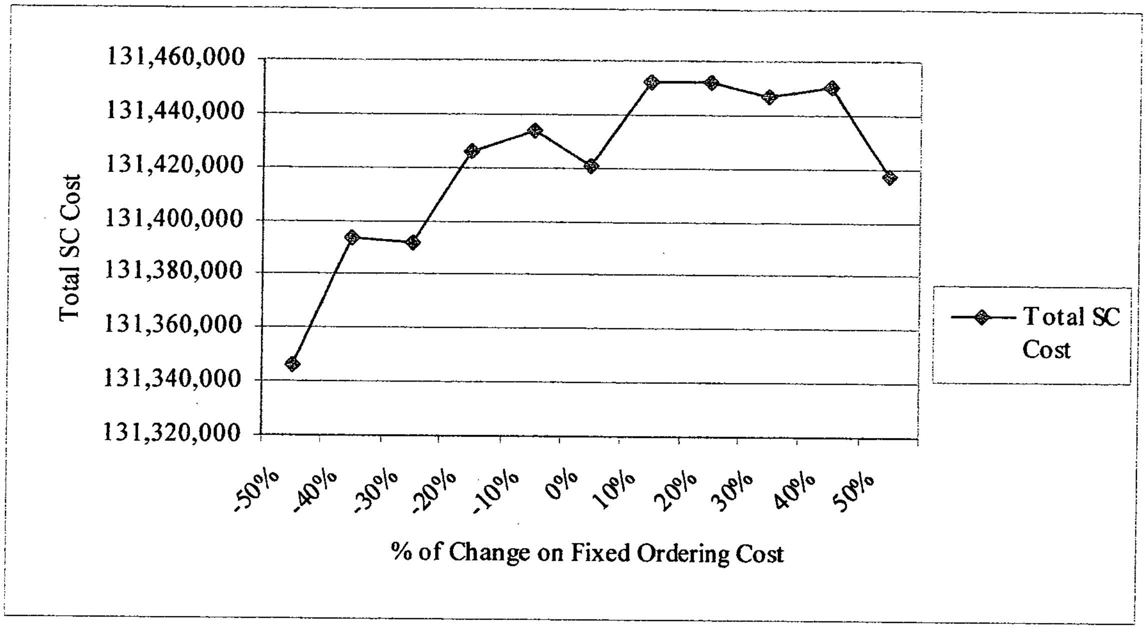

Figure 4.6 Total SC cost vs fixed ordering cost

Table 4.21 is the numerical result of analysis on the fixed raw material ordering cost. We plotted this result in Figure 4.6. The figure shows that total supply chain cost grows gradually when adding up the fixed ordering cost. However, the result indicates that the influence of the fixed ordering cost on the total supply chain cost is very small. We can conclude that the fixed raw materials ordering cost does not significantly affect total supply chain cost. It can be explained by that with the optimal raw materials procurement plan, the total fixed ordering cost has been very low and composes of almost a negligible part of the total supply chain cost. It is true that lowering the fixed ordering cost can lower the total supply chain cost slightly, but practically it is not the priority among cost reduction activities.

4.6.1.2 Analysis on Raw Material Inventory Carrying Cost

Table 4.22 and Figure 4.7 are the result of sensitivity analysis on raw material inventory carrying cost.

Table 4.22 Sensitivity analysis on material inventory carrying cost

Scale of change	Total RM inventory cost	Total SC Cost	% of change on SC cost
-50%	85,329,010	131,405,900	-0.011%
-40%	85,334,830	131,369,800	-0.038%
-30%	85,359,040	131,422,700	0.002%
-20%	85,351,040	131,403,700	-0.013%
-10%	85,354,770	131,412,700	-0.006%
0%	85,367,520	131,420,200	0.000%
10%	85,376,410	131,439,400	0.015%
20%	85,384,010	131,460,200	0.030%
30%	85,436,870	131,450,700	0.023%
40%	85,402,990	131,456,900	0.028%
50%	85,407,630	131,476,400	0.043%

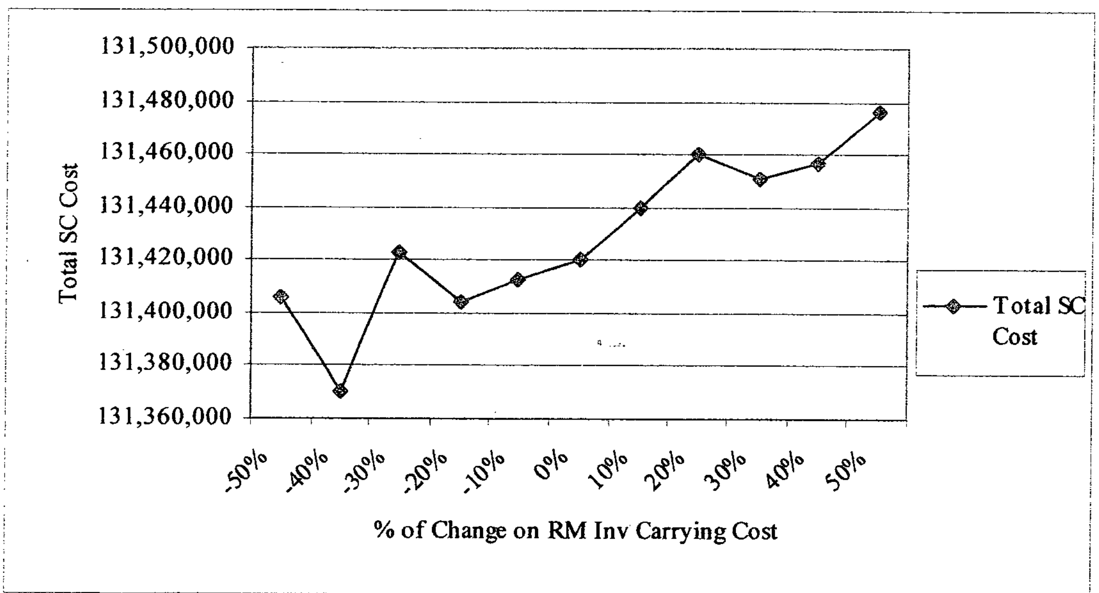

Figure 4.7 Total SC cost vs RM inventory carrying cost

The graph in Figure 4.7 shows a growing trend of the change of supply chain cost with the change of the raw material inventory carrying cost within the range from -50% to

+50%. However, the influence of raw material inventory carrying cost on the total supply chain cost is very small. With the optimal production and procurement plan, raw materials inventory has been kept to a very low level, and the total raw materials inventory carrying cost is a very small contribution to the total supply chain cost.

4.6.1.3 Analysis on Production Efficiency

Production efficiency can be mainly reflected in two aspects, mould production rate and worker hours required for each blade. These two aspects are correlated in some production steps, while in some other steps they are unrelated. For example, using automatic fabrics lay-up can result in less worker hours and shorter mould production cycle time, while resin filling and curing time reduction can only affect the mould production rate without much influence on worker hours required. Therefore, we should consider three situations when doing sensitivity analysis on production rate. One is that mould production rate changes but worker hours are not affected. Another one is that worker hours required changes but mould production rate stays the same. The third is that changes on both aspects affect each other.

Analysis on Mould Production Rate

As discussed above, in this situation, the mould production rate change is mainly due to resin injection and curing process in which labours are not involved. The analysis result is illustrated in Table 4.23.

Table 4.23 Sensitivity analysis on mould production rate

Scale of change	Production cost	Total SC Cost	% of change on SC cost
-20%	N/A	N/A	N/A
-16%	N/A	N/A	N/A
-12%	41,870,300	131,694,800	0.209%
-8%	41,890,010	131,526,200	0.081%
-4%	41,796,890	131,433,600	0.010%
0%	41,826,330	131,420,200	0.000%
4%	41,841,390	131,391,200	-0.022%
8%	41,842,510	131,361,600	-0.045%
12%	41,873,940	131,375,600	-0.034%
16%	41,868,070	131,350,000	-0.053%
20%	41,892,390	131,345,700	-0.057%

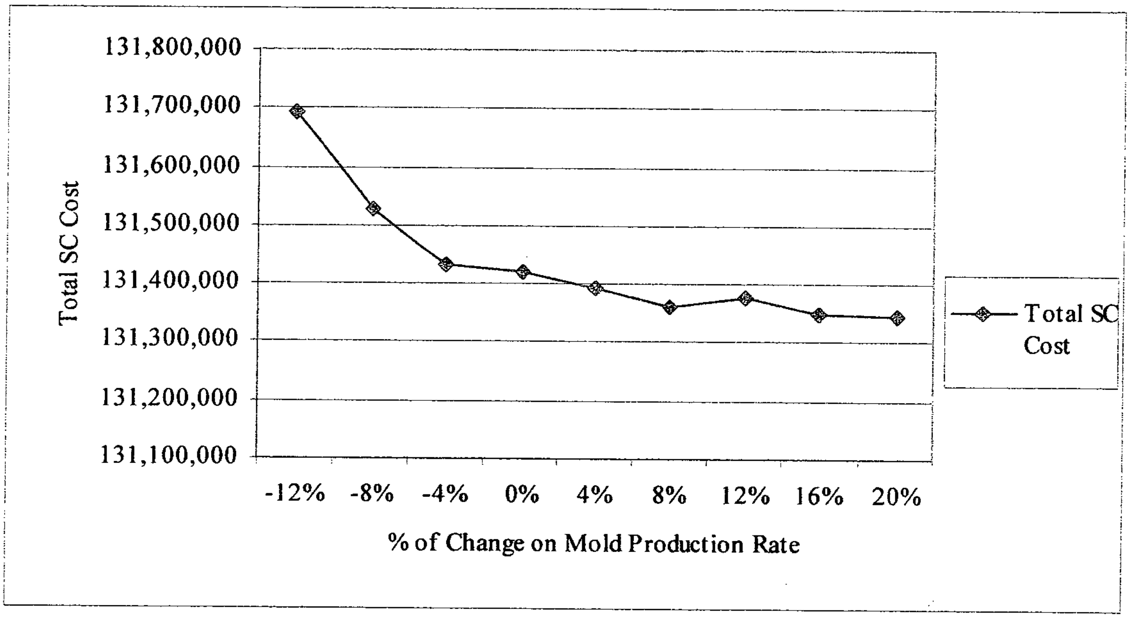

Figure 4.8 Total SC cost vs mould production rate

The plotted result of the analysis on mould production rates as shown in Figure 4.8 has two indications. First, no feasible solution is found when the mould production rates are under 88% of the original rates. It means that when the mould production rate is below a certain level, the manufacturer will fail to meet customers' demands. Second, the total supply chain cost decreases significantly until mould production rates reach a certain level. It indicates that with the reduction on injection and curing cycle time, factories gain more flexibility on production, which enables them to optimize production plan and thus lower products' cost. However, if mould production rate is high enough, improvement on it will no longer reduce products' cost significantly for the same level of customers' demands.

Analysis on Required Worker Hours for Each Product

In this situation, mould production rate remains unchanged, but required worker hours changes due to change on the number of workers or change on labour efficiency in the production steps which molding production is not involved. Table 4.24 and Figure 4.9 show the analysis result. The result shows that the required worker hours for each product have significant effect on the total supply chain cost. This indicates that improvement on labor production efficiency and productivity is an important element for total cost reduction. From Figure 4.9, we can see that the relationship between required worker hours and total supply chain cost is almost linear within the range of -20% to 20% of change on required worker hours. Therefore, in this range, total supply chain cost can be estimated by a linear function for a given value of required worker hours.

Table 4.24 Sensitivity analysis on required worker hours

Scale of change	Total RM inventory cost	Total SC Cost	% of change on SC cost
-20%	38,397,100	127,783,000	-2.768%
-16%	39,075,520	128,550,600	-2.184%
-12%	39,769,430	129,250,000	-1.651%
-8%	40,552,430	130,000,800	-1.080%
-4%	41,154,250	130,698,800	-0.549%
0%	41,826,330	131,420,200	0.000%
4%	42,520,510	132,085,500	0.506%
8%	43,227,680	132,868,100	1.102%
12%	43,905,390	133,592,800	1.653%
16%	44,527,900	134,220,900	2.131%
20%	45,281,810	135,003,800	2.727%

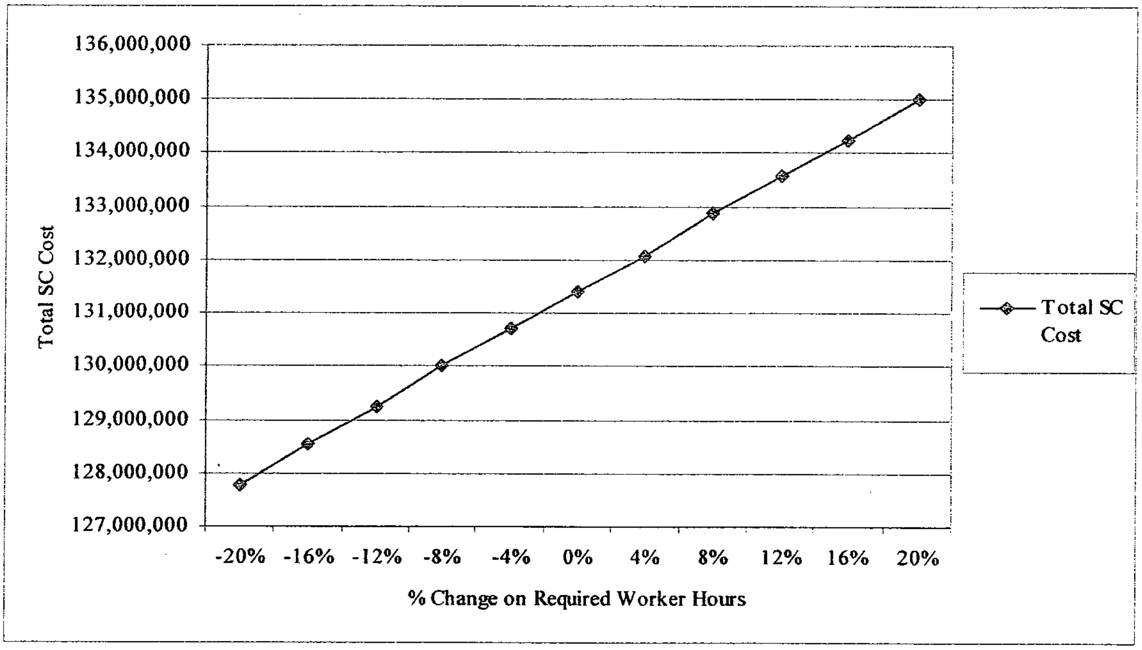

Figure 4.9 Total SC cost vs required worker hours

<u>*Analysis on Mould Production Rate & Required Worker Hours per Product*</u>

In this situation, we assume that production efficiency of some labour intensive steps involved in molding, such as mould preparation, preform lay-up and assembly preparation changes. This causes changes on both required worker hours and mould production rate. If 50% of mould production cycle time is from the labour intensive steps, the degree of change on mould production cycle time will be reduced by 50%. For example, if worker hours is reduced by 20%, the mould production cycle time decreases by 10%. Analysis result is shown in Table 4.25 and Figure 4.10.

Table 4.25 Sensitivity analysis on required worker hours and mould production rate

Scale of change		Total Prod. Cost	Total SC Cost	% of Change on SC Cost
Worker Hrs Req.	Mould Prod Rate			
-20%	11.1%	38,488,390	127,747,000	-2.795%
-16%	8.7%	39,178,590	128,477,900	-2.239%
-12%	6.4%	39,770,870	129,232,700	-1.665%
-8%	4.2%	40,452,660	129,925,200	-1.138%
-4%	2.0%	41,148,210	130,657,600	-0.580%
0%	0.0%	41,826,330	131,420,200	0.000%
4%	-2.0%	42,506,830	132,094,600	0.513%
8%	-3.8%	43,191,320	132,910,500	1.134%
12%	-5.7%	43,877,740	133,654,100	1.700%
16%	-7.4%	44,613,690	134,389,700	2.260%
20%	-9.1%	45,366,490	135,157,200	2.844%

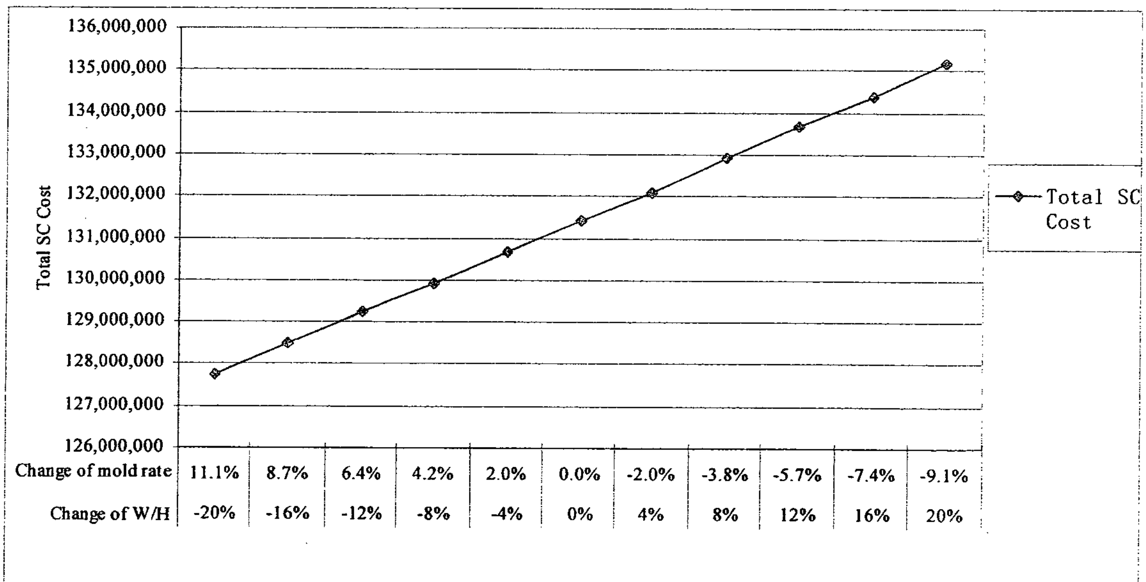

Figure 4.10 Total SC cost vs required worker hours and mould production rate

The analysis result shows that the production efficiency of the steps involving both molding and labours is a significant cost factor. Within the range of the change of the variables observed in our experiment, total supply chain cost changes almost linearly with the change of production efficiency.

4.6.1.4 Analysis on Finished Products Storage Cost

Table 4.26 and Figure 4.11 show the observation of the experiment of changing finished production storage cost within the range of -50% to +50%.

Table 4.26 Sensitivity analysis on finished product storage cost

Scale of Change	Total FG Inv. Cost	Total SC Cost	% of Change on SC Cost
-50%	231,604	131,192,300	-0.173%
-40%	288,196	131,215,000	-0.156%
-30%	330,070	131,291,100	-0.098%
-20%	384,566	131,332,500	-0.067%
-10%	427,893	131,382,200	-0.029%
0%	471,868	131,420,200	0.000%
10%	513,402	131,475,900	0.042%
20%	512,633	131,491,300	0.054%
30%	571,462	131,536,800	0.089%
40%	397,754	131,551,300	0.100%
50%	426,936	131,589,800	0.129%

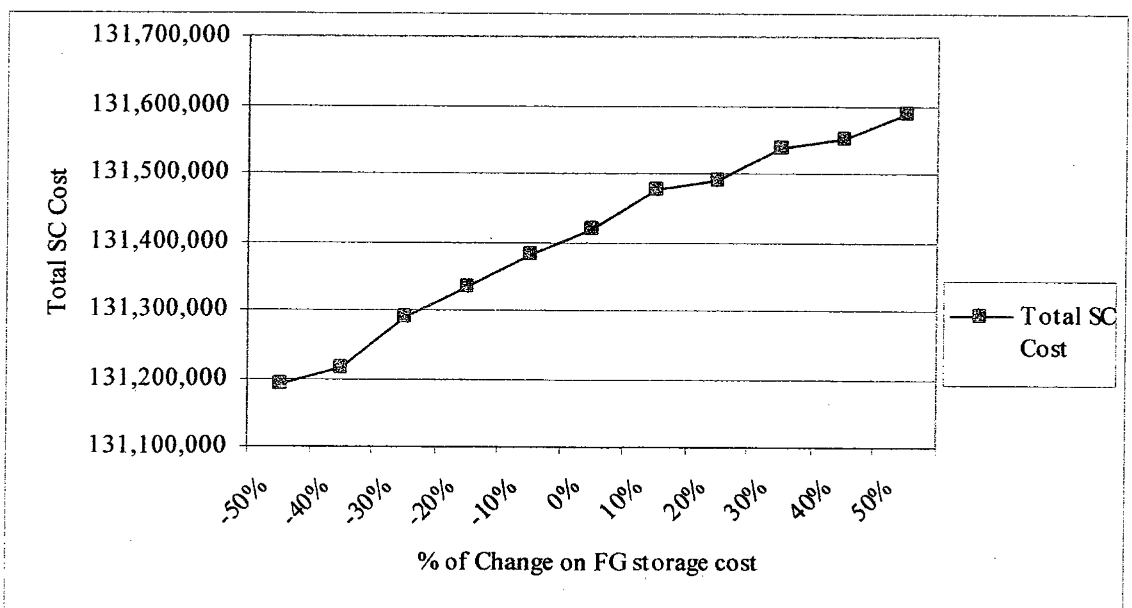

Figure 4.11 Total SC cost vs finished product storage cost

The result shows that total supply chain cost grows when finished products storing cost increases. However, the effect of finished products storing cost on the total supply chain cost is insignificant. Therefore, the unit finished product storage cost reduction may not be a priority on the list of operations improvement.

4.6.1.5 Analysis on Finished Products Transportation Cost

The observation of the experiment on transportation cost is shown in Table 4.27.

Table 4.27 Sensitivity analysis on finished product transportation freight

Scale of Change	Total FG Trans. Cost	Total SC Cost	% of Change on SC Cost
-50%	2,023,168	129,626,200	-1.365%
-40%	2,375,410	130,011,300	-1.072%
-30%	2,723,294	130,372,900	-0.797%
-20%	3,046,722	130,690,900	-0.555%
-10%	3,407,572	131,080,200	-0.259%
0%	3,754,469	131,420,200	0.000%
10%	4,107,393	131,735,500	0.240%
20%	4,344,954	132,131,200	0.541%
30%	4,718,053	132,459,300	0.791%
40%	5,032,411	132,815,900	1.062%
50%	5,408,690	133,160,200	1.324%

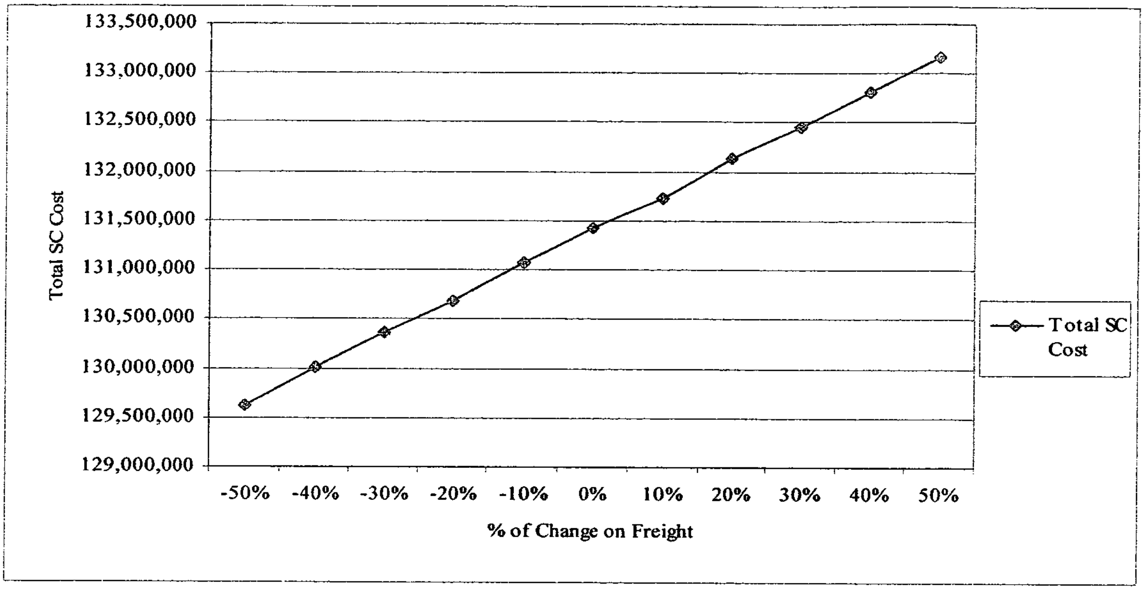

Figure 4.12 Total SC cost vs transportation cost

Figure 4.12 shows that the change of total supply chain cost is linear to the change of transportation cost. The result indicates that finished products transportation cost affects the total supply chain cost. As discussed earlier, with the increase of sizes of wind turbine blades, transportation cost has become a considerable part of the product cost. Therefore, lowering transportation cost will contribute to the total product cost reduction. The transportation cost reduction may be achieved by optimal transportation method selection, careful transportation route planning, etc.

4.6.2 Summary on Sensitivity Analysis

The product cost composition shows that raw material cost which is determined by product design, material selection and market price contributes to a substantial part of total supply chain cost. However, raw materials cost is not an issue to be considered from production planning point of view. Therefore, it is not selected for sensitivity analysis in this study. We choose some controllable factors which may affect production planning decisions. After carrying out sensitivity analysis on these factors, we conclude that production efficiency and finished products transportation freight are the two most important ones affecting the total supply chain cost. This result provides managerial implications to cost reduction activities in real life. If a wind turbine blade manufacturer is operating under an optimal planning system, the following improvements will gain it further cost reduction.

- Improving labor efficiency in the labor intensive production steps such as mould preparation, preform lay-up, assembly preparation, and finishing.
- Using automatic lay-up to shorten lay-up processing time.
- Reducing resin injection and curing cycle time.
- Choosing less costly finished product shipping method and route.

Chapter Five

Conclusions and Future Research

In this chapter, a brief summary of the research conducted in this thesis is presented. Future research opportunities will also be discussed.

5.1 Concluding Summary

In this thesis, the development of an aggregate production planning model for multi-site composite wind turbine blades manufacturing environment is presented. MILP methodologies are used to formulate the problem. This study uses a thorough mid-term to long-term production planning method to provide the essential information to decision makers. The model covers planning for operations through the whole supply chain incorporating raw material inventory level, equipment capacity, work force level, production quantity and sequence, finished products inventory level, and finished products transportation with the objectives of meeting customers' demands and minimizing total supply chain cost. To validate the model, a set of hypothetical data reflecting similar wind turbine blade manufacturing features are used for computation. The results show that the model can provide an optimal or near optimal solution within reasonable computing time. Sensitivity analysis was carried out to identify important cost factors and to provide directions for managerial operations in cost reduction. The contributions of this research are as follows.

- A mathematical production planning model was developed to optimize raw materials procurement, production, and finished products shipping plans for composite wind turbine blades manufacturing, which can potentially lower blades cost through scientific supply chain management.

- An analysis tool is provided to identify important cost factors.
- Linearization techniques were developed to formulate work force level change and production changeover in solving the developed model.

The implementation of the model can be easily extended to other similar environment of manufacturing large objects such as oil pipes and composite vessels by removing special features of wind turbine blades and adding features of other products.

5.2 Future Research

The developed model can give an optimal solution for the example problem within a satisfactory time. However, in real life, manufacturing problems can be more complicated, which drastically increases computation complexity. Therefore there are still opportunities to improve the model to accommodate the increased complexity. Future research can be done to extend the current study in the following aspects.

- To modify the model to be adaptable for larger scale of problems.
- To consider uncertainty of customers' demands in the model.
- To modify production capacity constraints so that more than one type of product to be produced at the same time can be considered.
- To introduce customers' satisfactory level and allow certain level of back orders with penalty.
- To add more constraints to limit early shipping of finished products.

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Appendix

Mathematical Model in LINGO

```
!Objective of the model;

[OBJ]min= Production_Cost

         +Finished_Goods_Inv_Cost

         +Finished_Goods_Transp_Cost

         +Raw_Materials_Inv_Cost;

!*******************************************************************;

!Parameters;

SETS:

MONTH/1..12/;

PRODUCT/1 2/:MOULD_PRODUCTION_RATE,WORKER_HOURS_REQUIRED,CUBE,FREIGHT;

CUSTOMER/1 2 3/;

PLANT/1 2/:FIXED_MONTHLY_COST,UNIT_LABOUR_COST,UNIT_LAYOFF_COST,

UNIT_RECRUITING_COST,FG_STORING_CAPACITY,CHANGEOVER_COST,

CHANGEOVER_TIME;

MATERIAL/FIBERGLASS RESIN CORE/: FIXED_ORDERING_COST,UNIT_MATERIAL_COST,

INVENTORY_CARRYING_COST,MOQ;

SET1(PRODUCT,CUSTOMER,MONTH):DEMAND;

SET2(PRODUCT,PLANT,MONTH):PROD_QTY,PROD_DAYS,

FG_BEGINNING_STOCK,ALPHA,BETA,GAMA,DELTA,SIGMA;

SET3(PRODUCT,PLANT):UNIT_EQUIPMENT_COST,NUMBER_OF_MOULDS,

FG_STORING_COST;

SET4(PLANT,MONTH):NUMBER_OF_WORKERS,RECRUIT,LAYOFF,RW,LW;

SET5(PRODUCT,PLANT,CUSTOMER):PERMIT_CHARGE;

SET6(PRODUCT,PLANT,CUSTOMER,MONTH):TRANSP_CAPACITY,TRANSP_QTY;
```

```
SET7(PLANT,CUSTOMER):DISTANCE;

SET8(MATERIAL,PLANT,MONTH):ORDER_QUANTITY,BEGINNING_INVENTORY,O;

SET9(MATERIAL,PRODUCT):USAGE;

SET10(MATERIAL,PLANT):SAFETY_STOCK;

ENDSETS

!***********************************************************;

DATA:

DEMAND=

0    0    0    45   60   54   54   45   0    0    0    0

0    0    0    0    0    0    0    0    0    0    0    0

0    0    45   60   60   60   60   60   60   0    0    0

0    0    0    0    0    0    0    0    0    0    0    0

0    0    0    0    90   90   108  150  120  90   81   90

30   54   0    0    0    0    0    0    0    0    0    0;


FIXED_MONTHLY_COST=

800000

1100000;


UNIT_EQUIPMENT_COST=

600   620

1650  1700;


MOULD_PRODUCTION_RATE=

0.91

0.46;


WORKER_HOURS_REQUIRED=

450
```

```
1201;

NUMBER_OF_MOULDS=
10      15
6       9;

UNIT_LABOUR_COST=
12
11.5;

UNIT_LAYOFF_COST=
300
265;

UNIT_RECRUITING_COST=
672
644;

CHANGEOVER_TIME=
2
3;

CHANGEOVER_COST=
8000
15000;

CUBE=
86
380;
```

```
FG_STORING_CAPACITY=
9000
15200;

FG_STORING_COST=
550   540
2500  2300;

FREIGHT=
2
6;

DISTANCE=
90     550    960
1080   720    180;

PERMIT_CHARGE=
17     50     67
67     50     17
25     75     100
100    75     25;

TRANSP_CAPACITY=
90     90     30     30     90     90     90     45     30     30     90     90
90     90     0      0      90     90     90     90     60     60     60     60
30     30     0      0      30     30     30     30     0      0      30     30
60     60     0      0      60     60     60     60     0      0      60     60
60     60     30     30     90     90     90     90     30     30     60     60
90     90     0      0      90     90     90     45     30     30     90     90
```

```
60   60   20   20   60   60   60   30   20   20   60   60
60   60   0    0    60   60   60   60   40   40   40   40
20   20   0    0    20   20   20   20   0    0    20   20
40   40   0    0    40   40   40   40   0    0    40   40
40   40   20   20   60   60   60   60   20   20   40   40
60   60   0    0    60   60   60   30   20   20   60   60;

FIXED_ORDERING_COST=
900
1500
700;

UNIT_MATERIAL_COST=
4.2
4.5
6;

INVENTORY_CARRYING_COST=
0.08
0.18
0.09;

MOQ=
5000
10000
2000;

USAGE=
2500  12000
```

```
1250  5800
190   865;

SAFETY_STOCK=
20000 20000
8000  8000
1000  1000;
ENDDATA

!*************************************************************;
!Constraints;
!1. PRODUCTION;
!Initializing number of workers at each plant in the first month;
NUMBER_OF_WORKERS(1,1)=130;
NUMBER_OF_WORKERS(2,1)=200;
G1=1000;
@for(PRODUCT(I):
     @sum(PLANT(F):@sum(MONTH(M):PROD_QTY(I,F,M)))
     <=@sum(CUSTOMER(J):@sum(MONTH(M):DEMAND(I,J,M)))
     );
@for(PLANT(F):
     ALPHA(2,F,1)=1;
     RECRUIT(F,1)=0;
     LAYOFF(F,1)=0;
     @for(MONTH(M):
          @for(PRODUCT(I):
               @bin(ALPHA(I,F,M));
               @bin(BETA(I,F,M));
               @bin(GAMA(I,F,M));
```

```
        @bin(DELTA(I,F,M));
        @bin(SIGMA(I,F,M));
        PROD_QTY(I,F,M)<=NUMBER_OF_MOULDS(I,F)*PROD_DAYS(I,F,M)
        *MOULD_PRODUCTION_RATE(I);
        PROD_QTY(I,F,M)>=GAMA(I,F,M);
        PROD_QTY(I,F,M)<=G1*GAMA(I,F,M);
        ALPHA(I,F,M)+BETA(I,F,M)>=GAMA(I,F,M);
        ALPHA(I,F,@wrap(M+1,12))-BETA(I,F,M)
        <=DELTA(I,F,@wrap(M+1,12));
        BETA(I,F,M)-ALPHA(I,F,@wrap(M+1,12))
        <=DELTA(I,F,@wrap(M+1,12));
        BETA(I,F,M)+ALPHA(I,F,@wrap(M+1,12))
        >=DELTA(I,F,@wrap(M+1,12));
        2-ALPHA(I,F,@wrap(M+1,12))-BETA(I,F,M)
        >=DELTA(I,F,@wrap(M+1,12));
        ALPHA(I,F,M)-BETA(I,F,M)<=SIGMA(I,F,M);
        BETA(I,F,M)-ALPHA(I,F,M)<=SIGMA(I,F,M);
        ALPHA(I,F,M)+BETA(I,F,M)>=SIGMA(I,F,M);
        2-ALPHA(I,F,M)-BETA(I,F,M)>=SIGMA(I,F,M);
        );
@sum(PRODUCT(I):ALPHA(I,F,M))=1;
@sum(PRODUCT(I):BETA(I,F,M))=1;
@sum(PRODUCT(I):GAMA(I,F,M))-1
<=0.5*@sum(PRODUCT(I):SIGMA(I,F,M));
@sum(PRODUCT(I):GAMA(I,F,M))>=@sum(PRODUCT(I):SIGMA(I,F,M));
@sum(PRODUCT(I):PROD_DAYS(I,F,M)
+0.5*(DELTA(I,F,M)+SIGMA(I,F,M))
*CHANGEOVER_TIME(F))<=22;
22*8*NUMBER_OF_WORKERS(F,M)
```

```
        >=@sum(PRODUCT(I):PROD_QTY(I,F,M)
        *WORKER_HOURS_REQUIRED(I));
        @bin(RECRUIT(F,M));!Decision variable;
        @bin(LAYOFF(F,M));!Decision variable;
        NUMBER_OF_WORKERS(F,@wrap(M+1,12))-NUMBER_OF_WORKERS(F,M)
        <=G1*RECRUIT(F,@wrap(M+1,12));
        NUMBER_OF_WORKERS(F,M)-NUMBER_OF_WORKERS(F,@wrap(M+1,12))
        <G1*(1-RECRUIT(F,@wrap(M+1,12)));
        NUMBER_OF_WORKERS(F,M)-NUMBER_OF_WORKERS(F,@wrap(M+1,12))
        <=G1*LAYOFF(F,@wrap(M+1,12));
        NUMBER_OF_WORKERS(F,@wrap(M+1,12))-NUMBER_OF_WORKERS(F,M)
        <G1*(1-LAYOFF(F,@wrap(M+1,12)));
        RECRUIT(F,@wrap(M+1,12))+LAYOFF(F,@wrap(M+1,12))<=1;
        RW(F,@wrap(M+1,12))<=G1*RECRUIT(F,@wrap(M+1,12));
        RW(F,@wrap(M+1,12))>=NUMBER_OF_WORKERS(F,@wrap(M+1,12))-
        NUMBER_OF_WORKERS(F,M)+G1*(RECRUIT(F,@wrap(M+1,12))-1);
        LW(F,@wrap(M+1,12))<=G1*LAYOFF(F,@wrap(M+1,12));
        LW(F,@wrap(M+1,12))>=NUMBER_OF_WORKERS(F,M)-
        NUMBER_OF_WORKERS(F,@wrap(M+1,12))
        +G1*(LAYOFF(F,@wrap(M+1,12))-1);
        )
    );
Total_Fixed_Facility_Cost=6*@sum(PLANT(F):FIXED_MONTHLY_COST(F));
Total_Variable_Equipment_Cost
=@sum(PLANT(F):@sum(MONTH(M):@sum(PRODUCT(I):
PROD_QTY(I,F,M)*UNIT_EQUIPMENT_COST(I,F))));

Total_Labour_Cost=@sum(PLANT(F):@sum(MONTH(M):
NUMBER_OF_WORKERS(F,M)*UNIT_LABOUR_COST(F)*22*8));
```

```
Total_Layoff_Cost=@sum(PLANT(F):@sum(MONTH(M):
LW(F,@wrap(M+1,12)))*UNIT_LAYOFF_COST(F));

Total_Recruiting_Cost=@sum(PLANT(F):@sum(MONTH(M):
RW(F,@wrap(M+1,12)))*UNIT_RECRUITING_COST(F));

Total_Changeover_Cost=0.5*@sum(PLANT(F):@sum(MONTH(M):@sum(PRODUCT(I):
DELTA(I,F,M)+SIGMA(I,F,M))*CHANGEOVER_COST(F))));

Production_Cost
=Total_Fixed_Facility_Cost+Total_Variable_Equipment_Cost+Total_Labour_C
ost+Total_Layoff_Cost+Total_Recruiting_Cost+Total_Changeover_Cost;

!2. FINISHED PRODUCTS;
@for(PRODUCT(I):
    @for(PLANT(F):
         FG_BEGINNING_STOCK(I,F,1)=0;
         @for(MONTH(M):
              FG_BEGINNING_STOCK(I,F,@wrap(M+1,12))
              =FG_BEGINNING_STOCK(I,F,M)+PROD_QTY(I,F,M)-
              @sum(CUSTOMER(J):TRANSP_QTY(I,F,J,M));
              )
         )
    );
@for(PLANT(F):
    @for(MONTH(M):
         @sum(PRODUCT(I):(FG_BEGINNING_STOCK(I,F,M)+PROD_QTY(I,F,M)
         -@sum(CUSTOMER(J):TRANSP_QTY(I,F,J,M)))*CUBE(I))
```

```
        <=FG_STORING_CAPACITY(F);
        )
    );
Finished_Goods_Inv_Cost
=@sum(MONTH(M):@sum(PLANT(F):@sum(PRODUCT(I):
0.5*(FG_BEGINNING_STOCK(I,F,M)
+FG_BEGINNING_STOCK(I,F,@wrap(M+1,12)))*FG_STORING_COST(I,F))));

@for(PRODUCT(I):
    @for(MONTH(M):
        @for(PLANT(F):
          @sum(CUSTOMER(J):@sum(MONTH(X)|X#LE#M:TRANSP_QTY(I,F,J,X)
          ))<=@sum(MONTH(X)|X#LE#M:PROD_QTY(I,F,X))
            );
        @for(CUSTOMER(J):
            @sum(PLANT(F):@sum(MONTH(X)|X#LE#M:TRANSP_QTY(I,F,J,X)))
            >=@sum(MONTH(X)|X#LE#M:DEMAND(I,J,X))
            )
        )
    );
@for(PLANT(F):
    @for(CUSTOMER(J):
        @for(MONTH(M):
            @for(PRODUCT(I):TRANSP_QTY(I,F,J,M)
                <=TRANSP_CAPACITY(I,F,J,M))
            )
        )
    );
```

```
Finished_Goods_Transp_Cost
=@sum(MONTH(M):@sum(PRODUCT(I):@sum(PLANT(F):@sum(CUSTOMER(J):
TRANSP_QTY(I,F,J,M)*(FREIGHT(I)*DISTANCE(F,J)
+PERMIT_CHARGE(I,F,J))))));


!3. RAW MATERIALS PURCHASING AND INVENTORY;
!Initializing the beginning inventory of three materials at each plant
in the first month;
BEGINNING_INVENTORY(@index(FIBERGLASS),1,1)=20000;
BEGINNING_INVENTORY(@index(FIBERGLASS),2,1)=20000;
BEGINNING_INVENTORY(@index(RESIN),1,1)=8000;
BEGINNING_INVENTORY(@index(RESIN),2,1)=8000;
BEGINNING_INVENTORY(@index(CORE),1,1)=1000;
BEGINNING_INVENTORY(@index(CORE),2,1)=1000;
G2=1000000;
@for(MATERIAL(U):
     @for(PLANT(F):
          @for(MONTH(M):
               @bin(O(U,F,M));
               ORDER_QUANTITY(U,F,M)>=O(U,F,M)*MOQ(U);
               BEGINNING_INVENTORY(U,F,M)+ORDER_QUANTITY(U,F,M)
               >=@sum(PRODUCT(I):PROD_QTY(I,F,M)*USAGE(U,I))
               +SAFETY_STOCK(U,F);
               BEGINNING_INVENTORY(U,F,@wrap(M+1,12))
               =BEGINNING_INVENTORY(U,F,M)+ORDER_QUANTITY(U,F,M)
               -@sum(PRODUCT(I):PROD_QTY(I,F,M)*USAGE(U,I));
               ORDER_QUANTITY(U,F,M)>=O(U,F,M);
               O(U,F,M)*G2>=ORDER_QUANTITY(U,F,M);
               )
```

```
            )
        );
Raw_Materials_Inv_Cost
=@sum(MONTH(M):@sum(PLANT(F):@sum(MATERIAL(U):
O(U,F,M)*FIXED_ORDERING_COST(U)
+ORDER_QUANTITY(U,F,M)*UNIT_MATERIAL_COST(U)
+BEGINNING_INVENTORY(U,F,@wrap(M+1,12))
*INVENTORY_CARRYING_COST(U))));
END;
```