Optimization and Cost Evaluation of RTM Production Systems

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Abstract

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In recent years, applications of composite materials have had significant growth in many industrial sectors. Light weight and high mechanical properties of composites supported by efficient manufacturing technologies such as resin transfer molding (RTM) make them better alternatives to metal products in several applications.

Cost analysis of composite manufacturing processes is important to increase their manufacturing competencies. Cost reduction of composite manufacturing processes offsets their high material cost drawback. Thus a competent manufacturing process, along with outstanding mechanical properties, makes composites desirable materials of choice.

A comprehensive production cost analysis for a hypothetical but realistic RTM manufacturing line is performed in this research. An optimized plant configuration is determined based on production volumes, resource utilization and material handling policies. Three different cases are studied to show how cost per item and profit values of the production behave on different production levels. In the first case production of a single product is studied while in the second and third cases two different products are assumed to be produced utilizing common facilities. An algorithm is proposed to search for optimal combination of production volumes of different products utilizing the common preconfigured production system. Cost fluctuations on different production volumes are analyzed to identify different factors which might influence the cost.

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1 Introduction

Over the past several years, applications of composite materials have pervaded many types of products. Excellent characteristics of composites such as light weight, high mechanical properties and environmental compatibilities have led them to play important roles in modern product structures. Different manufacturing processes are used to produce near shape composite products with lower assembly costs comparing with those used to produce metal products. However, the fact that composite manufacturing processes are developing very recently and are probably not matured enough still leaves much to be done in order to determine the optimal or near optimal manufacturing systems and production conditions to make their production costs competitive.

Considerable research effort has mainly been devoted to finding the optimal production variables of individual composite manufacturing process steps. Production systems with optimal stacking sequence of fabric layers, injection conditions, curing profiles, etc. have been studied to produce parts with higher qualities in shorter cycles. These investigations however, mainly focus on technical variables of separate process steps without taking into account the interactions between different steps of an entire manufacturing process. In order to investigate the overall cost effects of all participating steps, a thorough evaluation and optimization of the integrated process, corresponding resources and their interactions is also a much needed area of research. There are very limited studies on line balancing, cost evaluation, resource scheduling and optimization of a total production line of composite manufacturing processes as shown in the literature.

1.1 Motivation

Composites are surpassing metals in some applications since characteristics of composites better satisfy the requirements of those applications. In automotive industry for example, the low density of the composite materials is exploited to produce lighter cars with remarkably lower fuel consumption rates. Many parts of the modern airplanes are also manufactured utilizing composite materials since they are lighter than metals and provide a high level of mechanical properties. However, for cost sensitive products, higher material properties can not be the only criteria for material selection. Cost competency of manufacturing processes often plays an important role in deciding whether a material is preferred for an application. The necessity of manufacturing cost competency is of a greater importance for composite materials since their material costs are generally high. To make composite manufacturing processes cost competitive, optimal configuration of their production lines along with an overall cost analysis of the entire manufacturing process is very important.

Most research efforts for optimal composite manufacturing processes concentrate on injection, curing, material selection and structure of the composite products. Researchers paid more attention to such concepts since they have more tangible influences on the quality of the product and on the production cycle time. Much was done to find optimal stacking sequence of fabric layers, injection temperatures, injection pressures, injection mold gate-vent locations and curing temperature-pressure profiles. The entire process of RTM manufacturing however, includes many process steps with different levels of quality and cost influence. To have an estimation of the overall production cost, all steps and their respective interrelations should be taken into account. Production costs incurred by different tasks of a process often originate from their resource utilization. Some resources are commonly utilized and there exist many interactions between process tasks and utilized resources.

The main motivation of this research comes from the necessity for an overall cost evaluation and production line analysis of RTM processes. A production line analysis anticipates further cost effects of production elements such as resources. This anticipation makes it possible to evaluate the production costs based on tentatively optimized line configurations at different production levels. This way optimized cost behavior of the manufacturing process is evaluated on different production volumes. The result will help finding other potential cost reduction policies which might further increase the cost competency of the manufacturing process.

1.2 Research Background

As mentioned in Section 1.1, research in this area is very limited in the literature. Verrey et al. (2006) presented a study in the area of composites manufacturing cost evaluation. They calculated total production cost and cost per item values for four different RTM line configurations having different production capacities. Depending on the desired production volume, one of the two methods could be used and the consequent cost per item value was calculated based on the produced volume.

This research is an extension of that presented in Verrey et al. (2006). In this study a model was developed to determine an optimized configuration of the production line to produce a required volume with minimized cost. For this purpose many factors were taken into account such as number of required parallel units of resources as well as resource utilization plans and policies.

1.3 Scope and Objectives of the Thesis

RTM manufacturing process is one of the many processes used to produce composite products. Mass production compatibility of RTM manufacturing process makes it an interesting choice of cost evaluation and production line analysis. RTM production lines are usually designed and configured to produce single products. However, since tools are the only single purpose resource of an RTM process, different parts with similar material structures and geometries might also be produced utilizing common production facilities. Hence, it is important to consider cases where production facilities are utilized for producing more than one type of product. Also in some cases, a production line is already configured and specific pieces of equipment are allocated for production. In such cases no change in the configuration of equipment is desired. Instead, optimal production levels of different products leading to a maximum profit are the questions of interest.

This research is conducted for RTM manufacturing production lines with the following objectives:

- Analyzing the production line configuration at different production volumes to decide resource utilization plans reducing respective cost components of the total production cost
- Estimating the total production cost at different production volumes of a single product type based on cost reducing and resource utilization plans
- Estimating the total profit of producing two product types at different combinations of production volumes

- Evaluating the combinations of production volumes for two product types which are fully utilizing a fixed configuration of a production line
- Evaluating and analyzing cost behaviors at different production volumes for single product type and bi-product type cases

To avoid the computational intensiveness, a production line with two product types is considered and analyzed since it carries most common characteristics of multi product type cases. Results and findings can be extended to cases with more types of products.

1.4 Research Methodology

To evaluate, analyze and optimize an RTM manufacturing process, a hypothetical but realistic RTM production line is studied. Industrial engineering tools are applied to different production resources for cost reduction. Several definitions and assumptions are made to facilitate production cost calculations and to better take into account interactions of different resources of the RTM production line. Cost reduction measures are ordained to schedule and plan resources, material purchases and product deliveries such that cost is minimized.

After resources are configured and plans are set for different production volumes, an overall production cost calculation is conducted by summing the values of cost components identified based on a manufacturing cost break down structure.

MATLAB is used to perform these calculations for all integer production volumes of a predefined range and to plot a graph to illustrate how the cost per item is fluctuating while maintaining a basic trend.

In the bi-product type case, for each combination of production levels of the two product types, the same cost evaluation procedure was followed in MATLAB and a profit value was calculated.

The impact of having constraints on the number of the resources utilized was also studied in this research when two different product types are produced. The objective was to find the optimal combination of the production levels for those two product types. In this case, a limited number of alternatives were evaluated to reach the optimal solution quickly. Alternatives were limited since optimized alternatives are obviously among those fully utilizing the production line capacity. An algorithm was developed to find an optimal or near optimal solutions.

All calculation results were verified by an EXCEL spreadsheet model. This model is able to calculate costs and profits of individual production levels in parallel with MATLAB code.

1.5 Research Contributions

This research is an extension of that in Verrey et al. (2006) in which four different RTM manufacturing line configurations are used to study a thermoset and a thermoplastic automotive floor pan production at different production levels.

Contributions of the current research extend the work of Verrey et al. (2006) such that a configuration is automatically determined for any annual production volume and corresponding costs are calculated. In this research we can decide an optimized configuration of the production line and calculate production costs by applying resource planning and scheduling. For any desired production volume, the configuration of the production line is specified by assigning sufficient parallel units of resources. Other production planning issues such as material purchasing, production delivery, operating hours and equipment utilization procedures, are also determined for cost analysis and calculation.

This research contributes in RTM manufacturing technology cost evaluation and optimization and intends to bring cost competency to this technology with growing applications. Some parts of the modeling and the analysis approaches developed may be applied to other production systems with similar characteristics in processing and material flow. However, some particular aspects of the modeling and analysis are only applicable to RTM manufacturing systems.

1.6 Organization of the Thesis

In the next chapter, literature of composites manufacturing cost evaluation and optimization is reviewed. A brief explanation of different composites manufacturing optimization efforts is presented. In addition, cost evaluation and optimization for composite manufacturing processes are discussed in more details. In Chapter 3 the methodology used in this research to achieve the defined objective is described in detail. It includes assumptions made, policies defined to maintain cost components at their minimum and a cost estimation model. In Chapter 4, a production line for testing and illustrating the developed cost model is presented in detail. The model is applied to an RTM line. Results are discussed and reasons of irregular cost fluctuations are analyzed. Chapter 5 presents a summary and conclusions of this research.

2 Literature Review

Over the past several years many researchers made much effort in research on composite manufacturing process optimization. The majority of the published research is on liquid composite molding technology and focuses on injection of the resin into reinforcement and cure cycle of the resin. However, a comprehensive study of composites manufacturing process should include interactions between many different stages from fabric cutting to preforming, molding, curing, post curing, finishing, painting, packaging, etc.

In this chapter first a brief review is made on the literature of injection and curing optimization and modeling. Several research papers more closely related to the work developed in this thesis research will then be reviewed in more detail.

2.1 Injection and Cure Simulation and Optimization

The objectives of most optimization plans in composite manufacturing are cost reduction and mechanical properties improvement. Resin injection and cure cycle have been the two most appropriate targets of these studies. Cost is a dependent function of the cycle time while injection and cure cycles encompass longest cycle times of the manufacturing process. Mechanical properties of composites are also mostly determined by the performance and parameters of these two key stages of the manufacturing process.

2.1.1 Injection Simulation and Optimization

In addition to experimental analysis, different methods of simulation such as finite element method (FEM) have been used for liquid composite molding manufacturing process optimization. Simulation models are able to calculate the final value of objective functions such as filling time of the mold, pressure distribution in the mold cavity, etc. by having determined values of injection variables such as gate and vent locations, injection pressure, flow rate, temperature of the resin before injection, temperature of the mold during injection, etc.

Using a proper search method such as a genetic algorithm in parallel with an injection simulation model increases the efficiency of the search. Injection variables may converge to their optimal values in a shorter time and better objective function values can be attained.

Young (1994) considered the problem of finding the optimal gate location in mold geometry. He compared genetic algorithm (GA), hill climbing search method and random search algorithm as optimization tools to search for the optimal gate location in the mold geometry. The optimal gate location was evaluated based on inlet pressure value, maximum temperature difference in injection period and the time difference for the boundary nodes to be filled. The objective was to minimize a function consisting of all these values. Comparison of the results of different optimization tools revealed that the best solution was obtained by GA. Hill climbing search could find solutions in shorter calculation time however it was trapped in local optima most of the time. Random search needed much more computational efforts to converge to the optimal gate location.

Mathur et al. (1999) presented a model to find the optimized gate and vent location in the mold geometry of an injection process. They used finite element method to simulate the injection process and to evaluate the filling time and the void content of the final part. Different gate and vent locations in the mold mesh were searched by a GA working in parallel to the simulation model to converge to a solution with the minimum filling time and void content.

Nielsen and Pitchumani (2001) proposed an on-line method for controlling the flow front of the resin using neural networks. The neural network was trained with a series of numerical simulation inputs and outputs. Receiving flow front location at any time and flow rates of injecting inlets as inputs, the neural network was able to predict the next time interval flow front location of the resin. Flow fronts are traced with discrete spot checking in a 2D screen and compared with a predefined flow pattern. Simulated annealing method was used to search for the optimized flow rates at different instants. Optimal flow rates minimize the deviation of flow fronts from predefined patterns.

Jiang et al. (2001) found the optimal gate and vent locations among different nodes of mold geometry. The optimal locations of gate and vent result in minimum filling time and a uniform resin flow pattern. Numerical simulations were used to calculate the filling time and to predict the resin flow pattern. GA was coupled with the numerical simulation model to converge to the optimal solution more efficiently. They found that constant flow injection strategy leads to a vent-oriented smooth flow pattern while constant pressure strategy results in the shortest flow path.

Luo et al. (2001) developed a model to increase the effectiveness and the speed of the molding process. A neural network was trained by preliminary data from computer flow simulation models to predict discrete spots on the resin flow front at different time intervals by having the gate and the vent locations as inputs. Neural network model calculated the filling time of the injection process. This neural network was integrated to a genetic algorithm optimization tool to determine near optimal gate and vent locations.

Optimal solutions resulted in minimum total distances of discrete spots on the resin flow front from the vent at different time intervals. The filling time of the optimal solution was also minimized.

Kim et al. (2002) considered the RTM filling time minimization problem by searching for optimal gate location in the mold. They developed a numerical simulation method using control volume finite element. This numerical simulation model was first compared with visual experiments to be verified and then was coupled with GA to search for the optimal injection gate. Optimized injection gate fills up the mold at a constant injection pressure and in the shortest time. Sequential injection with multi-gates was found to operate more efficient comparing with simultaneous injections.

Gokce et al. (2002) considered the problem of minimizing the total filling time and the number of dry spots when all vents are reached by the resin. They used a branch and bound technique in parallel to an injection molding simulation model to optimize the gate locations in the mold. For this purpose the mold was divided to a mesh structure with discrete nodes. All nodes were considered as potential locations of the gate. Branch and bound limited the search area and resulted in faster convergence to the optimal solution.

Jiang et al. (2002) minimized the injection filling time and avoided air traps by determining the optimal vent locations. They proposed a mesh based method to predict resin flow without using numerical simulation models. GA was used in parallel with the mesh based method to conduct the search. In order to minimize the filling time, the maximum distance between any gate and vent was considered. Areas lacking vents were also minimized to avoid air traps. This effort resulted in shorter filling time and less dry spots.

Mathur et al. (2002) minimized the injection filling time by optimizing gate location in an injection process. They used a sensitivity-based algorithm to specify the gradient of the filling time with respect to the changes in the gate location. They then employed a gradient search procedure to find the optimum gate locations. In their sensitivity-based algorithm, the governing equations and boundary conditions of the process model were differentiated with respect to the gate locations. Differentiation of the model results in a system of equations. The system of equations was solved to bring forth a solution for the designed sensitivity fields at each time step.

Gou et al. (2003) considered an injection filling time and maximum pressure minimization problem. They used design of experiments (DOE) to predict the relationship between the variables and the responses. Numerical simulations were used for several primary trials to calculate the responses for the boundary variable values. These results were studied by the statistical tests such as variance test to find the most effective variables and bilateral interactions of these variables on the consequent responses. Variables which had remarkable correlations with corresponding responses were selected to make an empirical model using regression technique. These empirical models related the response values with effective variables based on linear functions. Graphical evaluation of the empirical models resulted in optimized values of the most effective variables i.e. gate and vent locations, number of gates, injection flow rate and the fiber volume fraction.

Ye et al. (2004) formulated an optimization model for a single gate -multiple vents location problem to increase the quality of the part and to minimize the filling time. They used an RTM simulation software, a graph based network and a heuristic search to find an optimal gate location having the least maximum distance from corresponding vent locations. Vent locations and gate location candidates were identified by the simulation software. Paths between the gate and corresponding vents were constructed by connecting the center of adjacent mesh elements toward a descending pressure trend. Their algorithm decreased the number of required simulations comparing with GA and branch and bound previously used in the literature of the research.

Gokce and Advani (2004) optimized gate and vent locations in LCM processes considering the race tracking phenomena. They utilized branch and bound search to find optimal gate location. To find corresponding vent locations, the authors exploited a map-based exhaustive search. They focused on the minimum filling time, minimum number of vents and maximum ratio of successful drains in different race tracking scenarios as their optimization objectives. Dealing with discrete probabilistic race tracking scenarios, weighted average values were considered in objective function calculations. They demonstrated the usefulness of their methodology by studying three cases and validated the results in a virtual manufacturing environment.

Gokce and Advani (2004) demonstrated how to cope with the ambiguity of vent location optimization as the result of race tracking phenomena. They assigned probabilistic distributions as the strength values of race tracking channels. Assigning different possible strength values to potential channels, they simulated a set of scenarios in which the last filling spot was considered as the vent location. Adding probabilities of scenarios in which a particular node becomes vent location develops a fitness map. An exhaustive search on created fitness map leads to the optimal vent location.

Minaie and Chen (2005) studied how to avoid dry spots forming when a location is determined as the vent. They used a real time control method. Real time control method monitors the resin flow front and compares it with a reference flow. Based on reference flow, all flow fronts from all gates reach the vent at the same time. A control system implements modifications on the flow rate and pressure of different gates to adopt the real time flow with the reference flow. This real time control made all flow fronts meet at a predefined vent location.

Lawrence and Advani (2005) studied the problem of reducing the variation of the resin flow front with an ideal predefined flow during the injection. They applied a combination of an offline and an online control method to achieve this purpose. Auxiliary gates and sensors were placed in different locations to detect the deviations online and to modify the flow. A modified version of the shortest path algorithm was adapted to distinguish which gate was responsible to react at each control interval. A flow conductance factor based on the permeability function and the distance was used to calculate the cost of paths between gates and sensors. Their control method resulted in flows with little deviation from the predefined ideal pattern.

2.1.2 Cure Cycle Simulation and Optimization

An optimum cure cycle temperature and pressure profile are defined to improve mechanical properties, to avoid defects emanating from residual stresses during the cure cycle and to reduce the cure cycle time for cost reduction purposes. Heat transfer and cure kinetics models are used to simulate the cure cycle conditions. The outputs of these simulations are then utilized to search for optimum cure profiles.

White and Hahn (1993) investigated how changes on cure cycle profile affect the level of residual stress, degree of cure and transverse modulus and transverse strength as measures of mechanical properties. These changes were investigated experimentally and by using numerical simulations. As the result, an optimal balance between variables was found. This optimal balance minimized the residual stress while retained the cycle time and mechanical properties of the produced part.

Chang et al. (1996) considered temperature profile optimization of composite manufacturing cure cycle. They used GA as their optimization tool to minimize the consolidation time and the over heat temperature. Constraints were considered for maximum heating rate and initial temperature values. Utilizing a simulation model imitating flow and thermal-chemical behaviors of the process, optimal or near optimal cure cycle was found in the feasible area.

Rai and Pitchumani (1997) considered temperature and pressure profiles optimizations separately. They integrated non-linear programming and numerical simulation of cure phenomena to find the optimal temperature profile. The optimal temperature profile problem consisted of cure cycle time as the objective function to be minimized and maximum temperature in part different layers, maximum temperature gradient, maximum temperature difference across different cross sections and minimum degree of cure as constraints. In the pressure profile optimization problem, the objective function was to minimize the area under pressure curve with respect to the time. Pressure profile was constrained to a maximum value of the consequent void fraction. These optimal profiles resulted in minimum cure cycle time without violating practical constraints to avoid quality loss.

Pillai et al. (1997) demonstrated how an optimal temperature profile minimizes the cure cycle time. To avoid residual stresses, the optimal profile prevents the stress development, exothermal damages and void and impurity content formation. They used a model-based optimization technique incorporated known heuristics to converge to near optimal solutions in a reasonable time. This method investigated different values of different control variables at different simulation time spots and evaluated how the process would evolve by time.

Duh et al. (2001) proposed a numerical method to estimate the optimum cure kinetics parameters. They exploited model based simulations and experimental data. They initiated the simulation with a user defined parameter set and compared the resultant temperature history of the simulation with a real injection experimental temperature history. The realistic experiment was conducted under similar conditions. Using least square method, an operating optimizer adopted new values of the parameter set in order to minimize the differences between the real and simulated temperature history.

Michaud et al. (2002) investigated the improvement of thick-sectioned RTM cure quality and cycle time. They evaluated the quality and the cycle time for different temperature patterns using cure simulation software. Quality was measured by extent of cure cross-over. Cure cross-over is the point where cure rate of central layers start to surpass that of the outer layers. Cycle time was measured based on 75% of resin final cure rate. A robust evolutionary strategy was used to search for the optimized pattern among a finite number of feasible patterns. This method was proposed by the author and was a modified version of GA. To deal with the stochastic nature of several variables, simulation was run more than once and the average value of the fitness function was compared. The result showed an optimized cure cycle needs to have at least one cooling stage.

Pantelelis (2003) studied cure cycle of a composite part manufacturing process. He considered minimizing deviation of the maximum temperature from the maximum cure rate, total cycle time and differences of maximum and minimum values of temperature between all adjacent pairs of layers. A simulation software consisting of physical, chemical and thermal equations was utilized to imitate the through thickness heat and cure evolutions. An evolution strategy and a complex box method were utilized to conduct the search toward better convergence. A complex box method was developed based on gradient search concept. The optimal solution accuracy and calculation time were compared for different search methods.

Ruiz and Trochu (2005) studied the optimization of cure cycle time and part deformation in a cure process. Different temperature patterns were studied to minimize the cure cycle time and stresses. Stresses in the cure cycles cause different types of deformation to the solid part. They utilized an evolutionary algorithm and constructed a principal objective function consisting of several sub-objective functions. The principal objective function was constructed based on a sigmoid function to accelerate the convergence rate of the optimization.

2.2 Technical Process Optimization

As shown in the literature much effort is done to optimize different composite manufacturing processes. Methods are invented, process conditions are modified, optimum processing procedures are selected or combinations of economic and quality issues are considered. Economic issues are related to variables affecting the cost, such as injection or cure cycle times, weight of product, etc. Quality is also the result of many variables such as stacking sequence of fabric layers, cure profile, injection, etc.

Mychajluk et al. (1996) considered the problem of minimizing the injection and cure cycle times both at the same time. They utilized a combinatorial model consisting of resin flow, void formation, heat transfer and cure kinetics sub-models. Such model was exploited to predict the cycle time when initial resin and mold injection temperatures, resin injection flow rate and mold processing temperature were identified. Consequent pressures and temperatures were constrained in a feasible region. Process and material characteristics were used to define pressure and temperature limitations.

Yu and Young (1997) studied production cost, part deformation and material degradation of injection and cure cycles. They minimized cycle time and maximized temperature difference in the part during injection and curing of an RTM process to reduce cost and the probability of part deformation or material degradation. They considered heating rate, mold temperature during filling, resin filling temperature and resin curing temperature as their input variables. An injection and cure simulation software was coupled with a GA optimizer to find optimal combination of considered variables. Their work resulted in more economical process cycles, parts with higher qualities and lower rates of discard.

Kassapoglou (1999) studied and formulated manufacturing characteristics and constraints for designing a helicopter fuselage frame using four different processes. Weight minimization problem was considered and solved for all processing methods. To minimize the weight, all structural constraints were assigned their lowest possible values in their allowable ranges. Minimum cost was obtained by letting structural values vary in their allowable ranges where one combination of all variables would minimize the total manufacturing cost. Another method was also proposed to optimize weight and cost at the same time. This method used the weight optimization solution and searched the vicinity of minimized weight solution to form a Pareto set of near optimal solutions.

Lin et al. (2000) studied the pitfalls of different optimization methods applied in RTM processes. They demonstrated how applications of optimization methods might create errors. It was also shown that for several purposes commonly applied optimization methods are not cost efficient. The authors recommend brute force search methods such as graphical methods for RTM problems having few variables. They emphasized on gradient based searches for RTM problems having many decision variables. They also listed several drawbacks of GA applications in RTM process optimization.

Loos (2001) presented a brief review of three new injection molding methods e.g. RTM, RFI, and VARTM. He then showed how one can simulate the process and have the outcome values of the interest with defining the input parameters. These values and parameters are mechanical and process measurements.

Li et al. (2002) studied reliabilities of the parts produced by composite manufacturing processes. They considered probabilistic values for input variables of composite manufacturing processes i.e. raw material characteristics and process conditions. A composite material manufacturing deterministic analyzer software was coupled with a reliability analyzer to study the reliabilities of the parts produced. They compared the probabilistic spring-in angle of a part with a limit value. In another case they compared the stochastic value of the part angle with the tool angle to estimate the probabilities of parts being accepted, rejected or accepted after an additional modifying process. Multiplying such probabilistic values with their corresponding costs, expected costs of the process was estimated. Summation of expected costs constructs the objective function of an optimization model. Optimization model found the optimal tool and mating structure angle difference leading to the minimum total manufacturing cost.

Tong et al. (2003) studied process condition optimization of a transfer molding process. An RTM process was utilized to produce electronic packages. They simulated the electronic package molding process based on combinations of six input variables. Five different quality measures were estimated based on outputs of the simulation model. Exploiting TOPSIS algorithm, the response of input variables to the resultant output quality measures was calculated. As the result, input variable levels were optimized based on their response values.

Yang et al. (2003) considered a composite material selection optimization problem. A neural network was used to simulate the process and to produce the desired output out of user defined inputs. Genetic algorithm was coupled with the neural network to take control over input selection process at different iterations. Their proposed method is a general method. It can be used for optimizing an objective function even when it is too complex to be calculated or when the relationship of inputs and the output function of interest is unknown.

Riche et al. (2003) studied structural design optimization of a part produced by compression RTM. Manufacturing process issues and different constraints were simultaneously taken into account at the early stages of design. They considered stacking sequence of layers in the preform, injection condition i.e. pressure or flow rate, compression rate and ratio of the laminate length filled only by injection before compression starts as variables to be tuned. They utilized the Globalized and Bounded Nelder-Mead algorithm as their optimization tool.

Li et al. (2003) demonstrated how input parameters of a process are optimized to improve multiple output characteristic of a product. To improve the responses simultaneously, a function called desirability function was defined. The value of the desirability function was the combination of all single response values. Exploiting the process historical data, a neural network was trained to predict the resultant responses of a set of input parameters. A genetic algorithm was employed to optimize the normalized input parameters between their possible variations. As the result the desirability function was maximized where all responses were in their allowable ranges.

Liu and Chen (2004) studied a new method for injection molding of thermoplastic composites. In their method, water was used to push back the thermoplastic melt to the mold. Sink line forming by the resin shrinkage was consequently prevented. The influences of five different factors on the penetration length of water in the mold were probed by trial tests. To limit the trial test runs, Taguchi orthogonal array design was exploited. Using such method, optimized factors for injection were detected and analyzed.

Park et al. (2004) illustrated how a process variable and a structural variable are optimized simultaneously at the early design stages. Stacking sequence of layers of preform laminates and resin injection gate(s) location(s) were considered as the variables influencing the filling time and the layers displacement. An optimization model was developed considering the filling time and the layers displacement in the objective function. To decrease the time and cost intensive numerical simulation of the resin flow, gate location optimization was done by using a semi-analytical method while the stacking sequence optimization was done utilizing a GA algorithm. They showed that the interrelation of the filling time and the product stiffness can be ignored if these two variables are optimized separately.

Park et al. (2005) studied weight minimization of a composite structure produced by RTM process. They took into account both the structural and the process constraints simultaneously since they have interrelations. A maximum limit value was considered for the displacement of layers or for the failure index of the structure under a certain load. A maximum limit was also considered for the mold filling time as the process constraint. GA was utilized to conduct the search for the optimum stacking sequence and number of layers in the feasible region. Optimized gate location was then searched based on determined stacking sequence and number of layers of the preform. As the result, a minimum weight was attained in the feasible area.

2.3 Composites Manufacturing Simulation, Cost Evaluation and Optimization

The majority of literature on composites manufacturing process optimization is devoted to process and design variables selection. Such process and design variables specify detail production characteristics, methods and procedures. Production variables influence product final cost and quality. In RTM technology which is the scope of this research for instance, stacking sequence of layers, gates and vents location in the mold, pressure and temperature of resin and mold in different stages of injection, injection flow rate or pressure and cure profile are variables of this type.

Despite the plentitude of articles published in process variable optimization, only few works investigated composite manufacturing processes from an overall production line point of view. Production of parts manufactured by RTM technology for instance, is a multiple step process. Among all process steps of the RTM process, tooling, injection and curing have received more attention. This attention seems to be reasonable since injection and cure have a determinative role in quality and cycle time of the process.

To have a more comprehensive knowledge about production steps and their interrelations, several studies were conducted to simulate the entire production process and to evaluate the total cost of production. Efforts were also made to reduce the production cost by optimizing shop floor variables. Such shop floor variables determine how different resources are arranged and utilized in a production plant and how they are interrelated toward their common goal.

Kendall et al. (1998) conducted an overall process modeling and optimization for an automotive component produced by liquid composite molding technology. They used discrete event simulation to imitate the behavior of different operations of the process. Many interactions of process operations were considered for overall system efficiency. Technical cost modeling (TCM) was integrated with discrete event simulation to overcome the incapability of discrete event simulation in monitoring variable costs of operations. Efficiencies of operations were measured based on utilization rates of exploited equipment and different scenarios were simulated to see how utilization rates of different machines are optimized. Scenarios were created by changing the number of parallel equipment or molds utilized in different operations of the process. Considering the required investment of different scenarios, variable costs were calculated by TCM technique and the total production cost was estimated. Variable costs depended on labor schedules and material consumption rates fulfilling the required production capacity. In order to decide the optimal configuration of the process for different production volumes, several configurations were considered and their production volumes and costs were calculated. Sensitivity analysis was also performed to investigate contributions of different items of the production cost or different process steps to the final production cost.

Bernet et al. (2002) studied cost and consolidation of yarn based composites. They developed an integrated cost estimation and consolidation model. Consolidation model monitors the quality of the product. They modeled the manufacturing process such that cost and quality are optimized at the same time. The cost model considers material cost, labor cost and overhead cost. Labor cost was then broken down to queue cost, setup cost, run cost, wait cost and move cost. Run cost was a function of run time. Run time influences both operator time and equipment cost. Equipment cost consists of different run time dependant cost elements such as depreciation cost, maintenance cost and utility cost. Since run time in manufacturing of yarn base composites depends on consolidation of resin and fibers, a consolidation model was constructed to relate manufacturing parameters to consolidation time and to the resulting void content. Void content reflects the quality of the part. The consolidation model determines the consolidation time based on the applied manufacturing parameters and the result is used in the run time element of the cost model. The minimum quality requirement was controlled by void content measure. Using run time data extracted from consolidation model, the cost model estimates production costs at different production levels of different manufacturing processes. On the other hand, the void content measure extracted from consolidation model constrained the manufacturing parameters to guarantee the minimum desired quality. Calculating cost of production utilizing different manufacturing processes, optimal alternative was selected based on minimum cost where the product quality was maintained.

Barlow et al. (2002) investigated production time of an aircraft component for two different production methods; RTM and VARTM. Since production steps of composite manufacturing processes are labor intensive, production time is a good indication of production cost. Significant time differences of RTM and VARTM process steps revealed the possibility of cost optimization by selecting better production processes. They estimated the cycle time of process steps. These equations takes into account different parameters of a process step such as setup time, delay time, steady state velocity of the process and dynamic time constant of the process (acceleration of a certain process before it reaches its steady state velocity). A cost variable was also defined for each process step to link the cycle time to the geometry of the product. In order to calculate the delay time and the steady state velocity, two experimental runs were used for two different geometries. Based on measured times and values of the cost variable, a linear equation was used to calculate the steady state velocity and the delay time based on the slope and the time intercept of the line respectively. The result showed a higher labor cost in VARTM process.

Verrey et al. (2006) studied production cost issues for two different types of composites for an automotive floor pan; a thermoset based composite and a thermoplastic based composite. In both cases carbon fibers were used as the reinforcement system. To verify the feasibility of obtaining parts with desired mechanical properties and also to characterize the optimized process parameters, injection and cure/polymerization phases were modeled for both thermoplastic (TP) and thermoset (TS) alternatives. Gel time limits the injection time and cure time is a time constraint for the mold to be reused in TS-RTM processes. Consequently, injection and cure times were desired outputs of their developed TS-RTM model. By using differential scanning calorimetry, heat flow of the cure process was monitored and predefined cure kinetic relations were adjusted parametrically. Estimated parameters let further predictions of the cure behavior having different process conditions. For thermoplastics, a model was developed to predict the degree of conversion and viscosity changes as a function of time, temperature and degree of conversion. Viscosity is the main limitation for the injection time in thermoplastic processes. The feasibilities of TS-RTM and TP-RTM processes were verified by using numerical cure/polymerization kinetics and injection models. Developed models were also used to estimate process cycle times of TS-RTM and TP-RTM processes.

Molding times were considered cycle times for both processes since molding is the bottleneck. Different cost components of the equipment such as investment cost, power consumption cost and cost of the area occupied on the shop floor were calculated based on previously estimated cycle times. Cost components were then calculated and distributed over the number of parts produced during a time limit. Fixed and overhead costs of the plant were also prorated over the individual items. Two different cases were considered: 1) Tools were dedicated to production based on shifts 2) Costs were calculated based on utilization time of the tools. This implies tools might be shared by other clients and/or products. Adding variable costs of production such as labor and material costs to distributed fixed costs, production cost per part was calculated for different production levels and separately for TS and TP alternatives. Possibility of replacing common TS-RTM process by TP-RTM process was investigated and analyzed at different production levels. Sensitivity analysis of cost was also conducted. As the result, waste reduction policy was found to be an important factor to make TP-RTM process a competitive option.

2.4 Summary

Despite much effort in composites manufacturing process optimization in recent years, only few works considered all production steps of a composite manufacturing process and took into account different interactions of production line components. The majority of literature in this area of research focuses on the dominant steps of the liquid molding process such as preform stacking, injection and curing. Dominancy of these steps originates from their long cycle times and their significant influence on the quality of the product.

In this research a hypothetical but realistic RTM production line is studied considering many aspects of production to show how production cost varies at different production volumes when the production line is configured for an optimized operation. The production line configuration is studied and optimized at different production levels. Several cost influencing issues such as material handling, resource scheduling and job sequencing of the equipment are considered to reduce the production cost at individual production levels. Considering separate scenarios for producing one and two different product types, the optimal production levels are investigated and studied. The impact of the simultaneous resource and production level constraints in the production line is also studied in a different scenario.

3 Methodology and Modeling Approach

In this chapter details of the problem considered in this research are first presented. The problem is an extension of that studied in Verrey et al. (2006). Model, formulation and solution methods developed will be presented afterwards.

3.1 Problem Introduction

Verrey et al. (2006) simulated four different RTM manufacturing processes of an automotive product to investigate the features of the production system. They also developed a methodology to calculate the unit production cost of the product for several production line configurations. Differences of the considered production line configurations were originated from utilizing different number of parallel units of equipment or utilizing equipment with different capacities.

In this research we extend their work such that for each production volume an optimized configuration is identified based on a mathematical model and the corresponding production cost is attained afterwards. In addition, the modeling and solution approach developed in this research considers more issues related to such production systems.

3.1.1 The Production System Description

RTM is a manufacturing process used to produce parts with high mechanical properties. Among the manufacturing processes used to produce composite parts, RTM is capable of producing parts with higher geometrical complexities and in relatively shorter cycle times. RTM manufacturing costs usually are not justifiable for low production volumes since the required facilities are rather expensive. Tailored fiber arrangements and low volatile organic compound (VOC) emissions are considered as RTM advantages.

In most cases a production line is configured to produce one type of product at high production volumes. Hence, production cost of unit product can be kept at low levels. On the other hand, different parts having similar dimensional properties and similar material structures might also be produced utilizing common production facilities. Minor modifications are required for equipment setup to produce different product types.

3.1.2 Details of the RTM Manufacturing Process

In RTM manufacturing process, resin is injected into a precut and preformed fiber bed in a closed mold under certain pressure and temperature. Resin is then cured and hardened in the closed mold with required temperature and pressure profiles. Tools are utilized and are clamped into presses to produce near shape parts. Molding is considered as the most important part of the RTM manufacturing process. Some preliminary steps are carried out to prepare fabric preforms and resin mixture. Some other steps improve mechanical and geometrical properties of the parts coming out of the injection mold.

Fibers are usually purchased and received in the form of rolls. To make near shape preforms, rolls are first cut to fabrics by different methods such as ultra sonic cutting. Fabrics are then stacked with a predefined sequence to maintain required mechanical properties. Stacking sequence of fabrics affects mechanical characteristics of the product. To remove moisture, in some cases, fabrics are dried in ovens before they are stacked. Glues or woven binds might be applied between fabric layers to hold the preform structure. Stacked fabrics are put into a near shape tool and are pressed to form a solid preform structure used in molding. As explained earlier, one or more preforms can be set into an RTM mold and the mold is clamped and pressed. An injection set pushes back the already prepared resin mixture into the preform bed to replace the air inside the entire mold cavity. The consolidated part stays in the mold after the injection. Pressure and temperature applied by the press cures the resin. After the part is cured to a certain level, it is extracted from the mold and the cure process is completed in a post-cure oven. Trimming and finishing operations are followed to improve the geometrical properties of the product. The products are finally packaged to get prepared for delivery.

3.1.3 Operational Features of RTM Production Line

An RTM production line consists of various production resources such as different types and units of equipment and labors. To carry out most of the process tasks, machines and labors are operating simultaneously. Simultaneous operations of machines and labors interrelates their operation and production rates. Production cells may be defined to categorize production resources involved in related operations. In different production cells, similar operations are executed by a group of resources. Operations of different resources in a production cell are synchronized and highly dependant. Such dependency determines a common operational schedule. If a failure occurs for any of the equipment in a production cell the entire operation of the cell is stopped. Different production cells are related by work in process buffers. Consequently different production cells might have different operational schedules.

In RTM manufacturing process, equipment and machines may be dedicated to one type of a product or are shared by different types of products. As mentioned earlier, since products with similar material structures and geometrical features might be produced utilizing common facilities, corresponding costs should be distributed to respective products based on their usage of the resources.

3.1.4 Terminology

To better analyze RTM production line and to develop a cost model for production cost reduction, several terms used in the cost modeling are given below:

Process Tasks: An RTM manufacturing process consists of several tasks having measurable times and utilizing different equipment and labors. To produce one unit of the final product, tasks are repeated for as many times as their outputs are consumed in the final product. At individual iterations of a task, required equipment and labors are dedicated to the work in process. Some tasks add materials or parts to the work in process.

Unit Processing Time: Unit processing time is considered as the duration of time a machine, a labor or a production cell is effectively utilized and operates to produce one unit of the final product. During the processing time machines and labors are used to perform process tasks in which they are required and are dedicated to the work in process.

Production Cells (Work Stations): The operation of a production cell starts from and ends in work in process buffers. Buffers do not exist inside production cells. Since operations of different resources of a production cell are synchronized, unit processing time of the production cell depends on the resource having the longest unit processing time. In cases where different units of a resource are operating in parallel, the unit processing time of the production cell is calculated based on unit processing time of its resources divided by corresponding number of their parallel units. When a failure occurs for any of the resources operating in a production cell, the entire operation of the production cell is interrupted.

Arrangement of Molds and Presses: In RTM manufacturing process a tool and a press are utilized in both the preforming and the molding production cells. Tools might be permanently fixed onto presses or they might be removed and fixed back onto presses at sequential operations. A tool and a press have to be fixed to each other when their common tasks are performed. If the tool is permanently set onto the press, the tool and the press are considered as one piece of equipment. If the tool is temporarily set onto the press, they will have different processing times. When a tool is not permanently attached to a press, fixing and removing tasks and corresponding times have to be considered in their operation.

3.2 Cost Reduction Issues

Comparing with conventional manufacturing such as metal machining, RTM production lines normally require higher equipment investments. High facility cost of RTM manufacturing processes requires high production volumes to justify their applications. Cost evaluation and optimization are of great importance for mass production technologies since the effects of small improvements are magnified to broader scales.

RTM products are used in cost sensitive applications such as in the automotive industry. Although light weight and high mechanical properties of composites are desirable in this sector, without a cost competent manufacturing process, composites do not have much opportunity to surpass their traditional competitors. Composite manufacturing processes are relatively new. Such technologies usually have large room for cost reduction.

3.3 Objectives of the Research

The first objective of this research is to develop a cost estimation model to calculate the minimized production cost of a hypothetical, but realistic RTM production line for different levels of production. Unit product cost is dependant on the production volume as well as many other aspects of the production process. Different production line configurations, resource scheduling and allocation policies for instance result in different equations estimating the production cost at different production volumes. In this research, different configurations are evaluated to minimize production cost while meeting production volume requirements.

Production facilities and market demands are two major factors to be considered in deciding the target production volume of a production line. Production capacities are restricted by financial limitations and market demand. In many cases, a target value is searched within the range of these limitations. Hence the second objective of this research is to investigate the production cost behavior at different production volumes and to decide the optimized production volume within a feasible range.

The developed model and cost analysis approach are also extended and modified to determine the optimal cost of manufacturing 2 types of products using the same production line.

To generalize the above mentioned objective to cases where more than one product type is produced in a production line, two modified objectives are also considered.

The two considered product types have close dimensions and are of the same material basis. The modified cost model calculates production cost and profit based on the optimized configuration of the production line. For cost behavior investigation and optimized production volume selection, combinations of two different production volumes are evaluated.

Profit fluctuations are also investigated when a fixed production line configuration is used to produce two different types of products. In this case the cost model calculates the profit of producing different combinations of production levels of corresponding product types fully utilizing the existing resources.

In summary, the objectives of the developed cost model are:

1. Finding the annual production level of an RTM production line within a limited range with the minimum cost per item value. Determining the corresponding optimized configuration of the production line at the optimized production level.

2. Finding the optimal combination of the production levels of two different product types within a limited range for maximum annual profit. Determining the corresponding optimized configuration of the production line.

3. Finding the optimal combination of the production levels of two product types which yields the maximum annual profit when a production line with a predetermined number of resources has been established.

3.4 Research Methodology

The RTM manufacturing process considered in this study has several constituent tasks. Following data or values are attributed to or calculated for individual tasks of the process:

- Required time for different tasks to produce one unit of the final product. This time is calculated based on the task time and the scrap rate as input parameters of the problem and also based on the quantity of the task output consumed in the final product.
- Resources utilized to perform different tasks
- Material monetary values along with their waste percentages consumed at different process tasks

Unit processing times of different resources of the production line are calculated by adding up required time of tasks utilizing those resources. Unit processing times of resources are used to calculate their utilization rates at different production volumes. Based on resource utilization rates, the required numbers of parallel units of resources are estimated. Machine downtimes are also taken into account.

Non-utilized times of equipment are allocated to external production demands following cost reduction measures. Allocations of facilities to external demands will help to increase the equipment utilization and to reduce unit product cost.

Equipment related costs are calculated using parameters such as price, amortization period, energy consumption rate, area occupancy on the shop floor, etc. Plant operation and overhead costs are distributed over the equipment based on the area they are occupying on the shop floor.

Labor cost is calculated based on operation times of different production cells. The operation times of production cells depend on the considered production level as well as the cell unit processing time. Parameters such as labor wage, work shift time, overtime and holiday wages are also taken into account.

Material cost depends on the price of raw materials consumed, scrap rates of different tasks and the production level. Optimized ordering frequencies for both raw material purchasing and final product delivery are also calculated based on economic ordering quantity (EOQ) concept. Corresponding ordering and inventory costs are added to the total production cost.

After all components of production cost are obtained, cost per item value is calculated. Calculations are repeated for all discrete production levels in a predefined range to identify the optimal production level.

3.5 Cost Reduction Measures

To reduce the total production cost of a production line, production variables must be set to their optimized values. The total production cost is often related to system configuration such as equipment utilization. We consider the following cost reduction measures in developing the model.

3.5.1 Allocating Parallel Units of Equipment

Additional equipment units are allocated to the production line when existing units reach their full capacities. To maintain the minimum cost, the least feasible number of parallel units of different equipment should be utilized.

3.5.2 The Operational Schedule of Production Cells

To have minimum labor cost and to avoid unnecessary setup times, production cells are scheduled to operate continuously until one delivery batch is produced or a work shift is complete. One delivery batch is equal to the required output of the production cell consumed in one delivery lot of the final product. A delivery lot is determined by the EOQ model. During the production period of a delivery batch, a production cell may stop operating for scheduled maintenances, holidays and scheduled non-working shifts.

Machine operators and other workers are paid higher wages for over time and holiday working hours. Depending on the production level, over time might be scheduled if regular shifts are exhausted. A production cell is scheduled to operate in holidays if production level is not attainable by operating during non-holiday hours. When a production cell is not operating to produce scheduled products, it might be allocated to produce external products.

The required annual operation time of different production cells is calculated based on the production level. If the estimated number of the required shifts is a non-integer, it has to be decided whether additional labors are employed or over time hours of the available labors are used. To reduce the labor cost, the amount of the fractional part of the calculated number and over time wage are compared.

In the two product type cases, the line switching frequency will be minimized. Setup durations decrease the overall production rate and lead to higher production costs.

Production cells having longer processing times determine the material flow in the production line and create a bottleneck. This implies that production cells with shorter processing times skip some of their operation shifts to balance the material flow. To avoid unscheduled stoppage periods, the sequence of the working and the non-working shifts should be scheduled for a production cell such that:

- The feed from the precedent cell is available for one complete shift. The feed might be supplied by either the buffer, a parallel operation of the precedent production cell or a combination of both.
- Subsequent cells especially those with long processing times receive enough feed when they are scheduled to operate.

3.5.3 Equipment Allocation to External Demands

To distribute equipment costs to different products, Rudd et al. (1997) considered two different cases with different distribution methods and equations. For situations where equipment is fully dedicated to one product type they applied the following equation to estimate the cost per piece:

$$\text{Cost per piece} = \left(\frac{\text{Annual investment}}{\text{Annual production volume}} \right) \tag{3.1}$$

On the other hand for situations involving partial machine utilization, or when different types of products are produced utilizing same equipment, they applied the following equation:

$$\text{Cost per piece} = \left(\frac{\text{Investment}}{\text{Volume}} \right) \times \left(\frac{\text{Production hours}}{\text{Total hours}} \right) \tag{3.2}$$

To reduce the equipment related costs, the non-utilized times of the equipment are allocated to possible external demands. Non-utilized times may be used for external demands completely or partially. If potential demands are satisfied completely, costs of the remaining non-utilized times of the equipment are distributed over the internal product(s).

3.5.4 Economic Ordering Quantity (EOQ) Model

Based on annual production volume, specified quantities of raw materials are ordered, purchased and consumed in the production line. The ordering frequency is planned by making a compromise between two major production costs: inventory cost and ordering cost. High ordering frequencies result in high ordering costs while inventory costs are kept low since raw materials are delivered to the production line more smoothly. On the other hand, low ordering frequencies result in high inventory costs and low ordering costs. Frequency of final product delivery is also following the same idea. An optimized delivery level is determined to reduce the sum of the inventory cost and delivery costs.

In cases with two product types, a common delivery frequency is calculated to minimize inventory and delivery costs of both products simultaneously.

In the EOQ model described above, only the capital cost of raw materials and final products are considered in the inventory cost component. A constant cost is considered for the storage facility in the process model based on a fixed storage area dedicated.

3.5.5 Optimal Configuration of Tools and Presses

As discussed in Section 3.1.4, two different arrangements are considered for tools and presses utilized in the RTM manufacturing process; permanently fixed tool and press units and separable tools and presses. The main advantage of the latter is that the number of parallel units of tools and presses are determined independently. Since tools have longer processing times and become bottlenecks before presses, in the temporary arrangement one tool is added and the production capacity increases. However, when tools and presses are separated at sequential operations, corresponding fixing and removing times increase the total processing time of the product. The production cost is increased consequently. The cost increase caused by the additional tasks involved, is considered as the disadvantage of the temporary arrangement.

In the fixed arrangements when the production capacity of one tool-press unit is reached, a second tool-press unit has to be added. Adding one tool-press unit is more costly than adding one tool only. However, it does not need the extra time to remove and attach the tool to the press.

Fig.3.1, illustrates the job sequence of tool and press when they are permanently attached to each other. As seen in Fig.3.1 the processing time of a permanently configured tool-press unit is calculated based on the following equation:

$$\text{Permanent config. processing time} = \text{Injection and Cure} + \text{Unloading} + \text{Loading} \quad (3.3)$$

In permanent configuration, the tool is 100% utilized while the press is idle in several durations waiting for the tool to get prepared for the next injection and cure cycle. To increase the production rate of such unit, either the unit will be duplicated or one unit of the bottleneck tool is added.

Fig 3.2 shows the job sequence of two tools operating along with one press in a temporary arrangement.

The processing time of the entire set is calculated by the following equation:

$$\text{Temp. Config. Processing Time} = \text{Injection and Cure} + \text{Tool Fixing and Removing} \quad (3.4)$$

To obtain a shorter processing time by the temporary configuration the following inequation is verified:

$$\text{Tool Fixing and Removing Time} < \text{Unloading Time} + \text{Loading Time} \quad (3.5)$$

Hence, temporary arrangement is only used when loading and unloading times are longer than tool fixing and removing times.

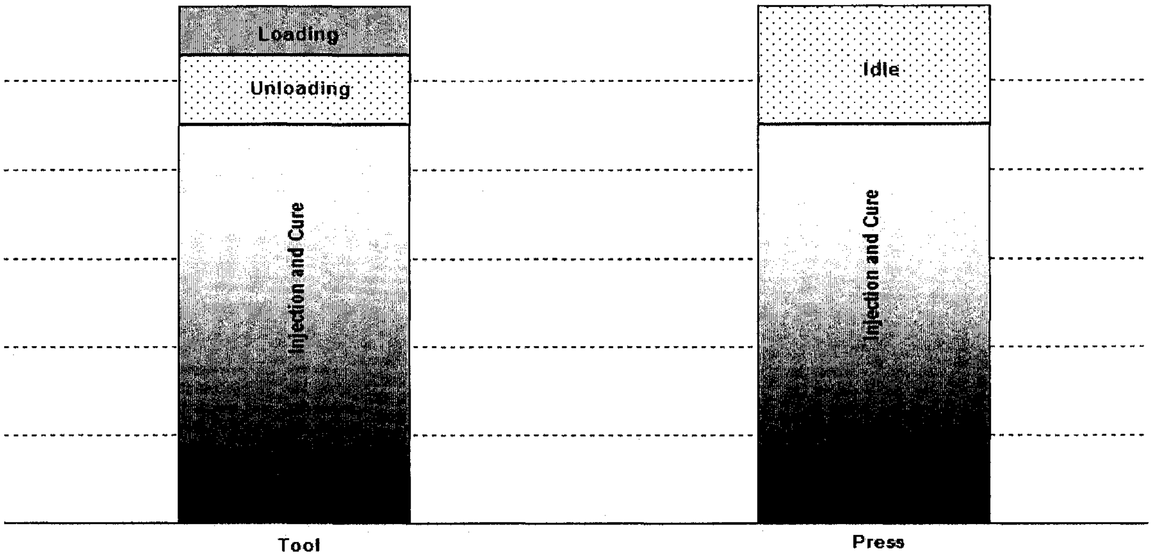


Fig. 3.1 Task Sequence of One Tool-Press Unit

In addition, time required to fix and remove the tool may increase variable costs of production. Such cost increase should be compared with cost reductions resulting from utilizing fewer units of press.

3.6 Cost Modeling

In this section, the cost model developed to calculate the total production cost is detailed. The cost model considers different low cost operation practices in calculating the minimum production cost.

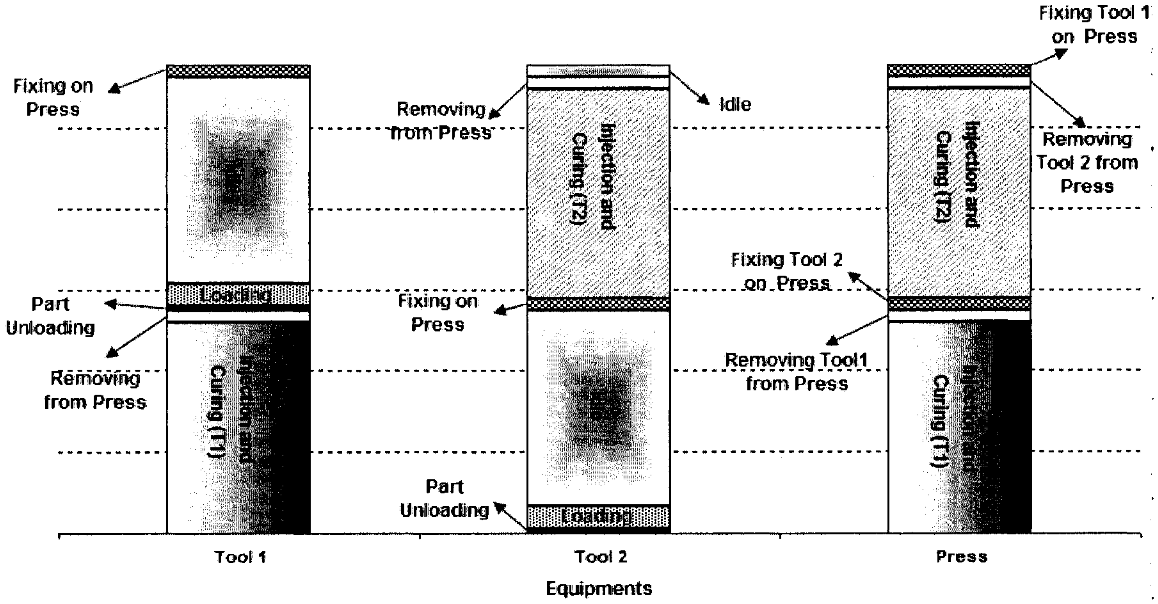


Fig. 3.2 Task Sequence of Two Tools Operating With One Press

3.6.1 Notations

As discussed earlier, the RTM process consists of several tasks executed in respective production cells. Notations for parameters and variables used in the model are given below:

Input Parameters:

$I =$ Total number of production cells

$J =$ Total number of process tasks

$K_i =$ Number of resources utilized in production cell $i, i = 1,...,I$

$T_j =$ Time of task $j,\ j = 1,...,J$

$Q_j =$ Quantity of task j output used in the final product, $j = 1,...,I$

$SR_j =$ Scrap rate of task $j, j = 1,...,J$

$CV_j =$ Monetary value of the materials consumed in the work in process up to the end of task $j, j = 1,...,J$

Process tasks are executed by utilizing at least one piece of equipment or one operator. Following terms are defined for the resources of the process:

PR_{ik} = External utilization demand time ratio for resource k in production cell i, $i = 1,...,I$, $k = 1,...,K$

FR_{ik} = Expected downtime ratio of resource k's operation time as a result of malfunctions, $i = 1,...,I$, $k = 1,...,K$

EP_{ik} = Cost of resource k in production cell $i, i = 1,...,I$, $k = 1,...,K$

DP_{ik} = Depreciation period for resource k in cell i, $i = 1,...,I$, $k = 1,...,K$

AR_{ik} = Area occupied on the shop floor by resource k in cell i, $i = 1,...,I$, $k = 1,...,K$

EC_{ik} = Energy consumption rate of resource k in cell $i, i = 1,...,I$, $k = 1,...,K$

SW_{ik} = Switching time of resource k in cell i to produce different product types $i = 1,...,I$, $k = 1,...,K$

Variable:

PL = Production level

3.6.2 Interrelating Quantities of the Cost Model

In order to produce one unit of the final product, several tasks may be repeated since more than one unit of their outputs may be required for the final product. The time required for a task to manufacture one unit of the final product is calculated by multiplying the task time and the quantity of its output used in the final product. A portion of the task output may be defective which will be discarded. Consequently, the corresponding production time of that task and of all previous tasks are wasted. IO_j is calculated by a recursive equation shown below to reflect time effect of the scrap rate of task j:

$$IO_j = IO_{(j+1)} \times \frac{1}{1-SR_j} \ , \ j = 1,\ldots,J-1 \tag{3.6}$$

Consequently, required time for different tasks to manufacture one good unit of the final product is calculated by the following equation:

$$FT_j = T_j \times Q_j \times IO_j \ , \ \ j = 1,\ldots,J \tag{3.7}$$

When the output of a task is defective and discarded, the monetary value of the raw material consumed in the item up to that step of the process is wasted. The expected cost associated with the scrap material for one unit of the final product is calculated by the following equation:

$$SV = \sum_{j=1}^{J} CV_j \times SR_j \times IO_j \quad \text{for } j = 1,\ldots,J \tag{3.8}$$

A task requires different resources to process the material. Processing time of a resource for producing one unit of the final product is calculated by adding the time of all tasks utilizing that resource:

$$CT_{ik} = \sum_{\{j|k\in j\}} FT_j \ \text{ for } k = 1,\ldots,K_i \ , i = 1,\ldots,I, j = 1,\ldots,J \tag{3.9}$$

Total required running time of a resource for producing *PL* units of the final product is calculated by multiplying the unit processing time and the planned production level *PL*. Resource utilization is then calculated using the total running time divided by the total available time of the planning period which is one year. Since second is the unit considered for the task time, total available time of the year is calculated accordingly. We use the following equation to estimate the resource utilization:

$$UR_{ik} = \frac{CT_{ik} \times PL}{24 \times 3600 \times 365} \ \text{ for } k = 1,\ldots,K_i \ , i = 1,\ldots,I \tag{3.10}$$

If any of the equipment in a production cell fails, the entire cell stops operating. Therefore, the expected downtime ratio of production cell's operation time is calculated by the following equation:

$$FR_i = \sum_{k=1}^{K_i} FR_{ik} - \sum_{k=1}^{K_i-1} \sum_{n=1}^{K_i-k} FR_{ik} \times FR_{i(k+n)} + \sum_{k=1}^{K_i-1} \sum_{n=1}^{K_i-k} \sum_{m=1}^{K_i-k-n} FR_{ik} \times FR_{i(k+n)} \times FR_{i(k+n+m)} - \ldots$$

$$\text{for } i = 1,\ldots,I \qquad (3.11)$$

Considering downtime due to system failure calculated by Eq. (3.11) and downtime due to scheduled maintenance, equipment utilization should be adjusted by the following equation where MT is the planned weekly maintenance time in hours:

$$RA_{ik} = \frac{(CT_{ik} \times PL)}{(3600 \times 365) \times (24 - \frac{MT}{7}) \times (1 - FR_i)} \quad \text{for } k = 1,\ldots,K_i \text{ , } i = 1,\ldots,I \qquad (3.12)$$

This ratio helps to determine the minimum number of the parallel resources required to meet the production level. If this value is 1.0, the corresponding equipment should operate during the entire planning period to produce PL items of the final product. If it is 1.2, two parallel units of the equipment should be allocated to the production line. In general, the number of parallel units of a resource is calculated by rounding up this value:

$$EQ_{ik} = \lceil RA_{ik} \rceil \quad \text{for } k = 1,\ldots,K_i \text{ , } i = 1,\ldots,I \qquad (3.13)$$

where $\lceil * \rceil$ is the integer greater than or equal to *

Having calculated the minimum number of the parallel resources required, the following equation is used to calculate the utilization rate of single units of the resources operating in parallel:

$$AE_{ik} = \frac{RA_{ik}}{EQ_{ik}} \quad \text{for } k = 1,\ldots,K_i \text{ , } i = 1,\ldots,I \qquad (3.14)$$

Different resources of a production cell operate in a synchronized mode. We can determine the required utilization of the production cell based on the resource having the maximum AE_{ik} value. AL_i is the time fraction during which a production cell is utilized to meet the production requirements and calculated by the following equation:

$$AL_i = Max\left\{AE_{ik} \middle| \; 1 \le k \le K_i \; \right\} \quad \text{for } i = 1,\ldots,I \qquad (3.15.a)$$

The production cell or any of the resources inside the production cell may be used for external demands during the remaining proportion of their available time calculated by:

$$RR_i = 1 - AL_i \qquad \text{for } i = 1,\ldots,I \qquad (3.15.b)$$

To estimate the labor cost of production, we need to know the annual operation time of different production cells. We assume that operators are paid when production cells are down due to unexpected failures of the equipment and are not paid during the time of scheduled maintenances. The following equation is used to calculate the annual operation hours of different production cells:

$$AH_i = AL_i \times 365 \times (24 - \frac{MT}{7}) \qquad (3.16)$$

The following equation is used to calculate the total working hours of a regular work shift during a one year planning period:

$$AS = (SH \times \frac{365}{7}) \times (1 - VR) \qquad (3.17)$$

where SH represents the weekly working hours of one regular work shift and VR is the ratio of vacation time over work time.

The following equation is then used to calculate the number of regular work shifts required to satisfy the annual production level:

$$NS_i = \frac{AH_i}{AS} \quad \text{for } i = 1,\ldots,I \tag{3.18}$$

NS_i may not be integer while the number of scheduled regular work shifts must be integer. When NS_i is not integer there are two options in scheduling the production cell; 1) schedule one complete regular work shift or 2) use overtime hours. If one complete work shift is scheduled for the fractional part of NS_i, operators in the corresponding cell are paid for a complete shift while they will not be working all the time. If the overtime hours are used labor cost will be higher during those hours. To decide if a complete regular shift should be scheduled, we compare the fractional part of NS_i and the value of HH calculated by:

$$HH = \frac{LW}{EX} \tag{3.19}$$

where LW and EX represent regular and overtime wages, respectively.

To reduce labor cost, a complete regular shift should be scheduled if the fractional part of NS_i is greater than HH. Otherwise, overtime hours should be used.

We assumed that at least one regular work shift will be scheduled for any production cell. Based on these considerations, we use the following equation to determine the number of regular work shifts to be scheduled for each cell:

$$DS_i = \begin{cases} 1 & \text{if} \quad NS_i \leq 1 \\ \lfloor HH \rfloor & \text{if} \quad NS_i > 1 \quad \text{and} \quad NS_i - \lfloor NS_i \rfloor \leq HH \\ \lceil HH \rceil & \text{if} \quad NS_i > 1 \quad \text{and} \quad NS_i - \lfloor NS_i \rfloor > HH \end{cases} \quad , i=1,\ldots,I \tag{3.20}$$

where $\lfloor * \rfloor$ is the integer less than or equal to *.

As discussed earlier, when the number of regular work shifts is smaller than the required production capacity calculated by NS_i, overtime hours for existing operators will be scheduled. The required over time hours can be calculated by:

$$RH_i = Max\{AH_i - DS_i \times AS, 0\} \quad i = 1,...,I \tag{3.21}$$

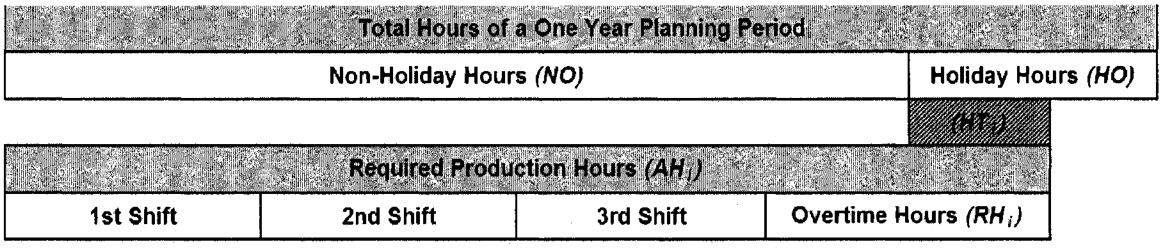
We also assume that holiday work wage is higher than that of regular and overtime hours. Holiday hours may be scheduled when the required production level can't be met using non-holiday hours. Considering system downtime for scheduled maintenance, we use the following equation to calculate the required holiday work hours in a one year planning period where NH is number of holidays in a calendar year:

$$HT_i = Max\left\{AH_i - 24 \times 365 - MT \times \frac{365}{7} + NH \times 24, 0\right\} \quad i = 1,...,I \tag{3.22}$$

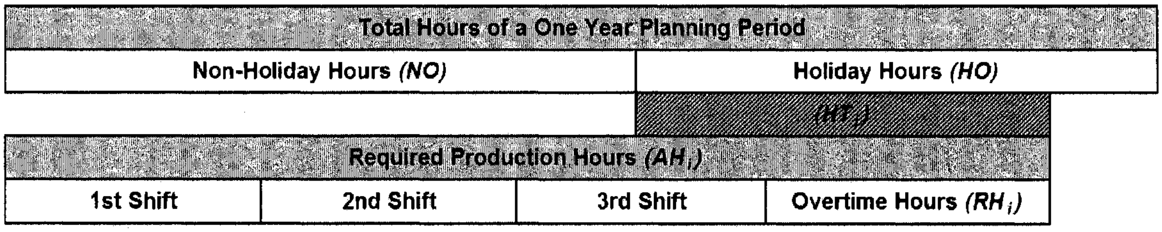
RH_i calculated by Eq. (3.21) is the difference between scheduled regular shift hours and the required production hours. The overtime cost is obtained when RH_i is multiplied by the overtime wage EX. To calculate the cost associated with holiday hours and to avoid duplication of cost calculations, possible overlaps of required overtime hours RH_i calculated in Eq. (3.21) and required holiday work hours HT_i calculated in Eq. (3.22) have to be separated accordingly. As can be seen in Fig.3.3, holiday hours may overlap with overtime hours and regular work shift hours. In case A shown in Fig. 3.3, HT_i is completely covered by the required overtime hours calculated by RH_i. Hence, we should only calculate the cost difference of holiday and overtime wages for the time interval HT_i. In case B a part of HT_i is covered by RH_i while the other part has overlap with regular shifts. For the interval which overlaps with regular shifts we have to calculate the cost difference of regular and holiday wages. The following equation is used to split the overtime and regular shift labor cost from that of holiday work:

$$HP_i = \begin{cases} RH_i \times (HX - EX) + (HT_i - RH_i) \times (HX - LW) & \text{if } HT_i \geq RH_i \\ HT_i \times (HX - EX) & \text{Otherwise} \end{cases} \quad , i=1,\ldots,I \quad (3.23)$$

where HX and EX are the holiday and overtime wage of the operators.



Case A $HT_i < RH_i$



Case B $HT_i > RH_i$

Fig. 3.3 Labor Payment Time Chart

Using the following equation, labor cost of the production can be calculated based on the hours calculated by Eq. (3.20), (3.21) and (3.23):

$$LC_{ik} = EQ_{ik} \times (LW \times DS_i \times SH \times \frac{365}{7} + RH_i \times EX + HP_i) \ , \ k = 1,\ldots,Ki, i = 1,\ldots,I \quad (3.24)$$

where EQ_{ik} is the number of operators working on tasks at the same time.

As discussed in Section 3.5.3, when the number of parallel units of the equipment is determined, there usually remains a non-utilized portion of the equipment capacity. This non-utilized portion exists since the calculated value is rounded up to an integer number. Fixed production costs are incurred for the non-utilized time portion of the equipment while no product is produced. It is more cost-effective to use the non-utilized portions of the equipment for possible external demands.

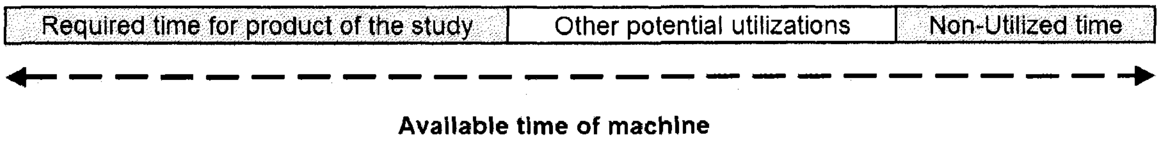


Fig. 3.4 Equipment Utilization Time Bar Chart

The external demand may not fully utilize the remaining equipment capacity. The non-utilized portion of the equipment capacity can be calculated by the following equation:

$$RC_{ik} = \max\{(EQ_{ik} \times (1 - AL_i) - PR_{ik}), 0\} \qquad , \; k=1,\ldots,K_i \, , \; i=1,\ldots,I \qquad (3.25)$$

where PR_{ik} is the external demand for a portion of the available capacity of machine k and AL_i is the time fraction during which the corresponding production cell is utilized to meet the production demand and is calculated by Eq. (3.15.a). RC_{ik} is the portion of the equipment capacity remained non-utilized. Corresponding fixed costs incurred with this portion of the equipment capacity should be considered in production cost calculations of our final product.

3.6.3 Cost Components

The RTM production costs considered in this research include fixed costs, variable costs and other costs. Fixed costs include those independent of production volume. On the other hand, variable costs change with production volume. Ordering, delivery and inventory costs are categorized as other costs since they are neither fixed costs nor variable costs. Interrelating values calculated in Section 3.6.2 are used to calculate all cost components shown in Fig.3.5.

Fixed Costs

Equipment Capital Cost:

The annual capital cost of a machine is the annual interest of the loan acquired to purchase the machine. It is calculated by:

$$IC_{ik} = IR \times (RC_{ik} + AL_i) \times EQ_{ik} \times EP_{ik} \quad ,k = 1,\dots,K_i \;,i = 1,\dots,I \qquad (3.26)$$

where IR is the interest rate of the capital.

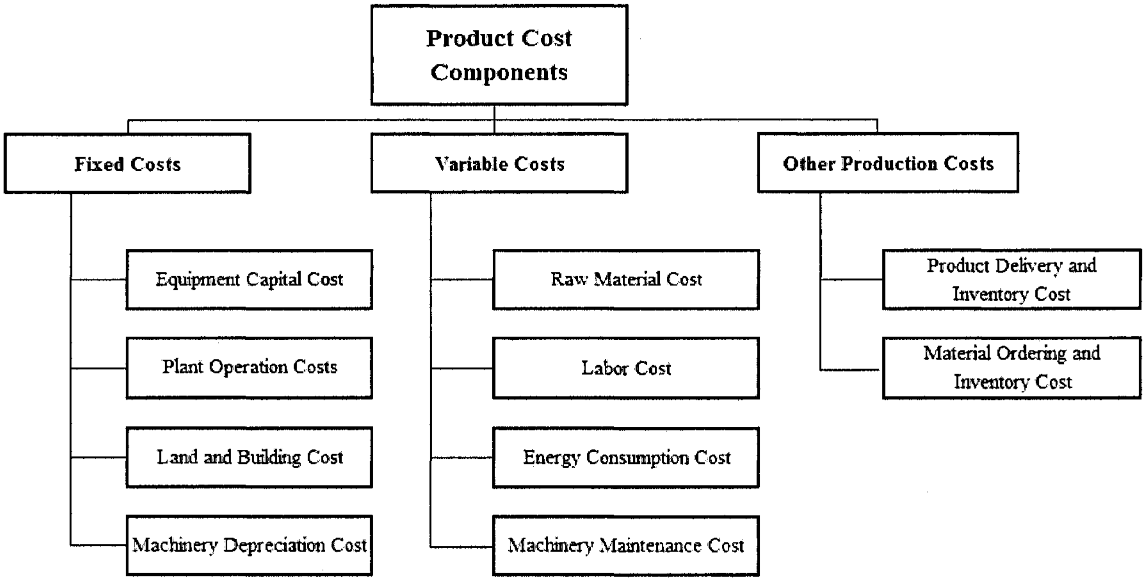


Fig. 3.5 Production Cost Breakdown Structure

The machinery capital cost does not depend on the machine usage and is considered as a fixed production cost. AL_i and RC_{ik} are time portions during which the machine is utilized to produce the final product or is remained non-utilized. If the machine is allocated to external demands, the cost of corresponding time portion is extracted from our cost calculations.

The total machinery capital cost is:

$$TC = \sum_{i=1}^{I} \sum_{k=1}^{K_i} IC_{ik} \qquad (3.27)$$

Plant Operation Cost:

It is assumed that the plant operation cost is a function of the area. Considering the time portion a piece of equipment is not allocated to external demands, the relevant portion of the equipment area can be calculated by:

$$OC_{ik} = (RC_{ik} + AL_{ik}) \times EQ_{ik} \times AR_{ik} \quad \text{for } k = 1,\dots,K_i \ , i = 1,\dots,I \qquad (3.28)$$

The total operation cost of the production system is calculated by adding the relevant area calculated for individual pieces of equipment and multiplying the result by the operation cost of the unit area:

$$TO = OP \times \sum_{i=1}^{I} \sum_{k=1}^{K_i} OC_{ik} \qquad (3.29)$$

Land and Building Cost:

Production area can normally be estimated based on the floor area occupied by the required machines and equipment. The two dimensional size of the equipment will be first measured to yield the floor area of the equipment. This area in square feet or square meters will then be multiplied with a "rule of thumb" coefficient to determine the estimated production area for the equipment. Following this approach we use the following equation to estimate the required production space for different machines or equipment:

$$BC_{ik} = WS \times AR_{ik} \times EQ_{ik} \quad , k = 1,\dots,K_i \ , i = 1,\dots,I \qquad (3.30)$$

where WS is the coefficient to calculate the production area of the equipment.

Following equation then specifies the relevant BC_{ik} time portion considering external utilization of the equipment:

$$CC_{ik} = (RC_{ik} + AL_i) \times BC_{ik} \quad , k = 1,\dots,K_i \ , i = 1,\dots,I \qquad (3.31)$$

The space and building cost of the production line is calculated by:

$$TA = LP \times \sum_{i=1}^{I} \sum_{k=1}^{K_i} CC_{ik} \tag{3.32}$$

where LP is the rental cost or the capital cost of the unit space.

Machinery Depreciation Cost:

Depreciation cost of a machine is the monetary value lost as the result of its finite life. Since machines are considered as the assets of the production system, this monetary lost is counted as an annual cost during the amortization period.

In this RTM cost analysis, we use the linear depreciation model to calculate equipment or machine depreciation costs. Annual depreciation cost of a machine is calculated by:

$$DC_{ik} = \frac{EP_{ik}}{DP_{ik}} \quad , k = 1,\ldots,K_i \, , i = 1,\ldots,I \tag{3.33}$$

The total machinery depreciation cost of the production system is calculated by:

$$TP = \sum_{i=1}^{I} \sum_{k=1}^{K_i} DC_{ik} \tag{3.34}$$

<u>**Variable Costs**</u>

Raw Material Cost:

Total material cost of production is calculated by multiplying the production level PL with the monetary value of all material used in the production. Considering the scraped material value calculated by equation 3-8, this cost is calculated by:

$$TM = PL \times \left(CV_J + SV \right) \tag{3.35}$$

Labor Cost:

Details of the labor cost structure were discussed in Section 3.6.2. The annual labor cost of production is calculated by the following equation:

$$TL = \sum_{i=1}^{I} \sum_{k=1}^{K_i} LC_{ik} \tag{3.36}$$

where LC_{ik} is calculated by the Eq. (3.24).

Energy Consumption Cost:

Energy is consumed when equipment operates. Hence, energy consumption cost of the equipment is a variable cost calculated by multiplying the scaled energy consumption rate LG with the equipment utilization rate.

$$EG_{ik} = 24 \times 365 \times LG \times UR_{ik} \times EC_{ik} \quad \text{for } k = 1,\ldots,K_i \text{ }, i = 1,\ldots,I \tag{3.37}$$

Total energy consumption cost of production in a one year planning period is estimated using the following equation:

$$TE = \sum_{i=1}^{I} \sum_{k=1}^{K_i} EG_{ik} \tag{3.38}$$

Machinery Maintenance Cost:

A variable cost is incurred for different machines utilized in the production system to avoid costly downtimes caused by malfunctions. This cost is usually spent on a preventive maintenance program. Based on preventive maintenance programs, machines are inspected and their parts are replaced on a regular basis. The annual maintenance cost of a machine is considered as a certain percentage of its purchasing price when its downtime reaches nearly zero and operates at full utilization rate. When downtimes are accepted more often, the required maintenance cost decreases. On the other hand, maintenance cost of a machine depends on its utilization. Higher utilization increases the probability of machine malfunction and as a result, higher maintenance costs are required to maintain the reliability level. We can use the following equation to calculate the machinery maintenance cost. MK is the percentage considered to calculate the maintenance cost of a machine based on its price.

$$MC_{ik} = MK \times (1 - FR_{ik}) \times EP_{ik} \times UR_{ik} \quad , k = 1, \ldots, K_i \, , i = 1, \ldots, I \tag{3.39}$$

The total machinery maintenance cost for the RTM production is then calculated by:

$$TI = \sum_{i=1}^{I} \sum_{k=1}^{K_i} MC_{ik} \tag{3.40}$$

Other Production Costs

Material Ordering and Inventory Costs:

To supply the production line with required raw materials, orders are made on regular basis with scheduled frequencies. There will be inventory costs incurred after ordered materials arrive and before they are used. Based on Economic Ordering Quantity (EOQ) model, the optimal frequency of ordering minimizes the sum of ordering and inventory costs. We follow the EOQ model to calculate the optimal number of orders made in a year.

$$N^* = \sqrt{\frac{IR \times TM}{2 \times MO}} \tag{3.41}$$

where TM is the annual cost of the material consumed to produce PL units of the final product, IR is the interest rate and MO is the cost of the unit ordering.

The total ordering and inventory cost of N^* orders is calculated by the following equation:

$$TR = \sqrt{2 \times IR \times TM \times MO} \tag{3.42}$$

Product Delivery and Inventory Costs:

The same EOQ approach can be used to determine the optimal delivery frequency and quantity of the final product. For the product, the monetary value of the average inventory level is calculated based on the annual production level and the unit price of the final product. The following equation calculates the total cost associated with storage of the final products and the deliveries made to the final customers. *SP* is the unit sale price of the product and *DC* is the fixed cost of a single delivery:

$$TD = \sqrt{2 \times SP \times PL \times DC \times IR} \tag{3.43}$$

Total Annual Production Cost

We can obtain the total production cost of the production line running at production level *PL*, by adding all considered cost components.

$$TPC=TD+TO+TS+TM+TE+TL+TA+TC+TI+TP+TR \tag{3.44}$$

The cost per item is calculated by total production cost divided by the production level:

$$CPI = \frac{TPC}{PL} \tag{3.45}$$

3.6.4 Overall Cost Evaluation and Optimum Production Level

To investigate unit product cost as it related to different production levels and to find a production level with minimum unit cost, the total production cost function was evaluated for different production levels. The minimum production cost was identified among different production levels. The model also determines the optimized system configurations corresponding to different production levels.

When separable tool-press is used in the RTM production, the cost calculation may need to be adjusted. If the numbers of tools and presses are same, there should be no tool set up and removal tasks considered in the calculation. On the other hand, when the model calculates different numbers of tools and presses, there requires set up and removal tasks to be considered in the calculation.

In the following two sections of this chapter we introduce modifications made to adjust the model for two different scenarios considered: Multi-product type RTM production and fixed configurations of the RTM production line.

3.7 Optimal Cost Calculation for Production of Two Product Types

With minor modifications, the cost analysis and optimization model discussed in previous sections can also be applied to find the optimized production cost when two different types of products are produced by the same system. The two different products should have common tasks and of similar sizes. However, different preforming and molding tools may be used in producing these different products. Task times, arrangement of fibers and preforms, material consumption rates and scrap rates may also be different.

Most of the equations developed for single type production will be the same for two product type system analysis. The model needs to be modified to cover common equipment utilization and other issues.

3.7.1 Additional Features of the Two Product Type Model

The cost analysis model for two product types is very similar to the single product type model. Common facility utilization of different product types, equipment switching process and common material handling are examples of its features.

Switching Time:

When two types of products are produced by the same RTM line, machines and equipment will be dedicated to one type of product for a certain time. When the system is switched to produce the other product type, system setups such as preparation of tools and materials will be required. Switching time reduces production capacity. The minimum number of switching processes required in the production system is calculated based on an EOQ model.

It is assumed that each year equal number of deliveries will take place for both product types. The optimal number of deliveries is calculated by:

$$N^* = \sqrt{\frac{(PL_1 \times SP_1 + PL_2 \times SP_2) \times IR}{2 \times (DC_1 + DC_2)}} \tag{3.46}$$

where PL_1 and PL_2 are production levels, SP_1 and SP_2 are sale prices and DC_1 and DC_2 are fixed delivery costs considered for products 1 and 2 respectively.

Switching process of the production line is planned once during each delivery of products. It implies that the production line is switched N^* times during a year.

3.7.2 Cost Model Modification

In multi product type systems, different product types are produced utilizing common facilities and equipment. Consequently, the model used to calculate the number of parallel units of equipment is different from that described in the single product type model.

For equipment k, the total amount of time required for switching between different product types is calculated by:

$$RW_{ik} = SW_{ik} \times N^* \quad , k = 1, \ldots, K_i \; , i = 1, \ldots, I \tag{3.47}$$

where SW_{ik} is the switching time of the equipment k.

The required units of each machine are calculated by the adjusted Eq. (3.13). Equipment utilization calculated by RA_{ik} in Eq. (3.12), is considered separately for PL_1 and PL_2 units of products 1 and 2. In addition, the required switching time of machines are considered.

$$EQ_{ik} = \left\lceil RA_{1ik} + RA_{2ik} + \frac{RW_{ik}}{365 \times 3600 \times (24 - \frac{MT}{7})} \right\rceil \quad , k = 1,\ldots,K_i \; , i = 1,\ldots,I \qquad (3.48)$$

where MT is weekly maintenance hours.

AE_{ik} and AL_i calculated by Eq. (3.14) and (3.15.a) in the single product type model are calculated separately for product 1 and 2, using the modified EQ_{ik} value from Eq. (3.48):

$$AE_{1ik} = \frac{RA_{1ik}}{EQ_{ik}} \quad , k = 1,\ldots,K_i \; , i = 1,\ldots,I \qquad (3.49)$$

$$AE_{2ik} = \frac{RA_{2ik}}{EQ_{ik}} \quad , k = 1,\ldots,K_i \; , i = 1,\ldots,I \qquad (3.50)$$

$$AL_{1i} = Max\left\{AE_{1ik} \middle| \; 1 \le k \le K_i \; \right\} \quad , i = 1,\ldots,I \qquad (3.51)$$

$$AL_{2i} = Max\left\{AE_{2ik} \middle| \; 1 \le k \le K_i \; \right\} \quad , i = 1,\ldots,I \qquad (3.52)$$

The portion of the available time of the year during which a production cell is utilized to meet production levels PL_1 and PL_2, consists of the time portions allocated to produce the two product types as well as the time portion considered for the switching process.

$$AL_i = AL_{1i} + AL_{2i} + \frac{LW_i}{365 \times 3600 \times (24 - \frac{MT}{7})} \quad ,i = 1,...,I \tag{3.53}$$

Where

$$LW_i = Max\{RW_{ik} |\ 1 \le k \le K_i\ \} \quad ,i = 1,...,I \tag{3.54}$$

Non-Fixed Cost Modifications:

In the bi-product cost model, all production cost components categorized under variable cost and other production cost are calculated using the same equations as those used in the single product type model. These cost components are separately defined and calculated for product 1 and 2.

Operators are not replaced each time the production line is switched to the other product; therefore labor cost is common for both product types. A common labor cost is calculated and distributed over two different product types. The common labor cost is calculated using the same equations as in the single product type model and based on *ALi* values calculated by Eq. (3.53).

Since a common delivery frequency is considered, delivery and inventory costs of the final products are calculated by the following modified equations:

$$TD_1 = \frac{PL_1 \times SP_1}{2 \times N^*} \times IR + DC_1 \times N^* \tag{3.55}$$

$$TD_2 = \frac{PL_2 \times SP_2}{2 \times N^*} \times IR + DC_2 \times N^* \tag{3.56}$$

where SP_1 and SP_2 are the sale price of products 1 and 2.

Fixed Costs Modifications:

In the single product type model, fixed cost components were calculated based on resource utilization. In the bi-product cost model, the equipment utilization time is separated for different product types and corresponding costs are calculated accordingly. Modified equations of the fixed cost components used in the bi-product type model are as following:

Machinery Capital Cost

$$IC_{1ik} = AL_{1i} \times EQ_{ik} \times EP_{ik} \times IR \quad ,i = 1,...,I \text{ and } k = 1,...,K_i \tag{3.57}$$

$$TC_1 = \sum_{i=1}^{I} \sum_{k=1}^{K_i} IC_{1ik} \tag{3.58}$$

$$IC_{2ik} = AL_{2i} \times EQ_{ik} \times EP_{ik} \times IR \quad ,i = 1,...,I \text{ and } k = 1,...,K_i \tag{3.59}$$

$$TC_2 = \sum_{i=1}^{I} \sum_{k=1}^{K_i} IC_{2ik} \tag{3.60}$$

$$IC_{3ik} = RC_{ik} \times EQ_{ik} \times EP_{ik} \times IR \quad ,i = 1,...,I \text{ and } k = 1,...,K_i \tag{3.61}$$

where IC_{3ik} is common for the two product types and will be distributed based on relative utilization of the corresponding cell.

Land and Building Cost

$$CC_{1ik} = AL_{1i} \times AR_{ik} \times EQ_{ik} \times LP \times IR \quad ,i = 1,...,I \text{ and } k = 1,...,K_i \tag{3.62}$$

$$TA_1 = \sum_{i=1}^{I} \sum_{k=1}^{K_i} CC_{1ik} \tag{3.63}$$

$$CC_{2ik} = AL_{2i} \times AR_{ik} \times EQ_{ik} \times LP \times IR \quad ,i = 1,...,I \text{ and } k = 1,...,K_i \tag{3.64}$$

$$TA_2 = \sum_{i=1}^{I} \sum_{k=1}^{K_i} CC_{2ik} \tag{3.65}$$

$$CC_{3ik} = RC_{ik} \times AR_{ik} \times EQ_{ik} \times LP \times IR \quad ,i = 1,...,I \text{ and } k = 1,...,K_i \tag{3.66}$$

where CC_{3ik} is common for the two product types and will be distributed based on relative utilization of the corresponding cell.

Plant Operation Cost

$$OC_{1ik} = AL_{1ik} \times EQ_{ik} \times AR_{ik} \times OP \ , i = 1,\dots,I \text{ and } k = 1,\dots,K_i \tag{3.67}$$

$$TO_1 = \sum_{i=1}^{I} \sum_{k=1}^{K_i} OC_{1ik} \tag{3.68}$$

$$OC_{2ik} = AL_{2ik} \times EQ_{ik} \times AR_{ik} \times OP \ , i = 1,\dots,I \text{ and } k = 1,\dots,K_i \tag{3.69}$$

$$TO_2 = \sum_{i=1}^{I} \sum_{k=1}^{K_i} OC_{2ik} \tag{3.70}$$

$$OC_{3ik} = RC_{ik} \times EQ_{ik} \times AR_{ik} \times OP \ , i = 1,\dots,I \text{ and } k = 1,\dots,K_i \tag{3.71}$$

where OC_{3ik} is common for the two product types and will be distributed based on relative utilization of the corresponding cell.

Depreciation Cost

$$DC_{1ik} = AL_{1ik} \times \frac{EP_{ik}}{DP_{ik}} \ , i = 1,\dots,I \text{ and } k = 1,\dots,K_i \tag{3.72}$$

$$TP_1 = \sum_{i=1}^{I} \sum_{k=1}^{K_i} DC_{1ik} \tag{3.73}$$

$$DC_{2ik} = AL_{1ik} \times \frac{EP_{ik}}{DP_{ik}} \ , i = 1,\dots,I \text{ and } k = 1,\dots,K_i \tag{3.74}$$

$$TP_2 = \sum_{i=1}^{I} \sum_{k=1}^{K_i} DC_{2ik} \tag{3.75}$$

$$DC_{3ik} = RC_{ik} \times \frac{EP_{ik}}{DP_{ik}} \ , i = 1,\dots,I \text{ and } k = 1,\dots,K_i \tag{3.76}$$

where DC_{3ik} is common for the two product types and will be distributed based on relative utilization of the corresponding cell.

Since tools are not shared between different product types, their costs are added to production costs of respective products.

Distribution of Common Costs:

Common costs are distributed over different product types based on relative utilization time of each cell. Hence, all common cost components are added to different production cells and are distributed over different product types based on relative utilization times. Following equations are used for common costs distribution:

$$FC_i = \sum_{k=1}^{K_i} IC_{3ik} + \sum_{k=1}^{K_i} CC_{3ik} + \sum_{k=1}^{K_i} OC_{3ik} + \sum_{k=1}^{K_i} LC_{ik} + \sum_{k=1}^{K_i} DC_{3ik} \quad ,i = 1,\ldots,I \tag{3.77}$$

$$FC_{1i} = FC_i \times \frac{AL_{1i}}{AL_{1i} + AL_{2i}} \quad ,1 = 1,\ldots,I \tag{3.78}$$

$$FC_{2i} = FC_i \times \frac{AL_{2i}}{AL_{1i} + AL_{2i}} \quad ,1 = 1,\ldots,I \tag{3.79}$$

After all modifications are made, the total production cost of product 1 and 2 are calculated by the following equations:

$$TPC_1 : \sum_{i=1}^{I} FC_{1i} + TD_1 + TI_1 + TP_1 + TC_1 + TA_1 + TO_1 + TE_1 + TM_1 + TS_1 + TR_1 \tag{3.80}$$

$$TPC_2 : \sum_{i=1}^{I} FC_{2i} + TD_2 + TI_2 + TP_2 + TC_2 + TA_2 + TO_2 + TE_2 + TM_2 + TS_2 + TR_2 \tag{3.81}$$

The objective is to maximize the total profit when products 1 and 2 are produced at levels PL_1 and PL_2, respectively. Total profit is calculated by the following equation:

$$TPR = SP_1 \times PL_1 + SP_2 \times PL_2 - TPC_1 - TPC_2 \tag{3.82}$$

3.8 Production with Fixed System Configuration

We also considered the situation where two product types are produced with a fixed system configuration. With fixed units of equipment, maximum profits are found among production levels of the two product types utilizing the available capacity.

As shown in Fig. 3.6, a fixed configuration of equipment has enough capacity to produce all the production levels of the two product types below the dashed line. When the production level of one product type is reduced, a certain capacity of the fixed configuration is released. The production level increase of the other product type depends on the relative utilization of the two products. The points on the dashed line may not be integer combinations of the production levels. Since the optimized integer pair is located close to the dashed line where the production line is running at a high utilization rate, the search for the optimal combination of the two product types can start from production level pair at one end of such line toward the other end of it.

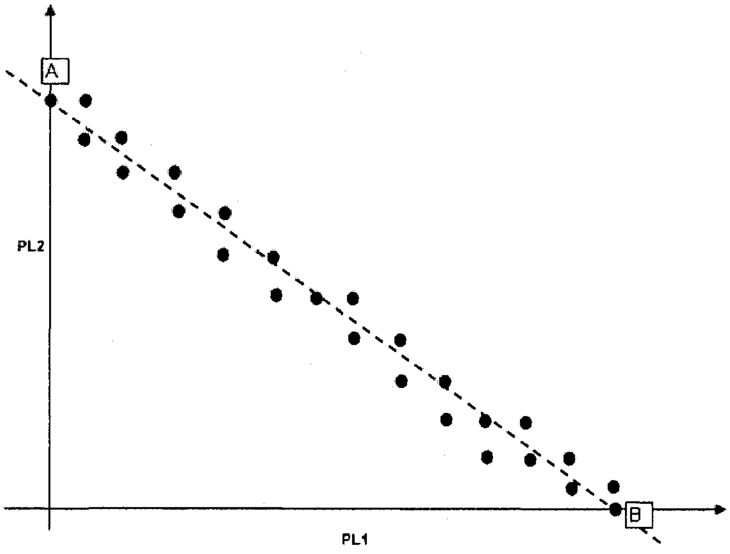


Fig. 3.6 Integer Optimization Search Around Maximum Capacity of Production

3.9 RTM Production Process Simulation

Production capacities of different system configurations can be found by calculating the maximum production time of different production cells. This production time is estimated based on task times, number of parallel units of equipment, annual working hours, downtime of the equipment and other parameters. To verify the analytical equations developed in this research in estimating the overall production time, we developed a discrete simulation model using ARENA software to simulate the operations of an RTM production system. In this simulation model one unit of each resource is utilized and the production line operates under similar conditions assumed in the cost analysis model.

ARENA is discrete event simulation software widely used in manufacturing and other industries (Kelton et al., 2004). It provides many built-in functions and animation features for easy model construction and visualization of results. In constructing a simulation model for the RTM production line, we utilized several types of ARENA "blocks" to represent various operations in the system.

Entities created in the model represent materials and work in process inventory. They flow in the model and pass through different blocks. Depending on the block, entities may be delayed, change a value or routed toward different directions. Process blocks, for example, delay entities during the operation time. Decide blocks separate entity directions based on defined conditions. Assign blocks are used to adjust values of certain attributes or variables by the entities flow. Hold blocks are used to delay entities for a period of time defined by conditions. Batch blocks join certain number of entities either temporarily or permanently. Separate blocks can be used to split joint items if they were temporarily batched previously. They are also used to duplicate the entities to several items. Queues represent accumulation of entities in the blocks where they are delayed.

In the model developed in this research to simulate the RTM manufacturing system, entities representing fabric rolls arrive to the system at a certain rate. After passing through a cutting process, they are duplicated to several entities resembling fabric cuts. They pass through all tasks considered in the RTM manufacturing process analytical model. At different blocks, entities are delayed for processing times. To imitate the production cell behavior, a hold block limits the number of the entities processed in cells. One entity is allowed in each production cell. When two or more fabrics form a preform or when several preforms form one unit of the final product, permanent batch blocks are used. A decide block is also used at the end of each task to allow scrapped parts exit the system.

The objective of the simulation in this research is to compare the simulated production capacity of the production line with that of the analytical model. The model is run for a predefined period of time and the number of produced items of the final product is calculated. The annual production capacity calculated by the simulation is compared with that by the analytical model.

In the following chapter, a hypothetical but realistic RTM process will be introduced with all the details. The process is analyzed by the analytical and the simulation models. The cost analysis model is implemented using MATLAB and Excel for data analysis, cost calculation and graph plotting.

4 Results and Discussion

In this chapter, the cost evaluation model discussed in the previous chapter will be computed using MATLAB and Excel based on a hypothetical RTM manufacturing process. The computational results will be analyzed and discussed in detail. ARENA is also used to simulate the RTM manufacturing process. The hypothetical RTM manufacturing system considered is an extension of that presented in Verrey et al. (2006). Some of the input parameters of the system are based on those in that paper. Other parameter values are estimated and acquired from experts working in this area. (Paul Trudeau, Research Assistant, at the Ecole Polytechnique de Montreal).

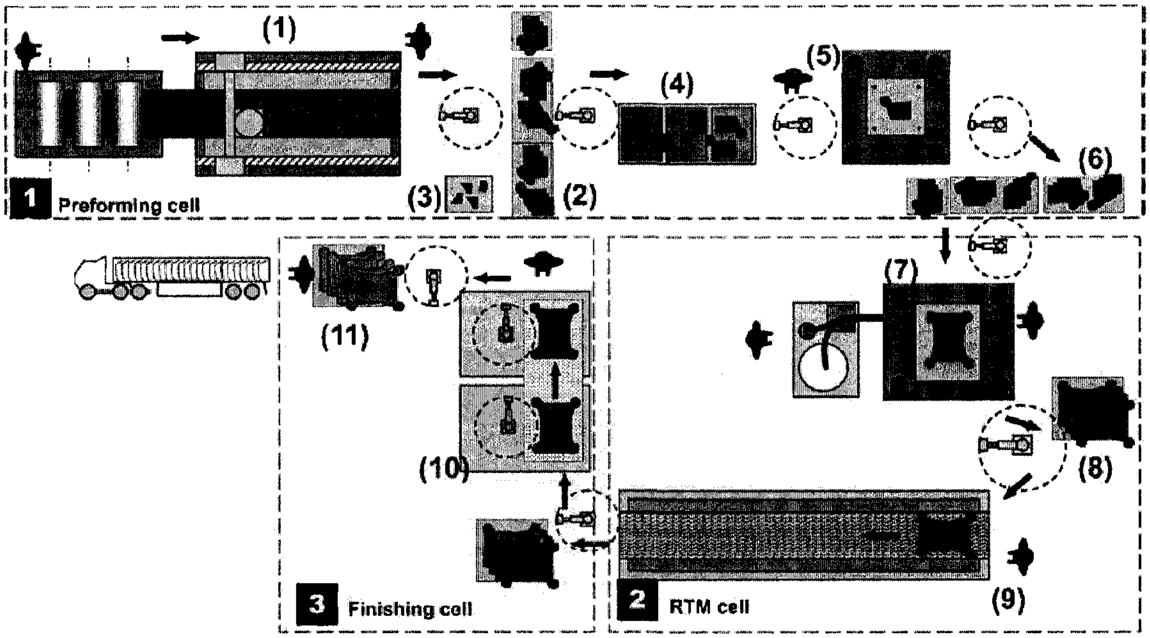


Fig. 4.1 Plant Diagram of Manufacturing Process of Automotive Floor Pan (Verrey et al., 2006)

4.1 Process Structure and Considered Parameter Values

Fig. 4.1 shows the production line for composite floor pan product studied in Verrey et al. (2006). This production system has 3 production cells, 8 pieces of equipment, 8 robots and 8 labors. An extended production system shown in Fig. 4.2 is considered in this research.

The entire manufacturing process is performed in the 5 following production cells:

- cutting cell
- preforming cell
- molding cell
- post cure cell
- trimming and packaging cell

There are 9 pieces of equipment, 7 operators and 9 robots operating in the above mentioned production cells. List of resources and corresponding parameters are given in Table 4.1.

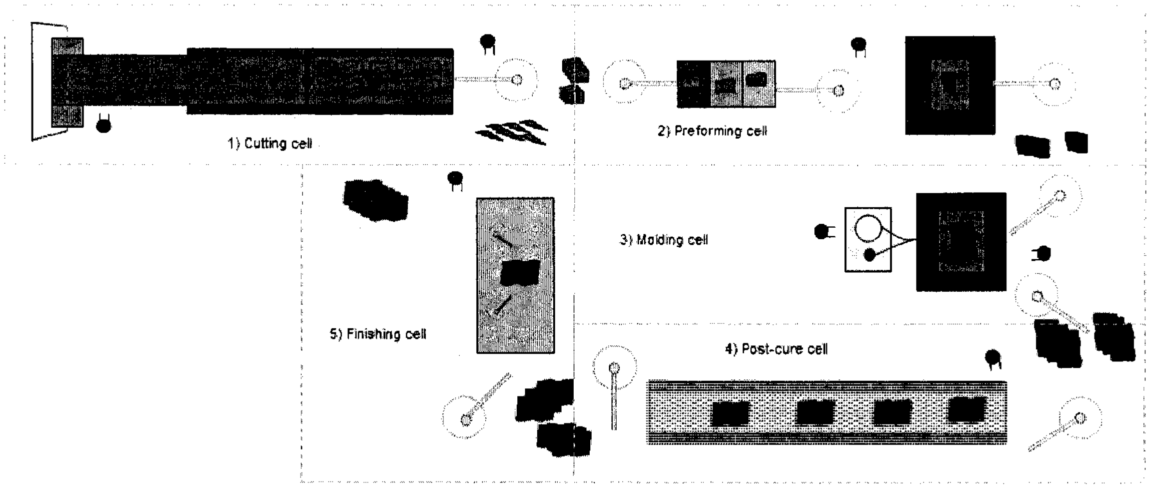


Fig. 4.2 Hypothetical Plant Diagram for RTM Manufacturing Process

Table 4. 1 Equipment List of RTM Manufacturing Process

No.	Cell	No. of Operators	No. of Robots	Equipment	Downtime (%)	Price (k$)	Depreciation Period (Yrs.)	Energy (kW)	Area (m^2)	External Demand Ratio (%)
1	Cutting	2	1	Fabric Roll Loading Station	1	60	7	15	25	50
2				Ultrasonic Cutting Machine	7	700	7	43	64	50
3	Preforming	1	3	IR Oven	8	68	7	150	15	40
4				Preforming Tool	1	35	5	0	80	0
5				Preforming Press	6	413	7	150	110	80
6	RTM	2	2	RTM Tool	12	920	5	50	50	0
7				RTM Press	6	680	7	100	70	70
8				Injection Set	8	170	7	20	15	80
9	Post-Cure	1	2	Post-Cure Oven	2	90	7	150	60	60
10	Trimming & Packaging	1	1	Trimming Machine	7	300	7	40	20	50
11				Packaging Machine	2	20	8	30	10	0
12	**General**			Robots	5	60	10	15	25	0
13				Half Robots	5	30	10	7.5	12.5	0

Compared to the system studied in Verrey et al. (2006), parameters related to tool and press were separated and a packaging machine was added. Estimated data for depreciation periods and expected downtimes were also included. Three square meters were considered as the required working space for each operator.

The following table summarizes the values of the parameters acquired and used in the production system:

Table 4. 2 Values of General Production Parameters

Fabric Cut Area (m2)	0.6
Fabric Roll Area (m2)	200
Fabric Waste Ratio	0.2
Fabric Layers in Preform	2
No. of Preforms in Final Part Unit	5
No. of Annual Holidays	10
Vacation Ratio of Labor Working Hours	0.04
1 Shift Weekly Hours	40
Overtime Labor Wage ($/hr)	30
Weekly Maintenance Time (Hours)	10
Maintenance Cost Ratio of Equipment Price	0.05
Interest Rate	0.075
Working Space Ratio	0.3
Land Rental ($/Year/m2)	0.75
Labor Wage ($/hr)	20
Energy Cost ($/kWh)	0.1
Operational Costs ($/m2)	90
Ordering Cost ($)	1000
Sale Price ($)	200
Delivery Cost ($)	2000
Holiday Labor Wage ($/hr)	40

Tasks of the RTM manufacturing process, corresponding times and scrape rates as well as equipment used to accomplish those tasks are listed in Table 4.4. Details of raw material consumed in the manufacturing process are given in Table 4.3.

Table 4. 3 Bill of Material (B.O.M) of RTM Manufacturing Process

Material(s) Description	Qty.	Unit	Usage per product	Waste Ratio[1]	Unit Price ($)
Fabric	0.6	m2	10	0.2	2.5
Glue	0.2	Kg	5	Inc.	5
Gel coat & demolding agent	0.05	Kg	1	Inc.	20
Resin set	2	Kg	1	Inc.	8
Packaging	1	Set	1	Inc.	3

Each preform is made of two fabric layers attached by glue. The final product consists of 5 preforms.

4.2 Tool and Press

Using the data in Table 4.4, we check the equation in Section 3.5.5 to see if separate tools and presses should be used for preforming and molding operations.

In this system, for preforming operation we have:

Tool setup time + tool removal time = 10+10=20

Total time of the tasks engaging the tool only =15+30+15=60

Since the total setup and removal time is less than the total time of the tasks engaging the tool only, the first condition in Eq. (3.5) is met to consider separate tool and press units for the preforming operation. For the RTM operation, we have:

Tool setup time + tool removal time = 30+30=60

Total time of the tasks engaging the tool only =60+20+5+5+3+30=123

---

[1] Inc.: Waste ratio is considered and included in the quantity of the material used.

Table 4. 4 RTM Manufacturing Process Breakdown Structure and Data

Step No.	Station	Task	Time (s)	Scrap Rate	Equipments/Labors		
1	Cutting	Loading Rolls Onto Rolling Station & Cleaning Cutting Mach.	300	0%	Loading Station	Cutting Mach.	Labor 1
2		Cutting Fabrics Out of Roll	50	5%	Loading Station	Cutting Mach.	Labor 2
3		Separating & Buffering Waste and Fabrics	25	0%	Robot 1		
4	Preforming	Laying Fabrics into Oven	10	0%	Robot 2		
5		Heating Fabrics	20	1%	IR Oven		
6		Draping 1st Fabric into Tool	15	0%	Preform Tool	Robot 3	
7		Spreading Glue Over 1st Fabric	30	2%	Preform Tool	Labor 3	
8		Draping 2nd Fabric into Tool	15	0%	Preform Tool	Robot 3	
9		Setting Tool into Press	10	0%	Preform Tool	Preform Press	Labor 3
10		Clamping the Tool	0	0%	Preform Tool	Preform Press	Labor 3
11		Pressing	30	3%	Preform Tool	Preform Press	
12		Opening the Tool	15	0%	Preform Tool	Preform Press	Labor 3
13		Extracting Preform and Buffering	15	1%	Preform Tool	Preform Press	Robot 4
14		Removing Tool from Press	10	0%	Preform Tool	Preform Press	Labor 3
15	RTM	Cleaning the Mold	60	0%	Molding Tool	Labor 4	
16		Applying Gel Coat and Demolding Agent	20	2%	Molding Tool	Labor 4	
17		Loading Preform into Tool	5	0%	Molding Tool	Robot 5	
18		Setting Tool into Press	30	0%	Molding Tool	Molding Press	Labor 4
19		Closing and Clamping Tool	5	0%	Molding Tool	Molding Press	Labor 4
20		Preparing Resin Mixture	20	5%	Injection Set	Labor 5	
21		Injecting Resin	82	7%	Injection Set	Molding Tool	Molding Press
22		Curing	460	5%	Molding Tool	Molding Press	
23		Removing Tool from Press	30	0%	Molding Tool	Molding Press	Labor 4
24		Opening the Tool	5	0%	Molding Tool	Labor 4	
25		Ejecting Part	3	0%	Molding Tool	Robot 6-1	
26		Extracting Part	30	1%	Molding Tool	Robot 6-1	
27		Buffering Injected Part	20	0%	Robot 6-1		
28	Post Cure	Laying Parts onto Post-Cure Oven	30	0%	Robot 6-2		
29		Post Cure	600	2%	Post-Cure Oven	Labor 6	
30		Buffering Post-Cure Parts	30	0%	Robot 7-1		
31	Trimming & Finishing	Cleaning Trimming Cell	30	0%	Trimming Mach.	Labor 7	
32		Putting Parts into Trimming Cell	30	0%	Trimming Mach.	Robot 7-2	
33		Trimming Part	300	3%	Trimming Mach.		
35		Packaging	20	0%	Packaging Mach.	Labor 7	Robot 8
36		Buffering Finished Part	5	0%	Robot 8		

Similar to that in preforming, the first condition in Eq. (3.5) is also met for the RTM operation to consider separate tool and press units.

Permanent jointure of tools and presses increases fixed costs of production since an extra unit of the press is utilized at certain production levels. On the other hand, temporary attachment of them increases energy consumption and maintenance costs since time of the tool setup and removal tasks are added to the processing times of tools and presses.

In Tables 4.5 and 4.6, energy consumption and maintenance costs related to tool and press units in preforming and RTM cells are calculated. Calculations are made for the processing time difference originating from the presence of tool setup and removal tasks in operation. As shown in Table 4.5., setup and removal tasks add 131.85 seconds to the processing times of tool and press units of the preforming operation. In the RTM operation, having separable tools add 69.86 seconds to the processing times of tool and press units.

As can be seen from Tables 4.5 and 4.6, separate tool and press configuration adds \$17438.68 to the preforming production cell total cost. This configuration increases the RTM production cell total cost by \$12346.1.

On the other hand utilizing one additional unit of the press will also increase the total production cost of the preforming and the RTM cells. Calculations are given in Table 4.7. Equipment capital cost, depreciation cost, land and building cost and operation costs are considered in these calculations.

Table 4. 5 Cost Difference of Preforming Operation for Joint and Separate Tool and Press

	Cycle time difference	Utilization rate difference	Maintenance cost difference	Energy consumption cost difference
Preforming tool	131.85	0.11	198.06	0.00
Preforming press	131.85	0.11	2219.05	15021.57
Total	-	-	**2417.11**	**15021.57**

Table 4. 6 Cost Difference of RTM Operation for Joint and Separate Tool and Press

	Cycle time difference	Utilization rate difference	Maintenance cost difference	Energy consumption cost difference
RTM tool	69.86	0.06	2451.78	2652.86
RTM press	69.86	0.06	1935.74	5305.72
Total	-	-	**4387.52**	**7958.58**

Table 4. 7 Costs of an Additional Press Unit in Preforming and RTM Cells

	Equip. Cost of Capital	Depreciation Cost	Land and Building Cost	Plant operation costs	**Total**
Preforming press	30975	59000	107.25	9900	**99982.25**
RTM press	51000	97142.86	68.25	6300	**104511.11**

Utilizing an additional unit of the preforming press incurs $99982 to the total cost of the preforimg operation while having separate tool and press units increase the cost by $17439. In the RTM cell, the additional press unit incurs $104511 versus the $12346 cost increase caused by setup and removal tasks. Since in both cases, the costs incurred by additional units of the press are higher than those associated with higher processing times of the tools, a separate configuration for tools and presses of both production cells will be cost effective.

4.3 Single Product Type Production

In the single product type production, one type of product is produced in a production line as discussed in Section 4.1. Depending on the production volume, numbers of parallel units of different equipment are determined. Applying the cost reduction policies discussed in Chapter 3 and using the parameter values given in Section 4.1, the corresponding production cost was calculated. The costs per item for the entire production volumes between 10,000 and 100,000 were calculated.

4.3.1 Cost Evaluation Results

Having calculated costs per item for different production volumes in the range of 10,000 and 100,000, the calculated cost values are plotted and shown in Fig.4.3.

The calculation starts at the volume level of 10,000 items since the cost value per item is significantly higher when production volumes are below 10,000 items. We notice that the fixed cost of the system is quite high requiring larger quantities for cost-effective production.

Fig 4.4 shows the annual profit of the production for this range based on the unit price of $200 per item.

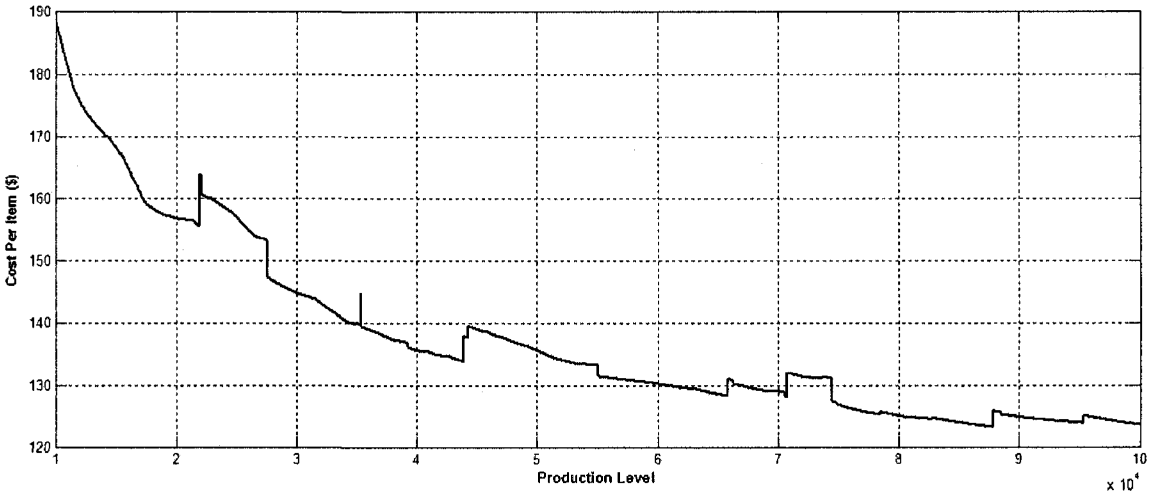


Fig. 4.3 Optimized Cost per Item Trend of a Single Product

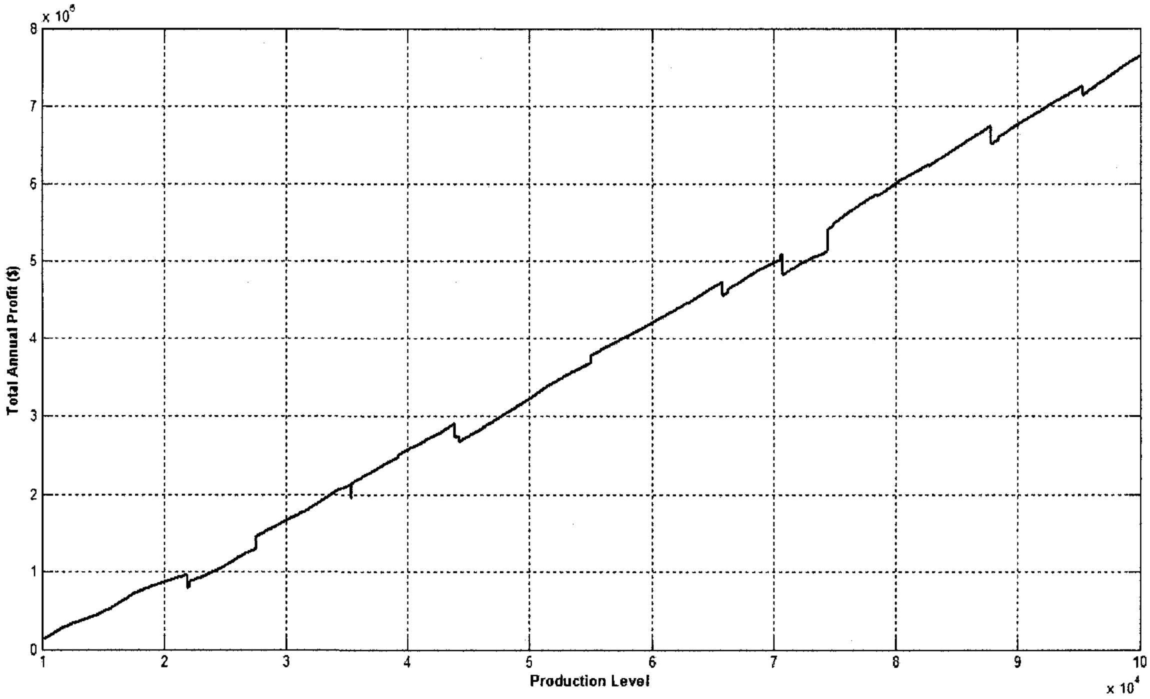


Fig. 4.4 Optimized Annual Profit Trend of a Single Product

4.3.2 Analysis

As can be seen in Fig. 4.3, generally cost per item decreases when production volume increases. This overall decreasing pattern seems reasonable since fixed costs of the production are distributed to larger number of items. However, there are sudden increases and decreases that require further analysis. The main reasons for the sudden increases observed in Fig. 4.3 are as following:

1. At several production levels, one or more pieces of equipment have reached their full capacities and to further increase the production level, additional units of the equipment are required. As the result, fixed costs of production have a sudden increase. This situation is observed in graphs of equipment capital cost, depreciation cost, land and building cost and operation costs of the plant. Fig. 4.5 shows behavior of the equipment capital cost when production volume increases from 10,000 to 100,000 items. The same general pattern exists for depreciation, land and building and operation costs of the plant.

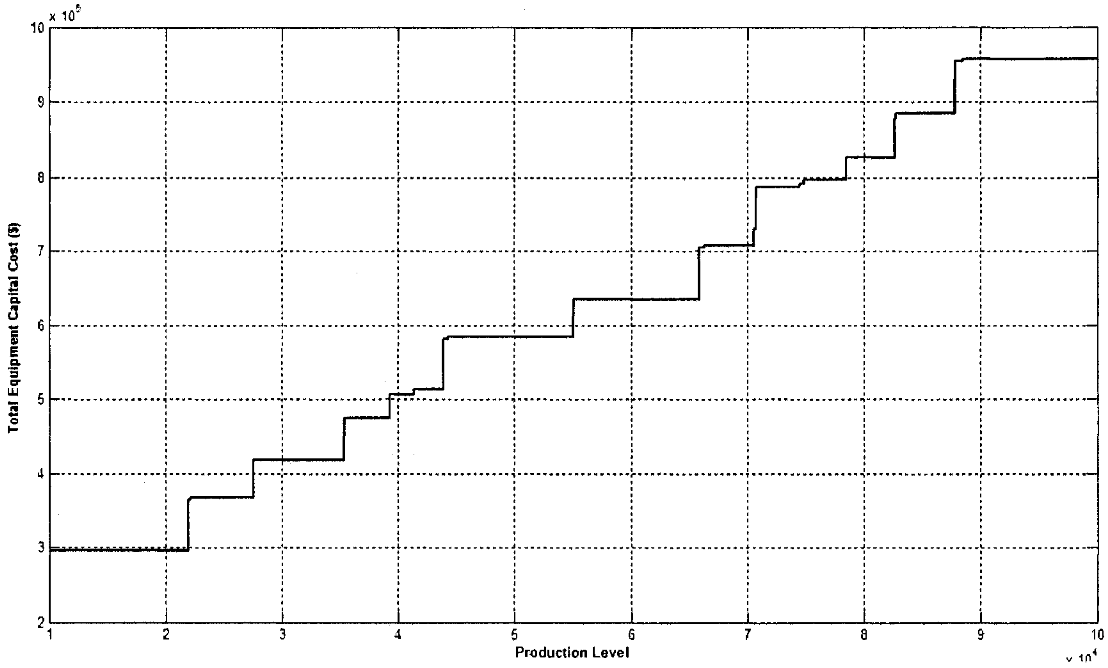


Fig. 4.5 Total Equipment Cost of Capital

2. A production cell is fully utilized during regular working shifts of the year. To increase production capacity overtime or holiday shift works are required. These increases may not be very steep since higher wage costs only apply to the parts produced outside regular shifts.

3. If the existing operators are fully utilized, producing more products requires hiring additional operators for common tasks. The additional labor forces hired are paid for the entire operation time of the production cell while the overall utilization of individual operators decreases. The sudden cost increase indicated by the circle in Fig.4.6 is of such nature.

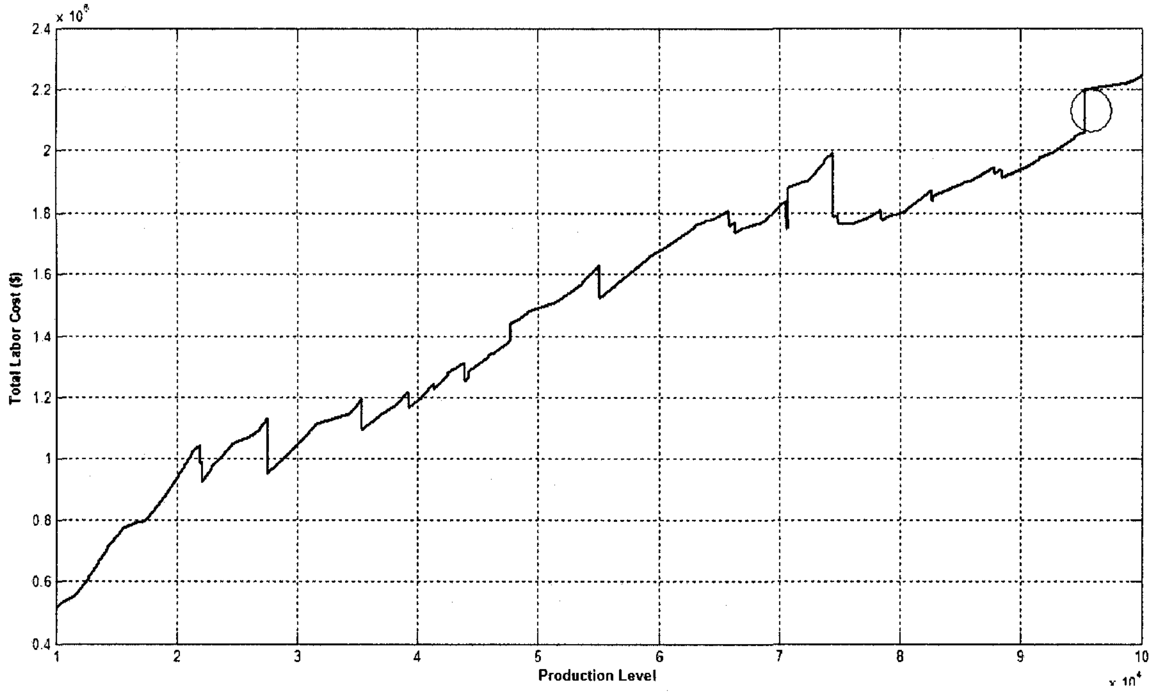


Fig. 4.6 Total Labor Cost of Production

4. When the same number of tools and presses are fully utilized, to increase the production capacity, an additional tool is added to the production line. This additional tool results in an unequal number of tools and presses. Consequently tool setup and

removal tasks are considered and the corresponding times are taken into account in the calculation process. This increases the time during which tools and presses are utilized to produce the same number of items. Variable costs such as maintenance cost and energy consumption cost will have sudden increases. However, this increase is lower than that of adding a tool-press set to the production line configuration. Sudden cost increases in Fig. 4.7 are of this type.

The following two reasons explain the sudden decreases observed in the cost graph shown in Fig.4.3:

1. Adding new tools and presses may also result in sudden cost reductions. When unequal numbers of tools and presses of an operation are fully utilized, to increase the production capacity one more unit of the press may be required. This additional press unit can make the number of tools and presses equal and consequently cancels corresponding setup and removal tasks in the process. This in turn reduces the processing time of the press and the tool. The cost reduction caused by reaching an equal number of tools and presses is lower than the cost increase incurred by adding one press unit to the line. Calculations in Section 4.2 support this observation. Sudden cost decreases observed in the total maintenance cost graph shown in Fig. 4.7 are of this type. Energy consumption cost is also following the same pattern.
2. Due to time interactions between different resources in a production cell, tools, labor or certain equipment may have idle time periods in their operation cycle. Fig. 4.8(a) shows a hypothetical operation cycle of one operator and one machine. In this operation cycle, the operator is busy for 2 minutes running the machine and is idle for one minute while the machine continues the operation. It takes 3 minutes for the part to be produced.

If the number of the parallel machines is increased by 2 as shown in Fig. 4.8(b) there would be no idle time for the operator since he or she would operate along with both machines. This operation cycle produces 2 items in 4 minutes. This implies a shorter processing time of the production cell. The production cell will produce the target production level in a shorter time. Two types of cost reduction may occur:

1) The number of parallel machines is increased and as the result, production cell processing time is decreased. Labor cost is reduced consequently.

2) The number of operators is increased. The required time for the production cell to produce the target production level, decreases. Machines are available to be allocated to external demands. As the result, a greater portion of equipment costs are diverted to the external products and the total production cost decreases.

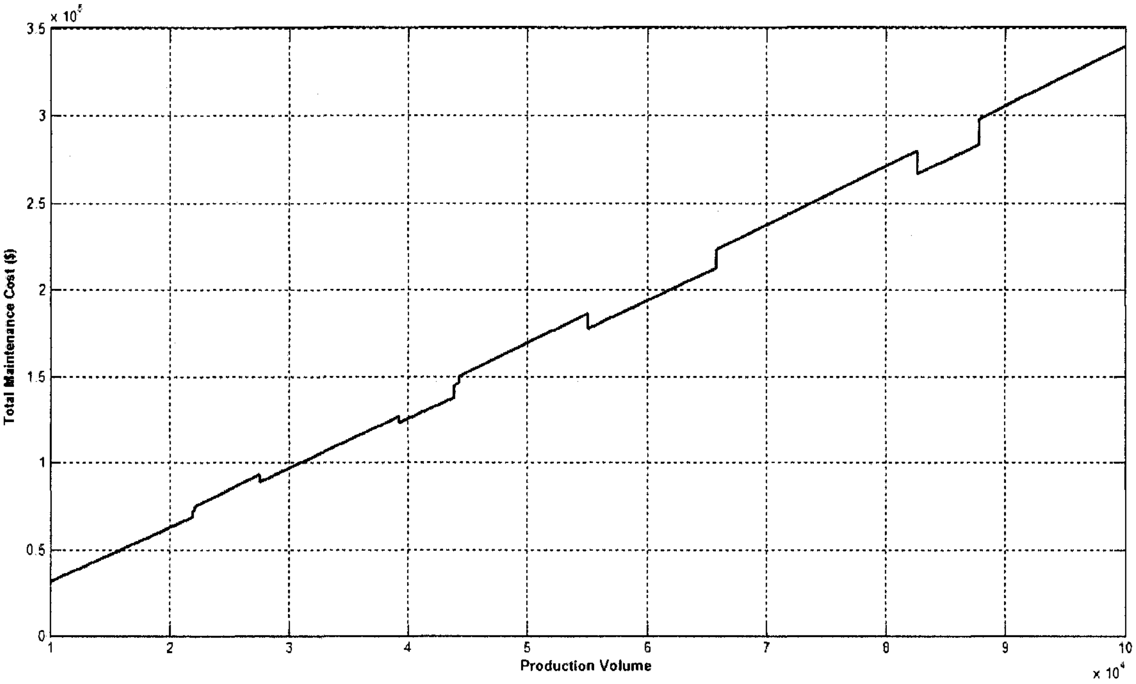


Fig. 4.7 Total Maintenance Cost of Production

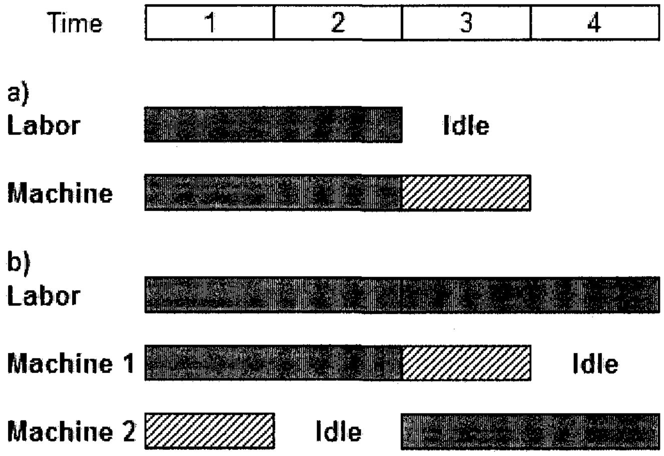


Fig. 4.8 Operational Cycles of Resources of a Production Cell

4.4 Two Product Type Case

We also used the developed model for cost analysis of the system producing two types of products. The first product has the same parameters considered in the single product calculation. The second product with similar dimensional properties was added. The main differences are in several parameters such as processing times, scrap rates and material consumption rates. These two products are also using different preforming and RTM tools. Tables 4.8 and 4.10 describe the details of the parameters considered for the second product.

For the preforming and the RTM operations of the second product, special tools are utilized. The data of the tools are shown in Table 4.9. Ordering cost of the materials for the second product is $900 and its unit price is assumed to be $150. Delivery cost is $1800 per delivery.

As discussed in Chapter 3, different combinations of production levels of the two product types result in different configurations of the production line and corresponding annual profit values. Basically, profit increases as production volume increases. There are also sudden changes as those observed in the cost per item graph in the single product case. The general increasing trend of profit is the result of the fix costs of the product distributed to larger number of product items. Sudden changes are caused by the same reasons discussed in the single product case.

Table 4. 8 Bill of Material (B.O.M) of the Second Product Type Considered

Material(s) Description	Qty.	Unit	Usage per product	Waste Ratio[2]	Unit Price ($)
Fabric	0.4	m2	9	0.18	2
Glue	0.15	Kg	3	Inc.	5
Gel coat & demolding agent	0.03	Kg	1	Inc.	25
Resin set	1.6	Kg	1	Inc.	7
Packaging	1	Set	1	Inc.	3

Table 4. 9 Specification of the Additional Tools Utilized for the Second Product Type

Tool	Price ($1000)	Depreciation Period (Yrs.)	Energy Consumption Rate (kW)	Area (m^2)
Preforming	30	6	0	70
RTM	870	6	40	40

We assume that production is in the ranges of [36000, 36200] for the first product and in [39600, 39800] for the second product. MATLAB was run to calculate the total profit value for the combination of the production levels in these two ranges. Fig. 4.9 shows a 3D graph with the 3 axes representing production levels of products 1 and 2 and the total profit value, respectively.

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[2] Inc.: Waste ratio is considered and included in quantity of material used.

Table 4. 10 RTM Manufacturing Process Details for the Second Product Type

Step No.	Station	Process	Time (s)	Scrap Rate
1	Cutting	Loading Rolls Onto Rolling Station & Cleaning Cutting Mach.	300	0%
2		Cutting Fabrics Out of Roll	45	5%
3		Separating & Buffering Waste and Fabrics	20	0%
4	Preforming	Laying Fabrics into Oven	10	0%
5		Heating Fabrics	18	1%
6		Draping 1st Fabric into Tool	15	0%
7		Spreading Glue Over 1st Fabric	25	2%
8		Draping 2nd Fabric into Tool	15	0%
9		Setting Tool into Press	10	0%
10		Clamping the Tool	0	0%
11		Pressing	28	3%
12		Opening the Tool	15	0%
13		Extracting Preform and Buffering	13	1%
14		Removing Tool from Press	10	0%
15	RTM	Cleaning the Mold	60	0%
16		Applying Gel Coat and Demolding Agent	18	2%
17		Loading Preform into Tool	4	0%
18		Setting Tool into Press	30	0%
19		Closing and Clamping Tool	5	0%
20	RTM	Preparing Resin Mixture	16	5%
21		Injecting Resin	70	9%
22		Curing	410	8%
23		Removing Tool from Press	30	0%
24		Opening the Tool	5	0%
25		Ejecting Part	3	0%
26		Extracting Part	27	1%
27		Buffering Injected Part	19	0%
28	Post Cure	Laying Parts on P-C Oven	26	0%
29		Post Cure	560	2%
30		Buffering Post-Cure Parts	30	0%
31	Trimming & Finishing	Cleaning Trimming Cell	30	0%
32		Putting Parts into T.C.	30	0%
33		Trimming Part	250	4%
35		Packaging	20	0%
36		Buffering Finished Part	5	0%

Sudden increases and decreases observed in Fig. 4.9 are the results of the same reasons discussed in the single product type case. The general incremental trend of the profit is obvious in different planes of this graph.

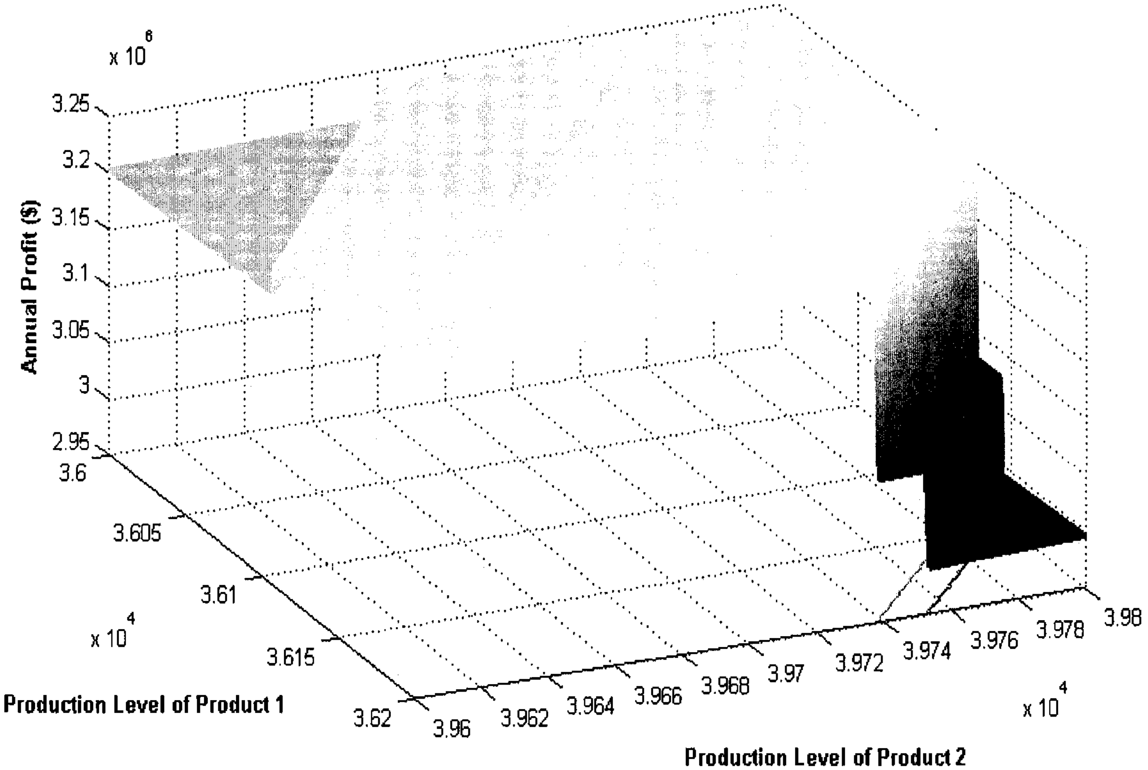


Fig. 4.9 Total Annual Profit of RTM System Producing Two Product Types

4.5 The Optimal Production Volume for Fixed System Configurations

A fixed configuration consisting of one unit of all the resources required for the RTM production system is considered. Production level pairs using full capacity of such system configurations incur minimum production costs. As the result higher annual profits are attained when such production level pairs are produced.

To maintain the same resource utilization level, the production level of a product type is increased when the production level of the other product type is decreased. The rate of such replacement depends on the relative utilization of different product types.

Fig.4.10 shows production level pairs approximately utilizing the non-duplicating RTM line configuration at the highest capacity. Steep of the line shown in Fig.4.10 is according to the relative system utilization of the product types.

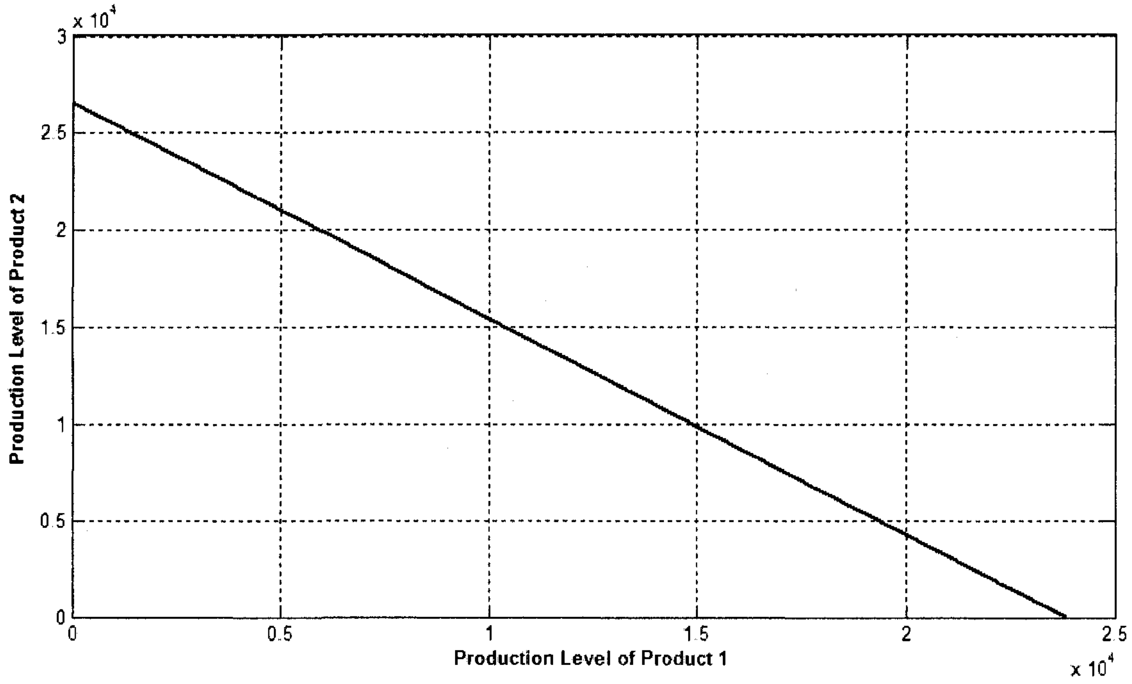


Fig. 4.10 Production Level Pairs Using Full Capacity of a Non-Duplicating Resource Configuration

The entire production level pairs shown in Fig.4.10 were solved in the cost model discussed in Section 3.7 and corresponding profit values were calculated. Fig. 4.11 shows the profit values obtained from production level pairs considered in Fig. 4.10. The plot in Fig. 4.11 implies that the highest profit value is attained when one product type is produced. Based on unit price and resource utilization for each product type, unit profit value of one product is higher than the other product. Consequently producing the product having higher unit profit value will be more cost effective.

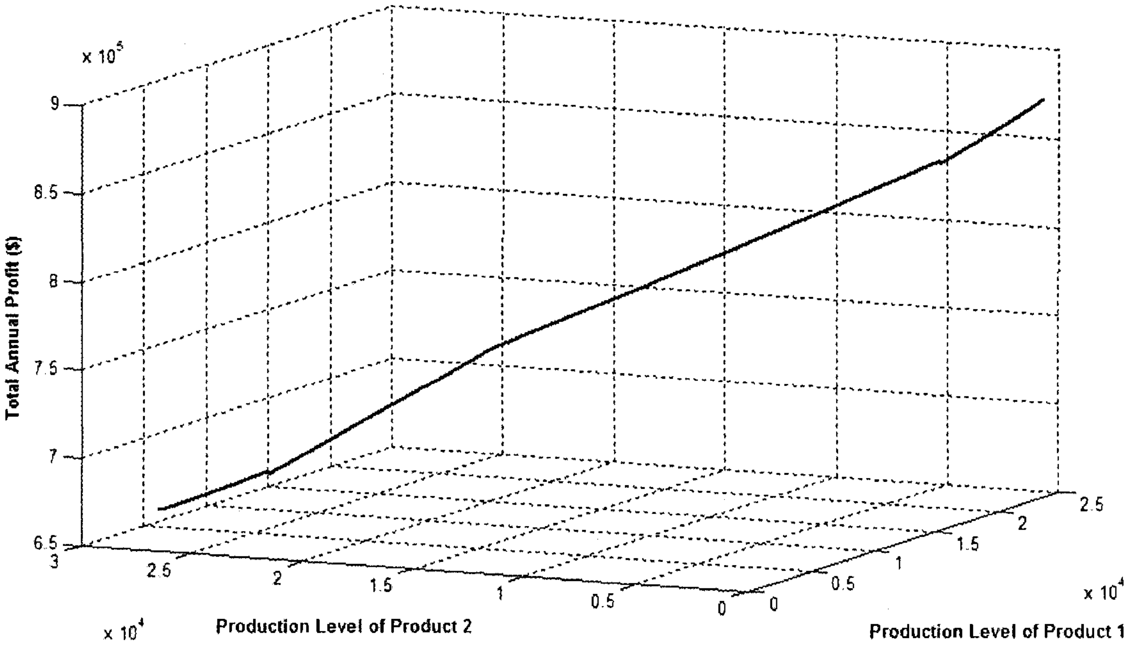


Fig. 4.11 Non-Duplicating Resource Configuration Annual Profit

4.6 Simulation of the RTM Production Line

As mentioned in Chapter 3, we also developed a simulation model using ARENA software to verify the results obtained from the cost model for non-duplicating configuration of the RTM production line. The simulation model has the same parameter values used in the mathematical model. Fig 4.13 presents the list of different processes and corresponding parameter values used in the simulation model. Fig. 4.14 presents a list of resources and corresponding values allocated to different tasks. Fig. 4.15 shows the model built in ARENA to simulate the RTM manufacturing process. Fig.4.16 shows the model in ARENA with animation incorporated.

ARENA Model:

As shown in Fig 4.15, different blocks are used to simulate the material flow in the RTM manufacturing process. Material and works in process are entities of the RTM manufacturing system simulated. Rectangular blocks represent process tasks of the RTM manufacturing system. Other types of blocks are also used for different functions of the model.

Process Blocks:

In the data sheet shown in Fig. 4.13, parameter values are set for process blocks used in the model. The first column of the data in Fig. 4.13 lists process blocks by the names used for them. The "action" column defines the type of the action to be taken over the entity and the resources used in the process block. "Seize Delay Release" action implies that resources of the process are seized to serve the entity. Delay implies that both the resources and the entity are delayed to accomplish the operation. Delay time representing the task time is given in the last column of the table in Fig.4.13.

Times assigned to the process tasks in Fig.4.13 are those considered in Table 4.4 taking into account of downtime of the equipment.

Resource:

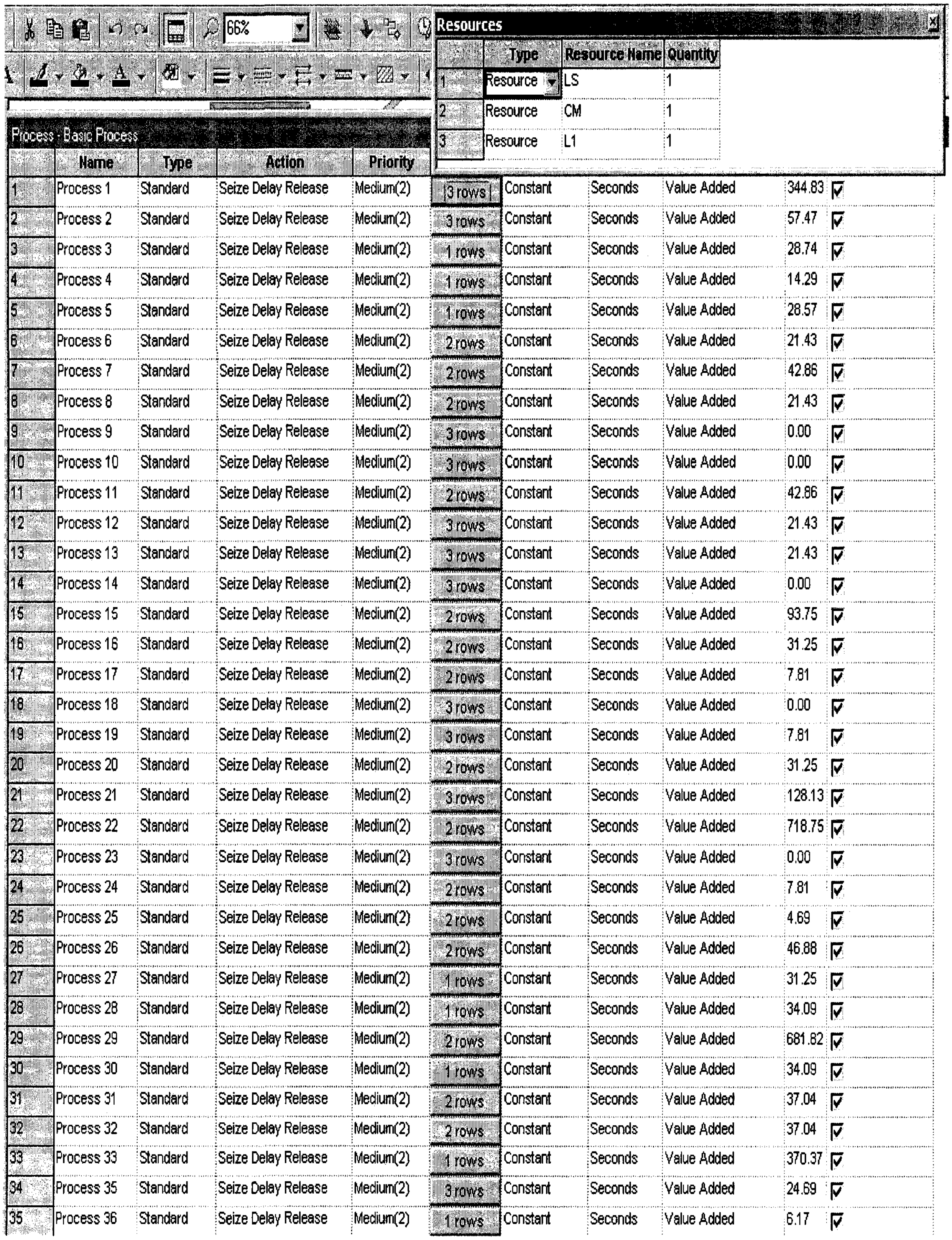
Fig. 4.14 lists the resources utilized in the RTM production line. The number of the parallel units is set in the "Capacity" column. The column "Type" defines if the resource is available on a fixed basis or the quantity of the resource is following a schedule.

4.6.1 Simulation Results

Since the simulation model developed is mainly based on deterministic parameters, outputs reach the steady state after the model is run for few hours. A 10 hour warm-up period was considered for this purpose. The model was run for 100 hours considering a 10 hour per week scheduled maintenance. Assuming a constant production rate in the steady state, simulation model can estimates the production capacity of the one year planning period operation having 8239 working hours.

ARENA model produced 265 items during 100 hours running period. This value estimates the annual capacity by 21,833 items when multiplied by (8239/100).The cost model calculates the production capacity of the same configuration by 23,880 items.

A comprehensive statistical report is also generated by ARENA which will be attached at the end of this dissertation.



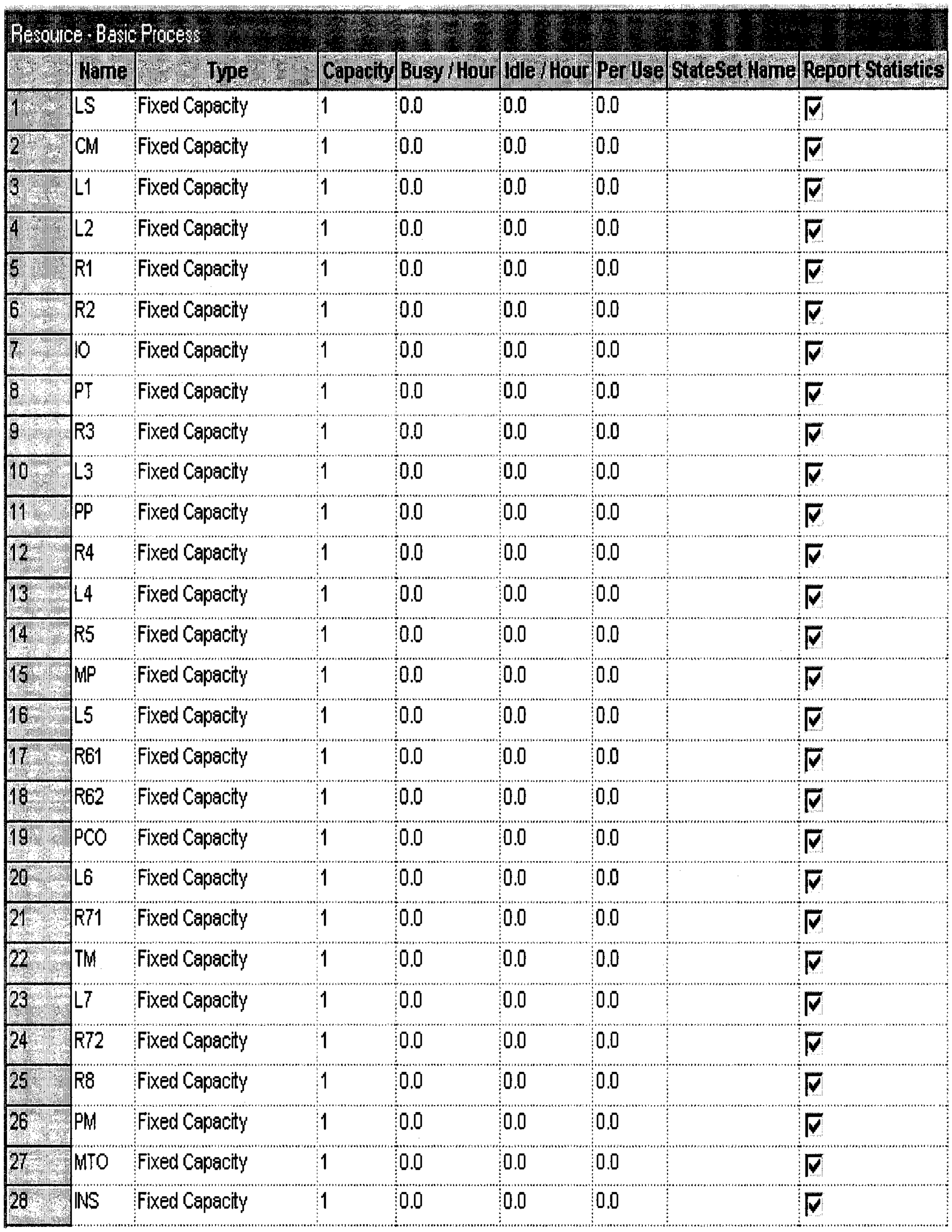
Resources

	Type	Resource Name	Quantity
1	Resource	LS	1
2	Resource	CM	1
3	Resource	L1	1

Process - Basic Process

	Name	Type	Action	Priority						
1	Process 1	Standard	Seize Delay Release	Medium(2)	3 rows	Constant	Seconds	Value Added	344.83	☑
2	Process 2	Standard	Seize Delay Release	Medium(2)	3 rows	Constant	Seconds	Value Added	57.47	☑
3	Process 3	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Seconds	Value Added	28.74	☑
4	Process 4	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Seconds	Value Added	14.29	☑
5	Process 5	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Seconds	Value Added	28.57	☑
6	Process 6	Standard	Seize Delay Release	Medium(2)	2 rows	Constant	Seconds	Value Added	21.43	☑
7	Process 7	Standard	Seize Delay Release	Medium(2)	2 rows	Constant	Seconds	Value Added	42.86	☑
8	Process 8	Standard	Seize Delay Release	Medium(2)	2 rows	Constant	Seconds	Value Added	21.43	☑
9	Process 9	Standard	Seize Delay Release	Medium(2)	3 rows	Constant	Seconds	Value Added	0.00	☑
10	Process 10	Standard	Seize Delay Release	Medium(2)	3 rows	Constant	Seconds	Value Added	0.00	☑
11	Process 11	Standard	Seize Delay Release	Medium(2)	2 rows	Constant	Seconds	Value Added	42.86	☑
12	Process 12	Standard	Seize Delay Release	Medium(2)	3 rows	Constant	Seconds	Value Added	21.43	☑
13	Process 13	Standard	Seize Delay Release	Medium(2)	3 rows	Constant	Seconds	Value Added	21.43	☑
14	Process 14	Standard	Seize Delay Release	Medium(2)	3 rows	Constant	Seconds	Value Added	0.00	☑
15	Process 15	Standard	Seize Delay Release	Medium(2)	2 rows	Constant	Seconds	Value Added	93.75	☑
16	Process 16	Standard	Seize Delay Release	Medium(2)	2 rows	Constant	Seconds	Value Added	31.25	☑
17	Process 17	Standard	Seize Delay Release	Medium(2)	2 rows	Constant	Seconds	Value Added	7.81	☑
18	Process 18	Standard	Seize Delay Release	Medium(2)	3 rows	Constant	Seconds	Value Added	0.00	☑
19	Process 19	Standard	Seize Delay Release	Medium(2)	3 rows	Constant	Seconds	Value Added	7.81	☑
20	Process 20	Standard	Seize Delay Release	Medium(2)	2 rows	Constant	Seconds	Value Added	31.25	☑
21	Process 21	Standard	Seize Delay Release	Medium(2)	3 rows	Constant	Seconds	Value Added	128.13	☑
22	Process 22	Standard	Seize Delay Release	Medium(2)	2 rows	Constant	Seconds	Value Added	718.75	☑
23	Process 23	Standard	Seize Delay Release	Medium(2)	3 rows	Constant	Seconds	Value Added	0.00	☑
24	Process 24	Standard	Seize Delay Release	Medium(2)	2 rows	Constant	Seconds	Value Added	7.81	☑
25	Process 25	Standard	Seize Delay Release	Medium(2)	2 rows	Constant	Seconds	Value Added	4.69	☑
26	Process 26	Standard	Seize Delay Release	Medium(2)	2 rows	Constant	Seconds	Value Added	46.88	☑
27	Process 27	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Seconds	Value Added	31.25	☑
28	Process 28	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Seconds	Value Added	34.09	☑
29	Process 29	Standard	Seize Delay Release	Medium(2)	2 rows	Constant	Seconds	Value Added	681.82	☑
30	Process 30	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Seconds	Value Added	34.09	☑
31	Process 31	Standard	Seize Delay Release	Medium(2)	2 rows	Constant	Seconds	Value Added	37.04	☑
32	Process 32	Standard	Seize Delay Release	Medium(2)	2 rows	Constant	Seconds	Value Added	37.04	☑
33	Process 33	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Seconds	Value Added	370.37	☑
34	Process 35	Standard	Seize Delay Release	Medium(2)	3 rows	Constant	Seconds	Value Added	24.69	☑
35	Process 36	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Seconds	Value Added	6.17	☑

Fig. 4.12 Process and Resource Assignment in ARENA



	Name	Type	Capacity	Busy / Hour	Idle / Hour	Per Use	StateSet Name	Report Statistics
1	LS	Fixed Capacity	1	0.0	0.0	0.0		☑
2	CM	Fixed Capacity	1	0.0	0.0	0.0		☑
3	L1	Fixed Capacity	1	0.0	0.0	0.0		☑
4	L2	Fixed Capacity	1	0.0	0.0	0.0		☑
5	R1	Fixed Capacity	1	0.0	0.0	0.0		☑
6	R2	Fixed Capacity	1	0.0	0.0	0.0		☑
7	IO	Fixed Capacity	1	0.0	0.0	0.0		☑
8	PT	Fixed Capacity	1	0.0	0.0	0.0		☑
9	R3	Fixed Capacity	1	0.0	0.0	0.0		☑
10	L3	Fixed Capacity	1	0.0	0.0	0.0		☑
11	PP	Fixed Capacity	1	0.0	0.0	0.0		☑
12	R4	Fixed Capacity	1	0.0	0.0	0.0		☑
13	L4	Fixed Capacity	1	0.0	0.0	0.0		☑
14	R5	Fixed Capacity	1	0.0	0.0	0.0		☑
15	MP	Fixed Capacity	1	0.0	0.0	0.0		☑
16	L5	Fixed Capacity	1	0.0	0.0	0.0		☑
17	R61	Fixed Capacity	1	0.0	0.0	0.0		☑
18	R62	Fixed Capacity	1	0.0	0.0	0.0		☑
19	PCO	Fixed Capacity	1	0.0	0.0	0.0		☑
20	L6	Fixed Capacity	1	0.0	0.0	0.0		☑
21	R71	Fixed Capacity	1	0.0	0.0	0.0		☑
22	TM	Fixed Capacity	1	0.0	0.0	0.0		☑
23	L7	Fixed Capacity	1	0.0	0.0	0.0		☑
24	R72	Fixed Capacity	1	0.0	0.0	0.0		☑
25	R8	Fixed Capacity	1	0.0	0.0	0.0		☑
26	PM	Fixed Capacity	1	0.0	0.0	0.0		☑
27	MTO	Fixed Capacity	1	0.0	0.0	0.0		☑
28	INS	Fixed Capacity	1	0.0	0.0	0.0		☑

Fig. 4.13 Resource Definition in ARENA Model

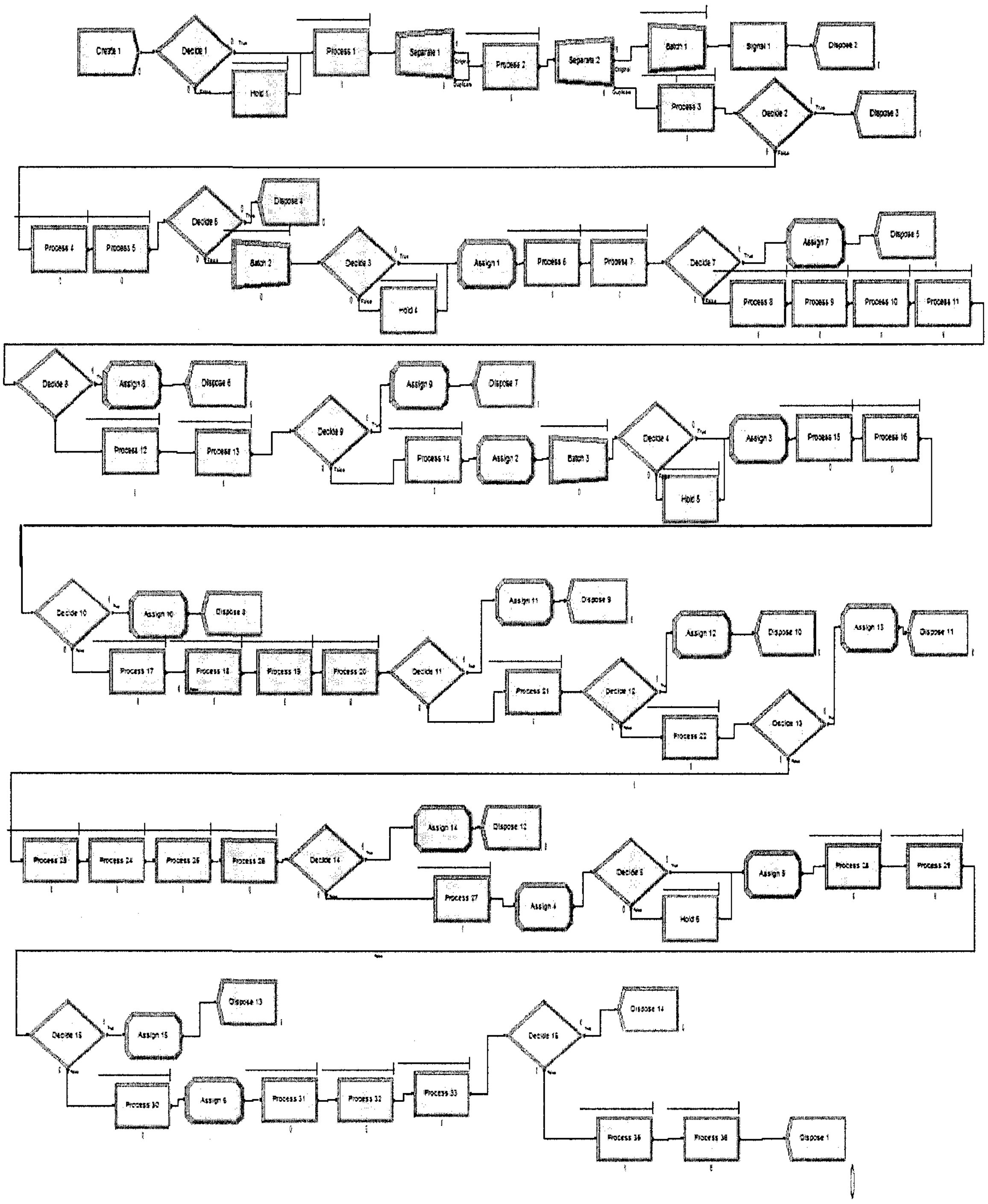


Fig. 4.14 Overall RTM Manufacturing Process Model in ARENA

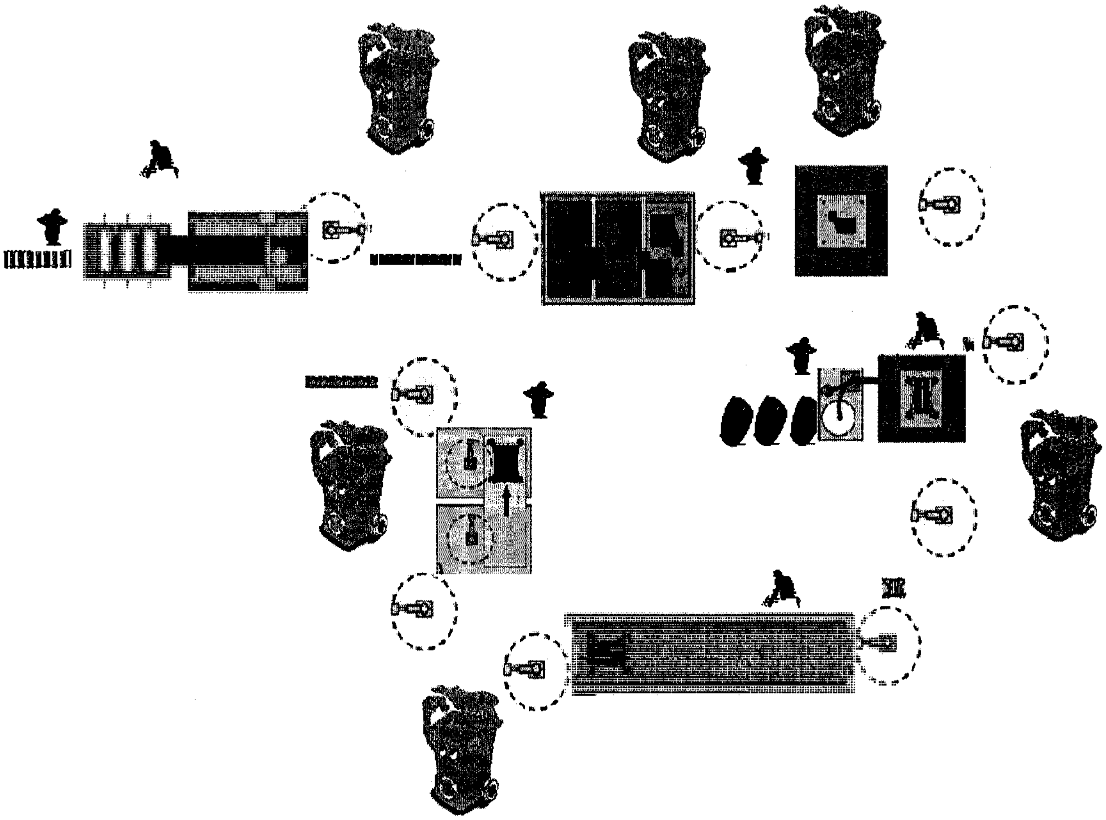


Fig. 4.15 Overall RTM Manufacturing Process Animated Model in ARENA

5 Conclusion

In this chapter, we first briefly summarize and discuss the research conducted in this thesis. We then present several observations and overall conclusions. Future research topics will be discussed at the end of the chapter.

5.1 Summary

Desirable properties of composite materials lead to their wide applications in many industrial sectors such as aerospace, automotive and sport products. Light weight, high mechanical properties, corrosion resistance and environmental friendly characteristics of composites are their principal benefits over other types of materials. However, costs of composite are normally higher than those of metal products. Manufacturing processes used to produce composite products do not have very long history. Composites manufacturing processes can be improved to reduce the rather high cost of composite products. Many research efforts have been made for this purpose in various manufacturing processes. Adjustment of technical variables such as stacking sequence of fabric layers, injection temperature and pressure profiles, gate and vent locations in the injection molds can improve product quality and reduce production time as well as production costs. On the other hand, research in this area is limited and often does not provide overall cost evaluation or optimization of the entire production system. Studying and obtaining optimal configurations of composite production systems such as an RTM process is of great importance. Optimal coordination of different production resources, better material supply and product delivery have much influence on the total production cost. In this research, an analytical model was developed for cost analysis and reduction of an RTM manufacturing system at different production levels. Effects of production scheduling and material handling on production cost were also studied. Specifically, the following related issues were studied in this research:

- Identifying production cells based on interrelations of different manufacturing resources of the process
- Constructing a production cost calculation framework reflecting the nature of the production system
- Reducing production cost by increasing resource utilization and optimizing operation schedule of production
- Adjusting production sequence to reduce the costs associated with production cycle time

Different functions of the analytical model were programmed to automatically calculate the optimized production cost of an RTM manufacturing process for various production levels. In the second phase of this research, the cost calculation model was solved for different levels of production to investigate the behavior of the manufacturing cost function. Cost fluctuations were observed and further investigated to determine the causes of irregular cost changes at certain production levels. The analytical model was also used to determine the optimal production level leading to more cost effective production.

The developed model can be applied with minor modifications for cost reduction in an RTM system where two different types of products are produced. In such applications however, more complicated issues such as production line switching were considered in model modifications. Total profits of producing different product types at different levels were calculated. Optimal combinations of production levels giving the maximum profits were identified.

5.2 Observations

Computational results show maximum utilizations of individual resources may not correspond to minimum production cost of the whole system. Combination of interrelations of different resources, the number of parallel units of equipment and different processing times will result in idle times of resources. Reducing idle times of most expensive resources can best reduce the overall production cost.

Equipment maintenance cost and overall energy consumption cost are linear functions, increasing with production level. Equipment capital cost, machine depreciation cost, land and building cost as well as plant operation costs are showing a stepwise trend due to their fixed cost nature. Since labor cost is associated with several different factors such as wage and salary structure, it behaves more irregularly. The same behavior is also observed for raw material cost, ordering cost and inventory cost.

The developed model can be used as a decision support tool for finding the optimal production level or combinations of production levels in composites manufacturing. When the production level is to be determined, the model can be used to find optimized system configurations for maximum profit. Also the proposed algorithm is a useful tool to find the optimal combination of production levels of various product types when the facilities of the production line have been configured.

The modeling and analysis approach developed in this work may be applicable to similar production systems with continuous characteristics in their material flow. With minor modifications the model may be applied to other manufacturing systems such as metal casting and metal rolling.

5.3 Future Research Directions

More composite materials are used in many areas of today's industry due to their desirable characteristics in many applications. Yet, much remains to be done to increase the cost competency of composites. One way to reduce the cost of composite products is to reduce the production cost and to improve the manufacturing processes. Research presented in this thesis is an attempt in this direction for overall production system optimization to minimize composite manufacturing cost. The following important issues can be addressed in future research along this direction:

- To develop a comprehensive simulation model for the RTM system analysis and cost reduction
- To optimize the configuration of the RTM manufacturing systems considering the effect of idle cycles of the resources in a cell operation
- To model and evaluate the cost of other composites manufacturing processes such as filament winding, etc.

Since many variables of composite manufacturing processes bear certain amount of uncertainties, stochastic cost evaluation of an RTM process or other processes used to manufacture composite products should be investigated.

Other industrial engineering tools such as linear programming and integer programming have been widely used for traditional manufacturing process optimization.

These tools can also be utilized for optimal production planning and control in composite production and manufacturing systems.

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7 Appendix 1. ARENA Output (SIMAN Report)

```
SIMAN Run Controller.

717.65317 Minutes>
                          ARENA Simulation Results
                                 ENCS

                        Summary for Replication 1 of 1

Project: Unnamed Project                     Run execution date : 2/15/2008
Analyst: ENCS                               Model revision date: 2/15/2008

Replication ended at time      : 6000.0 Minutes
Statistics were cleared at time: 600.0 Minutes (Friday, February 15, 2008, 10:00:00)
Statistics accumulated for time: 5400.0 Minutes
Base Time Units: Minutes

                             TALLY VARIABLES

Identifier                    Average   Half Width  Minimum   Maximum
Observations
____________________________________________________________________________

____________________

Entity 1.VATime                 32.775    2.7115    .47900    261.48     776
Entity 1.NVATime                .00000    .00000    .00000    .00000     776
Entity 1.WaitTime               3713.9    591.36    .00000    73515.     776
Entity 1.TranTime               .00000    .00000    .00000    .00000     776
Entity 1.OtherTime              .00000    .00000    .00000    .00000     776
Entity 1.TotalTime              682.11    (Corr)    .47900    5749.2     776
Process 15.Queue.WaitingTime    .00000    .00000    .00000    .00000     332
Process 9.Queue.WaitingTime     .00000    .00000    .00000    .00000    1890
Process 23.Queue.WaitingTime     .00000   (Insuf)   .00000    .00000     273
Process 31.Queue.WaitingTime     .00000   (Insuf)   .00000    .00000     269
Process 36.Queue.WaitingTime     .00000   (Insuf)   .00000    .00000     265
Batch 2.Queue.WaitingTime        .51701    .00887    .00000    7.6628    5180
Process 11.Queue.WaitingTime     .00000    .00000    .00000    .00000    1890
Process 16.Queue.WaitingTime     .00000    .00000    .00000    .00000     332
Process 24.Queue.WaitingTime    .00000    (Insuf)   .00000    .00000     273
Process 29.Queue.WaitingTime    .00000    (Insuf)   .00000    .00000     272
Hold 4.Queue.WaitingTime        853.61    (Corr)    152.78    1540.6    1920
Batch 3.Queue.WaitingTime        5.9081    .07219    .00000    15.715    1835
Process 5.Queue.WaitingTime      .00000    .00000    .00000    .00000    5240
Process 32.Queue.WaitingTime     .00000    (Insuf)   .00000    .00000     269
```

```
Process 17.Queue.WaitingTime      .00000   .00000   .00000   .00000    329
Process 25.Queue.WaitingTime      .00000   (Insuf)  .00000   .00000    273
Hold 5.Queue.WaitingTime          371.14   (Corr)   81.664   602.88    332
Process 12.Queue.WaitingTime      .00000   .00000   .00000   .00000    1845
Process 6.Queue.WaitingTime       .00000   .00000   .00000   .00000    1920
Process 20.Queue.WaitingTime      .00000   .00000   .00000   .00000    329
Process 33.Queue.WaitingTime      .00000   (Insuf)  .00000   .00000    269
Process 18.Queue.WaitingTime      .00000   .00000   .00000   .00000    329
Process 1.Queue.WaitingTime       .00000   (Insuf)  .00000   .00000    20
Process 13.Queue.WaitingTime      .00000   .00000   .00000   .00000    1844
Process 7.Queue.WaitingTime       .00000   .00000   .00000   .00000    1920
Process 21.Queue.WaitingTime      .00000   (Insuf)  .00000   .00000    315
Process 26.Queue.WaitingTime      .00000   (Insuf)  .00000   .00000    273
Hold 1.Queue.WaitingTime          3266.5   (Insuf)  783.96   5749.0    20
Hold 6.Queue.WaitingTime          --       --       --       --        0
Process 2.Queue.WaitingTime       128.33   (Corr)   .00000   254.78    5518
Process 14.Queue.WaitingTime      .00000   .00000   .00000   .00000    1833
Process 19.Queue.WaitingTime      .00000   .00000   .00000   .00000    329
Process 27.Queue.WaitingTime      .00000   (Insuf)  .00000   .00000    272
Process 35.Queue.WaitingTime      .00000   (Insuf)  .00000   .00000    265
Process 3.Queue.WaitingTime       .00000   .00000   .00000   .00000    5518
Process 8.Queue.WaitingTime       .00000   .00000   .00000   .00000    1890
Process 22.Queue.WaitingTime      .00000   (Insuf)  .00000   .00000    281
Process 30.Queue.WaitingTime      .00000   (Insuf)  .00000   .00000    269
Batch 1.Queue.WaitingTime         127.39   (Corr)   .00000   254.78    5340
Process 28.Queue.WaitingTime      .00000   (Insuf)  .00000   .00000    272
Process 10.Queue.WaitingTime      .00000   .00000   .00000   .00000    1890
Process 4.Queue.WaitingTime       .00000   .00000   .00000   .00000    5240

                        DISCRETE-CHANGE VARIABLES

Identifier                  Average  Half Width  Minimum   Maximum  Final Value
_______________________________________________________________________________
______________________________

Entity 1.WIP                21720.   (Corr)     4224.0    39170.   39170.
L1.NumberBusy               .02129   (Insuf)    .00000    1.0000   .00000
L1.NumberScheduled          1.0000   (Insuf)    1.0000    1.0000   1.0000
L1.Utilization              .02129   (Insuf)    .00000    1.0000   .00000
L2.NumberBusy               .97871   .00213     .00000    1.0000   1.0000
L2.NumberScheduled          1.0000   (Insuf)    1.0000    1.0000   1.0000
L2.Utilization              .97871   .00213     .00000    1.0000   1.0000
L3.NumberBusy               .37596   6.7E-04 .00000       1.0000   1.0000
L3.NumberScheduled          1.0000   (Insuf)    1.0000    1.0000   1.0000
L3.Utilization              .37596   6.7E-04 .00000       1.0000   1.0000
L4.NumberBusy               .14260   .00668     .00000    1.0000   .00000
```

L4.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
L4.Utilization	.14260	.00668	.00000	1.0000	.00000
L5.NumberBusy	.03173	.00136	.00000	1.0000	.00000
L5.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
L5.Utilization	.03173	.00136	.00000	1.0000	.00000
L6.NumberBusy	.57239	.01301	.00000	1.0000	.00000
L6.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
L6.Utilization	.57239	.01301	.00000	1.0000	.00000
L7.NumberBusy	.05095	.00111	.00000	1.0000	.00000
L7.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
L7.Utilization	.05095	.00111	.00000	1.0000	.00000
PCO.NumberBusy	.57239	.01301	.00000	1.0000	.00000
PCO.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
PCO.Utilization	.57239	.01301	.00000	1.0000	.00000
LS.NumberBusy	1.0000	.00000	.00000	1.0000	1.0000
LS.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
LS.Utilization	1.0000	.00000	.00000	1.0000	1.0000
MP.NumberBusy	.75600	.00741	.00000	1.0000	.00000
MP.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
MP.Utilization	.75600	.00741	.00000	1.0000	.00000
PM.NumberBusy	.02019	5.9E-04	.00000	1.0000	.00000
PM.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
PM.Utilization	.02019	5.9E-04	.00000	1.0000	.00000
PP.NumberBusy	.49401	.00168	.00000	1.0000	1.0000
PP.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
PP.Utilization	.49401	.00168	.00000	1.0000	1.0000
PT.NumberBusy	1.0000	.00000	.00000	1.0000	1.0000
PT.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
PT.Utilization	1.0000	.00000	.00000	1.0000	1.0000
R1.NumberBusy	.48942	9.7E-04	.00000	1.0000	1.0000
R1.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
R1.Utilization	.48942	9.7E-04	.00000	1.0000	1.0000
R2.NumberBusy	.23111	.00175	.00000	1.0000	.00000
R2.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
R2.Utilization	.23111	.00175	.00000	1.0000	.00000
R3.NumberBusy	.25200	5.7E-04	.00000	1.0000	.00000
R3.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
R3.Utilization	.25200	5.7E-04	.00000	1.0000	.00000
R4.NumberBusy	.12197	9 .1E-04	.00000	1.0000	.00000
R4.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
R4.Utilization	.12197	9.1E-04	.00000	1.0000	.00000
R5.NumberBusy	.00793	3.3E-04	.00000	1.0000	.00000
R5.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000
R5.Utilization	.00793	3.3E-04	.00000	1.0000	.00000
R8.NumberBusy	.02524	7.4E-04	.00000	1.0000	.00000
R8.NumberScheduled	1.0000	(Insuf)	1.0000	1.0000	1.0000

```
R8.Utilization                      .02524    7.4E-04 .00000    1.0000    .00000
CM.NumberBusy                       1.0000    .00000   .00000   1.0000    1.0000
CM.NumberScheduled                  1.0000    (Insuf)  1.0000   1.0000    1.0000
CM.Utilization                      1.0000    .00000   .00000   1.0000    1.0000
R61.NumberBusy                      .06967    .00150   .00000   1.0000    1.0000
R61.NumberScheduled                 1.0000    (Insuf)  1.0000   1.0000    1.0000
R61.Utilization                     .06967    .00150   .00000   1.0000    1.0000
R62.NumberBusy                      .02862    5.4E-04 .00000    1.0000    .00000
R62.NumberScheduled                 1.0000    (Insuf)  1.0000   1.0000    1.0000
R62.Utilization                     .02862    5.4E-04 .00000    1.0000    .00000
INS.NumberBusy                      .15630    .00399   .00000   1.0000    .00000
INS.NumberScheduled                 1.0000    (Insuf)  1.0000   1.0000    1.0000
INS.Utilization                     .15630    .00399   .00000   1.0000    .00000
R71.NumberBusy                      .02830    8.2E-04 .00000    1.0000    .00000
R71.NumberScheduled                 1.0000    (Insuf)  1.0000   1.0000    1.0000
R71.Utilization                     .02830    8.2E-04 .00000    1.0000    .00000
R72.NumberBusy                      .03075    7.8E-04 .00000    1.0000    .00000
R72.NumberScheduled                 1.0000    (Insuf)  1.0000   1.0000    1.0000
R72.Utilization                     .03075    7.8E-04 .00000    1.0000    .00000
TM.NumberBusy                       .36931    .00805   .00000   1.0000    1.0000
TM.NumberScheduled                  1.0000    (Insuf)  1.0000   1.0000    1.0000
TM.Utilization                      .36931    .00805   .00000   1.0000    1.0000
MTO.NumberBusy                      .94203    .00119   .00000   1.0000    1.0000
MTO.NumberScheduled                 1.0000    (Insuf)  1.0000   1.0000    1.0000
MTO.Utilization                     .94203    .00119   .00000   1.0000    1.0000
IO.NumberBusy                       .46204    .00337   .00000   1.0000    1.0000
IO.NumberScheduled                  1.0000    (Insuf)  1.0000   1.0000    1.0000
IO.Utilization                      .46204    .00337   .00000   1.0000    1.0000
Process 15.Queue.NumberInQueu .00000      (Insuf)  .00000   .00000    .00000
Process 9.Queue.NumberInQueue .00000      (Insuf)  .00000   .00000    .00000
Process 23.Queue.NumberInQueu .00000      (Insuf)  .00000   .00000    .00000
Process 31.Queue.NumberInQueu .00000      (Insuf)  .00000   .00000    .00000
Process 36.Queue.NumberInQueu .00000      (Insuf)  .00000   .00000    .00000
Batch 2.Queue.NumberInQueue     .49607    .00572   .00000   2.0000    1.0000
Process 11.Queue.NumberInQueu .00000      (Insuf)  .00000   .00000    .00000
Process 16.Queue.NumberInQueu .00000      (Insuf)  .00000   .00000    .00000
Process 24.Queue.NumberInQueu .00000      (Insuf)  .00000   .00000    .00000
Process 29.Queue.NumberInQueu .00000      (Insuf)  .00000   .00000    .00000
Hold 4.Queue.NumberInQueue      409.20    (Corr)   72.000   743.00    743.00
Batch 3.Queue.NumberInQueue     2.0058    .01192   .00000   5.0000    1.0000
Process 5.Queue.NumberInQueue .00000      (Insuf)  .00000   .00000    .00000
Process 32.Queue.NumberInQueu .00000      (Insuf)  .00000   .00000    .00000
Process 17.Queue.NumberInQueu .00000      (Insuf)  .00000   .00000    .00000
Process 25.Queue.NumberInQueu .00000      (Insuf)  .00000   .00000    .00000
Hold 5.Queue.NumberInQueue      25.093    (Corr)   5.0000   42.000    41.000
Process 12.Queue.NumberInQueu .00000      (Insuf)  .00000   .00000    .00000
```

```
Process 6.Queue.NumberInQueue .00000    (Insuf)  .00000    .00000    .00000
Process 20.Queue.NumberInQueue .00000   (Insuf)  .00000    .00000    .00000
Process 33.Queue.NumberInQueue .00000   (Insuf)  .00000    .00000    .00000
Process 18.Queue.NumberInQueue .00000   (Insuf)  .00000    .00000    .00000
Process 1.Queue.NumberInQueue  .00000   (Insuf)  .00000    .00000    .00000
Process 13.Queue.NumberInQueue .00000   (Insuf)  .00000    .00000    .00000
Process 7.Queue.NumberInQueue  .00000   (Insuf)  .00000    .00000    .00000
Process 21.Queue.NumberInQueue .00000   (Insuf)  .00000    .00000    .00000
Process 26.Queue.NumberInQueue .00000   (Insuf)  .00000    .00000    .00000
Hold 1.Queue.NumberInQueue     19787.   (Corr)   3597.0    35977.    35977.
Hold 6.Queue.NumberInQueue     .00000   (Insuf)  .00000    .00000    .00000
Process 2.Queue.NumberInQueue  129.23   (Corr)   .00000    266.00    14.000
Process 14.Queue.NumberInQueue .00000   (Insuf)  .00000    .00000    .00000
Process 19.Queue.NumberInQueue .00000   (Insuf)  .00000    .00000    .00000
Process 27.Queue.NumberInQueue .00000   (Insuf)  .00000    .00000    .00000
Process 35.Queue.NumberInQueue .00000   (Insuf)  .00000    .00000    .00000
Process 3.Queue.NumberInQueue  .00000   (Insuf)  .00000    .00000    .00000
Process 8.Queue.NumberInQueue  .00000   (Insuf)  .00000    .00000    .00000
Process 22.Queue.NumberInQueue .00000   (Insuf)  .00000    .00000    .00000
Process 30.Queue.NumberInQueue .00000   (Insuf)  .00000    .00000    .00000
Batch 1.Queue.NumberInQueue    131.10   (Corr)   .00000    267.00    252.00
Process 28.Queue.NumberInQueue  .00000   (Insuf)  .00000    .00000    .00000
Process 10.Queue.NumberInQueue  .00000   (Insuf)  .00000    .00000    .00000
Process 4.Queue.NumberInQueue   .00000   (Insuf)  .00000    .00000    .00000

                           COUNTERS

Identifier                   Count  Limit
_________________________________________________________________

Final Product Produced          265  Infinite

                           OUTPUTS

Identifier                  Value
_________________________________________________________________

Entity 1.NumberIn             46215.
Entity 1.NumberOut             11270.
L1.NumberSeized               20.000
L1.ScheduledUtilization       .02129
L2.NumberSeized               5518.0
L2.ScheduledUtilization       .97871
L3.NumberSeized               9378.0
L3.ScheduledUtilization       .37596
L4.NumberSeized               1868.0
```

L4.ScheduledUtilization	.14260
L5.NumberSeized	329.00
L5.ScheduledUtilization	.03173
L6.NumberSeized	272.00
L6.ScheduledUtilization	.57239
L7.NumberSeized	534.00
L7.ScheduledUtilization	.05095
PCO.NumberSeized	272.00
PCO.ScheduledUtilization	.57239
LS.NumberSeized	5538.0
LS.ScheduledUtilization	1.0000
MP.NumberSeized	1527.0
MP.ScheduledUtilization	.75600
PM.NumberSeized	265.00
PM.ScheduledUtilization	.02019
PP.NumberSeized	11192.
PP.ScheduledUtilization	.49401
PT.NumberSeized	16922.
PT.ScheduledUtilization	1.0000
R1.NumberSeized	5518.0
R1.ScheduledUtilization	.48942
R2.NumberSeized	5240.0
R2.ScheduledUtilization	.23111
R3.NumberSeized	3810.0
R3.ScheduledUtilization	.25200
R4.NumberSeized	1844.0
R4.ScheduledUtilization	.12197
R5.NumberSeized	329.00
R5.ScheduledUtilization	.00793
R8.NumberSeized	530.00
R8.ScheduledUtilization	.02524
CM.NumberSeized	5538.0
CM.ScheduledUtilization	1.0000
R61.NumberSeized	818.00
R61.ScheduledUtilization	.06967
R62.NumberSeized	272.00
R62.ScheduledUtilization	.02862
INS.NumberSeized	644.00
INS.ScheduledUtilization	.15630
R71.NumberSeized	269.00
R71.ScheduledUtilization	.02830
R72.NumberSeized	269.00
R72.ScheduledUtilization	.03075
TM.NumberSeized	807.00
TM.ScheduledUtilization	.36931
MTO.NumberSeized	3339.0

```
MTO.ScheduledUtilization          .94203
IO.NumberSeized                   5240.0
IO.ScheduledUtilization           .46204
System.NumberOut                  776.00


Simulation run time: 3.07 minutes.
Simulation run complete.
```