DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

A HYBRID APPROACH TO SETTING ORDER PROMISING TIMES IN A SUPPLY CHAIN NETWORK

by

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İZMİR

A HYBRID APPROACH TO SETTING ORDER PROMISING TIME IN A SUPPLY CHAIN NETWORK

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Gülay AY

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İZMİR

M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"A HYBRID APPROACH TO SETTING ORDER PROMISING TIME IN A SUPPLY CHAIN NETWORK"** completed by **GÜLAY AY** under supervision of **PROF.DR.SEMRA TUNALI** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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This thesis is dedicated to my beloved mother Fethiye Ay and to my beloved father İrfan Ay.

Gülay AY

A HYBRID APPROACH TO SETTING ORDER PROMISING TIME IN A SUPPLY CHAIN NETWORK

ABSTRACT

This M.Sc study suggests a hybrid approach for setting realistic order promising times for a produce-order manufacturing company operating within a supply chain environment.

The proposed hybrid approach combines the analytical and simulation modeling to bring together the advantages of both approaches. In first step, an analytic model minimizing the overall costs of production, distribution, transportation, inventory holding, and shortage costs subject to the various kinds of constraints is developed to generate optimum production and distribution plans. In the second step, another analytic model which incorporates these production plans as constraints is developed to generate optimal scheduling decisions. In the last stage, a simulation model which reflects the dynamic and stochastic nature of manufacturing environment is utilized to evaluate realistically the effects of these scheduling decisions. Mainly, this simulation model helped to set realistic order promising times for customers.

Keywords: Simulation, Mathematical programming, Hybrid Approach, Flow type production scheduling, scheduling of parallel machines in a flow type production environment, production and distribution planning in supply chain

BİR TEDARİK ZİNCİRİ ORTAMINDA TESLİM ZAMANLARININ AYARLANMASI PROBLEMİNE HİBRİT YAKLAŞIM METODU İLE ÇÖZÜM GETİRİLMESİ

ÖZ

Bu yüksek lisans çalışmasında, bir tedarik zinciri içerisinde faaliyet gösteren ve siparişe göre üretim yapan bir fabrikada müşterilere gerçekçi teslim tarihleri verilmesi problemine çözüm olarak bir hibrit yaklaşım önerilmiştir.

Önerilen hibrit yaklaşım her iki yaklaşımın da kullanıcıya sağladığı avantajlardan faydalanmak için analitik ve simulasyon modellerini tek algoritma içerisinde birleştirir. Birinci aşamada üretim, dağıtım, envanter, stok, kıtlık maliyetini minimize eden bir analitik model ile tedarik zinciri içerisinde üretim ve dağıtım planlanır. İkinci aşamada, birinci aşamada elde edilen sonuçlara göre kısıtlar yapılandırılarak optimum çizelgeleme kararları alınır. Son aşamada, ikinci aşamada elde edilen çizelgeleme kararlarının gerçekçi olarak değerlendirilebilmesi amacıyla üretim ortamının stokastik ve dinamik yapısını yansıtan bir simulasyon modeli kullanılır. Yapılandırılan bu simulasyon modeli müşteriler için gerçekçi teslim zamanları verilmesine yardımcı olur.

Anahtar Sözcükler: Simülasyon, Matematiksel programlama, Hibrit yaklaşım, Akış tipi üretimin çizelgelenmesi, Akış tipi üretimde paralel makinelerin çizelgelenmesi, Tedarik zincirinde üretimin ve dağıtımın planlanması

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CHAPTER ONE

INTRODUCTION

Supply chain management (SCM) involves the management of material and information flow among the members of chain such as vendors, manufacturing plants and distribution centers. The main processes in supply chain are the production planning, control, distribution and logistics. The production planning and control describes the design of process and management of entire manufacturing process, for example material handling, scheduling and inventory control, etc. The distribution and logistics process determines how products are transported from the factory or warehouse to customers (Lee & Kim, 2002). Effective management of all these processes provides the manufacturing companies great advantages in time based competition.

Recent trends in time based competition require products to be completed in shorter time and with more reliable delivery dates. At the operational level, this can be made possible via better planning, scheduling and due-date management. Due-dates can be set either externally by the most immediate customer, or internally by the scheduling system. When dates are externally set, the scheduling system is charged with appropriate prioritization and synchronization to accommodate timely flow of operations. Internally set due-dates usually reflect current factory congestion levels, manufacturing system capacity, and job content. In either case, tight due-dates and on-time completion are challenges to the scheduler. (Veral, 2001)

The traditional solution to the production planning and scheduling problem in large-scale factories is to use Enterprise Resource Planning (ERP) modules for determining lot sizes, inventories, etc. But in small-scale factories these costly systems are replaced with easily acquired solution methodologies such as mathematical modeling. However, when used alone, analytical approaches generally fail in modeling the realistic aspects of production systems such as queuing and stochasticity.

To overcome with the modeling difficulty and to model stochastic and dynamic systems in detail a hybrid procedure integrating analytic and simulation model of manufacturing systems could be very useful. Approaches to solve production planning and scheduling problems by either analytic or simulation modeling alone offers specific advantages and disadvantages. However, a combination of these approaches might lead some of the advantages while avoiding their disadvantages alone. (Byrne & Bakir, 1999)

This M.Sc study suggests a hybrid approach for setting realistic due dates for a produce-order manufacturing company operating within a supply chain environment.

The proposed hybrid approach combines the analytical and simulation modeling to bring together the advantages of both approaches. In first step, an analytic model minimizing the overall costs of production, distribution, transportation, inventory holding, and shortage costs subject to the various kinds of constraints is developed to generate optimum production and distribution plans. In the second step, another analytic model which incorporates these production and distribution plans as constraints is developed to generate optimal scheduling decisions. In the last stage, a simulation model which reflects the dynamic and stochastic nature of manufacturing environment is utilized to evaluate realistically the effects of these scheduling decisions. Mainly, this simulation model helped to set realistic due-dates for customers.

This M.Sc study has been organized as follows. The following chapter presents the background information about the problem area and the methodologies employed to solve this problem. The survey of relevant literature is given in Chapter 3. The proposed approach to solve the production and scheduling problem in a supply chain environment is presented in Chapter 4. An industrial case study illustrating the implementation of the proposed approach is given in Chapter 5. Finally, the concluding remarks are presented in Chapter 6.

CHAPTER TWO
BACKGROUND INFORMATION

This chapter first presents background information about the due date setting problem in supply chain network. Next, the methodologies, employed to solve this problem, such as mathematical programming and simulation are explained.

2.1 Supply Chain Management

Edgar, E. B. (2000) describes the supply chain to be the physical infrastructure, including suppliers, plants, warehouses, customers and transportation, within which the flow of goods from the origin of raw material to the customer occurs. Procurement, production and distribution are the stages that are included in a supply chain. Figure 2.1 illustrates three stages.

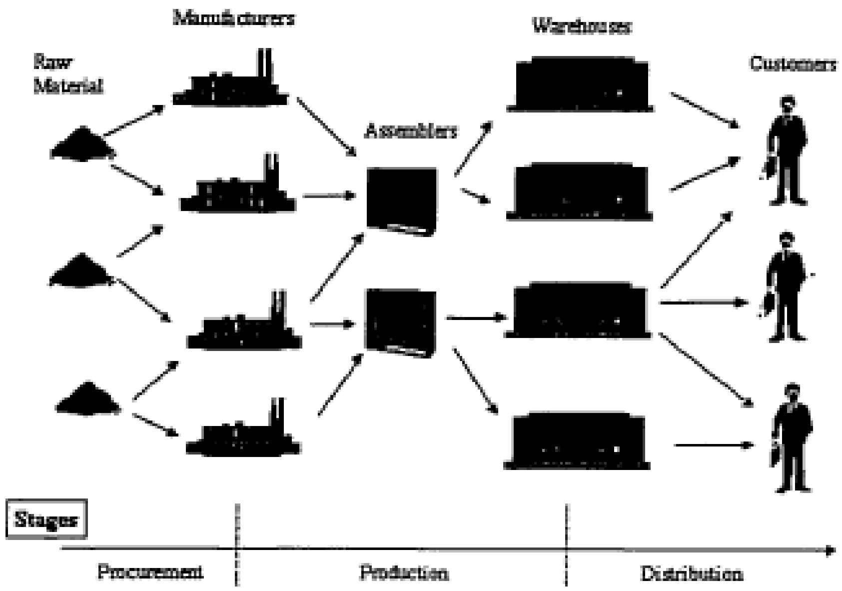

Figure 2.1 Stages of a supply chain (Edgar, 2000)

Supply Chain Management (SCM) is the set of functions that control the flow of material and information among the supply chain stages. The relevant SCM decisions can be viewed hierarchically in three different layers: strategic, tactical and operational. These levels are shown in Figure 2.2. The strategic level deals with long-term decisions such as facility location and capacity specification. The tactical level deals with medium-term decisions including capacity allocation to products and source-supply relations with distribution points. The operational level deals with near-term decisions including shop-floor production and scheduling decisions as well as product delivery.

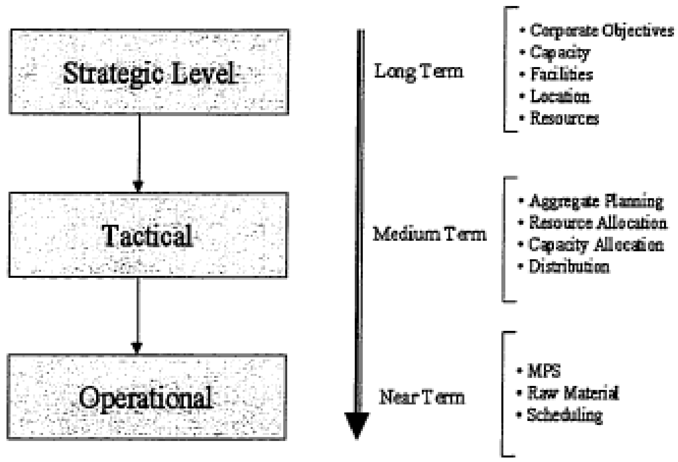

Figure 2.2 Decision levels in supply chain management
(Edgar, 2000)

It is clear that the coordination of the production and distribution components in a supply chain network is essential to make good decisions for all stages. Lee, H. & Billingtion, C. (1992) list the problems that are faced with in management of supply chain network as follows:

- No supply chain metrics are defined to evaluate the overall performance of the supply chain.
- Inadequate definition of customer service.
- The customers are not properly informed about their order status.
- Lack of a centralized database of the supply chain. Leading to defective internal inform system.
- The impact of uncertainties is underestimated or completely ignored when taking supply chain decisions.
- Simplistic inventory stocking policies are implemented.

- Discrimination against internal customers placing more emphasis on external customers.
- Poor coordination in long and globalized supply chains.
- Employing incomplete shipment methods analysis in analyzing a supply chain.
- Incorrect assessment of inventory costs.
- Ignoring internal organizational barriers in evaluating the performance of supply chain.
- Product-Process design without supply chain consideration.
- Separation of supply chain design from operational decisions.
- Incomplete supply chain specification.

Although not all of the above problems can be tackled through coordination, a coordinated approach will help a lot in dealing more effectively with them. Figure 2.3 illustrates some of the important issues that take place in a supply chain network.

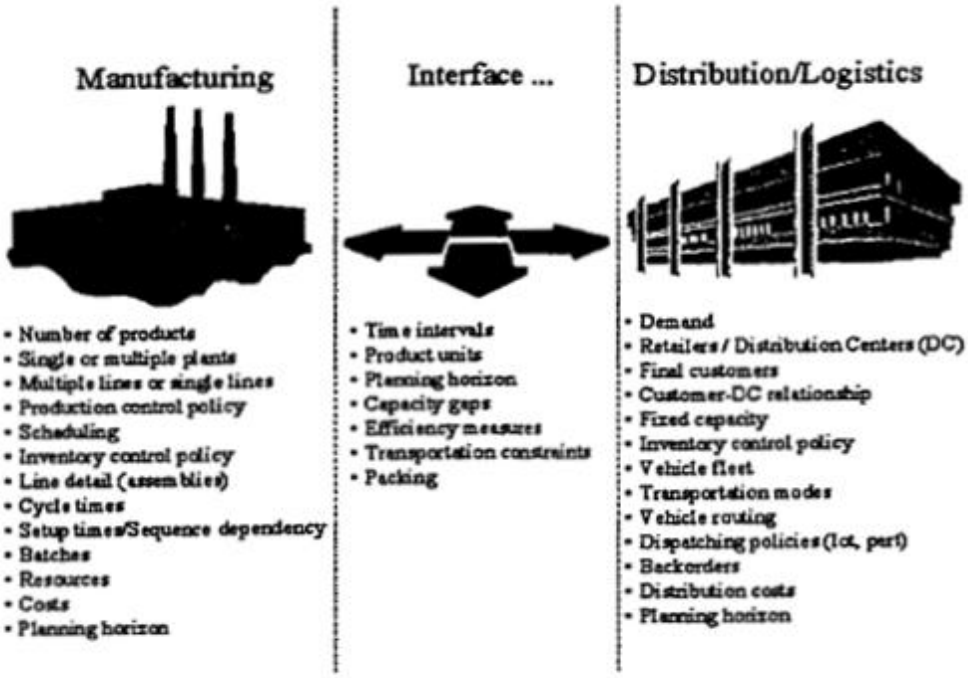

Figure 2.3 Production-distribution interface (Edgar, 2000)

Edgar, E. B. (2000) states that regarding the interface, all of the below considerations are needed to be taken into account when constructing a coordinated model:

- Time intervals and planning horizon
- Product units
- Efficiency measure
- Capacity gaps
- Transportation constraints

In the literature with respect to their problem scope and application areas supply chain models can also be classified into various frameworks which are given below:

1. Supplier selection/inventory control
2. Production/distribution
3. Location/inventory control
4. Location/routing
5. Inventory control/transportation

The main objective in SCM is to minimize total supply chain cost while constructing a coordinated model to meet the given demand. The cost function includes the following terms: (Shapiro, 2001)

- Raw material and other acquisition costs
- Inbound transportation costs
- Facility investment costs
- Direct and indirect manufacturing costs
- Direct and indirect distribution center costs
- Inventory holding costs
- Interfacility transportation costs
- Outbound transportation costs

According to Global Supply Chain Associates (2003), 10% improvements in supply chain costs and 25% improvements in supply chain cycle time are typical in many applications. The typical questions answered during the construction of a supply chain are as follows: (Ramesh, 2004)

- How many plants? Where should they be located?
- How much production capacity of each process in each plant?
- How vertically integrated?
- What products should be produced in each plant?
- What demand regions should each plant serve?
- Which vendors should serve each plant?
- Which parts should be purchased from each vendor?
- Should we ship direct from the plants or use warehouses?
- How many warehouses should be operated and where should each be located?
- What is the service area for each distribution center?
- What modes of transportation to use?
- How best to use in-transit merge to fulfill orders?
- Should I oursource logistics? Which functions?

During constructing the supply chain environment, the problems that supply chain models being able to face should be designated. During design, planning and operation of a supply chain models the problems described below can be faced:

- Supplier selection
- Outsource planning
- Operational strategy selection: This problem includes selecting the strategy to operate the supply chain. The problem examples are as follows:
    - How to choose between PUSH, PULL, and Hybrid PUSH-PULL
    - How to choose the strategy such as STS (stock-to-sales), MTS (make-to-stock), ATO (assembly-to-order), MTO (make-to-order), at each stage of the supply chain

- Capacity planning: Capacity planning is a process that determines the amount of capacity required to produce in the future. This function includes establishing, measuring, and adjusting limits or levels of capacity. In general, this planning includes the process of determining in detail the amount of labor and machine resources required to accomplish the tasks of production.

- Resource planning: Resource planning is capacity planning conducted at the business plan level. It is the process of establishing, measuring, and adjusting limits or levels of long-range capacity. Resource planning decisions always require top management approval.

- Lead-time planning: Individual components of lead-time can include order preparation time, queuing time, processing time, move or transportation time, and receiving and inspection time.

- Production planning: There are two phases of production planning: the first phase is an aggregate production planning and the second phase is an operational production planning.

An “Aggregate production plan” implies budgeted levels of finished products, inventory, production backlogs, and plans and changes in the work force to support the production strategy (Shigeki & Sanjay, 2004). Aggregate planning usually includes total sales, total production, targeted inventory, and targeted customer backlog on families of products.

According to Shigeki, U. & Sanjay, J. (2004) when the system works by taking into cosideration the given plan, to estimate the production rates is one of the primary purposes of the aggregate production plan. The production rate is an important decision parameter since it determines whether the system is meeting its’ management’s objective of satisfying customer demand while keeping the work force relatively stable. As the production plan affects many company functions, so it is normally prepared with information from marketing, and coordinated with the functions of manufacturing, engineering, finance, materials, etc. It is the function of setting the overall level of manufacturing output (production plan) and other activities to best satisfy the current customer orders, while meeting general business objectives as expressed in the overall business plan such as profitability, productivity, competitive customer due dates, and so on. The sales and production capabilities are compared, and a business strategy that includes a production plan, budgets, and supporting plans for materials and work force requirements, is developed. (Shigeki & Sanjay, 2004)

As presented in Figure 2.4, the solution methodologies employed to deal with these problems can be placed into four groups:

1. Deterministic models
2. Stochastic models
3. Hybrid models
4. Information Technology (IT)-driven models

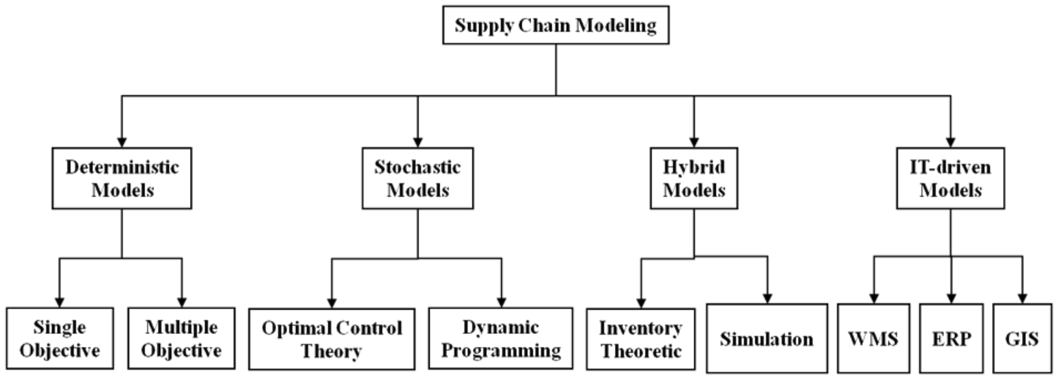

Figure 2.4 The classification of solution methodologies (WMS: Warehouse management system, GIS: Geographical information system)

In this M.Sc study to solve the production /distribution planning and scheduling problem in a supply chain network, one deterministic model with single objective is investigated. All used data are deterministic and objective function is a cost function that minimizes total supply chain cost. The problems tackled with in the study are first aggregate production planning problem and second resource planning problem. The aggregate production planning problem is investigated within supply chain network. The resource planning problem is investigated within one factory. The following section gives a brief summary to a production planning problem in supply chain networks.

2.2 Production Planning in Supply Chain Networks

In supply chain networks overall objective is to produce and deliver finished products to end customers in the most cost effective and timely manner as mentioned preceding section. Pinedo, 2004 says the coordination of operations in all stages of the global supply chain is a necessity, the models and solution techniques for each stage have to be integrated within one framework.

While the first stage involves a multi-stage medium term planning process using aggregate data, the following stage involves detailed short term scheduling which are usually applied more frequently than planning procedures, at each one of stages separately.

The medium term planning process attempts to minimize the total cost over all the stages (Pinedo, 2004). The costs that have to be minimized in this optimization process include production costs, holding and storage costs, transportation costs, non-delivery costs, tardiness costs, handling costs, costs for increases in resource capacities (e.g., scheduling third shifts), and costs for increases in storage capacities (Pinedo & Kreipl, 2004).

During the medium term optimization process input data are considered in an aggregate form. For example, time is frequently measured in weeks or months rather than days. Distinctions are usually only made between major product families, and no distinctions are made between different products within one family (Pinedo, 2004). A setup cost may be taken into account, but it may only be considered as a function of the product itself and not as a function of the sequence (Pinedo, 2004).

The results of this optimization process are daily or weekly production quantities for all product families at each location or facility as well as the amounts scheduled for transport every week between the locations (Pinedo, 2004). The production of the orders require a certain amount of the capacities of the resources at the various facilities, but no detailed scheduling takes place in the medium term optimization (Pinedo, 2004). The output for detailed scheduling consists of the allocation of resources to the various product families, the assignment of products to the various facilities in each time period, and the inventory levels of the finished goods at the various locations.

The following section gives a brief summary to a scheduling problem in a manufacturing environment.

2.3 Scheduling in Manufacturing Environment

The output of the medium term planning process serves as an input to the detailed (short term) scheduling process. In solving a scheduling problem the scope is considerably narrower, but the level of detail taken into consideration is considerably higher. (Pinedo, 2004)

The level of detail in scheduling is increased in the following dimensions: (Pinedo & Chao, 1999)

(i). the time is measured in a smaller unit (e.g., days or hours)
(ii). the horizon is shorter,
(iii). the product demand is more precisely defined, and
(iv). the facility is not a single entity, but a collection of resources or machines.

Interaction between a planning module and a scheduling module in supply chain networks may be intricate. A scheduling module may cover only a relatively short term horizon (e.g., one month), whereas the planning module may cover a longer time horizon (e.g., six months). After the schedule has been fixed for the first month (fixing the schedule for this month requires some input from the planning module), the planning module does not consider this first month anymore; it assumes the schedule for the first month to be fixed. However the planning module still tries to optimize the second up to the sixth month. (Pinedo, 2004)

While interaction is being done between medium and short term stages in a supply chain a feedback mechanism between these stages is required to have. This feedback mechanism enables achieving the goal of producing and delivering finished products to end customers in a most cost effective and timely manner. The interaction between these stages involves several iterations. During this iterative process, accuracy of input data used for the medium term planning can be tested and also rescheduling can be done more easily in case of a major disruption.

For better understanding scheduling systems few taxonomies are explained. Below the following taxonomies are presented that reflects differences in how the problems are modeled:

- Discrete parts manufacturing
- Process manufacturing
- Job-shop scheduling
- Hybrid scheduling

Discrete parts manufacturing refers to environments in which individual machines produce a number of similar items. The machines are intermittently set up to make lots of each item. Planning horizons vary from a few days to several weeks. Demands for the company's finished products are assumed to be known with certainty in each period of the planning horizon. These demands are satisfied from finished or semifinished goods inventory; that is, production is either *make-to-stock* of standard products, such as refrigerators or tires, or *assembly-to-stock* of products for which a small amount of customization is allowed, such as automobiles or printed circuit boards.

Process planning and scheduling problems arise in capital intensive companies that manufacture products such as petroleum products, food products, paper, glass, industrial gases, and soap.

Job-shop scheduling refers to an environment in which a number of jobs, each having a variety of tasks, which may be processed on different machines in different sequences, are undertaken (Sunil & Peter, 2001). Moreover, some tasks can be undertaken only if other tasks have been completed. Typical job shops include plants that overhaul and repair jet engines and foundries that manufacture customized castings (Sunil & Peter, 2001). In general, make-to-*order* manufacturing involves elements of job-shop scheduling.

The objective of the basic job-shop scheduling model is to sequence tasks on the machines to which they have been assigned so as to minimize the total time required to complete all scheduled jobs. (Sunil & Peter, 2001)

The constraints of the basic job-shop scheduling model fall into two categories. The first set describes precedence relationships among tasks associated with each job. These constraints determine the time when each is the completion time of the job's final task. The second task describes precedence relationships corresponding to sequencing tasks from different jobs on each machine. Zero-one variables are defined for each pair of tasks to be processed on the machine, say tasks A and B, where a value of 0 corresponds to processing A before B and a value of 0 corresponds to processing B before A (Sunil & Peter, 2001).

Some manufacturing environments include multiple stages that discussed above. Their hybrid nature makes them more difficult to control because diverse production planning activities and practices need to be integrated.

Although to define scheduling problem in words is often easy, unfortunately scheduling models can be difficult to perform and implement (Pinedo & Chao, 1999). For understanding scheduling problems, heuristic scheduling models and systems can be summarized as follows:

A formal schedule may or may not be given in advance, but simple practical changes may be handled just by adjusting the whole schedule in a flexible way. The emphasis is on scheduling resource by resource, keeping each resource busy with the most important activity available. When a resource becomes free, the "highest priority" activity among those currently available is performed next (Morton & Pentico, 1993). Resources follow a predefined rules being a set of heuristics commonly used in scheduling. The choice of rule is often determined by the objective selection. Known dispatching rules in literature are given following:

- Job slack
- Job slack ratio
- Scheduled start date
- Earliest due date (EDD)
- Subsequent processing times
- Service in random order (SIRO)
- Earliest release date first (ERD)
- Shortest processing time first (SPT)
- Longest processing time first (LPT)
- Shortest setup time first (SST)
- Least flexible job first (LFJ)
- Experiment rule (ER)

Dispatching rules give quick and simple solutions to scheduling problem since they are not iterative procedures. The performance of rules varies according to different conditions. In respect of production area the choice of rule can become different.

Even if a system gets implemented and used, machine environment in a factory may change drastically. If the system is not flexible enough to provide suitable schedules for the new environment, a change in the scheduler may derail the system.

To summarize, the following points could be taken into consideration when designing, developing, and implementing a scheduling system. (Pinedo, 1995)

1. Visualize how the operating environment will evolve over the lifetime of the system before the design process actually starts.

2. Get all the persons affected by the scheduling system involved in the design process. The development process has to be a team effort, and those involved have to approve the design specifications.

3. Determine which part of the system can be handled by off-the-shelf software. Using the appropriate commercial code speeds up the development process considerably.
4. Keep the design of the code modular. This is necessary, not only to facilitate the entire programming effort but also to facilitate changes in the system after its implementation.
5. Make the objectives of the algorithms embedded in the system consistent with the performance measures by which people who follow the schedules are being judged.
6. Do not take the data integrity of the database for granted. The system has to be able to deal with faulty or missing data and provide the necessary safeguards.
7. Capitalize on potential side benefits of the system, for example, spin-off reports for distribution to key people. This enlarges the supporters' base of the system.
8. Make provisions to ensure easy rescheduling, not only buy the scheduler but also by others in case the scheduler is absent.
9. Keep in mind that the installment of the system requires patience. It may take months or even years before the system runs smoothly. This period should be period of continuous improvement.
10. Do not underestimate the necessary maintenance of the system after installation. The effort required to keep the system in use on a regular basis is considerable.

Under these considerations scheduling problem turns into a complicated problem. To simplify the complexity of manufacturing environments, most of the scheduling problems are solved under assumptions listed below: (Ceryan, 2008)

- Single parts and batches of parts are always treated as a single job.
- Job cancellation is not allowed.
- Preemption is not allowed.
- Each job visits all machines exactly once.
- Machines are always available.

- Jobs are all known in advance.
- The problem is purely deterministic.
- Processing times are independent of the schedule.
- Machines are the only resources modeled.
- Work-in-process is allowed.
- Machines are able to process one job at a time.
- Precedence constraints can be occurred.

It should be noted that in this M.Sc study, while long-term refers to three months, short-term refers to ten days. Namely the proposed supply chain model is solved for three months and the scheduling model is solved for ten days. During modeling manufacturing environment experiment rule (ER) rule is applied. Products follow one flow except from parallel machines during manufacturing. The production is going on according to make-to-order policy in study. In the following section methodologies to solve production and scheduling problem such as mathematical models and simulation models are explained briefly.

2.4 Methodologies to Solve Production Planning and Scheduling Problem

Representation of scheduling problems in real-world usually is very different from the mathematical models studied by researches in academia. It is not easy to list all the differences between these problems and the theoretical models because every real-world scheduling problem has its own particular idiosyncrasies (Pinedo, 1995). Nevertheless, a number of differences which are taken from Pinedo, 1995 are common and therefore worth mentioning.

Firstly, theoretical models usually assume that there are n jobs to be scheduled and that after scheduling these n jobs the problem is solved. In the real world there may be n jobs in the system at any time, but new jobs are added continuously. Scheduling the current n jobs has to be done without a perfect knowledge of the near future. Hence some provisions have to be made to be prepared for the unexpected. The dynamic nature may require, for example, that slack times are built into the schedule to accommodate unexpected rush jobs or machine breakdowns.

Secondly, theoretical models usually do not emphasize the resequencing problem. In practice, the following problem often occurs: there exists a schedule, which was constructed based on certain assumptions, and an unexpected event occurs that requires either major or minor modifications in the existing schedule. The rescheduling process, which is sometimes referred to as reactive scheduling, may have to satisfy certain constraints. Resequencing may be required within scheduling processes.

Thirdly, machine environments in the real world are often more complicated. Processing restrictions and constraints may be very involved. They may be either machine dependent, job dependent, or time dependent.

Fourthly, in the mathematical models, the priorities of the jobs are assumed to be fixed, that is, they do not change over time. In practice, the priority of a job often fluctuates over time and it may do so as a random function. A low-priority job may become suddenly a high-priority job.

Fifthly, mathematical models often do not take preferences into account. In a model a job either can or cannot be processed on a given machine. That is, whether or not the job can be scheduled on a machine is a 0-1 proposition. In reality, it often occurs that a job can be scheduled on a given machine, but that for some reason there is a preference to schedule it on another one. Scheduling it on the first machine would only be done in case of an emergency and may involve additional costs.

Sixthly, most theoretical models do not take machine availability constraints into account; it is usually assumed that machines are available at all times. In the real world, machines are usually not continuously available. There are many reasons why machines may not be in operation. At times preventive maintenance may be scheduled. The machines may also be subjects to a random breakdown and repair process.

Seventhly, most penalty functions considered in research are piecewise linear, for example, the tardiness of a job, the unit penalty, and so on. In practice, there usually does exist a committed shipping date or due date. However, the penalty function is typically not piecewise linear. In practice, the penalty function may take, for example, the shape of an “S” (see Figure 2.5). Such a penalty function may be regarded as a function that lies somewhere in between the tardiness function and the unit penalty function.

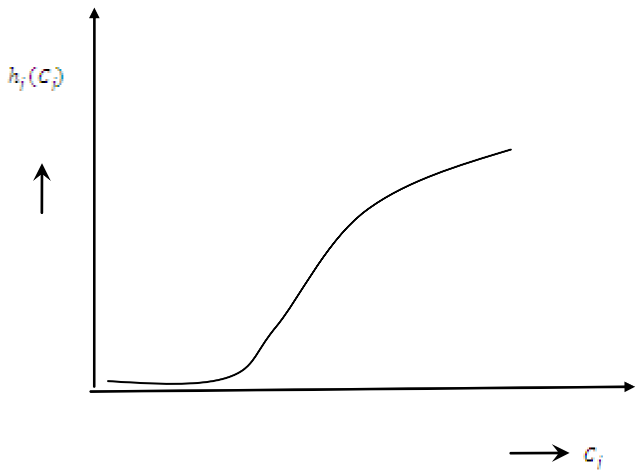

Figure 2.5 A penalty function in practice (Pinedo, 1995)

Eighthly, most theoretical research has focused on models with a single objective. In the real world, there are usually a number of objectives. Not only are there several objectives, but their respective priorities may vary over time and may even depend on the particular scheduler in charge. One particular combination of objectives appears to occur very often, especially in the process industry, namely the minimization of the sum of the weighted tardiness and the minimization of the sum of the sequence-dependent setup times (especially on bottleneck machines). The minimization of the sum of the weighed tardinesses is important because maintaining quality of service is usually an objective that carries weight. The minimization of the sum of the sequence-dependent setup times is important as, to a certain extent, it increases the throughput. When such a combination is the overall objective, the weights given to the two objectives may not be fixed. The weights may depend on the time as well as on the current status of the production environment. If the workload is relatively large, then minimization of the sequence-dependent setup times is more important; if the workload is relatively light, minimization of the sum of the weighted tardinesses is more important.

Ninthly, the scheduling process is, in practice, often strongly connected with the assignment of shifts and the scheduling of overtime. Whenever the workload appears to be excessive and due dates appear to be too tight, the decision maker may have the option to schedule overtime or put in extra shifts to meet the committed shipping dates.

Tenthly, the stochastic models usually assume very special processing time distributions. The exponential distribution, for example, is a distribution that has been studied at length. In realty, processing times usually are not distributed exponentially.

Another important aspect of random processing times is correlation. Successive processing times on the same machine tend to be highly positively correlated in practice. In the stochastic models, usually all processing times are assumed to be independent draws from given distribution(s). One of the effects of a positive correlation is an increase in the variance of the performance measures.

Processing time distributions may be subject to change due to learning or deterioration. When the distribution corresponds to a manual operation, then the possibility of learning exists. The person performing the operation may be able to reduce the average time he needs for performing the operation. If the distribution corresponds to an operation in which a machine is involved, then the aging of the machine may have as an effect an increase in the average processing time.

In spite of the many differences between the real world and the mathematical models, the general consensus is that the theoretical research done in the past has not been a complete waste of time. It has provided more valuable insights into many scheduling problems after it has been used with methods which can reflect the real-world characteristics. Mathematical models for scheduling have been getting more useful and realistic by adding the simulation systems for getting the solution to theoretical problems such as dynamic nature of manufacturing environment, resequencing, machine restrictions, job or machine priority and preferences.

Pinedo, M. & Chao, X. (1999) explain the most commonly used techniques to solve scheduling problems:

(i). dispatching rules,
(ii). shifting bottleneck techniques,
(iii). local search procedures (e.g., genetic algorithms), or
(iv). integer programming techniques.
(v). simulation modeling

In M.Sc study Arena 10.0 simulator is used in conjunction with analytical modeling to deal with a dynamic scheduling problem in a specified company. The further details about these two methodologies being used are given in the following section.

2.4.1 Mathematical Programming

As mentioned preceding section for scheduling a high variety of different techniques are used. Jain, S. & others (1999) explained the majority of methodologies for solving scheduling problems to be able to be grouped into four main categories: rule-based methods (assignment and dispatching rules), randomized search methods (simulated annealing, tabu search and genetic algorithm), mathematical programming methods, and constraint logic programming methods (artificial intelligence). Mathematical programming formulations' briefs are given in the following section.

In production and distribution area there is a large class of mathematical programs in which the constraints can be divided into a set of *conjunctive* constraints and one more sets of *disjunctive* constraints. A set of constraints is called conjunctive if each one of the constraints has to be satisfied. A set of constraints is called disjunctive if at least one of the constraints has to be satisfied but not necessarily all. In the standard linear program all constraints are conjunctive. The fact that the integer variable has to be either 0 or 1 can be enforced by a pair of disjunctive linear constraints. This implies that the single machine problem with precedence constraints and the total weighted completion time objective can be formulated as a disjunctive program as well. (Pinedo, 1995)

In M.Sc study precedence and preferences constraints in manufacturing area are constructed with disjunctive and conjunctive constraints. Scheduling area is modeled as MIP model and supply chain area is modeled as LP model.

In the following there are two solution examples to LP and IP problems. Morton, T. & Pentico, D. (1993) solved the general parallel machine makespan problem with minimum makespan objective. In the linear problem jobs j are numbered in order of arrival, C_{max} is the makespan, a_k is the first availability of machine k, x_{jk} is the fraction of job j assigned to machine k, p_{jk} is the processing time of job j on machine k, r_j is the ready time of job j, and j' is an index representing jobs arriving no earlier than j. Removal of the equations with r_j produces the equations for the static arrival case but the problem has dynamic nature.

min C_{max}

s.t.

$a_k + \sum_{j=1,n} x_{jk} p_{jk} \leq C_{max}$ for each machine *k*

$\sum_{k=1,m} x_{jk} = 1$ for each job *j*

$r_j + \sum_{j'=j,n} x_{j'k} p_{j'k} \leq C_{max}$ for each job *j* and machine *k*

$x_{jk} \geq 0$ for each assignment *jk*

In the solution model each machine equation simply states that the completion time of that machine must be less than or equal to the makespan. Each job equation simply says that all of that job must be assigned somewhere. Each job/machine equation states that all jobs arriving after *j* and assigned to machine *k* cannot be more than the makespan. The assignment inequalities simply state that assignments can be fractional but not negative.

Makespan problems become very difficult when there are more than two machines. Branch-and-bound has had some success in exactly solving smaller problems, perhaps with three or four machines and 10 or 15 jobs for the makespan criterion. Morton, T. & Pentico, D. (1993) gave an example to the *m*-machine flow shop problem with makespan objective:

C_m is the completion time of all jobs on m.

C_{jk} is the completion time of job j on machine k.

C_{jkt} is 1 if $C_{jk} = t$; 0 otherwise.

x_{jkt} is 1 if job j is scheduled on machine k in period t; 0 otherwise.

p_{jk} is the processing time of job j on machine k.

T is the total number of time periods in the model.

r_j is the arrival time of job j.

a_k is the initial availability time of machine k.

min $\mathrm{C_m}$

s.t.

$\mathrm{C_{jk}} = \sum_{\mathrm{t=1,T}} \mathrm{t\, C_{jkt}}$	for all j, k	(1)
$x_{jkt} = \sum_{u=t,t+p_{jk}-1} C_{jku}$	for all j, k, t	(2)
$C_m \geq C_{jm}$	for all j	(3)
$C_{j1} \geq r_j + p_{j,1}$	for all j	(4)
$C_{jk} \geq C_{j,k-1} + p_{j,k}$	for all j, k	(5)
$\sum_{j=1,n} x_{jkt} \leq 1$	for all k, t	(6)
$x_{jkt} = 0$	$t < a_k$, all j, k	(7)
$C_{jk} \in \{0,1\}$	for all j, k, t	(8)

In the solution model the objective is to minimize the makespan or completion time on machine m. In equation (1) precisely one term of the sum will be nonzero, yielding t, where t is the actual completion time of job j on machine k. Equation (2) says that job j will be processing on machine k in time t if and only if it completes somewhere between t and $t + p_{jk} - 1$. Constraint (3) says that the overall makespan must be at least as large as the completion time for each job. Constraint (4) says that no job can start until it arrives. Constraint (5) says that an operation cannot complete until the previous one does plus the current operation process time. Constraint (6) says that at most one operation may be using machine k at any time period t. Equation (7) says that no job may process until the machine initially becomes available. Constraint (8) says that part of operation jk cannot finish on machine k in period t; either none or all will.

Pinedo M. & Kreipl S. (2004) present a standard medium term planning model for a supply chain in their research. There are three stages in chain to be seen in Figure 2.6. Stage 1, the first and most upstream stage has two factories in parallel. They both feed Stage 2, which is a distribution center (dc). Both Stages 1 and 2 can deliver to a customer, which is a part of Stage 3. The factories have no room for finished goods storage and the customer does not want to receive any early deliveries.

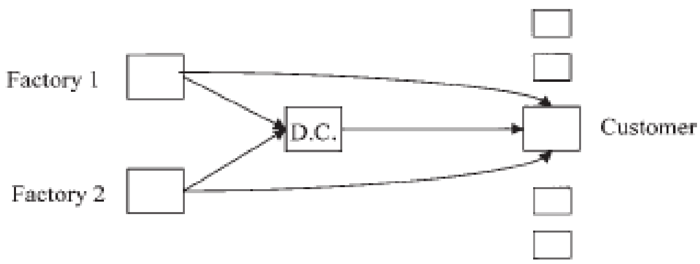

Figure 2.6 A system with three stages.

Pinedo M. and Kreipl S. revealed a typical SC model presented below;

i (i 1, 2, 3, 4), refers to time period

j (j 1, 2), refers to product family

k (k 1, 2), refers to factory

l (l 1, 2, 3) refers to stage

p refers to a production parameter.

s refers to a storage parameter

t refers to a transportation parameter

D_{ij2} is the demand for product family j at the dc level (stage 2) by the end of week i

D_{ij3} is the demand for product family j at the customer level (stage 3) by the end of week i

Production times and costs are given:

c_{jk}^{p} is the cost to produce 1 unit of family j in factory k

t_{jk}^{p} is the time (in hours) to produce 1000 units of family j in factory k

Storage costs and transportation data include:

c_2^{s} *is* the storage cost for 1 unit of any type in the dc per week

c_{k2o}^{t} is the transportation cost for a unit of any type from factory k to the dc

c_{ko3}^{t} is the transportation cost for a unit of any type from factory k to the customer

c_{ko3}^{t} = the transportation cost for a unit of any type from the dc to the customer.

t^{t} is all transportation times are assumed to be identical and equal to one week.

- from any one of the two factories to the dc,
- from any one of the two factories to the customer,
- from the dc to the customer.

The following weights and penalty costs are given:

w_j^{n} *is* the tardiness cost per unit per week for an order of family j products that arrive late at the dc

w_j^{m} *is* the tardiness cost per unit per week for an order of family j products that arrive late t the customer

π is the penalty for never delivering one unit of product

Decision variables:

x_{ijk} = number of units of family *j* produced at plant *k* during period *i*.

y_{ijk2} = number of units of family *j* transported from plant *k* to the dc in week *i*.

y_{ijk3} = number of units of family *j* transported from plant *k* to customer in week *i*.

z_{ij} = number of units of family *j* transported from the dc to the customer in week *i*.

q_{0j2} = number of units of family *j* in storage at the dc at time 0.

q_{ij2} = number of units of family *j* in storage at the dc in week *i*.

x_{ijk} = number of units of family *j* produced at plant *k* during period *i*.

y_{ijk2} = number of units of family *j* transported from plant *k* to the dc in week *i*.

y_{ijk3} = number of units of family *j* transported from plant *k* to customer in week *i*.

z_{ij} = number of units of family *j* transported from the dc to the customer in week *i*.

q_{0j2} = number of units of family *j* in storage at the dc at time 0.

q_{ij2} = number of units of family *j* in storage at the dc in week *i*.

The objective is to minimize the total of the production costs, transportation costs, storage costs, tardiness costs, and penalty costs for non-delivery over a horizon of 4 weeks:

$$\sum_{i=1}^{4}\sum_{j=1}^{2}\sum_{k=1}^{2} c^{p}_{jk} x_{ijk} + \sum_{i=1}^{4}\sum_{j=1}^{2}\sum_{k=1}^{2} c^{T}_{k2} y_{ijk2} + \sum_{i=1}^{4}\sum_{j=1}^{2}\sum_{k=1}^{2} c^{T}_{k3} y_{ijk3}$$

$$+ \sum_{i=1}^{4}\sum_{j=1}^{2} c^{s}_{2} q_{ij2} + \sum_{i=1}^{3}\sum_{j=1}^{2} w''_{j} v_{ij2} + \sum_{i=1}^{3}\sum_{j=1}^{2} w'''_{j} v_{ij3} + \sum_{j=1}^{2} \pi v_{4j2} + \sum_{j=1}^{2} \pi v_{4j3}$$

Weekly production capacity constraints:

$$\sum_{j=1}^{2} t^{p}_{j1} x_{ij1} \le 168 \quad i = 1, \ldots, 4;$$

$$\sum_{j=1}^{2} t^{p}_{j2} x_{ij2} \le 168 \quad i = 1, \ldots, 4;$$

Transportation constraints:

$$y_{ij1l} \le UB_{j1l} \quad i = 1, \dots, 4;$$

$$y_{ij1l} \ge LB_{j1l} \ or \ y_{ij1l} = 0 \quad i = 1, \dots, 4;$$

$$y_{ij2l} \le UB_{j2l} \quad i = 1, \dots, 4;$$

$$y_{ij2l} \ge LB_{j2l} \ or \ y_{ij2l} = 0 \quad i = 1, \dots, 4;$$

$$\sum_{l=2}^{3} y_{ijkl} = x_{ijk} \quad i = 1, \dots, 4; \quad j = 1, 2, \quad k = 1, 2;$$

$$\sum_{k=1}^{2} y_{ijk3} + z_{ij} \le D_{i+1,j,3} + v_{ij3} \quad i = 1, \dots, 3; \quad j = 1, 2;$$

$$z_{1j} \le \max(0, q_{0j2}) \quad j = 1, 2;$$

$$z_{ij} \le q_{i-1,j,2} + y_{i-1,j,1,2} + y_{i-1,j,2,2} \quad i = 2, 3, 4; \quad j = 1, 2;$$

Storage constraints:

$$q_{1j2} = \max(0, q_{0j2} - D_{1j2} - z_{1j}) \quad j = 1, 2;$$

$$q_{ij2} = \max(0, q_{i-1,j,2} + y_{i-1,j,1,2} + y_{i-1,j,2,2} - D_{ij2} - z_{ij} - v_{i-1,j,2}) \quad j=1, 2 \quad i=2, 3, 4;$$

Regarding number of jobs tardy and number of jobs not delivered constraints:

$$v_{1j2} = \max(0, D_{1j2} - q_{0j2}) \quad j = 1, 2;$$

$$v_{ij2} = \max(0, D_{ij2} + v_{i-1,j,2} + z_{ij} - q_{ij2} - y_{i-1,j,1,2} - y_{i-1,j,2,2}) \quad j = 1, 2; \quad i = 2, 3, 4;$$

$$v_{1j3} = \max(0, D_{1j3}) \quad j = 1, 2;$$

$$v_{ij3} = \max(0, D_{ij3} + v_{i-1,j,3} - z_{i-1,j} - y_{i-1,j,1,3} - y_{i-1,j,2,3}) \quad j = 1, 2; \quad i = 2, 3, 4.$$

In M.Sc study one supply chain system is modeled by LP (linear program) and is solved with using branch-and-bound techniques.

Because of the possibility of multiple feasible regions and multiple locally optimal points within such regions, there is no way to determine with certainty that the problem is infeasible, the objective is unbounded, or that an optimal solution is the global optimum across all feasible regions. Some nonlinear programming algorithms such as sequential quadratic programming (SQP), the method of moving asymptotes (MMP) and the generalized reduced gradient method (GRG) have been used in structural design problems. (Ramesh, 2004)

Ramesh, M. (2004) mentioned about applying NLP (Non-linear programming) approaches to supply chain problems being extremely challenging because:

- The NLP approach involves significant complexity with unwieldy models and extensive computational complexity. The development and maintenance of the models is also cumbersome.

- The NLP approaches may converge to a local optimal solution and may not necessarily converge to a global optimal solution. This is a property of all mathematical algorithms and happens because nonlinear optimization models may have several solutions that are locally optimal and it is hard to guarantee, when searching in the dark, that the current solution found is globally optimal.

For scheduling different solution techniques can be classified in two main groups: optimum solution methodologies and approximate solution searching methodologies. In M.Sc study the focused point in the solution is to reach optimum value for obtaining priorities and preferences in spite of it requires enormous computation time to reach.

There are various classes of methods that are useful for obtaining optimal solutions. One class of methods is referred to as Dynamic Programming. It is basically a complete enumeration scheme that attempts, via a divide and conquers approach, to minimize the amount of computation to be done (Pinedo, 1995). The approach solves a series of subproblems until it finds a solution for the original problem.

If a planning and scheduling problem can be formulated as an Integer Program, then various other techniques can be applied to this problem. The best known methods for solving integer programs are:

- branch-and-bound methods,
- cutting plane methods,
- hybrid methods.

The first class of methods, branch-and-bound is one of the most popular classes of techniques used for Integer Programming. The branching refers to a partitioning of the solution space; each part of the solution space is then considered separately. The bounding refers to the development of lower bounds for parts of the solution space (assuming the objective has to be minimized). If a lower bound on the objective in one part of the solution space is larger than an integer solution already found in a different part of the solution space, the corresponding part of the former solution space can be disregarded. Thus in branch and bound system a tree is constructed. From every node that corresponds to a noninteger solution a branching occurs to two other nodes, and so on. The bounding process is straight forward. If a solution at a node is noninteger, then this value provides a lower bound for all the solutions. The branch-and-bound procedure stops when all nodes of the tree either have an integer solution or a noninteger solution that is higher than an integer solution at another node. The node with the best integer solution provides an optimal solution for the original integer program. (Pinedo, 2005)

The second class of methods, cutting plane methods, focuses on the linear program relaxation of the integer program.

Hybrid methods typically combine ideas from various different approaches. For example, the cutting plane method has become popular through its use in combination with branch-and-bound. When brand-and-bound is used in conjunction with cutting plane techniques it is referred to as branch-and-cut.

In M.Sc study, a branch-and-bound solution method was employed in the real-world scheduling problem being formed in Lingo 9.0. In the following simulation modeling is described briefly as the solution methodology to M.Sc study.

2.4.2 Simulation Modeling

Simulation is one of the most powerful analysis tool available for the design and operation of complex processes or systems. (Kozan, 2003)

Pegden, C. D. & others (1990) define simulation as the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behavior of the system and/or evaluating various strategies for the operation of the system.

Simulation modeling can be thought of as an experimental and applied methodology that seeks to accomplish the following:

- describe the behavior of systems,
- construct theories or hypotheses that account for the observed behavior,
- use the model to predict future behavior, the effects produced by changes in the system or in its method of operation.

2.4.2.1 Simulation Modeling in Supply Chain Network

The need to simulate and redesign supply chain processes to allow decision makers to explore various options and scenarios that are customer and value driven has been recognized. Simulation has been identified as one of the best methods to analyze supply chains. (Sunil & Peter, 2001)

One of the major issues in the creation of supply chain simulation is the level of detail at which each of the links in the chain should be modeled (Jain & others, 1999). In any simulation study, the level of detail model depends on the purpose of the effort. (Erkollar, 2001)

Supply chain modeling can be performed using different algorithms. But if simulation is used for supply chain modeling, evaluation of operating performance is done prior to the implementation of a system: (Yoon & Harris, 2008)

- It enables companies to perform powerful what-if analyses leading them to better planning decisions;
- it permits the comparison of various operational alternatives without interrupting the real system;
- it permits time compression so that timely policy decisions can be made.

According to Yoon, C. & Harris, M., 2008 simulation tools aid human planner to make a right decision by providing information. However, human planner should be able to interpret and modify the plan in order to achieve better supply chain performances.

Benefits of supply chain simulation are as follows: (Yoon & Harris, 2008)

- It helps to understand the overall supply chain processes and characteristics by graphics/animation.
- Able to capture system dynamics: using probability distribution, user can model unexpected events in certain areas and understand the impact of these events on the supply chain.
- It could dramatically minimize the risk of changes in planning process: By what-if simulation, user can test various alternatives before changing plan.

2.4.2.2 Simulation Modeling in Scheduling

To generate production schedules on an operational basis, simulation is a Finite Capacity Scheduler (FCS). Simulation competes with other FCS methods, such as optimization algorithms and job-at-a-time sequencers. However, simulation-based FCS has a number of important advantages that make it a powerful solution for scheduling applications. (Pegden, 2000)

The simulation constructs a schedule by simulating the flow of work through the facility and by making “quick” decisions based on the scheduling rules specified.

In simulation-based scheduling, there are two types of decision rules that can be applied as each job step is scheduled: an operation selection rule and a resource selection rule. If a resource becomes available and there are several operations waiting to be processed by the resource, the operation selection rule is used to select the operation that is processed next. If an operation becomes available and it can be processed on more than one resource, the resource selection rule is used to decide which resource is used to process the operation. Some of these rules are focused on objectives such as maximizing throughput, maintaining high utilization on a bottleneck, minimizing changeovers, or meeting specified due dates. (Pinedo, 2000)

Simulation competes against a number of different approaches for attacking the finite-capacity scheduling problem. It has a number of benefits that make it a compelling solution in these applications. (Pegden, 2000)

These benefits include the following:

1. Extremely fast execution. A simulation model can typically generate a new schedule in a few seconds or minutes. This is critical in responding to unplanned events such as material shortages or machine breakdowns.
2. Flexible decision logic. Simulation can incorporate a wide range of decision rules to focus on any type of objective or represent any type of complex decision-making.
3. Simple implementation. Simulation-based finite capacity scheduling is relatively simple to implement. This lowers the cost and reduces the implementation time.
4. High quality schedules. Compared to alternate methods that load an entire job at a time, simulation can generate very high quality schedules that often do a better job of maximizing resource utilization.

In addition to these benefits, simulation may have some special consideration in scheduling. Although in theory any general-purpose simulation language can be used as the basis for a finite capacity scheduler, there are a number of unique characteristics of this application domain that demand a number of special modeling features that may or may not be included in a simulation tool (Miller & Pegden, 2000). These include the following: (Pinedo, 2000)

1. Interactive Gantt chart display.
2. Specialized reports.
3. Integration with external data sources.
4. Specialized scheduling rules.

The applications of simulation modeling in many different service and production areas are wide and varied. Simulation can be used in manufacturing to: (Ceryan, 2008)

- Model "as-is" and "to-be" manufacturing and support operations from the supply chain level down to the shop floor.
- Evaluate the manufacturability of new product designs.
- Support the development and validation of process data for new products.
- Assist in the engineering of new production systems and processes.
- Evaluate their impact on overall business performance.
- Evaluate resource allocation and scheduling alternatives.
- Analyze layouts and flow of materials within production areas, lines and workstations.
- Perform capacity planning analyses.
- Determine production and material handling resource requirements.
- Develop metrics to allow the comparison of predicted performance against "best in class" benchmarks to support continuous improvement of manufacturing operations.

2.4.2.3 Simulation Modeling Framework

The purpose of simulation modeling is to support the decision maker so as to solve a problem. To merge good problem-solving techniques with good software-engineering practice is essential to be a good simulation modeler. Simulation study steps can be listed as follows to have a good simulation models: (Pegden & others, 1990)

1. Problem Definition: Clearly defining the goals of the study and purposes.
2. Project Planning: Being sure that to have sufficient personnel, management support, computer hardware, and software resources to do the jobs.
3. System Definition: Determining the boundaries and restrictions to be used in defining the system and investigating how the system works.
4. Conceptual Model Formulation: Developing a preliminary model either graphically (block diagrams, etc) or in pseudo-code to define the component, descriptive variables, and interactions that constitute the system.
5. Preliminary Experimental Design: Selecting the measures of effectiveness to be used, the factors to be varied, and the levels of those factors to be investigated, for example what data need to be gathered from the model, in what form, and to what extent.
6. Input Data Preparation: Identifying and collecting the input data needed by the model.
7. Model Translation: Formulating the modeling an appropriate simulation language.
8. Verification and Validation: Confirming that the model operates the way the analyst intended and that the output of the model is believable and representative of the output of the real system.
9. Final Experimental Design: Designing an experiment that will yield the desired information and determining how each of the test runs specified in the experimental design is to be executed.
10. Experimentation: Executing the simulation to generate the desired data and to perform a sensitivity analysis.

11. Analysis and Interpretation: Drawing inferences from the data generated by the simulation.
12. Implementation and Documentation: Putting the results to use, recording the findings, and documenting the model and its use.

In the following brief summaries of simulation modeling stages are given.

Simulation studies are initiated because a problem is faced by a decision maker or group of decision makers and a solution is needed. To make simulation diagnosis, we must thoroughly familiar with all relevant aspects of the organization's operations. Minimally the following steps had to be performed according to Pinedo, M. (1995):

1. Identify the primary decision makers and the decision-making process relative to the system being studied.
2. Determine the relevant objectives of each of those responsible for some aspect of the decision.
3. Identify the other participants in the final decision and determine their objectives.
4. Determine which aspects of the situation are subject to the control of the decision makers and the range of control that can be exercised.
5. Identify those aspects of the environment or problem context that can affect the outcome of possible solutions but that are beyond the control of the decision makers.

The entire process of designing the model, validating it, and designing experiments from the resulting experimentation must be closely tied to the specific purpose of the model. No one should build a model without having an explicit goal. So simulation experiments are conducted for a wide variety of purposes, including the following:

- Evaluation
- Comparison
- Prediction
- Sensitivity analysis

- Optimization
- Functional relations
- Bottleneck analysis

In M.Sc study the purpose of using simulation is estimating the performance of the system under some projected set of conditions. Namely we use simulation for prediction of system reply under some inputs.

The main points of the modeling are abstraction and simplification. To design a model of the real system that neither oversimplifies the system to the point where the model becomes trivial nor carries so much detail that it becomes clumsy and prohibitively expensive is wanted. The most significant danger lies in the model's becoming too detailed and including elements that contribute little or nothing to understand the problem. Frequently, the analyst includes too much detail, rather than too little. (Pinedo, 1995)

The manufacturing system in M.Sc study is a little complicated for having parallel machines. To cope with that difficulty we develop a mathematical model which gives us jobs sequence. For simplifying the model the breakdowns' times of researches are assumed in processing times.

Simulation is defined as being experimentation via a model to gain information about a real-world process or system. The design of experiments is evaluated in two different stages of a simulation study. It first comes into play very early, before the model design has been finalized. As early as possible, we want to select which measures of effectiveness we will use, which factors we will vary, and how many levels of each of those factors we will investigate. Thus, experimental designs are economical because they reduce the number of experimental trials required and provide a structure for the investigator's learning process. (Pinedo, 1995)

In M.Sc study ten replications are made for having more information about the system behavior and outputs are written down for commenting on them. We use simulation to learn the most about the behavior of the system for the lowest possible cost.

So as to collect data, there are two approaches in practical life. The first is the classical approach, where a designed experiment is conducted to collect the data. The second is the exploratory approach, where questions are addressed by means of existing data that the modeler had no hand in collecting. The first approach is generally better in terms of control and the second approach is generally better in terms of cost. (Pinedo, 1995)

Even if the decision to sample the appropriate element is made correctly, Lawrence, M. L. (2004) warns that there are several things that can be "wrong" with a data set: Vending machine sales will be used to illustrate the difficulties.

- Wrong amount of aggregation. We desire to model daily sales, but have only monthly sales.
- Wrong distribution in time. We have sales for this month and want to model next month's sales.
- Wrong distribution in space. We want to model sales at a vending machine in location A, but only have sales figures on a vending machine at location B.
- Censored data. We want to model demand, but we only have sales data.
- Insufficient distribution resolution. We want the distribution of number the of soda cans sold at a particular vending machine, but our data is given in cases, effectively rounding the data up to the next multiple of 24.

In M.Sc study data collection and input data are obtained with exploratory approach. Mainly, by planning department historical data collection is made for analyses. For determining processing and arrival times' distribution input analyzer is used by using historical data.

In literature, the language developers focused their attention on three objectives:

1. reduced model development time,

2. improved accuracy, and
3. improved communication.

One must be aware that the capability of any package is directly dependent upon the capability of the underlying language. Arena simulator, one of today's most advanced and widely used simulation languages is used in M.Sc study.

Simulation models are increasingly being used in problem solving and to aid in decision-making. The developers and users of these models, the decision makers using information obtained from the results of these models, and the individuals affected by decisions based on such models are all rightly concerned with whether a model and its results are "correct". This concern is addressed through model verification and validation. (Sargent, 2005)

Model verification; is often defined as "ensuring that the computer program of the computerized model and its implementation are correct" and is the definition adopted here. (Sargent, 2005)

Model validation; is usually defined to mean "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model". (Sargent, 2005)

Sargent, R. G. (2005) describes three basic approaches for deciding whether a simulation model is valid:

- Model development team itself makes the decision as to whether a simulation model is valid. It is the frequently used one.
- Independent verification and validation (IV&V), uses a third (independent) party to decide whether the simulation model is valid.
- Scoring model.

A combination of techniques is generally used in many models for verification and validation. These techniques which are explained in the paper of Sargent, R. G.

(2005) are used for validating and verifying the all model:

- **Animation;** The model's operational behavior is displayed graphically as the model moves through time. For example the movements of parts through a factory during a simulation run are shown graphically.
- **Comparison to Other Models;** Various results (outputs) of the simulation model being validated are compared to results of other valid models. For example, (1) simple cases of a simulation model are compared to known results of analytic models, and (2) the simulation model is compared to other simulation models that have been validated.
- **Degenerate Tests;** The degeneracy of the model's behavior is tested by appropriate selection of values of the input and internal parameters.
- **Event Validity;** The "events" of occurrences of the simulation model are compared to those of the real system to determine if they are similar. For example, compare the number of fires in a fire department simulation.
- **Extreme Condition Tests;** The model structure and outputs should be plausible for any extreme and unlikely combination of levels of factors in the system. For example, if in-process inventories are zero, production output should usually be zero.
- **Face Validity;** Asking individuals knowledgeable about the system whether the model and/or its behavior are reasonable.
- **Historical Data Validation;** If historical data exist part of the data is used to build the model and the remaining data are used to determine (test) whether the model behaves as the system does. (This testing is conducted by driving the simulation model with either samples from distributions or traces)
- **Historical Methods;** The three historical methods of validation are *rationalism*, *empiricism*, and *positive economics*.

  - Rationalism assumes that everyone knows whether the underlying assumptions of a model are true.

  - Empiricism requires every assumption and outcome to be empirically validated.

  - Positive economics requires only that the model be able to predict the future and is not concerned with a model's assumptions or structure.

- **Internal Validity;** A large amount of variability (lack of consistency) may cause the model's results to be questionable and if typical of the problem entity, may question the appropriateness of the policy or system being investigated.
- **Operational Graphics;** Values of various performance measures, e.g., the number in queue and percentage of servers busy, are shown graphically as the model runs through time; i.e., the dynamical behaviors of performance indicators are visually displayed as the simulation model runs through time to ensure they are correct.
- **Multistage Validation;** Combining the three historical methods of rationalism, empiricism, and positive economics into a multistage process of validation is proposed. This validation method consists of (1) developing the model's assumptions on theory, observations, and general knowledge, (2) validating the model's assumptions where possible by empirically testing them, and (3) comparing (testing) the input-output relationships of the model to the real system.
- **Parameter Variability-Sensitivity Analysis;** This technique consists of changing the values of the input and internal parameters of a model to determine the effect upon the model's behavior or output.
- **Predictive Validation;** The model is used to forecast the system's behavior, and then comparisons are made between the system's behavior and the model's forecast to determine if they are the same. The system data may come from an operational system or be obtained by conducting experiments on the system, e.g., field tests.
- **Traces;** Behaviors of different types of specific entities in the model are followed through the model to determine if the model's logic is correct and if the necessary accuracy is obtained.
- **Turing Tests;** Individuals who are knowledgeable about the operations of the system being modeled are asked if they can discriminate between system and model outputs.

After verifying and validating the model, we have to deal with issues such as how long to run the model (or sample sizes), what to do about starting conditions, whether the output data are correlated, and what statistical tests are valid on the data (Shannon, 1998).

Because the output of a simulation model is a sample of system behavioral data, all concerns regarding statistical inference from samples apply. We are most concerned that the data be representative of typical system behavior that the sample size be large enough to provide some stated level of confidence in the performance measure estimates, and that none of the assumptions underlying the statistical calculations be violated. (Pinedo, 1995)

Documentation and reporting are linked to implementation. Careful documentation can help us to learn from previous mistakes; it may even provide a source of submodels that can be used again in future projects (Arena contact center user's guide, August 10, 2009).

2.4.3 Hybrid Simulation & Analytic Models & Modeling

Shanthikumar, J. G. & Sargent, R. G. (1983) describe the hybrid simulation & analytic model as a mathematical model which combines identifiable simulation and analytic models.

Two types of mathematical models are important here: analytic and simulation. An analytic model is a set of equations that characterize a system or a problem entity. Its solution procedure usually uses either an analytical equation or a numerical algorithm that has been developed for the set of model equations to obtain the desired results. A simulation model is a dynamic or an operating model of a system or problem entity and that "mimics" the operating behavior of the system or problem entity and contains its functional relationships. The simulation model is often called the conceptual model and is frequently a flowchart model. Its solution procedure consists of running a computerized model of the conceptual model, usually called the simulator, collecting data on its behavior, and analyzing the data to obtain the desired results. (Shanthikumar & Sargent, 1983)

Analytic versus simulation models have comparative advantages and disadvantages being known. While simulation models allow any degree of realism of the system desired, analytic models fail in modeling the dynamic and stocahastic characteristics of systems. Unfortunately, in the cost of using these models the opposite is often true.

Basically, there are two costs beyond the cost of developing the models themselves: the cost of developing the solution procedure and the cost of using the solution procedure. The cost of developing or obtaining a solution procedure for an analytic model can be from low to high while the cost of developing the solution procedure for a simulation model is usually medium to high. The cost of using the solution procedure of an analytic model is usually low if the solution procedure uses an analytical equation and varies between low and high if the solution procedure uses a numerical algorithm. The cost of using the solution procedure of a simulation model is usually medium to high. We include in the cost of using the solution procedure of a simulation model the cost of running the simulator to obtain the desired accuracies, the desired confidence interval lengths of performance measures of interest. The use of analytic models for problem solving is usually preferred if sufficient model realism and solutions for the desired performance measures can be obtained at reasonable costs. (Shanthikumar & Sargent, 1983)

According to Shanthikumar, J. G. & Sargent, R. G. (1983) the purpose of using a hybrid simulation & analytic model in problem solving would usually be:

(1) to reduce the cost of developing a model solution procedure, or
(2) to reduce the amount of computational effort required to obtain acceptable answers instead of using (a) a (pure) simulation model, or (b) the numerical solution procedure of an analytic model when its computational effort is excessive.

Shanthikumar, J. G. & Sargent, R. G. (1983) classify hybrid models by identifying the model that is most important in a pair of simulation and optimization models. They present four classes of hybrid simulation & analytic models and they emphasize that the boundaries dividing these classes are very thin:

1. Hybrid models whose behavior over time is obtained by alternating between using independent simulation and analytic models.
2. Hybrid models in which a simulation model and an analytical model operate in parallel over time, with interactions through their solution procedure.
3. Hybrid models in which a simulation model is used in a subordinate way for an analytic model of the total system.
4. Hybrid models in which a simulation model is used as an overall model of the total system and requires values from the solution procedure of an analytical model representing a proportion of the system for some or all of its input parameters.

If solution procedure of independently developed analytic and simulation models of the total system are used together in problem solving, we call this hybrid simulation/analytic modeling (Sargent, 1994). It is the main point to know that the difference between hybrid simulation/analytic models and hybrid modeling is that hybrid modeling occurs through using the solution procedures together, either sequentially or iteratively.

Mathematical programming, simulation, and hybrid modeling are also the main modeling approaches used for supply chain configuration. A comprehensive evaluation of supply chain configuration decisions requires utilization of multiple models. There are two alternatives in employing these models: 1) independent models exchanging input-output data, and 2) fully integrated models where selected functions of one model are implemented by another. Application of independent models and interpretation of their often seemingly contradicting results cause difficulties for decision modelers. Therefore, the area of hybrid modeling that can be perceived as the development of a model consisting of two or more highly integrated models is appealing. Such hybrid models exploit the strengths of multiple models to provide a single answer to decision modelers. (Charu & Janis, 2007)

According to Charu, C. & Janis, G. (2007) hybrid mathematical programming simulation models are aimed at combining the strengths of mathematical programming and simulation models and reducing the impact of limitations characteristic of these models. Mathematical programming models are generally well suited to dealing with spatial issues, while simulation models are more appropriate for dealing with temporal issues. Although the cost of model development and usage can be substantial for mathematical programming models, it is generally lower than for similar simulation models.

If viewed from the supply chain configuration perspective, differences between mathematical programming and simulation are particularly noticeable. Mathematical programming models can be perceived as providing the base decision-making functionality. Their main advantage is an ability to quickly evaluate a large number of alternative configurations. Simulation models, on the other hand, provide the functionality needed to cover the entire scope of the supply chain configuration, especially dynamic and stochastic factors. Given that these factors are very important for reconfigurable supply chains, hybrid models are particularly appropriate for decision making in this case. Simulation alone can be rarely applied for establishing supply chain configuration because evaluation of a large number of alternative configurations is not computationally feasible. (Charu & Janis, 2007)

In M.Sc study, a hybrid approach which combines analytical and simulation modeling is employed to deal with a real-world supply chain planning and scheduling problem. The following section presents the review of relevant literature.

CHAPTER THREE
LITERATURE REVIEW & RESEARCH MOTIVATION

This chapter presents a review of recent literature employing hybrid approach to solve production planning and scheduling problem. Next, a review of current literature particularly related to order promising and due date quoting in supply chain network is provided.

3.1 Production Planning and Scheduling Using Hybrid Approach

Byrne, M. D. & Bakir, M. A. (1999) suggest a hybrid method for solving multi-period multi-product production-planning problem. They aim at meeting the market demand while keeping the inventories as low as possible. A simulation model which takes into consideration the stochasticity in the operation times and/or transportation times supports the analytic model of the manufacturing system. The limitations of this study are that the setup times are sequence independent and deterministically known. Moreover, in estimating resource capacity, it estimated that the resources will be always available.

Kim, B. & Kim, S. (2001) extend the idea of Byrne, M. D. & Bakir, M. A. (1999) to find the capacity-feasible production plan using the analytic and simulation models together. At each simulation run, the status of the jobs and the utilization of the resources are captured and this information is then sent to the linear programming model to determine the production plan which minizes the total cost. As a result of experimenting through a case study, Kim, B. & Kim, S. (2001) state that compared to the approach proposed by Byrne, M. D. & Bakir, M. A. (1999) their approach finds a better solution in a less number of iterations.

Byrne, M.D. & Hossain, M. M. (2005) suggest a hybrid approach combining mathematical programming and simulation modeling to carry out production planning and scheduling. Moreover, the authors introduce the concept of unit load in Just-in-time manufacturing environment to reduce the level of WIP and total flow time.

Lot sizing and scheduling problem (LSSP) becomes a significant problem especially in multi-site manufacturing system under the effect of multi-product and multi-period demand. Gnoni, M. G. & others (2002) solve this problem by employing a hybrid approach. In another study, Gnoni, M. G. & others (2003) compare the performance of two different lot sizing and scheduling approaches in multi-site manufacturing system under the effect of multi-product and multi-period demand.

Venkateswaran, J. & Jones, A. (2004) propose simulation-based production planning architecture which involves system dynamics (SD) components at the higher decision level and discrete event simulation (DES) components at the lower decision level. The proposed architecture has four modules: Enterprise-level decision maker, SD model of enterprise, Shop-level decision maker and DES model of shop. The decision makers select the optimal set of control parameters based on the estimated behavior of the system. These control parameters are used by the SD and DES models to determine best plan based on the actual behavior of the system Following section gives a review of relevant literature on order promising and due date setting.

3.2 Order Promising and Due Date Setting in Supply Chain Network

Much literature exists for production planning and scheduling, but there is little work on setting due dates that serve as the inputs to developing a production schedule. This is called Order Promising.

In order to enhance the accuracy of order promising and the reliability of order fulfillment there is plenty of researches focusing on the issue of Available-To-Promise (ATP). Chen, C. Y. & others (2001) describe ATP as a decision-making mechanism. The methods to set ATP times in an order promising system can be classified into two main groups: order due date quoting algorithms and order quantity quoting algorithms. Ozdamar, L. & Yazgaç, T. (1997) propose a capacity driven planning system to set order due dates for a make-to-order (MTO) production systems using the first method. The authors also employ order quantity quoting algorithms which allows customized configuration and takes into account of a variety of realistic supply chain constraints, such as material compatibility, substitution preferences capacity utilization, and material reserve. Using these two methods, they determine which orders to accept and, for each accepted order, they specify a delivery time and a delivery quantity. Moreover, the authors carry out simulation experiments to investigate the sensitivity of supply chain performance to changes in certain parameters, such as batching interval size for collecting orders and customer order flexibility for product configuration.

In case that the customer demands are more than available capacity of manufacturing resources, manufacturers need to make a preference to allocate manufacture resources to products of higher profits or more important customers. Lin, J. T. & Chen, J. H. (2005) propose one order promising mechanism that considers material and capacity constraints after order penetration point.

Grant, H., Moses, S., & Goldsman, D. (2002) evaluate the performance of alternative methods for promising the delivery of orders using simulation. The authors bring new vision to traditional due-date estimation by modifying scheduled due dates by a buffer amount.

Torres & Nakatani (1998) give attention to logistic-manufacturing networks. Information systems have also gained great importance, and are now an integral part of many logistic systems. Ruiz, A. J. & Nakatani, K. (1998) integrate information technology (IT) and simulation for decision making that is often called real-time simulation to set order due dates in logistic-manufacturing networks. They emphasize that the implementation of the simulation-based due date assignment methodology in logistic-manufacturing networks result in two major benefits. First, the delivery performance improves dramatically as due dates are based on a completion forecast that derives from real-time information about resources, queues, schedules, and the system variability. Second, in cases where delivery performance is not a problem, the simulation-based approach provides due date options (priority orders at a premium price, etc).

More recent industry practices, which utilize advances in computing technology, involve negotiation of due dates with the customer using online factory information and software that enables finite-scheduling with what-if analyses capability. Although a very powerful tool, such technology driven scheduling and due date setting is not wide-spread due to two reasons: (1) the cost of purchasing the software; and (2) the cost of implementation, which can prove to be even costlier that the software itself (Veral, 2001). Unlike the study of Ruiz, A. J. & Nakatani, K. (1998) in which a slack value is put for setting dynamic due dates, the study of Veral, E. A. (2001) does not use any slack value to set due dates.

Hegedus, M. G. & Hopp, W. J. (2001) propose a new model incorporating simultaneously inventory costs, fill rate issues, and service level issues for quoting due dates in a make-to-order environment where customers request due dates using MRP. While most due date setting literature focuses on the manufacturing process, this is the only formulation to our knowledge that explicitly models an uncertain supplier lead-time process. In addition, the supply process model is unique in that it incorporates transient supply information using data available in MRP.

Under prompt responses to customers' demands and high profitability objectives, production scheduling is considered to be one of the most important strategic technologies. Especially in make-to-order production, the most important requirements for production scheduling are to fulfill the due-date for each job. Arakawa, M., Fuyuki, M., & Inoue, I. (2002) propose a simulation-based scheduling method for minimizing the due date deviation.

During the survey of current literature, we have note a few studies dealing with order promising in supply chain network. Venkatadri, U. & others (2005) develop an order promising model constructed with LP for supply chain management. The authors particularly search an answer to the question of how a supplier firm should take part in the process of negotiating with the customer to quote due dates and prices, and etc.

3.3 Motivation for This Thesis Study

Based on the review of current relevant literature, we can state that the most commonly used methodologies to solve integrated production-distribution and order promising problem are analytic and simulation models. But there are a few studies combinig these two approaches. An analytic model is a set of equations that describe a system and its solution procedure can use either an analytic equation or a numerical algorithm that has been developed to obtain the desired results. A simulation model is a dynamic model of a system that reflects the operating behavior of the system. Frequently analytic models ignore realism while simulation models allow whatever degree is desired of realism from the system. The strengths and limitations of these two approaches when they are used alone are summarized in Table 3.1.

Table 3.1 Summary of strengths and limitations of analytic and simulation models (Charu & Janis, 2007)

	Analytic models	**Simulation**
Strengths	- Evaluation of large number of alternative configurations - Exact results - Capabilities for efficient analysis	- Realistic representation of the problem - Accounting for dynamic and stochastic factors - Availability of different performance measures
Limitations	- Quickly increasing model complexity if dynamic, stochastic and nonlinear factors are added	- Expensive development and usage - Interpretation of results

We think that taking into consideration the dynamic nature of a manufacturing system is very important in setting order promising times. During the survey of current literature, we have noted a few study employing simulation for due date setting. It has been observed that in most of the studies, the due dates were set with highly simplified parametric approaches such as CON (using a constant allowance), TWK (using proportional to work content), SLK (using a constant slack), NOPS (using number of operations in a job) (Shams, 2007). However, the accuracy of order due date estimation greatly depends on considering the current system congestion. Having observed great potential of hybrid approaches in generating efficient production schedules, in this M.Sc study we decided to combine mathematical modeling with simulation to estimate order promising times for a manufacturing company operating in supply chain environment.

It should be noted that using analytic and simulation models together for setting order promising plans in SC can provide the following advantages:

- In real systems, due to the various kinds of uncertain factors such as unexpected delays, queuing, breakdowns, and operation time, analytic models cannot reflect the dynamic behavior of real consumed operation time. Namely analytic models give importance to obtain optimality between all constraints, but not give importance to dynamic nature of manufacturing environment.
- Simulation does give proper values for estimating any performance measures by means of including unexpected delays, queuing, breakdowns, etc. but not consider optimality between constraints.
- Analytic models ignore realism while simulation models allow any degree of realism of the system. Therefore, the combination of two models may give better solutions by means of being realistically more feasible than those analytic models (Lee & Kim, 2002).

The details of the proposed hybrid approach are presented in the following section.

CHAPTER FOUR
A HYBRID APPROACH TO SETTING ORDER PROMISING TIMES IN A SUPPLY CHAIN NETWORK

This M.Sc study suggests a hybrid approach for setting order promising times for a produce-to-order manufacturing company operating within a supply chain environment.

This hybrid approach consists of the following steps:

Step 1. The analytic model representing the SC network is solved to generate production-distribution plans.

Step 2. These production plans are incorporated as constraints to another analytic model developed for scheduling and the model is solved to generate scheduling decisions for each workcenter for each period.

Step 3. These scheduling decisions are loaded to the manufacturing simulation model as input and Order Promising Times (OPTs) are estimated.

Once the OPTs are estimated realistically by taking into consideration the dynamic and stochastic nature of the manufacturing floor, these dates are negotiated with the customers.

As shown in Figure 4.1, the supply chain system studied in this thesis consists of six main members; supplier, subcontractors, factory, stack buffer, warehouses, and customers. All raw materials are transformed to parts by subcontractors. Following, these parts are transformed to products in the factory and before the products are distributed to the customers they are stored in warehouses or in stack buffer.

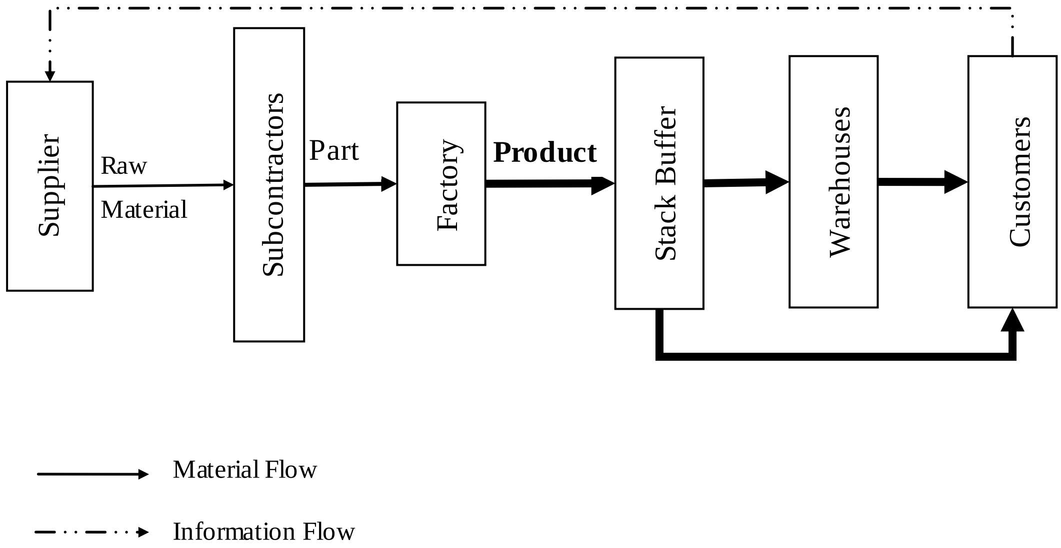

Figure 4.1 Six main members of the supply chain network

The flow of data during the implementation of this three-step hybrid approach is presented in Figure 4.2.

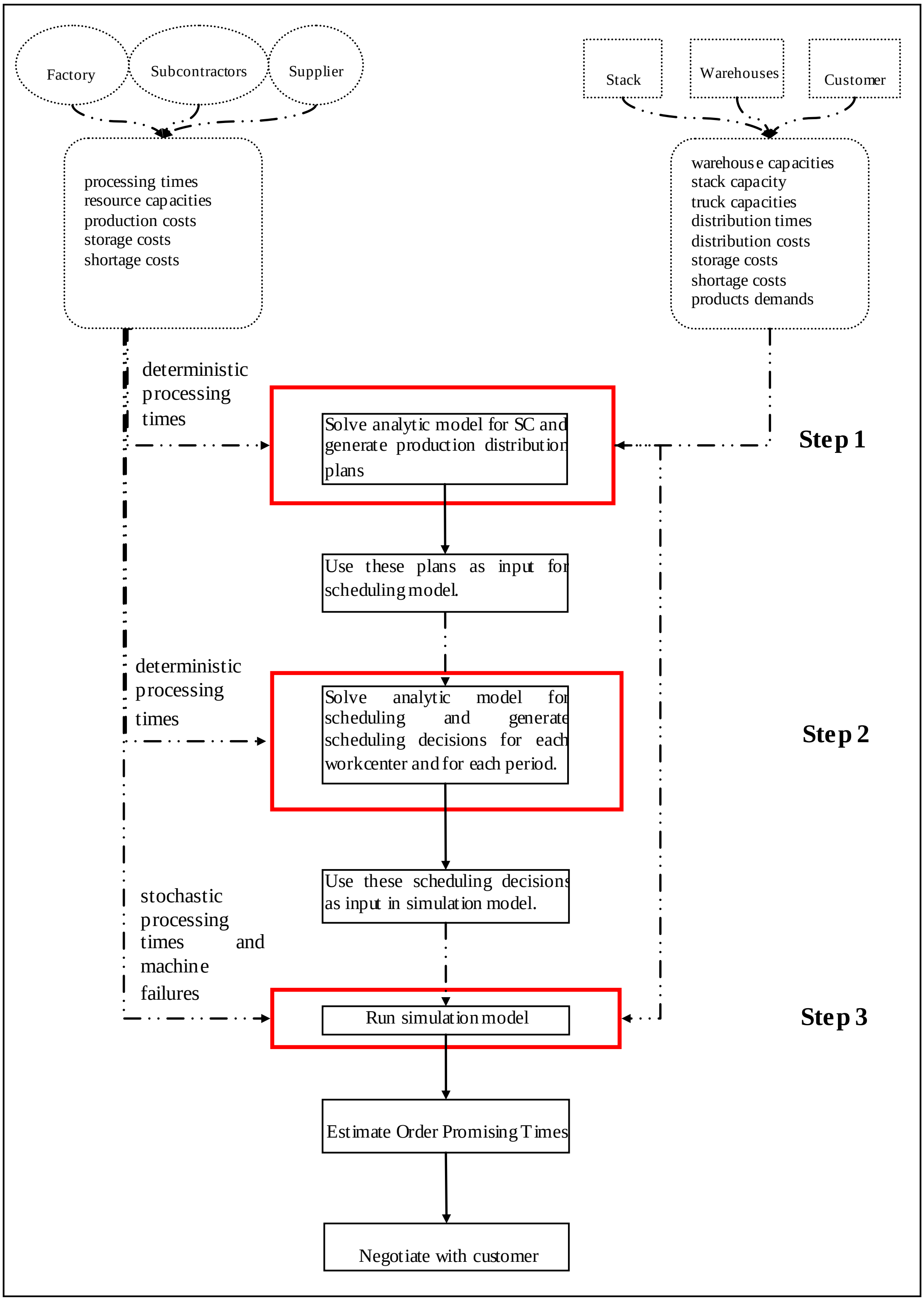

Figure 4.2 Flow diagram of the proposed hybrid approach

The details of this three-step approach combining mathematical and simulation modeling are given in the following sections.

4.1 Step 1: Developing an Analytical Model for Production and Distribution Planning

In this step, an analytic model minimizing the overall costs of production and distribution (transportation, inventory holding, storage, and shortage costs) subject to the various kinds of constraints is developed to generate optimum production and distribution plans. It should be noted that production planning starts with a schedule for final products that is converted into a schedule of requirements for parts and raw materials.

This mathematical model is a cost minimization formulation of an integrated production-distribution system in supply chain and provides optimal production-distribution plans for each period that minimize the sum of variable production and distribution costs by means of resource capacity and inventory balance constraints.

This mathematical model does not allow backlogging. If the unsatisfied demand appears in the previous period, it is not transferred to the next periods, and a deficit cost occurs. It should be noted that the mathematical model given below does not take into consideration any cost aspects from the point of supplier, rather it only considers the availability of raw materials.

The mathematical model is shown below:

INDEX

t period index ($t = 1,2,\dots,T$)

i part index ($i = 1,2,\dots,I$)

j product index ($j = 1,2,\dots,J$)

u subcontractor index ($u = 1,2,\dots,U$)

p warehouse index ($p = 1,2,\dots,P$)

q customer index ($q = 1,2,\dots,Q$)

k raw material index ($k = 1,2,\dots,K$)

PARAMETERS

D_{jt}	*demand for product j in period t*
D_{jqt}	*demand for product j at customer q in period t*
a_{ij}	*number of units of part i used to make one unit of product j*
d_{ki}	*number of units of raw material k used to make one unit of part i*
bk_{kt}	*available amount of raw material k at supplier in period t*
ci_{it}	*cost to produce a unit of part i in period t*
cj_{jt}	*cost to produce a unit of product j in period t*
ck_{kt}	*cost to purchase a unit of raw material k in period t*
hi_{it}	*cost to hold a unit of part i in period t*
hj_{jt}	*cost to hold a unit of product j in period t*
hk_{kt}	*cost to hold a unit of raw material k in period t*
πi_{it}	*unit cost of sales lost for part i in period t*
πj_{jt}	*unit cost of sales lost for product j in period t*
πk_{kt}	*unit cost of sales lost for raw material k in period t*
ai_{iu}	*processing time to produce a unit of part i at subcontractor u*
aj_j	*processing time to produce a unit of product j*
$optj_t$	*operation time capacity of factory in period t*
$optu_{ut}$	*operation time capacity of subcontractor u in period t*
STL_{jt}	*storage cost of product j at stack point in period t*
STP_{jpt}	*storage cost of product j at warehouse p in period t*
STQ_{jqt}	*storage cost of product j at customer q in period t*
SHL_{jt}	*shortage cost of product j at stack point in period t*
SHP_{jpt}	*shortage cost of product j at warehouse p in period t*
SHQ_{jqt}	*shortage cost of product j at customer q in period t*
TLP_p	*the cost of transporting any product from stack point to warehouse p*
TLQ_q	*the cost of transporting any product from stack point to customer q*

TPQ_{pq} *the cost of transporting any product from warehouse p to customer q*

TI_u *the cost of transporting any part from subcontractor u to factory*

HCL_t *product holding capacity at stack buffer in period t*

HCP_{pt} *product holding capacity at warehouse p in period t*

HCQ_{qt} *product holding capacity at customer q in period t*

HCI_t *part holding capacity at factory in period t*

DOP_t *distribution operation time capacity at stack point, warehouses and subcontractors in period t*

A_{jp} *distribution time to transport product j from stack point to warehouse p*

B_{jq} *distribution time to transport product j from stack point to customer q*

C_{jpq} *distribution time to transport product j from warehouse p to customer q*

D_{iu} *distribution time to transport part i from subcontractor u to factory*

DECISION VARIABLES

X_{iut} *production quantity of part i in subcontractor u in period t*

Y_{jt} *production quantity of product j in factory in period t*

Ii_{it} *amount of inventory of part i in factory in period t*

Ii_{it}^{+} *amount of end of period inventory of part i in factory in period t*

Ii_{it}^{-} *amount of end of period deficit of part i in factory in period t*

Ij_{jt} *amount of inventory of product j in factory in period t*

Ij_{jt}^{+} *amount of end of period inventory of product j in factory in period t*

Ij_{jt}^{-} *amount of end of period deficit of product j in factory in period t*

E_{kt} *number of units of raw material k coming from the supplier in period t*

Ik_{kt} *amount of inventory of raw material k in factory in period t*

Ik_{kt}^{+} *amount of end of period inventory of raw material k in factory in period t*

Ik_{kt}^{-} *amount of end of period deficit of raw material k in factory in period t*

LP_{jpt} *amount of product j transported from stack point to warehouse p in period t*

LQ_{jqt}	*amount of product j transported from stack point to customer q in period t*
PQ_{jqt}	*amount of product j transported from warehouse p to customer q in period t*
L_{jt}	*amount of product j stored at stack point in period t*
L^+_{jt}	*amount of end of period inventory of product j at stack point in period t*
L^-_{jt}	*amount of end of period deficit of product j at stack point in period t*
P_{jpt}	*amount of product j stored at warehouse p in period t*
P^+_{jpt}	*amount of end of period inventory of product j at warehouse p in period t*
P^-_{jpt}	*amount of end of period deficit of product j at warehouse p in period t*
Q_{jqt}	*amount of product j stored at customer q in period t*
Q^+_{jqt}	*amount of end of period inventory of product j at customer q in period t*
Q^-_{jqt}	*amount of end of period deficit of product j at customer q in period t*

$$\begin{aligned}\min z = \sum_{t=1}^{T}\Bigg\{ & \sum_{i=1}^{I}\sum_{u=1}^{U}\left(ci_{it}X_{iut} + hi_{it}I^+_{it} + \pi i_{it}I^-_{it}\right) + \sum_{j=1}^{J}\left(cj_{jt}Y_{jt} + hj_{jt}Ij^+_{jt} + \pi j_{it}Ij^-_{jt}\right) \\ & + \sum_{k=1}^{K}\left(ck_{kt}E_{kt} + hk_{kt}Ik^+_{kt} + \pi k_{kt}Ik^-_{kt}\right) + \sum_{j=1}^{J}\left(STL_{jt}L^+_{jt} + SHL_{jt}L^-_{jt}\right) \\ & + \sum_{j=1}^{J}\sum_{p=1}^{P}\left(STP_{jpt}P^+_{jpt} + SHP_{jpt}P^-_{jpt}\right) \\ & + \sum_{j=1}^{J}\sum_{q=1}^{Q}\left(STQ_{jqt}Q^+_{jqt} + SHQ_{jqt}Q^-_{jqt}\right) + \sum_{j=1}^{J}\sum_{p=1}^{P} TLP_p LP_{jpt} \\ & + \sum_{j=1}^{J}\sum_{q=1}^{Q} TLQ_q LQ_{jqt} + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{q=1}^{Q} TPQ_{pq} PQ_{jpqt} + \sum_{i=1}^{I}\sum_{u=1}^{U} TI_u X_{iut}\Bigg\}\end{aligned}$$

subject to

$$Ij_{jt} = Ij_{j,t-1} + Y_{jt} - D_{jt} \qquad \forall j,t \qquad \text{(A1)}$$

$$Ii_{it} = Ii_{i,t-1} + \textstyle\sum_{u=1}^{U} X_{iut} - \sum_{j=1}^{J} a_{ij}Y_{jt} \qquad \forall i,t \qquad \text{(A2)}$$

$$Ik_{kt} = Ik_{k,t-1} + E_{kt} - \textstyle\sum_{i=1}^{I}\sum_{u=1}^{U} d_{ki}X_{iut} \qquad \forall k,t \qquad \text{(A3)}$$

$$\sum_{i=1}^{I} \sum_{u=1}^{U} d_{ki} X_{iut} \leq bk_{kt} \qquad \forall k,t \qquad \text{(A4)}$$

$$\sum_{i=1}^{I} ai_{iu} X_{iut} \leq optu_{ut} \qquad \forall u,t \qquad \text{(A5)}$$

$$\sum_{j=1}^{J} aj_j Y_{jt} \leq optj_t \qquad \forall t \qquad \text{(A6)}$$

$$Ij_{jt} = Ij_{jt}^{+} - Ij_{jt}^{-} \qquad \forall j,t \qquad \text{(A7)}$$

$$Ii_{it} = Ii_{it}^{+} - Ii_{it}^{-} \qquad \forall i,t \qquad \text{(A8)}$$

$$Ik_{kt} = Ik_{kt}^{+} - Ik_{kt}^{-} \qquad \forall k,t \qquad \text{(A9)}$$

$$L_{jt} = L_{j,t-1} + Y_{jt} - \sum_{p=1}^{P} LP_{jpt} - \sum_{q=1}^{Q} LQ_{jqt} \qquad \forall j,t \qquad \text{(A10)}$$

$$P_{jpt} = P_{jp,t-1} + LP_{jpt} - \sum_{q=1}^{Q} PQ_{jpqt} \qquad \forall j,p,t \qquad \text{(A11)}$$

$$Q_{jqt} = Q_{jq,t-1} + \sum_{p=1}^{P} PQ_{jpqt} + LQ_{jqt} - D_{jqt} \qquad \forall j,q,t \qquad \text{(A12)}$$

$$\sum_{j=1}^{J} Y_{jt} \leq HCL_t \qquad \forall t \qquad \text{(A13)}$$

$$\sum_{j=1}^{J} LQ_{jqt} + \sum_{j=1}^{J} \sum_{p=1}^{P} PQ_{jpqt} \leq HCQ_{qt} \qquad \forall q,t \qquad \text{(A14)}$$

$$\sum_{j=1}^{J} LP_{jpt} \leq HCP_{pt} \qquad \forall p,t \qquad \text{(A15)}$$

$$\sum_{i=1}^{I} \sum_{u=1}^{U} X_{iut} \leq HCI_t \qquad \forall t \qquad \text{(A16)}$$

$$\sum_{j=1}^{J} \sum_{p=1}^{P} A_{jp} LP_{jpt} + \sum_{j=1}^{J} \sum_{q=1}^{Q} B_{jq} LQ_{jqt} + \sum_{i=1}^{I} \sum_{p=1}^{P} \sum_{q=1}^{Q} C_{jpq} PQ_{jpqt} + \sum_{i=1}^{I} \sum_{u=1}^{U} D_{iu} X_{iut} \leq DOP_t \qquad \forall t \qquad \text{(A17)}$$

$$L_{jt} = L_{jt}^{+} - L_{jt}^{-} \qquad \forall j,t \qquad \text{(A18)}$$

$$P_{jpt} = P_{jpt}^{+} - P_{jpt}^{-} \qquad \forall j,p,t \qquad \text{(A19)}$$

$$Q_{jqt} = Q^{+}_{jqt} - Q^{-}_{jqt} \qquad \forall j, q, t \qquad \text{(A20)}$$

I_{it}, I_{jt}, I_{kt}, L_{jt}, P_{jpt}, Q_{jqt} *variables are the unrestricted in sign* (A21)

All other variables ≥ 0 (A22)

The objective function of the model tries to minimize the overall costs made up of production, transportation, storage and shortage costs. Constraints A1, A2 and A3 assure inventory balance for products, parts and raw materials, respectively. Constraints A4 are the raw materials availability equations at supplier. Constraints A5 are the operation time capacity constraints at the subcontractors. Similarly, Constraints A6 are the operation time capacity constraints at the factory. Constraints A7, A8 and A9 state the net inventory for products, parts and raw materials, respectively. That is, the net inventory at the end of the period equals the inventory on hand (if any) minus the inventory deficit. Constraints A10, A11 and A12 assure the inventory balance in stack buffer, warehouses and customers, respectively. For example; the amount of product stored at stack buffer in period t is the sum of the amount of product produced in period t and the amount of product stored in the previous period and subtract the amount of product transported from the stack buffer to warehouses or customers. Constraints A13 to A16 guarantee that the end of period inventory at the factory, stack buffer, subcontractors, warehouses and customers should not exceed the related holding capacity. Constraints A17 are the distribution operation time capacity constraints for the stack buffer, warehouses and subcontractors. Constraints A18, A19 and A20 are the net inventory equations for the stack buffer, warehouses and customers, respectively. Finally, constraints A21 and A22 are the global cardinality constraints.

Next step involves developing an analytic model to generate scheduling decisions for each workcenter at each period. It should be noted that the solution obtained in this step is used as input for the second step.

4.2 Step 2: Developing an Analytical Model for Production Scheduling

In this step, another analytic model which incorporates these production plans as constraints is developed to generate optimal scheduling decisions. These decisions are then sent to the simulation model of the manufacturing floor as input.

This model solves a flow type scheduling problem which involves five workcenters. The parts are processed in batches through these five workcenters. Except for workcenter *i'* which has *l* parallel machines, all other workcenters involve only one machine. The model generates scheduling decisions by minimizing makespan.

The mathematical model minimizing the makespan is shown below:

<u>INDEX</u>

i	*work center index (i = 1, 2,…, M_i)*
i'	*work center index which includes parallel machines*
j	*product index (j = 1,2,…,J)*
b	*batch index (b =1,2,…,B)*
k	*operation index in i'. workcenter (k = 1, 2,…,K)*
l	*parallel machine index in i'. workcenter (l = 1, 2,…,L)*

<u>PARAMETERS</u>

p_{ijb}	*processing time of work center i for batch b of product j*
$p_{i'jbkl}$	*processing time of work center i' for operation k of batch b of product j at machine l*

<u>DECISION VARIABLES</u>

y_{ijb}	*starting time of processing product j at work center i for batch b*
$y_{i'jbkl}$	*starting time of processing product j for operation k at work center i' in machine l for batch b*

$$a_{jbkl} \quad \left\{ \begin{array}{l} 1, operation\ k\ of\ batch\ b\ of\ product\ j\ is\ completed\ at\ workcenter\ i' \\ \quad in\ machine\ l \\ 0, operation\ k\ of\ batch\ b\ of\ product\ j\ is\ completed\ at\ workcenter\ i' \\ \quad in\ other\ parallel\ machine \end{array} \right\}$$

$$g_{ijbj'b'} \quad \left\{ \begin{array}{l} 1, in\ workcenter\ i\ batch\ b\ of\ product\ j\ is\ processed\ before\ batch\ b' \\ \quad of\ part\ j' \\ 0, in\ workcenter\ i\ batch\ b\ of\ product\ j\ is\ processed\ after\ batch\ b' \\ \quad of\ part\ j' \end{array} \right\}$$

$$g_{i'jbkj'b'k'l} \left\{ \begin{array}{l} 1, in\ workcenter\ i'operation\ k\ of\ batch\ b\ of\ product\ j\ is\ processed \\ \quad before\ at\ machine\ l \\ 0, in\ workcenter\ i'operation\ k'of\ batch\ b'of\ product\ j'is\ processed \\ \quad before\ at\ machine\ l\ or\ both\ of\ them\ or\ only\ one\ of\ them\ are \\ \quad not\ processed\ at\ machine\ l \end{array} \right\}$$

min C_{max}

subject to

$$y_{ijb} - y_{i-1,jb} - p_{i-1,jb} \geq 0 \qquad \forall (i \neq 1, i'), j, b \qquad \text{(B1)}$$

$$y_{i'jb} - \sum_l y_{i'jbkl} = 0 \qquad \forall j, b, (k = 1) \qquad \text{(B2)}$$

$$C_{max} - y_{ijb} \quad - p_{ijb} \quad \geq 0 \qquad i = M_{i,}\ \forall j, b \qquad \text{(B3)}$$

$$\sum_l y_{i'jbkl} - y_{i'-1,jb} - p_{i'-1,jb} \geq 0 \qquad \forall (k = 1), j, b \qquad \text{(B4)}$$

$$\sum_l y_{i'jbkl} - y_{i'jb,k-1,l} - p_{i'jb,k-1,l} \geq 0 \qquad \forall j, b, k \neq 1, l \qquad \text{(B5)}$$

$$y_{ijb} + p_{ijb} \leq y_{ij'b} + M\left(1 - g_{ijbj'b}\right) \qquad \forall i, j, j' > j, b \qquad \text{(B6)}$$

$$y_{ij'b} + p_{ij'b} \leq y_{ijb} + M g_{ijbj'b} \qquad \forall i, j, j' > j, b \qquad \text{(B7)}$$

$$y_{ijb} + p_{ijb} \leq y_{ijb'} + M\left(1 - g_{ijbjb'}\right) \qquad \forall i, j, b, b' > b \qquad \text{(B8)}$$

$$y_{ijb'} + p_{ijb'} \leq y_{ijb} + M g_{ijbjb'} \qquad \forall i, j, b, b' > b \qquad \text{(B9)}$$

$$y_{ijb} + p_{ijb} \leq y_{ij'b'} + M\left(1 - g_{ijbj'b'}\right) \qquad \forall i, j, j' > j, b, b' > b \qquad \text{(B10)}$$

$$y_{ij'b'} + p_{ij'b'} \leq y_{ijb} + M g_{ijbj'b'} \qquad \forall i, j, j' > j, b, b' > b \qquad \text{(B11)}$$

$$y_{i'jbkl} + p_{i'jbkl}\boldsymbol{a_{jbkl}} \leq y_{i'j'bkl} + M\left(1 - g_{i'jbkj'bkl}\right) \qquad \forall j, j' > j, b, k, l \qquad \text{(B12)}$$

$$y_{i'j'bkl} + p_{i'j'bkl}\boldsymbol{a_{j'bkl}} - \boldsymbol{M}\textstyle\sum_{l'} \boldsymbol{a_{jbkl'}} \leq y_{i'jbkl} + M g_{i'jbkj'bkl}$$

$$\forall j, j' > j, b, k, l \qquad \text{(B13)}$$

$$y_{i'jbkl} + p_{i'jbkl}a_{jbkl} \leq y_{i'jb'kl} + M\left(1 - g_{i'jbkjb'kl}\right) \qquad \forall j, b, b' > b, k, l \qquad \text{(B14)}$$

$$y_{i'jb'kl} + p_{i'jb'kl}a_{jb'kl} - M\textstyle\sum_{l'} a_{jbkl'} \leq y_{i'jbkl} + M g_{i'jbkjb'kl}$$

$$\forall j, b, b' > b, k, l \qquad \text{(B15)}$$

$$y_{i'jbkl} + p_{i'jbkl}a_{jbkl} \leq y_{i'j'b'kl} + M\left(1 - g_{i'jbkj'bkl}\right)$$

$$\forall j, j' > j, b, b' > b, k, l \qquad \text{(B16)}$$

$$y_{i'j'b'kl} + p_{i'j'b'kl}a_{j'b'kl} - M\textstyle\sum_{l'} a_{jbkl'} \leq y_{i'jbkl} + M g_{i'jbkj'b'kl}$$

$$\forall j, j' > j, b, b' > b, k, l \qquad \text{(B17)}$$

$$y_{i'jbkl} + p_{i'jbkl}a_{jbkl} \leq y_{i'j'bk'l} + M\left(1 - g_{i'jbkj'bk'l}\right)$$

$$\forall j, j' > j, b, k, k' > k, l \qquad \text{(B18)}$$

$$y_{i'j'bk'l} + p_{i'j'bk'l}a_{j'bk'l} - M\textstyle\sum_{l'} a_{jbkl'} \leq y_{i'jbkl} + M g_{i'jbkj'bk'l}$$

$$\forall j, j' > j, b, k, k' > k, l \qquad \text{(B19)}$$

$$y_{i'jbkl} + p_{i'jbkl}a_{jbkl} \leq y_{i'jb'k'l} + M\left(1 - g_{i'jbkjb'k'l}\right)$$

$$\forall j, b, b' > b, k, k' > k, l \quad \text{(B20)}$$

$$y_{i'jb'k'l} + p_{i'jb'k'l}a_{jb'k'l} - M\sum_{l'} a_{jbkl'} \leq y_{i'jbkl} + Mg_{i'jbkjb'k'l}$$

$$\forall j, b, b' > b, k, k' > k, l \quad \text{(B21)}$$

$$y_{i'jbkl} + p_{i'jbkl}a_{jbkl} \leq y_{i'j'b'k'l} + M(1 - g_{i'jbkj'b'k'l})$$

$$\forall j, j' > j, b, b' > b, k, k' > k, l \quad \text{(B22)}$$

$$y_{i'j'b'k'l} + p_{i'j'b'k'l}a_{j'b'k'l} - M\sum_{l'} a_{jbkl'} \leq y_{i'jbkl} + Mg_{i'jbkj'b'k'l}$$

$$\forall j, j' > j, b, b' > b, k, k' > k, l \quad \text{(B23)}$$

$$y_{i'jbkl} \leq M(1 - a_{jbkl'}) \qquad \forall j, b, k, l, l' > l \quad \text{(B24)}$$

$$My_{i'jbkl'} \geq a_{jbkl'} \qquad \forall j, b, k, l, l' > l \quad \text{(B25)}$$

$$y_{i'jbkl'} \leq M(1 - a_{jbkl}) \qquad \forall j, b, k, l, l' > l \quad \text{(B26)}$$

$$My_{i'jbkl} \geq a_{jbkl} \qquad \forall j, b, k, l \quad \text{(B27)}$$

$$\sum_l a_{jbkl} = 1 \qquad \forall j, b, k \quad \text{(B28)}$$

$$g_{ijbj'b} + g_{ij'bjb} = 1 \qquad \forall i, j, j' > j, b \quad \text{(B29)}$$

$$g_{ijbjb'} + g_{ijb'jb} = 1 \qquad \forall i, j, b, b' > b \quad \text{(B30)}$$

$$g_{ijbj'b'} + g_{ij'b'jb} = 1 \qquad \forall i, j, j' > j, b, b' > b \quad \text{(B31)}$$

$$\sum_l (g_{i'jbkj'bkl} + g_{i'j'bkjbkl}) \leq 1 \qquad \forall j, j' > j, b, k \quad \text{(B32)}$$

$$\sum_l (g_{i'jbkjb'kl} + g_{i'jb'kjbkl}) \leq 1 \qquad \forall j, b, b' > b, k \quad \text{(B33)}$$

$$\sum_l (g_{i'jbkj'b'kl} + g_{i'j'b'kjbkl}) \leq 1 \qquad \forall j, j' > j, b, b' > b, k \quad \text{(B34)}$$

$$\sum_l (g_{i'jbkj'bk'l} + g_{i'j'bk'jbkl}) \leq 1 \qquad \forall j, j' > j, b, k, k' > k \qquad \text{(B35)}$$

$$\sum_l (g_{i'jbkjb'k'l} + g_{i'jb'k'jbkl}) \leq 1 \qquad \forall j, b, b' > b, k, k' > k \qquad \text{(B36)}$$

$$\sum_l (g_{i'jbkj'b'k'l} + g_{i'j'b'k'jbkl}) \leq 1 \qquad \forall j, j' > j, b, b' > b, k, k' > k \qquad \text{(B37)}$$

$$a_{jbkl}, a_{jb'kl}, a_{jbkl'}, g_{ijbjb'}, g_{ijbj'b}, g_{ijb'jb}, g_{ij'bjb}, g_{i'jbkjb'kl}, g_{i'jbkj'bkl},$$

$$g_{i'jb'kjbkl}, g_{i'j'bkjbkl} \in [0,1] \; and \; integer$$

(B38)

All y_{ijb} and y_{ijbkl} variables ≥ 0 (B39)

The objective function of the scheduling model minimizes the makespan. Constraints B1 state that no two jobs can be processed at the same time except for the work center with parallel machines. For the parallel machine work center, constraints B2 set the starting time of a job. Constraints B3 define the makespan. Constraints B4 and B5 enable sequencing the products at parallel machine workcenter. Constraints B6 through B11 build the connection between ***y*** and ***g*** variables. But, the parallel machime work center is not considered in these constraints. Rather, parallel machine work center is handled with constraints B12 to B23. With these constraint sets, the relation between ***y*** and ***g*** variables are built with the help of another variable, ***a***, which also includes the machine index. These constraints are different from constraints B6 through B11 with having a_{jbkl} variables and $M \sum_{l'} a_{jbkl}$ values. The constraints B24 to B27 are the parallel machine selection rules at the parallel machine work center. Constraints B28 state that a job is processed at only one machine among the parallel machines. Constraints B29 to B31 guarantee that all jobs are processed on single machine work ceneters. Parallel machine work center is handled with constraints B32 to B37. These constraints state that every job is processed by at most one of the parallel machines. Finally, constraints B38 and B39 are the cardinality constraints.

The next step involves constructing a stochastic discrete-event simulation model of manufacturing floor and then running it to estimate OPTs.

4.3 Step 3: Simulation Modeling for Estimating OPTs

In this step, a simulation model of manufacturing floor is developed and run to estimate OPTs. The main advantage of simulation modeling is that it incorporates the stochastic nature of input data and also dynamic nature of a material handling sytem into the modeling procedure so that the features of a manufacturing floor can be captured more realistically.

Since these features are difficult to include in an analytic model, the scheduling decisions identified by the analytic model may not be feasible if they are put into practice. Hence, in this study a hybrid procedure integrating analytic and simulation modeling is proposed to generate scheduling decisions. Mainly, this simulation model helps to set realistic OPTs for customers. It should be noted that the output generated in earlier two steps (see Figure 4.2) serve as input in simulation modeling.

The following chapter presents an industrial case study to illustrate how the steps of the proposed hybrid approach are implemented.

CHAPTER FIVE
AN INDUSTRIAL CASE STUDY

In this chapter, the implementation of the proposed hybrid approach is illustrated by employing an industrial case study.

5.1 Application Environment

The problem considered in this thesis study involves setting order promising times for a produce-order manufacturing company operating within a supply chain environment. This problem is solved in three steps by combining analytical and simulation modeling.

The manufacturing company which takes place in this supply chain environment was found in 1983 and started to work rapidly for growing automotive industry by edging towards the production of brake system components which need high precision. Since the mid 90s the company has entered into world markets and in a relatively short time it became a major export enterprise for automotive products.

Since 2006, the company has been conducting its operations in Bursa Organized Industrial Zone. The main operations of the company are mould making, forging, machining of brass and steel parts, and assembly-test of finished or semi-finished products. The company adopts customer oriented manufacturing and marketing practices for better conforming to increasing demands of the competitive environment, and for assuring its prevalence in the future.

The supply chain system in which this manufacturing company operates can be divided into two parts. The first part named as "Production System" involves subcontractors and the factory which convert raw materials into parts and parts into products. The second part called "Distribution System" consists of stack buffer, warehouses, and customers.

Based on customer requirements, various products which are made brass, steel and aluminum are produced via mould making, hot forging, precision machining

(CNC lathes, boring tools, etc.) and finishing (product assembly, test and packaging, etc) operations. These products are targeted for supplying various component needs of the following industries:

- Automotive
- HVAC industry (Heating, Ventilation, Air Conditioning system)
- Construction / building
- Electricity transmission and distribution
- Flow transmission and control
- White goods
- Agricultural hardware
- Ship and yacht making
- Rail transportation
- Medical equipment

The production system consists of five main departments which are explained briefly below:

1. Method and Engineering Department: Being the first step of production process, method and design directly affects the success of quality and performance.
2. Mould Department: The fabrication of the moulds and apparatuses are carried out here. This facility ensures that the production is under control in terms of speed, accuracy, quality, fluency and economy.
3. Forging Department: In this section, serial production of high quality pieces takes place. The process is realized on manual or automated forging lines, where the presses of various tons are fed by continuous-type furnaces. Quality is kept under control, naturally, during the production. Besides, the forging section is reinforced with surface cleaning and sand blasting facilities.
4. Machining Department: The CNC lathes and CNC vertical machining centers take place in this department.

5. Packaging Department: In this department, each product is placed into packages specially designed for that product so as to ensure that no damage during the transportation will occur.

The distribution system contains one stack buffer and two warehouses to store the products before they are transferred to the customers. While the stack buffer is located in the factory, the two warehouses are located outside the factory. The customer orders can be met directly both from stack buffer and warehouses.

The following section presents a real-world production planning and scheduling problem studied in this M.Sc Study.

5.2 Problem Description

As mentioned in earlier section, various industrial products are produced in the factory and the company operates on the basis of make to order policy. Among these industrial products, the volume of production for "Construction / Building Systems" such as "valve body" is highest in comparison to others. Since any efficiency gained in production of these products will have a great contribution to the success of the factory, in this M.Sc study we decided to focus on this group of products. However, since our objective in this study is to illustrate the implementation of our hybrid approach in a real-world environment, we just considered the production of two main industrial products taking place in this group, which are namely Gehause and Lwyon valve bodies. It should be noted that in the following sections these two products, Gehause and Lwyon will be named as PR1 and PR2, respectively.

These two products are subject to processing in two stages: As given in Figure 5.1, first, to produce the parts, the cutting process is carried out on steel bars by five subcontractors. The raw material holding capacity of supplier per month is 50000 steel bars. Once the cutting process is completed, the parts are transferred to the factory to start the second stage. It should be noted that the part holding capacity of the factory is at most 1,000,000 units per month. In the following stage, the parts are converted into products by five workcenters whose monthly production capacity is

775 hours per month. The operations carried out in these workcenters are forging, surface processing, sanding, packaging and finishing.

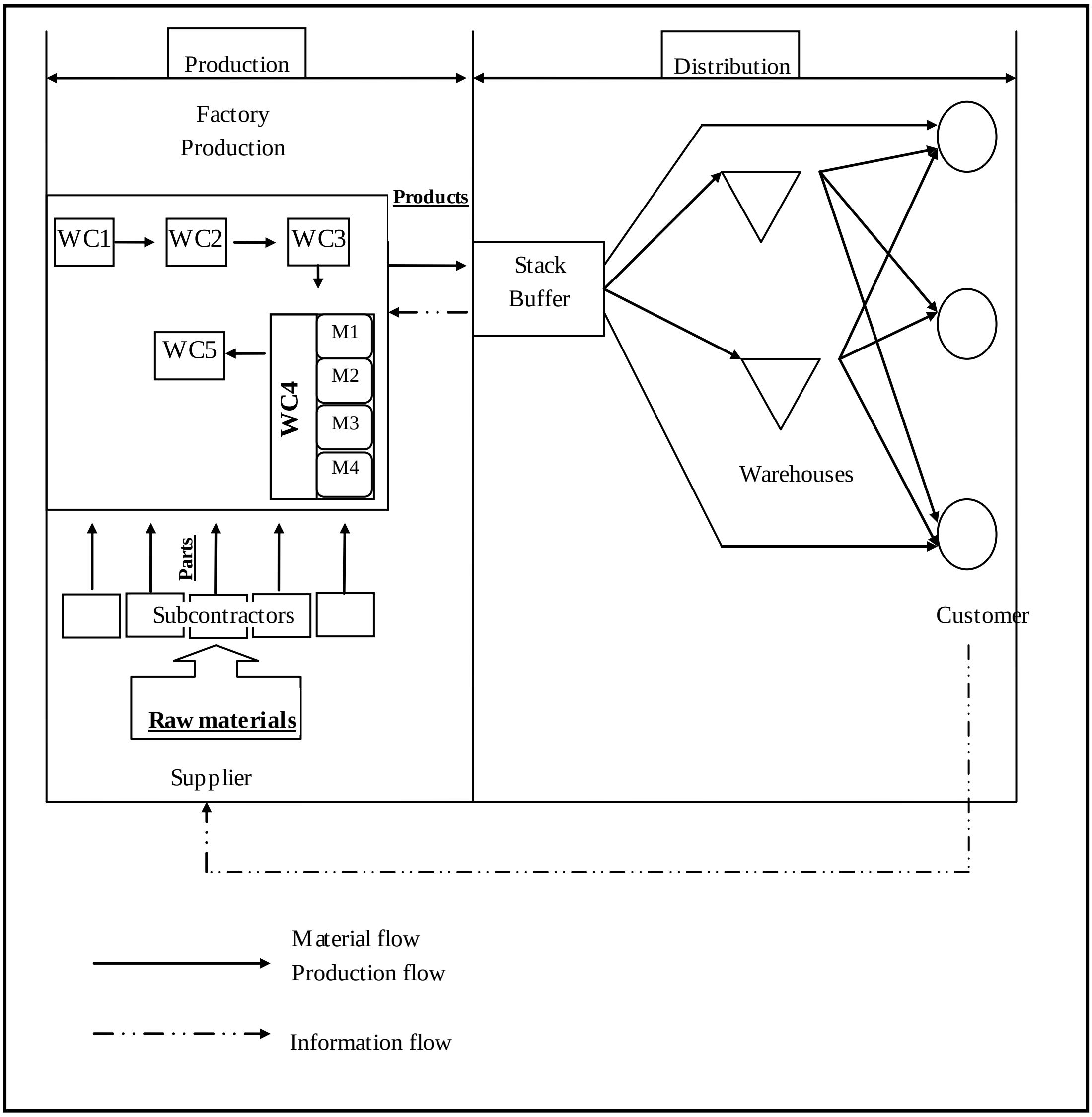

Figure 5.1 Supply chain system under study

To produce the parts P1 and P2, five types of raw materials are used. These raw materials are named as RM1, RM2, RM3, RM4 and RM5 in Table 5.1. It should be noted that one unit of part P1 is converted into one unit of product PR1 and likewise, one unit of part P2 is converted into one unit of product PR2. As seen in Table 5.1, there are two alternatives to produce one unit of part P1 which is to be converted to the product PR1 in the factory: use 0.01 units RM1 or use 0.0133 units of RM3. Likewise, to produce one unit of part P2 either raw RM2 or RM5 is used.

Table 5.1 Raw material requirements for part production

Raw Materials		Parts	
		P1 (8cm)	P2 (5,5 cm)
RM1	steel bar Ø6,2 cm X 8 m length	0.01 units	NA*
RM2	steel bar Ø5,7 cm X 6 m length	NA	0.009 units
RM3	steel bar Ø6,2 cm X 6 m length	0.0133 units	NA
RM4	steel bar Ø4,8 cm X 8 m length	NA	NA
RM5	steel bar Ø5,7 cm X 8 m length	NA	0.0069 units

* NA: Not Applicable

As mentioned earlier, as a result of cutting process, the raw materials are converted into parts by five subcontractors. The cutting process times are given in Table 5.2. The data given in this table imply that only the second or the fourth subcontractor can produce the part P1.

Table 5.2 Cutting processing times

	Cutting Processing Time (in seconds)				
	Subcontractor				
Parts	1	2	3	4	5
P1	NA*	4.848	NA	8.727	NA
P2	NA	21.818	39.273	25.412	NA

* NA: Not Applicable

Following the cutting process, in the factory, these parts are converted into products PR1 and PR2 by going through five workcenters. The products are processed in batches; once a batch is completed it is transferred to the next workcenter using three forklifts. As seen in Figure 5.1, except for workcenter four which has four parallel CNC lathes, all other workcenters have only one resource. The part routing information including processing times in each workcenter is summarized in Table 5.3. It should be noted that all processing times given in this table include efficiency loss and setup times and these values are the averages of past data recorded in the factory. As seen in Table 5.2, unlike product PR2, the product PR1 goes through two operations in the fourth workcenter and these two operations are carried out one of the parallel machines given in Table 5.3.

Table 5.3 Product routing and mean operation times (in seconds)

Product Type	Total Number of Operations	Workcenter Visitation Sequence	Operation No	Parallel Machine No	Mean Operation Time (in seconds)
PR1	6	1	1	-	21.32
		2	2	-	39
		3	3	-	23
		4	4	1	55.11
				3	60.11
			5	1	67.413
				2	68.13
				3	68.13
				4	68.13
		5	6	-	22.4
PR2	5	1	1	-	22.5
		2	2	-	8
		3	3	-	18
		4	4	2	76.25
				4	76.25
		5	5	-	9.6

The costing information such as production, shortage and storage costs per unit of raw material, part and product are summarized in Table 5.4. For instance, as shown in the table, the costs of production, storage and shortage per unit of part P1 in period one are 13, 1.5, and 3 dollars, respectively.

Table 5.4 Costing information; ( ) = storage cost, [ ] = shortage cost

	Production, Storage and Shortage costs per unit per month (in dollars)		
Items	Month 1	Month 2	Month 3
RM1	8 (1.5) [5]	8 (2) [4]	5 (3) [5]
RM2	6 (1) [7]	9 (2) [5]	6 (2) [4]
RM3	6 (2) [4]	6 (2) [4]	8 (4) [5]
RM4	5 (1.5) [4]	5 (2) [6]	7 (3) [5]
RM5	7 (2) [6]	5 (2) [7]	10 (3) [9]
P1	13 (1.5) [3]	14 (2) [6]	12 (3) [7]
P2	13 (1) [4]	14 (2) [4]	15 (2) [7]
PR1	35 (1.5) [15]	30 (2) [10]	40 (3) [18]
PR2	35 (1) [16]	37 (2) [14]	42 (2) [17]

The second part of this supply chain system which is shown as "distribution" in Figure 5.1 involves one stack buffer, two warehouses and three customers. The storing capacity for the stack buffer and warehouses are 500000, and 4800000 units per month, respectively. The distribution system has three trucks in order to transport products or parts to supply chain members. The monthly capacity of these trucks is 528 hours (8 hours/day * 22 days/month * 3 units). The distribution times per unit of products are shown in Table 5.5. These values are obtained by taking into consideration the transportation batch size for each product. For instance; the distribution times for one unit of product PR1 and PR2 from stack to the warehouse one are 1.74 and 1.38 seconds, respectively.

Table 5.5 Distribution times per unit of product (in seconds)

		To:	Distribution times per unit (in seconds)				
PR1/PR2			Warehouse		Customer		
			1	2	1	2	3
From:	Stack		1.74/1.38	1.554/1.2	3.42/2.7	2.64/2.1	4.14/3.3
	Warehouse 1		-	-	1.92/1.5	1.68/1.32	2.28/1.8
	Warehouse 2		-	-	2.1/1.68	1.5/1.2	1.92/1.5

Monthly storage and shortage costs per unit of products are given in Table 5.6.

Table 5.6 Monthly storage and shortage costs; ( ) = shortage cost

		Monthly Storage and Shortage Costs per Unit of Product (in dollars)					
		Warehouse		Customer			Stack
Month	Product	1	2	1	2	3	
1	PR1	5 (8)	5 (6)	4 (9)	5(7)	5 (8)	2 (7)
	PR2	6 (5)	6 (7)	3 (8)	3 (6)	3 (6)	3 (8)
2	PR1	5(8)	5(7)	4 (9)	5(7)	5 (8)	2 (8)
	PR2	6(5)	5(6)	3 (8)	3(6)	4 (6)	3 (9)
3	PR1	7(7)	7 (6)	4 (9)	5 (7)	5 (8)	2 (7)
	PR2	4(5)	5(5)	7 (8)	5 (7)	3 (6)	3 (8)

The unit transportation costs among the supply chain members (i.e., stack, warehouses and customers) are given in Table 5.7. It should be noted that the transportation cost from five subcontractors to the factory which are not listed in this table are accepted as 4, 2, 6, 3 and 5 dollars, respectively.

Table 5.7 Unit transportation cost (in dollars)

			Unit transportation cost (in dollars)				
		To:	Warehouse		Customer		
			1	2	1	2	3
From:	Stack		6	8	8	9	13
	Warehouse 1		-	-	3	5	4
	Warehouse 2		-	-	5	8	6

The factory operates three shifts in a day and the total unproductive time including coffee/lunch breaks and cleaning of the machinery is assumed to be two hours per day.

Given the processing capacity of subcontractors and factory and also the holding capacity of stack and warehouses, the objective in this problem setting is to generate optimum production and distribution plans so that the customer orders received can be satisfied. To deliver the orders received on promised due dates, first three-month long term production plans are generated by carrying out the first step of the proposed hybrid approach. Next, this monthly production plan is splitted into three scheduling periods, namely into ten-day scheduling periods and for each period the step two of the proposed hybrid appproach is implemented to generate optimal scheduling decisions. Lastly, simulation modeling is employed to set realistic promising times for each order received. It is suggested that this three-step hybrid approach will be implemented every other ten-day scheduling period.

However, for illustrative purposes, in this case study we just focused on the first scheduling period of the first month. The sustomer orders received during the first ten-day of the scheduling period are presented in Table 5.8.

Table 5.8 Customer orders received for first ten-day scheduling period

Product: Customer	Order no	Demands Month 1	2	3
PR1: C1	1	550	240	550
	2	280	300	170
	3	120	260	280
	4	300		
	5	250		
PR1: C2	6	400	500	300
	7	200	480	366
	8	234	354	
PR1: C3	9	300	246	260
	10	250	280	340
	11	284	340	66
PR2: C1	12	140	120	300
	13	230	62	200
	14	230	150	
PR2: C2	15	130	110	170
	16	202	90	330
PR2: C3	17	400	200	500

As mentioned earlier, backlogging is not allowed and if the received customer order can not be produced under given capacity constraints a deficit cost occurs.

The issues need to be dealt with in this problem setting by taking into consideration all members of this supply chain network are:

1. What are the optimum production and distribution plans for a planning horizon of three months?
2. How to convert these three-month production and distribution plans into ten-day short term scheduling decisions for each work center?
3. How to set realistic OPTs for each order received?

In the following sections, the proposed methodologies followed to deal with these three issues are explained in detail.

5.3 Implementing Proposed Hybrid Approach

This section explains the solution methodologies employed to answer above questions.

5.3.1 Step 1: Mathematical Modeling for Production and Distribution Planning

To generate optimum production and distribution plans for a planning horizon of three months, the mathematical model presented in section 4.1 is employed. The indexes used in this LP model have been initialized as follows:

t (t = 1, 2, 3) refers to time period t.

i (i = 1, 2) refers to part i.

j (j = 1, 2) refers to product j.

k (k = 1, …, 5) refers to raw material k.

u (u = 1, …, 5) refers to subcontractor u.

p (p = 1, 2) refers to warehouse p.

q (q = 1, 2, 3) refers to customer q.

The objective is to minimize total of the production costs, storage costs, shortage cost, and transportation costs over a horizon of three months. To become more conservative, the maximum of entries given in Table 5.3 is taken into consideration to initialize the processing times for parallel machines.

The LP model is formulated as follows:

$$\min z = \sum_{t=1}^{3}\left\{\sum_{i=1}^{2}\sum_{u=1}^{5}(ci_{it}X_{iut} + hi_{it}I_{it}^{+} + \pi i_{it}I_{it}^{-}) + \sum_{j=1}^{2}(cj_{jt}Y_{jt} + hj_{jt}Ij_{jt}^{+} + \pi j_{jt}Ij_{jt}^{-})\right.$$
$$+ \sum_{k=1}^{5}(ck_{kt}E_{kt} + hk_{kt}Ik_{kt}^{+} + \pi k_{kt}Ik_{kt}^{-}) + \sum_{j=1}^{2}(STL_{jt}L_{jt}^{+} + SHL_{jt}L_{jt}^{-})$$
$$+ \sum_{j=1}^{2}\sum_{p=1}^{2}(STP_{jpt}P_{jpt}^{+} + SHP_{jpt}P_{jpt}^{-})$$
$$+ \sum_{j=1}^{2}\sum_{q=1}^{3}(STQ_{jqt}Q_{jqt}^{+} + SHQ_{jqt}Q_{jqt}^{-}) + \sum_{j=1}^{2}\sum_{p=1}^{2}TLP_{p}LP_{jpt}$$
$$\left.+ \sum_{j=1}^{2}\sum_{q=1}^{3}TLQ_{q}LQ_{jqt} + \sum_{j=1}^{2}\sum_{p=1}^{2}\sum_{q=1}^{3}TPQ_{pq}PQ_{jpqt} + \sum_{i=1}^{2}\sum_{u=1}^{5}TI_{u}X_{iut}\right\}$$

subject to

$Ij_{jt} = Ij_{j,t-1} + Y_{jt} - D_{jt}$ $\quad j = 1,2;\ t = 1,2,3$ (A1)

$Ii_{it} = Ii_{i,t-1} + \sum_{u=1}^{\infty} X_{iut} - \sum_{j=1}^{J} a_{ij}Y_{jt}$ $\quad i = 1,2;\ t = 1,2,3$ (A2)

$Ik_{kt} = Ik_{k,t-1} + E_{kt} - \sum_{i=1}^{2}\sum_{u=1}^{5} d_{ki}X_{iut}$ $\quad k = 1,\dots,5;\ t = 1,2,3$ (A3)

$\sum_{i=1}^{2}\sum_{u=1}^{5} d_{ki}X_{iut} \leq 50000$ $\quad k = 1,\dots,5;\ t = 1,2,3$ (A4)

$\sum_{i=1}^{2} ai_{iu}X_{iut} \leq 2790000$ $\quad u = 1,\dots,5;\ t = 1,2,3$ (A5)

$\sum_{j=1}^{2} aj_{j}Y_{jt} \leq 2790000$ $\quad t = 1,2,3$ (A6)

$Ij_{jt} = Ij_{jt}^{+} - Ij_{jt}^{-}$ $\quad j = 1,2;\ t = 1,2,3$ (A7)

$$Ii_{it} = Ii_{it}^{+} - Ii_{it}^{-} \qquad i = 1,2;\ t = 1,2,3 \qquad \text{(A8)}$$

$$Ik_{kt} = Ik_{kt}^{+} - Ik_{kt}^{-} \qquad k = 1,\dots,5;\ t = 1,2,3 \qquad \text{(A9)}$$

$$L_{jt} = L_{j,t-1} + Y_{jt} - \sum_{p=1}^{2} LP_{jpt} - \sum_{q=1}^{3} LQ_{jqt} \qquad j = 1,2;\ t = 1,2,3 \qquad \text{(A10)}$$

$$P_{jpt} = P_{jp,t-1} + LP_{jpt} - \sum_{q=1}^{3} PQ_{jpqt} \qquad j = 1,2;\ p = 1,2;\ t = 1,2,3 \qquad \text{(A11)}$$

$$Q_{jqt} = Q_{jq,t-1} + \sum_{p=1}^{2} PQ_{jpqt} + LQ_{jqt} - D_{jqt}$$
$$j = 1,2;\ q = 1,2,3;\ t = 1,2,3 \qquad \text{(A12)}$$

$$\sum_{j=1}^{2} Y_{jt} \leq 500000 \qquad t = 1,2,3 \qquad \text{(A13)}$$

$$\sum_{j=1}^{2} LQ_{jqt} + \sum_{j=1}^{2} \sum_{p=1}^{2} PQ_{jpqt} \leq 5000000 \qquad q = 1,2,3;\ t = 1,2,3 \qquad \text{(A14)}$$

$$\sum_{j=1}^{2} LP_{jpt} \leq 4800000 \qquad p = 1,2;\ t = 1,2,3 \qquad \text{(A15)}$$

$$\sum_{i=1}^{2} \sum_{u=1}^{5} X_{iut} \leq 1000000 \qquad t = 1,2,3 \qquad \text{(A16)}$$

$$\sum_{j=1}^{2} \sum_{p=1}^{2} A_{jp} LP_{jpt} + \sum_{j=1}^{2} \sum_{q=1}^{3} B_{jq} LQ_{jqt} + \sum_{j=1}^{2} \sum_{p=1}^{2} \sum_{q=1}^{3} C_{jpq} PQ_{jpqt} + \sum_{i=1}^{2} \sum_{u=1}^{5} D_{iu} X_{iut} \leq 31680$$
$$t = 1,2,3 \qquad \text{(A17)}$$

$$L_{jt} = L_{jt}^{+} - L_{jt}^{-} \qquad j = 1,2;\ t = 1,2,3 \qquad \text{(A18)}$$

$$P_{jpt} = P_{jpt}^{+} - P_{jpt}^{-} \qquad j = 1,2;\ p = 1,2;\ t = 1,2,3 \qquad \text{(A19)}$$

$$Q_{jqt} = Q_{jqt}^{+} - Q_{jqt}^{-} \qquad j = 1,2;\ q = 1,2,3;\ t = 1,2,3 \qquad \text{(A20)}$$

I_{it}, I_{jt}, I_{kt}, L_{jt}, P_{jpt}, Q_{jqt} *variables are the unrestricted in sign* (A21)

All other variables ≥ 0 (A22)

Running these data through the LP solver called Lindo 9.0 yields the production and distribution plans shown in tables from 5.9 to 5.11. The optimum solution has been found after 17,475 iterations. The Lindo 9.0 solution report is given in Appendix A in detail.

Table 5.9 Optimal solutions for production

	Products		Parts					Raw materials				
			P1 / P2									
	PR1	PR2	U1	U2	U3	U4	U5	RM1	RM2	RM3	RM4	RM5
Month 1	9504	4216		9504/ 4216				95	56	127	0	29
Month 2	10784	1984		10784/ 1984				108	0	144	0	45
Month 3	4616	4504		4616/ 4504				47	41	62	0	0

As seen in Table 5.9, the optimum production plan suggests producing 9504, 10784 and 4616 units of product one during the first, second and third month, respectively. In this table, to denote the amount of parts produced by five subcontractors the symbol “U” is used. For instance, the optimum plan given in this table suggests that in first month, 9504 units of part one and 4216 units of part two should be produced by subcontractor two. Lastly, regarding raw material entries, the table says that the supplier provides 95 units of raw material one during the first month of three-month planning horizon.

Optimal distribution plans are presented in Table 5.10. In this table, DPR1 and DPR2 represent the amount of final product type one and two, respectively which are distributed from stack to customers or stack to warehouses or warehouses to customers. Moreover, the symbols S, W, and C represent the stack buffer, warehouse and customer, respectively. SC1 represents the amount of products distributed from stack to customer one; SW1 represents the amount of products distributed from stack to warehouse one; W1C1 represents the amount of products distributed from warehouse one to customer one. For example, in the first month, 4500 units of product one are distributed from stack buffer to the customer one.

Table 5.10 Optimal solution for distribution plans

	Stack-Customers	Stack-Warehouses	Warehouses-Customers

	DPR1			DPR2			DPR1		DPR2		DPR1			DPR2		
	SC1	SC2	SC3	SC1	SC2	SC3	SW1	SW2	SW1	SW2	W1C1	W1C2	W1C3	W1C1	W1C2	W1C3
Month 1	4500	2500		1800	1000		2500		1200				2500			1200
Month 2	2400	3400		1000	600		2600		600				2600			600
Month 3	3000	2000		1500	1500		2000		1500				2000			1500

Table 5.11 shows optimal inventory plans for raw material, part and products. For instance, in the first month, 216 units of product two are stored in the system. The optimal solution found suggests that all finished products and raw material inventories are stored in stack buffer and in factory, respectively.

Table 5.11 Optimal solutions for inventory

	Products		Parts		Raw materials				
	IPR1	IPR2	IP1	IP2	IRM1	IRM2	IRM3	IRM4	IRM5
Month 1	4	216				18			
Month 2	2388	0							31
Month 3	4	4							

As a summary, the optimal monthly production plans generated for each type of product is splitted into ten-day short term scheduling periods and regarding the first scheduling period, the production targets for product PR1 and product PR2 are set to 3168 units and 1406 units, respectively. As mentioned earlier, the products are produced in batches and deciding the number of batches to realize these production targets is also a planning issue. Having not dealt with this issue in this thesis study we assumed that the total number of batches is six.

5.3.2 Step 2: Mathematical Modeling for Production Scheduling

As mentioned above, in this step, the three-month production and distribution plans generated in earlier step are converted into ten-day short term scheduling decisions for each workcenter. To generate optimum production and distribution plans for a planning horizon of three months, the MIP model presented in section 4.2 is employed.

The indexes and parameters used in this MIP model have been initialized as follows:

i (i = 1,…, 5) refers to workcenter i.

i’ (i’ = 4) refers to workcenter i’ which includes parallel machines.

j (j = 1, 2) refers to product j.

b (b = 1, 2,…, 6) refers to batch b.

k (k = 1, 2) refers to operation k in workcenter i’.

l (l = 1,…, 4) refers to parallel machine l in workcenter i’.

p_{ijb} refers to batch processing time of workcenter i, product j, and batch b.

$p_{i'jbkl}$ refers to batch processing time of workcenter i’, product j, batch b, operation k and machine l

Given these indexes and parameters, the MIP model formulated in section 4.2 is solved to generate scheduling decisions for each resource. As mentioned earlier, the maximum value of batching index is set to six implying that at most six batches of two products will be produced in any moment.

Given the first ten-day of the first month’s optimal production plan, which calls for producing 3168 units of PR1 and 1406 units of PR2, the total six number of batches to meet this production target can occur in five different ways (see Table 5.12).

Table 5.12 Five scheduling scenarios

	Products				Performance measure
	PR1		PR2		
Scenario	The number of batches	Batch sizes	The number of batches	Batch sizes	Min C_{max} (hour)
1	1	3168	5	282	200.46
2	2	1584	4	352	117.43
3	3	1056	3	469	89.76
4	4	792	2	703	76.09
5	5	634	1	1406	**71.84**

The suggested MIP model has been run for these five scenarios using Lindo 9.0. As seen in Table 5.12, among the five scenarios, the minimum makespan (i.e., 71.84 hours) is found under the fifth scenario, which suggests fixing the number of batches to five and one for PR1 and PR2, respectively. The solution report for scenario five is given in Appendix B. It should be noted that in Table 5.13 while the five batches of product one are numbered as 1, 2, 3, 4, and 5, the only batch of product two is numbered as 6. This table lists the tasks to be scheduled based on product routing information given earlier in Table 5.3. The task scheduling decisions taken under the fifth scenario are summarized in Table 5.14.

Table 5.13 Task definitions

Batch no.	Workcenter	Operation no.	Task no.
1	1	1	1
	2	2	2
	3	3	3
	4	4	4
		5	5
	5	6	6
⋮	⋮	⋮	⋮
5	1	1	25
	2	2	26
	3	3	27
	4	4	28
		5	29
	5	6	30
6	1	1	31
	2	2	32
	3	3	33
	4	4	34
	5	5	35

Table 5.14 Task scheduling decisions

<table>
<tr><th colspan="3">Workcenter</th><th>Task sequence</th></tr>
<tr><td colspan="3">1.</td><td>19-13-31-7-1-25</td></tr>
<tr><td colspan="3">2.</td><td>20-14-32-8-2-26</td></tr>
<tr><td colspan="3">3.</td><td>21-15-33-9-3-27</td></tr>
<tr><td rowspan="4">4.</td><td rowspan="4">Paralel machine</td><td>1</td><td>16-10-4-5</td></tr>
<tr><td>2</td><td>34</td></tr>
<tr><td>3</td><td>22-17-28</td></tr>
<tr><td>4</td><td>23-11-29</td></tr>
<tr><td colspan="3">5.</td><td>24-18-12-35-6-30</td></tr>
</table>

As mentioned earlier, the next step involves first developing a dynamic and stochastic simulation model of the manufacturing environment and then using these task scheduling decisions as input in this simulation model in order to realistically estimate order promising times for customers.

5.3.3 Step 3: Order Promising Time Estimation Using Simulation

In this step, a simulation model which reflects dynamic and stochastic nature of the manufacturing floor is developed to estimate OPTs. It should be noted that when only analytic approaches are employed for production planning, manufacturing system characteristics such as queuing, machine breakdowns, stochastic natures of processing times and transportation delays are difficult to include in the analytic model.

On the other hand, just being a descriptive tool, when used alone, simulation modeling can not generate optimal scheduling decisions. So in this study, by combining analytic modeling with simulation modeling, we aim at bringing their advantages together and at the same time mitigate their disadvantages.

Applying the first step of our proposed hybrid approach suggested producing 9504 units of product PR1 and 1406 units of product PR2 during the first month of three-month planning horizon. Next, we implemented the second step of our proposed hybrid approach and assumed that these production targets were realized by setting the total number of bathes to six during the first ten-day of the first three-month planning horizon. Namely, while the first product is produced in five batches with a batch size of 634 units, the second product is produced as one batch with a batch size of 1406 units. We also generated task sequencing decisions for each work center as earlier summarized in Table 5.14.

The role of this step in this hybrid approach is to implement these scheduling decisions under stochastic and dynamic nature of the manufacturing floor by employing simulation modeling. As mentioned earlier in section 5.2, the manufacturing floor consists of five workcenters. Among these, only the fourth workcenter has four parallel machines. The parts are transferred among the workcenters in batches by three forklifts based on the part routing information given in Table 5.3. Unlike earlier two steps in which part processing times are assumed as deterministic, in this step, Input Analyzer of Arena 10.0 has been employed to fit an appropriate distribution function to each processing time (see Table 5.15).

Table 5.15 Batch processing times in factory (in hours)

Product Type	Total Number of Operations	Workcenter Visitation Sequence	Operation No	Parallel Machine No	Batch Operation Time
PR1	6	1	1	-	Norm (3.75, 0.18)
		2	2	-	Norm (6.87, 0.23)
		3	3	-	Norm (4.05, 0.21)
		4	4	1	Norm (9.72, 0.023)
				3	Norm (10.6, 0.013)
			5	1	Norm (11.84, 0.036)
				2	Norm (12.02, 0.02)
				3	Norm (12.02, 0.011)
				4	Norm (12.02, 0.18)
		5	6	-	Norm (3.95, 0.015)
PR2	5	1	1	-	Norm (8.79, 0.27)
		2	2	-	Norm (3.12, 0.28)
		3	3	-	Norm (7.03, 0.27)
		4	4	2	Norm (29.72, 0.039)
				4	Norm (29.72, 0.029)
		5	5	-	Norm (3.75, 0.27)

The further assumptions under which this simulation model has been developed can be summarized as follows:

- The parts are processed in batches, unless a batch is completed, the parts can not be transferred to the next resource.
- The velocity of the forklifts is 3 meter/second.
- The first workcenter and one of the paralel machines in the fourth workcenter (i.e., machine one) can be subject to failure. The machine failure records kept in the factory have been analyzed using Input Analyzer of Arena 10 and the distributions summarized in Table 5.16 have been assumed for time between failures and repair times.

Table 5.16 Modeling machine failures

	Time between two failures (in hours)	Repair time (in hours)
Workcenter 1	Norm (13, 5.01)	0.7 + Weib (0.0518, 4.45)
Machine 1/ Workcenter 4	0.7 + Weib (0.0518, 4.45)	Norm (0.436, 0.31)

- In case of a machine failure, part preemption is not allowed.
- The batches are processed based on the scheduling decisions obtained in step two of the proposed hybrid approach.
- The factory operates three shifts.

Before the simulation model has been coded in Arena 10, a conceptual model which reflects the control structure of the simulation model has been developed (see Figure 5.2).

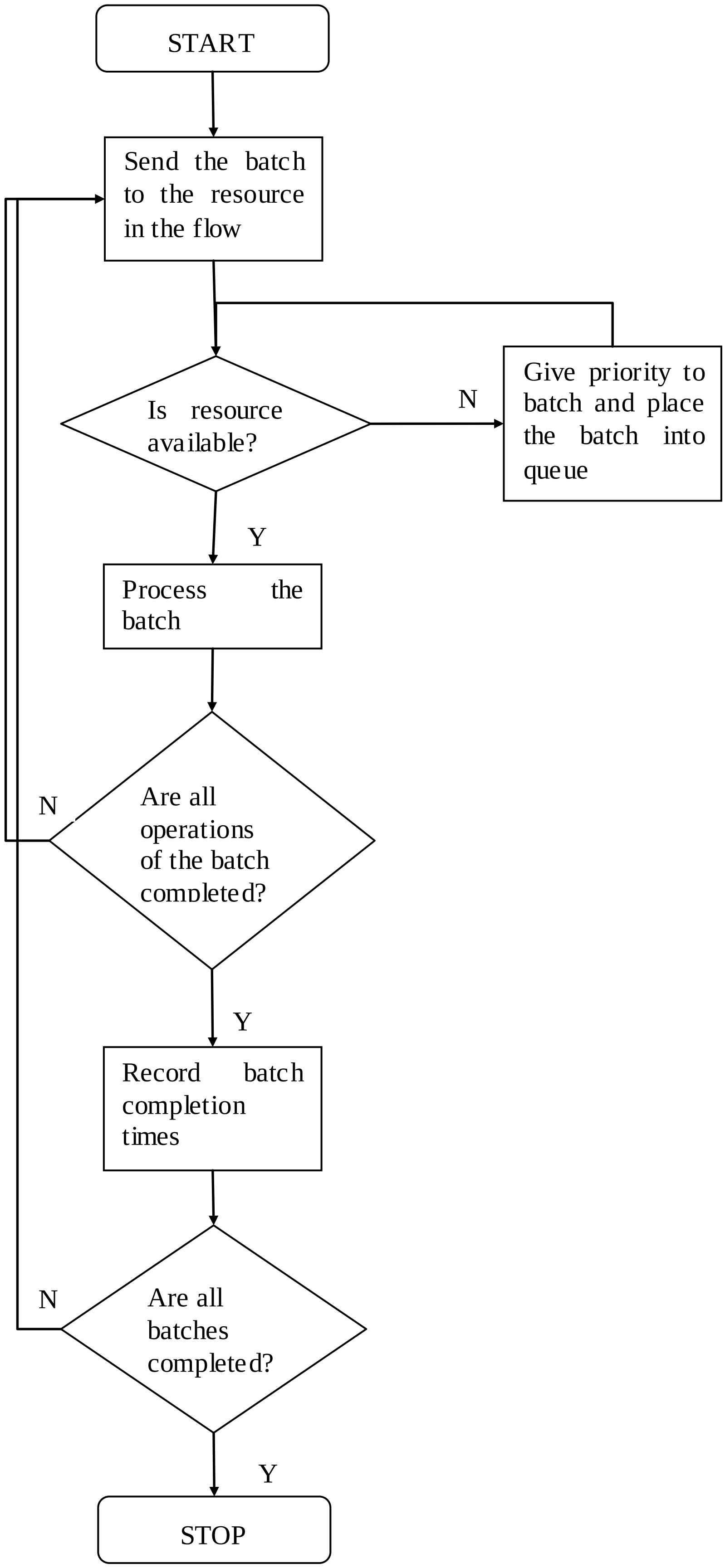

Figure 5.2 Control structure of the simulation model

As seen in Figure 5.2, the parts are processed in batches and the simulation stops when all batches are completed. Due to the stochastic nature of simulation modeling, once coded this model has been run for ten times to estimate order completion times. The Arena code of this manufacturing floor can be found in Appendix C.

It should be noted that the verification and validation of a simulation model is essential in a simulation study. In this study, the verification has been done with the “trace facility” available in Arena 10.0. The use of trace is the tracking of entities (i.e., batches) through overall model to determine if the conceptual model has been accurately transferred to the coded simulation model. Extreme condition tests also helped to verify the accuracy of the model developed. Moreover, the simulation model has been validated by using historical input validation technique. In the following sections, the results of the simulation modeling to set realistic order promising times for customers are explained.

5.3.3.1 Experimental Studies to Estimate OPTs.

As mentioned earlier, due to the stochastic nature of simulation, the model developed has been run for ten times until all batches are completed. As summarized in the preceding section, the number of batches for product PR1 and product PR2 were set to five and one, respectively.

Table 5.17 presents the estimated average completion times and also related upper and lower limits of the %95 confidence interval obtained from simulation runs.

It should be noted that in estimating order promising times, rather than average batch completion time, the upper limit of %95 confidence interval for batch completion time has been preferred. In doing so it has been aimed at reducing the risk of not completing the orders on time.

Table 5.17 The estimated batch completion times

			0.95 confidence interval for batch completion times (in days)		
Product	Batch number	Batch size	Average	Upper limit	Lower limit
PR1	1	634	3.04	3.49	2.48
	2		4.05	4.54	3.62
	3		3.41	4.18	2.30
	4		2.70	2.79	2.67
	5		4.29	4.73	3.95
PR2	6	1406	3.74	3.86	3.60

By taking into consideration both estimated batch completion times and also the order quantities given in Table 5.8, order promising times are estimated and these dates are presented to the customer for negotiation. For instance, as given in Table 5.8, for product one, five orders amounting to 550, 280, 120, 300 and 250, respectively are received from the first customer. Hence, based on estimated upper limits of batch completion times given in Table 5.17, while the first order can be delivered to the customer at the end of day three, the fifth order can be delivered at the end of day five.

Besides estimating OPTs, this three-step hybrid approach helped us taking the following decisions for this manufacturing company operating in a supply chain environment.

- Regarding raw material requirements, 95 units of raw material one, 56 units of raw material two, 127 units of raw material three, and 29 units of raw material five are suggested to be purchased.
- Among five subcontractors, the subcontractor two is suggested to carry out the cutting process.
- It is suggested to produce 9504 units of Gehause and 4216 units of Lwyon.
- Four units of Gehause and 416 units of Lwyon are suggested to be stored in the stack buffer.

- Regarding the storage of raw material, 18 units of raw material two is suggested to be stored in the factory.
- It is suggested to deliver 4500 units of Gehause from stack buffer to customer one, 2500 units of Gehause from stack buffer to customer two, 1800 units of Lwyon from stack buffer to customer one, and finally 1000 units of Lwyon from stack buffer to customer two.
- Regarding the distribution plan for customer three, it is suggested to deliver 2500 units of Gehause from stack buffer to warehouse one, and then from warehouse one to customer three. As for product two, 1200 units of Lwyon is delivered from stack buffer to warehouse one, and then from warehouse one to customer three.

It should be noted that above decisions will be implemented during the first month of the planning horizon and these decisions will be revised every other ten day by employing this hybrid approach.

CHAPTER SIX
CONCLUSION

In today's competitive environment, customer satisfaction is an important factor for continuousness of companies' existence. In other words, to respond customer orders quickly plays an important role in order to get reputation in the market and to avoid paying penalty costs.

Setting the order promising times realistically results in more attainable goals, hence avoids dissatisfaction of the customers. In many MRP environments, order promising times are based on the estimated flow time of an order plus some slack. Several order promising time assignment methods have been proposed in literature. But most of these methods ignore the dynamic and stochastic nature of manufacturing systems.

It should be noted that setting the order promising times is even a more difficult problem to solve in supply chain environment since supply chains are composed of independent suppliers, manufacturers, customers and all of them are a separate business entity searching for maximizing its own profits.

This study suggests a hybrid approach for setting realistic order promising times for a produce-order manufacturing company operating within a supply chain environment. This hybrid approach combines the analytical and simulation modeling to bring together the advantages of both approaches and to mitigate their disadvantages. An analytical model is a set of equations which tends to find an exact solution under some simplified assumptions. Unlike an analytical model, a simulatiom model is an operating model of a system which takes into consideration dynamic and stochastic factors such as unexpected delays, breakdowns. However, a simulation model is not a prescriptive tool, rather it is a descriptive tool and it provides approximate solutions. Therefore, the combination of two models may give better solutions.

This hybrid approach involves three steps. In the first step, an analytic model minimizing the overall costs of production, distribution, transportation, inventory holding, and shortage costs subject to the various kinds of constraints is developed to generate optimum production and distribution plans. In the second step, another analytic model which incorporates these production plans as input is developed to generate optimal scheduling decisions. In the last step, a simulation model which reflects the dynamic and stochastic nature of manufacturing environment is utilized to estimate OPTs realistically.

Besides giving a conceptual framework for the proposed three-step hybrid approach, this study also focuses on a real-world industrial case study and illustrates the implementation of each step in detail. It is hoped that this study will create more awareness on the need of integrating analytical approaches and simulation modeling to deal more efficiently with production planning and scheduling problem in a supply chain environment. As a result, more practitioners and academicians will be attracted to this research area.

As a future work, this study can be extended to deal with the problem of determining optimal batch sizes in a multi-period multi-product manufacturing environment. Another extension could be to add more generic futures to the simulation model developed so that it can be easily adapted to other manufacturing environments.

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APPENDICES

Appendix A. Results of the Supply Chain Production and Distribution Problem

Variable	Value	Reduced Cost
X111	0.000000	0.000000
X121	9504.000	0.000000
X131	0.000000	0.000000
X141	0.000000	0.000000
X151	0.000000	0.000000
IIA11	0.000000	4.500000
IIE11	0.000000	0.000000
X211	0.000000	0.000000
X221	4216.000	0.000000
X231	0.000000	4.000000
X241	0.000000	0.000000
X251	0.000000	0.000000
IIA21	0.000000	0.4800000E-02
IIE21	0.000000	4.995200
X112	0.000000	0.000000
X122	10784.00	0.000000
X132	0.000000	0.000000
X142	0.000000	0.000000
X152	0.000000	0.000000
IIA12	0.000000	2.003400
IIE12	0.000000	5.996600
X212	0.000000	0.000000
X222	1984.000	0.000000
X232	0.000000	4.000000
X242	0.000000	0.000000
X252	0.000000	0.000000
IIA22	0.000000	0.9952000
IIE22	0.000000	5.004800
X113	0.000000	0.000000
X123	4616.000	0.000000
X133	0.000000	0.000000
X143	0.000000	0.000000
X153	0.000000	0.000000
IIA13	0.000000	17.15640

IIE13	0.000000	0.000000
X213	0.000000	0.000000
X223	4504.000	0.000000
X233	0.000000	4.000000
X243	0.000000	0.000000
X253	0.000000	0.000000
IIA23	0.000000	19.10230
IIE23	0.000000	0.000000
Y11	9504.000	64.65980
IJA11	4.000000	0.000000
IJE11	0.000000	16.50000
Y21	4216.000	40.10230
IJA21	216.0000	0.000000
IJE21	0.000000	17.00000
Y12	10784.00	53.15980
IJA12	2388.000	0.000000
IJE12	0.000000	12.00000
Y22	1984.000	39.09750
IJA22	0.000000	16.00000
IJE22	0.000000	0.000000
Y13	4616.000	59.15640
IJA13	4.000000	0.000000
IJE13	0.000000	0.000000
Y23	4504.000	64.10230
IJA23	4.000000	0.000000
IJE23	0.000000	0.000000
E11	95.04000	0.000000
IKA11	0.000000	1.500000
IKE11	0.000000	5.000000
E21	55.80000	0.000000
IKA21	17.85600	0.000000
IKE21	0.000000	8.000000
E31	126.4032	0.000000
IKA31	0.000000	2.000000
IKE31	0.000000	4.000000
E41	0.000000	16.50000
IKA41	0.000000	0.000000
IKE41	0.000000	5.500000
E51	29.09040	0.000000

IKA51	0.000000	4.000000
IKE51	0.000000	4.000000
E12	107.8400	0.000000
IKA42	0.000000	0.000000
IKE12	0.000000	1.000000
E22	0.000000	2.000000
IKA22	0.000000	3.000000
IKE22	0.000000	4.000000
E32	143.4272	0.000000
IKA32	0.000000	0.000000
IKE32	0.000000	6.000000
E42	0.000000	15.00000
IKE42	0.000000	10.00000
E52	44.76720	0.000000
IKA52	31.07760	0.000000
IKE52	0.000000	9.000000
E13	46.16000	0.000000
IKA43	0.000000	0.000000
IKE13	0.000000	0.000000
E23	40.53600	0.000000
IKA23	0.000000	8.000000
IKE23	0.000000	0.000000
E33	61.39280	0.000000
IKA33	0.000000	12.00000
IKE33	0.000000	0.000000
E43	0.000000	13.00000
IKE43	0.000000	0.000000
E53	0.000000	3.000000
IKA53	0.000000	10.00000
IKE53	0.000000	0.000000
LA11	4.000000	0.000000
LE11	0.000000	9.000000
LA21	216.0000	0.000000
LE21	0.000000	11.00000
LA12	2388.000	0.000000
LE12	0.000000	10.00000
LA22	0.000000	8.000000
LE22	0.000000	4.000000
LA13	4.000000	0.000000

LE13	0.000000	9.000000
LA23	4.000000	0.000000
LE23	0.000000	11.00000
PA111	0.000000	3.000000
PE111	0.000000	10.00000
PA211	0.000000	3.000000
PE211	0.000000	8.000000
PA121	0.000000	3.000000
PE121	0.000000	8.000000
PA221	0.000000	3.000000
PE221	0.000000	10.00000
PA112	0.000000	3.000000
PE112	0.000000	10.00000
PA212	0.000000	11.00000
PE212	0.000000	0.000000
PA122	0.000000	7.000000
PE122	0.000000	5.000000
PA222	0.000000	10.00000
PE222	0.000000	1.000000
PA113	0.000000	11.00000
PE113	0.000000	3.000000
PA213	0.000000	7.000000
PE213	0.000000	2.000000
PA123	0.000000	9.000000
PE123	0.000000	4.000000
PA223	0.000000	6.000000
PE223	0.000000	4.000000
QA111	0.000000	13.00000
QE111	0.000000	0.000000
QA211	0.000000	11.00000
QE211	0.000000	0.000000
QA121	0.000000	12.00000
QE121	0.000000	0.000000
QA221	0.000000	9.000000
QE221	0.000000	0.000000
QA131	0.000000	13.00000
QE131	0.000000	0.000000
QA231	0.000000	9.000000
QE231	0.000000	0.000000

QA112	0.000000	13.00000
QE112	0.000000	0.000000
QA212	0.000000	11.00000
QE212	0.000000	0.000000
QA122	0.000000	12.00000
QE122	0.000000	0.000000
QA222	0.000000	9.000000
QE222	0.000000	0.000000
QA132	0.000000	13.00000
QE132	0.000000	0.000000
QA232	0.000000	10.00000
QE232	0.000000	0.000000
QA113	0.000000	13.00000
QE113	0.000000	0.000000
QA213	0.000000	15.00000
QE213	0.000000	0.000000
QA123	0.000000	12.00000
QE123	0.000000	0.000000
QA223	0.000000	12.00000
QE223	0.000000	0.000000
QA133	0.000000	13.00000
QE133	0.000000	0.000000
QA233	0.000000	9.000000
QE233	0.000000	0.000000
LP111	2500.000	0.000000
LP211	1200.000	0.000000
LP112	2600.000	0.000000
LP212	600.0000	0.000000
LP113	2000.000	0.000000
LP213	1500.000	0.000000
LP121	0.000000	0.000000
LP221	0.000000	4.000000
LP122	0.000000	0.000000
LP222	0.000000	4.000000
LP123	0.000000	4.000000
LP223	0.000000	4.000000
LQ111	4500.000	0.000000
LQ211	1800.000	0.000000
LQ112	2400.000	0.000000

LQ212	1000.000	0.000000
LQ113	3000.000	0.000000
LQ213	1500.000	0.000000
LQ121	2500.000	0.000000
LQ221	1000.000	0.000000
LQ122	3400.000	0.000000
LQ222	600.0000	0.000000
LQ123	2000.000	0.000000
LQ223	1500.000	0.000000
LQ131	0.000000	3.000000
LQ231	0.000000	3.000000
LQ132	0.000000	3.000000
LQ232	0.000000	3.000000
LQ133	0.000000	3.000000
LQ233	0.000000	3.000000
PQ1111	0.000000	1.000000
PQ2111	0.000000	1.000000
PQ1112	0.000000	1.000000
PQ2112	0.000000	1.000000
PQ1113	0.000000	1.000000
PQ2113	0.000000	1.000000
PQ1121	0.000000	2.000000
PQ2121	0.000000	2.000000
PQ1122	0.000000	2.000000
PQ2122	0.000000	2.000000
PQ1123	0.000000	2.000000
PQ2123	0.000000	2.000000
PQ1131	2500.000	0.000000
PQ2131	1200.000	0.000000
PQ1132	2600.000	0.000000
PQ2132	600.0000	0.000000
PQ1133	2000.000	0.000000
PQ2133	1500.000	0.000000
PQ1211	0.000000	5.000000
PQ2211	0.000000	1.000000
PQ1212	0.000000	5.000000
PQ2212	0.000000	1.000000
PQ1213	0.000000	1.000000
PQ2213	0.000000	1.000000

PQ1221	0.000000	7.000000
PQ2221	0.000000	3.000000
PQ1222	0.000000	7.000000
PQ2222	0.000000	3.000000
PQ1223	0.000000	3.000000
PQ2223	0.000000	3.000000
PQ1231	0.000000	4.000000
PQ2231	0.000000	0.000000
PQ1232	0.000000	4.000000
PQ2232	0.000000	0.000000
PQ1233	0.000000	0.000000
PQ2233	0.000000	0.000000
IJ11	4.000000	0.000000
IJ21	216.0000	0.000000
IJ12	2388.000	0.000000
IJ22	0.000000	0.000000
IJ13	4.000000	0.000000
IJ23	4.000000	0.000000
II11	0.000000	0.000000
II21	0.000000	0.000000
II12	0.000000	0.000000
II22	0.000000	0.000000
II13	0.000000	0.000000
II23	0.000000	0.000000
IK11	0.000000	0.000000
IK21	17.85600	0.000000
IK31	0.000000	0.000000
IK41	0.000000	0.000000
IK51	0.000000	0.000000
IK12	0.000000	0.000000
IK22	0.000000	0.000000
IK32	0.000000	0.000000
IK42	0.000000	0.000000
IK52	31.07760	0.000000
IK13	0.000000	0.000000
IK23	0.000000	0.000000
IK33	0.000000	0.000000
IK43	0.000000	0.000000
IK53	0.000000	0.000000

M121	1188.000	0.000000
M221	527.0000	0.000000
M122	1348.000	0.000000
M222	248.0000	0.000000
M123	577.0000	0.000000
M223	563.0000	0.000000
M231	0.000000	0.000000
M232	0.000000	0.000000
M233	0.000000	0.000000
M141	0.000000	16.00000
M241	0.000000	8.000000
M142	0.000000	0.000000
M242	0.000000	8.000000
M143	0.000000	8.000000
M243	0.000000	8.000000
K11	1188.000	0.000000
K21	527.0000	0.000000
K12	1348.000	0.000000
K22	248.0000	0.000000
K13	577.0000	0.000000
K23	563.0000	0.000000
IKA12	0.000000	3.000000
IKA13	0.000000	5.000000
L11	4.000000	0.000000
L21	216.0000	0.000000
L12	2388.000	0.000000
L22	0.000000	0.000000
L13	4.000000	0.000000
L23	4.000000	0.000000
P111	0.000000	0.000000
P121	0.000000	0.000000
P211	0.000000	0.000000
P221	0.000000	0.000000
P112	0.000000	0.000000
P122	0.000000	0.000000
P212	0.000000	0.000000
P222	0.000000	0.000000
P113	0.000000	0.000000
P123	0.000000	0.000000

P213	0.000000	0.000000
P223	0.000000	0.000000
Q111	0.000000	0.000000
D111	4500.000	0.000000
Q211	0.000000	0.000000
D211	1800.000	0.000000
Q121	0.000000	0.000000
D121	2500.000	0.000000
Q221	0.000000	0.000000
D221	1000.000	0.000000
Q131	0.000000	0.000000
D131	2500.000	0.000000
Q231	0.000000	0.000000
D231	1200.000	0.000000
Q112	0.000000	0.000000
D112	2400.000	0.000000
Q212	0.000000	0.000000
D212	1000.000	0.000000
Q122	0.000000	0.000000
D122	3400.000	0.000000
Q222	0.000000	0.000000
D222	600.0000	0.000000
Q132	0.000000	0.000000
D132	2600.000	0.000000
Q232	0.000000	0.000000
D232	600.0000	0.000000
Q113	0.000000	0.000000
D113	3000.000	0.000000
Q213	0.000000	0.000000
D213	1500.000	0.000000
Q123	0.000000	0.000000
D123	2000.000	0.000000
Q223	0.000000	0.000000
D223	1500.000	0.000000
Q133	0.000000	0.000000
D133	2000.000	0.000000
Q233	0.000000	0.000000
D233	1500.000	0.000000

Appendix B. Results of the Scheduling Problem

Variable	Value	Reduced Cost
CMAX	71.84000	0.000000
Y211	27.48000	0.000000
Y111	20.61000	0.000000
Y212	20.61000	0.000000
Y112	16.86000	0.000000
Y213	10.62000	0.000000
Y113	3.750000	0.000000
Y214	3.750000	0.000000
Y114	0.000000	1.000000
Y215	34.35000	0.000000
Y115	30.60000	0.000000
Y221	17.49000	0.000000
Y121	8.070000	0.000000
Y311	37.17000	0.000000
Y312	28.57000	0.000000
Y313	17.49000	0.000000
Y314	10.62000	0.000000
Y315	41.22000	0.000000
Y321	21.54000	0.000000
Y411	42.34000	0.000000
Y412	32.62000	0.000000
Y413	21.54000	0.000000
Y414	14.67000	0.000000
Y415	45.27000	0.000000
Y421	30.47000	0.000000
Y41111	42.34000	0.000000
Y41113	0.000000	0.000000
Y41211	32.62000	0.000000
Y41213	0.000000	0.000000
Y41311	21.54000	0.000000
Y41313	0.000000	0.000000
Y41411	0.000000	0.000000
Y41413	14.67000	0.000000
Y41511	0.000000	0.000000
Y41513	45.27000	0.000000
Y42102	30.47000	0.000000

Y42104	0.000000	0.000000
Y41121	52.10000	0.000000
Y41122	0.000000	0.000000
Y41123	0.000000	0.000000
Y41124	0.000000	0.000000
Y41221	0.000000	0.000000
Y41222	0.000000	0.000000
Y41223	0.000000	0.000000
Y41224	43.85000	0.000000
Y41321	0.000000	0.000000
Y41322	0.000000	0.000000
Y41323	31.26000	0.000000
Y41324	0.000000	0.000000
Y41421	0.000000	0.000000
Y41422	0.000000	0.000000
Y41423	0.000000	0.000000
Y41424	25.27000	0.000000
Y41521	0.000000	0.000000
Y41522	0.000000	0.000000
Y41523	0.000000	0.000000
Y41524	55.87000	0.000000
Y511	63.94000	0.000000
Y512	55.87000	0.000000
Y513	51.92000	0.000000
Y514	37.29000	0.000000
Y515	67.89000	0.000000
Y521	60.19000	0.000000
G11112	0.000000	0.000000
G11113	0.000000	0.000000
G11121	0.000000	0.000000
G11213	0.000000	0.000000
G11221	0.000000	0.000000
G11321	1.000000	0.000000
G21112	0.000000	-50000.00
G21113	0.000000	0.000000
G21121	0.000000	0.000000
G21213	0.000000	0.000000
G21221	0.000000	-50000.00
G21321	1.000000	50000.00

G31112	0.000000	0.000000
G31113	0.000000	0.000000
G31121	0.000000	0.000000
G31213	0.000000	0.000000
G31221	0.000000	0.000000
G31321	1.000000	0.000000
G51112	0.000000	0.000000
G51113	0.000000	0.000000
G51121	0.000000	0.000000
G51213	0.000000	0.000000
G51221	1.000000	0.000000
G51321	1.000000	0.000000
G11114	0.000000	0.000000
G11214	0.000000	0.000000
G11314	0.000000	0.000000
G21114	0.000000	0.000000
G21214	0.000000	0.000000
G21314	0.000000	-50000.00
G31114	0.000000	0.000000
G31214	0.000000	0.000000
G31314	0.000000	0.000000
G51114	0.000000	0.000000
G51214	0.000000	0.000000
G51314	0.000000	0.000000
G11421	1.000000	0.000000
G21421	1.000000	0.000000
G31421	1.000000	0.000000
G51421	1.000000	0.000000
G11115	1.000000	0.000000
G11215	1.000000	0.000000
G11315	1.000000	0.000000
G21115	1.000000	50000.00
G21215	1.000000	0.000000
G21315	1.000000	0.000000
G31115	1.000000	0.000000
G31215	1.000000	0.000000
G31315	1.000000	0.000000
G51115	1.000000	0.000000
G51215	1.000000	0.000000

G51315	1.000000	0.000000
G11521	0.000000	0.000000
G21521	0.000000	0.000000
G31521	0.000000	0.000000
G51521	0.000000	0.000000
G11415	1.000000	0.000000
G21415	1.000000	0.000000
G31415	1.000000	0.000000
G51415	1.000000	0.000000
G41111211	0.000000	0.000000
A1111	1.000000	0.000000
A1211	1.000000	0.000000
A1113	0.000000	0.000000
G41111311	0.000000	0.000000
A1311	1.000000	0.000000
G41211311	0.000000	0.000000
A1213	0.000000	0.000000
G41121221	0.000000	0.000000
A1121	1.000000	0.000000
A1221	0.000000	0.000000
A1122	0.000000	0.000000
A1123	0.000000	0.000000
A1124	0.000000	0.000000
G41121321	0.000000	0.000000
A1321	0.000000	0.000000
G41221321	1.000000	0.000000
A1222	0.000000	0.000000
A1223	0.000000	0.000000
A1224	1.000000	0.000000
G41111121	1.000000	0.000000
G41111221	0.000000	0.000000
G41211221	0.000000	0.000000
G41211321	0.000000	0.000000
G41311321	0.000000	0.000000
A1313	0.000000	0.000000
G41111123	0.000000	0.000000
G41111223	0.000000	0.000000
G41111323	0.000000	0.000000
A1323	1.000000	0.000000

G41211223	0.000000	0.000000
G41211323	1.000000	0.000000
G41121222	0.000000	0.000000
G41121322	0.000000	0.000000
A1322	0.000000	0.000000
G41221322	0.000000	0.000000
G41122102	1.000000	0.000000
A2102	1.000000	0.000000
G41222102	1.000000	0.000000
G41322102	0.000000	0.000000
A1324	0.000000	0.000000
G41111213	0.000000	0.000000
G41111313	0.000000	0.000000
G41211313	0.000000	0.000000
G41121223	1.000000	0.000000
G41121323	0.000000	0.000000
G41221323	0.000000	0.000000
G41121224	0.000000	0.000000
G41121324	1.000000	0.000000
G41221324	0.000000	0.000000
G41122104	0.000000	0.000000
A2104	0.000000	0.000000
G41222104	0.000000	0.000000
G41322104	0.000000	0.000000
G41211111	1.000000	0.000000
G41311111	1.000000	0.000000
G41311211	1.000000	0.000000
G41221121	0.000000	0.000000
G41321121	0.000000	0.000000
G41321221	0.000000	0.000000
G41121111	0.000000	0.000000
G41221111	0.000000	0.000000
G41221211	0.000000	0.000000
G41321211	0.000000	0.000000
G41321311	1.000000	0.000000
G41121113	0.000000	0.000000
G41221113	0.000000	0.000000
G41321113	0.000000	0.000000
G41221213	0.000000	0.000000

G41321213	0.000000	0.000000
G41221122	0.000000	0.000000
G41321122	0.000000	0.000000
G41321222	0.000000	0.000000
G42101122	0.000000	0.000000
G42101222	0.000000	0.000000
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Appendix C. Arena program for the production system