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GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

PRODUCTION PLANNING IMPLEMENTATION IN A REAL LIFE SYSTEM

by
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İZMİR

PRODUCTION PLANNING IMPLEMENTATION IN A REAL LIFE SYSTEM

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M.Sc THESIS EXAMINATION RESULT FORM

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PRODUCTION PLANNING IMPLEMENTATION IN A REAL LIFE SYSTEM

ABSTRACT

Nowadays, the integration of production planning and order acceptance decisions has an important subject for make-to-order production systems. Production companies try to accept orders which provide more profit in a competitive environment. In contrast to classical production planning problems, capacity constrained short-term production planning problem which contains decisions about order acceptance, selling price and due date assignment for orders was studied for make-to-order production systems in this thesis. Regular time, overtime and subcontracting are considered as source options. Moreover, the mixed-integer non-linear programming model where selling prices and due dates are constant parameters and the multi-objective mixed-integer non-linear programming model where selling prices and due dates are decision variables were developed. The linearization method was applied to these non-linear mathematical programming models. The mixed-integer linear programming model where selling prices and due dates are constant parameters and the multi-objective mixed-integer linear programming model where selling prices and due dates are decision variables were developed after an application of the linearization method and these models were solved by using Lingo 14.0 software. In order to solve the multi-objective mixed-integer linear programming model where selling prices and due dates are decision variables, ε-constraint method was used. Proposed multi-objective mixed-integer linear programming model where selling prices and due dates are decision variables was implemented in the automotive brake disc manufacturing company in order to analyze the results of the model in a real life system.

Keywords: Production planning, order acceptance decision, selling price assignment, due date assignment, mathematical programming, linearization method, make-to-order production systems

BİR GERÇEK HAYAT SİSTEMİNDE ÜRETİM PLANLAMA UYGULAMASI

ÖZ

Günümüzde, üretim planlama ve sipariş kabul kararlarının entegre edilmesi siparişe göre üretim yapan sistemler için önemli bir konudur. Üretim firmaları rekabet ortamında daha fazla kar sağlayacak siparişleri kabul etmeye çalışmaktadır. Bu tezde, klasik üretim planlama problemlerinin aksine siparişlerin kabul edilmesi, siparişlerin satış fiyatları ve teslim tarihlerinin atanmasıyla ilgili kararları içeren kapasite kısıtlı kısa dönem üretim planlama problemi, siparişe göre üretim yapan sistemler için çalışılmıştır. Normal mesai, fazla mesai ve fason üretim kaynak alternatifleri olarak düşünülmektedir. Ayrıca, siparişlerin satış fiyatlarının ve teslim tarihlerinin sabit parametreler olduğu karışık tamsayılı doğrusal olmayan programlama modeli ve siparişlerin satış fiyatlarının ve teslim tarihlerinin karar değişkeni olduğu çok amaçlı karışık tamsayılı doğrusal olmayan programlama modeli geliştirilmiştir. Doğrusal olmayan bu matematiksel programlama modellerine doğrusallaştırma yöntemi uygulanmıştır. Doğrusallaştırma yöntemi uygulamasından sonra, siparişlerin satış fiyatlarının ve teslim tarihlerinin sabit parametreler olduğu karışık tamsayılı doğrusal programlama modeli ve siparişlerin satış fiyatlarının ve teslim tarihlerinin karar değişkeni olduğu çok amaçlı karışık tamsayılı doğrusal programlama modeli geliştirilmiştir ve bu modeller Lingo 14.0 yazılımı kullanılarak çözülmüştür. Siparişlerin satış fiyatlarının ve teslim tarihlerinin karar değişkeni olduğu çok amaçlı karışık tamsayılı doğrusal programlama modelini çözmek amacıyla ε-kısıt yöntemi kullanılmıştır. Siparişler için satış fiyatlarının ve teslim tarihlerinin karar değişkeni olduğu, önerilen çok amaçlı karışık tamsayılı doğrusal programlama modeli sonuçların bir gerçek hayat sisteminde analiz edilmesi için otomobil fren diski imalat firmasında uygulanmıştır.

Anahtar kelimeler: Üretim planlama, sipariş kabul kararı, satış fiyatı atama, teslim tarihi atama, matematiksel programlama, doğrusallaştırma yöntemi, siparişe göre üretim sistemleri

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CHAPTER ONE
INTRODUCTION

1.1 Background

Nowadays, the integration of production planning and order acceptance decisions has an important role in production. Although revenue management (RM) is applied in service sector like airlines, hotels, cruise lines, rental car companies, the importance of the application of RM in make-to-order production systems has been increasing. Make-to-order production systems apply order acceptance strategy which is generally used in RM in order to determine profitable orders.

Production companies who apply order acceptance strategy consider in-house capacity and outsourcing capacity and their processing costs in order to determine selling prices and due dates which bring high profit. Because production cost, the value of selling price and due date affect the profit of producers.

Production planners must consider selling price, due date and order acceptance decisions in addition to capacity constraints, in contrast to the classical production planning applications. Because, production companies try to reach their goals in a competitive environment.

1.2 Scope and Research Goals of Thesis

The capacity constrained short-term production planning problem which has order acceptance, selling price, due date decisions in order to gain higher total net profit for make-to-order production system was studied in this thesis, in contrast to classical production planning problems.

In this thesis, the mathematical formulation of the model which was proposed by Chen, Mestry, Damodaran, & Wang (2009) was revised and some wrong constraints were reformulated. More detailed information about revisions and reformulations on the constraints of the study of Chen et al. (2009) is available in Chapter 6. The mixed-integer non-linear programming model where selling prices and due dates are constant parameters and the multi-objective mixed-integer non-linear programming model where selling prices and due dates are decision variables were developed in this thesis. Considering the selling prices and due dates as decision variables, in contrast to study of Chen et al. (2009) has changed the functioning logic of the model. Moreover, this practical improvement, revisions and reformulations were improved the model of Chen et al. (2009). There are two objectives in the multi-objective mixed-integer non-linear programming model where selling prices and due dates are decision variables. These are, the total net profit maximization and the total due date minimization.

The linearization method in the explanations of Coelho (2013) was applied to the non-linear mathematical programming models. The mixed-integer linear programming model where selling prices and due dates are constant parameters and the multi-objective mixed-integer linear programming model where selling prices and due dates are decision variables were developed after an application of the linearization method and these models were solved by using Lingo 14.0 software. The multi-objective mixed-integer linear programming model where selling prices and due dates are decision variables was solved by using ε-constraint method. More detailed information about the solution method of the problem and the linearization method is available in Chapter 6.

The purpose of the thesis is developing the mathematical programming model in order to make a short-term production planning with selling price, due date and order acceptance decisions and many other practical constraints for make-to-order production system. Selling prices and due dates which are constant parameters in the model of Chen et al. (2009) were transformed into decision variables in order to reach the purpose of this thesis.

Mixed-integer linear programming model where selling prices and due dates are constant parameters was tested under different resource utilization rates. Scenarios were created for testing the multi-objective mixed-integer linear programming model where selling prices and due dates are decision variables according to different value range of selling prices and due dates under different resource utilization rates. The proposed multi-objective mixed-integer linear programming model was implemented in the automotive brake disc manufacturing company which is in Manisa industrial zone, in order to analyze the results of the model in a real life.

1.3 Structure of the Thesis

There are nine chapters in this thesis and organized as follows. The background, scope and research goals of thesis are presented in Chapter 1.

In Chapter 2, literature review which is categorized according to sections is presented. The literature review about price and due date decisions, order acceptance and bid price strategies in revenue management, integration of production planning and revenue management decisions, subcontracting and overtime options in production planning take part in this chapter as sections.

In Chapter 3, the information about the production systems and production planning is given. Characteristics of make-to-order production systems, differences between make-to-order and make-to stock production systems, lead time, steps of production planning, demand management, capacity management, order fulfillment are explained in this chapter.

Chapter 4 begins with revenue management definitions. Steps and levels of revenue management, the pricing and revenue optimization (PRO) and dynamic pricing with examples are explained in this chapter.

In Chapter 5, revenue management in manufacturing companies and make-to-order production systems, revenue management for production planning and order acceptance strategy are explained.

In Chapter 6, the capacity constrained short-term production planning problem which has order acceptance, selling price and due date decisions for make-to-order production system, solution method of the problem and linearization method are explained. More detailed information about the mathematical formulation of the problem is available in this chapter. The mixed-integer non-linear programming model and the multi-objective mixed-integer non-linear programming model are explained in this chapter. Furthermore, detailed information about the application of the linearization method to non-linear constrains and non-linear objective functions is available in this chapter. Linear form of non-linear constraints and non-linear objective functions take part in this chapter, the mixed-integer linear programming model and the multi-objective mixed-integer linear programming model are presented in Appendix 1 and Appendix 2.

In Chapter 7, the mixed-integer linear programming model where selling prices and due dates are constant parameters is solved in order to test the four examples in the study of Chen et al. (2009) and solution results are explained. The mixed-integer linear programming model where selling prices and due dates are constant parameters is solved in order to test the base case in the study of Chen et al. (2009) under different resource utilization rates and solution results are explained. Also, twelve scenarios are compared for the multi-objective mixed-integer linear programming model where selling prices and due dates are decision variables according to different value range of selling prices and due dates under different resource utilization rates in this chapter.

In Chapter 8, the case study in the brake disc manufacturing company is explained. The results of the proposed multi-objective mixed-integer linear programming model which is implemented in the brake disc manufacturing company are explained in this chapter.

Finally, the conclusion which contains summary of the thesis and future research is provided in Chapter 9.

CHAPTER TWO
LITERATURE REVIEW

2.1 Price and Due Date Decisions

Make-to-order (MTO) firms need to determine due date and price quotation according to capacity planning in a competitive environment (H. Zhou & S. Zhou, 2009). Weng (1996) presented a model about manufacturing lead time planning problem for make-to-order production systems where lead time sensitive and lead time insensitive customers had been. The purpose of the study is increasing the utilization rate of the system where manufacturing flow times are stochastic. The problem was modeled as a queuing system, so lead time sensitive customers had a priority and there was a first come first served (FCFS) discipline for each order group. Although, the earliness and tardiness costs were considered for time sensitive customers, these costs were not considered for lead time insensitive customers. Palaka, Erlebacher, & Kropp (1998) studied capacity utilization, lead time setting and pricing decisions for make-to-order production system for maximizing the revenue. Customers which had lead time dependent demand were served on a first come first served basis and they assumed that customers arrived by Poisson process and processing times of the orders were exponentially distributed. Also, lateness penalty cost, production cost and work-in-process (WIP) inventory cost were considered in this study. Moodie (1999) researched strategies of price and due date negotiation. According to Moodie's problem, firm's purpose is maximizing its long term net revenue and bidding process defines the firm's demand management negotiation strategy. Moodie (1999) considered only price and due date, quality was not considered in this study. Moodie & Bobrowski (1999) considered demand management in a job shop where the number of potential customers were affected from past delivery service level. The firm can make a negotiation with customers about the over price and promised delivery date. Penalties for early or tardy jobs and inventory holding costs were ignored and they assumed that rejecting the customers' order would not affect the future potential orders in this study. Moodie (2013) presented a research in order to test overtime policies by using different negotiation strategies which are related with price and due date. Also, the important points of overtime negotiation strategy and determination of the overtime necessity were studied. Germs & Van Foreest (2013) extended the Markov Decision Process (MDP) model of Germs & Van Foreest (2011). They analyzed the benefits of lead time which depend on family and introduced two simple heuristic policies. The objective of their model is maximizing long-run average reward. They assumed that customers arrived according to Poisson process and inter-arrival times were independent and distributed exponentially. Xiao, Shi, & Chen (2014) developed a game theoretic model in order to study the price and lead time competition for make-to-order supply chains. They considered one manufacturer and one retailer where consumers were sensitive to lead time and price. Also, they created two scenarios which were lead time-decision-first scenario and wholesale-price-decision-first scenario for examining the effect of the sequence of decisions about the price and lead time.

Some authors studied a pricing and due date setting problem with contingent orders. In the study of Easton & Moodie (1999), a model which included pricing and due date decisions with contingent orders for make-to-order production systems was proposed. Static and single source case was considered and the goal of the model was determining the price and lead time for orders. Watanapa & Techanitisawad (2005) extended Easton & Moodie's (1999) model to a model with multiple customer segments. They modified the winning probability function in order to define the stochastic nature of customer's decision. Earliest due date (EDD) for time critical orders and first come first served (FCFS) for regular orders were applied as sequencing rules. A simplified pattern search algorithm was used for searching optimal price and due date more efficiently. H. Zhou & S. Zhou (2009) extended Easton & Moodie's (1999) model with considering service level constraints. They modified the respond function for explaining the effect of delivery confidence on customer by average service level. The purpose of the study is optimizing price and lead time under service level constraints with contingent orders. S. C. Liu & C. H. Liu (2009) studied a simultaneous pricing, due date setting and scheduling problem (SPDSP) with contingent orders in make-to-order production system. They used a hybrid heuristic which contained Tabu Search (TS) and Simulated Annealing (SA) in order to search the non-polynomial problem more effective than pure global search heuristic methods.

2.2 Order Acceptance and Bid Price Strategies in Revenue Management

Revenue management (RM) is a systematic approach for evaluating the opportunity costs of accepting or rejecting orders (Martinez & Arredondo, 2010). Selection of orders according to their contribution is generally used in revenue management (Spengler, Volling, Wittek, & Akyol, 2008). Bid price is a popular approach for capacity control in revenue management (Spengler et al., 2008). Miller (1969) considered the system which included *n* server and *m* customer classes in an infinite planning horizon. Objective of the study is accepting or rejecting customers in order to maximize the expected rewards. Miller (1969) assumed that there were Poisson arrivals and exponential service time and there was not a backlogging or preemption in the study. Lippman & Ross (1971) studied the problem which was formulated as a semi-Markov decision process for maximizing the long run average return in a single server traffic reward system. Balachandran & Schaefer (1981) presented a non-linear model in order to solve the optimal acceptance of job orders. They assumed that orders for several products came to the system by Poisson process. Matsui (1985) presented a stochastic model for job shop control and discussed the economics of job shop production. Semi-Markov decision process, the operation rate, reward rate and mean shop time were used for formulating the model. Also, Poisson process was used as an arrival of jobs and first come first served (FCFS) discipline was used in the study. Six order selection strategies were created and these strategies were compared. Akkan (1997) developed heuristics in order to minimize the cost of rejecting orders and inventory holding cost due to the early completion of orders. The performance of these heuristics was compared with some common heuristics by simulation experiments. McGill & Van Ryzin (1999) presented a survey about the revenue management. This survey includes an overbooking control, forecasting, pricing and seat inventory control. Lewis & Slotnick (2002) examined the multi-period job selection problem in order to maximize profit with considering processing cost and weighted lateness cost. Their model guarantees timeliness with money-back guarantees and job selection decisions affect future orders. They presented an optimal dynamic programming and developed a number of myopic heuristics. Also, processing times, revenues and due dates are known in the model. Barut & Sridharan (2005) searched the effectiveness of a tactical demand-capacity management policy for order driven production systems in order to maximize revenue. Order acceptance and rejection policies are used for multiple product classes when demand exceeds capacity over the short term. Rehkopf & Spengler (2005) provided a mathematical formulation about network problem in make-to-order systems and their model depends on the stochastic dynamic programming approach. Also, order acceptance and rejection decisions were studied. Spengler, Rehkopf, & Volling (2007) provided a decision support system for accepting or rejecting orders for short term sales in order to maximize profit in iron and steel industry. They implemented a static bid price approach for selecting orders and they used the formulation of multi-dimensional knapsack problem in order to determine the bid prices. The different side of this study is converting the multi-dimensional problem to one dimensional problem. Spengler et al. (2008) extended traditional bid price based revenue management by using dynamic bid price policies in make-to-order production systems. Hintsches, Spengler, Volling, Wittek, & Priegnitz (2010) implemented linear programming approach for real life application of revenue management in make-to-order production system. They used simulation in order to incorporate the characteristics of the real world process. Components of their simulation model are demand generation, simulation of order acceptance, determination of shadow price and collection of statistics. First come first served (FCFS) policy, deterministic linear programming (DLP) bid price policy and randomized linear programming (RLP) bid price policy were analyzed in this study. Martinez & Arredondo (2010) proposed a novel approach for order acceptance policy in make-to-order production system. Their approach is related with learning and updating an order acceptance policy dynamically. Arredondo & Martinez (2010) developed a novel approach about dynamic order acceptance under uncertainty for make-to-order production system. Effectiveness of different order acceptance heuristics were compared and Average-Reward Reinforcement Learning for Order Acceptance (ARLOA) algorithm was proposed in this study. Cheraghi, Dadashzadeh, & Venkitachalam (2010) presented a survey about the revenue management. Their survey contains three category, these are capacity management, marketing segmentation and pricing. Volling, Akyol, Wittek, & Spengler (2012) proposed a two stage bid price control approach for the revenue management in make-to-order production systems.

2.3 Integration of Production Planning and Revenue Management Decisions

Order acceptance and capacity allocation decisions have an important impact for make-to-order firm's performance when demand is more than firm's capacity (Fan & Chen, 2008). Because unused capacity is a lost revenue for make-to-order firms (Chen et al., 2009). Models which integrate production planning and order acceptance decisions help to increase the overall profit of the company (Brahimi, 2014). Harris & Pinder (1995) presented the model about pricing and capacity reallocation in assemble to order environment. Also, this study gives an information about characteristics of revenue management environment and components of revenue management systems. Kapuscinski & Tayur (2000) studied a basic discrete time model about the dynamic capacity reservation in order to minimize the total expected cost for make-to-order production systems. The sensitivity of the waiting time changes according to customer type. There is no inventory and late shipment is not permitted in the study. Calosso, Cantamessa, Vu, & Villa (2003) studied negotiation process which was integrated with production planning and they proposed three mixed integer linear programming models. Ashayeri & Selen (2003) developed a strategic aggregate production planning model which supported decisions at the aggregate level with regard to order acceptance, purchasing and detailed production planning. Also, the mixed integer linear programming model was tested in pharmaceutical company in Netherlands. Gupta & Wang (2004) searched the effect of capacity choices and demand uncertainty on the optimal profit and they analyzed two scenarios. Although all orders are produced in a make-to-order fashion in the first scenario, finished goods inventory is kept for contractual orders in the second scenario. They formulated the problem as a Markov Decision Process and considered two types of order. Defregger & Kuhn (2007) considered the capacity allocation problem for make-to-order company with limited inventory capacity. They proposed a heuristic for their model and used a discrete time Markov decision in their problem. They tried to give a decision about how much capacity should be saved for high value customers without rejecting many orders which come from low value customers. In this study, they also considered that how much inventory should be saved for high value customers. Fan & Chen (2008) proposed a model by using stochastic dynamic programming for make-to-order production systems which had multi-machines and multi-products. Their model is about the order acceptance and capacity allocation. Chen et al. (2009) proposed a linear programming model about short term capacity planning in make-to-order production systems. The study contains order acceptance and rejection decisions in order to maximize the total net profit. According to their model, tardy delivery is not allowed, so orders which are selected can't exceed their due dates. Regular time, overtime and outsourcing were considered as source options in this study. Modarres & Sharifyazdi (2009) presented a capacity allocation problem which was formulated in a static one period model by applying the revenue management. They assumed that the production capacity was stochastic and demands came from frequent customers and occasional customers who paid different prices for the same product. Chaharsooghi, Honarvar, Modarres, & Kamalabadi (2011) studied the role of flexibility of price, delivery and lead time for make-to-order production with limited production capacity. Stochastic demand function was considered, so they developed two stage stochastic programming model in order to determine the production quantity, price and lead time. In this study, due dates and prices set at the beginning of the planning horizon and the production decision is given after the arrival of orders. Mestry, Damodaran, & Chen (2011) used mixed integer linear programming model which had order selection and capacity allocation decisions in make-to-order production system. Branch and price algorithm was used to solve the problem effectively and regular time and overtime were considered as source options in this study. Akbar, Anandipa, & Ma'ruf (2013) solved the capacity planning problem which was based on the study of Mestry et al. (2011) by using the heuristic approach. Brahimi, Aouam, & Aghezzaf (2015) integrated production planning decisions and order acceptance decisions with considering load dependent lead times. They formulated the problem as a mixed integer linear programming and they proposed two relax-and-fix heuristic methods for large size problems.

Some studies on the production planning and order acceptance integration include flexible due date. Kolisch (1998) considered order selection problem simultaneously in order to maximize the revenue. Customers have a time window for due date in this study. According to Kolisch (1998), this study includes three research areas and these are: order selection, resource constrained project scheduling and due date assignment. Charnsirisakskul, Griffin, & Keskinocak (2004) modeled the simultaneous order selection and scheduling problem with lead time flexibility for increasing the revenue. They determined that, when the lead time flexibility is useful in order to increase the profit of manufacturer. Also, tardiness penalty cost for orders which couldn't be completed before the preferred due dates and holding cost for work-in-process inventory were considered. The proposed model is for single machine and multiple products production systems with negligible setup times and no buffers. They compared the benefits of lead time flexibility and partial fulfilling order flexibility by numerical analyses. Brahimi (2014) developed a new production planning problem which contained the integration of order acceptance and due date flexibility with realistic capacity constraints. Also, due date had a time interval and work-in-process inventory was considered in this study. Mixed integer linear programming (MILP) formulation was presented and relax and fixed heuristic was used for the problem.

Setup time and setup costs are considered in some studies which integrate production planning and order acceptance. Wester, Wijngaard, & Zijm (1992) studied the interdependence between production planning, order acceptance and scheduling in a production to order environment which had one bottleneck machine by considering setup times and due dates. Three basic approaches which were about the order acceptance and scheduling were researched and compared by simulation in this study. Özdamar & Yazgaç (1997) proposed a linear capacity planning model in order to minimize backorder and overtime costs for multi-stage make-to-order production systems. The end items in each order were grouped into product families, order due date and setup were considered. Geunes, Romeijn, & Taaffe (2002) provided a model for integrated production planning and order selection in order to maximize the profit. They considered un-capacitated and capacitated versions of the single stage in a set of time period production planning problem. They solved un-capacitated order selection problem (UOS) by using a shortest path network structure. According to their new approach, they interpreted arc lengths in terms of net contribution to profit and they tried to find the longest path in the graph. Also, they discussed a Lagrangian relaxation for capacitated order selection problem and setup cost, inventory holding cost and production cost were considered in this study. Oğuz, Salman, & Yalçın (2010) defined a model about order acceptance and scheduling decisions in order to maximize total revenue for make-to-order production systems. They defined orders according to their due dates, processing times, deadlines, release dates and sequence dependent setup times. They considered a single machine environment and proposed three heuristic algorithms for solving large size problems. Huang, Lu, & Wan (2011) considered the integrated order selection and production scheduling problem with sequence-dependent setup times and setup costs for make-to-order production systems. They formulated the problem as a resource-constrained profitable tour problem (RCPTP) and they developed a heuristic algorithm.

2.4 Subcontracting and Overtime Options in Production Planning

Subcontracting is an important option in order to overcome capacity shortages during high demand periods (Thürer, Stevenson, & Qu, 2015). We can gain the potential maximum benefit from outsourcing by making efficient and effective production plan and schedule (Qi, 2009). Overtime is the other strategy for capacity expansion in production planning.

Lee, Lim, Lee, Jun, & Kim (1997) studied multi-period part selection and loading problems for flexible manufacturing systems in order to minimize subcontracting cost. They decomposed the problem as the part selection problem and the loading problem and they developed three iterative algorithms in order the solve these two problems. Yang, Yan & Sethi (1999) studied the optimal production planning problem in pull flow lines which contained multiple machines and multiple products. The objective of this study is minimizing the total inventory and backlog cost overtime. Coman & Ronen (2000) provided a linear programming formulation about the outsourcing problem in order to determine which products to manufacture and which to outsource. Baykasoglu (2001) formulated the multiple-objective aggregate production planning problem as a pre-emptive goal-programming and this model was solved by multiple-objective Tabu Search algorithm. An object-oriented program which was named as MOAPPS 1.0 (Multiple Objective Aggregate Production Planning Software) was developed during this study. The model which is for multiple product and multiple period includes subcontracting, overtime and setup decisions. Bertrand & Sridharan (2001) developed four different decision rules for make-to-order systems in order to determine which orders to subcontract. The purpose of the study is achieving the high level capacity utilization of in-house capacity. Lee, Jeong, & Moon (2002) studied advanced planning and scheduling (APS) with due date and outsourcing decisions. Their problem includes machine selection for each operation, the decision of operation sequence, makespan minimization and outsourcing. Also, they developed genetic algorithm based heuristic approach in order to solve the problem. Merzifonluoglu, Geunes, & Romeijn (2007) provided a model which integrated capacity, demand and production planning with subcontracting and overtime options in order to maximize the profit. Chen & Li (2008) proposed an analytical model which included subcontracting and detailed job scheduling decisions for make-to-order systems. They tried to determine which orders should be produced in-house and which orders should be subcontracted in order to reduce total production and subcontracting costs. Furthermore, they determined a production schedule for orders that were produced in-house. They developed heuristic and compared their model and the model without subcontracting option for studying the value of subcontracting. Qi (2009) studied a two stage production scheduling problem with outsourcing option. Heuristic algorithm was developed in order to solve the problem and the objective of the problem was minimizing outsourcing cost and makespan. Allocation of jobs between the manufacturer and the outside supplier and making a corresponding schedule for both the in-house production and the outside supplier's production form the problem. Pastor, Altimiras & Mateo (2009) presented a mixed-integer linear programming model for production planning with considering overtime and subcontracting options in a woodturning company. The goal of this study is meeting the demand with minimizing overtime and subcontracting costs. Lusa, Corominas, Olivella & Pastor (2009) proposed a mathematical model for production planning with working time accounts (WTAs). They defined an upper and lower working hours in order to bound normal time and overtime working hours. Thürer, Stevenson, Qu, & Filho (2014) extended the study of Bertrand & Sridharan (2001) by developing four new subcontracting rules for make-to-order systems. They compared four existing rules and new four rules by using a simulation model. Thürer et al. (2015) studied the impact of limited subcontractor capacity for make-to-order companies. They tested the performance of the three best performing subcontracting rules with limited subcontractor capacity.

CHAPTER THREE
PRODUCTION SYSTEMS AND PRODUCTION PLANNING

3.1 Production Systems

Production is an activity which is resulted as a physical existence or a service in order to create the benefit from the management perspective (Kobu, 2010).

3.1.1 Components of Production System

The system is an entire and formed from components which have a relationship each other and come together in order to realize the purpose. Components of the system are inputs, output, conversion (production process), feedback and environment. Production process is the conversion of inputs of the system to product or service in order to create benefit (Kobu, 2010).

According to Kobu (2010), four properties of components which characterize the production process are important, these are:

1. Efficiency: Efficiency is defined as the produced output according to per unit of input.
2. Effectiveness: Effectiveness is defined as the degree of realization of the production system's purposes. Efficiency is the doing things right and effectiveness is doing the right thing. Efficiency measures how well resources are used, but effectiveness determines to what measure the realization of the purposes.
3. Capacity: Capacity measures the degree of production which is realized by production system.
4. Flexibility: Flexibility is responding to the sudden demand changes or starting the production of new products easily.

3.1.2 Decisions of Production System

Decisions of production system are listed below (Kobu, 2010):

1. Process: The most important decision is the selection of the type of the production system. The other decisions are type of machines, layout and degree of automation.
2. Capacity: Volume of the production system, quantity of workforce, number of shift and overtime are capacity decisions.
3. Stocks: Safety stock, meeting the demand timely, effectiveness of the stock registration systems and optimum balance between stock degree, holding cost and order cost are the stock decisions.
4. Workforce: Work measurement, method development, education, work simplification and incentive fee method are workforce decisions in order to use the existing workforce efficiently.
5. Quality: Although production management is not responsible from quality decisions directly, manufacturing and quality control need to give some decisions like determination of quality control points and interpreting the measurement solutions together.

3.2 Make-to-Order (MTO) Production Systems

The characteristics of make-to-order firms are defined by Hendry & Kingsman (1989) and listed below (Easton & Moodie, 1999):

- Predicting the demand of MTO firms is difficult.
- MTO firms have few standard product designs.
- MTO firms rarely have finished goods inventory.
- Capacity planning and scheduling decisions begin when the order comes.
- Capacity may be increased by hiring employee, subcontracting or overtime in busy periods.
- Capacity may be decreased by layoffs or dismissals in slow periods.

Good quality, attractive price, short lead times and technical ability are necessities in order to win customer order in competitive environment where MTO firms operate (Hendry & Kingsman, 1993). While MTO firms want long due date and high price, customers want short due date and low price, so these desires cause conflict under capacity constraints (S. C. Liu & C. H. Liu, 2009).

Lead time estimation and negotiation are important issues for MTO firms (Easton & Moodie, 1999).

1. Lead Time Estimation: Lead time is important for winning orders. Because, tardy deliveries effect future orders negatively and cause a penalty cost (Easton & Moodie, 1999).
2. Negotiation: Negotiation that is between customer and bidder is important for MTO firms in a competitive environment. Determination of boundary between expected profit and loss is the necessity for the manager of MTO firm (Easton & Moodie, 1999).

Each buyer negotiates with several sellers and each seller negotiates with several buyers in the market. Both sellers and buyers want to have the best combination of due date and price (Moodie, 2013) and unused capacity is a lost revenue for MTO firms (Chen et al., 2009).

MTO firms should determine five important points which are listed below for overtime negotiation strategy (Moodie, 2013):

1. Bargaining factors (Price, due date etc).
2. Due date estimation methods.
3. Value of normal time and overtime rates.
4. Overtime policies.
5. Overtime scheduling rules.

3.2.1 Differences Between Make-to-Order (MTO) and Make-to-Stock (MTS) Production Systems

Some differences between MTO and MTS systems are defined by authors in the literature, these are:

1. Standard products are produced in a large quantities and stocked in MTS system. Although products can be modified according to customer requirements, there is not much difference between products in MTS system. Different products are produced in a low value according to customers' design and specification in MTO systems (Muda & Hendry, 2002).
2. While MTS firms achieve customers' orders by inventory, MTO firms can start processing orders after they come (Chen et al., 2009).
3. Whereas MTO firms meet the demand by saving the capacity, MTS firms meet the demand by inventory (Cheraghi et al., 2010).

According to Huang et al. (2011), manufacturing firms have been transferring traditional mass production to mass customization and MTS strategy to MTO strategy.

3.2.2 Price and Due Date Determination for Make-to-Order (MTO) Production Systems

Due date and price management are managerial challenges in today's competitive market, so order segmentation and resource allocation which is based on the order sensitivity to price and time, increase the profit and capacity utilization of the companies (Chaharsooghi et al., 2011).

Price and due date determination is a common dilemma for make-to-order firms. Although the firm suggests long lead time, the firm may deliver before due date. Although the firm suggests short lead time, the firm may deliver late and so service level reputation of the firm reduces (Moodie, 1999).

Demand management negotiation strategy gives an answer about due date quotation and negotiation with price and due date. The following questions are important for the demand management negotiation strategy (Moodie, 1999):

- What is the latest due date which should be considered by the firm?
- What is the earliest due date which can be considered by the firm?
- What should be the price which is given between earliest due date and latest due date by the firm?
- When should the overtime be scheduled?
- Should the negotiation be done over due date and/or price by the firm?
- How will the reactions of competitors be towards to due date and price?
- When should the overall capacity be changed due to forecast orders?

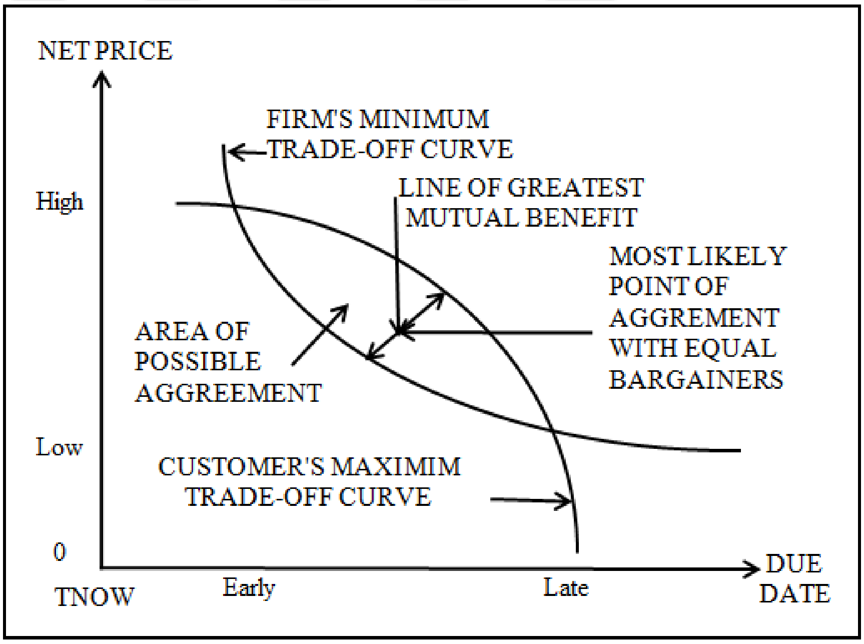

Figure 3.1 Negotiation theory of Raiffa (Moodie, 1999)

We can show the trade-off curves and feasible region for agreements in Figure 3.1. If the combination of price and due date is in the feasible region, possible agreement occurs. If the combination of price and due date is out of the feasible region, there will not be an agreement between the firm and customer (Moodie, 1999).

3.3 Lead Time

Lead time and inventory holding flexibility create a trade-off between completing orders late or early, because these decisions associated with tardiness and holding costs (Charnsirisakskul et al., 2004).

Increasing of waiting time usually decreases the satisfaction of customers in many manufacturing environment, result of this action is decreasing of the revenue or increasing of the cost (Charnsirisakskul et al., 2004).

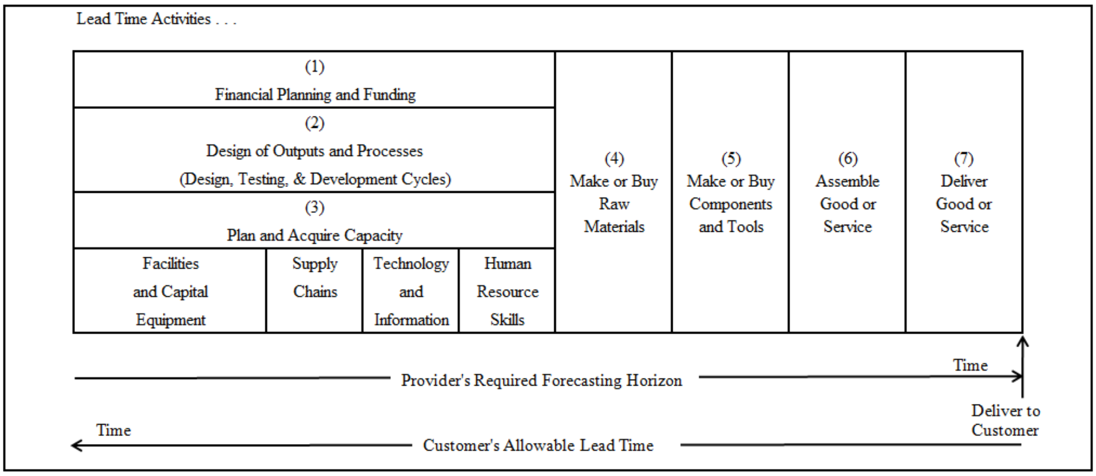

Figure 3.2 Requirements of forecasting lead time (Knod & Schonberger, 2001).

Forecasting of lead time requirements is shown in Figure 3.2. Lead time is measured by providers and customers (Knod & Schonberger, 2001).

1. Provider's Perspective: Knod & Schonberger (2001) define seven lead time activities which are shown in Figure 3.2. The first three activities are related with financial planning, output and process design and capacity planning for a product family or market group. The last four activities (4-7) are operations which are supported by purchasing and other specialists (Knod & Schonberger, 2001).
2. Customer's Perspective: According to Knod & Schonberger (2001), "for customers, allowable lead time is a statement not only of how long they are willing to wait but also of what they are willing to wait for" (p. 87). Although

customers wait only for delivery in make-to-stock systems, they wait for assembly and delivery in assemble to order (ATO) systems. Customers wait for component in addition to assembly and delivery in job oriented and make-to-order systems (Knod & Schonberger, 2001).

3.4 Production Planning

We can determine what, when and how much to produce in order to satisfy customer demand without high backorder and inventory cost by production planning (Sule, 2008).

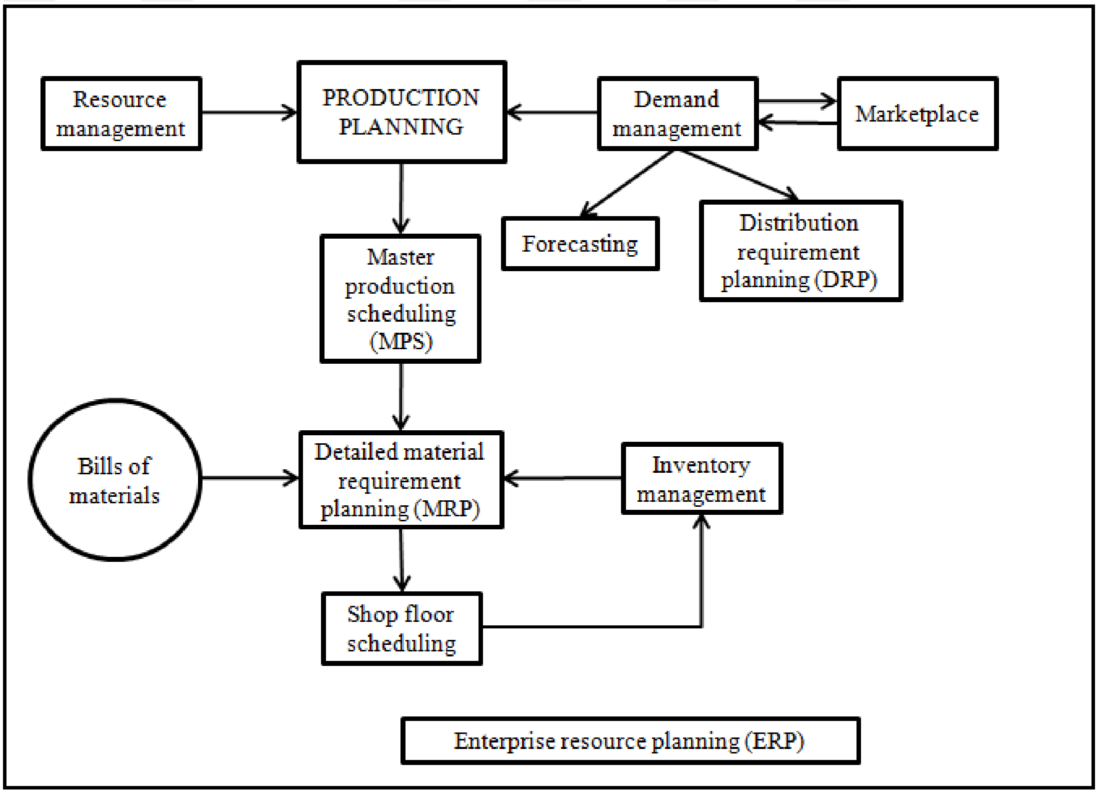

Figure 3.3 Diagram of production planning (Sule, 2008).

Planning is an important activity for companies in order to achieve the best goals for the organization. Planning has numerous level, capacity and materials availability must be planned by manufacturing operations (Dilworth, 1992).

According to Figure 3.3, production planning begins with the marketplace and demand management is the input of production planning. Master Production Schedule (MPS) is the output of the aggregate planning. Products are disintegrated into several components in Material Requirement Planning (MRP) and requirement for each component is determined with Bills of Materials (BOM). After these stages, the shop floor schedule is done for each component (Sule, 2008).

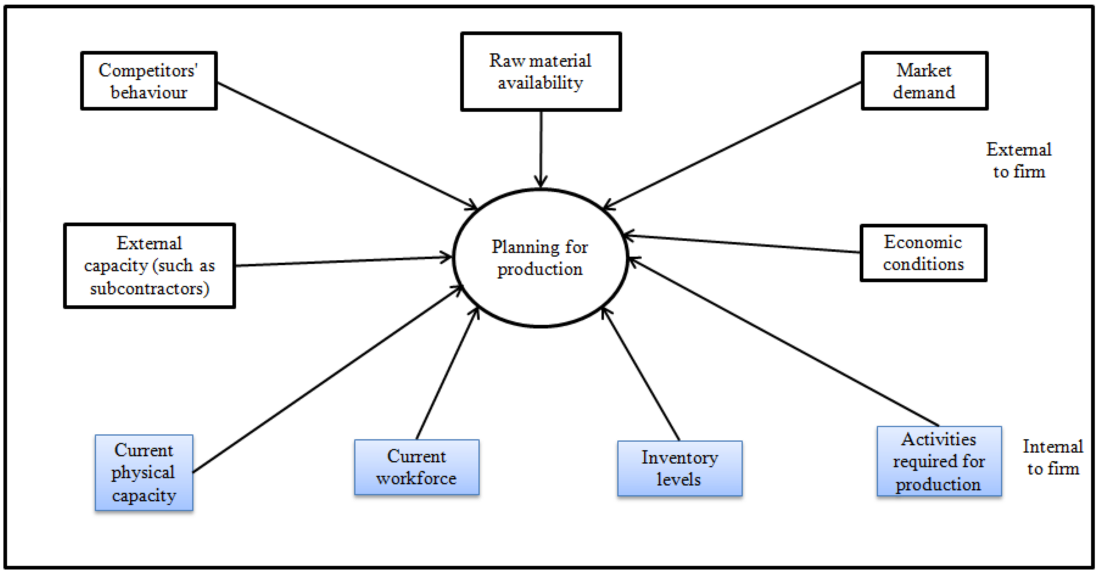

Figure 3.4 Internal and external factors of production planning system (Chase et al., 2006)

The required inputs to production planning system are shown in Figure 3.4 and they are listed below (Chase, Jacobs, & Aquilano, 2006):

- competitors' behavior,
- external capacity (such as subcontractors),
- current physical capacity,
- raw material availability,
- current workforce,
- inventory levels,
- market demand,
- economic conditions,
- activities required for production.

3.4.1 Production Capacity Dimensions

Dimensions of production capacity are listed below (Gaither & Frazier, 2002):

1. Available quantity of each production resource: Number of workers and number of machines are constraints for production capacity.
2. Provided quantity of capacity by each type of resource.
3. Capacity determination: The capacity is determined by the gateway operation or the first operation in product-focused production, although capacity is determined by the bottleneck operation in process-focused production.
4. Costs of hiring and laying off employees effect the production capacity.

3.4.2 Master Production Schedule (MPS)

Dilworth (1992) defines master production schedule (MPS) as "the plan that states what is to be produced, how many are to be completed and when they are to be completed" (p. 304). Production plan is disaggregated into the MPS, so the quantity of each product family which are produced in a quarter is divided by the weeks in the quarter (Dilworth, 1992).

3.4.3 Material Requirements Planning (MRP)

Planning the requirements for dependent demand items is the primary purpose of material requirements planning (MRP). Master production schedule (MPS), inventory status records and product structure records are the inputs of MRP as shown in Figure 3.5 (Tersine, 1994).

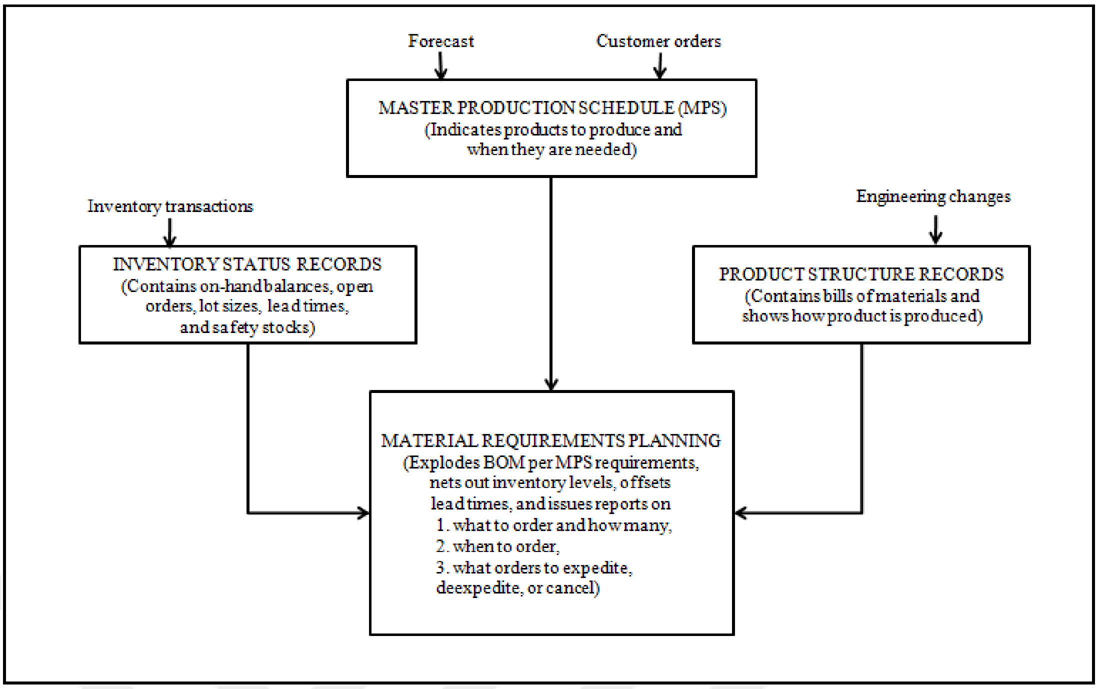

Figure 3.5 Inputs of MRP (Tersine, 1994)

Tersine (1994) defines bills of materials (BOM) as "a list of the items, ingredients or materials needed to produce an end item or product" (p. 342). BOM is both the simple list of dependent demand items and the structured list which describes the sequence of steps in manufacturing the product (Tersine, 1994).

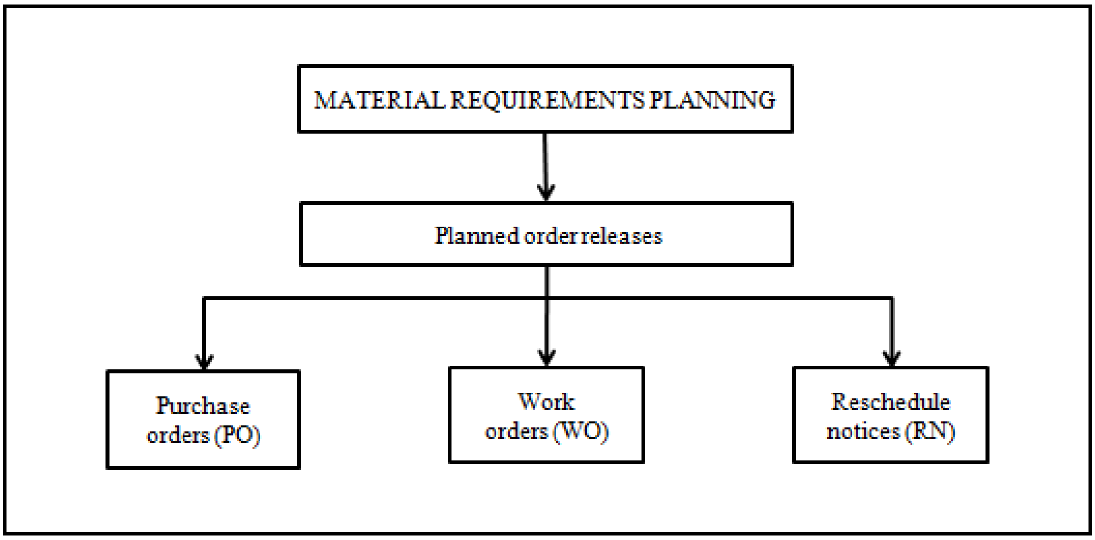

Figure 3.6 Outputs of MRP (Tersine, 1994)

Planned order releases which include purchase orders (PO), work orders (WO) and reschedule notices (RN) are the outputs of MRP as shown in Figure 3.6. The planned order releases give an information about the quantity and time period about the purchasing or working orders (Tersine, 1994).

3.4.4 Demand Management

Croxton, Lambert, & Garcia-Dastugue (2002) define demand management as "the supply chain management process that balances the customers' requirements with the capabilities of the supply chain" (p. 51). According to Croxton et al. (2002) demand management includes demand forecasting, synchronizing the demand with production procurement and distribution. We can reduce demand variability and improve operational flexibility with demand management. The purpose of the application of demand management is meeting customers' demand effectively and efficiently (Croxton et al., 2002).

3.4.4.1 Decisions of Demand Management

According to Talluri & Van Ryzin (2004), revenue management addresses three types of decisions and these are structural decisions, price decisions and quantity decisions. Structural decisions give an information about which terms of trade to offer and how to bundle products, which selling format and segmentation (or differentiation) mechanism to use. Price decisions are about how to set posted prices, individual-offer prices and reserve prices, how to markdown, how to price across product categories and how to price overtime. Quantity decisions are related with accepting or rejecting orders, capacity allocation for different segment, product or channels (Talluri & Van Ryzin, 2004).

3.4.4.2 Objectives of Demand Management

Knod & Schonberger (2001) define four objectives of demand management activities which are listed below:

1. Planning for demand: This objective is related with resource planning or capacity planning, staffing or scheduling. Worker training, new partnership, new equipment or new technology are examples of this objective.
2. Recognizing and accounting for all sources of demand: This objective is related with demand forecasting.
3. Reprocessing of demand: This objective is related with order processing and fulfillment activities.
4. Nature of demand or effect of timing and quantity.

3.4.4.3 Demand Management in the Perspective of Organization

The core activities of operations management are shown in Figure 3.7. Master planning for operations includes demand management, capacity planning and master scheduling. Business strategy, operations strategy, master planning for operations and its components and order fulfillment are core elements of operations management (Knod & Schonberger, 2001). According to Knod & Schonberger (2001) "master planning is high-level operations planning. It is equal in importance to financial planning, market analyses and design and development initiatives-the 'other' line functions' high-level plans" (p. 81).

Sule (2008) grouped the outside plant factors which influence the demand, these are:

- advertising,
- pricing,
- package deals,
- promotions,
- specify appointment times.

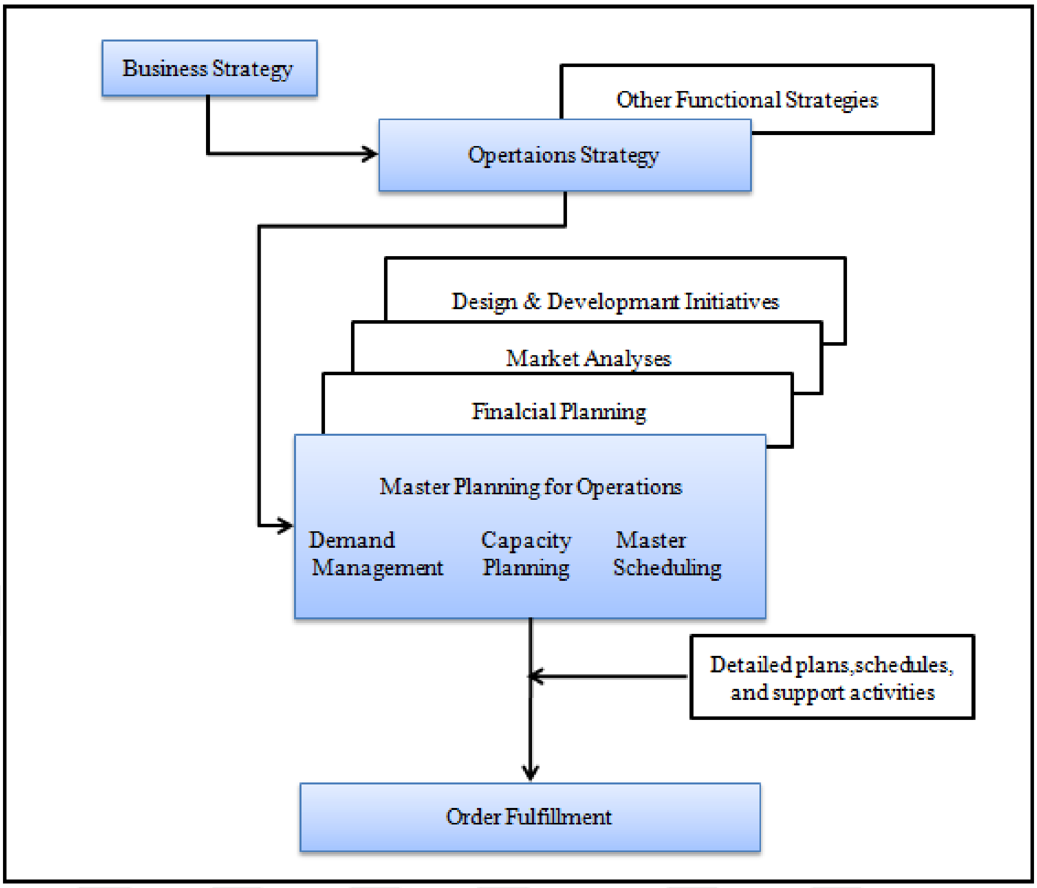

Figure 3.7 Elements of operations management (Knod & Schonberger, 2001).

3.4.5 Sales and Operations Planning

Chase et al. (2006), define sales and operations planning as "a process to help give better customer service, lower inventory, shorten customer lead times, stabilize production rates and give top management a handle on the business" (p. 560). The process is related with sales, operations, product development and finance, also we can balance demand and supply with this process (Chase et al., 2006). According to Chase et al. (2006), aggregate means the major groups of products.

The overview of major operations planning activities are shown in Figure 3.8 which takes into consideration of the time dimension (Chase et al., 2006).

Sales and operations planning is called aggregate planning, demand and supply are balanced by this process. Aggregation is made by product families on the supply side and it is made by groups of customers on the demand side. Individual product production schedules are made by the result of sales and operations planning. The amounts and dates of specific items required for each order are generated by Master Production Schedule (Chase et al., 2006).

Products are disintegrated into several components in Material Requirement Planning (Sule, 2008). Daily or weekly order scheduling is the final activity (Chase et al., 2006).

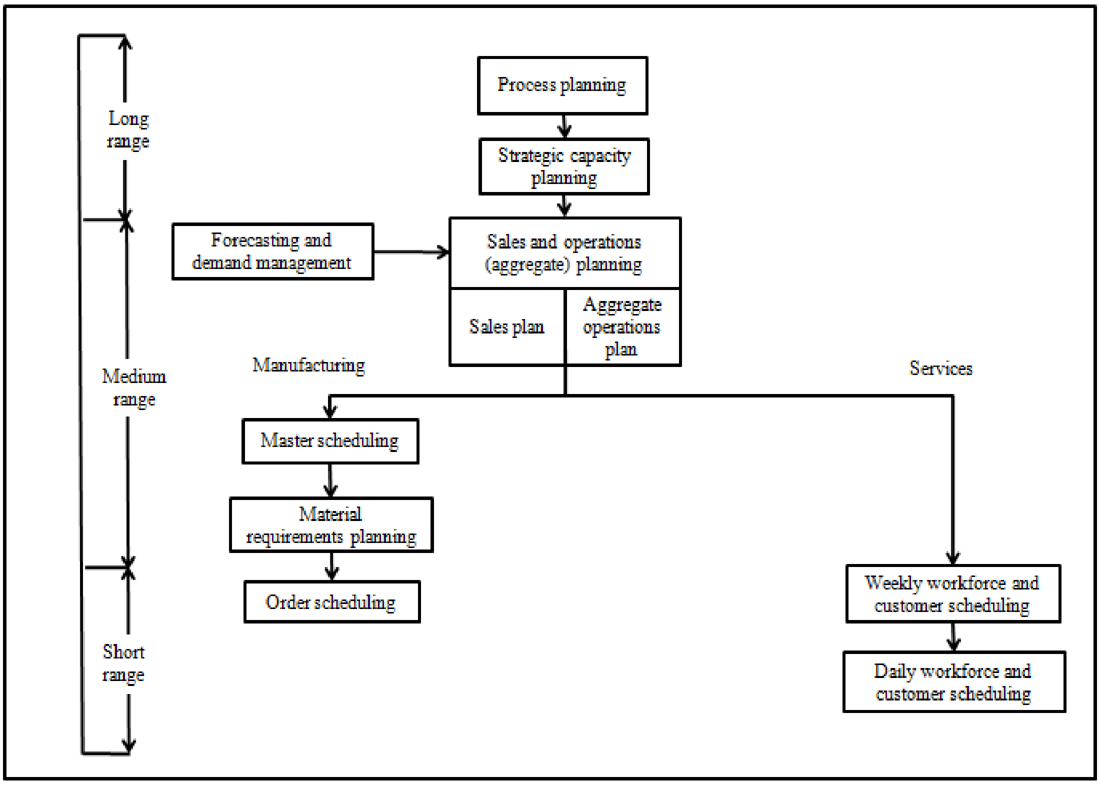

Figure 3.8 Operations planning activities (Chase et al., 2006)

3.4.6 Business Planning

According to Dilworth (1992) "business planning addresses both the long-and intermediate-range decisions for running the overall business" (p. 300).

Long range business planning includes plant expansions, major equipment purchase and investment on new facilities. Intermediate-range planning can be referred as a sales and operation planning (Dilworth, 1992).

According to Dilworth (1992) "the portion of the intermediate-range business plan which the operations function is responsible for implementing is usually called the production plan in a manufacturing company" (p. 301).

The total amount of output which is to produced for each period in the planning horizon is named as a production plan (Dilworth, 1992).

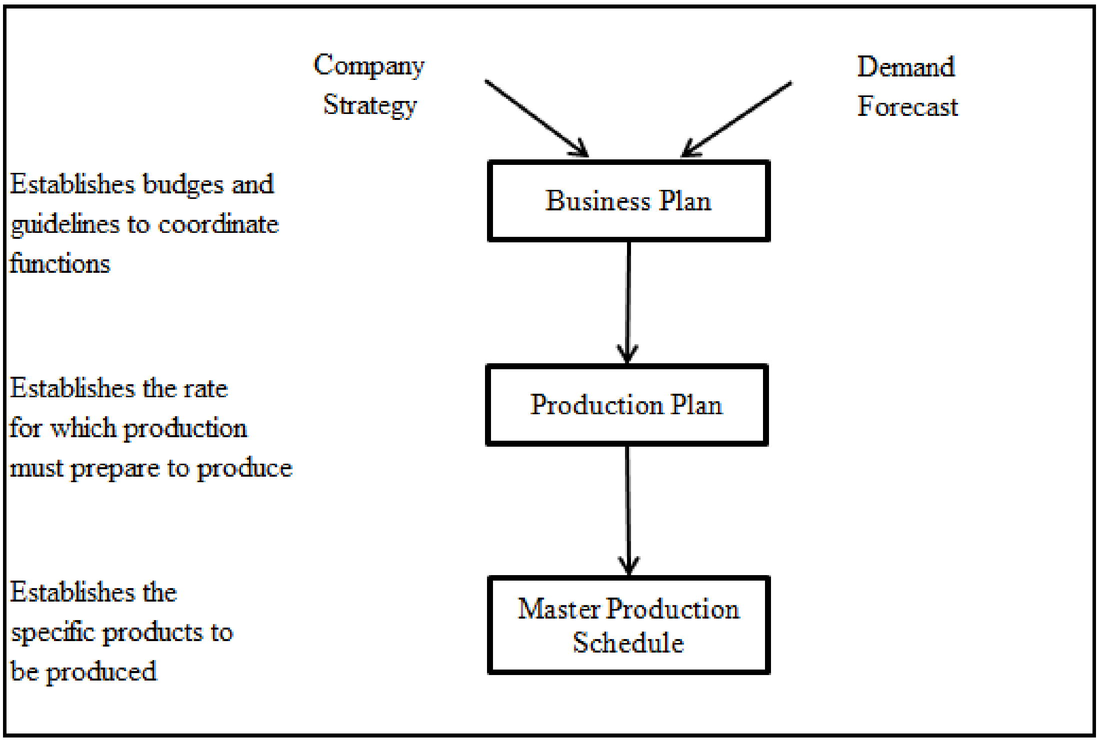

Figure 3.9 Planning levels (Dilworth, 1992)

Master Production Schedule shows when the specific products to be produced. The planning steps are shown in Figure 3.9 (Dilworth, 1992).

Make-to-order companies take orders for items and deliver them according to lead times, while make-to-stock companies forecast demand for related periods within the planning horizon (Dilworth, 1992).

3.5 Capacity Management

Chase et al. (2006) give a dictionary definition of the capacity as " 'the ability to hold, receive, store or accommodate' " (p. 430). Also, Chase et al. (2006) define the capacity as "the amount of output that a system is capable of achieving over a specific period of time" (p. 430).

Operations managers must look at inputs and outputs in order to manage the capacity, because the capacity is related with what is to be produced. Also the time dimension is important for capacity management, so time horizon of the capacity must be defined (Chase et al., 2006).

According to Chase et al. (2006), the plant manager (PM) must give decisions about using the capacity best in order to meet demand for products, because short term demand may be greater than the capacity during peak demand periods.

3.5.1 Time Horizons in Capacity Planning

1. Long-range capacity planning: Long-range capacity planning is greater than one year (Chase et al., 2006). Main subjects of long-term capacity planning are (Chen et al., 2009):

    - vertical integrations among suppliers,
    - facility locations,
    - production methods,
    - production strategies.

2. Medium-range capacity planning: Monthly or quarterly plans form the intermediate-range capacity planning (Chase et al., 2006). Main subjects of medium- term capacity planning are (Chen et al., 2009) :

    - inventory policy,

- utility requirement,
- labor level (hiring and lay off labor, overtime or part time study),
- facility modification,
- material-supply control,
- outsourcing.

There are two main approaches for the medium-term capacity planning. These are level capacity approach and matching demand approach. According to level capacity approach, difference between supply and demand is balanced by inventory, overtime working, subcontracting, backlog and part time labor. Balance of supply and demand is provided with hiring and laying off labor in matching demand approach. MTO production systems use hybrid approach. Overtime and subcontracting strategies are generally used by MTO firms against to demand fluctuations (Chen et al., 2009).

3. Short-range capacity planning: Short-range capacity planning is done for less than one month. This type of planning includes daily or weekly scheduling process. Also overtime, personnel transfer are thought as alternatives in the short-range capacity planning (Chase et al., 2006).

3.5.2 Options of Adding Capacity

Chase et al. (2006) group the options of adding capacity under three categories:

1. Maintaining system balance: One way is scheduling overtime, subcontracting and leasing equipment in order to add capacity for bottlenecks. Second way is using buffer inventories at the bottleneck stage.
2. Frequency of capacity additions: According to Chase et al. (2006), costs of upgrading capacity too frequently and upgrading capacity too infrequently should be considered. Removing and replacing old equipments and training employees on the new equipments create direct costs and there is an opportunity cost during the changeover period. If the firm adds the capacity

infrequently, the firm purchases in larger chunks, so upgrading capacity is expensive too.

3. External sources of capacity: Outsourcing and capacity sharing are two common strategies in order to expand the capacity externally.

3.5.3 Capacity Requirements

Chase et al. (2006), define the capacity as "the amount of resource inputs available relative to output requirements over a particular period of time" (p. 431) and suggest three steps which are listed below in order to determine capacity requirements:

1. Forecasting for sales,
2. Calculating equipment and labor requirements,
3. Projecting labor and equipment availabilities.

3.5.4 Group (Family) Capacity Planning

According to Nahmias (2009), "when the types of items produced are similar, an aggregate production unit can correspond to an 'average' item, but if many different types of items are produced, it would be more appropriate to consider aggregate units ..." (p. 127).

According to Ashayeri & Selen (2003), decisions at the aggregate level are:

- order acceptance,
- detailed production planning,
- purchasing.

Three steps which can be applied for both MTO and MTS production for group capacity planning in larger organizations are listed below (Knod & Schonberger, 2001):

1. Grouping products which have same process into families and selecting units for aggregate capacity planning.
2. Customer demand is projected for each capacity group.
3. Making a production plan.

3.6 Order Fulfillment

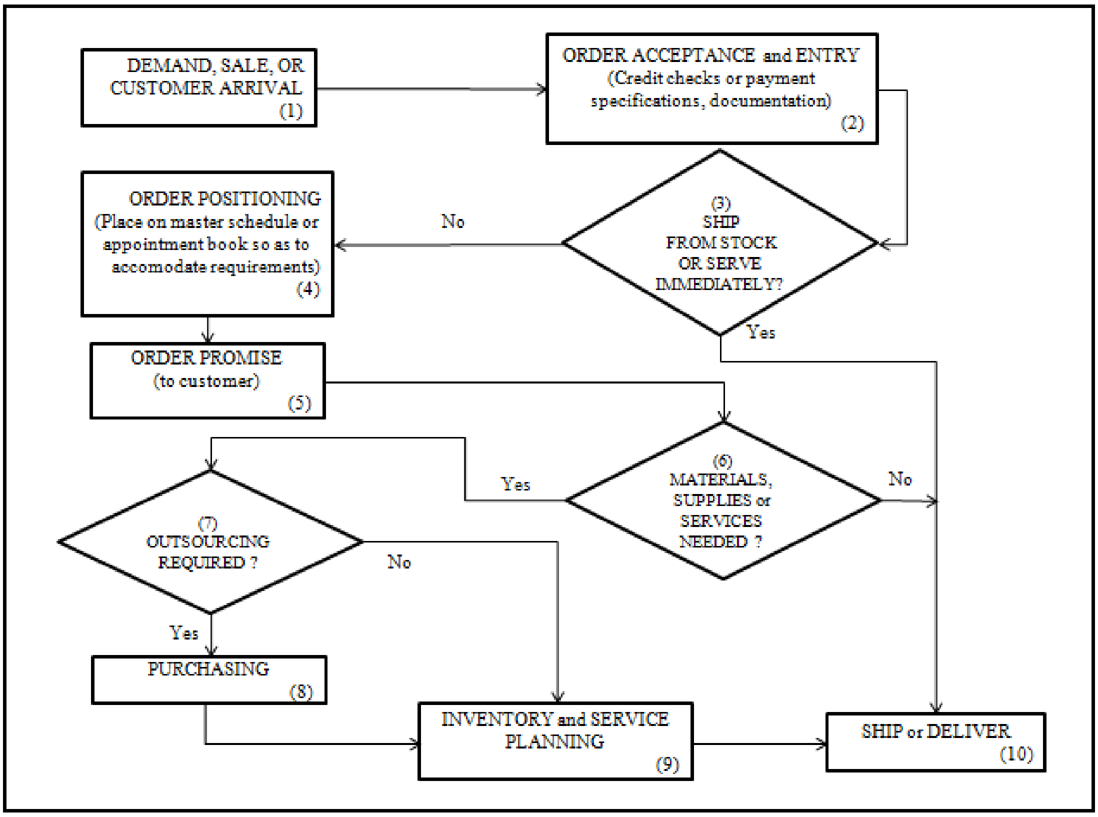

Figure 3.10 Sequence of order fulfillment (Knod & Schonberger, 2001).

The sequence of order fulfillment is shown in Figure 3.10. After demand arrives into the system order acceptance stage starts. If the order is accepted, stock position is controlled. If there is enough stock, ship or delivery process starts. If there is not enough stock, order is positioned and needs for materials, supplies or services are analyzed for customers. If outsourcing is required, shipping starts after purchasing, inventory and service planning. If outsourcing is not required, order is delivered after inventory and service planning (Knod & Schonberger, 2001).

CHAPTER FOUR
REVENUE MANAGEMENT

4.1 Revenue Management (RM)

Revenue management (RM) is defined by various authors in the literature. Chase et al. (2006) define RM as "the process of allocating the right type of capacity to the right type of customer at the right price and time to maximize revenue or yield" (p. 576). Chase et al. (2006) find RM as a powerful approach in order to make the demand more predictable. Cheraghi et al. (2010) define RM as "the science of using past history and current levels of order activity to forecast demand as accurately as possible in order to set and update pricing and product availability decisions across various sales channels to maximize profitability" (p. 63).

According to Phillips (2005) "pricing and revenue optimization is a tactical function...., pricing and revenue optimization is concerned with determining the prices that will be in place tomorrow and next week" (p. 1).

Chase et al. (2006) think that RM is most effective from an operational perspective when,

- "demand can be segmented by customer
- fixed costs are high and variable costs are low
- inventory is perishable
- product can be sold in advance
- demand is highly variable" (p. 577).

RM can be thought as the complement of supply chain management (SCM) with the objective of decreasing the production cost and delivery cost. Synonymous names of RM are yield management, demand management, pricing and revenue management, demand-chain management, pricing and revenue optimization and revenue process optimization (Talluri & Van Ryzin, 2004).

Although RM originates from airline industry, RM is applied in large sector scale such as cruise lines, hotels, rental car firms, event ticketing agents and freight transportation companies (Phillips, 2005).

4.2 Newness about Revenue Management

Although RM is a very old idea, modern economic theory addresses many demand management decisions such as optimization, segmentation, non-linear pricing (Talluri & Van Ryzin, 2004).

According to Talluri & Van Ryzin (2004), we can model demand and economic conditions, estimate and forecast market response, quantify the uncertainties faced by decision makers and compute optimal solutions for complex decision problems by means of scientific advances in operations research, economics and statistics (Talluri & Van Ryzin, 2004).

We can store huge amount of data, implement and manage highly detailed demand-management decisions, solve complex algorithms quickly by means of advances in information technology. Improvements of science and technology bring to new point of view to revenue management (Talluri & Van Ryzin, 2004).

4.3 Steps of Revenue Management

RM generally includes four steps which are listed below (Talluri & Van Ryzin, 2004):

1. data collection,
2. estimation and forecasting,
3. optimization,
4. control.

The process flow of RM is shown in Figure 4.1. According to four steps of RM, after collecting and storing relevant historical data such as price, demand etc., estimation of the parameters of the demand model starts. No-show and cancellation rates can be given as an example of estimation parameters. Finding the optimal set of controls such as price, discount, markdown, overbooking limit and allocation take part in the optimization step. Control step starts after the optimization (Talluri & Van Ryzin, 2004).

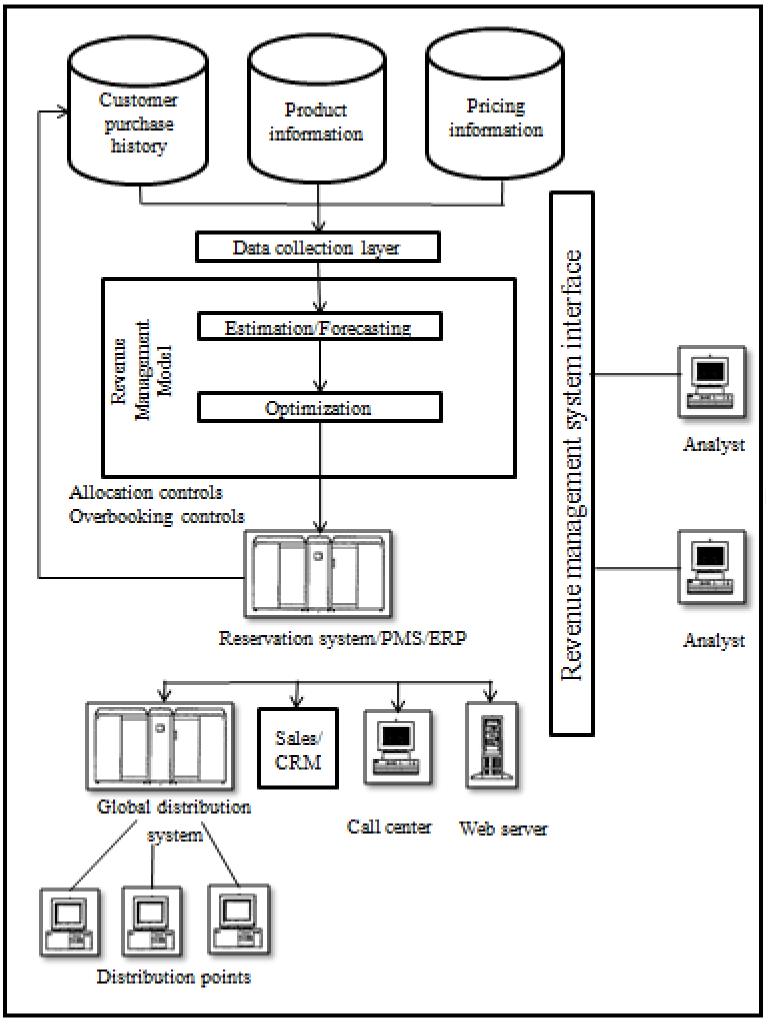

Figure 4.1 Process flow of revenue management (Talluri & Van Ryzin, 2004)

4.4 Revenue Management's Levels

There are three levels of RM decisions as shown in Table 4.1.

Table 4.1 Levels of revenue management decisions (Phillips, 2005)

Level	**Description**	**Frequency**
Strategic	Segment market and differentiate prices	Quarterly or annually
Tactical	Calculate and update booking limits	Daily or weekly
Booking control	Determine which bookings to accept and which to reject	Real time

4.4.1 Tactical Revenue Management

Calculating and updating booking limits periodically is the job of tactical RM (Phillips, 2005).

4.4.1.1 Elements of Tactical Revenue Management

There are three elements of tactical revenue management, these are (Phillips, 2005):

- Capacity allocation: Capacity allocation decisions give an information about how many units to sell at lower prices and how many to reserve for sale at a higher price.
- Network management: Network management is important for determining how should bookings be managed across a network of resources.
- Overbooking: Overbooking decisions give an information about the number of total bookings which are accepted for a product in the face of uncertain no-shows and cancellations in the future.

4.5 Revenue Management System

The typical RM system is shown in Figure 4.2. Calculating and updating the booking limits within the reservation system are the primary jobs of a RM system.

We can generate and update forecasts for all product fare/class combinations for all future dates by the forecasting module. Bookings and cancellations come to the reservation system from different channels and booking limits are calculated according to this information (Phillips, 2005).

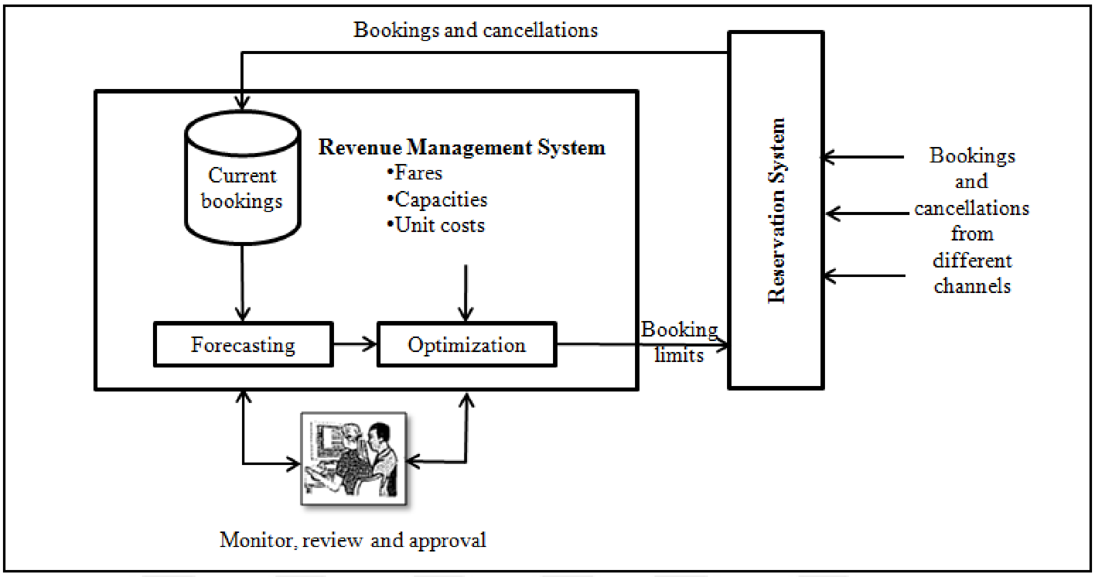

Figure 4.2 Revenue management system (Phillips, 2005).

4.6 Pricing and Revenue Optimization (PRO)

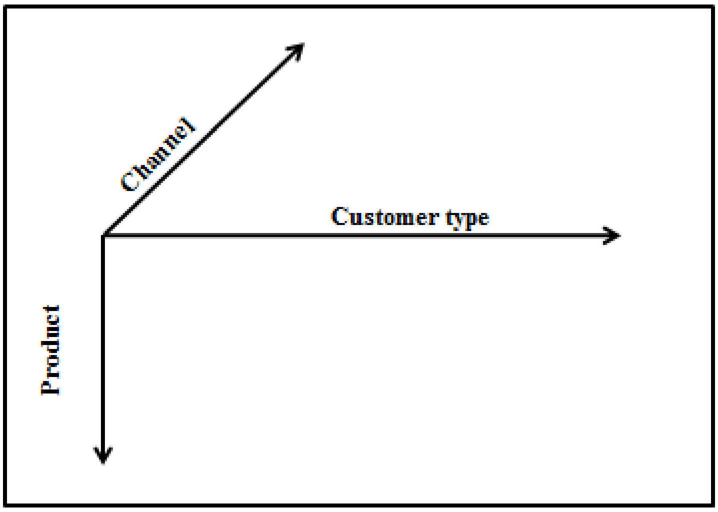

Figure 4.3 Pricing and revenue optimization cube's dimensions (Phillips, 2005)

According to Phillips (2005), "the goal of pricing and revenue optimization is to provide the right price, for every product to every customer segment, through every channel and to update those prices over time in response to changing market conditions" (p. 26). The dimensions of PRO is shown in Figure 4.3.

4.6.1 Factors which Effect the Pricing and Revenue Optimization (PRO)

According to Phillips (2005), four factors which are listed below affect the decisions of PRO:

- The success of RM in the airlines improves PRO decisions.
- The adaptation of enterprise resource planning (ERP) and customer relationship management (CRM) software system improves PRO decisions.
- Increasing of e-commerce ability for managing and updating pricing fast in the online environment improve PRO decisions.
- The success of supply chain management improves PRO decisions. Because, SCM tries to find a way to fill orders at lowest cost and wish to maximize profitability.

4.6.2 The Process of Pricing and Revenue Optimization (PRO)

According to Phillips (2005) there are two components for successful PRO:

- a consistent business process which focused on pricing,
- the software and analytical capabilities.

The PRO process is shown in Figure 4.4. This process involves eight activities and four of these activities are part of operational PRO, the other four activities are part of supporting PRO (Phillips, 2005).

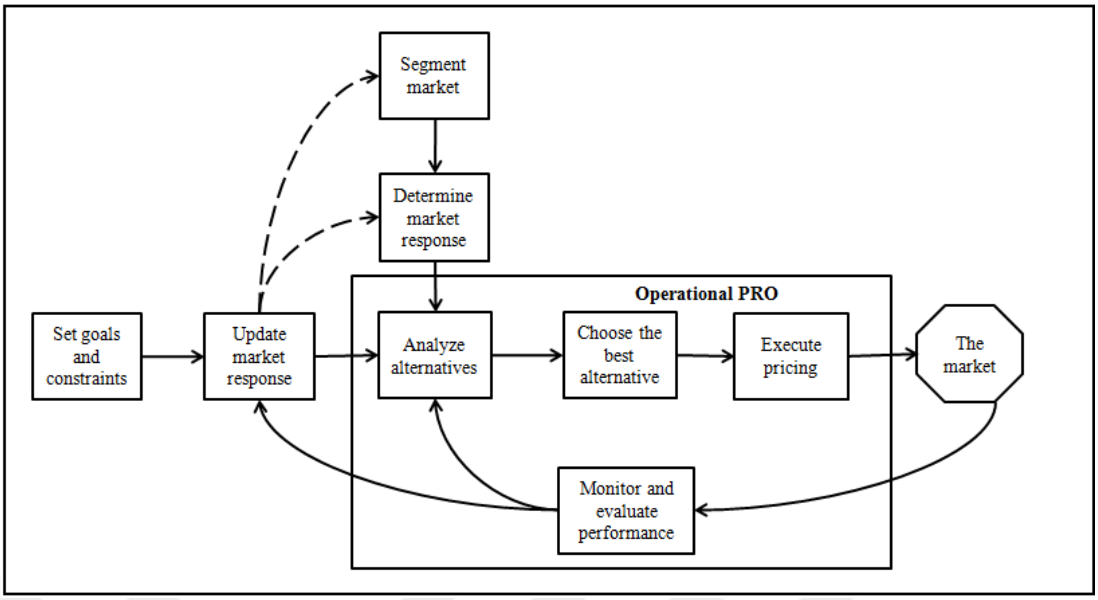

Figure 4.4 The process of pricing and revenue optimization (Phillips, 2005)

4.6.2.1 Operational Activities of PRO

The operational PRO activities which are explained below work in order to set and update prices (Phillips, 2005):

- Analyze alternatives: This activity includes comparing pricing alternatives under different scenarios and solving the underlying optimization problem in order to recommend new prices for every element of PRO cube.
- Choose the best alternative: After the analysis of prices, we need to determine which prices should be set. Software packages are equipped with what-if capability in order to understand the effect of different assumptions on the recommendations.
- Execute pricing: The prices are communicated to the market in this step.
- Monitor and evaluate performance: Results of expectations and goals are compared and evaluated in this step.

4.6.2.2 Supporting Activities of PRO

Supporting PRO activities which are explained below provided key inputs to the operational PRO activities (Phillips, 2005):

- Set goals and business rules: Determining the goals and business rules in the initial step of supporting PRO activities. Maximizing expected total contribution is the goal of pricing and revenue optimization.
- Segment the market: Market segmentation is an important subject for pricing and revenue optimization in order to maximize the profit.
- Determine price response: Calculating the corresponding price response functions for each market segment is an important theme in this step.
- Update price response: The parameters of the models need to be changed, so updating price response function is an important for pricing and revenue optimization.

4.6.2.3 The Dimension of Time

Prices changed once a quarter in the past, but they change once a week, once a day or once an hour now, so changing prices more rapidly according to market conditions is an important issue (Phillips, 2005).

4.7 Dynamic Pricing

Talluri & Van Ryzin (2004) say that "in terms of business practice, varying prices is often the most natural mechanism for revenue management" (p. 175).

Personalized pricing, display and trade promotions, discounts, auctions, clearance sales, markdowns and pricing negotiations are the forms of dynamic pricing in most retail and industrial trades (Talluri & Van Ryzin, 2004).

4.7.1 Price-Based RM and Quantity-Based RM

While some industries such as retailing use price-based RM, other industries such as airlines use quantity-based RM. Also, price-based RM and quantity-based RM may be used in the same industry (Talluri & Van Ryzin, 2004).

Whereas price-based RM operates by rationing the selling price, quantity-based RM operates by rationing quantity of sales. Although we can reduce sales by increasing price in price-based RM, we can reduce sales by limiting supply in quantity-based RM. According to Talluri & Van Ryzin (2004), price-based rationing is more profitable than quantity-based rationing. Because, we can both reduce sales and increase revenue by increasing price at the same time (Talluri & Van Ryzin, 2004).

4.7.2 Examples for Dynamic Pricing

Examples for dynamic pricing are listed below (Talluri & Van Ryzin, 2004):

- Consumer-Packaged Goods Promotions: Promotion is the form of price-based RM and it is used in the consumer packaged goods (CPG) industry such as coffee, yogurt, soap etc. Retailers want to increase sales by using promotion approach.
- Discount Airline Pricing: Airlines sell tickets at different prices for different flights during the booking period and they change prices according to capacity and demand. Customers who buy the ticket early pay lower price. Because, demand is more price sensitive far from the time of service.
- Style-Goods Markdown Pricing: Retailers which sell style or fashion goods apply price-based RM and markdown pricing is used in order to clear inventory before the end of the season. Customer who purchase product early have higher willingness to pay. Because, they want to either use the product for a full season or be first to own the product. After markdown pricing decisions, people can have the product by paying lower prices.

4.7.3 Examples of Dynamic Pricing According to Industries

Examples of dynamic pricing according to industries are listed below (Talluri & Van Ryzin, 2004):

- Manufacturing: Pricing-software technology supports pricing and discount decisions in manufacturing.
- E-business: Internet is used to gain training efficiencies on the industrial side, so e-business has a strong influence on pricing decisions.
- Retailing: Retailers which especially sell seasonal goods develop science-based software for pricing. Most of this software try to optimize markdown decisions.

4.7.4 Factors of Dynamic Pricing Problems

There are two factors which must be considered in dynamic pricing problems, these are (Talluri & Van Ryzin, 2004):

- Factors which influence customers' purchase decisions and sophistication of the customers' decision making process.
- Level of competition and the size of customer population.

CHAPTER FIVE
REVENUE MANAGEMENT IN PRODUCTION

5.1 Revenue Management for Manufacturing Companies

There is a significant interest the application of RM in manufacturing, so many supply chain management and enterprise resource planning technology vendors offer pricing-optimization systems for manufacturers (Talluri & Van Ryzin, 2004).

Make-to-order firms generally produce in small lots which are related with specific orders and they typically have to price a continuous stream of bids and request for quotes (RFQ) (Talluri & Van Ryzin, 2004).

If the bid is accepted, the order is scheduled into the production planning and SCM systems make an optimization of scheduling of current and new orders. The core objective of most SCM systems is meeting the delivery deadlines with the lowest cost, so SCM vendors work on incorporating demand-management functions and price-optimization in their systems (Talluri & Van Ryzin, 2004).

5.2 Order Acceptance Strategy

Martinez & Arredondo (2010) define the order acceptance as "a key success factor for revenue management in make-to-order (MTO) manufacturing systems where a fixed manufacturing capacity and great variety of offered products are challenged by pronounced fluctuations in demand and profitability" (p. 1189).

RM is a systematic approach for accepting or rejecting orders. Selectivity of an order acceptance strategy effects the success of make-to-order production systems (Martinez & Arredondo, 2010). Order acceptance and rejection decisions are related with order selection strategy (Cheraghi et al., 2010). Because of the limitation on capacity, firms try to select orders in order to maximize the revenue. Also, processing of the orders should be considered in order to use the capacity efficiently.

Firms should select orders in order to use capacity efficiently and increase revenue in a competitive MTO environment (Oğuz et al., 2010).

According to Arredondo & Martinez (2010) "order acceptance under uncertainty is a critical decision making problem at the interface between customer relationship management and production planning of order driven manufacturing systems" (p. 70).

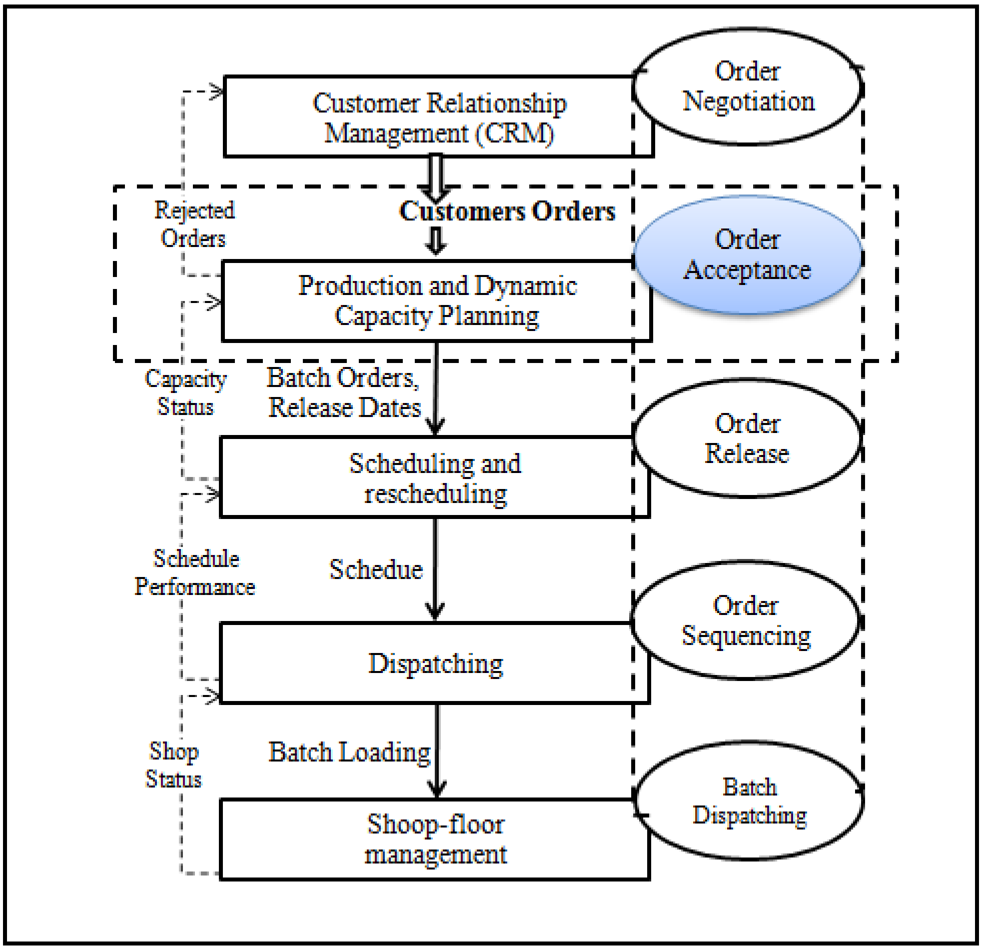

Figure 5.1 Functions' hierarchy in order acceptance strategy (Martinez & Arredondo, 2010)

Selection of orders according to their contribution is generally used in RM. Bid price is one of the most popular approach for capacity control in RM. If revenue is more than opportunity cost, order is accepted according to the bid price approach (Spengler et al., 2008).

Capacity control is typically related with bid price in make-to-order RM. But the performance of this approach is receding because of stochastic demand (Volling et al., 2012).

Hierarchy of functions in order acceptance are shown in Figure 5.1. The manager of make-to-order firm accepts, negotiates or rejects the order according to its revenue contribution. Production planning, dynamic capacity planning and scheduling steps are done for accepted orders (Martinez & Arredondo, 2010).

5.3 Revenue Management in Make-to-Order (MTO) Production Systems

Application of RM techniques in make-to-order manufacturing system has been increasing because of the success of RM in retail and service industry (Fan & Chen, 2008).

Order acceptance and capacity allocation decisions have an important impact for MTO firms' performance when demand is more than firm's capacity (Fan & Chen, 2008). Companies which apply RM sometimes have to reject orders or vary prices in order to maximize overall contribution margin (Hintsches et al., 2010).

Important operational decisions like capacity planning and scheduling don't begin before the customer order comes to make-to-order firms (Hendry & Kingsman, 1989). Resource requirement, completion time of the order and direct costs of the order must be estimated by the make-to-order firms (Easton & Moodie, 1999). Cost calculation which is critical in MTO production systems is based on the estimation of material costs, labor rates and machine time (Talluri & Van Ryzin, 2004).

Although bidding competition is effected by many different factors, price generally has a significant role. Make-to-order firms suggest short lead times in order to win more orders, so they aim earning higher profits than their near competitors. However, promising to customers an early delivery date causes risks for tardy deliveries. Also, estimating a certain lead time is very important for make-to-order firms (Easton & Moodie, 1999).

5.4 Revenue Management for Production Planning

In order to satisfy customer's demand by allocating resources, there has been interest in capacity management with RM (Akkan, 1997).

Because of the limited capacity, manufacturing firm would not accept all orders in order not to effect the firm's overall profitability negatively. This approach is the opposite to MRP-based systems, because these systems accept all the demand and try to complete demands with minimum cost (Akkan, 1997).

Effective capacity utilization and saving the capacity for valuable customers are important for RM (Cheraghi et al., 2010). The detailed representation of machine workload is the idea of order selection problem from a scheduling perspective (Calosso et al., 2003). Models which integrate production planning and order acceptance decisions help to increase the overall profitability of the company (Brahimi, 2014).

There is a trade-off between the maximizing the capacity utilization and the maximizing the revenue in manufacturing firms where RM is applied (Harris & Pinder, 1995).

RM links the demand management and capacity planning to the front end activities of finance and marketing as shown in Figure 5.2 (Harris & Pinder, 1995).

Determination of the best schedule of production in order to meet demands, causes a challenge for production planning managers. Selecting only a subset of customer orders becomes necessary when the manufacturer has a limited capacity (Geunes et al., 2002).

According to Muda and Hendry (2002), the world class MTO firms should integrate the marketing and production functions which are related with customer enquiries.

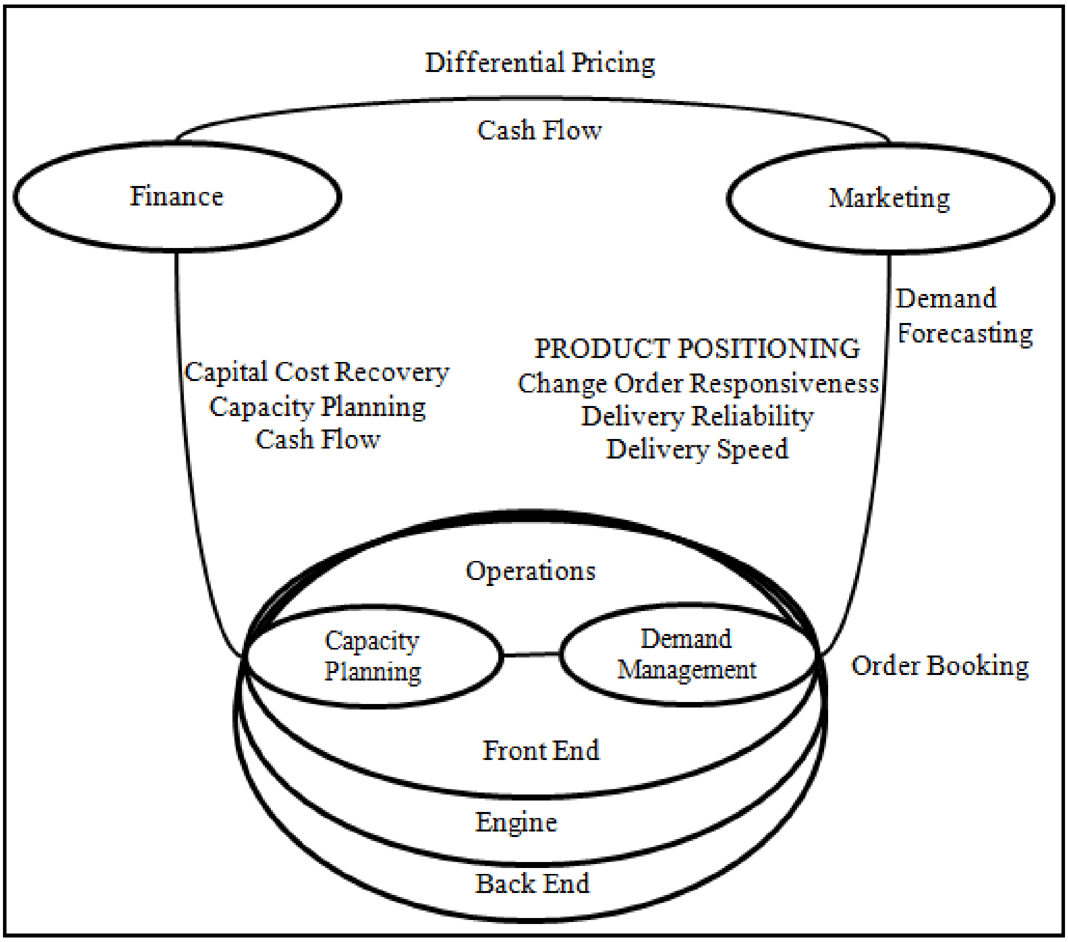

Figure 5.2 Strategic linkages which are provided by revenue management (Harris & Pinder, 1995)

CHAPTER SIX
PROBLEM DEFINITION AND MATHEMATICAL FORMULATION OF THE PROBLEM

6.1 Problem Definition

In this study, mixed-integer non-linear programming model where selling prices and due dates are constant parameters are considered, also multi-objective mixed-integer non-linear programming model where selling prices and due dates are decision variables are considered for short-term production planning problem for make-to-order production system.

In order to reach the objectives of the models, orders are accepted or rejected in contrast to classical production planning problems. Regular time, overtime and outsourcing are the source options in the problem. Orders can't exceed their due dates, because tardy delivery is not allowed. Each resource which is available during regular time and overtime has one or more machines. Also the capacity of outsourcing is large enough. Orders are processed according to their routes, because each order has more than one job. The processing times of jobs on different resources and the process route of each order are known in the problem. The values of selling prices and due dates are known at the beginning of the planning horizon in the model where selling prices and due dates are constant parameters. Minimum and maximum values of selling prices and due dates are known at the beginning of the planning horizon in the model where selling prices and due dates are decision variables.

The total net profit, list of accepted orders and number of assigned hours for processing job j of item i on resource k of source r in time period t are outputs of the model where selling prices and due dates are constant parameters; the total net profit, the value of total due date, selling price and due date values of each order, list of accepted orders and number of assigned hours for processing job j of item i on resource k of source r in time period t are outputs of the model where selling prices and due dates are decision variables.

6.1.2 Problem Assumptions

Problem assumptions in this study are the same as the study of Chen et al. (2009) and listed below.

1. Capacity of outsourcing is 24 hours per day and large enough for fulfilling any outsourcing.
2. Outsourced job is available at the facility of subcontractor either after the regular time or after overtime.
3. Number of available hours of regular time is equal to number of available hours of overtime in each time period.
4. Resource breakdowns and setups are not considered.

6.2 Mathematical Formulation of the Problem

6.2.1 Mathematical Model and the Solution Method of the Problem

The mathematical model which was initially proposed by Chen et al. (2009) was modified and improved in this study. Some mistakes in the formulation of some constraints in the model of Chen et al. (2009) were identified, so the core mathematical model which was proposed by Chen et al. (2009) was revised and reformulated. The revisions and the reformulations which are made in the mathematical model of Chen et al. (2009) are explained in the next paragraph.

The capacity constraint for outsourcing was transformed into a non-linear constraint in order to provide outsourcing capacity correctly and linearization method in the explanations of Coelho (2013) was applied to this constraint. λ was added to the constraint which indicated the relation between binary and continuous variable in order to determine the least unit of time of processing job j of item i on resource k. Precedence constraints between jobs of each order were revised and reformulated in order to provide precedence relation correctly. Moreover, the constraint which was for determining the available hours of outsourcing was revised and reformulated in order to calculate the remaining hours of outsourcing correctly. After these revisions and reformulations, mixed-integer non-linear programming model where selling prices and due dates are constant parameters was developed and this model was solved by Lingo 14.0 software after linearization.

In contrast to model of Chen et al. (2009) where selling prices and due dates were constant parameters, selling prices and due dates were considered as decision variables which have minimum and maximum bounds in this study. Mixed-integer non-linear mathematical programming model was improved by the consideration of selling prices and due dates as decision variables and using two objective functions. This important and practical improvement has changed the functioning logic of the model. Objective functions and the due date constraint became non-linear after this improvement. Finally, the multi-objective mixed-integer non-linear programming model was developed for capacity constrained production planning problem which had order acceptance, pricing and due date decisions and many other practical constraints. The linearization method in the explanations of Coelho (2013) was applied to non-linear objective functions and due date constraint.

After linearization, the multi-objective mixed-integer non-linear programming model was solved by Lingo 14.0 software. The objectives of the model are total net profit maximization and the total due date minimization, ε-constraint method is used for these two objectives. Multi-objective mixed-integer non-linear programming model is solved after linearization according to the first objective, after than the second objective is selected for optimization and the first objective is considered as a constraint under ε-constraint method.

The mixed-integer non-linear programming model is explained in section 6.2.2 and the multi-objective mixed-integer non-linear programming model is explained in section 6.2.3. The linearization method is explained in section 6.3. The mixed-integer linear programming model is presented in Appendix 1 and the multi-objective mixed-integer linear programming model is presented in Appendix 2.

6.2.2 Mixed-Integer Non-Linear Programming Model

6.2.2.1 Sets, Parameters and Decision Variables

Sets, parameters and decision variables which are formed by developing the mathematical model of Chen et al. (2009) are described as follows. These parameters and decision variables are for the mathematical model where selling prices and due dates are constant parameters.

Sets:

I : Items $\{i \in I\}$
J_i : Jobs (operations) in item i $\{j \in J_i\}$
K : Resources $\{k \in K\}$
R : Sources $\{r \in R\}$
T: Time periods $\{t \in T\}$

Parameters:

S_i : Selling price of item i
d_i : Due date of item i
p_{ijk} : Processing time of job j of item i on resource k
c_{kr} : The cost of processing on resource k of source r per hour
b_{krt} : Number of available hours of resource k of source r in time period t
l_{rt} : Number of available hours of source r in time period t

Decision Variables:

X_{ijkrt} : Number of assigned hours for processing job j of item i on resource k of source r in time period t
Y_{ijkrt} : 1, if job j of item i is assigned for processing on resource k of source r in time period t; 0, otherwise

Z_i : 1, if the item i is accepted; 0, otherwise

O_{ij} : 1, if the job j of item i is processed in outsourcing; 0, otherwise

6.2.2.2 Mathematical Formulation

Mathematical formulation of the mixed-integer non-linear programming model where selling prices and due dates are constant parameters is explained below. The mixed-integer non-linear programming model was formed by revising and reformulating the mathematical model of Chen et al. (2009).

$$Maximize \sum_{i\in I} S_i * Z_i - \sum_{i\in I}\sum_{j\in J_i}\sum_{k\in K}\sum_{r\in R}\sum_{t\in T} X_{ijkrt} * c_{kr} \quad (6.1)$$

$$\sum_{i\in I}\sum_{j\in J_i} X_{ijkrt} \leq b_{krt} \quad \forall\, k \in K, r \in R, t \in T \quad (6.2)$$

$$\sum_{r\in R\setminus\{|R|\}}\sum_{t\in T} X_{ijkrt} + \sum_{r\in\{|R|\}}\sum_{t\in T} X_{ijkrt} = p_{ijk} * Z_i \quad (6.3)$$

$$\forall\, i \in I, j \in J_i, k \in K$$

$$\sum_{r\in\{|R|\}}\sum_{t\in T} X_{ijkrt} = p_{ijk} * O_{ij} \quad \forall\, i \in I, j \in J_i, k \in K \quad (6.4)$$

$$\sum_{j\in J_i}\sum_{k\in K} X_{ijkrt} \leq l_{rt} \quad \forall\, i \in I, r \in R\setminus\{|R|\}, t \in T \quad (6.5)$$

$$\sum_{j\in J_i}\sum_{k\in K} X_{ijk|R|t} * O_{ij} \leq l_{|R|t} \quad \forall\, i \in I, r \in \{|R|\}, t \in T \quad (6.6)$$

$$\sum_{j\in J_i}\sum_{k\in K}\sum_{r\in R} X_{ijkrt} \leq 24 \quad \forall\, i \in I, t \in T \quad (6.7)$$

$$X_{ijkrt} \geq \lambda * Y_{ijkrt} \quad \forall\, i \in I, j \in J_i, k \in K, r \in R, t \in T \quad (6.8)$$

$$X_{ijkrt} \leq Y_{ijkrt} * p_{ijk} \quad \forall\, i \in I, j \in J_i, k \in K, r \in R, t \in T \quad (6.9)$$

$$\sum_{k\in K} Y_{i|J_i|krt} * t \leq d_i * Z_i \quad \forall\, i \in I, j \in \{|J_i|\}, r \in R, t \in T \quad (6.10)$$

$$\alpha * \left(\sum_{r'\in R}\sum_{t'=1}^{t-1} X_{i(j-1)kr't'}\right) + \sum_{r'=1}^{r} X_{i(j-1)kr't} \geq p_{i(j-1)k} * \sum_{k'\in K} Y_{ijk'rt} \quad (6.11)$$

$$\forall\, i \in I, j \in J_i\setminus\{1\}, k \in K, r \in R\setminus\{|R|\}, t \in T$$

$$if\ t = 1, \alpha = 0; if\ t > 1, \alpha = 1$$

$$\sum_{r\in R}\sum_{t'=1}^{t} X_{i(j-1)krt'} \geq p_{i(j-1)k} * \sum_{k'\in K}\sum_{r\in\{|R|\}} Y_{ijk'rt} \quad (6.12)$$

$$\forall\, i \in I, j \in J_i\setminus\{1\}, k \in K, t \in T$$

$$\sum_{j' \in J_i} \sum_{k \in K} \sum_{r' \in \{|R|\}} X_{ij'kr't} + \sum_{k \in K} Y_{ijkrt} * r * l_{rt} \leq 24 \tag{6.13}$$

$$\forall\, i \in I, j \in J_i \setminus \{|J_i|\}, r \in R \setminus \{|R|\}, t \in T$$

$$X_{ijkrt} \geq 0 \quad \forall\, i \in I, j \in J_i, k \in K, r \in R, t \in T \tag{6.14}$$

$$X_{ijk\,|R|t} \leq 24 \quad \forall\, i \in I, j \in J_i, k \in K, r \in \{|R|\}, t \in T \tag{6.15}$$

$$Y_{ijkrt} \in \{0,1\} \quad \forall\, i \in I, j \in J_i, k \in K, r \in R, t \in T \tag{6.16}$$

$$Z_i \in \{0,1\} \quad \forall\, i \in I \tag{6.17}$$

$$O_{ij} \in \{0,1\} \quad \forall\, i \in I, j \in J_i \tag{6.18}$$

Objective function (6.1) is to maximize the total net profit by using the value of total revenue and total processing cost. Constraint (6.2) ensures that the available time of resource *k* of source *r* in time period *t* can't be exceeded. Constraint (6.3) ensures that allocated total number of hours for processing of job *j* of item *i* must be equal to its processing time. Constraint (6.4) is to outsource the job *j* of item *i* completely. Constraint (6.5) ensures that each item can't be processed more than the capacity of regular time and overtime in each time period. Constraint (6.6) ensures that each item can't be processed more than the capacity of outsourcing in each time period. Constraint (6.6) is non-linear, because of the product of a continuous variable $X_{ijk|R|t}$ and a binary variable O_{ij}. Linear form of constraint (6.6) with linearization constraints is explained in section 6.3.1. Constraint (6.7) ensures that each item can be processed maximum 24 hours in each time period. Constraint (6.8) and constraint (6.9) indicate the relation between binary variable Y_{ijkrt} and continuous variable X_{ijkrt}. If Y_{ijkrt} is 0, X_{ijkrt} takes the value of 0. If Y_{ijkrt} is 1, X_{ijkrt} is at least λ units of time. λ is 0.5 in this study. The completion time of the last job of item *i* ($|J_i|$) can't exceed the due date of item *i* by constraint (6.10).

Constraint (6.11) and constraint (6.12) are precedence constraints between jobs of each order. Constraint (6.11) ensures that job *j* of item *i* can be processed in time period *t* only after the processing job *(j-1)* of item *i* is completed. The first term of constraint (6.11) is for time periods which are up to *t*, so this term is not used when *t=1*. The job *(j-1)* of item *i* can be processed in regular time, overtime and outsourcing up to period t. According to second term of constraint (6.11), if job *(j-1)* of item i is completed during regular time, the processing of job j of item i can be started in regular time in time period t. If job *(j-1)* of item i is completed during overtime, the processing of job j of item i can be started in overtime in time period t. Constraint (6.12) ensures that job j of item i can be processed in outsourcing only after the processing of job *(j-1)* of item i is completed. Constraint (6.13) ensures that jobs of item i can't be processed in outsourcing more than available hours. For example, regular time capacity is 11 hours and overtime capacity is 11 hours. If previous job of job j of item i is completed during regular time, remaining outsourcing hours are 13; if previous job of job j of item i is completed during overtime, remaining outsourcing hours are 2. Constraint (6.14) is a non-negativity restriction for X_{ijkrt}. Constraint (6.15) expresses that the maximum bound of $X_{ijk|R|t}$ is 24. Constraints (6.16) - (6.18) are binary restrictions for decision variables Y_{ijkrt}, Z_i and O_{ij}.

6.2.3 Multi-Objective Mixed-Integer Non-Linear Programming Model

6.2.3.1 Sets, Parameters and Decision Variables

Sets, parameters and decision variables which are formed by developing the mathematical model of Chen et al. (2009) are described as follows. These parameters and decision variables are for the mathematical model where selling prices and due dates are decision variables.

Sets:

I : Items $\{i \in I\}$
J_i : Jobs (operations) in item i $\{j \in J_i\}$
K : Resources $\{k \in K\}$
R : Sources $\{r \in R\}$
T: Time periods $\{t \in T\}$

Parameters:

$Smin_i$: Minimum selling price of item i

$Smax_i$: Maximum selling price of item i

$dmin_i$: Minimum due date of item i

$dmax_i$: Maximum due date of item i

p_{ijk} : Processing time of job j of item i on resource k

c_{kr} : The cost of processing on resource k of source r per hour

b_{krt} : Number of available hours of resource k of source r in time period t

l_{rt} : Number of available hours of source r in time period t

Decision Variables:

S_i : Selling price of item i

d_i : Due date of item i

X_{ijkrt} : Number of assigned hours for processing job j of item i on resource k of source r in time period t

Y_{ijkrt} : 1, if job j of item i is assigned for processing on resource k of source r in time period t; 0, otherwise

Z_i : 1, if the item i is accepted; 0, otherwise

O_{ij} : 1, if the job j of item i is processed in outsourcing; 0, otherwise

6.2.3.2 Mathematical Formulation

Mathematical formulation of the multi-objective mixed-integer non-linear programming model where selling prices and due dates are decision variables is explained below. The multi-objective mixed-integer non-linear programming model was formed by revising and reformulating the mathematical model of Chen et al. (2009), improving the mathematical model of Chen et al. (2009) by transforming selling price and due date parameters into decision variables and using two objective functions.

$$Maximize \sum_{i\in I} S_i * Z_i - \sum_{i\in I} \sum_{j\in J_i} \sum_{k\in K} \sum_{r\in R} \sum_{t\in T} X_{ijkrt} * c_{kr} \quad (6.19)$$

$$Minimize \sum_{i\in I} d_i * Z_i \quad (6.20)$$

$$\sum_{i\in I} \sum_{j\in J_i} X_{ijkrt} \le b_{krt} \quad \forall\, k \in K, r \in R, t \in T \quad (6.21)$$

$$\sum_{r\in R\setminus\{|R|\}} \sum_{t\in T} X_{ijkrt} + \sum_{r\in\{|R|\}} \sum_{t\in T} X_{ijkrt} = p_{ijk} * Z_i \quad (6.22)$$

$$\forall\, i \in I, j \in J_i, k \in K$$

$$\sum_{r\in\{|R|\}} \sum_{t\in T} X_{ijkrt} = p_{ijk} * O_{ij} \quad \forall\, i \in I, j \in J_i, k \in K \quad (6.23)$$

$$\sum_{j\in J_i} \sum_{k\in K} X_{ijkrt} \le l_{rt} \quad \forall\, i \in I, r \in R \setminus \{|R|\}, t \in T \quad (6.24)$$

$$\sum_{j\in J_i} \sum_{k\in K} X_{ijk|R|t} * O_{ij} \le l_{|R|t} \quad \forall\, i \in I, r \in \{|R|\}, t \in T \quad (6.25)$$

$$\sum_{j\in J_i} \sum_{k\in K} \sum_{r\in R} X_{ijkrt} \le 24 \quad \forall\, i \in I, t \in T \quad (6.26)$$

$$X_{ijkrt} \ge \lambda * Y_{ijkrt} \quad \forall\, i \in I, j \in J_i, k \in K, r \in R, t \in T \quad (6.27)$$

$$X_{ijkrt} \le Y_{ijkrt} * p_{ijk} \quad \forall\, i \in I, j \in J_i, k \in K, r \in R, t \in T \quad (6.28)$$

$$\sum_{k\in K} Y_{i|J_i|krt} * t \le d_i * Z_i \quad \forall\, i \in I, j \in \{|J_i|\}, r \in R, t \in T \quad (6.29)$$

$$\alpha * (\sum_{r'\in R} \sum_{t'=1}^{t-1} X_{i(j-1)kr't'}) + \sum_{r'=1}^{r} X_{i(j-1)kr't} \ge p_{i(j-1)k} * \sum_{k'\in K} Y_{ijk'rt} \quad (6.30)$$

$$\forall\, i \in I, j \in J_i \setminus \{1\}, k \in K, r \in R \setminus \{|R|\}, t \in T$$

$$if\ t = 1, \alpha = 0; if\ t > 1, \alpha = 1$$

$$\sum_{r\in R} \sum_{t'=1}^{t} X_{i(j-1)krt'} \ge p_{i(j-1)k} * \sum_{k'\in K} \sum_{r\in\{|R|\}} Y_{ijk'rt} \quad (6.31)$$

$$\forall\, i \in I, j \in J_i \setminus \{1\}, k \in K, t \in T$$

$$\sum_{j'\in J_i} \sum_{k\in K} \sum_{r'\in\{|R|\}} X_{ij'kr't} + \sum_{k\in K} Y_{ijkrt} * r * l_{rt} \le 24 \quad (6.32)$$

$$\forall\, i \in I, j \in J_i \setminus \{|J_i|\}, r \in R \setminus \{|R|\}, t \in T$$

$$X_{ijkrt} \ge 0 \quad \forall\, i \in I, j \in J_i, k \in K, r \in R, t \in T \quad (6.33)$$

$$X_{ijk|R|t} \le 24 \quad \forall\, i \in I, j \in J_i, k \in K, r \in \{|R|\}, t \in T \quad (6.34)$$

$$S_i \ge Smin_i \quad \forall\, i \in I \quad (6.35)$$

$$S_i \le Smax_i \quad \forall\, i \in I \quad (6.36)$$

$$d_i \geq dmin_i \quad \forall\, i \in I \tag{6.37}$$

$$d_i \leq dmax_i \quad \forall\, i \in I \tag{6.38}$$

$$Y_{ijkrt} \in \{0,1\} \quad \forall\, i \in I, j \in J_i, k \in K, r \in R, t \in T \tag{6.39}$$

$$Z_i \in \{0,1\} \quad \forall\, i \in I \tag{6.40}$$

$$O_{ij} \in \{0,1\} \quad \forall\, i \in I, j \in J_i \tag{6.41}$$

There are two objective functions in this mathematical model. Objective function (6.19) is to maximize the total net profit by using the value of total revenue and total processing cost. Objective function (6.19) is non-linear, because of the product of a continuous variable S_i and a binary variable Z_i. Linear form of objective function (6.19) with linearization constraints is explained in section 6.3.1. Objective function (6.20) is to minimize the total due date. Objective function (6.20) is non-linear, because of the product of a continuous variable d_i and a binary variable Z_i. Linear form of objective function (6.20) with linearization constraints is explained in section 6.3.1.

Constraint (6.21) ensures that the available time of resource k of source r in time period t can't be exceeded. Constraint (6.22) ensures that allocated total number of hours for processing of job j of item i must be equal to its processing time. Constraint (6.23) is to outsource the job j of item i completely. Constraint (6.24) ensures that each item can't be processed more than the capacity of regular time and overtime in each time period. Constraint (6.25) ensures that each item can't be processed more than the capacity of outsourcing in each time period. Constraint (6.25) is non-linear, because of the product of a continuous variable $X_{ijk|R|t}$ and a binary variable O_{ij}. Linear form of constraint (6.25) with linearization constraints is explained in section 6.3.1. Constraint (6.26) ensures that each item can be processed maximum 24 hours in each time period. Constraint (6.27) and constraint (6.28) indicate the relation between binary variable Y_{ijkrt} and continuous variable X_{ijkrt}. If Y_{ijkrt} is 0, X_{ijkrt} takes the value of 0. If Y_{ijkrt} is 1, X_{ijkrt} is at least λ units of time. λ is 0.5 in this study. The completion time of the last job of item i ($|J_i|$) can't exceed the due date of item i by constraint (6.29). Constraint (6.29) is non-linear, because of the product of a continuous variable d_i and a binary variable Z_i. Linear form of constraint (6.29) with linearization constraints is explained in section 6.3.1.

Constraint (6.30) and constraint (6.31) are precedence constraints between jobs of each order. Constraint (6.30) ensures that job j of item i can be processed in time period t only after the processing job *(j-1)* of item i is completed. The first term of constraint (6.30) is for time periods which are up to t, so this term is not used when $t=1$. The job *(j-1)* of item i can be processed in regular time, overtime and outsourcing up to period t. According to second term of constraint (6.30), if job *(j-1)* of item i is completed during regular time, the processing of job j of item i can be started in regular time in time period t. If job *(j-1)* of item i is completed during overtime, the processing of job j of item i can be started in overtime in time period t. Constraint (6.31) ensures that job j of item i can be processed in outsourcing only after the processing of job *(j-1)* of item i is completed. Constraint (6.32) ensures that jobs of item i can't be processed in outsourcing more than available hours. For example, regular time capacity is 11 hours and overtime capacity is 11 hours. If previous job of job j of item i is completed during regular time, remaining outsourcing hours are 13; if previous job of job j of item i is completed during overtime, remaining outsourcing hours are 2.

Constraint (6.33) is a non-negativity restriction for X_{ijkrt}. Constraint (6.34) expresses that the maximum bound of $X_{ijk|R|t}$ is 24. Constraint (6.35) expresses the minimum bound of S_i and constraint (6.36) expresses the maximum bound of S_i. Constraint (6.37) expresses the minimum bound of d_i and constraint (6.38) expresses the maximum bound of d_i. Constraints (6.39) - (6.41) are binary restrictions for decision variables Y_{ijkrt}, Z_i and O_{ij}.

6.3 Introduction of the Linearization Method

The linearization method in the explanations of Coelho (2013) was applied to non-linear objective functions and non-linear constraints in this thesis. This method is for linearization of the product of a binary and a continuous variable.

Consider that the expression is $y = B * x$, B is a continuous variable and x is a binary variable in this expression. The continuous variable B is bounded below by zero and above by *Bmax*. Inequalities which are for the linearization of $y = B * x$ are explained below (Coelho, 2013).

$$y \leq Bmax * x \tag{6.42}$$

$$y \leq B \tag{6.43}$$

$$y \geq B - (1 - x) * Bmax \tag{6.44}$$

$$y \geq 0 \tag{6.45}$$

Inequality (6.42) and inequality (6.45) ensure that if *x=0*, *y* will be zero. Also, inequality (6.42) and inequality (6.45) determine the value interval of *B* when *x=1*. Inequality (6.43) and inequality (6.44) ensure that if *x=1*, *y* will be equal to *B*. Also, inequality (6.43) and inequality (6.44) determine the value interval of *B* when *x=0*.

If *B* is bounded below by *Bmin* and above by *Bmax*, the form of the inequalities which are for the linearization of $y = B * x$ are explained below (Coelho, 2013).

$$y \geq Bmin * x \tag{6.46}$$

$$y \leq Bmax * x \tag{6.47}$$

$$y \geq B - (1 - x) * Bmax \tag{6.48}$$

$$y \leq B - (1 - x) * Bmin \tag{6.49}$$

$$y \leq B + (1 - x) * Bmax \tag{6.50}$$

Inequality (6.46) and inequality (6.47) ensure that if *x=0*, *y* will be zero. Also, inequality (6.46) and inequality (6.47) determine the value interval of *B* when *x=1*. Inequality (6.48) and inequality (6.49) ensure that if *x=1*, *y* will be equal to *B*. Also, inequality (6.48) and inequality (6.49) determine the value interval of *B* when *x=0*. Inequality (6.50) ensures that *Bmax* is positive.

6.3.1 Application of the Linearization Method to Non-Linear Constraints and Non-Linear Objective Functions

Linearization of the product of $X_{ijk|R|t}$ and O_{ij} :

$X_{ijk|R|t}$ is a continuous variable and O_{ij} is a binary variable in non-linear constraint (6.51). $W_{ijk|R|t}$ is created for the linearization of constraint (6.51). $W_{ijk|R|t}$ is the number of assigned hours for processing job *j* of item *i* on resource *k* of outsourcing in time period *t*. $W_{ijk\,|R|t} = X_{ijk\,|R|t} * O_{ij}$ and $|R|$ expresses outsourcing. If O_{ij} is 1, $W_{ijk|R|t}$ takes the value of $X_{ijk|R|t}$, otherwise takes the value of 0.

The continuous variable $X_{ijk|R|t}$ is bounded below by zero and above by 24. The linearization method in the explanations of Coelho (2013) was applied to constraint (6.51). Constraint (6.52) is a linear form of constraint (6.51) with linearization constraints (6.53) - (6.56).

$$\sum_{j\in J_i}\sum_{k\in K} X_{ijk\,|R|t} * O_{ij} \le l_{|R|t} \quad \forall\, i \in I, r \in \{|R|\}, t \in T \tag{6.51}$$

$$\sum_{j\in J_i}\sum_{k\in K} W_{ijk\,|R|t} \le l_{|R|t} \quad \forall\, i \in I, r \in \{|R|\}, t \in T \tag{6.52}$$

$$W_{ijk\,|R|t} \le 24 * O_{ij} \quad \forall\, i \in I, j \in J_i, k \in K, r \in \{|R|\}, t \in T \tag{6.53}$$

$$W_{ijk\,|R|t} \le X_{ijk\,|R|t} \quad \forall\, i \in I, j \in J_i, k \in K, r \in \{|R|\}, t \in T \tag{6.54}$$

$$W_{ijk\,|R|t} \ge X_{ijk\,|R|t} - \left(1 - O_{ij}\right) * 24 \tag{6.55}$$

$$\forall\, i \in I, j \in J_i, k \in K, r \in \{|R|\}, t \in T$$

$$W_{ijk\,|R|t} \ge 0 \quad \forall\, i \in I, j \in J_i, k \in K, r \in \{|R|\}, t \in T \tag{6.56}$$

Constraints (6.53) - (6.56) are for the linearization of the product of $X_{ijk|R|t}$ and O_{ij}. Constraint (6.53) and constraint (6.56) ensure that if job *j* of item *i* is not outsourced ($O_{ij}=0$), number of assigned hours for processing job *j* of item *i* on resource *k* of outsourcing in time period *t* ($W_{ijk|R|t}$) will be zero. Also, constraint (6.53) and constraint (6.56) determine the value interval of $X_{ijk|R|t}$ when $O_{ij}=1$. Constraint (6.54) and constraint (6.55) ensure that if job *j* of item *i* is outsourced ($O_{ij}=1$), number of assigned hours for processing job j of item i on resource k of outsourcing in time period t ($W_{ijk|R|t}$) will be equal to $X_{ijk|R|t}$. Also, constraint (6.54) and constraint (6.55) determine the value interval of $X_{ijk|R|t}$ when $O_{ij}=0$.

Constraint (6.52) is a linear form of constraint (6.6) which is in the mixed-integer non-linear programming model in section 6.2.2 with linearization constraints (6.53) - (6.56). Also, constraint (6.52) is a linear form of constraint (6.25) which is in the multi-objective mixed-integer non-linear programming model in section 6.2.3 with linearization constraints (6.53) - (6.56).

Constraints (6.53) - (6.56) are used in the mixed-integer linear programming model which is presented in Appendix 1 for determining minimum and maximum bounds of $X_{ijk|R|t}$ in addition to linearization duty. Because, constraints (6.53) - (6.56) perform constraint (6.15)'s duty in the mixed-integer non-linear programming model in section 6.2.2.

Constraints (6.53) - (6.56) are used in the multi-objective mixed-integer linear programming model which is presented in Appendix 2 for determining minimum and maximum bounds of $X_{ijk|R|t}$ in addition to linearization duty. Because, constraints (6.53) - (6.56) perform constraint (6.34)'s duty in the multi-objective mixed-integer non-linear programming model in section 6.2.3.

Linearization of the product of S_i and Z_i:

S_i is a continuous variable and Z_i is a binary variable in non-linear objective function (6.57). Q_i is created for the linearization of objective function (6.57), $Q_i = S_i * Z_i$. If Z_i is 1, Q_i takes the value of S_i, otherwise takes the value of 0.

The continuous variable S_i is bounded below by $Smin_i$ and above by $Smax_i$. The linearization method in the explanations of Coelho (2013) was applied to objective function (6.57). Objective function (6.58) is a linear form of objective function (6.57) with linearization constraints (6.59) - (6.63).

$$Maximize \sum_{i\in I} S_i * Z_i - \sum_{i\in I} \sum_{j\in J_i} \sum_{k\in K} \sum_{r\in R} \sum_{t\in T} X_{ijkrt} * c_{kr} \quad (6.57)$$

$$Maximize \sum_{i\in I} Q_i - \sum_{i\in I} \sum_{j\in J_i} \sum_{k\in K} \sum_{r\in R} \sum_{t\in T} X_{ijkrt} * c_{kr} \quad (6.58)$$

$$Q_i \geq Smin_i * Z_i \quad \forall\, i \in I \quad (6.59)$$

$$Q_i \leq Smax_i * Z_i \quad \forall\, i \in I \quad (6.60)$$

$$Q_i \geq S_i - (1 - Z_i) * Smax_i \quad \forall\, i \in I \quad (6.61)$$

$$Q_i \leq S_i - (1 - Z_i) * Smin_i \quad \forall\, i \in I \quad (6.62)$$

$$Q_i \leq S_i + (1 - Z_i) * Smax_i \quad \forall\, i \in I \quad (6.63)$$

Constraints (6.59) - (6.63) are for the linearization of the product of S_i and Z_i. Constraint (6.59) and constraint (6.60) ensure that if item i is not accepted ($Z_i=0$), Q_i will be zero. Also, constraint (6.59) and constraint (6.60) determine the value interval of S_i when $Z_i=1$. Constraint (6.61) and constraint (6.62) ensure that if item i is accepted ($Z_i=1$), Q_i will be equal to S_i. Also, constraint (6.61) and constraint (6.62) determine the value interval of S_i when $Z_i=0$. Constraint (6.63) expresses that maximum value of selling price is positive.

Objective function (6.58) is a linear form of objective function (6.19) which is in the multi-objective mixed-integer non-linear programming model in section 6.2.3 with linearization constraints (6.59) - (6.63).

Constraints (6.59) - (6.63) are used in the multi-objective mixed-integer linear programming model which is presented in Appendix 2 for determining minimum and maximum bounds of S_i in addition to linearization duty. Because, constraints (6.59) - (6.63) perform constraint (6.35) and constraint (6.36)'s duty in the multi-objective mixed-integer non-linear programming model in section 6.2.3.

Linearization of the product of d_i and Z_i:

Z_i is a binary variable and d_i is a continuous variable in non-linear objective function (6.64) and non-linear constraint (6.66). H_i is created for the linearization of objective function (6.64) and constraint (6.66), $H_i = d_i * Z_i$. If Z_i is 1, H_i takes the value of d_i, otherwise takes the value of 0.

The continuous variable d_i is bounded below by $dmin_i$ and above by $dmax_i$. The linearization method in the explanations of Coelho (2013) was applied to objective function (6.64) and constraint (6.66). Objective function (6.65) is a linear form of objective function (6.64) with linearization constraints (6.68) - (6.72). Constraint (6.67) is a linear form of constraint (6.66) with linearization constraints (6.68) - (6.72).

$$Minimize \sum_{i \in I} d_i * Z_i \tag{6.64}$$

$$Minimize \sum_{i \in I} H_i \tag{6.65}$$

$$\sum_{k \in K} Y_{i|J_i|krt} * t \leq d_i * Z_i \quad \forall\, i \in I, j \in \{|J_i|\}, r \in R, t \in T \tag{6.66}$$

$$\sum_{k \in K} Y_{i|J_i|krt} * t \leq H_i \quad \forall\, i \in I, j \in \{|J_i|\}, r \in R, t \in T \tag{6.67}$$

$$H_i \geq dmin_i * Z_i \quad \forall\, i \in I \tag{6.68}$$

$$H_i \leq dmax_i * Z_i \quad \forall\, i \in I \tag{6.69}$$

$$H_i \geq d_i - (1 - Z_i) * dmax_i \quad \forall\, i \in I \tag{6.70}$$

$$H_i \leq d_i - (1 - Z_i) * dmin_i \quad \forall\, i \in I \tag{6.71}$$

$$H_i \leq d_i + (1 - Z_i) * dmax_i \quad \forall\, i \in I \tag{6.72}$$

Constraints (6.68) - (6.72) are for the linearization of the product of d_i and Z_i. Constraint (6.68) and constraint (6.69) ensure that if item i is not accepted ($Z_i=0$), H_i will be zero. Also, constraint (6.68) and constraint (6.69) determine the value interval of d_i when $Z_i=1$. Constraint (6.70) and constraint (6.71) ensure that if item i is accepted ($Z_i=1$), H_i will be equal to d_i. Also, constraint (6.70) and constraint (6.71) determine the value interval of d_i when $Z_i=0$. Constraint (6.72) expresses that maximum value of due date is positive.

Objective function (6.65) is a linear form of objective function (6.20) which is in the multi-objective mixed-integer non-linear programming model in section 6.2.3 with linearization constraints (6.68) - (6.72). Constraint (6.67) is a linear form of constraint (6.29) which is in the multi-objective mixed-integer non-linear programming model in section 6.2.3 with linearization constraints (6.68) - (6.72).

Constraints (6.68) - (6.72) are used in the multi-objective mixed-integer linear programming model which is presented in Appendix 2 for determining minimum and maximum bounds of d_i in addition to linearization duty. Because, constraints (6.68) - (6.72) perform constraint (6.37) and constraint (6.38)'s duty in the multi-objective mixed-integer non-linear programming model in section 6.2.3.

CHAPTER SEVEN
COMPUTATIONAL STUDY

7.1 Computational Study for the Model where Selling Prices and Due Dates are Constant Parameters

The mixed-integer linear programming model where selling prices and due dates are constant parameters is solved by using Lingo 14.0 software in order to test the four examples in the study of Chen et al. (2009). Global optimal solutions are found after the computational study with Lingo 14.0 software for these four examples.

The data are based on the study of Chen et al. (2009). Information about sets is shown in Table 7.1 and data about the cost ($) of processing on resource *k* of source *r* per hour are shown in Table 7.2. Regular time is expressed by 1, overtime is expressed by 2 and outsourcing is expressed by 3 in the set of sources.

Table 7.1 Information about sets

Items	$i \in I = \{1,2,3,4\}$
Jobs	$J \in J_i = \{1,2,3,4\}$
Resources	$k \in K = \{1,2,3\}$
Sources	$r \in R = \{1,2,3\}$
Time Periods	$t \in T = \{1,2,3,4\}$

Table 7.2 The cost of processing on resource k of source r ($ / hour)

Resource	**Source type**		
	1	**2**	**3**
1	100	150	250
2	200	250	350
3	100	200	150

Regular time is 8 hours, overtime is 8 hours per day in this computational study. Also, outsourcing runs 24 hours per day and the capacity of outsourcing is large enough in this computational study.

Data about the selling prices, due dates and processing times are shown in related tables of each example. R.T expresses regular time, O.T expresses overtime, O.S expresses outsourcing and each time period expresses one day in the tables of examples. Number of assigned hours for processing job *j* of item *i* on resource *k* of source *r* in time period *t* take part in the tables of examples.

The first example is the base case and the results of this example are shown in Table 7.3. The total net profit is found as $10100 and the fourth order is rejected.

Table 7.3 Example 1

i	S_i ($)	d_i (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4		
						R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	12000	4	1	2	8	8											
			2	3	20						20						
			3	1	16							8	8				
			4	2	9										8	1	
2	12000	4	1	2	12		8		4								
			2	2	14				4	8		2					
			3	3	5							0.5			4.5		
			4	1	10												10
3	12000	4	1	2	8			8									
			2	3	9				8			1					
			3	2	14							6	8				
			4	1	13										8	5	
4	10000	4	1	1	6	Not Selected											
			2	1	18												
			3	2	17												
			4	2	6												

Table 7.4 Example 2

i	S_i ($)	d_i (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4		
						R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	12000	4	1	2	8	Not Selected											
			2	3	20												
			3	1	16												
			4	2	9												
2	12000	4	1	2	12	8	4										
			2	2	14		4		8	2							
			3	3	5							5					
			4	1	10								2.5		7.5		
3	12000	4	1	2	8			8									
			2	3	9				8	1							
			3	2	14					6		8					
			4	1	13								4.5		0.5	8	
4	11000	4	1	1	6	6											
			2	1	18	2			8			8					
			3	2	17								8		8	1	
			4	2	6											6	

When the selling price of the fourth order is increased from $10000 to $11000, the first order is rejected and the second order, the third order and the fourth order are accepted. The total net profit is found as $11100 and the results of this example are shown in Table 7.4.

Table 7.5 Example 3

i	S_i ($)	d_i (Day)	j	k	p_{ijk} (Hour)	**Time Period 1**			**Time Period 2**			**Time Period 3**			**Time Period 4**		
						R.T	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**
1	13000	4	1	2	8			8									
			2	3	20				8	4		8					
			3	1	16								8		8		
			4	2	9												9
2	12000	4	1	2	12	8	4										
			2	2	14		4			2			8				
			3	3	5										5		
			4	1	10												10
3	12000	4	1	2	8			8									
			2	3	9			9									
			3	2	14				8	6							
			4	1	13					2		8				3	
4	11000	4	1	1	6	6											
			2	1	18	2	8		8								
			3	2	17							8			8	1	
			4	2	6											6	

If the selling price of the first order and the fourth order are increased, all the orders are accepted. Total net profit is found as $12000, when the selling price of the first order is $13000 and the selling price of the fourth order is $11000. The results of this example are shown in Table 7.5.

Table 7.6 Example 4

i	S_i ($)	d_i (Day)	j	k	p_{ijk} (Hour)	**Time Period 1**			**Time Period 2**			**Time Period 3**			**Time Period 4**		
						R.T	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**
1	12000	3	1	2	8	Not Selected											
			2	3	20												
			3	1	16												
			4	2	9												
2	12000	4	1	2	12	8	4										
			2	2	14		4		0.5	4.5		5					
			3	3	5							3			2		
			4	1	10										6	4	
3	12000	3	1	2	8			8									
			2	3	9			9									
			3	2	14				7.5	3.5		3					
			4	1	13							5	8				
4	10000	4	1	1	6	6											
			2	1	18	2	0.5		8	4.5		3					
			3	2	17								7		8	2	
			4	2	6											6	

Due dates of the four orders are the same in the previous examples. When due dates of the first and the third order are decreased to three days, the total net profit is found as \$9650 and the first order is rejected. The results of this example are shown in Table 7.6. The first and the second operations of the third order are outsourced because of the shorter due date, so total processing cost increases and the total net profit decreases.

Table 7.7 Summary table for four examples

		Example 1	**Example 2**	**Example 3**	**Example 4**
Order 1	Selling Price (\$)	12000	12000	13000	12000
	Due Date (Day)	4	4	4	3
Order 2	Selling Price (\$)	12000	12000	12000	12000
	Due Date (Day)	4	4	4	4
Order 3	Selling Price (\$)	12000	12000	12000	12000
	Due Date (Day)	4	4	4	3
Order 4	Selling Price (\$)	10000	11000	11000	10000
	Due Date (Day)	4	4	4	4
Total Net Profit (\$)		**10100**	**11100**	**12000**	**9650**

Selling price and due date values of each order in four examples and the total net profits which are found in these examples are presented in Table 7.7.

7.2 Computational Study for the Model where Selling Prices and Due Dates are Constant Parameters under Different Resource Utilization Rates

The mixed-integer linear programming model where selling prices and due dates are constant parameters is solved by using Lingo 14.0 in order to test the base case in the study of Chen et al. (2009) under different resource utilization rates. Global optimal solutions are found after the computational study with Lingo 14.0 software when the resource utilization rates are 70.31 %, 81.25 %, 90.63 % and selling prices and due dates are constant parameters.

The selling prices of the first three orders are $12000 and the selling price of the fourth order is $10000. Due dates of all orders are four days. Resource utilization rates are calculated according to in-house capacity which contains regular time and overtime for four days.

Table 7.8 Information about sets

Items	i ϵ I = {1,2,3,4}
Jobs	J ϵ Ji = {1,2,3,4}
Resources	k ϵ K = {1,2,3}
Sources	r ϵ R = {1,2,3}
Time Periods	t ϵ T = {1,2,3,4}

Table 7.9 The cost of processing on resource k of source r ($ / hour)

Resource	**Source type**		
	1	**2**	**3**
1	100	150	250
2	200	250	350
3	100	200	150

Information about sets is shown in Table 7.8 and data about the cost ($) of processing on resource *k* of source *r* per hour are shown in Table 7.9. Regular time is expressed by 1, overtime is expressed by 2 and outsourcing is expressed by 3 in the set of sources.

Regular time is 8 hours, overtime is 8 hours per day in this computational study. Also, outsourcing runs 24 hours per day and the capacity of outsourcing is large enough in this computational study.

Data about the selling prices, due dates and processing times which are calculated according to resource utilization rates are shown in related tables of the results of each Lingo model. R.T expresses regular time, O.T expresses overtime, O.S expresses outsourcing and each time period expresses one day in the tables of the results of Lingo models. Number of assigned hours for processing job *j* of item *i* on resource *k* of source *r* in time period *t* take part in the tables of the results of Lingo models.

Table 7.10 Results of Lingo model where selling prices and due dates are constant parameters under 70.31 % resource utilization rate

i	**S_i (\$)**	**d_i (Day)**	**j**	**k**	**p_{ijk} (Hour)**	**Time Period 1**			**Time Period 2**			**Time Period 3**			**Time Period 4**		
						R.T	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**
1	12000	4	1	2	4	4											
			2	3	26	4	0.5		8	5.5		8					
			3	1	12								5		7		
			4	2	5										1	4	
2	12000	4	1	2	6				6								
			2	2	7				2			5					
			3	3	7										7		
			4	1	7										1	6	
3	12000	4	1	2	4	4											
			2	3	12			12									
			3	2	7					7							
			4	1	9							7	2				
4	10000	4	1	1	4	4											
			2	1	13	4			8			1					
			3	2	9							3			6		
			4	2	3										1	2	

All orders are accepted and the total net profit is found \$25500, when the resource utilization rate is 70.31 %. The processing of the third order can be completed in three days. The results of Lingo model where selling prices and due dates are constant parameters under 70.31 % resource utilization rate are shown in Table 7.10.

Table 7.11 Results of Lingo model where selling prices and due dates are constant parameters under 81.25 % resource utilization rate

i	**S_i (\$)**	**d_i (Day)**	**j**	**k**	**p_{ijk} (Hour)**	**Time Period 1**			**Time Period 2**			**Time Period 3**			**Time Period 4**		
						R.T	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**
1	12000	4	1	2	5	3	2										
			2	3	30			8			22						
			3	1	13							8	5				
			4	2	5								0.5		0.5	4	
2	12000	4	1	2	7				7								
			2	2	8				1			4.5	2.5				
			3	3	8										8		
			4	1	8											8	
3	12000	4	1	2	5	5											
			2	3	14	1			8			5					
			3	2	8							3	5				
			4	1	11								3		8		
4	10000	4	1	1	5	5											
			2	1	15	3	4		8								
			3	2	10					6		0.5			3.5		
			4	2	4										4		

When the resource utilization rate is increased to 81.25 %, all orders are accepted and the total net profit is found \$21700. The results of Lingo model where selling prices and due dates are constant parameters under 81.25 % resource utilization rate are shown in Table 7.11.

Table 7.12 Results of Lingo model where selling prices and due dates are constant parameters under 90.63 % resource utilization rate

i	**S_i (\$)**	**d_i (Day)**	**j**	**k**	**p_{ijk} (Hour)**	**Time Period 1**			**Time Period 2**			**Time Period 3**			**Time Period 4**		
						R.T	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**
1	12000	4	1	2	5	5											
			2	3	34			16			18						
			3	1	15							8	3		4		
			4	2	6										0.5	5.5	
2	12000	4	1	2	8	3			5								
			2	2	9				3	6							
			3	3	9							1			8		
			4	1	9												9
3	12000	4	1	2	5		5										
			2	3	15				8			7					
			3	2	10							1	8		1		
			4	1	12										4	8	
4	10000	4	1	1	5.5	5.5											
			2	1	16.5	2.5	6		8								
			3	2	11					1.5		7			2.5		
			4	2	4										4		

The total net profit is found \$17600, when the resource utilization rate is 90.63 %. The results of Lingo model where selling prices and due dates are constant parameters under 90.63 % resource utilization rate are shown in Table 7.12.

These test results show that the total net profit decreases, if the resource utilization rate is increased. The total processing cost increases when the workload is increased, so the total net profit is affected. Also, the test results are the indicators about the necessity of planning the production with variable selling price and necessity of increasing selling prices according to the increase of resource utilization rate. Because selling price must be increased when the workload is increased in order not to lose profit.

Selling price and due date values of each order in Lingo models where selling prices and due dates are constant parameters under different resource utilization rates and the total net profits which are found in these Lingo models are presented in Table 7.13.

Table 7.13 Summary table for Lingo models where selling prices and due dates are constant parameters under different resource utilization rates

		Resource Utilization Rate (%)		
		70.31%	**81.25%**	**90.63%**
Order 1	Selling Price ($)	12000	12000	12000
	Due Date (Day)	4	4	4
Order 2	Selling Price ($)	12000	12000	12000
	Due Date (Day)	4	4	4
Order 3	Selling Price ($)	12000	12000	12000
	Due Date (Day)	4	4	4
Order 4	Selling Price ($)	10000	10000	10000
	Due Date (Day)	4	4	4
Total Net Profit ($)		**25500**	**21700**	**17600**

7.3 Computational Study for the Model where Selling Prices and Due Dates are Decision Variables under Different Resource Utilization Rates

Twelve scenarios are created in order to test the multi-objective mixed-integer linear programming model where selling prices and due dates are decision variables under different resource utilization rates by using Lingo 14.0 software. Global optimal solutions are found after the computational study with Lingo 14.0 software when the resource utilization rates are 70.31 %, 81.25 % , 90.63 % and selling prices and due dates are decision variables. Data about minimum and maximum selling prices and due dates of orders in twelve scenarios under different resource utilization rates are shown in Table 7.14.

Table 7.14 Data about selling prices and due dates of orders in twelve scenarios under different resource utilization rates

		Order 1		Order 2		Order 3		Order 4	
		Smin-Smax ($)	dmin-dmax (Day)	Smin-Smax ($)	dmin-dmax (Day)	Smin-Smax ($)	dmin-dmax (Day)	Smin-Smax ($)	dmin-dmax (Day)
Resource Utilization Rate: 70.31 %	**Scenario 1**	11000-13000	3-4	11000-13000	3-4	11000-13000	3-4	9000-11000	3-4
	Scenario 2	11000-13000	2-4	11000-13000	2-4	11000-13000	2-4	9000-11000	2-4
	Scenario 3	10000-14000	3-4	10000-14000	3-4	10000-14000	3-4	8000-12000	3-4
	Scenario 4	10000-14000	2-4	10000-14000	2-4	10000-14000	2-4	8000-12000	2-4
Resource Utilization Rate: 81.25%	**Scenario 5**	11000-13000	3-4	11000-13000	3-4	11000-13000	3-4	9000-11000	3-4
	Scenario 6	11000-13000	2-4	11000-13000	2-4	11000-13000	2-4	9000-11000	2-4
	Scenario 7	10000-14000	3-4	10000-14000	3-4	10000-14000	3-4	8000-12000	3-4
	Scenario 8	10000-14000	2-4	10000-14000	2-4	10000-14000	2-4	8000-12000	2-4
Resource Utilization Rate: 90.63 %	**Scenario 9**	11000-13000	3-4	11000-13000	3-4	11000-13000	3-4	9000-11000	3-4
	Scenario 10	11000-13000	2-4	11000-13000	2-4	11000-13000	2-4	9000-11000	2-4
	Scenario 11	10000-14000	3-4	10000-14000	3-4	10000-14000	3-4	8000-12000	3-4
	Scenario 12	10000-14000	2-4	10000-14000	2-4	10000-14000	2-4	8000-12000	2-4

The base case in the study of Chen et al. (2009) is adapted to these twelve scenarios. Four orders, three resources and three sources are used like the study of Chen et al. (2009). The cost ($) of processing on resource *k* of source *r* per hour is the same as in their study and processing time of operations are revised according the resource utilization rates in this computational study. Also, selling prices and due dates are decision variables in these twelve scenarios. Selling prices of orders are changed $1000 and $2000 according to the base case values in the study of Chen et al. (2009) in order to determine minimum and maximum values of selling prices. Due date values of orders are constant and four days in the base case of the study of Chen et al. (2009), so due date values are decreased one day and two days in order to determine the minimum values of due dates, maximum values of due dates are taken as four days. Resource utilization rates are calculated according to in-house capacity which contains regular time and overtime for four days.

Information about sets is shown in Table 7.15 and data about the cost ($) of processing on resource *k* of source *r* per hour are shown in Table 7.16. Regular time is expressed by 1, overtime is expressed by 2 and outsourcing is expressed by 3 in the set of sources.

Table 7.15 Information about sets

Items	i ϵ I = {1,2,3,4}
Jobs	J ϵ Ji = {1,2,3,4}
Resources	k ϵ K = {1,2,3}
Sources	r ϵ R = {1,2,3}
Time Periods	t ϵ T = {1,2,3,4}

Table 7.16 The cost of processing on resource k of source r ($/hour)

Resource	**Source type**		
	1	**2**	**3**
1	100	150	250
2	200	250	350
3	100	200	150

Regular time is 8 hours, overtime is 8 hours per day in this computational study. Also, outsourcing runs 24 hours per day and the capacity of outsourcing is large enough in this computational study.

Data about the minimum and maximum selling prices, minimum and maximum due dates and processing times are shown in related tables of the results of each Lingo model. R.T expresses regular time, O.T expresses overtime, O.S expresses outsourcing and each time period expresses one day in the tables of the results of Lingo models. Number of assigned hours for processing job *j* of item *i* on resource *k* of source *r* in time period *t* take part in the tables of the results of Lingo models.

The first four scenarios are created for 70.31 % resource utilization rate, the scenarios between five and eight are created for 81.25 % resource utilization rate and the last four scenarios are created for 90.63 % resource utilization rate.

The total net profit is found as $29500 in scenario 1 and scenario 2. Total due date is found as fifteen days which meets the optimal total net profit value of $29500 and the due date of the third order can be shortened to three days in both scenario 1 and scenario 2. The Lingo model of scenario 1 is presented in Appendix 3 and Appendix 4. The total net profit is found as $33500 in scenario 3 and scenario 4. This value is higher than scenario 1 and scenario 2, because of the maximum selling prices in scenario 3 and scenario 4.

The due date of the third order can be shortened to three days and the total due date is found as fifteen days which meets the optimal total net profit value of $33500 in scenario 3 and scenario 4. Although the minimum due date values of all orders are two days in scenario 2 and scenario 4, only the third order's due date can be decreased to three days. The results of the first four scenarios are shown in Table 7.17, Table 7.18, Table 7.19 and Table 7.20.

Table 7.17 Scenario 1

i	$Smin_i$ (\$)	$Smax_i$ (\$)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	11000	13000	3	4	1	2	4	4											
					2	3	26	4			8	5.5		8	0.5				
					3	1	12								4.5		7.5		
					4	2	5										0.5	4.5	
2	11000	13000	3	4	1	2	6		4		1			1					
					2	2	7							7					
					3	3	7										7		
					4	1	7										0.5	6.5	
3	11000	13000	3	4	1	2	4	4											
					2	3	12			12									
					3	2	7				7								
					4	1	9				0.5			8	0.5				
4	9000	11000	3	4	1	1	4	4											
					2	1	13	4			7.5	1.5							
					3	2	9								2		7		
					4	2	3										0.5	2.5	

Table 7.18 Scenario 2

i	$Smin_i$ (\$)	$Smax_i$ (\$)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	11000	13000	2	4	1	2	4	4											
					2	3	26	4			8	1		8	5				
					3	1	12								3		7	2	
					4	2	5											5	
2	11000	13000	2	4	1	2	6		6										
					2	2	7		0.5					6.5					
					3	3	7										7		
					4	1	7										1	6	
3	11000	13000	2	4	1	2	4	4											
					2	3	12			12									
					3	2	7				7								
					4	1	9				1			8					
4	9000	11000	2	4	1	1	4	4											
					2	1	13	4	2		7								
					3	2	9				1	0.5		1.5			6		
					4	2	3										2	1	

Table 7.19 Scenario 3

i	Smin$_i$ ($)	Smax$_i$ ($)	dmin$_i$ (Day)	dmax$_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	10000	14000	3	4	1	2	4	4											
					2	3	26	4			8	6		8					
					3	1	12								4		8		
					4	2	5											5	
2	10000	14000	3	4	1	2	6				6								
					2	2	7				2			5					
					3	3	7										7		
					4	1	7											7	
3	10000	14000	3	4	1	2	4	4											
					2	3	12			12									
					3	2	7					7							
					4	1	9							8	1				
4	8000	12000	3	4	1	1	4	4											
					2	1	13	4			8	1							
					3	2	9							3	0.5		5.5		
					4	2	3										2.5	0.5	

Table 7.20 Scenario 4

i	Smin$_i$ ($)	Smax$_i$ ($)	dmin$_i$ (Day)	dmax$_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	10000	14000	2	4	1	2	4	4											
					2	3	26	4	6		8			8					
					3	1	12								3.5		8	0.5	
					4	2	5											5	
2	10000	14000	2	4	1	2	6		6										
					2	2	7							6.5			0.5		
					3	3	7										7		
					4	1	7											7	
3	10000	14000	2	4	1	2	4	4											
					2	3	12			12									
					3	2	7				7								
					4	1	9				1			8					
4	8000	12000	2	4	1	1	4	4											
					2	1	13	4	2		7								
					3	2	9				1			1.5	2		4.5		
					4	2	3										3		

The total net profit is found as $25700 in scenario 5 and scenario 6. Although the minimum and maximum values of selling prices of orders are the same in scenario 1, scenario 2, scenario 5, scenario 6, the total net profit of scenario 5 and scenario 6 is less than scenario 1 and scenario 2. This result shows that, the total processing cost increases and the total net profit decreases, if the resource utilization rate is increased.

The total net profit is found as $29700 in scenario 7 and scenario 8. This value is higher than the value of scenario 5 and scenario 6, because of the maximum selling prices in scenario 7 and scenario 8. Also, this value is less than scenario 3 and scenario 4, because of the effect of resource utilization rate on the total net profit.

The total due date of orders is found as sixteen days which meets the optimal total net profit value of $25700 in scenario 5 and scenario 6, no order's due date can be shortened in these scenarios.

The total due date of orders is found as sixteen days which meets the optimal total net profit value of $29700 in scenario 7 and scenario 8, no order's due date can be shortened in these two scenarios like scenario 5 and scenario 6. The results of scenario 5, scenario 6, scenario 7 and scenario 8 are shown in Table 7.21, Table 7.22, Table 7.23 and Table 7.24.

Table 7.21 Scenario 5

i	**$Smin_i$ ($)**	**$Smax_i$ ($)**	**$dmin_i$ (Day)**	**$dmax_i$ (Day)**	**j**	**k**	**p_{ijk} (Hour)**	**Time Period 1**			**Time Period 2**			**Time Period 3**			**Time Period 4**		
								R.T	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**
1	11000	13000	3	4	1	2	5	3	2										
					2	3	30			6			24						
					3	1	13							8	4.5		0.5		
					4	2	5											5	
2	11000	13000	3	4	1	2	7				7								
					2	2	8				1	2.5		4.5					
					3	3	8										8		
					4	1	8											8	
3	11000	13000	3	4	1	2	5	5											
					2	3	14	3			8			3					
					3	2	8							3.5	4.5				
					4	1	11								3.5		7.5		
4	9000	11000	3	4	1	1	5	5											
					2	1	15	3	4		8								
					3	2	10					3					7		
					4	2	4										1	3	

Table 7.22 Scenario 6

i	**$Smin_i$ ($)**	**$Smax_i$ ($)**	**$dmin_i$ (Day)**	**$dmax_i$ (Day)**	**j**	**k**	**p_{ijk} (Hour)**	**Time Period 1**			**Time Period 2**			**Time Period 3**			**Time Period 4**		
								R.T	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**
1	11000	13000	2	4	1	2	5	0.5	4.5										
					2	3	30			6			24						
					3	1	13							8	5				
					4	2	5										5		
2	11000	13000	2	4	1	2	7	2.5			4.5								
					2	2	8				3.5			4.5					
					3	3	8										8		
					4	1	8											8	
3	11000	13000	2	4	1	2	5	5											
					2	3	14	3			6.5			4.5					
					3	2	8							3.5	4.5				
					4	1	11								3		8		
4	9000	11000	2	4	1	1	5	5											
					2	1	15	3	2.5		8	1.5							
					3	2	10					6.5			3.5				
					4	2	4										3	1	

Table 7.23 Scenario 7

i	$Smin_i$ (\$)	$Smax_i$ (\$)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	10000	14000	3	4	1	2	5	0.5	4.5										
					2	3	30			8			22						
					3	1	13							8	5				
					4	2	5										4.5	0.5	
2	10000	14000	3	4	1	2	7	2.5			4.5								
					2	2	8				3.5			4.5					
					3	3	8							0.5			7.5		
					4	1	8										0.5	7.5	
3	10000	14000	3	4	1	2	5	5											
					2	3	14	3			6			5					
					3	2	8							3	5				
					4	1	11								3		7.5	0.5	
4	8000	12000	3	4	1	1	5	5											
					2	1	15	3	4		8								
					3	2	10					7		0.5	2.5				
					4	2	4								0.5		3.5		

Table 7.24 Scenario 8

i	$Smin_i$ (\$)	$Smax_i$ (\$)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	10000	14000	2	4	1	2	5	3	2										
					2	3	30			8			22						
					3	1	13							8	4.5		0.5		
					4	2	5										5		
2	10000	14000	2	4	1	2	7				7								
					2	2	8				1	2		4.5	0.5				
					3	3	8										8		
					4	1	8											8	
3	10000	14000	2	4	1	2	5	5											
					2	3	14	1.5			8			4.5					
					3	2	8							3.5	4.5				
					4	1	11								3.5		7.5		
4	8000	12000	2	4	1	1	5	5											
					2	1	15	3	3.5		8	0.5							
					3	2	10					6			0.5		3	0.5	
					4	2	4											4	

The total net profit of scenario 9 and scenario 10 is \$21600 which is less than scenario 1, scenario 2, scenario 5 and scenario 6, in spite of having the same minimum and maximum selling prices.

Also, the total net profit is found as \$25600 in scenario 11 and scenario 12 and this value is less than scenario 3, scenario 4, scenario 7 and scenario 8, despite having the same minimum and maximum selling prices in these scenarios. Reason of these results is the resource utilization rate. Increase on the resource utilization rate reduces the total net profit. Also, the total net profit of scenario 11 and scenario 12 is higher than scenario 9 and scenario 10 because of the values of maximum selling prices.

Due date of the fourth order is shortened to three days in the last four scenarios. The total due date of orders is found as fifteen days which meets the optimal total net profit value of $21600 in scenario 9 and scenario 10. The total due date of orders is found as fifteen days which meets the optimal total net profit value of $25600 in scenario 11 and scenario 12.

The results of the last four scenarios are shown in Table 7.25, Table 7.26, Table 7.27 and Table 7.28. Furthermore, selling prices take maximum values in twelve scenarios.

Table 7.25 Scenario 9

i	$Smin_i$ ($)	$Smax_i$ ($)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	11000	13000	3	4	1	2	5	5											
					2	3	34			16			18						
					3	1	15							8	3		4		
					4	2	6										4	2	
2	11000	13000	3	4	1	2	8	3	3		2								
					2	2	9				6	0.7		2.3					
					3	3	9							1			8		
					4	1	9												9
3	11000	13000	3	4	1	2	5		5										
					2	3	15				8			7					
					3	2	10								6		4		
					4	1	12										4	8	
4	9000	11000	3	4	1	1	5.5	5.5											
					2	1	16.5	2.5	6		8								
					3	2	11					7.3		3.7					
					4	2	4							2	2				

Table 7.26 Scenario 10

i	$Smin_i$ ($)	$Smax_i$ ($)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	11000	13000	2	4	1	2	5	5											
					2	3	34			16			18						
					3	1	15							8	3		4		
					4	2	6										4	2	
2	11000	13000	2	4	1	2	8		6		2								
					2	2	9				6			3					
					3	3	9							1			8		
					4	1	9												9
3	11000	13000	2	4	1	2	5	3	2										
					2	3	15				8			7					
					3	2	10							1	5		4		
					4	1	12										4	8	
4	9000	11000	2	4	1	1	5.5	5.5											
					2	1	16.5	2.5	6		8								
					3	2	11					8		3					
					4	2	4							1	3				

Table 7.27 Scenario 11

i	Smin$_i$ (\$)	Smax$_i$ (\$)	dmin$_i$ (Day)	dmax$_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	10000	14000	3	4	1	2	5	5											
					2	3	34			10			24						
					3	1	15							8	3		4		
					4	2	6										4	2	
2	10000	14000	3	4	1	2	8		6		2								
					2	2	9				6			3					
					3	3	9							1			8		
					4	1	9												9
3	10000	14000	3	4	1	2	5	3	2										
					2	3	15				8			7					
					3	2	10								6		4		
					4	1	12										4	8	
4	8000	12000	3	4	1	1	5.5	5.5											
					2	1	16.5	2.5	6		8								
					3	2	11					8		3					
					4	2	4							2	2				

Table 7.28 Scenario 12

i	Smin$_i$ (\$)	Smax$_i$ (\$)	dmin$_i$ (Day)	dmax$_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	10000	14000	2	4	1	2	5	5											
					2	3	34			10			24						
					3	1	15							8	3		4		
					4	2	6										4	2	
2	10000	14000	2	4	1	2	8		6		2								
					2	2	9				6	3							
					3	3	9							1			8		
					4	1	9												9
3	10000	14000	2	4	1	2	5	3	2										
					2	3	15				8			7					
					3	2	10								6		4		
					4	1	12										4	8	
4	8000	12000	2	4	1	1	5.5	5.5											
					2	1	16.5	2.5	6		8								
					3	2	11					5		6					
					4	2	4							2	2				

The values of selling prices which are obtained in twelve scenarios are shown in Figure 7.1. The values of due dates which are obtained in twelve scenarios are shown in Figure 7.2.

The graphic which is related with the total net profit of twelve scenarios is shown in Figure 7.3. Also, the graphic which is related with the total due date of twelve scenarios is shown in Figure 7.4.

Although the total due date of orders can be decreased in the first four scenarios and in the last four scenarios, the value of total due date can't be decreased in the other scenarios.

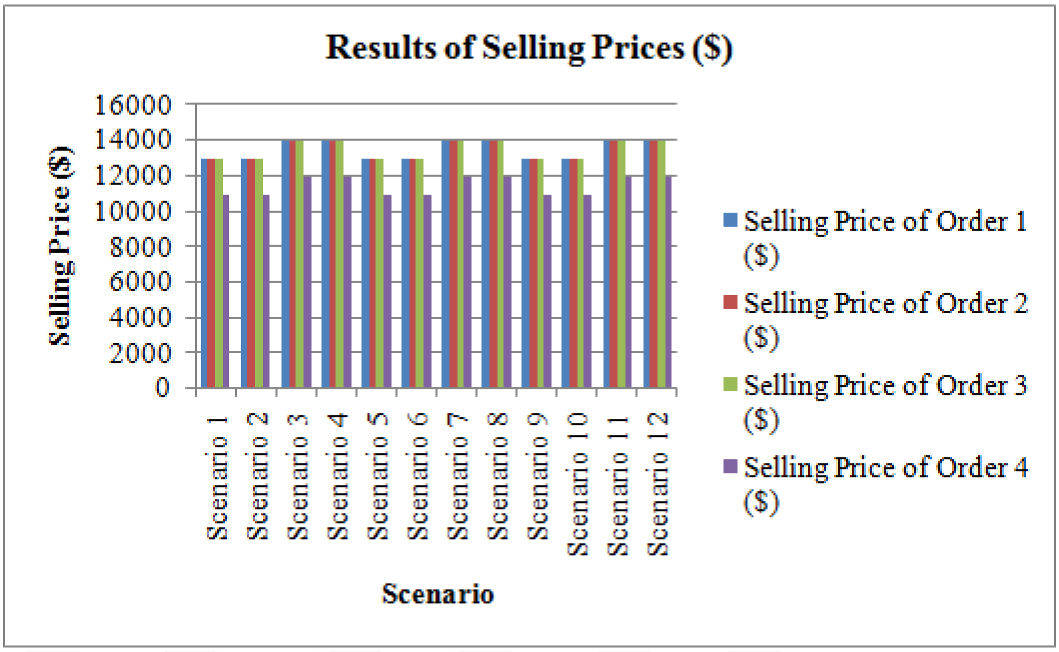

Figure 7.1 The selling prices in twelve scenarios

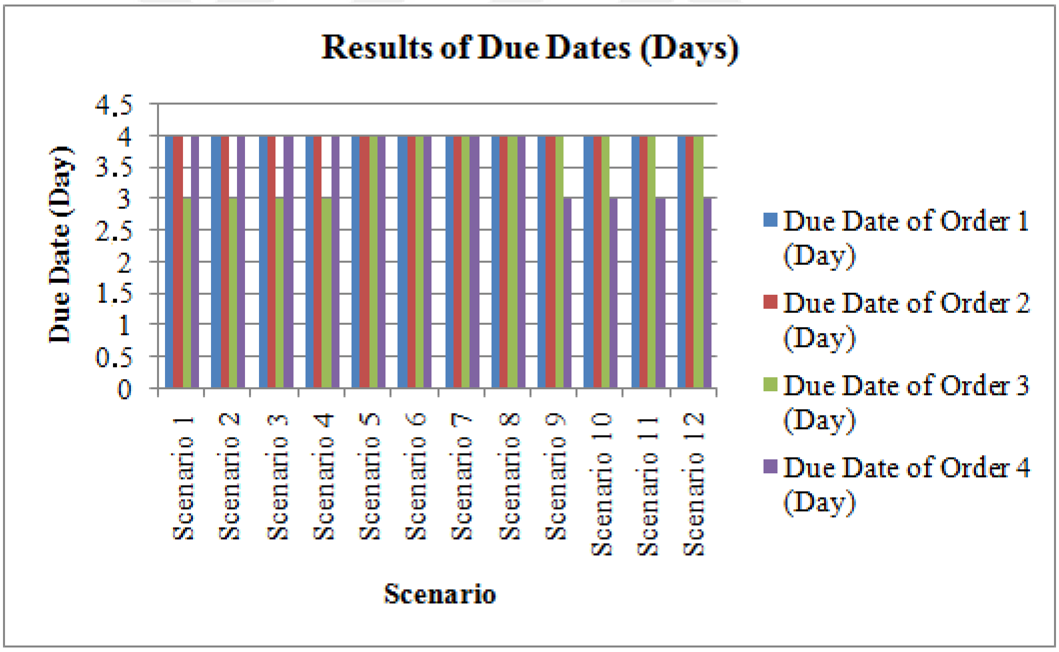

Figure 7.2 The due dates in twelve scenarios

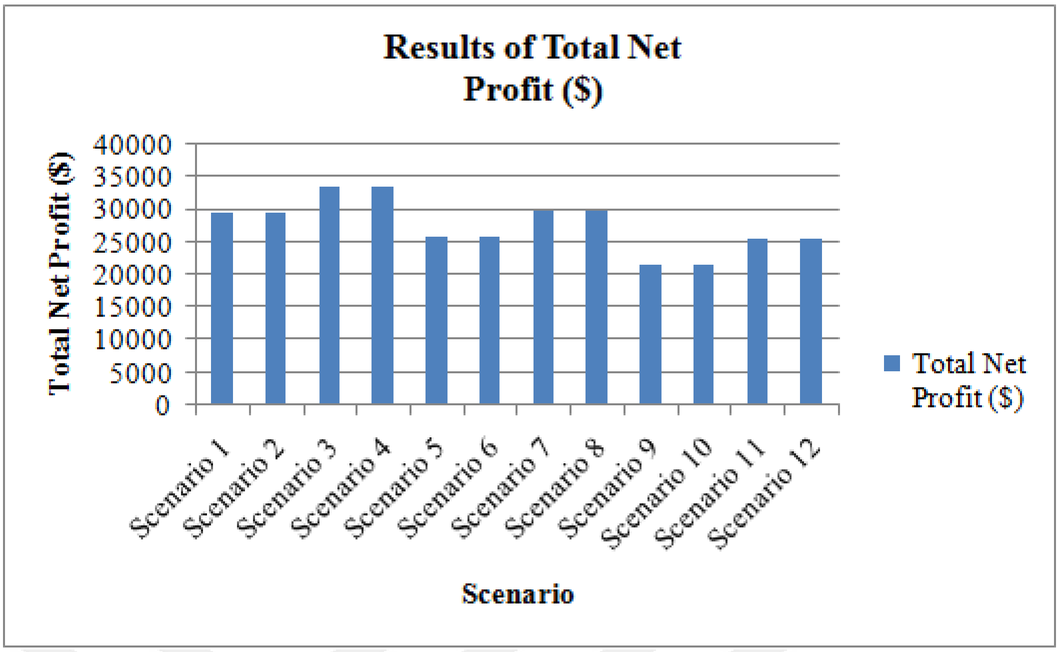

Figure 7.3 The total net profit in twelve scenarios

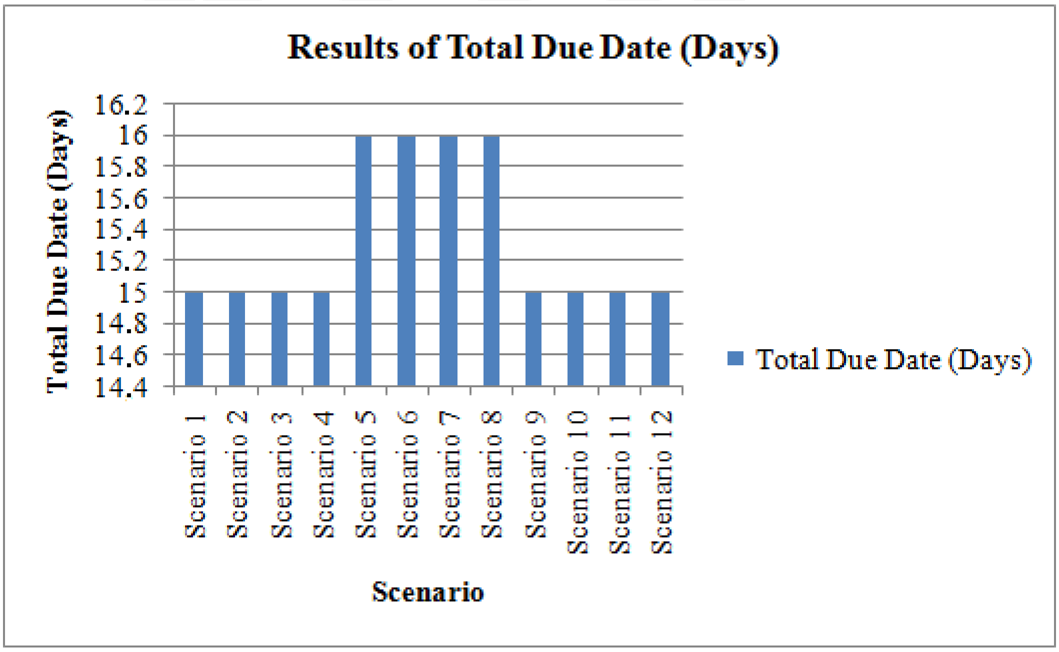

Figure 7.4 The total due date in twelve scenarios

CHAPTER EIGHT
CASE STUDY

8.1 Process Flow in the Automotive Brake Disc Manufacturing Company

The case study was implemented in the automotive brake disc manufacturing company in Manisa industrial zone. The automotive brake disc is shown in Figure 1. The process flow of the automotive brake disc manufacturing company is explained in the next paragraphs.

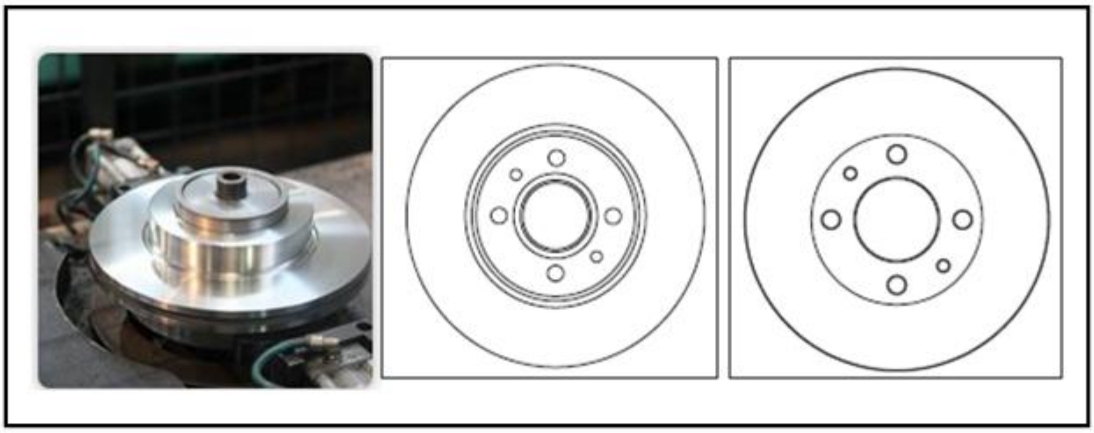

Figure 8.1 Automotive brake disc

Materials which come from suppliers, go to the quality control. Molding sand preparation, molding and liquid metal preparation are done for casting process. If sand testing and melting analysis are positive, casting process starts. The number of product on the casting slab affects the casting quantity of brake disc. The number of product on the casting slab changes according to the type of brake disc. Sandblasting process starts on brake discs which pass the eye control after casting. Eye control, hardness, micro-structure and shrinkage test porosity control are applied to brake discs after sandblasting process in order to start grinding. Finally, accepted brake discs are sent to the semi-finished product storage. Rejected brake discs which can't pass the tests between processes is used in the liquid metal preparation as a scrap. Process flowchart of casting, sandblasting and grinding is presented in Figure 8.2.

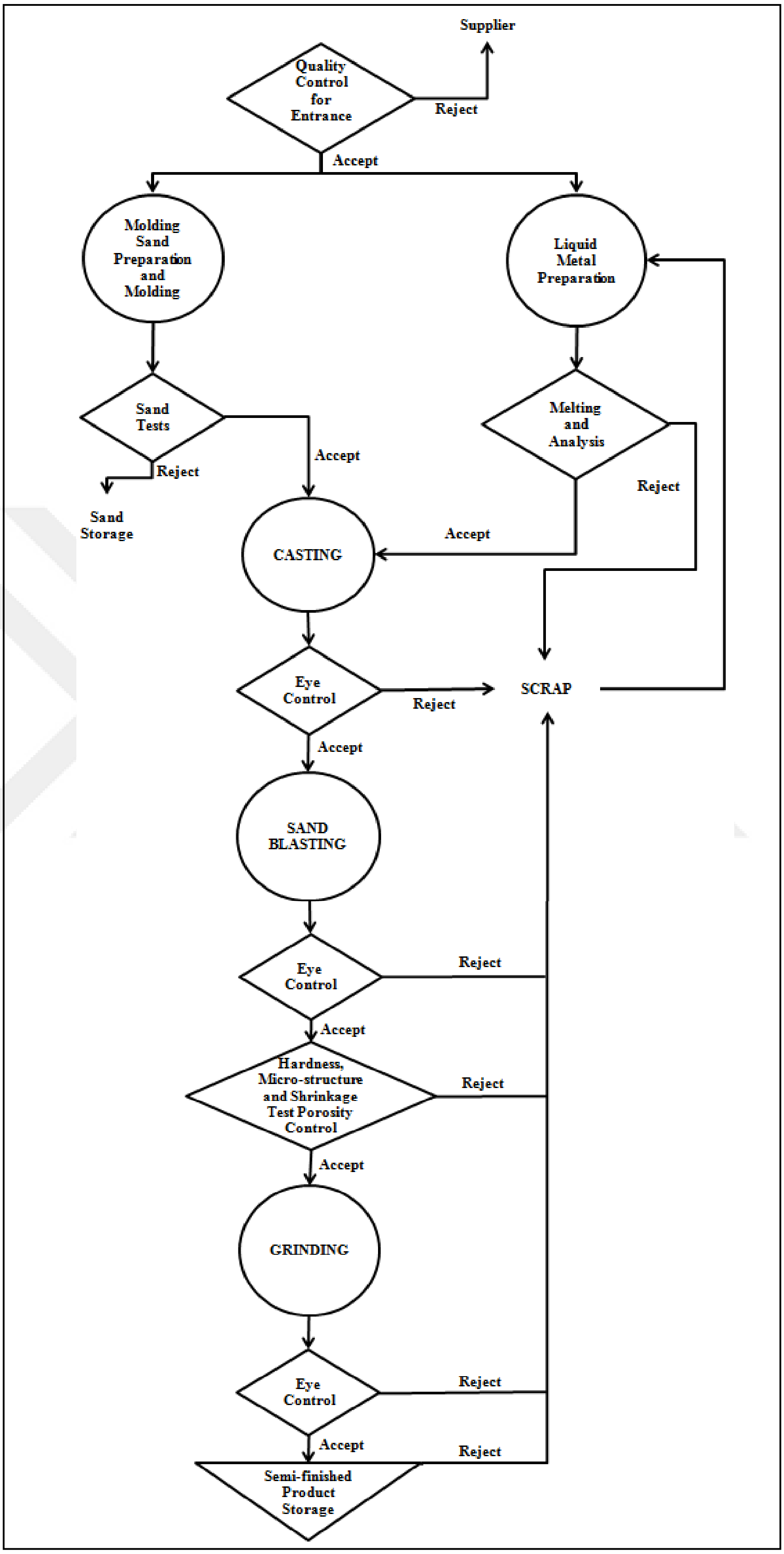

Figure 8.2 Process flowchart of casting, sandblasting and grinding

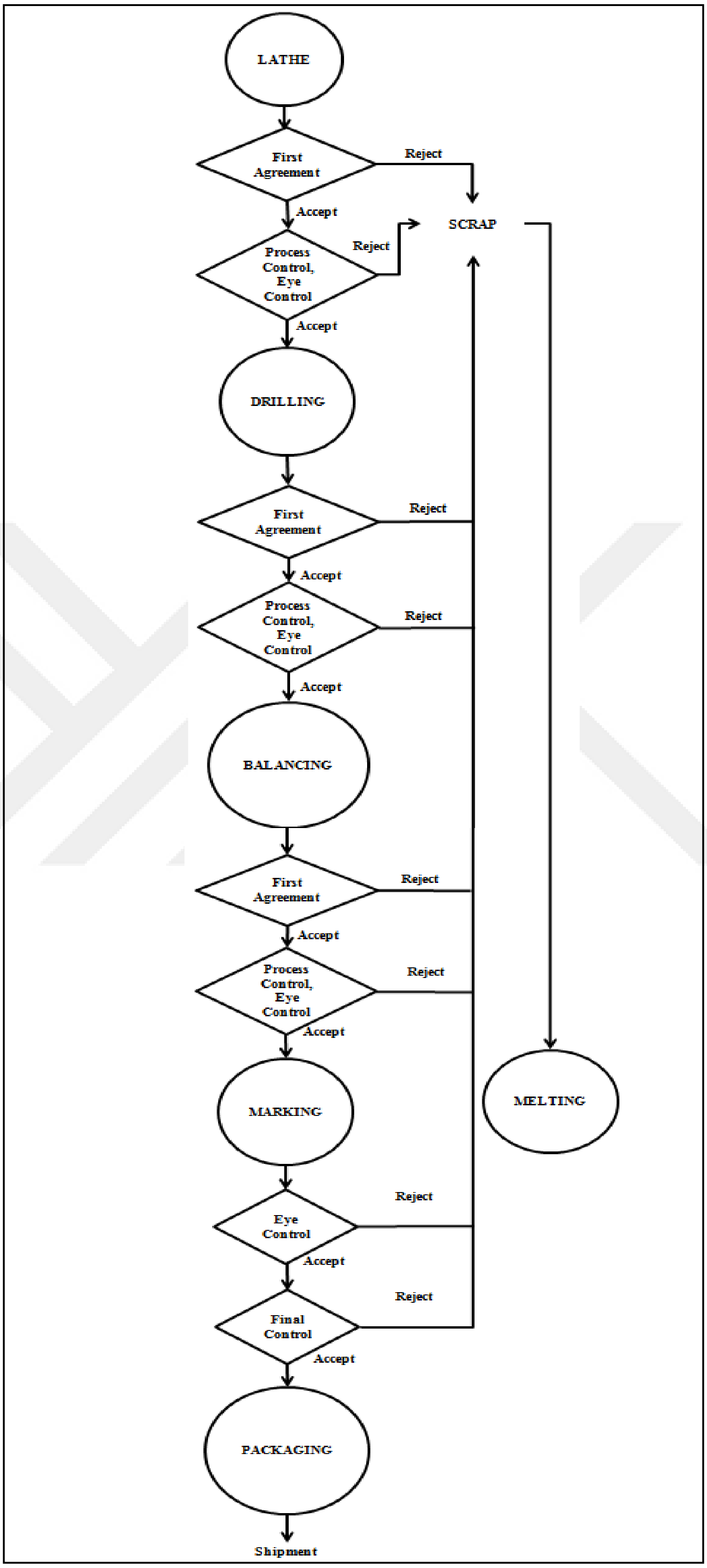

Figure 8.3 Process flowchart of the machining which contains lathe, drilling, balancing and marking

Machining starts with lathe process on brake discs after grinding process. Drilling, balancing and marking are applied to brake discs after lathe respectively. Process control and eye control are the decision points about brake discs between lathe, drilling, balancing and marking processes. Before packaging, eye control and final control are done and brake discs are prepared to shipment. Brake discs which are rejected on the control points are used in melting as a scrap. Process flowchart of the machining which contains lathe, drilling, balancing and marking is presented in Figure 8.3.

8.2 Problem Definition

Proposed multi-objective mixed-integer linear programming model where selling prices and due dates are decision variables was implemented in the automotive brake disc manufacturing company in Manisa industrial zone in order to analyze the results of the model in a real life system. The multi-objective mixed-integer linear programming model which is presented in Appendix 2 is used in the case study.

There are three sources which are regular time, overtime and outsourcing in the problem. Brake disc manufacturing company has regular time shift and overtime shift and each shift works 11 hours per day and 6 days in a week. We assume that outsourcing works 24 hours in a day and the capacity of outsourcing is large enough. All machines of the company can work in both regular time shift and overtime shift.

Each resource has a capacity of 11 hours in each shift in the company per day. Each resource capacity in outsourcing is 24 hours and large enough per day. Each job of orders can be outsourced in the company and outsourcing capacity is large enough for processing of orders which come from the company according to the model assumption.

There are ten orders which are manufactured in the company frequently are defined for the case study and type of brake discs change according to orders.

Seven machine based jobs are defined to use in the problem. Job route which is shown in Figure 8.4 is casting, sandblasting, grinding, lathe, drilling, balancing and marking.

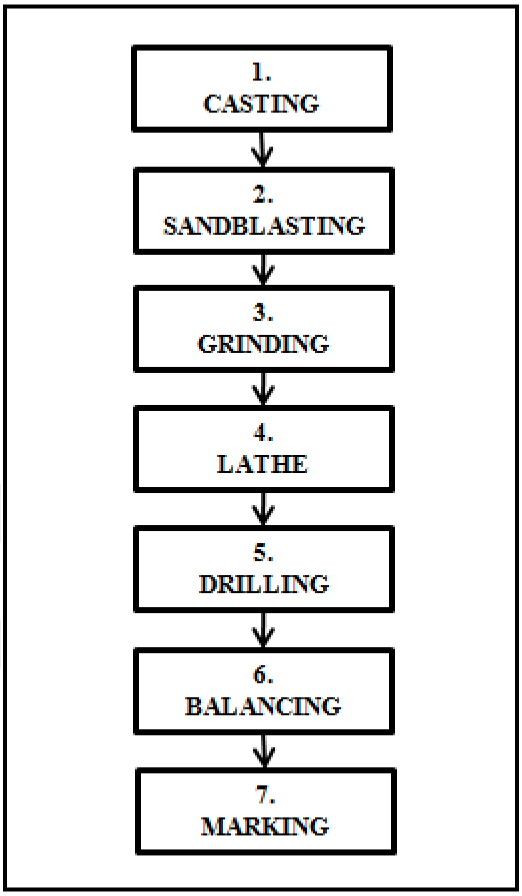

Figure 8.4 Job route which is used in the problem

Seven orders have seven jobs and three orders have six jobs in the problem. The job route of seven orders is casting, sandblasting, grinding, lathe, drilling, balancing and marking and the job route of three orders is casting, sandblasting, grinding, lathe, drilling and marking.

There are seven resources in the problem these are:

1. Casting
2. Sandblasting
3. Grinding

4. Lathe
5. Drilling
6. Balancing
7. Marking

Although seven orders are processed in all of these resources, the sixth job of three orders which have six jobs processed in the seventh resource, so orders are manufactured according to flow-shop process in the case study.

Data about the cost (TL) of processing on resource *k* of source *r* per hour are shown in Table 8.1. Regular time is expressed by 1, overtime is expressed by 2 and outsourcing is expressed by 3 in Table 8.1.

Table 8.1 The cost of processing on resource k of source r (TL / hour)

Resource	**Source Type**		
	1	**2**	**3**
1	48	50.4	52.8
2	30	31.5	33
3	42	44.1	46.2
4	13.5	14.18	14.85
5	13.5	14.18	14.85
6	1.5	1.58	1.65
7	1.5	1.58	1.65

8.3 Implementation of the Multi-Objective Mixed-Integer Linear Programming Model in the Automotive Brake Disc Manufacturing Company

8.3.1 Implementation of the Multi-Objective Mixed-Integer Linear Programming Model for Six-Days Demand

The demand quantity of ten orders are calculated for 6 days and the short-term production planning is realized when planning time period is 6 days in this section. Minimum due date of each order is determined as 3 days and maximum due date of each order is determined as 6 days. Data about the minimum and maximum selling prices, due dates and processing times of jobs of orders are shown in related tables of production plans. R.T expresses regular time, O.T expresses overtime, O.S expresses outsourcing and each time period expresses one day in the tables of production plans. Number of assigned hours for processing job *j* of item *i* on resource *k* of source *r* in time period *t* take part in the tables of production plans. Elapsed run time for finding the global optimal solution in Lingo 14.0 software increases, if the number of order in the mathematical model is increased. Because of this reason, the multi-objective mixed-integer linear programming model is solved for 6 orders, 7 orders, 8 orders, 9 orders and 10 orders for 6-days demand when planning time period is 6 days by Lingo 14.0 software. Elapsed run time is determined 3 hours for the multi-objective mixed-integer linear programming model which has different number of orders.

The feasible solution is found as 221365.9 TL for the multi-objective mixed-integer linear programming model which has 6 orders for 6-days demand when planning time period is 6 days under 3 hours elapsed run time by Lingo 14.0 software. This solution is found according to the first objective function of the multi-objective mixed-integer linear programming model and the solution which obtain total net profit value higher than or equal to this feasible solution isn't found according to the second objective function under 3 hours elapsed run time. The production plan which has 6 orders for 6-days demand when planning time period is 6 days according to the first objective is shown in Table 8.2, all orders are accepted in this production plan.

The feasible solution is found as 0 TL for the multi-objective mixed-integer linear programming model which has 7 orders for 6-days demand when planning time period is 6 days under 3 hours elapsed run time by Lingo 14.0 software. This solution is found according to the first objective function of the multi-objective mixed-integer linear programming model and the total due date which obtain total net profit value higher than or equal to this feasible solution is found 0 according to the second objective function. Because of the rejection of all orders, the table of this production plan can't be formed.

Table 8.2 Production plan which has 6 orders for 6-days demand when planning time period is 6 days according to the first objective

i	$Smin_i$ (TL)	$Smax_i$ (TL)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4			Time Period 5			Time Period 6		
								R.T	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**
1	34090.98	52450.86	3	6	1	1	4				4														
					2	2	2				2														
					3	3	32							7	11		11	3							
					4	4	3													3					
					5	5	3.5													3.5					
					6	6	23.5													4.5	11		8		
					7	7	3																3		
2	43732.92	67281.06	3	6	1	1	4	4																	
					2	2	2	2																	
					3	3	32	5	1		11	11		4											
					4	4	3							3											
					5	5	3.5							3.5											
					6	6	23.5							0.5	2.5		11			6.5			3		
					7	7	3																3		
3	22487.85	34596.87	3	6	1	1	4	4																	
					2	2	1	1																	
					3	3	16	6	10																
					4	4	1.5				1.5														
					5	5	3.5				3.5														
					6	6	12				1.5			10.5											
					7	7	1.5																1.5		
4	16410.24	25248.30	3	6	1	1	4	0.5									3.5								
					2	2	2										2								
					3	3	18.5											8					7	3.5	
					4	4	2																	2	
					5	5	2.5																	2.5	
					6	7	3																	3	
5	11950.68	18387.53	3	6	1	1	2	0.5			1.5														
					2	2	1.5							1.5											
					3	3	14													3.5			4	6.5	
					4	4	2																	2	
					5	5	2.5																	2.5	
					6	7	2																		2
6	20064.66	30866.22	3	6	1	1	2	2																	
					2	2	2	1.5			0.5														
					3	3	18.5													7.5	11				
					4	4	2.5																2.5		
					5	5	2.5																2.5		
					6	7	3																3		

Table 8.3 Production plan which has 8 orders for 6-days demand when planning time period is 6 days according to the first objective

i	$Smin_i$ (TL)	$Smax_i$ (TL)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4			Time Period 5			Time Period 6		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	34090.98	52450.86	3	6	1	1	4	1			3														
					2	2	2				2														
					3	3	32				6	4		11	11										
					4	4	3										3								
					5	5	3.5										3.5								
					6	6	23.5										3	11		6.5			3		
					7	7	3																3		
2	43732.92	67281.06	3	6	1	1	4				4														
					2	2	2				2														
					3	3	32				5	7					10.5	9.5							
					4	4	3													3					
					5	5	3.5													3.5					
					6	6	23.5													4.5	11		8		
					7	7	3																3		
3	22487.85	34596.87	3	6	1	1	4	4																	
					2	2	1	1																	
					3	3	16	5	11																
					4	4	1.5				1.5														
					5	5	3.5				3.5														
					6	6	12				6	6													
					7	7	1.5							1.5											
4	19529.16	30046.73	3	6	1	1	2	2																	
					2	2	1.5	1.5																	
					3	3	24			11			13												
					4	4	2							2											
					5	5	3.5							3.5											
					6	6	17.5							4.5	11		2								
					7	7	2																2		

Table 8.3 Production plan which has 8 orders for 6-days demand when planning time period is 6 days according to the first objective (continues)

i	$Smin_i$ (TL)	$Smax_i$ (TL)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4			Time Period 5			Time Period 6		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
5	18467.34	28412.36	3	6	1	1	2	2																	
					2	2	1.5	1.5																	
					3	3	24			13			11												
					4	4	2.5							2.5											
					5	5	2							2											
					6	6	17.5							6.5			6							5	
					7	7	2																	2	
6	16410.24	25248.30	3	6	1	1	4				0.5						3.5								
					2	2	2										2								
					3	3	18.5										0.5			3.5			11	3.5	
					4	4	2																	2	
					5	5	2.5																	2.5	
					6	7	3																	3	
7	11950.68	18387.53	3	6	1	1	2				2														
					2	2	1.5				1.5														
					3	3	14													7.5				6.5	
					4	4	2																	2	
					5	5	2.5																	2.5	
					6	7	2																		2
8	20064.66	30866.22	3	6	1	1	2	2																	
					2	2	2	2																	
					3	3	18.5	6										1.5			11				
					4	4	2.5																2.5		
					5	5	2.5																2.5		
					6	7	3																3		

The feasible solution is found as 277129.2 TL for the multi-objective mixed-integer linear programming model when the number of order is increased to 8 and planning time period is 6 days for 6-days demand under 3 hours elapsed run time by Lingo 14.0 software. This solution is found according to the first objective function of the multi-objective mixed-integer linear programming model and the solution which obtain total net profit value higher than or equal to this feasible solution isn't found according to the second objective function under 3 hours elapsed run time. The production plan which has 8 orders for 6-days demand when planning time period is 6 days according to the first objective is shown in Table 8.3, all orders are accepted in this production plan.

The feasible solution is found as 297487.2 TL for the multi-objective mixed-integer linear programming model when the number of order is increased to 9 and planning time period is 6 days for 6-days demand under 3 hours elapsed run time by Lingo 14.0 software. This solution is found according to the first objective function of the multi-objective mixed-integer linear programming model and the solution which obtain total net profit value higher than or equal to this feasible solution isn't found according to the second objective function under 3 hours elapsed run time. The production plan which has 9 orders for 6-days demand when planning time period is 6 days according to the first objective is shown in Table 8.4, all orders are accepted in this production plan.

The feasible solution is found as 284028.2 TL for the multi-objective mixed-integer linear programming model which has 10 orders for 6-days demand when planning time period is 6 days under 3 hours elapsed run time by Lingo 14.0 software. This solution is found according to the first objective function of the multi-objective mixed-integer linear programming model. The production plan which has 10 orders for 6-days demand when planning time period is 6 days according to the first objective is shown in Table 8.5, the first order is rejected in this production plan.

Table 8.4 Production plan which has 9 orders for 6-days demand when planning time period is 6 days according to the first objective

i	$Smin_i$ (TL)	$Smax_i$ (TL)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4			Time Period 5			Time Period 6		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	34090.98	52450.86	3	6	1	1	4	4																	
					2	2	2	2																	
					3	3	32	3.5			5	11		11			1.5								
					4	4	3										3								
					5	5	3.5										3.5								
					6	6	23.5										3	11		7			2.5		
					7	7	3																3		
2	43732.92	67281.06	3	6	1	1	4				2			2											
					2	2	2							2											
					3	3	32								11		9.5	11		0.5					
					4	4	3													3					
					5	5	3.5													3.5					
					6	6	23.5													4	11		8.5		
					7	7	3																2.5	0.5	
3	22487.85	34596.87	3	6	1	1	4	1			3														
					2	2	1				1														
					3	3	16												16						
					4	4	1.5													1.5					
					5	5	3.5													3.5					
					6	6	12															12			
					7	7	1.5																1.5		
4	19529.16	30046.73	3	6	1	1	2	2																	
					2	2	1.5	1.5																	
					3	3	24	7.5	11		5.5														
					4	4	2				2														
					5	5	3.5				3.5														
					6	6	17.5					10.5		6.5	0.5										
					7	7	2													2					
5	18467.34	28412.36	3	6	1	1	2	2																	
					2	2	1.5	1.5																	
					3	3	24			7			17												
					4	4	2.5							2.5											
					5	5	2							2											
					6	6	17.5							0.5			8							9	
					7	7	2																	2	

Table 8.4 Production plan which has 9 orders for 6-days demand when planning time period is 6 days according to the first objective (continues)

i	$Smin_i$ (TL)	$Smax_i$ (TL)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4			Time Period 5			Time Period 6		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
6	13984.71	21513.16	3	6	1	1	2	2																	
					2	2	1.5	1.5																	
					3	3	20			13			7												
					4	4	1.5							1.5											
					5	5	2							2											
					6	6	14.5							4	10.5										
					7	7	2										2								
7	16410.24	25248.30	3	6	1	1	4				4														
					2	2	2				2														
					3	3	18.5				0.5									1	10.5		6.5		
					4	4	2																2		
					5	5	2.5																2.5		
					6	7	3																	3	
8	11950.68	18387.53	3	6	1	1	2										2								
					2	2	1.5										1			0.5					
					3	3	14													9.5			4.5		
					4	4	2																2		
					5	5	2.5																2.5		
					6	7	2																2		
9	20064.66	30866.22	3	6	1	1	2				2														
					2	2	2				2														
					3	3	18.5									18.5									
					4	4	2.5													2.5					
					5	5	2.5													2.5					
					6	7	3													1			2		

Table 8.5 Production plan which has 10 orders for 6-days demand when planning time period is 6 days according to the first objective

i	Smin$_i$ (TL)	Smax$_i$ (TL)	dmin$_i$ (Day)	dmax$_i$ (Day)	j	k	p$_{ijk}$ (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4			Time Period 5			Time Period 6		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	34090.98	52450.86	3	6	1	1	4	**Not Selected**																	
					2	2	2																		
					3	3	32																		
					4	4	3																		
					5	5	3.5																		
					6	6	23.5																		
					7	7	3																		
2	43732.92	67281.06	3	6	1	1	4				4														
					2	2	2				2														
					3	3	32					11		10	10.5		0.5								
					4	4	3										3								
					5	5	3.5										3.5								
					6	6	23.5													10.5	11		2		
					7	7	3																3		
3	22487.85	34596.87	3	6	1	1	4	4																	
					2	2	1	1																	
					3	3	16	5.5	10.5																
					4	4	1.5				1.5														
					5	5	3.5				3.5														
					6	6	12				6	6													
					7	7	1.5													1.5					
4	19529.16	30046.73	3	6	1	1	2	2																	
					2	2	1.5	1.5																	
					3	3	24			11			13												
					4	4	2							2											
					5	5	3.5							3.5											
					6	6	17.5							5.5	1		11								
					7	7	2													2					
5	18467.34	28412.36	3	6	1	1	2	2																	
					2	2	1.5	1.5																	
					3	3	24	5.5	0.5		6.5			0.5				11							
					4	4	2.5													2.5					
					5	5	2													2					
					6	6	17.5													0.5			9	8	
					7	7	2																	2	

Table 8.5 Production plan which has 10 orders for 6-days demand when planning time period is 6 days according to the first objective (continues)

i	$Smin_i$ (TL)	$Smax_i$ (TL)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4			Time Period 5			Time Period 6		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
6	13984.71	21513.16	3	6	1	1	2	2																	
					2	2	1.5	1.5																	
					3	3	20			13			7												
					4	4	1.5							1.5											
					5	5	2							2											
					6	6	14.5							5.5				9							
					7	7	2													2					
7	25340.70	38983.56	3	6	1	1	4	1			3														
					2	2	2				2														
					3	3	32						4			24			4						
					4	4	3.5													3.5					
					5	5	2.5													2.5					
					6	6	23.5															2.5			21
					7	7	3																		3
8	16410.24	25248.30	3	6	1	1	4							4											
					2	2	2							2											
					3	3	18.5										8			10.5					
					4	4	2																2		
					5	5	2.5																2.5		
					6	7	3																3		
9	11950.68	18387.53	3	6	1	1	2				2														
					2	2	1.5							1.5											
					3	3	14							0.5						0.5	3		8	2	
					4	4	2																	2	
					5	5	2.5																	2.5	
					6	7	2																	2	
10	20064.66	30866.22	3	6	1	1	2				2														
					2	2	2				2														
					3	3	18.5				4.5				0.5		2.5				8		3		
					4	4	2.5																2.5		
					5	5	2.5																2.5		
					6	7	3																3		

Table 8.6 Production plan which has 10 orders for 6-days demand when planning time period is 6 days

i	$Smin_i$ (TL)	$Smax_i$ (TL)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4			Time Period 5			Time Period 6		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	34090.98	52450.86	3	6	1	1	4			4															
					2	2	2			2															
					3	3	32			18			14												
					4	4	3						3												
					5	5	3.5						3.5												
					6	6	23.5						3.5			20									
					7	7	3									3									
2	43732.92	67281.06	3	6	1	1	4	4																	
					2	2	2	2																	
					3	3	32			6			10						1			15			
					4	4	3															3			
					5	5	3.5															3.5			
					6	6	23.5															2.5			21
					7	7	3																		3
3	22487.85	34596.87	3	6	1	1	4	1			3														
					2	2	1				1														
					3	3	16												16						
					4	4	1.5													1.5					
					5	5	3.5													3.5					
					6	6	12													1	11				
					7	7	1.5															1.5			
4	19529.16	30046.73	3	6	1	1	2	**Not Selected**																	
					2	2	1.5																		
					3	3	24																		
					4	4	2																		
					5	5	3.5																		
					6	6	17.5																		
					7	7	2																		
5	18467.34	28412.36	3	6	1	1	2		2																
					2	2	1.5		1.5																
					3	3	24									24									
					4	4	2.5										2.5								
					5	5	2										2								
					6	6	17.5										3	4.5		10					
					7	7	2														2				

Table 8.6 Production plan which has 10 orders for 6-days demand when planning time period is 6 days (continues)

i	$Smin_i$ (TL)	$Smax_i$ (TL)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4			Time Period 5			Time Period 6		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
6	13984.71	21513.16	3	6	1	1	2	**Not Selected**																	
					2	2	1.5																		
					3	3	20																		
					4	4	1.5																		
					5	5	2																		
					6	6	14.5																		
					7	7	2																		
7	25340.70	38983.56	3	6	1	1	4	4																	
					2	2	2	2																	
					3	3	32	5	5		11	11													
					4	4	3.5							3.5											
					5	5	2.5							2.5											
					6	6	23.5							4.5	11		8								
					7	7	3										3								
8	16410.24	25248.30	3	6	1	1	4				4														
					2	2	2				2														
					3	3	18.5							7.5	11										
					4	4	2										2								
					5	5	2.5										2.5								
					6	7	3												3						
9	11950.68	18387.53	3	6	1	1	2							2											
					2	2	1.5							1.5											
					3	3	14																11	3	
					4	4	2																	2	
					5	5	2.5																	2.5	
					6	7	2																		2
10	20064.66	30866.22	3	6	1	1	2	2																	
					2	2	2	2																	
					3	3	18.5	6	6									3.5		3					
					4	4	2.5													2.5					
					5	5	2.5													2.5					
					6	7	3													3					

The feasible total due date which obtain total net profit value higher than or equal to 284028.2 TL is found as 38 days under 3 hours elapsed run time. The results of this production plan which is formed when the second objective is selected for optimization and the first objective is thought as a constraint under ε-constraint method is shown in Table 8.6, the fourth and the sixth orders are rejected in this production plan.

Due dates which are found according to the first objective function and the second objective function of the multi-objective mixed-integer linear programming model according to the different number of orders for 6-days demand when planning time period is 6 days by Lingo 14.0 software are shown in Table 8.7.

Table 8.7 Results of due dates

	Results of Due Dates according to the First Objective Function (Day)									
Number of Orders	**Order 1**	**Order 2**	**Order 3**	**Order 4**	**Order 5**	**Order 6**	**Order 7**	**Order 8**	**Order 9**	**Order 10**
6	6	6	6	6	6	6				
7	3	3	3	3	3	3	3			
8	6	6	6	6	6	6	6	6		
9	6	6	6	6	6	6	6	6	6	
10	3	6	6	6	6	6	6	6	6	6
	Results of Due Dates according to the Second Objective Function (Day)									
Number of Orders	**Order 1**	**Order 2**	**Order 3**	**Order 4**	**Order 5**	**Order 6**	**Order 7**	**Order 8**	**Order 9**	**Order 10**
6	…	…	…	…	…	…				
7	3	3	3	3	3	3	3			
8	…	…	…	…	…	…	…	…		
9	…	…	…	…	…	…	…	…	…	
10	3	6	5	3	5	6	4	4	6	5

The due date of each order is found as 6 days in the multi-objective mixed-integer linear programming model which has 6 orders for 6-days demand when planning time period is 6 days under 3 hours elapsed run time by Lingo 14.0 software. This solution is found according to the first objective function of the multi-objective mixed-integer linear programming model and all orders are completed in time period 6 as shown in Table 8.2.

The due date of each order is found as 3 days in the multi-objective mixed-integer linear programming model which has 7 orders for 6-days demand when planning time period is 6 days under 3 hours elapsed run time by Lingo 14.0 software. This solution is found according to the first objective function of the multi-objective mixed-integer linear programming model, the values of minimum due dates are assigned to all orders and all orders are rejected.

The due date of each order is found as 6 days in the multi-objective mixed-integer linear programming model when the number of order is increased to 8 and planning time period is 6 days for 6-days demand under 3 hours elapsed run time by Lingo 14.0 software. This solution is found according to the first objective function of the multi-objective mixed-integer linear programming model. Although the values of maximum due dates are assigned to all orders, the third order is completed in time period 3 as shown in Table 8.3. The last job of orders can be completed before the found due dates, because of the due date constraint in the mathematical model.

The due date of each order is found as 6 days in the multi-objective mixed-integer linear programming model when the number of order is increased to 9 and planning time period is 6 days for 6-days demand under 3 hours elapsed run time by Lingo 14.0 software. This solution is found according to the first objective function of the multi-objective mixed-integer linear programming model. Although the values of maximum due dates are assigned to all orders, the fourth order is completed in time period 5 and the sixth order is completed in time period 4 as shown in Table 8.4. The last job of orders can be completed before the found due dates, because of the due date constraint in the mathematical model.

The due date of the first order is found as 3 days and the due dates of the other orders are found 6 days in the multi-objective mixed-integer linear programming model which has 10 orders for 6-days demand when planning time period is 6 days under 3 hours elapsed run time by Lingo 14.0 software. This solution is found according to the first objective function of the multi-objective mixed-integer linear programming model. According to this solution minimum due date value is assigned to the first order and this order is rejected. Although the values of maximum due dates are assigned to the other orders the third order, the fourth order and the sixth order are completed in time period 5 as shown in Table 8.5. The last job of orders can be completed before the found due dates, because of the due date constraint in the mathematical model.

The results of due dates which are found in the multi-objective mixed-integer linear programming model which has 10 orders for 6-days demand when planning time period is 6 days under 3 hours elapsed run time by Lingo 14.0 software according to the second objective function are shown in Table 8.7. All selected orders are completed according to found due dates as shown in Table 8.6. Feasible minimum due date values which obtain total net profit value higher than or equal to 284028.2 TL are found when the second objective is selected for optimization and the first objective is thought as a constraint under ε-constraint method.

Table 8.8 Results of selling prices

	Results of Selling Prices according to the First Objective Function (TL)									
Number of Orders	**Order 1**	**Order 2**	**Order 3**	**Order 4**	**Order 5**	**Order 6**	**Order 7**	**Order 8**	**Order 9**	**Order 10**
6	52450.86	67281.06	34596.87	25248.30	18387.53	30866.22				
7	34090.98	43732.92	22487.85	19529.16	16410.24	11950.68	20064.66			
8	52450.86	67281.06	34596.87	30046.73	28412.36	25248.30	18387.53	30866.22		
9	52450.86	67281.06	34596.87	30046.73	28412.36	21513.16	25248.30	18387.53	30866.22	
10	34090.98	67281.06	34596.87	30046.73	28412.36	21513.16	38983.56	25248.30	18387.53	30866.22
	Results of Selling Prices according to the Second Objective Function (TL)									
Number of Orders	**Order 1**	**Order 2**	**Order 3**	**Order 4**	**Order 5**	**Order 6**	**Order 7**	**Order 8**	**Order 9**	**Order 10**
6	…	…	…	…	…	…				
7	34090.98	43732.92	22487.85	19529.16	16410.24	11950.68	20064.66			
8	…	…	…	…	…	…	…	…		
9	…	…	…	…	…	…	…	…	…	
10	52450.86	67281.06	34596.87	19529.16	27074.11	13984.71	38983.56	25248.30	18387.53	30866.22

Selling prices which are found according to the first objective function and the second objective function of the multi-objective mixed-integer linear programming model according to the different number of orders for 6-days demand when planning time period is 6 days by Lingo 14.0 software are shown in Table 8.8.

Results of the first objective function and the second objective function of the multi-objective mixed-integer linear programming model according to the different number of orders for 6-days demand when planning time period is 6 days by Lingo 14.0 software are shown in Table 8.9.

Table 8.9 Results of the first objective function and the second objective function in production plans

	Results of the First Objective Function			Results of the Second Objective Function		
Number of Orders	**Elapsed Run Time**	**State**	**Objective Value (TL)**	**Elapsed Run Time**	**State**	**Objective Value (Day)**
6	3 hours	Feasible	221365.9	3 hours	Unknown	…
7	3 hours	Feasible	0	1 second	Global Optimal	0
8	3 hours	Feasible	277129.2	3 hours	Unknown	…
9	3 hours	Feasible	297487.2	3 hours	Unknown	…
10	3 hours	Feasible	284028.2	3 hours	Feasible	38

8.3.2 Implementation of the Multi-Objective Mixed-Integer Linear Programming Model for Five-Days Demand

The demand quantity of ten orders are calculated for 5 days and the short-term production planning is realized when planning time period is 6 days in this section. The demand quantity of orders are decreased when planning time period is 6 days in order to find the global optimal solutions according to different number of orders. The multi-objective mixed-integer linear programming model is solved for 6 orders, 7 orders, 8 orders, 9 orders and 10 orders for 5-days demand when planning time period is 6 days by Lingo 14.0 software.

Minimum due date of each order is determined as 3 days and maximum due date of each order is determined as 6 days. Data about the minimum and maximum selling prices, due dates and processing times of jobs of orders are shown in related tables of production plans. R.T expresses regular time, O.T expresses overtime, O.S expresses outsourcing and each time period expresses one day in the tables of production plans. Number of assigned hours for processing job *j* of item *i* on resource *k* of source *r* in time period *t* take part in the tables of production plans.

The global optimal solution is found as 184437.4 TL for the multi-objective mixed-integer linear programming model which has 6 orders for 5-days demand when planning time period is 6 days by Lingo 14.0 software and elapsed run time is 1 minute 17 seconds. The amount of demand of six orders is reduced when planning time period is 6 days, global optimal solution can be found according to the first objective function of the multi-objective mixed-integer linear programming model. The production plan which has 6 orders for 5-days demand when planning time period is 6 days according to the first objective is shown in Table 8.10, all orders are accepted in this production plan.

Four scenarios are created for the multi-objective mixed-integer linear programming model which has 6 orders for 5-days demand when planning time period is 6 days. These scenarios are applied when the second objective is selected for the optimization and the first objective is thought as a constraint under ε-constraint method.

The feasible total due date which meets the global optimal total net profit value of 184437.4 TL is found as 32 days under 3 hours elapsed run time in scenario 1. Although the amount of demand of 6 orders is reduced when planning time period is 6 days, global optimal total due date which meet the total net profit value of 184437.4 TL can't be found under 3 hours elapsed run time. All orders are accepted in this production plan and results of this scenario is shown in Table 8.11.

Table 8.10 Production plan which has 6 orders for 5-days demand when planning time period is 6 days according to the first objective

i	$Smin_i$ (TL)	$Smax_i$ (TL)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4			Time Period 5			Time Period 6		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	28409.15	43709.05	3	6	1	1	4	4																	
					2	2	2	2																	
					3	3	26.5		5.5		10.5	10.5													
					4	4	2.5							2.5											
					5	5	3							3											
					6	6	19.5							5.5			11			0.5			2.5		
					7	7	2.5																2.5		
2	36444.10	56067.55	3	6	1	1	4	4																	
					2	2	2	2																	
					3	3	26.5	3						10.5	10.5		2.5								
					4	4	2.5										2.5								
					5	5	3										3								
					6	6	19.5											0.5		10.5			8.5		
					7	7	2.5																2.5		
3	18788.55	28905.61	3	6	1	1	2	2																	
					2	2	1	1																	
					3	3	13.5	8	5.5																
					4	4	1.5				1.5														
					5	5	3				3														
					6	6	10				6.5			3.5											
					7	7	1.5							1.5											
4	13675.20	21040.25	3	6	1	1	4				4														
					2	2	2				0.5			1.5											
					3	3	15.5													9.5			6		
					4	4	1.5																1.5		
					5	5	2																2		
					6	7	2.5																1.5	1	
5	9953.16	15314.11	3	6	1	1	2				2														
					2	2	1.5				1.5														
					3	3	12				0.5	0.5			0.5						10.5				
					4	4	1.5																1.5		
					5	5	2																2		
					6	7	2																2		
6	16720.55	25721.85	3	6	1	1	2	0.5			1.5														
					2	2	2				2														
					3	3	15.5							0.5			8.5			1.5			5		
					4	4	2																2		
					5	5	2																2		
					6	7	2.5																2	0.5	

Table 8.11Production plan which has 6 orders for 5-days demand when planning time period is 6 days-scenario 1

i	$Smin_i$ (TL)	$Smax_i$ (TL)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4			Time Period 5			Time Period 6		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	28409.15	43709.05	3	6	1	1	4				4														
					2	2	2				2														
					3	3	26.5				0.5	1.5		10.5	11		3								
					4	4	2.5										2.5								
					5	5	3										3								
					6	6	19.5											0.5		11			8		
					7	7	2.5																2.5		
2	36444.10	56067.55	3	6	1	1	4	4																	
					2	2	2	2																	
					3	3	26.5	3	6.5		8	9													
					4	4	2.5							2.5											
					5	5	3							3											
					6	6	19.5							5.5			11						3		
					7	7	2.5																2.5		
3	18788.55	28905.61	3	6	1	1	2	2																	
					2	2	1	1																	
					3	3	13.5	8	3.5		2														
					4	4	1.5				1.5														
					5	5	3				3														
					6	6	10				4.5			5.5											
					7	7	1.5							1.5											
4	13675.20	21040.25	3	6	1	1	4	4																	
					2	2	2	2																	
					3	3	15.5		0.5											11			4		
					4	4	1.5																1.5		
					5	5	2																2		
					6	7	2.5																2.5		
5	9953.16	15314.11	3	6	1	1	2	0.5			1.5														
					2	2	1.5				1.5														
					3	3	12							0.5				4.5					7		
					4	4	1.5																1.5		
					5	5	2																2		
					6	7	2																0.5	1.5	
6	16720.55	25721.85	3	6	1	1	2	0.5			1.5														
					2	2	2				2														
					3	3	15.5				0.5	0.5					8	6.5							
					4	4	2													2					
					5	5	2													2					
					6	7	2.5													2.5					

The total net profit is reduced from 184437.4 TL to 184000 TL when the first objective thought as a constraint and the second objective is selected for the optimization under ε-constraint method in order to analyze the changes of due date values in scenario 2. The global optimal total due date which obtain total net profit value higher than or equal to 184000 TL is found as 18 days and elapsed run time is 23 minutes, 15 seconds. The obtained total net profit is 184156.785 TL in scenario 2. All orders are accepted in scenario 2 and results of this scenario is shown in Table 8.12.

The total net profit is reduced from 184437.4 TL to 180000 TL when the first objective thought as a constraint and the second objective is selected for the optimization under ε-constraint method in order to analyze the changes of due date values in scenario 3. The global optimal total due date which obtain total net profit value higher than or equal to 180000 TL is found as 18 days and elapsed run time is 5 minutes, 39 seconds. The obtained total net profit is 184173.625 TL in scenario 3. All orders are accepted in scenario 3 and results of this scenario is shown in Table 8.13.

The total net profit is reduced from 184437.4 TL to 170000 TL when the first objective thought as a constraint and the second objective is selected for the optimization under ε-constraint method in order to analyze the changes of due date values in scenario 4. The global optimal total due date which obtain total net profit value higher than or equal to 170000 TL is found as 18 days and elapsed run time is 4 minutes, 35 seconds. The obtained total net profit is 184185.905 TL in scenario 4. All orders are accepted in scenario 4 and results of this scenario is shown in Table 8.14.

Table 8.12 Production plan which has 6 orders for 5-days demand when planning time period is 6 days-scenario 2

i	$Smin_i$ (TL)	$Smax_i$ (TL)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4			Time Period 5			Time Period 6		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	28409.15	43709.05	3	6	1	1	4			4																	
					2	2	2			2																	
					3	3	26.5			8			18.5														
					4	4	2.5						2.5														
					5	5	3						3														
					6	6	19.5							11	8.5												
					7	7	2.5								2.5												
2	36444.10	56067.55	3	6	1	1	4	4																			
					2	2	2	2																			
					3	3	26.5	5	11		9.5	1															
					4	4	2.5					2.5															
					5	5	3						1			2											
					6	6	19.5									19.5											
					7	7	2.5									2.5											
3	18788.55	28905.61	3	6	1	1	2			2																	
					2	2	1			1																	
					3	3	13.5			13.5																	
					4	4	1.5				1.5																
					5	5	3					3															
					6	6	10					7.5			2.5												
					7	7	1.5									1.5											
4	13675.20	21040.25	3	6	1	1	4	4																			
					2	2	2	2																			
					3	3	15.5	5			0.5	10															
					4	4	1.5					0.5		1													
					5	5	2									2											
					6	7	2.5									2.5											
5	9953.16	15314.11	3	6	1	1	2		2																		
					2	2	1.5				1.5																
					3	3	12				1			11													
					4	4	1.5									1.5											
					5	5	2									2											
					6	7	2									2											
6	16720.55	25721.85	3	6	1	1	2			2																	
					2	2	2			2																	
					3	3	15.5			0.5			5.5			9.5											
					4	4	2									2											
					5	5	2									2											
					6	7	2.5									2.5											

Table 8.13 Production plan which has 6 orders for 5-days demand when planning time period is 6 days-scenario 3

i	**$Smin_i$ (TL)**	**$Smax_i$ (TL)**	**$dmin_i$ (Day)**	**$dmax_i$ (Day)**	**j**	**k**	**p_{ijk} (Hour)**	**Time Period 1**			**Time Period 2**			**Time Period 3**			**Time Period 4**			**Time Period 5**			**Time Period 6**		
								R.T	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**
1	28409.15	43709.05	3	6	1	1	4	4																	
					2	2	2	2																	
					3	3	26.5	5	11		10.5														
					4	4	2.5						2.5												
					5	5	3						3												
					6	6	19.5						7.5			12									
					7	7	2.5									2.5									
2	36444.10	56067.55	3	6	1	1	4			4															
					2	2	2			2															
					3	3	26.5			18			8.5												
					4	4	2.5						2.5												
					5	5	3						3												
					6	6	19.5						10			9.5									
					7	7	2.5									2.5									
3	18788.55	28905.61	3	6	1	1	2	2																	
					2	2	1	1																	
					3	3	13.5	6				7.5													
					4	4	1.5					1		0.5											
					5	5	3							3											
					6	6	10							7.5	2.5										
					7	7	1.5								1.5										
4	13675.20	21040.25	3	6	1	1	4	4																	
					2	2	2									2									
					3	3	15.5									15.5									
					4	4	1.5									1.5									
					5	5	2									2									
					6	7	2.5									2.5									
5	9953.16	15314.11	3	6	1	1	2	1	1																
					2	2	1.5						1.5												
					3	3	12						12												
					4	4	1.5						1.5												
					5	5	2							2											
					6	7	2							2											
6	16720.55	25721.85	3	6	1	1	2			2															
					2	2	2				2														
					3	3	15.5					0.5		11	4										
					4	4	2								2										
					5	5	2								2										
					6	7	2.5								2.5										

Table 8.14 Production plan which has 6 orders for 5-days demand when planning time period is 6 days-scenario 4

i	Smin$_i$ (TL)	Smax$_i$ (TL)	dmin$_i$ (Day)	dmax$_i$ (Day)	j	k	p$_{ijk}$ (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4			Time Period 5			Time Period 6		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	28409.15	43709.05	3	6	1	1	4	4																	
					2	2	2	2																	
					3	3	26.5			10.5			16												
					4	4	2.5						2.5												
					5	5	3						3												
					6	6	19.5							11	8.5										
					7	7	2.5								2.5										
2	36444.10	56067.55	3	6	1	1	4	4																	
					2	2	2	2																	
					3	3	26.5	3.5	11		5.5	6.5													
					4	4	2.5					2.5													
					5	5	3						2			1									
					6	6	19.5									19.5									
					7	7	2.5									2.5									
3	18788.55	28905.61	3	6	1	1	2			2															
					2	2	1			1															
					3	3	13.5			13.5															
					4	4	1.5			1.5															
					5	5	3				3														
					6	6	10				7.5				2.5										
					7	7	1.5								1.5										
4	13675.20	21040.25	3	6	1	1	4		4																
					2	2	2		2																
					3	3	15.5				5.5			10											
					4	4	1.5							0.5	1										
					5	5	2								2										
					6	7	2.5								2.5										
5	9953.16	15314.11	3	6	1	1	2	2																	
					2	2	1.5	1.5																	
					3	3	12	7.5				4.5													
					4	4	1.5							1.5											
					5	5	2							2											
					6	7	2							2											
6	16720.55	25721.85	3	6	1	1	2		2																
					2	2	2			2															
					3	3	15.5									15.5									
					4	4	2									2									
					5	5	2									2									
					6	7	2.5									2.5									

Due dates which are found according to the first objective function and the second objective function of the multi-objective mixed-integer linear programming model according to 6 orders for 5-days demand when planning time period is 6 days by Lingo 14.0 software are shown in Table 8.15.

Table 8.15 Results of due dates for 6 orders

		Results of Due Dates according to the First Objective Function (Day)					
	Number of Orders	**Order 1**	**Order 2**	**Order 3**	**Order 4**	**Order 5**	**Order 6**
	6	6	6	3	6	6	6
		Results of Due Dates according to the Second Objective Function (Day)					
Scenarios	**Number of Orders**	**Order 1**	**Order 2**	**Order 3**	**Order 4**	**Order 5**	**Order 6**
Scenario 1: Total Net Profit ≥184437.4 TL	**6**	6	6	3	6	6	5
Scenario 2: Total Net Profit ≥184000 TL	**6**	3	3	3	3	3	3
Scenario 3: Total Net Profit ≥180000 TL	**6**	3	3	3	3	3	3
Scenario 4: Total Net Profit ≥170000 TL	**6**	3	3	3	3	3	3

The due date of the third order is found as 3 days and the due date of the other orders are found as 6 days in the multi-objective mixed-integer linear programming model which has 6 orders for 5-days demand when planning time period is 6 days by Lingo 14.0 software. This solution is found according to the first objective function of the multi-objective mixed-integer linear programming model.

The results of due dates which are found in the multi-objective mixed-integer linear programming model according to 6 orders for 5-days demand when planning time period is 6 days by Lingo 14.0 software according to the second objective function in four scenarios are shown in Table 8.15. All orders are completed according to found due dates as shown in Table 8.11, Table 8.12, Table 8.13 and Table 8.14. Minimum due date values which obtain total net profit value higher than or equal to target total net profits in four scenarios are found when the second objective is selected for optimization and the first objective is thought as a constraint under ε-constraint method, so orders can't be completed before these found due dates.

Although the feasible total due date is found as 32 days in scenario 1, the global optimal total due date is found as 18 days in the other scenarios. According to the found total due date values which obtain total net profit value higher than or equal to target total net profits of scenario 2, scenario 3 and scenario 4, all orders take minimum due dates values in these scenarios. These results show that, if the total net profit is reduced, the total due date is decreased and global optimal solutions can be found under short elapsed run time.

Selling prices which are found according to the first objective function and the second objective function of the multi-objective mixed-integer linear programming model according to 6 orders for 5-days demand when planning time period is 6 days by Lingo 14.0 software are shown in Table 8.16.

Table 8.16 Results of selling prices for 6 orders

		Results of Selling Prices according to the First Objective Function (TL)					
	Number of Orders	**Order 1**	**Order 2**	**Order 3**	**Order 4**	**Order 5**	**Order 6**
	6	43709.05	56067.55	28905.61	21040.25	15314.11	25721.85
		Results of Selling Prices according to the Second Objective Function (TL)					
Scenarios	**Number of Orders**	**Order 1**	**Order 2**	**Order 3**	**Order 4**	**Order 5**	**Order 6**
Scenario 1: Total Net Profit ≥184437.4 TL	**6**	43709.05	56067.55	28905.61	21040.25	15314.11	25721.85
Scenario 2: Total Net Profit ≥184000 TL	**6**	43709.05	56067.55	28905.61	21040.25	15314.11	25721.85
Scenario 3: Total Net Profit ≥180000 TL	**6**	43709.05	56067.55	28905.61	21040.25	15314.11	25721.85
Scenario 4: Total Net Profit ≥170000 TL	**6**	43709.05	56067.55	28905.61	21040.25	15314.11	25721.85

Results of the first objective function and the second objective function of the multi-objective mixed-integer linear programming model which has 6 orders for 5-

days demand when planning time period is 6 days by Lingo 14.0 software are shown in Table 8.17.

Table 8.17 Results of the fisrt objective function and the second objective function for 6 orders

	Results of the First Objective Function			Results of the Second Objective Function				
Number of Orders	**Elapsed Run Time**	**State**	**Objective Value (TL)**	**Scenarios**	**Elapsed Run Time**	**State**	**Objective Value (Day)**	**Obtained Total Net Profit (TL)**
6	1 minute 17 seconds	Global Optimal	184437.4	Scenario 1: Total Net Profit ≥184437.4 TL	3 hours	Feasible	32	184437.4
6	1 minute 17 seconds	Global Optimal	184437.4	Scenario 2: Total Net Profit ≥184000 TL	23 minutes 15 seconds	Global Optimal	18	184156.785
6	1 minute 17 seconds	Global Optimal	184437.4	Scenario 3: Total Net Profit ≥180000 TL	5 minutes 39 seconds	Global Optimal	18	184173.625
6	1 minute 17 seconds	Global Optimal	184437.4	Scenario 4: Total Net Profit ≥170000 TL	4 minutes 35 seconds	Global Optimal	18	184185.905

The feasible solution is found as 208340.6 TL for the multi-objective mixed-integer linear programming model when the number of order is increased to 7 and planning time period is 6 days for 5-days demand under 3 hours elapsed run time by Lingo 14.0 software. This solution is found according to the first objective function of the multi-objective mixed-integer linear programming model. Although the amount of demand of 7 orders is reduced when planning time period is 6 days, global optimal total net profit can't be found and the solution which obtain total net profit value higher than or equal to this feasible solution can't be found according to the second objective function under 3 hours elapsed run time. The production plan which has 7 orders for 5-days demand when planning time period is 6 days according to the first objective is shown in Table 8.18, all orders are accepted in this production plan.

The feasible solution is found as 230865.5 TL for the multi-objective mixed-integer linear programming model when the number of order is increased to 8 and planning time period is 6 days for 5-days demand when under 3 hours elapsed run time by Lingo 14.0 software. This solution is found according to the first objective function of the multi-objective mixed-integer linear programming model. Although the amount of demand of 8 orders is reduced when planning time period is 6 days, global optimal total net profit can't be found and the solution which obtain total net profit value higher than or equal to this feasible solution can't be found according to the second objective function under 3 hours elapsed run time. The production plan which has 8 orders for 5-days demand when planning time period is 6 days according to the first objective is shown in Table 8.19, all orders are accepted in this production plan.

The feasible solution is found as 247806.5 TL for the multi-objective mixed-integer linear programming model which has 9 orders for 5-days demand when planning time period is 6 days under 3 hours elapsed run time by Lingo 14.0 software. This solution is found according to the first objective function of the multi-objective mixed-integer linear programming model. Although the amount of demand of 9 orders is reduced when planning time period is 6 days, global optimal total net profit can't be found and the solution which obtain total net profit value higher than or equal to this feasible solution can't be found according to the second objective function under 3 hours elapsed run time. The production plan which has 9 orders for 5-days demand when planning time period is 6 days according to the first objective is shown in Table 8.20, all orders are accepted in this production plan.

The feasible solution is found as 278709.1 TL for the multi-objective mixed-integer linear programming model which has 10 orders for 5-days demand when planning time period is 6 days under 3 hours elapsed run time by Lingo 14.0 software. This solution is found according to the first objective function of the multi-objective mixed-integer linear programming model. Although the amount of demand of 10 orders is reduced when planning time period is 6 days, global optimal total net profit can't be found and the solution which obtain total net profit value higher than or equal to this feasible solution can't be found according to the second objective under 3 hours elapsed run time. The production plan which has 10 orders for 5-days demand when planning time period is 6 days according to the first objective is shown in Table 8.21, all orders are accepted in this production plan.

Table 8.18 Production plan which has 7 orders for 5-days demand when planning time period is 6 days according to the first objective

i	Smin$_i$ (TL)	Smax$_i$ (TL)	dmin$_i$ (Day)	dmax$_i$ (Day)	j	k	p$_{ijk}$ (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4			Time Period 5			Time Period 6		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
					1	1	4	4																	
					2	2	2	2																	
					3	3	26.5				0.5	1		11	11		3								
1	28409.15	43709.05	3	6	4	4	2.5										2.5								
					5	5	3										3								
					6	6	19.5										2.5	3.5		11			2.5		
					7	7	2.5																2.5		
					1	1	4	3			1														
					2	2	2				2														
					3	3	26.5					9					8	9.5							
2	36444.10	56067.55	3	6	4	4	2.5													2.5					
					5	5	3													3					
					6	6	19.5														11		8.5		
					7	7	2.5																2.5		
					1	1	2	2																	
					2	2	1	1																	
					3	3	13.5	8	5.5																
3	18788.55	28905.61	3	6	4	4	1.5				1.5														
					5	5	3				3														
					6	6	10				5			5											
					7	7	1.5													1.5					
					1	1	2	2																	
					2	2	1.5	1.5																	
					3	3	20	3	5.5		10.5	1													
4	16264.92	25024.51	3	6	4	4	2							2											
					5	5	3							3											
					6	6	14.5							6			8.5								
					7	7	2													2					

Table 8.18 Production plan which has 7 orders for 5-days demand when planning time period is 6 days according to the first objective (continues)

i	$Smin_i$ (TL)	$Smax_i$ (TL)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4			Time Period 5			Time Period 6		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
5	13675.20	21040.25	3	6	1	1	4				4														
					2	2	2				2														
					3	3	15.5													9	1.5			5	
					4	4	1.5																	1.5	
					5	5	2																	2	
					6	7	2.5																	2.5	
6	9953.16	15314.11	3	6	1	1	2				2														
					2	2	1.5				0.5			1											
					3	3	12													2			6.5	3.5	
					4	4	1.5																	1.5	
					5	5	2																	2	
					6	7	2																	2	
7	16720.55	25721.85	3	6	1	1	2				2														
					2	2	2				2														
					3	3	15.5											1.5			9.5		4.5		
					4	4	2																2		
					5	5	2																2		
					6	7	2.5																2.5		

Table 8.19 Production plan which has 8 orders for 5-days demand when planning time period is 6 days according to the first objective

i	$Smin_i$ (TL)	$Smax_i$ (TL)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4			Time Period 5			Time Period 6		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	28409.15	43709.05	3	6	1	1	4				4														
					2	2	2				2														
					3	3	26.5				0.5	3.5			0.5		10.5	11		0.5					
					4	4	2.5													2.5					
					5	5	3													3					
					6	6	19.5													1	11		7.5		
					7	7	2.5																2.5		
2	36444.10	56067.55	3	6	1	1	4	4																	
					2	2	2	2																	
					3	3	26.5	5						11	10.5										
					4	4	2.5										2.5								
					5	5	3										3								
					6	6	19.5										5.5	10.5					3.5		
					7	7	2.5																2.5		
3	18788.55	28905.61	3	6	1	1	2	2																	
					2	2	1	1																	
					3	3	13.5	6	7.5																
					4	4	1.5				1.5														
					5	5	3				3														
					6	6	10				6.5			0.5	2.5		0.5								
					7	7	1.5													1.5					
4	16264.92	25024.51	3	6	1	1	2	2																	
					2	2	1.5	1.5																	
					3	3	20		3.5		10.5	6													
					4	4	2							2											
					5	5	3							3											
					6	6	14.5							4				0.5		10					
					7	7	2													0.5			1.5		

Table 8.19 Production plan which has 8 orders for 5-days demand when planning time period is 6 days according to the first objective (continues)

i	**Smin$_i$ (TL)**	**Smax$_i$ (TL)**	**dmin$_i$ (Day)**	**dmax$_i$ (Day)**	**j**	**k**	**p$_{ijk}$ (Hour)**	**Time Period 1**			**Time Period 2**			**Time Period 3**			**Time Period 4**			**Time Period 5**			**Time Period 6**		
								R.T	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**	**R.T**	**O.T**	**O.S**
5	15380.58	23663.32	3	6	1	1	2	2																	
					2	2	1.5	1.5																	
					3	3	20			13			7												
					4	4	2							2											
					5	5	1.5							1.5											
					6	6	14.5							6.5	3		5								
					7	7	2													2					
6	13675.20	21040.25	3	6	1	1	4				4														
					2	2	2							2											
					3	3	15.5										0.5			4	11				
					4	4	1.5																1.5		
					5	5	2																2		
					6	7	2.5																2.5		
7	9953.16	15314.11	3	6	1	1	2	0.5			1.5														
					2	2	1.5				1.5														
					3	3	12													6.5				5.5	
					4	4	1.5																	1.5	
					5	5	2																	2	
					6	7	2																	2	
8	16720.55	25721.85	3	6	1	1	2	0.5						1.5											
					2	2	2							2											
					3	3	15.5																11	4.5	
					4	4	2																	2	
					5	5	2																	2	
					6	7	2.5																	2.5	

Table 8.20 Production plan which has 9 orders for 5-days demand when planning time period is 6 days according to the first objective

i	$Smin_i$ (TL)	$Smax_i$ (TL)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4			Time Period 5			Time Period 6		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	28409.15	43709.05	3	6	1	1	4							4											
					2	2	2							2											
					3	3	26.5							5			11	10.5							
					4	4	2.5													2.5					
					5	5	3													3					
					6	6	19.5													5.5	11		3		
					7	7	2.5																2.5		
2	36444.10	56067.55	3	6	1	1	4	4																	
					2	2	2	2																	
					3	3	26.5	5			2	6.5		2	11										
					4	4	2.5										2.5								
					5	5	3										3								
					6	6	19.5										5	2.5		5.5			6.5		
					7	7	2.5																2.5		
3	18788.55	28905.61	3	6	1	1	2	1			1														
					2	2	1				1														
					3	3	13.5				9	4.5													
					4	4	1.5																1.5		
					5	5	3																3		
					6	6	10																1.5	8.5	
					7	7	1.5																	1.5	
4	16264.92	25024.51	3	6	1	1	2	2																	
					2	2	1.5	1.5																	
					3	3	20						17			3									
					4	4	2										2								
					5	5	3										3								
					6	6	14.5										6	8.5							
					7	7	2													1			1		
5	15380.58	23663.32	3	6	1	1	2	2																	
					2	2	1.5	1.5																	
					3	3	20			13			7												
					4	4	2							2											
					5	5	1.5							1.5											
					6	6	14.5							6	8.5										
					7	7	2										2								

Table 8.20 Production plan which has 9 orders for 5-days demand when planning time period is 6 days according to the first objective (continues)

i	Smin$_i$ (TL)	Smax$_i$ (TL)	dmin$_i$ (Day)	dmax$_i$ (Day)	j	k	p$_{ijk}$ (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4			Time Period 5			Time Period 6		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
6	11661.99	17940.04	3	6	1	1	2	2																	
					2	2	1.5	1.5																	
					3	3	17	6	11																
					4	4	1.5				1.5														
					5	5	2				2														
					6	6	12.5				7.5			5											
					7	7	1.5							1.5											
7	13675.20	21040.25	3	6	1	1	4				4														
					2	2	2							2											
					3	3	15.5							4						6.5			5		
					4	4	1.5																1.5		
					5	5	2																2		
					6	7	2.5																2.5		
8	9953.16	15314.11	3	6	1	1	2				2														
					2	2	1.5				0.5			1											
					3	3	12											0.5					6	5.5	
					4	4	1.5																	1.5	
					5	5	2																	2	
					6	7	2																	2	
9	16720.55	25721.85	3	6	1	1	2							2											
					2	2	2							2											
					3	3	15.5													4.5	11				
					4	4	2																2		
					5	5	2																2		
					6	7	2.5																2.5		

Table 8.21 Production plan which has 10 orders for 5-days demand when planning time period is 6 days according to the first objective

i	$Smin_i$ (TL)	$Smax_i$ (TL)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4			Time Period 5			Time Period 6		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
1	28409.15	43709.05	3	6	1	1	4	4																	
					2	2	2	2																	
					3	3	26.5	3.5			9.5			8.5			5								
					4	4	2.5										2.5								
					5	5	3										3								
					6	6	19.5										0.5	8			11				
					7	7	2.5																2.5		
2	36444.10	56067.55	3	6	1	1	4				4														
					2	2	2				2														
					3	3	26.5						10.5			16									
					4	4	2.5										2.5								
					5	5	3										3								
					6	6	19.5										5.5	3		11					
					7	7	2.5																2.5		
3	18788.55	28905.61	3	6	1	1	2	1			1														
					2	2	1				1														
					3	3	13.5					11		2.5											
					4	4	1.5							1.5											
					5	5	3							3											
					6	6	10							4	1		5								
					7	7	1.5										1.5								
4	16264.92	25024.51	3	6	1	1	2							2											
					2	2	1.5							1.5											
					3	3	20											11		9					
					4	4	2													2					
					5	5	3																3		
					6	6	14.5																5.5	9	
					7	7	2																	2	
5	15380.58	23663.32	3	6	1	1	2	2																	
					2	2	1.5	1.5																	
					3	3	20	7.5	11		1.5														
					4	4	2				2														
					5	5	1.5				1.5														
					6	6	14.5				6	5.5		1	2										
					7	7	2										2								

Table 8.21 Production plan which has 10 orders for 5-days demand when planning time period is 6 days according to the first objective (continues)

i	$Smin_i$ (TL)	$Smax_i$ (TL)	$dmin_i$ (Day)	$dmax_i$ (Day)	j	k	p_{ijk} (Hour)	Time Period 1			Time Period 2			Time Period 3			Time Period 4			Time Period 5			Time Period 6		
								R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S	R.T	O.T	O.S
6	11661.99	17940.04	3	6	1	1	2				2														
					2	2	1.5				0.5			1											
					3	3	17								11		6								
					4	4	1.5										1.5								
					5	5	2													2					
					6	6	12.5															12.5			
					7	7	1.5																1.5		
7	21117.25	32486.30	3	6	1	1	4	4																	
					2	2	2	2																	
					3	3	26.5			13			13.5												
					4	4	3							3											
					5	5	2							2											
					6	6	19.5							6	8								5.5		
					7	7	2.5																2.5		
8	13675.20	21040.25	3	6	1	1	4							4											
					2	2	2							2											
					3	3	15.5													2			10	3.5	
					4	4	1.5																	1.5	
					5	5	2																	2	
					6	7	2.5																	2.5	
9	9953.16	15314.11	3	6	1	1	2				2														
					2	2	1.5							1.5											
					3	3	12														11		1		
					4	4	1.5																1.5		
					5	5	2																2		
					6	7	2																2		
10	16720.55	25721.85	3	6	1	1	2				2														
					2	2	2				2														
					3	3	15.5												15.5						
					4	4	2													2					
					5	5	2													2					
					6	7	2.5													2.5					

Table 8.22 Results of due dates

	Results of Due Dates according to the First Objective Function (Day)									
Number of Orders	**Order 1**	**Order 2**	**Order 3**	**Order 4**	**Order 5**	**Order 6**	**Order 7**	**Order 8**	**Order 9**	**Order 10**
7	6	6	6	6	6	6	6			
8	6	6	6	6	6	6	6	6		
9	6	6	6	6	6	6	6	6	6	
10	6	6	6	6	6	6	6	6	6	5
	Results of Due Dates according to the Second Objective Function (Day)									
Number of Orders	**Order 1**	**Order 2**	**Order 3**	**Order 4**	**Order 5**	**Order 6**	**Order 7**	**Order 8**	**Order 9**	**Order 10**
7	…	…	…	…	…	…	…			
8	…	…	…	…	…	…	…	…		
9	…	…	…	…	…	…	…	…	…	
10	…	…	…	…	…	…	…	…	…	…

Due dates which are found according to the first objective function and the second objective function of the multi-objective mixed-integer linear programming model according to the different number of orders for 5-days demand when planning time period is 6 days under 3 hours elapsed run time by Lingo 14.0 software are shown in Table 8.22.

The due date of each order is found as 6 days in the multi-objective mixed-integer linear programming model which has 7 orders for 5-days demand when planning time period is 6 days under 3 hours elapsed run time by Lingo 14.0 software. This solution is found according to the first objective function of the multi-objective mixed-integer linear programming model. Although the values of maximum due dates are assigned to all orders, the third order and the fourth order are completed in time period 5 as shown in Table 8.18. The last job of orders can be completed before the found due dates, because of the due date constraint in the mathematical model.

The due date of each order is found as 6 days in the multi-objective mixed-integer linear programming model when the number of orders is increased to 8 and planning time period is 6 days for 5-days demand under 3 hours elapsed run time by Lingo 14.0 software. This solution is found according to the first objective function of the multi-objective mixed-integer linear programming model. Although the values of maximum due dates are assigned to all orders, the third order and the fifth order are completed in time period 5 as shown in Table 8.19. The last job of orders can be completed before the found due dates, because of the due date constraint in the mathematical model.

The due date of each order is found as 6 days in the multi-objective mixed-integer linear programming model when the number of orders is increased to 9 and planning time period is 6 days for 5-days demand under 3 hours elapsed run time by Lingo 14.0 software. This solution is found according to the first objective function of the multi-objective mixed-integer linear programming model. Although the values of maximum due dates are assigned to all orders, the fifth order is completed in time period 4 and the sixth order is completed in time period 3 as shown in Table 8.20. The last job of orders can be completed before the found due dates, because of the due date constraint in the mathematical model.

The due date of the first nine orders are found as 6 days and the due date of the tenth order is found as 5 days in the multi-objective mixed-integer linear programming model when the number of orders is increased to 10 and planning time period is 6 days for 5-days demand under 3 hours elapsed run time by Lingo 14.0 software. This solution is found according to the first objective function of the multi-objective mixed-integer linear programming model. Although the values of maximum due dates are assigned the first nine orders, the third order and the fifth order are completed in time period 4 as shown in Table 8.21. The last job of orders can be completed before the found due dates, because of the due date constraint in the mathematical model.

Selling prices which are found according to the first objective function and the second objective function of the multi-objective mixed-integer linear programming model according to the different number of orders for 5-days demand when planning time period is 6 days under 3 hours elapsed run time by Lingo 14.0 software are shown in Table 8.23.

Table 8.23 Results of selling prices

	Results of Selling Prices according to the First Objective Function (TL)									
Number of Orders	**Order 1**	**Order 2**	**Order 3**	**Order 4**	**Order 5**	**Order 6**	**Order 7**	**Order 8**	**Order 9**	**Order 10**
7	43709.05	56067.55	28905.61	25024.51	21040.25	15314.11	25721.85			
8	43709.05	56067.55	28905.61	25024.51	23663.32	21040.25	15314.11	25721.85		
9	43709.05	56067.55	28905.61	25024.51	23663.32	17940.04	21040.25	15314.11	25721.85	
10	43709.05	56067.55	28905.61	25024.51	23663.32	17940.04	32486.30	21040.25	15314.11	25721.85
	Results of Selling Prices according to the Second Objective Function (TL)									
Number of Orders	**Order 1**	**Order 2**	**Order 3**	**Order 4**	**Order 5**	**Order 6**	**Order 7**	**Order 8**	**Order 9**	**Order 10**
7	…	…	…	…	…	…	…			
8	…	…	…	…	…	…	…	…		
9	…	…	…	…	…	…	…	…	…	
10	…	…	…	…	…	…	…	…	…	…

Results of the first objective function and the second objective function of the multi-objective mixed-integer linear programming model according to the different number of orders for 5-days demand when planning time period is 6 days under 3 hours elapsed run time by Lingo 14.0 software are shown in Table 8.24.

Table 8.24 Results of the fisrt objective function and the second objective function in production plans

	Results of the First Objective Function			Results of the Second Objective Function		
Number of Orders	**Elapsed Run Time**	**State**	**Objective Value (TL)**	**Elapsed Run Time**	**State**	**Objective Value (Day)**
7	3 hours	Feasible	208340.6	3 hours	Unknown	…
8	3 hours	Feasible	230865.5	3 hours	Unknown	…
9	3 hours	Feasible	247806.5	3 hours	Unknown	…
10	3 hours	Feasible	278709.1	3 hours	Unknown	…

CHAPTER NINE
CONCLUSION

9.1 Summary

The capacity constrained short-term production planning problem which contains decisions about order acceptance, selling price and due date assignment for orders was studied for make-to-order production systems in this thesis, in contrast to classical production planning problems. The mathematical formulation of the model which was proposed by Chen et al. (2009) was revised and some wrong constraints were reformulated.

The mixed-integer non-linear programming model where selling prices and due dates are constant parameters was developed after revisions and reformulations of the mathematical formulation of the model which was proposed by Chen et al. (2009).

Selling prices and due dates which are constant parameters in the mathematical model of Chen et al. (2009) were transformed into decision variables in order to provide decisions about selling price and due date assignment in the mathematical programming model. After this improvement, the multi-objective mixed-integer non-linear programming model where selling prices and due dates are decision variables was developed in this thesis.

Linearization method in the explanations of Coelho (2013) was applied to non-linear mathematical models. The mixed-integer linear programming model where selling prices and due dates are constant parameters and the multi-objective mixed-integer linear programming model where selling prices and due dates are decision variables were developed after an application of the linearization method and these models were solved by using Lingo 14.0 software.

The mixed-integer linear programming model where selling prices and due dates are constant parameters was solved in order to test the four examples in the study of

Chen et al. (2009) and solution results were explained. The mixed-integer linear programming model where selling prices and due dates are constant parameters was solved in order to test the base case in the study of Chen et al. (2009) under different resource utilization rates and solution results were explained. Also, twelve scenarios were compared for the multi-objective mixed-integer linear programming model where selling prices and due dates are decision variables according to different value range of selling prices and due dates under different resource utilization rates.

The case study was realized in the automotive brake disc manufacturing company in order to analyze the results of the proposed multi-objective mixed-integer linear programming model in real life.

9.2 Future Research

The meta-heuristics methods should be used in order to work with big size problems. Because the elapsed run time increases in Lingo 14.0 software in order to find the global optimal solution, if the number of order is increased in the multi-objective mixed-integer linear programming model.

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APPENDICES

APPENDIX 1: Mixed-Integer Linear Programming Model

Sets, parameters and decision variables which are formed by developing the mathematical model of Chen et al. (2009) are described as follows. These parameters and decision variables are for the mixed-integer linear programming model where selling prices and due dates are constant parameters. $W_{ijk|R|t}$ was added as a decision variable, result of revising the capacity constraint of outsourcing in the mathematical model of Chen et al. (2009).

Sets:

I : Items $\{i \in I\}$
J_i : Jobs (operations) in item i $\{j \in J_i\}$
K : Resources $\{k \in K\}$
R : Sources $\{r \in R\}$
T: Time periods $\{t \in T\}$

Parameters:

S_i : Selling price of item i
d_i :Due date of item i
p_{ijk} : Processing time of job j of item i on resource k
c_{kr} : The cost of processing on resource k of source r per hour
b_{krt} : Number of available hours of resource k of source r in time period t
l_{rt} : Number of available hours of source r in time period t

Decision Variables:

X_{ijkrt} : Number of assigned hours for processing job j of item i on resource k of source r in time period t

Y_{ijkrt} : 1, if job j of item i is assigned for processing on resource k of source r in time period t; 0, otherwise

$W_{ijk|R|t}$: Number of assigned hours for processing job j of item i on resource k of outsourcing in time period t. $W_{ijk|R|t}$ is the product of $X_{ijk|R|t}$ and O_{ij} and $|R|$ expresses outsourcing. If O_{ij} is 1, $W_{ijk|R|t}$ takes the value of $X_{ijk|R|t}$; otherwise takes the value of 0.

Z_i : 1, if the item i is accepted; 0, otherwise

O_{ij} : 1, if the job j of item i is processed in outsourcing; 0, otherwise

The mixed-integer linear programming model where selling prices and due dates are constant parameter is presented below. The mixed-integer linear programming model was formed by revising and reformulating the mathematical model of Chen et al. (2009) and using the linearization method in the explanations of Coelho (2013).

$$Maximize \sum_{i\in I} S_i * Z_i - \sum_{i\in I}\sum_{j\in J_i}\sum_{k\in K}\sum_{r\in R}\sum_{t\in T} X_{ijkrt} * c_{kr} \tag{A.1}$$

$$\sum_{i\in I}\sum_{j\in J_i} X_{ijkrt} \leq b_{krt} \quad \forall\, k\in K, r\in R, t\in T \tag{A.2}$$

$$\sum_{r\in R\setminus\{|R|\}}\sum_{t\in T} X_{ijkrt} + \sum_{r\in\{|R|\}}\sum_{t\in T} X_{ijkrt} = p_{ijk} * Z_i \tag{A.3}$$

$$\forall\, i\in I, j\in J_i, k\in K$$

$$\sum_{r\in\{|R|\}}\sum_{t\in T} X_{ijkrt} = p_{ijk} * O_{ij} \quad \forall\, i\in I, j\in J_i, k\in K \tag{A.4}$$

$$\sum_{j\in J_i}\sum_{k\in K} X_{ijkrt} \leq l_{rt} \quad \forall\, i\in I, r\in R\setminus\{|R|\}, t\in T \tag{A.5}$$

$$W_{ijk|R|t} \leq 24 * O_{ij} \quad \forall\, i\in I, j\in J_i, k\in K, r\in\{|R|\}, t\in T \tag{A.6}$$

$$W_{ijk|R|t} \leq X_{ijk|R|t} \quad \forall\, i\in I, j\in J_i, k\in K, r\in\{|R|\}, t\in T \tag{A.7}$$

$$W_{ijk|R|t} \geq X_{ijk|R|t} - \left(1 - O_{ij}\right) * 24 \tag{A.8}$$

$$\forall\, i\in I, j\in J_i, k\in K, r\in\{|R|\}, t\in T$$

$$W_{ijk|R|t} \geq 0 \quad \forall\, i\in I, j\in J_i, k\in K, r\in\{|R|\}, t\in T \tag{A.9}$$

$$\sum_{j\in J_i}\sum_{k\in K} W_{ijk|R|t} \leq l_{|R|t} \quad \forall\, i\in I, r\in\{|R|\}, t\in T \tag{A.10}$$

$$\sum_{j\in J_i}\sum_{k\in K}\sum_{r\in R} X_{ijkrt} \leq 24 \quad \forall\, i\in I, t\in T \tag{A.11}$$

$$X_{ijkrt} \geq \lambda * Y_{ijkrt} \quad \forall\, i\in I, j\in J_i, k\in K, r\in R, t\in T \tag{A.12}$$

$$X_{ijkrt} \leq Y_{ijkrt} * p_{ijk} \quad \forall\, i \in I, j \in J_i, k \in K, r \in R, t \in T \tag{A.13}$$

$$\sum_{k \in K} Y_{i|J_i|krt} * t \leq d_i * Z_i \quad \forall\, i \in I, j \in \{|J_i|\}, r \in R, t \in T \tag{A.14}$$

$$\alpha * \left(\sum_{r' \in R} \sum_{t'=1}^{t-1} X_{i(j-1)kr't'}\right) + \sum_{r'=1}^{r} X_{i(j-1)kr't} \geq p_{i(j-1)k} * \sum_{k' \in K} Y_{ijk'rt} \tag{A.15}$$

$$\forall\, i \in I, j \in J_i \setminus \{1\}, k \in K, r \in R \setminus \{|R|\}, t \in T$$

$$if\ t = 1, \alpha = 0; if\ t > 1, \alpha = 1$$

$$\sum_{r \in R} \sum_{t'=1}^{t} X_{i(j-1)krt'} \geq p_{i(j-1)k} * \sum_{k' \in K} \sum_{r \in \{|R|\}} Y_{ijk'rt} \tag{A.16}$$

$$\forall\, i \in I, j \in J_i \setminus \{1\}, k \in K, t \in T$$

$$\sum_{j' \in J_i} \sum_{k \in K} \sum_{r' \in \{|R|\}} X_{ij'kr't} + \sum_{k \in K} Y_{ijkrt} * r * l_{rt} \leq 24 \tag{A.17}$$

$$\forall\, i \in I, j \in J_i \setminus \{|J_i|\}, r \in R \setminus \{|R|\}, t \in T$$

$$X_{ijkrt} \geq 0 \quad \forall\, i \in I, j \in J_i, k \in K, r \in R, t \in T \tag{A.18}$$

$$Y_{ijkrt} \in \{0,1\} \quad \forall\, i \in I, j \in J_i, k \in K, r \in R, t \in T \tag{A.19}$$

$$Z_i \in \{0,1\} \quad \forall\, i \in I \tag{A.20}$$

$$O_{ij} \in \{0,1\} \quad \forall\, i \in I, j \in J_i \tag{A.21}$$

APPENDIX- 2: Multi-Objective Mixed-Integer Linear Programming Model

Sets, parameters and decision variables which are formed by developing the mathematical model of Chen et al. (2009) are described as follows. These parameters and decision variables are for the multi-objective mixed-integer linear programming model where selling prices and due dates are decision variables. $W_{ijk|R|t}$ was added as a decision variable, result of revising the capacity constraint of outsourcing in the mathematical model of Chen et al. (2009). Q_i and H_i were added as decision variables because of converting the selling price and due date parameters into decision variables.

Sets:

I : Items $\{i \in I\}$
J_i : Jobs (operations) in item i $\{j \in J_i\}$
K : Resources $\{k \in K\}$
R : Sources $\{r \in R\}$
T: Time periods $\{t \in T\}$

Parameters:

$Smin_i$: Minimum selling price of item i
$Smax_i$: Maximum selling price of item i
$dmin_i$: Minimum due date of item i
$dmax_i$: Maximum due date of item i
p_{ijk} : Processing time of job j of item i on resource k
c_{kr} : The cost of processing on resource k of source r per hour
b_{krt} : Number of available hours of resource k of source r in time period t
l_{rt} : Number of available hours of source r in time period t

Decision Variables:

S_i : Selling price of item i

d_i :Due date of item i

Q_i : Product of S_i and Z_i. If Z_i is 1, Q_i takes the value of S_i; otherwise takes the value of 0.

H_i : Product of d_i and Z_i. If Z_i is 1, H_i takes the value of d_i; otherwise takes the value of 0.

X_{ijkrt} : Number of assigned hours for processing job j of item i on resource k of source r in time period t

Y_{ijkrt} : 1, if job j of item i is assigned for processing on resource k of source r in time period t; 0, otherwise

$W_{ijk|R|t}$: Number of assigned hours for processing job j of item i on resource k of outsourcing in time period t. $W_{ijk|R|t}$ is the product of $X_{ijk|R|t}$ and O_{ij} and $|R|$ expresses outsourcing. If O_{ij} is 1, $W_{ijk|R|t}$ takes the value of $X_{ijk|R|t}$; otherwise takes the value of 0.

Z_i : 1, if the item i is accepted; 0, otherwise

O_{ij} : 1, if the job j of item i is processed in outsourcing; 0, otherwise

The multi-objective mixed-integer linear programming model where selling prices and due dates are decision variables is presented below. The multi-objective mixed-integer linear programming model was formed by revising and reformulating the mathematical model of Chen et al. (2009), improving the mathematical model of Chen et al. (2009) by transforming selling price and due date parameters into decision variables, using two objective functions and applying the linearization method in the explanations of Coelho (2013).

$$Maximize \sum_{i \in I} Q_i - \sum_{i \in I} \sum_{j \in J_i} \sum_{k \in K} \sum_{r \in R} \sum_{t \in T} X_{ijkrt} * c_{kr} \quad \text{(A.22)}$$

$$Minimize \sum_{i \in I} H_i \quad \text{(A.23)}$$

$$\sum_{i \in I} \sum_{j \in J_i} X_{ijkrt} \leq b_{krt} \quad \forall\, k \in K, r \in R, t \in T \quad \text{(A.24)}$$

$$\sum_{r \in R \setminus \{|R|\}} \sum_{t \in T} X_{ijkrt} + \sum_{r \in \{|R|\}} \sum_{t \in T} X_{ijkrt} = p_{ijk} * Z_i \quad \text{(A.25)}$$

$$\forall\, i \in I, j \in J_i, k \in K$$

$$\sum_{r\in\{|R|\}}\sum_{t\in T} X_{ijkrt} = p_{ijk} * O_{ij} \quad \forall\, i \in I, j \in J_i, k \in K \tag{A.26}$$

$$\sum_{j\in J_i}\sum_{k\in K} X_{ijkrt} \le l_{rt} \quad \forall\, i \in I, r \in R \setminus \{|R|\}, t \in T \tag{A.27}$$

$$W_{ijk\,|R|t} \le 24 * O_{ij} \quad \forall\, i \in I, j \in J_i, k \in K, r \in \{|R|\}, t \in T \tag{A.28}$$

$$W_{ijk\,|R|t} \le X_{ijk\,|R|t} \quad \forall\, i \in I, j \in J_i, k \in K, r \in \{|R|\}, t \in T \tag{A.29}$$

$$W_{ijk\,|R|t} \ge X_{ijk\,|R|t} - \left(1 - O_{ij}\right) * 24 \tag{A.30}$$

$$\forall\, i \in I, j \in J_i, k \in K, r \in \{|R|\}, t \in T$$

$$W_{ijk\,|R|t} \ge 0 \quad \forall\, i \in I, j \in J_i, k \in K, r \in \{|R|\}, t \in T \tag{A.31}$$

$$\sum_{j\in J_i}\sum_{k\in K} W_{ijk\,|R|t} \le l_{|R|t} \quad \forall\, i \in I, r \in \{|R|\}, t \in T \tag{A.32}$$

$$\sum_{j\in J_i}\sum_{k\in K}\sum_{r\in R} X_{ijkrt} \le 24 \quad \forall\, i \in I, t \in T \tag{A.33}$$

$$X_{ijkrt} \ge \lambda * Y_{ijkrt} \quad \forall\, i \in I, j \in J_i, k \in K, r \in R, t \in T \tag{A.34}$$

$$X_{ijkrt} \le Y_{ijkrt} * p_{ijk} \quad \forall\, i \in I, j \in J_i, k \in K, r \in R, t \in T \tag{A.35}$$

$$\sum_{k\in K} Y_{i|J_i|krt} * t \le H_i \quad \forall\, i \in I, j \in \{|J_i|\}, r \in R, t \in T \tag{A.36}$$

$$\alpha * \left(\sum_{r'\in R}\sum_{t'=1}^{t-1} X_{i(j-1)kr't'}\right) + \sum_{r'=1}^{r} X_{i(j-1)kr't} \ge p_{i(j-1)k} * \sum_{k'\in K} Y_{ij\,k'rt} \tag{A.37}$$

$$\forall\, i \in I, j \in J_i \setminus \{1\}, k \in K, r \in R \setminus \{|R|\}, t \in T$$

$$if\ t = 1, \alpha = 0; if\ t > 1, \alpha = 1$$

$$\sum_{r\in R}\sum_{t'=1}^{t} X_{i(j-1)krt'} \ge p_{i(j-1)k} * \sum_{k'\in K}\sum_{r\in\{|R|\}} Y_{ij\,k'rt} \tag{A.38}$$

$$\forall\, i \in I, j \in J_i \setminus \{1\}, k \in K, t \in T$$

$$\sum_{j'\in J_i}\sum_{k\in K}\sum_{r'\in\{|R|\}} X_{ij'kr't} + \sum_{k\in K} Y_{ijkrt} * r * l_{rt} \le 24 \tag{A.39}$$

$$\forall\, i \in I, j \in J_i \setminus \{|J_i|\}, r \in R \setminus \{|R|\}, t \in T$$

$$Q_i \ge Smin_i * Z_i \quad \forall\, i \in I \tag{A.40}$$

$$Q_i \le Smax_i * Z_i \quad \forall\, i \in I \tag{A.41}$$

$$Q_i \ge S_i - (1 - Z_i) * Smax_i \quad \forall\, i \in I \tag{A.42}$$

$$Q_i \le S_i - (1 - Z_i) * Smin_i \quad \forall\, i \in I \tag{A.43}$$

$$Q_i \leq S_i + (1 - Z_i) * Smax_i \quad \forall\, i \in I \tag{A.44}$$

$$H_i \geq dmin_i * Z_i \quad \forall\, i \in I \tag{A.45}$$

$$H_i \leq dmax_i * Z_i \quad \forall\, i \in I \tag{A.46}$$

$$H_i \geq d_i - (1 - Z_i) * dmax_i \quad \forall\, i \in I \tag{A.47}$$

$$H_i \leq d_i - (1 - Z_i) * dmin_i \quad \forall\, i \in I \tag{A.48}$$

$$H_i \leq d_i + (1 - Z_i) * dmax_i \quad \forall\, i \in I \tag{A.49}$$

$$X_{ijkrt} \geq 0 \quad \forall\, i \in I, j \in J_i, k \in K, r \in R, t \in T \tag{A.50}$$

$$Y_{ijkrt} \in \{0,1\} \quad \forall\, i \in I, j \in J_i, k \in K, r \in R, t \in T \tag{A.51}$$

$$Z_i \in \{0,1\} \qquad \forall\, i \in I \tag{A.52}$$

$$O_{ij} \in \{0,1\} \qquad \forall\, i \in I, j \in J_i \tag{A.53}$$

APPENDIX 3: Lingo Model 1

The multi-objective mixed-integer linear programming model where selling prices and due dates are decision variables has two objective functions. Lingo model 1 which is shown below is coded according to the first objective function (total net profit maximization) of the multi-objective mixed-integer linear programming model where selling prices and due dates are decision variables.

Lingo model 1:

```
SETS:
ITEMS/1..4/:S_PRICE,DUE_DATE,Z,S_PRICE_MIN,S_PRICE_MAX,DUE_DAT
E_MIN,DUE_DATE_MAX,Q,H;
JOBS/1..4/;
ROUTES(ITEMS,JOBS)/1 1,1 2,1 3,1 4,
                   2 1,2 2,2 3,2 4,
                   3 1,3 2,3 3,3 4,
                   4 1,4 2,4 3,4 4/;
RESOURCES/1..3/;
SOURCES/1..3/:ALTERNATIVE;
TIME_PERIOD/1..4/:PERIOD;
PROCESSING_TIME(ROUTES,RESOURCES):p;
PROCESSING_COST(RESOURCES,SOURCES):c;
RESOURCE_HOURS(RESOURCES,SOURCES,TIME_PERIOD):b;
SOURCE_HOURS(SOURCES,TIME_PERIOD):l;
PROCESSING(ROUTES,RESOURCES,SOURCES,TIME_PERIOD):X,Y,W;
OUTSOURCING(ROUTES):O;
ENDSETS
DATA:
S_PRICE_MIN=11000 11000 11000 9000;
S_PRICE_MAX=13000 13000 13000 11000;
DUE_DATE_MIN=3 3 3 3;
```

```
DUE_DATE_MAX=4 4 4 4;
ALTERNATIVE=1 2 3;
PERIOD=1 2 3 4;
p=0 4 0
   0 0 26
   12 0 0
   0 5 0
   0 6 0
   0 7 0
   0 0 7
   7 0 0
   0 4 0
   0 0 12
   0 7 0
   9 0 0
   4 0 0
   13 0 0
   0 9 0
   0 3 0;
c=100 150 250
   200 250 350
   100 200 150;
  b=8 8 8 8
     8 8 8 8
     24 24 24 24
     8 8 8 8
     8 8 8 8
     24 24 24 24
     8 8 8 8
     8 8 8 8
     24 24 24 24;
l=8 8 8 8
```

```
  8 8 8 8
  24 24 24 24;
ENDDATA

MAX=@SUM(ITEMS(I):Q(I))-
@SUM(PROCESSING(I,J,K,R,T):X(I,J,K,R,T)*c(K,R));                    (A.54)

@FOR(RESOURCES(K):@FOR(SOURCES(R):@FOR(TIME_PERIOD(T):@SU
M(ROUTES(I,J):X(I,J,K,R,T))<=b(K,R,T))));                           (A.55)

@FOR(ROUTES(I,J):@FOR(RESOURCES(K):@SUM(SOURCES(R)|R#NE#3:@
SUM(TIME_PERIOD(T):X(I,J,K,R,T)))+@SUM(SOURCES(R)|R#EQ#3:
@SUM(TIME_PERIOD(T):X(I,J,K,R,T)))=p(I,J,K)*Z(I)));                 (A.56)

@FOR(ROUTES(I,J):@FOR(RESOURCES(K):@SUM(SOURCES(R)|R#EQ#3:@
SUM(TIME_PERIOD(T):X(I,J,K,R,T)))=p(I,J,K)*O(I,J)));                (A.57)

@FOR(ITEMS(I):@FOR(SOURCES(R)|R#NE#3:@FOR(TIME_PERIOD(T):@SU
M(ROUTES(I,J):@SUM(RESOURCES(K):X(I,J,K,R,T)))<=l(R,T))));          (A.58)

@FOR(ROUTES(I,J):@FOR(RESOURCES(K):@FOR(SOURCES(R)|R#EQ#3:@F
OR(TIME_PERIOD(T):W(I,J,K,R,T)<=24*O(I,J)))));                      (A.59)

@FOR(ROUTES(I,J):@FOR(RESOURCES(K):@FOR(SOURCES(R)|R#EQ#3:@F
OR(TIME_PERIOD(T):W(I,J,K,R,T)<=X(I,J,K,R,T)))));                   (A.60)

@FOR(ROUTES(I,J):@FOR(RESOURCES(K):@FOR(SOURCES(R)|R#EQ#3:@F
OR(TIME_PERIOD(T):W(I,J,K,R,T)>=X(I,J,K,R,T)-(1-O(I,J))*24))));     (A.61)

@FOR(ROUTES(I,J):@FOR(RESOURCES(K):@FOR(SOURCES(R)|R#EQ#3:@F
OR(TIME_PERIOD(T):W(I,J,K,R,T)>=0))));                              (A.62)
```

```
@FOR(ITEMS(I):@FOR(SOURCES(R)|R#EQ#3:@FOR(TIME_PERIOD(T):@SU
M(ROUTES(I,J):@SUM(RESOURCES(K):W(I,J,K,R,T)))<=l(R,T))));          (A.63)

@FOR(ITEMS(I):@FOR(TIME_PERIOD(T):@SUM(ROUTES(I,J):@SUM(RESO
URCES(K):@SUM(SOURCES(R):X(I,J,K,R,T))))<=24));          (A.64)

@FOR(ROUTES(I,J):@FOR(RESOURCES(K):@FOR(SOURCES(R):@FOR(TIM
E_PERIOD(T):X(I,J,K,R,T)>=0.5*Y(I,J,K,R,T)))));          (A.65)

@FOR(ROUTES(I,J):@FOR(RESOURCES(K):@FOR(SOURCES(R):@FOR(TIM
E_PERIOD(T):X(I,J,K,R,T)<=Y(I,J,K,R,T)*p(I,J,K)))));          (A.66)

@FOR(ROUTES(I,J)|J#EQ#4:@FOR(SOURCES(R):@FOR(TIME_PERIOD(T):@
SUM(RESOURCES(K):Y(I,J,K,R,T)*PERIOD(T))<=H(I))));          (A.67)

@FOR(ROUTES(I,J)|J#GT#1:@FOR(RESOURCES(K):@FOR(SOURCES(R)|R#N
E#3:@FOR(TIME_PERIOD(T)|T#EQ#1:
@SUM(SOURCES(M)|M#LE#R:X(I,J-1,K,M,T))>=p(I,J-
1,K)*@SUM(RESOURCES(N):Y(I,J,N,R,T))))));          (A.68)

@FOR(ROUTES(I,J)|J#GT#1:@FOR(RESOURCES(K):@FOR(SOURCES(R)|R#N
E#3:@FOR(TIME_PERIOD(T)|T#GT#1:@SUM(SOURCES(M):
@SUM(TIME_PERIOD(S)|S#LT#T:X(I,J-
1,K,M,S)))+@SUM(SOURCES(M)|M#LE#R:X(I,J-1,K,M,T))>=p(I,J-
1,K)*@SUM(RESOURCES(N):Y(I,J,N,R,T))))));          (A.69)

@FOR(ROUTES(I,J)|J#GT#1:@FOR(RESOURCES(K):@FOR(TIME_PERIOD(T)
:@SUM(SOURCES(R):@SUM(TIME_PERIOD(S)|S#LE#T:X(I,J-1,K,R,S)))
>=p(I,J-
1,K)*@SUM(RESOURCES(N):@SUM(SOURCES(R)|R#EQ#3:Y(I,J,N,R,T))))));
                                                            (A.70)
```

@FOR(ROUTES(I,J)|J#LT#4:@FOR(SOURCES(R)|R#NE#3:@FOR(TIME_PERIOD(T):@SUM(ROUTES(I,G):@SUM(RESOURCES(K):@SUM(SOURCES(M)|M#EQ#3:X(I,G,K,M,T)))+
@SUM(RESOURCES(K):Y(I,J,K,R,T)*ALTERNATIVE(R)*l(R,T))<=24))); (A.71)

@FOR(ITEMS(I):Q(I)>=S_PRICE_MIN(I)*Z(I)); (A.72)

@FOR(ITEMS(I):Q(I)<=S_PRICE_MAX(I)*Z(I)); (A.73)

@FOR(ITEMS(I):Q(I)>=S_PRICE(I)-(1-Z(I))*S_PRICE_MAX(I)); (A.74)

@FOR(ITEMS(I):Q(I)<=S_PRICE(I)-(1-Z(I))*S_PRICE_MIN(I)); (A.75)

@FOR(ITEMS(I):Q(I)<=S_PRICE(I)+(1-Z(I))*S_PRICE_MAX(I)); (A.76)

@FOR(ITEMS(I):H(I)>=DUE_DATE_MIN(I)*Z(I)); (A.77)

@FOR(ITEMS(I):H(I)<=DUE_DATE_MAX(I)*Z(I)); (A.78)

@FOR(ITEMS(I):H(I)>=DUE_DATE(I)-(1-Z(I))*DUE_DATE_MAX(I)); (A.79)

@FOR(ITEMS(I):H(I)<=DUE_DATE(I)-(1-Z(I))*DUE_DATE_MIN(I)); (A.80)

@FOR(ITEMS(I):H(I)<=DUE_DATE(I)+(1-Z(I))*DUE_DATE_MAX(I)); (A.81)

@FOR(PROCESSING(I,J,K,R,T):@BIN(Y(I,J,K,R,T))); (A.82)

@FOR(ITEMS(I):@BIN(Z(I))); (A.83)

@FOR(OUTSOURCING(I,J):@BIN(O(I,J))); (A.84)

Lingo code (A.54) is to maximize the total net profit by using the value of total revenue and total processing cost. Lingo code (A.55) ensures that the available time of resource *k* of source *r* in time period *t* can't be exceeded. Lingo code (A.56) ensures that allocated total number of hours for processing of job *j* of item *i* must be equal to its processing time. Lingo code (A.57) is to outsource the job *j* of item *i* completely. Lingo code (A.58) ensures that each item can't be processed more than the capacity of regular time and overtime in each time period.

Lingo codes (A.59) - (A.62) are for the linearization of the product of $X_{ijk|R|t}$ and O_{ij}. Lingo code (A.59) and Lingo code (A.62) ensure that if job *j* of item *i* is not outsourced ($O_{ij}=0$), number of assigned hours for processing job *j* of item *i* on resource *k* of outsourcing in time period *t* ($W_{ijk|R|t}$) will be zero. Also, Lingo code (A.59) and Lingo code (A.62) determine the value interval of $X_{ijk|R|t}$ when $O_{ij}=1$. Lingo code (A.60) and Lingo code (A.61) ensure that if job *j* of item *i* is outsourced ($O_{ij}=1$), number of assigned hours for processing job *j* of item *i* on resource *k* of outsourcing in time period *t* ($W_{ijk|R|t}$) will be equal to $X_{ijk|R|t}$. Also, Lingo code (A.60) and Lingo code (A.61) determine the value interval of $X_{ijk|R|t}$ when $O_{ij}=0$. Lingo code (A.63) ensures that each item can't be processed more than the capacity of outsourcing in each time period.

Lingo code (A.64) ensures that each item can be processed maximum 24 hours in each time period. Lingo code (A.65) and Lingo code (A.66) indicate the relation between binary variable Y_{ijkrt} and continuous variable X_{ijkrt}. If Y_{ijkrt} is 0, X_{ijkrt} takes the value of 0. If Y_{ijkrt} is 1, X_{ijkrt} is at least 0.5 hours of time. The completion time of the last job of item *i* ($|J_i|$) can't exceed the due date of item *i* by Lingo code (A.67).

Lingo code (A.68) and Lingo code (A.69) ensure that job *j* of item *i* can be processed in time period *t* only after the processing job *(j-1)* of item *i* is completed. Lingo code (A.68) is for $t=1$ and Lingo code (A.69) is for $t>1$. Lingo code (A.70) ensures that job *j* of item *i* can be processed in outsourcing only after the processing of job *(j-1)* of item *i* is completed. Lingo code (A.71) ensures that jobs of item *i* can't be processed in outsourcing more than available hours.

Lingo codes (A.72) - (A.76) are for the linearization of the product of S_i and Z_i. Lingo code (A.72) and Lingo code (A.73) ensure that if item i is not accepted ($Z_i=0$), Q_i will be zero. Also, Lingo code (A.72) and Lingo code (A.73) determine the value interval of S_i when $Z_i=1$. Lingo code (A.74) and Lingo code (A.75) ensure that if item i is accepted ($Z_i=1$), Q_i will be equal to S_i. Also, Lingo code (A.74) and Lingo code (A.75) determine the value interval of S_i when $Z_i=0$. Lingo code (A.76) expresses that maximum value of selling price is positive.

Lingo codes (A.77) - (A.81) are for the linearization of the product of d_i and Z_i. Lingo code (A.77) and Lingo code (A.78) ensure that if item i is not accepted ($Z_i=0$), H_i will be zero. Also, Lingo code (A.77) and Lingo code (A.78) determine the value interval of d_i when $Z_i=1$. Lingo code (A.79) and Lingo code (A.80) ensure that if item i is accepted ($Z_i=1$), H_i will be equal to d_i. Also, Lingo code (A.79) and Lingo code (A.80) determine the value interval of d_i when $Z_i=0$. Lingo code (A.81) expresses that maximum value of due date is positive.

Lingo codes (A.82) - (A.84) are binary restrictions for decision variables Y_{ijkrt}, Z_i and O_{ij}.

APPENDIX 4: Lingo Model 2

The multi-objective mixed-integer linear programming model where selling prices and due dates are decision variables has two objective functions. Lingo model 2 which is shown below is coded when the second objective function (total due date minimization) is selected for optimization and the first objective function (total net profit maximization) is thought as a constraint under ε-constraint method in the multi-objective mixed-integer linear programming model where selling prices and due dates are decision variables.

Lingo model 2:

```
SETS:
ITEMS/1..4/:S_PRICE,DUE_DATE,Z,S_PRICE_MIN,S_PRICE_MAX,DUE_DAT
E_MIN,DUE_DATE_MAX,Q,H;
JOBS/1..4/;
ROUTES(ITEMS,JOBS)/1 1,1 2,1 3,1 4,
                   2 1,2 2,2 3,2 4,
                   3 1,3 2,3 3,3 4,
                   4 1,4 2,4 3,4 4/;
RESOURCES/1..3/;
SOURCES/1..3/:ALTERNATIVE;
TIME_PERIOD/1..4/:PERIOD;
PROCESSING_TIME(ROUTES,RESOURCES):p;
PROCESSING_COST(RESOURCES,SOURCES):c;
RESOURCE_HOURS(RESOURCES,SOURCES,TIME_PERIOD):b;
SOURCE_HOURS(SOURCES,TIME_PERIOD):l;
PROCESSING(ROUTES,RESOURCES,SOURCES,TIME_PERIOD):X,Y,W;
OUTSOURCING(ROUTES):O;
ENDSETS
DATA:
S_PRICE_MIN=11000 11000 11000 9000;
```

```
S_PRICE_MAX=13000 13000 13000 11000;
DUE_DATE_MIN=3 3 3 3;
DUE_DATE_MAX=4 4 4 4;
ALTERNATIVE=1 2 3;
PERIOD=1 2 3 4;
p=0 4 0
  0 0 26
  12 0 0
  0 5 0
  0 6 0
  0 7 0
  0 0 7
  7 0 0
  0 4 0
  0 0 12
  0 7 0
  9 0 0
  4 0 0
  13 0 0
  0 9 0
  0 3 0;
c=100 150 250
  200 250 350
  100 200 150;
 b=8 8 8 8
   8 8 8 8
   24 24 24 24
   8 8 8 8
   8 8 8 8
   24 24 24 24
   8 8 8 8
   8 8 8 8
```

```
    24 24 24 24;

l=8 8 8 8
  8 8 8 8
  24 24 24 24;
ENDDATA

MIN=@SUM(ITEMS(I):H(I));                                                    (A.85)

@SUM(ITEMS(I):Q(I))-
@SUM(PROCESSING(I,J,K,R,T):X(I,J,K,R,T)*c(K,R))>=29500;                     (A.86)

@FOR(RESOURCES(K):@FOR(SOURCES(R):@FOR(TIME_PERIOD(T):@SU
M(ROUTES(I,J):X(I,J,K,R,T))<=b(K,R,T))));                                   (A.87)

@FOR(ROUTES(I,J):@FOR(RESOURCES(K):@SUM(SOURCES(R)|R#NE#3:@
SUM(TIME_PERIOD(T):X(I,J,K,R,T)))+@SUM(SOURCES(R)|R#EQ#3:
@SUM(TIME_PERIOD(T):X(I,J,K,R,T)))=p(I,J,K)*Z(I)));                         (A.88)

@FOR(ROUTES(I,J):@FOR(RESOURCES(K):@SUM(SOURCES(R)|R#EQ#3:@
SUM(TIME_PERIOD(T):X(I,J,K,R,T)))=p(I,J,K)*O(I,J)));                        (A.89)

@FOR(ITEMS(I):@FOR(SOURCES(R)|R#NE#3:@FOR(TIME_PERIOD(T):@SU
M(ROUTES(I,J):@SUM(RESOURCES(K):X(I,J,K,R,T)))<=l(R,T))));                  (A.90)

@FOR(ROUTES(I,J):@FOR(RESOURCES(K):@FOR(SOURCES(R)|R#EQ#3:@F
OR(TIME_PERIOD(T):W(I,J,K,R,T)<=24*O(I,J)))));                              (A.91)

@FOR(ROUTES(I,J):@FOR(RESOURCES(K):@FOR(SOURCES(R)|R#EQ#3:@F
OR(TIME_PERIOD(T):W(I,J,K,R,T)<=X(I,J,K,R,T)))));                           (A.92)
```

@FOR(ROUTES(I,J):@FOR(RESOURCES(K):@FOR(SOURCES(R)|R#EQ#3:@FOR(TIME_PERIOD(T):W(I,J,K,R,T)>=X(I,J,K,R,T)-(1-O(I,J))*24)))); (A.93)

@FOR(ROUTES(I,J):@FOR(RESOURCES(K):@FOR(SOURCES(R)|R#EQ#3:@FOR(TIME_PERIOD(T):W(I,J,K,R,T)>=0)))); (A.94)

@FOR(ITEMS(I):@FOR(SOURCES(R)|R#EQ#3:@FOR(TIME_PERIOD(T):@SUM(ROUTES(I,J):@SUM(RESOURCES(K):W(I,J,K,R,T)))<=l(R,T)))); (A.95)

@FOR(ITEMS(I):@FOR(TIME_PERIOD(T):@SUM(ROUTES(I,J):@SUM(RESOURCES(K):@SUM(SOURCES(R):X(I,J,K,R,T))))<=24)); (A.96)

@FOR(ROUTES(I,J):@FOR(RESOURCES(K):@FOR(SOURCES(R):@FOR(TIME_PERIOD(T):X(I,J,K,R,T)>=0.5*Y(I,J,K,R,T))))); (A.97)

@FOR(ROUTES(I,J):@FOR(RESOURCES(K):@FOR(SOURCES(R):@FOR(TIME_PERIOD(T):X(I,J,K,R,T)<=Y(I,J,K,R,T)*p(I,J,K))))); (A.98)

@FOR(ROUTES(I,J)|J#EQ#4:@FOR(SOURCES(R):@FOR(TIME_PERIOD(T):@SUM(RESOURCES(K):Y(I,J,K,R,T)*PERIOD(T))<=H(I)))); (A.99)

@FOR(ROUTES(I,J)|J#GT#1:@FOR(RESOURCES(K):@FOR(SOURCES(R)|R#NE#3:@FOR(TIME_PERIOD(T)|T#EQ#1:
@SUM(SOURCES(M)|M#LE#R:X(I,J-1,K,M,T))>=p(I,J-1,K)*@SUM(RESOURCES(N):Y(I,J,N,R,T)))))); (A.100)

@FOR(ROUTES(I,J)|J#GT#1:@FOR(RESOURCES(K):@FOR(SOURCES(R)|R#NE#3:@FOR(TIME_PERIOD(T)|T#GT#1:@SUM(SOURCES(M):
@SUM(TIME_PERIOD(S)|S#LT#T:X(I,J-1,K,M,S)))+@SUM(SOURCES(M)|M#LE#R:X(I,J-1,K,M,T))>=p(I,J-1,K)*@SUM(RESOURCES(N):Y(I,J,N,R,T)))))); (A.101)

```
@FOR(ROUTES(I,J)|J#GT#1:@FOR(RESOURCES(K):@FOR(TIME_PERIOD(T)
:@SUM(SOURCES(R):@SUM(TIME_PERIOD(S)|S#LE#T:X(I,J-1,K,R,S)))
>=p(I,J-
1,K)*@SUM(RESOURCES(N):@SUM(SOURCES(R)|R#EQ#3:Y(I,J,N,R,T))))));
```
(A.102)

```
@FOR(ROUTES(I,J)|J#LT#4:@FOR(SOURCES(R)|R#NE#3:@FOR(TIME_PERI
OD(T):@SUM(ROUTES(I,G):@SUM(RESOURCES(K):@SUM(SOURCES(M)|M
#EQ#3:X(I,G,K,M,T))))+
@SUM(RESOURCES(K):Y(I,J,K,R,T)*ALTERNATIVE(R)*l(R,T))<=24)));
```
(A.103)

`@FOR(ITEMS(I):Q(I)>=S_PRICE_MIN(I)*Z(I));` (A.104)

`@FOR(ITEMS(I):Q(I)<=S_PRICE_MAX(I)*Z(I));` (A.105)

`@FOR(ITEMS(I):Q(I)>=S_PRICE(I)-(1-Z(I))*S_PRICE_MAX(I));` (A.106)

`@FOR(ITEMS(I):Q(I)<=S_PRICE(I)-(1-Z(I))*S_PRICE_MIN(I));` (A.107)

`@FOR(ITEMS(I):Q(I)<=S_PRICE(I)+(1-Z(I))*S_PRICE_MAX(I));` (A.108)

`@FOR(ITEMS(I):H(I)>=DUE_DATE_MIN(I)*Z(I));` (A.109)

`@FOR(ITEMS(I):H(I)<=DUE_DATE_MAX(I)*Z(I));` (A.110)

`@FOR(ITEMS(I):H(I)>=DUE_DATE(I)-(1-Z(I))*DUE_DATE_MAX(I));` (A.111)

`@FOR(ITEMS(I):H(I)<=DUE_DATE(I)-(1-Z(I))*DUE_DATE_MIN(I));` (A.112)

`@FOR(ITEMS(I):H(I)<=DUE_DATE(I)+(1-Z(I))*DUE_DATE_MAX(I));` (A.113)

```
@FOR(PROCESSING(I,J,K,R,T):@BIN(Y(I,J,K,R,T)));                    (A.114)

@FOR(ITEMS(I):@BIN(Z(I)));                                          (A.115)

@FOR(OUTSOURCING(I,J):@BIN(O(I,J)));                                (A.116)
```

Lingo code (A.85) is to minimize total due date. Lingo code (A.86) is to provide the total net profit value which is found in Lingo model 1. Lingo code (A.85) is selected for optimization and Lingo code (A.86) is thought as a constraint under ε-constraint method. Explanations of the other Lingo codes (A.87-A.116) of Lingo model 2 are the same as explanations of Lingo model 1.