MINIMIZATION OF TARDINESS IN AFTER-SALES PRODUCTION OF WIRE-HARNESS IN AUTOMOTIVE INDUSTRY WITH HIGH PRODUCT VARIETY

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MINIMIZATION OF TARDINESS IN AFTER-SALES PRODUCTION OF WIRE-HARNESS IN AUTOMOTIVE INDUSTRY WITH HIGH PRODUCT VARIETY

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This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

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In recent years, suppliers provide better after-sales services due to increasing competition in the wire-harness automotive supply industry to keep their customers loyal. This is the main reason why after-sales production changes its direction and becomes a marketing tactic. Therefore, high production efficiency in the system is desired, and the number of tardy jobs would be decreased. This study addresses a real-life problem of minimizing weighted tardiness in after-sales production of a wire-harness company by releasing only feasible jobs into the system. First, an integer programming model is proposed. Then, a heuristic algorithm is proposed with its computational results to have an applicable and user-friendly application which is fast enough to solve real large-scale problem. Performance of heuristic is compared with one of the traditional metaheuristics in the literature. Results present that proposed heuristic method provides better solutions in shorter computational times. Also, an application of weighted tardiness minimization is presented at the end of the thesis.

Keywords: after-sales, tardiness, heuristic, mathematical modelling, production planning

ÖZ

OTOMOTIV SANAYİSİNDEKİ YÜKSEK ÜRÜNLÜ KABLO SATIŞ SONRASI ÜRETİMİNDEKİ GEÇ KALMIŞ İŞLERİ MİNİMUM SEVİYEYE İNDİRME

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Son yıllarda, otomotiv elektrik-kablo yan sanayisindeki artan rekabet nedeniyle, tedarikçiler müşterilerini elde tutabilmek için daha iyi satış sonrası hizmet sunmaktadırlar. Bu satış sonrası üretimin yönünün değişmesinin ve bir pazarlama stratejisi haline gelmesinin ana nedenidir. Bundan dolayı, yüksek üretim verimliliği sistemde istenilmekte ve geciken iş sayıları enküçüklenecektir. Bu çalışma sadece üretilebilir işleri üretime vererek kablo yan sanayisindeki bir şirketin satış sonrası üretiminde ağırlıklı gecikmelerin en aza indirilmesi ile ilgili gerçek bir yaşam problemini içerir. İlk olarak tam sayılı matematiksel programlama modeli önerilmiştir. Daha sonra, gerçek büyük boyutlu problemin çözülmesinde yeterince hızlı olan uygulanabilir ve kullancı dostu bir uygulama elde etmek için sonuçları ile birlikte sezgisel bir yöntem önerilmiştir. Sezgiselin performansı literatürdeki geleneksel meta-sezgisel yöntemlerden bir tanesi ile karşılaştırılmıştır. Sonuçlar önerilen sezgiselin daha kısa süre içersinde daha iyi sonuçlar verdiğini göstermektedir. Ayrıca, ağırlıklı gecikmeleri enküçükleyen bir uygulama tezin sonunda sunulmuştur.

Anahtar Kelimeler: Satış sonrası, sezgisel, matematiksel modelleme, üretim planlama

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Chapter 1

Introduction

After-sales production system has a high variety of product range and low demand for each product (Jönke, 2012; p. 5). Building up stock leads to obsolete finished goods in inventories since customers may never demand such goods. Besides, wire-harness company wastes its valuable raw materials in the production process due to common components in different products. Therefore, a make-to-stock type of manufacturing system is inefficient for the after-sales production system. This is the reason that the company of interest in this study applies a make-to-order type of manufacturing system. In this type of manufacturing system, production quantities are equal to actual demands. However, the pull-type of system has to be flawless especially for the after-sales production system. The reason is that lead times are shorter than mass production, customers require those goods when unexpected and undesired events are occurred (Szwejczewski et al., 2015; p. 5335). These events can be car accidents, defective manufacturing or repair and maintenance. Customers desire to respond these kinds of events immediately and they expect the same quick respond from suppliers as well (Dombrowski and Malorny, 2017; p. 326). This study is motivated by the issues that an after-sales service company faces. Particularly, current pull-type system of the company is inefficient because the company cannot determine whether jobs are producible or not. Infeasible tasks decrease production performance and increase tardiness. Also, tardiness leads to penalty costs and loss of customer satisfaction. Therefore, this thesis aims to solve the issues of the current system by reducing the tardiness and planning performance.

In this chapter, Section 1.1 presents the motivation for this research. Section 1.2 summarizes the after-sales production system, explains its main challenges together with production planning in after-sales and tardiness in Sections 1.2.1, 1.2.2 and 1.2.3. Section

1.3 explains the research methodology applied in this study. Finally, Section 1.4 summarizes the chapters of this thesis.

1.1. Research Motivation

Due to decrease in profits and fierce competition for car sales, after sales service is expected to grow in the near future (Aboltis and Rivza, 2014; p. 342). This expected grow is mainly due to the increase in total volume of cars, that is, from 1.02 billion in 2010 to 2.28 billion in 2050 and also due to elevated costs of spare parts, components and an increase use of replacement modules (Aboltis and Rivza, 2014; p. 345). However, cars using better technologies would have longer maintenance intervals and this would lead to reduce service requirements (Aboltis and Rivza, 2014; p. 345). Therefore, after-sales service constitutes an important part of profits of car manufacturers (Gissler, 2008) and also it is described as an entrepreneurship model for car and spare parts manufacturers (Jönke, 2012; p. 5). With regard to the automotive industry in Turkey, Demiroglu and Yunculer (2016) point out the increase growth in sales of light vehicles (i.e., automobiles and light commercial vehicles) by 25 percent during 2015 and they present the trend of growth since 1993 (Demiroglu and Yunculer, 2016; p. 98).

Main products offered by original equipment manufacturers (OEMs) are getting more and more interchangeable (Dombrowski and Malorny, 2016; p. 246), and they are almost the same according to functionality, price, quality and technical characteristics (Dombrowski and Malorny, 2017; p. 324). In addition, new services for business-to-customer, business-to-business are offered due to the technological advancements in after sales services to obtain competitive advantages (Dombrowski and Malorny, 2017; p. 324). Also, 75-80 % of the company profits are accounted for services that support the primary products (Dombrowski and Malorny, 2017; p.324; Dombrowski and Malorny, 2016; p.246). This is one of the reasons why after sales service has high margins apart from long contract agreements.

The main motivation of this study is based on low production planning performance of the after-sales of the interested company. This issue could not be improved for a long time in the system. Therefore, the company never reaches its profit targets. Due to high number of tardy jobs, the company loses its profits. This is the reason that minimizing tardiness in after-sales production carries a significant importance for the company of interest. The stiff competition among the companies to satisfy the urgent expectations of customers signals the wire-harness companies to improve their production efficiency to restore customer service levels. At this stage, minimizing the tardiness satisfies the needs of wire-harness companies. Furthermore, minimizing tardiness can be applied in any sectors, not only for the sub-automotive sector. Another motivation for this study is that after-sales production system is not so widely studied in the literature. Only a few studies related with production planning in after-sales services exist (see Chapter 4).

In summary, the motivation of this thesis is originated from a real-life problem in the after-sales service sector. Besides, this study provides an opportunity to develop an application that creates a feasible production planning schedule by using the proposed heuristic method. Minimizing tardiness improves the production performance and reduces penalty costs. Thus, the monetary savings and the customer satisfaction levels would be increased for the system.

1.2. Description of After Sales Services

Dombrowski and Malorny (2017) and also Dombrowski et al. (2011) define the characteristics of after-sales service as its very high economic independency, high margins, stable or growth during crisis times, long service intervals and contracts, long lasting and intensive customer relationships and high growth and innovation potential (see Table 1). Besides these characteristics, they describe main challenges of the after-sales service as a volatile and hence poorly predictable demand, a high-level individuality and non-standardized customer orders (Dombrowski and Malorny, 2017; p.324). In addition, characteristics of short response times together with higher quality service expectations and delivery of spare parts as well as high mix and highly variant of main products make after service business more complex (Dombrowski and Malorny, 2017; p.324; Dombrowski and Malorny, 2016; p. 246). Table 1 presents the comparison of sales and after-sales service in the following.

Table 1: Comparison between sales and after-sales service.

	Product Sales	After-Sales Service
Independency of economic situation	Low	Very high
Margin	Low	High
Behavior in times of crisis	Profit and sales collapse	Stable or growth
Forecast horizon	Short product life cycles	Long service contracts
Contact to customer	Singular customer contact	Long lasting contact
Gathering customer needs	Limited	Intensive
Growth and innovation potential	Often already limited	High

The after-sales service is categorized by three different types according to organizational structure. These three types are: (1) spare parts service, (2) customer service and (3) accessories business (see Table 2) (Dombrowski and Malorny, 2016; p. 247)

Table 2: Categorization of after-sales service.

After-Sales Service		
Spare Part Service	Customer Service	Accessories
Disposition	Maintenance	License products
Pricing	Repair	Technical equipment
Spare parts sales	Overhaul	
Spare parts logistics	Training and qualification	
Demand Forecast	Installation and operation	
	Product observation	

First type service, spare part service, includes services such as disposition, pricing, sales, logistics and demand forecasts. Second type service, customer service, covers maintenance, repair, overhaul, training and qualification, installation and operation. Third type service, accessories business, contains license products or technical equipment (Dombrowski and Malorny, 2016; p. 247).

1.2.1. High Product Variety

After-sales production has a high product variety since it covers various model years and long-term service agreements. Definition of the model year is the same as cars with different variations according to their production years. Figure 1 represents an example of after-sales products for a single car for 3 years period.

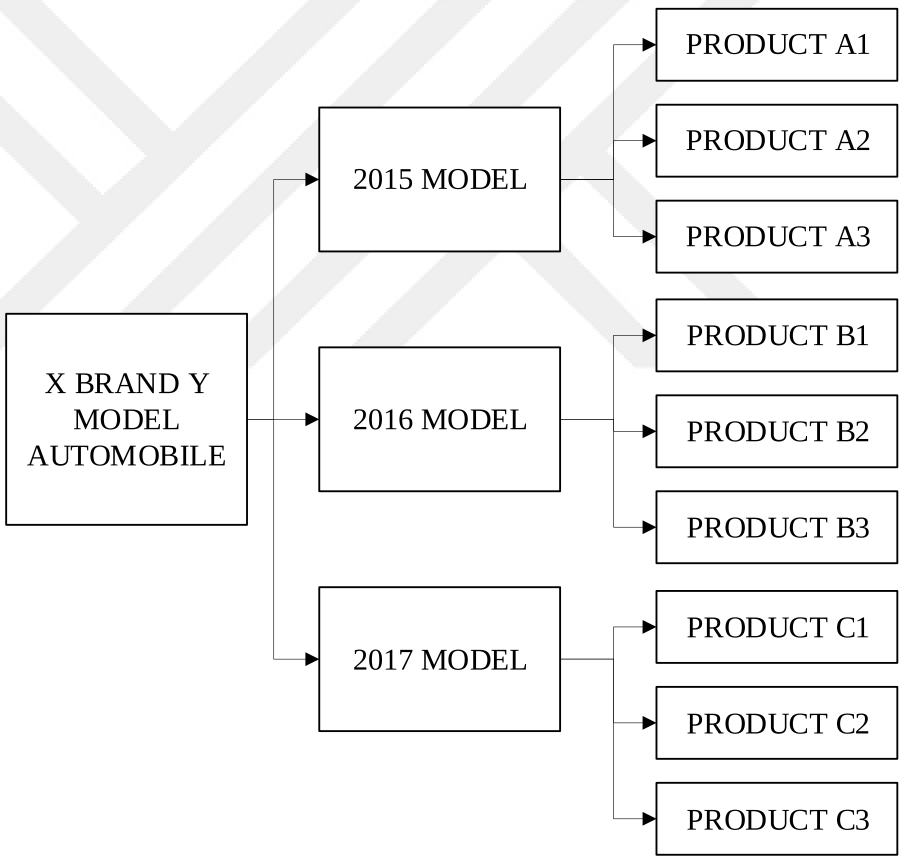

Figure 1: Example of after-sales products.

As Figure 1 displays, x brand 2017 model and x brand 2016 model cars are basically the same cars with different modifications. However, their harnesses are slightly or sometimes completely different than each other. In addition, long term agreements lead to higher product varieties. In mass production, each product has only a few versions, however, in after-sales production each product has a number of versions between 15 and 20 according to the range of agreement coverage. Therefore, product variety of after-sales is at least 15 or 20 times higher than the mass production. Next section explains main difficulties of after-sales service briefly.

1.2.2. Difficulties in After-Sales Service

Complex and high variation in processes result in non-standardized and un-customized processes. Therefore, OEMs and their employees are not able to follow process standards or structured processes. Main difficulties in after-sales service are given as follows.

1. High number of various work contents
2. Varying lead times
3. Fluctuating customer demand (Dombrowski and Malorny, 2016; p. 247)

Above issues result in non-added-value processes which means these problems do not add value for the customer (Dombrowski and Malorny, 2016; p. 247). Overall, above difficulties cause waiting times, wastes, scraps and reworks in the after-sales production (Dombrowski and Malorny, 2016; p. 247)

1.2.3. Production Planning and Tardiness

Materials Requirements Planning (MRP), introduced by Orlicky (1976), is a production planning and scheduling method that is extensively studied and applied by the academics and practitioners (Ozturk and Ornek, 2010; p.151). It applies the finished goods data received from Master Production Schedule (MPS) and determines the production orders using the product structures (i.e., Bills of Material) and available inventories for finished goods, components and raw materials (Vollmann et al., 1997). In general, production planning can be defined as a process to determine the production levels of each time period over a planning horizon (Gicquel et al., 2018; p.1). It is a crucial task since it has different product varieties and hence, resources available for them are inflexible and restricted due to available capacities (Gicquel et al., 2018; p.2). Also, it has conflicting objectives such as satisfying a certain level of customer service and minimization of total costs of production and inventory (Gicquel et al., 2018; p.2).

Production planning in after-sales service studies in this thesis is similar to the multi-item and multi-resource production planning with single-stage, dynamic demand and capacitated production. Accordingly, the problem studied is similar to the capacitated lot-sizing problem (CLSP). CLSP is regarded as the simplest form of big-time bucket problems according to length of planning periods that does not give scheduling results (Ozturk and Ornek, 2010; p.151). Also, the problem is reported as a class of NP-hard problem (Hein et al., 2018; p.2) However, this study also addresses the scheduling of orders by controlling the availabilities of their resource materials in one level. Another difference is that this study aims minimization of target orders with weighted penalty costs rather than minimization of total production and inventory costs as given in the literature (see Ozturk and Ornek, 2010).

With regard to tardiness, it is referred to as a measure of a delay in executing certain operations (Lee et al., 2015; p. 13). As Section 1.2 points that a company does not keep safety stocks for after-sales demands, an acceptable tolerance of delay is reduced to almost zero for both a customer and the company. Otherwise, the company has to deal with the penalty cost, planning performance and loss of customer satisfaction levels. This is the reason this study focuses on minimizing total weighted tardiness and examines it at length in the literature. (see Chapter 3).

1.3. Research Methodology

The after-sales production system and the tardiness are presented in the previous sections. This section presents the research methodology applied in this study.

According to the steps of the study applied, the research methodology in this thesis can be defined under the category of quantitative-model based Operations Management research, particularly as an axiomatic quantitative research (see Bertrand and Fransoo, 2002). Main focus is to get solutions from a constructed model and ensure that these solutions give feedbacks on the problem construct (Bertrand and Fransoo, 2002; p.249). Also, this study is composed of conceptualization, modeling, model solving and implementation steps (Bertrand and Fransoo, 2002; p.252). For conceptualization, production planning in after-sales service and problem description are given in Chapters 2 and Chapter 3. This is followed by quantitative analyses of the system. Thus, data collection, data structures and their analyses steps are given in Sections 5.1 and 5.2. As for modeling and model solving, mathematical modelling, solutions of it and heuristic development (see Chapter 6) are given in Section 5.3. With regard to implementation steps, a demonstrative example (see Chapter 7) and the experimental analyses (see Chapter 8) are presented respectively.

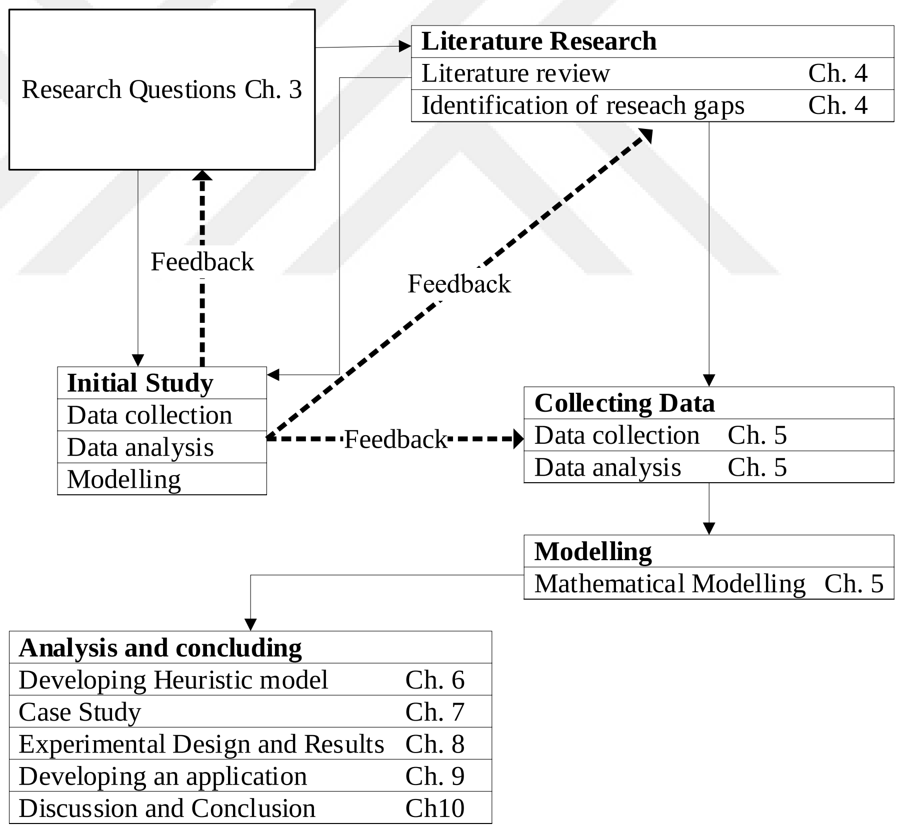

Figure 2: Research procedure.

According to Figure 2, this study starts on data collection, data analyses, conceptual modeling steps according to the research questions determined for the thesis study. Then, relevant literature research is discussed. The analyses of literature provides feedback on research questions and problem statement in this study. After, using the collected data, a mathematical model is developed. Based on the results, a new heuristic is developed and it is tested on both demonstrative example and the real data using the experimental design. An application on tardiness minimization is created to be used in industry. Finally, the study is ended with conclusions.

1.4. Summary

This section explains steps of this study. First, Chapter 2 briefly defines after-sales production system in automotive industry. In addition, characteristics of after-sales production is defined in this chapter.

Chapter 3 explains the problem definition, and it discusses the performances of the production. Also, this chapter discusses the shortbacks and its effects of current after-sales production system.

Based on the problem definition in Chapter 3, related literature is reviewed and analyzed in Chapter 4. Results and methodologies of the reviewed studies in the literature are compared and discussed in this chapter in order to address research methodology and problem domain of this study.

Chapter 5 explains the mathematical model developed for the problem. Objective function, constraints, sets, indicates, parameters and decision variables are represented with the notation in this chapter. In addition, Chapter 5 explains how datasets are collected and it represents analyses of collected data.

Chapter 6 presents and discusses the structure of the proposed heuristic method. First, the main steps of the proposed heuristic and pseudo-code are presented, then its complexity is discussed in this chapter.

Chapter 7 tests the model with a demonstrative example and displays data and results for the example. This chapter compares the results of the mathematical model with the results of the heuristic method.

Chapter 8 presents the results of experimental design provided for testing the heuristic method. It compares the results of heuristic method with the results of one of the traditional metaheuristic, and discusses the performance of proposed heuristic method.

Chapter 9 presents an application environment that embeds the proposed heuristic method with a real dataset for tardiness minimization.

Finally, Chapter 10 presents the concluding remarks and future research.

Chapter 2

After-Sales Production System in Automotive Industry

This chapter explains the after-sales production systems of a wire-harness company of interest. Section 2.1 describes current production system briefly. Section 2.2 addresses types of operation flows in the production. Finally, Section 2.3 presents concluding remarks at the end of the chapter.

2.1. Description of Production System

This study focuses on increasing the productivity of after-sales production in automotive industry with reducing tardiness. The production system of an international company that operates in free Industrial Zone of Izmir, Turkey, is taken as a representative system for this study to examine after-sales service production. To describe to production system, after-sales production is observed over a year, and flow diagrams of after-sales operations are generated (see Figures 3 and 4). The selected company produces wire-harnesses which are special electrical cables for automobiles. Current serial production system represents a typical mass production that is similar to a flow-shop production system.

Assembly lines of the company are dedicated to production of panels. Each specific customer order requires its own production of panels. Production procedures are exactly the same as serial production of panels. However, these panels need to be changed frequently in after-sales production since product variety is significantly higher than the serial production. In addition, since all demands are for after-sales service, quantities are lower than serial production demands. Therefore, after-sales production carries both flow-shop and job-shop system characteristics for wire harness industry. The main reason of huge product variety in after-sales is that agreements cover more than one or two decades in the automotive industry. Companies have to provide after-sales services according to those agreements. Thus, they cannot produce a specific product more than one year because car model changes every year so that product could change as well. For instance, twenty years later, a brand x model car has twenty different types of harnesses and the company should provide after-sales service for all of them. Besides, there are more than one brand, and each brand has more than one car model. This is the reason that product range is enormous when compared to serial product range. In serial production, each model has only one specific product.

To summarize, system carries both flow and job-shop system characteristics. This situation creates some difficulties. For instance, after-sales production system cannot easily adapt to production variety like job-shop system since production lines (i.e., panels) are for the mass production. On the other hand, after-sales production system outputs cannot be as high as flow-shop system due to low and unpredictable demands, high setup times related to product variety and unskilled workers for old models.

Next section presents flows of operations and examines each flow separately. Flows of operations are pre-production, assembly and post-production phases.

2.2. Flows of Operations

Product groups are categorized as both big and small product families and this section describes two production phases for them. These families are different for different product types. Particularly, small family product groups are front and rear doors as well as roof top and rear spoiler. Big family product groups are floor, engine and IP. The difference between small and big families becomes apparent only in the post-production phase given in Section 2.2.3.

Production process has three main sub-production phases. These are pre-production, assembly production and post-production phases. These three phases are valid for both small and big family product groups. Main difference between these groups appears in only post-production phase. Apart from this, sub-production and assembly production phases are completely identical for small and big families (see Figures 3 and 4).

After pre-production phase, released job begins to build up in the assembly phase. Section 2.2.2 presents this phase for both product groups. Section 2.2.3 examines post-production phase which is a quality control phase. A finished good needs to pass all required tests in this phase.

2.2.1. Pre-Production Phase

In this section, pre-production phase is explained for both big and small families. Pre-Production phase is basically a control phase. It designates whether selected job is feasible or not before releasing the job into the system. In the current system, this phase is non-functional, and company wants to release only feasible jobs into the production system in order to increase production performance, resource management efficiency, and reduce the tardiness. With regard to infeasible released jobs, company suffers on tardiness, waste and low production performance. An improved job release mechanism decides which jobs are feasible, and it creates a production schedule for them. Also, with required data, such as arrival date of missing material, this phase can determine a feasible production start date of an infeasible job, and it can create a new production schedule including infeasible jobs.

2.2.1.1. Production Planning and Scheduling in the Company of Interest

Current system does not check infeasibility, it considers all jobs are feasible since all requirements are listed and ordered by SAP MRP software. Company tries to check all requirement by manually, however due to high product variety, they fail all the time. Their current efficiency is between 30% and 40% mostly because of the missing components. If all components are available, in other words, they are in warehouse or work in process stock (WIP stock), then process can get an approval and considered as a feasible job. Otherwise, arrivals dates of missing goods must be checked and determined. If determined arrival dates are out of time range, then production should be canceled and re-scheduled for nearest available time.

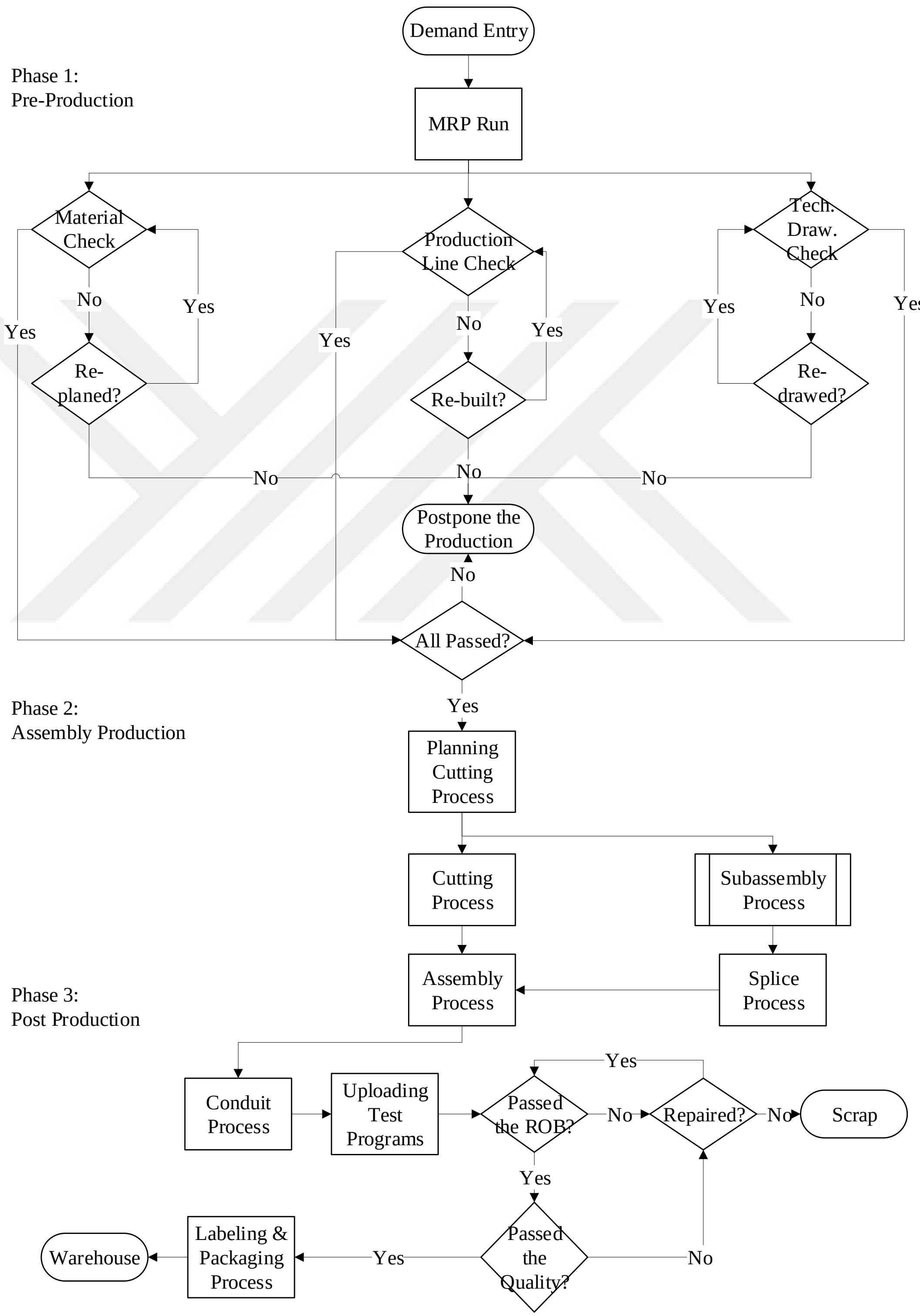

Figure 3: Flow diagram of small families.

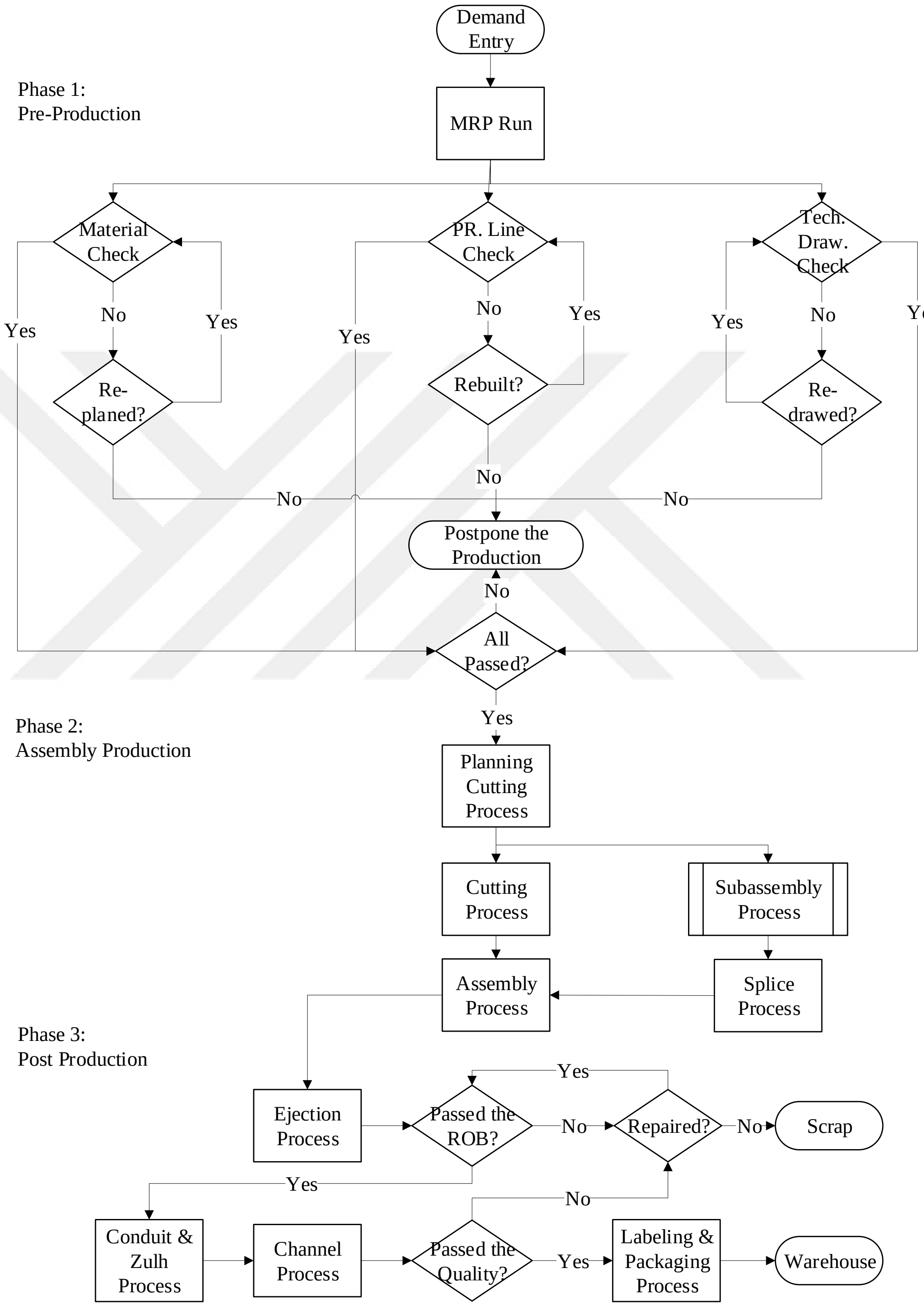

Figure 4: Flow diagram of big families.

Current system starts with receiving customer demands. These demands are scheduled according to their priority levels. These priority levels are high, medium and low according to their penalty costs. Scheduled demands are then uploaded into the software system (MRP module in the commercial ERP system). During the MRP run, the planning steps involves the checking available raw materials, panels and line capacities and technical drawings. If one of these checking represents unavailability, re-planned, re-drawing or re-built decisions are given and production is postponed to next periods. After the MRP runs, if all orders passed checking steps, it determines and lists all required raw materials in order to build desired finished goods according to lot sizing of products and components for each demand's order lead time. List of required components are then ordered for their suppliers (see Phase 1 in Figures 3 and 4). Pre-production phase starts after required resource data collection. Then assembly production phase is followed in the Section 2.2.2.

2.2.2. Assembly Production Phase

This section presents the assembly production phase. After pre-production phase is completed successfully, cutting and production department starts to decide cutting and dispatching dates (see Phase 2 in Figures 3 and 4). Cutting is a process which runs parallel to sub-assembly process. These processes cannot start immediately at the beginning of production. Components for cutting like cables and leads need to be placed in front of the production line just before the assembly process, and this is the reason why both departments work in simultaneously and in coordination. Leads are assembled components. That is, they are neither components nor finished goods, they consist of two or three components.

With regard to subassembly process, cables and leads enter to splice process, and then these sub-goods are covered with water-proof material in assembly process. During the assembly process, all components, cables and leads are gather according to Kanban card of production board, and then the assembly process starts. This phase relays on hand work. Workers are required during whole assembly process. After this process, conduit process can start for small families. As for big families, next step is ejection process. In

Figure 3, test programs are uploaded after assembly process, if they pass the tests, they move to the post-production. Next subsection describes post-production phase for both small and big family product groups.

2.2.3. Post-Production Phase

This section examines the post-production phase individually. This phase is for quality control tests and storage process. The reason of separation is due to different test requirements for both families. Quality control tests are usually for software, electricity and sealing.

In production panel of big families, there are not any spots for those tests since product overspreads to the entire product panel. Besides, required number of test of floor, engine and IP harnesses are bigger than required number of test doors, roof top and rear spoiler harnesses. Additionally, tests are more specific and complicated for big families. In order to complete quality control tests, product requires other panels which are specialized for those tests.

However, production panel of small families has enough test spots since doors, roof top and rear spoiler harnesses are small size harnesses. Therefore, they cover small space on panels and test modules can be built into empty spaces of panel. Therefore, small family product group does not require additional panels, only one panel is enough. For this reason, the company separates them as big and small families since small families require only one panel while big families require two or more panels for the production.

2.3. Concluding Remarks

Chapter 2 explains the after-sales production systems in wire-harness industry. Section 2.1 describes the production system of interest. Section 2.2 addresses flows of operations in the production system for both small and big family product groups. Section 2.2.1 and 2.2.2 explain common processes that are pre-production and assembly production phases. It is noted that scheduling of after-sales production is described as part of the pre-production phase in Subsection 2.2.1.1. Then, post-production phases are briefly described separately for both product groups.

In short, pre-production phase given in Section 2.2.1 includes the scheduling of after-sales production, and at this stage, complete and correct control of raw materials, technical drawings and production panels are crucial for the job release and production schedule since infeasible jobs reduces the performance of after-sales production system (see Section 2.2.1.1). Therefore, issues that affect the planning performance such as tardiness and number of infeasible jobs are discussed in the following chapter.

Chapter 3

Problem Definition

In this chapter, causes and effects of tardiness, problem statement and concluding remarks are presented. Section 3.1. explains causes and effects of the tardiness. Problem definition and problem statement are given in Section 3.2. Also, this section explains and discusses main reasons of problems and their effects for the company of interest. Section 3.3 represents concluding remarks of this chapter.

3.1. Causes and Effects of Tardiness

After-sales production system consists of three production phases as described in previous chapter (see Chapter 2). Among these three phases, the first phase, pre-production phase has three sub-process running simultaneously and it covers majority of production issues (about 90%). Under this phase, Figure 5 depicts main causes of tardy jobs under four groups. These groups are: materials, process, equipment and capacity.

With regard to materials, 70% - 80% of problems occurs in component-control process of pre-production phase due to the missing components (see Figure 5). The reasons are that agreements can be as long as twenty years and producing a twenty-year old product is difficult because all required components are also twenty years old. Procurement of these materials from suppliers is not easy since suppliers usually do not produce the same products for such a long time. Another problem is the inexistence of suppliers. Therefore, it becomes impossible to purchase required components. Due to these problems, materials can be missing, and this situation creates infeasibility.

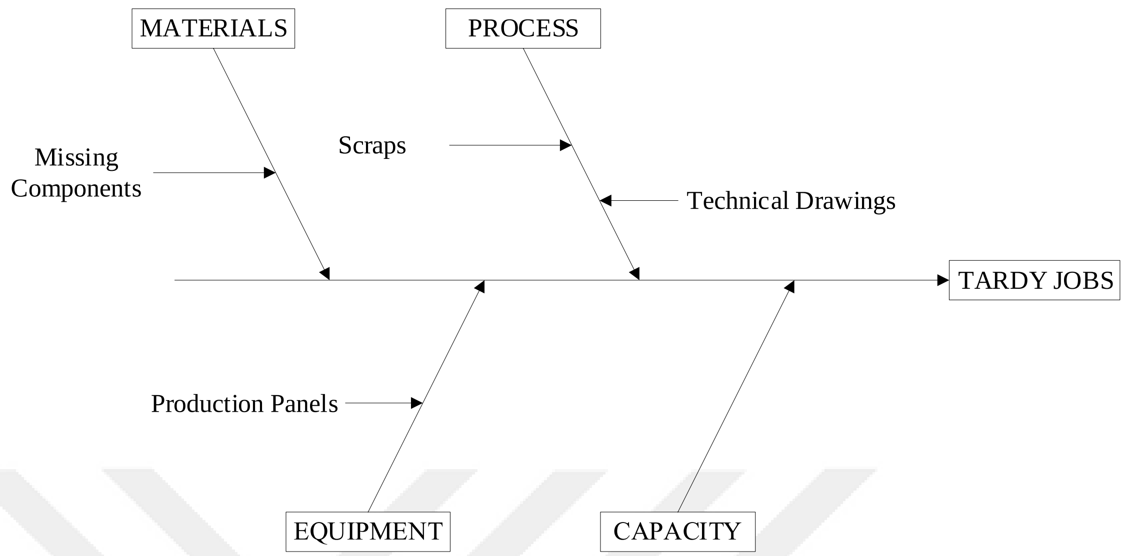

Figure 5: Cause-effect diagram.

With regard to issues caused by the process, releasing jobs without controlling availabilities of all components stops the production at some point due to lack of required resource. This situation creates inefficiency in productivity. This situation is unacceptable for the company. Company prefers to cancel the production in the first place (see Figures 3 and 4). The reason is that loss time due to the abandoned process is greater than the lead time of the process. Loss time of interrupted production is bigger than whole production's lead time due to combination of required reallocation and reschedule time. Therefore, infeasible jobs are not released into the production.

With regard to issues with equipment, production team starts to check production panels and available workers which have more skills and experiences than other regular workers for planned production. Each product has its own panel so if it is not built in the production zone then production team finds and builds the panel. If panel is not available, then production is canceled (see equipment in Figure 5). The same reasons and effects are valid for all three sub pre-production processes given in Figures 3 and 4. Production cancellation due to lack of panels is really low since company stores them all the time. However, over the years, panels become damaged, this is the reason panels need to be checked for every production.

In the meantime, technical drawings and method papers are checked by engineering team (see process in Figure 5). Company also stores these papers, but over the time these papers get damaged. If they are not in useable shape or if they are missing in plant library, then team requests those documents from customers and service centers. Even one document is missing then all production should be canceled. Once all feasibility criteria are met then the job can be released into production. In the next section, the problem definition and problem statement are described.

3.2. Problem Statement

This section introduces thesis objectives and the problem definition. Main aim of this study is to release only feasible jobs into the system by avoiding line stoppages on any points of production. Line stoppages have significant impact on production efficiency. Production efficiency is calculated by ratio of actual produced quantity over target quantity (%). When a line stoppage is occurred, production hours is lost therefore production efficiency decreases. Main reasons of line stoppages are lack of raw material, production panel or technical drawing as described in Section 3.1. In addition, line stoppage causes waste of valuable resources such as working hours and raw materials. Besides that, additional requirements such as re-allocation, re-setup and re-plan time is occurred. Besides inefficiency, unfinished tasks can also cause tardiness. Accordingly, the problem statement is given in the following.

Problem statement: the objective of this study is to minimize of tardiness in after-sales production of wire-harness in automotive industry with high product variety.

As Section 1.2.1 refers, after-sales production has high product variety especially in automotive industry. Therefore, high product variety has significant influence on after-sales sector. Supplier companies agreed to provide after-sales services according to agreed contracts between them and car manufacturer companies. These contracts are usually signed for fifteen, even twenty years long. The reason of that is customers always desire to have long after-sales services. Therefore, supplier companies use long-term after-sales services as a marketing tactic. However, this situation increases product variety since after-sales coverage period is extended. In additional to that, automobile model year change increases the product variety in after-sales sector (see Section 1.2.1). Therefore, supplier companies have to deal with old and new many products and that is the reason why high product variety is as significant as tardiness in the after-sales production system.

After-sales production is relatively more complicated than serial production system. The reasons are unreliable customer forecasts, zero safety stock, shorter action time and high product variety (see Section 1.2.2). Short response time and zero safety stocks reduce tolerance of tardiness to almost zero. Each tardy job returns as a penalty cost to the company. To sum up, short response time, low tardiness tolerance and high product variety are main challenges for after-sales production system.

Further, in current production system of interest, production efficiency is significantly low, particularly between 30% and 40%. This is unacceptable for the company. This is the reason why tardiness is defined and analyzed in order to determine the shortbacks of the after-sales production system. This study represents a methodology which not only integrates feasible job release on after-sales environment, but also provides a reduction of tardiness in the wire-harness industry. In addition, no study is published for after-sales production systems in regard to this objectives in the literature.

3.3. Concluding Remarks

Section 3.2 defines the problem of this thesis study and Section 3.1 explains main challenges as well as reasons in the after-sales production. It highlights the importance of high product variety and negative effects of tardiness. Due dates, short reaction times and high product variety are expected in after-sales sector, and they are manageable as long as feasibility of jobs are known. Early infeasibility knowledge allows to manage tardy jobs without losing any resource and satisfaction levels of customers. Minimized tardiness also improves the production efficiency which is also another of the goal of this study. With this viewpoint, next chapter presents the relevant literature research.

Chapter 4

Literature Research

In following the section, relevant studies in the literature are surveyed. This is followed by the summary of the literature in Section 4.2. Finally, this chapter is ended with a discussion of the literature in Section 4.3.

4.1. Literature Review

This section reviews the literature under four categories. These categories are after-sales service, jobs release, capacitated lot sizing and tardiness. Literature review under each category is given in the following.

With regard to after-sales service, supplier companies realize that after-sales services enable high revenues. Also, they improve customer satisfaction and loyalty (Dombrowski and Malorny, 2016; p. 246). The study by Saccani et al. (2007) addresses configuration of the after-sales supply chain. They analyze three configuration choices which are degree of vertical integration, the degree of centralization, and the decoupling of activities (Saccani et al., 2007; p. 52). Results of the study show that there are many different configuration choices and there is no “one best way” (Saccani et al., 2007; p. 52). Legnani et al. (2009) propose a framework which provides a common representation of the after-sales services. To validate proposed framework, three case studies in the industrial context are considered (Legnani et al., 2009; p. 113). Dombrowski and Malorny (2016) describe general characteristics of after-sales service and types of after-sale services. They point out the lack of a holistic approach based on lean principles on structuring of such services and they present a structural approach on it. On another study, Dombrowski and Malorny (2017) present a methodological approach which shows how to implement principles, methods and tools of lean production system into after-sales production system (Dombrowski and Malorny, 2017; p. 324). Onar et al. (2017) develop a new dynamic performance evaluation method in order to measure the performance of after-sales companies by using intuitionistic fuzzy sets. The method considered is regarded as useable in the after-sales industry. Cevikcan and Durmuşoğlu (2014) introduce a job release and scheduling methodology for one-stage parallel machines where sequence dependent setup times exist. Their study proposes a heuristic method which provides an integration between job release and job scheduling in order to utilize the capacity achievement for a flow-shop system (Cevikcan and Durmusoglu, 2014; p. 318). They report issues on job release and scheduling partially for the electric-wire harness industry. They report a 25% of decrease gained in manufacturing lead time (Cevikcan and Durmusoglu, 2014; p. 318).

With regard to job release in the literature, Ashby and Uzsoy (1995) introduce a new scheduling heuristic method which bonds scheduling, order release and sequencing for a job shop manufacturing company. Their algorithm considers setup times and due dates for order release decisions (Ashby and Uzsoy, 1995; p. 290). In the meantime, due date performance is improved. Their study proves that order release techniques and dispatching rules have effects on system efficiency. Choi et al. (1997) solve multi-job order release problem whose objective is to minimize the sum of mean shop floor flow times of orders subject to due-date constraint. A heuristic algorithm is proposed for the problem by decomposing the load profile of the shop. The heuristic divides the load profile into two parts for unreleased and released jobs (Choi et al., 1997; p. 765). Moon and Yun (1996) determine an optimal release time where the flow time is a random variable with a known probability distribution. In this study, authors report a line search algorithm that finds a job release time (Moon and Yun, 1997; p. 109).

As for the capacitated lot sizing, recent research studies are briefly presented herein. Gicquel et al. (2008) present a literature review on capacitated lot sizing (CLS). As they highlight, CLS problems are applied generally in the situations where inflexible resources exist in the productions. They categorize the CLS models according to number of resources, number of levels and planning horizon intervals as single-level single-resource models, single-level multi-resource models and multi-level multi-resource models (Gicquel et al., 2008). Further, they analyze first two types of models according to planning horizon intervals that are referred to as big-bucket models and small-bucket models (Gicquel et al., 2008). Under the last category, they present the solution approaches as exact methods, specialized heuristics, mathematical-programming based heuristics and metaheuristics (Gicquel et al., 2008). Ozturk and Ornek (2010) introduce a mixed integer programming model for multi-level multi-resource CLS problem. Their model includes linked lot sizes, the problem of which is referred to as CLS with link lot sizes (CLSPL), and they present a numerical example and computational results of their model (Ozturk and Ornek, 2010). Roshani et al. (2017) provide CLS problem in an integrated manufacturing and remanufacturing framework. Their methodology includes a relax-and-fix heuristic since they report that the generalized version of CLS problem is an NP-hard problem. They solve their problem with some experimental instances (Roshani et al., 2017). Similarly, Hein et al. (2018) present a Genetic Algorithm (GA) heuristic for solving the CLS problem and they highlight that GA gives better results than constructive heuristics.

With regard to tardiness in the scheduling literature, there are many studies that consider makespan minimization (see Logendran and Nudtasomboon, 1991; p. 217). However, tardiness objectives have more attention than the studies with the objectives of makespan minimization. To illustrate, Baker and Scudder (1990) consider problems with earliness and tardiness at length (Baker and Scudder, 1990; p.22). Vepsalainen and Morton (1987) develop priority rule based greedy heuristics for the job-shop system with the minimization of total weighted tardiness (Vepsalainen and Morton, 1987; p. 1035). Singer and Pinedo (1998) develop a branch-and-bound approach that minimizes the total weighted tardiness in job-shops. In their another study, a shifting bottleneck approach for minimizing the total weighted tardiness in a job shop is developed (Singer and Pinedo, 1999; p. 1). According to previous studies in the literature, significant number of studies takes tardiness reduction into account. In another study, criteria based due dates for dispatching are evaluated as they are considered more suitable for flow and job shop environments (Ruiz and Minella, 2008; p. 451). Naderi et al. (2009) propose a model that minimizes the total weighted tardiness in a flexible flow-shop system. Results demonstrate that proposed mixed-integer linear programming model together with electromagnetism algorithm are more effective than two high performing metaheuristics (i.e. genetic and tabu search) in the literature (Naderi et al., 2009; p. 9625). Fazlollahtabar et al. (2015) consider earliness and tardiness minimization in a multiple automated guided vehicle manufacturing system by embedding heuristic algorithms (Fazlollahtabar et al., 2015; p. 131). As regard to the other studies on tardiness minimization, the book by Hentenryck and Michel (2005) presents constraint programming applications for job-shop problems. Hentenryck et al. (2009) present an application of constraint programming for minimizing the total weighted tardiness (Hentenryck et al., 2009; p. 241). Choi et al. (2009) combine their method with genetic algorithm (GA) and an optimization module. GA is adapted to solve the complex scheduling problem while the optimization module is suggested for dealing with tardiness. Results show that the proposed model shortens the generation time of production plan and reduces the production cost in make-to-order based production projects (Choi et al., 2009; p.113).

4.2. Discussion

This section discusses literature studies which are examined in Chapter 4. Table 3 provides a list of studies that consider tardiness minimization in the literature. Accordingly, authors, objective and methodology, the approach and the type of production system are given for each study.

The approach is categorized as whether mathematical programming (MP) or heuristic method (HM) is applied, and the production system is categorized whether the study is applied in a job-shop or flow-shop type of system. According to the objective function, some papers apply tardiness together with earliness (see Table 3, Baker and Scudder, 1990; Naderi et al., 2009; Fazlollahtabar et al., 2015). Table 3 displays that some papers apply tardiness using by weighting coefficients and calculate total weighted tardiness (see Vepsalainen and Morton, 1987; Singer and Pinedo, 1998 and 1999; Hentenryck et al, 2009; Naderi et al., 2009). According to the methodology applied, some papers use exact methods to obtain solutions like branch and bound and shifting bottleneck (see Table 3, Singer and Pinedo, 1998 and 1999). On the other hand, some papers in the literature apply metaheuristics like simulated annealing (Naderi et al., 2009). As Table 3 shows, the other papers use customized heuristic methods or mathematical programming.

Table 3: Summary of papers on tardiness minimization in the literature.

Literature		Approach		System	
Authors	Objective and Methodology	MP	HM	Job Shop	Flow Shop
Vepsalainen and Morton, (1987)	To minimize weighted tardiness costs with a heuristic method.		x		x
Baker and Scudder, (1990)	To minimize earliness and tardiness penalties with mathematical modeling.	x			x
Singer and Pinedo, (1998)	To minimize total weighted tardiness with branch-and-bound approach		x	x	
Pinedo and Singer, (1999)	To minimize total weighted tardiness with shifting bottleneck approach		x	x	
Hentenryck et al, (2009)	To minimize the total weighted tardiness with constraint programming	x			x
Ruiz and Minella, (2008)	To review and evaluation of multi objective algorithms with 23 heuristic methods		x		x
Naderi et al. (2009)	To minimize total weighted tardiness with simulated annealing approach		x		x
Choi et al., (2009)	To minimize tardiness with two-phase heuristic algorithms		x		
Çevikcan and Durmuşoğlu, (2014)	To develop a heuristic method integrates with job release and job scheduling.		x		x
Fazlollahtabar et al. (2015)	To minimize earliness and tardiness with mathematical modelling	x			x

4.3. Summary

This thesis aims to solve a real-life production control problem in wire-harness after-sales industry. Also, it develops a production schedule to reduce the tardiness in production planning. The problem studied in this thesis is single-level multi-resource capacitated production planning with penalty costs dependent on the type of products. These are major characteristics of the developed methodology. As a minimization of the tardiness, the real-life tardiness problem in after-sales production is strongly NP-hard. Section 5.2 justifies this by solving the problem with mathematical model. Considering the literature (see Section 4.1), it proves that most of the relevant literature on minimizing tardiness in job shop environment uses exact methods and not many research is available for this type of production environment (see Table 3). This study presents a job release scheduling mechanism to reduce tardiness with using real data for after-sales production environment. To achieve this, a new heuristic method is developed. Development of proposed heuristic method is later applied in an applicable and user-friendly application (see Section 3.1).

Chapter 5

Methodology

This chapter explains the methodology followed in this thesis. The collected data for the problem is presented in Section 5.1. Then, proposed mathematical model is given with its notations, sets and parameters in Section 5.2.

5.1. Data Collection

Required data for solving problem is gathered from the company of interested in automotive industry. Over a year, entire operations of after-sales production of the company are observed. Collected data consists of customer demands, capacity, bill of materials, process times, inventory levels and penalty costs for tardiness.

Demands of customer are gathered for thirty-eight weeks for each product. These demands are collected from twenty-one different customer plants under three car manufacturer brands. Customers send their demands via electronic document interchange (EDI) (see Appendix A).

A single one planning period represents one week and total planning horizon is considered as thirty-eight weeks. In addition, these periods also stand for due-dates for each demand. Production has to start at the beginning of the period and finished goods have to be dispatched at end of the same period. Each period has the same capacity of 2400 minutes.

There are thirty-seven different products. In order to produce these products, eighty-nine different raw materials are required. Each raw material can be used for more than one product (see Appendix B).

Process times and tardiness penalty costs are given in Appendix C for each product. Process times are defined by engineering team of the company. However, penalty costs are defined by the production planning team. They use these penalty costs to identify priority of products. Therefore, each product has its own tardiness penalty cost (see Appendix C)

Initial inventories and scheduled orders are collected for the first planning period. In the real life, these inventories and orders change almost every week according to new demands (see Appendix D). Next section presents analyses of collected data.

5.2. Analyses of Collected Data

This section analyses collected data. First, data analysis of customer demands for a period of 38 weeks is represented. Figure 6 presents the descriptive statistics results of total demand. As Figure 6 shows, mean is 105,13 while coefficient variable is 52,42. This indicates the existence of high demand fluctuations. This could be also attributed to high demand range between 12 and 234.

Variable	DD	Mean	SE Mean	StDev	Variance	CoefVar	Sum
Total Demand	Demand	105,13	8,94	55,11	3037,31	52,42	3995,00

Variable	DD	Minimum	Maximum
Total Demand	Demand	12,00	234,00

Figure 6: Descriptive statistics of total demand.

Histogram of total demand is presented in Figure 7. Histogram visualizes the distribution of total demand for 38 weeks. Accordingly, the distribution does not show any particular statistical distribution pattern.

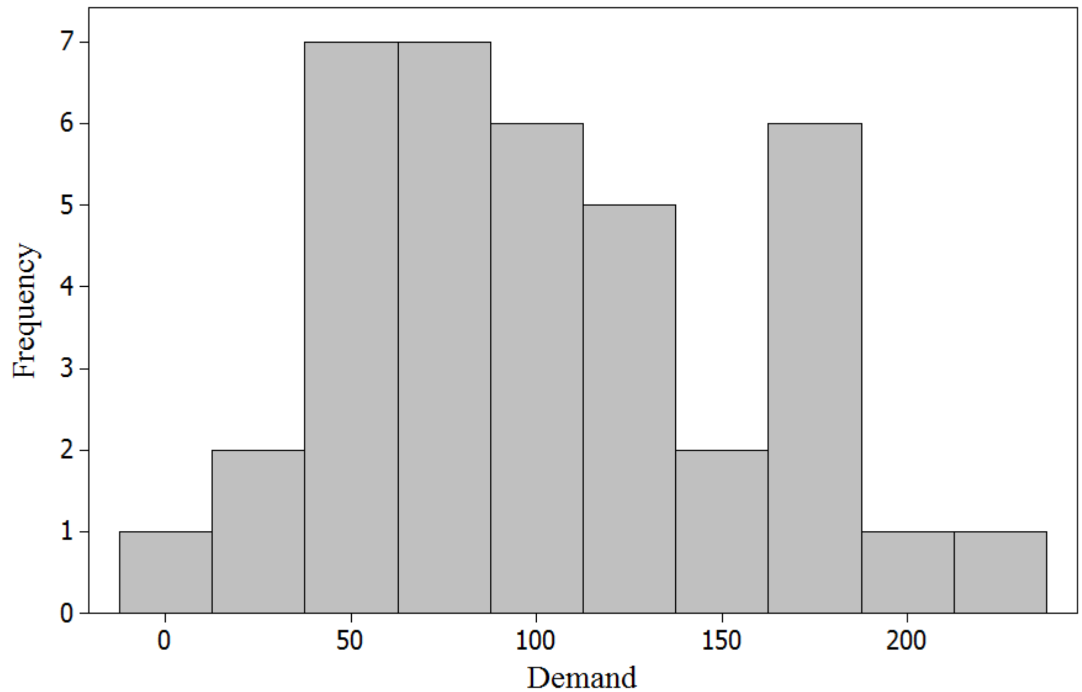

Figure 7: Histogram of total demand.

Figure 8 presents results of descriptive statistics of required materials. Figure 8 shows that eighty raw materials are required in order to produce one product. Some of these raw materials can be identical. Coefficient variable is 15,46 while mean is 80,38. This situation validates the high production variety since each product requires different kind and amount of raw materials.

Descriptive Statistics:

Variable	Mean	SE Mean	StDev	Variance	CoefVar	Sum
Quantity	80,38	1,32	12,43	154,51	15,46	7154,00

Figure 8: Descriptive statistics of material requirement.

Histogram of required materials is given in Figure 9. It visualizes product variety by showing amount of materials used per unit of finished product.

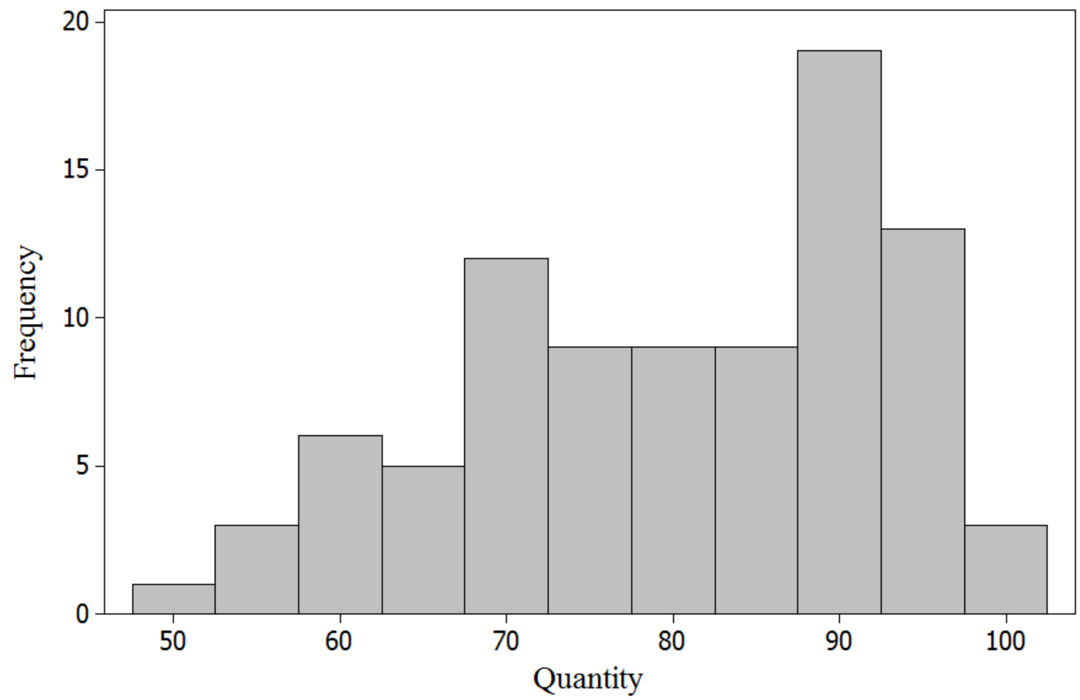

Figure 9: Histogram of material requirement.

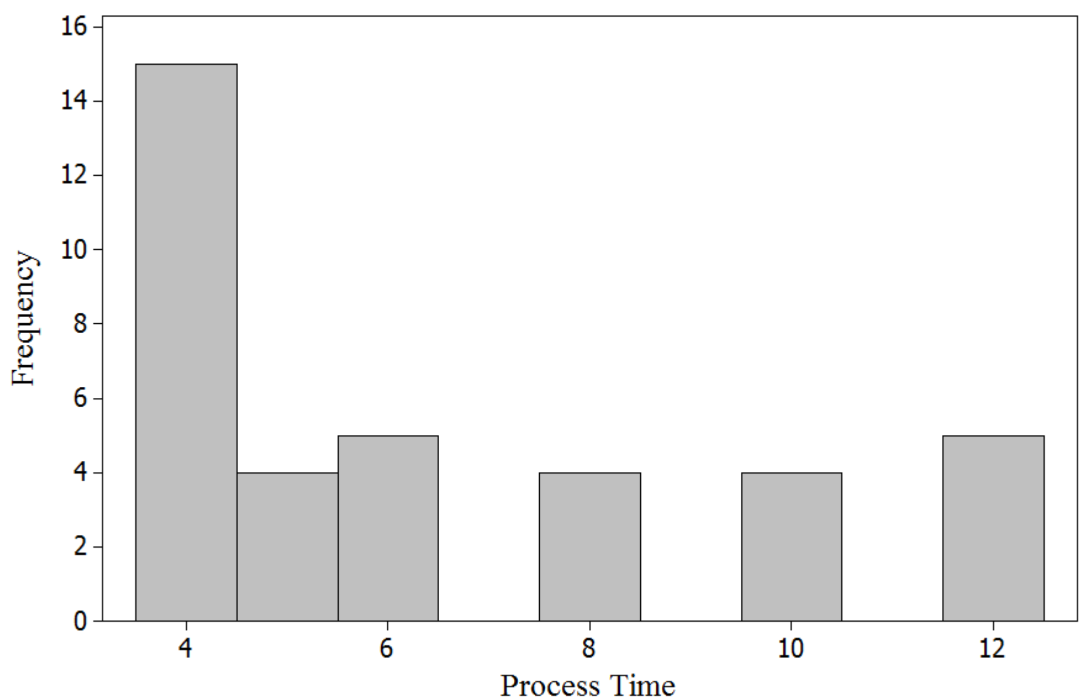

Figure 10: Histogram of total process time.

Figures 10 and 11 displays histogram and descriptive statistics results of process time. As Section 2.2.3 mentions that products are divided into two groups which are small and big families. Small families require less time since all process can be performed in the same production panel while big families have to transfer a test panel. Therefore, big families require more time. Figure 10 proves this situation, since process times are around two numbers which are 5 minutes and 12 minutes.

Descriptive Statistics: Process Time

Variable	Mean	SE Mean	StDev	Variance	CoefVar	Sum
Process Time	6,541	0,485	2,950	8,700	45,10	242,000

Figure 11: Descriptive statistics of process time.

As Section 5.1 mentions tardiness penalty cost are provided by the production planning team of the company. This study uses these data in order to identify priority of each product. Descriptive statistics of penalty costs are given in Figure 12.

Descriptive Statistics: Penalty Cost

Variable	Mean	SE Mean	StDev	Variance	CoefVar	Sum
Penalty Cost	14,32	2,12	12,88	165,78	89,89	530,00

Figure 12: Descriptive statistics of tardiness penalty cost.

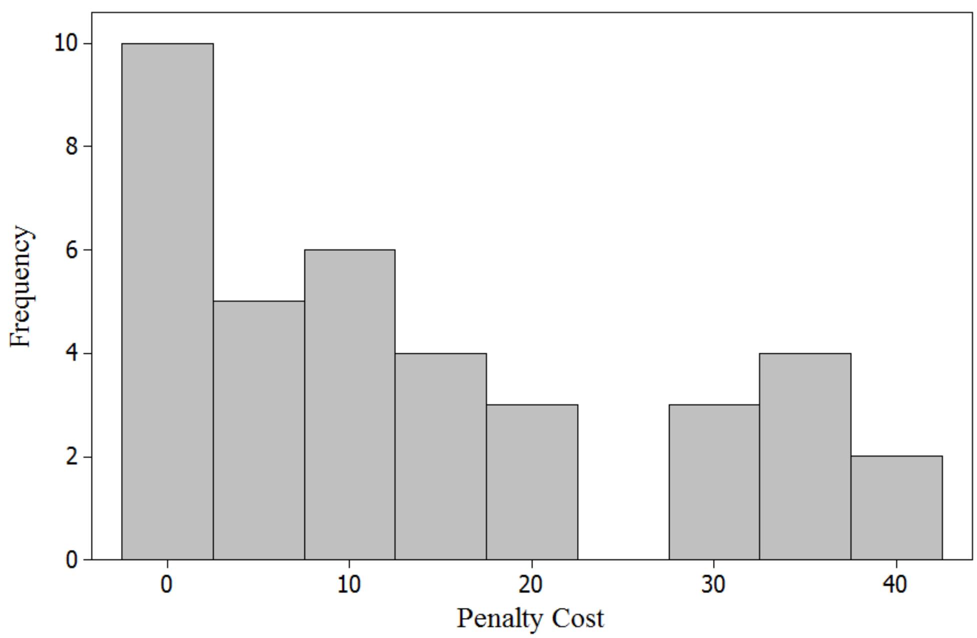

Figure 13: Histogram of total penalty cost.

Histogram of tardiness penalty cost is represented in Figure 13. Products are divided into three categories according to their tardiness penalty costs. Products, which has penalty cost between 30 and 40 euros, belongs to high priority group. Similarly, products, which has penalty cost between 1 and 10 euros, belongs to low priority group. Rest of the products belongs to medium priority group. In the next section, proposed mathematical model is explained.

5.3. Mathematical Model

Mathematical programming is not an efficient solution method since the problem studied in this study is NP-hard (see Chapter 4). Accordingly, the problem studied in this study is similar to single-level multi-resource capacitated lot sizing problem with the objective of minimization of weighted tardiness. To present the objective of the problem and production constraints, the followed mathematical model with its notations are given in the following.

$\boldsymbol{Indesis}$

$j = index\ for\ jobs\ where\ j = 1, \ldots, J$

$m = index\ for\ production\ panels\ where\ m = 1, \ldots, M$

$i = index\ for\ raw\ materials\ i = 1, \ldots, I$

$h = index\ for\ technical\ drawings\ where\ h = 1, \ldots, H$

$t = index\ for\ planning\ period\ where\ t = 1, \ldots, T$

Parameters

$p_j = processing\ time\ of\ job\ j$

$d_{jt} = customer\ demand\ of\ job\ j\ in\ planning\ period\ t$

$pc_j = penalty\ cost\ for\ job\ j$

$a_{ji} =\ amount\ of\ raw\ material\ i\ required\ for\ job\ j$

$PJ_{jm} =\ 1\ if\ production\ panel\ m\ is\ required\ for\ job\ j, 0\ otherwise$

$TDJ_{jh} = 1\ if\ technical\ drawing\ h\ is\ required\ for\ job\ j, 0\ otherwise$

$b_{i0} = beginning\ inventory\ of\ raw\ material\ i$

$Pb_{m0} = beginning\ inventory\ of\ production\ panel\ m$

$TDb_{h0} = beginning\ inventory\ of\ technical\ drawing\ h$

$CAP = fix\ capacity\ for\ all\ periods$

$or_{it} = amount\ of\ ordered\ raw\ material\ i\ in\ period\ t,\ t > 1$

$Por_{mt} = amount\ of\ ordered\ production\ panel\ m\ in\ period\ t,\ t > 1$

$TDor_{ht} = amount\ of\ technical\ drawing\ h\ in\ period\ t,\ t > 1$

Decision variables

$x_{jt} = amount\ of\ job\ j\ to\ be\ produced\ in\ period\ t$

$b_{it} = ending\ inventory\ of\ raw\ material\ i\ in\ planning\ period\ t$

$Pb_{mt} = ending\ inventory\ of\ production\ panel\ m\ in\ planning\ period\ t$

$TDb_{ht} = ending\ inventory\ of\ technical\ drawing\ h\ in\ planning\ period\ t$

$Tardy_{jt} = amount\ of\ tardy\ job\ j\ at\ period\ t$

$Totald_{jt} = total\ order\ amount\ of\ job\ j\ in\ period\ j$

Objective function:

$$minimize\ \sum_{t\epsilon T}\sum_{j\epsilon J}(pc_j Tardy_{jt}) \tag{1}$$

Subject to:

$$\sum_{j=1}^{J} a_{ji}x_{jt} \le b_{it}, \qquad \forall i, \forall t \tag{2}$$

$$b_{i1} = b_{i0} \qquad \forall i, t = 1 \tag{3}$$

$$b_{it} = b_{i(t-1)} - \sum_{j=1}^{J} a_{ji}x_{jt-1} + or_{it}, \qquad \forall i, t > 1 \tag{4}$$

$$\sum_{j=1}^{J} p_j x_{jt} \le CAP, \qquad \forall t \tag{5}$$

$$Totald_{jt} = d_{jt}, \qquad \forall j, t = 1 \tag{6}$$

$$Totald_{jt} = d_{jt} + Tardy_{jt-1}, \qquad \forall j, t > 1 \tag{7}$$

$$Tardy_{jt} = Totald_{jt} - x_{jt,} \qquad \forall t, \forall j \tag{8}$$

$$x_{jt} \le Totald_{jt}, \qquad \forall t, \forall j \tag{9}$$

$$Pb_{m1} = Pb_{m0} \qquad \forall m, t = 1 \tag{10}$$

$$TDb_{h1} = TDb_{h0} \qquad \forall h, t = 1 \tag{11}$$

$$PJ_{jm}x_{jt} \le Pb_{mt} \qquad \forall t, \forall m, \forall j \tag{12}$$

$$TDJ_{jh}x_{jt} \le TDb_{ht} \qquad \forall t, \forall h, \forall j \tag{13}$$

$$Pb_{mt} = Pb_{mt-1} + Por_{mt} \qquad \forall m, t > 1 \tag{14}$$

$$TDb_{ht} = TDb_{ht-1} + TDor_{ht} \qquad \forall h, t > 1 \tag{15}$$

$$or_{\boldsymbol{it}} \ge 0, \qquad \forall t, \forall i \tag{16}$$

$$b_{\boldsymbol{it}} \ge 0, \qquad \forall t, \forall i \tag{17}$$

$$x_{\boldsymbol{jt}} \ge 0, \qquad \forall t, \forall j \tag{18}$$

$$Tardy_{jt} \ge 0 \qquad \forall t, \forall j \tag{19}$$

Objective function (1) minimizes penalty costs of tardy jobs for all planning periods and jobs. The constraint (2) ensures that total number of used raw materials cannot exceed their stock level on planning period *t*. The constraint (3) ensures that beginning inventory of material *i* is equal to initial inventory of material *i*. The constraint (4) updates inventory level of material *i*. It adds beginning inventory of last period to ordered quantity of current period and subtracts usage of last period to find beginning inventory of current period. The constraint (5) makes sure that total process time cannot exceed the capacity. The constraint (6) secures that total demand in period 1 is equal to customer demand in period 1. Scheduled orders can cause tardy jobs feasible again in the following periods. Therefore, in constraint (7), tardy jobs from previous periods are placed into current customer demands. Tardy jobs are defined in constraint (8). The constraint (9) defines that produced quantity of job j cannot exceed total demand of job j in planning period t. Constraints (10) and (11) set beginning inventories of production panel m and technical drawing h. Constraints (12) and (13) ensure that jobs cannot process without required panels and drawings. Constraints (14) and (15) update inventory of panels and drawings. Nonnegativity constraints are defined in constraints (16), (17), (18) and (19).

Chapter 6

Proposed Heuristic Method

This chapter explains the heuristic algorithm developed in this study. The steps of the proposed heuristic method are explained in detail in Section 6.1. This is followed by the representation of pseudo-code and the complexity analysis of the algorithm in Section 6.2.

6.1. Steps of the Heuristic Method

Proposed heuristic method is composed of three main parts. In the Part 1, initial values are set for first three steps. Part 2 includes steps 4, 5, 6, 7 and 8. In this part, problem function is called for the current sequence. The function runs for all jobs and all periods. At the end of the period, it returns a solution. In the Part 3, solution is controlled. If it is a better solution, then it is saved. If solution is not better, then current sequence is divided into three parts according to penalty costs of jobs. Then, each sequence is randomly mixed, and reunited to generate a new and different sequence. The reason of this division is to narrow the solution space. The heuristic runs until desired number of test instances is reached. At the end, the last saved solution is the best solution.

Figure 14 demonstrates the overall procedure of the proposed heuristic algorithm. To create the initial solution in Step 0, a job sequence is appended to the problem. This sequence represents a production order, and it connects jobs to the related parameters such as penalty cost, raw material, process time and setup requirements. The steps of the developed heuristic are given in the following.

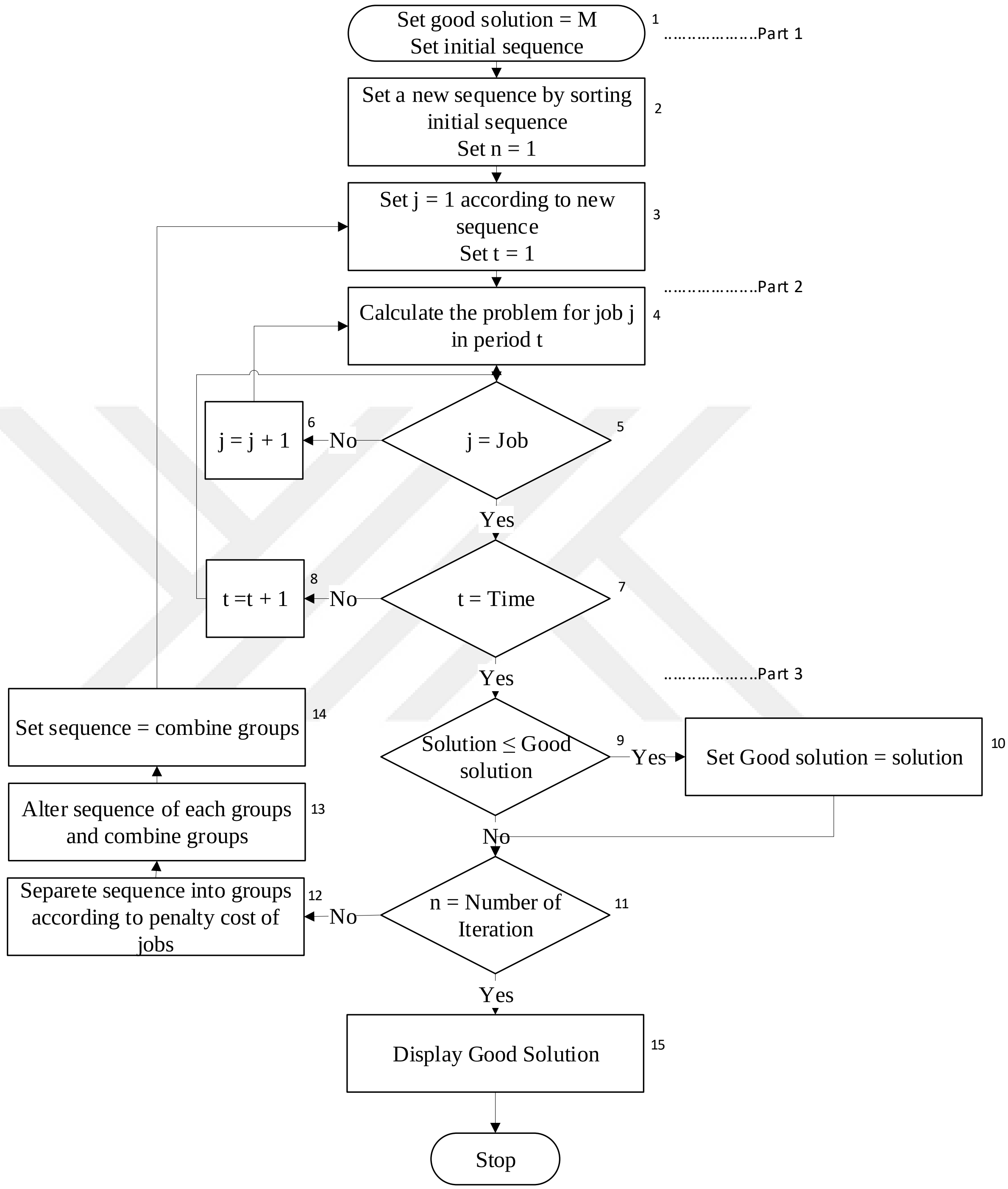

Figure 14: Flowchart of proposed heuristic method.

$Step$ 1: $Initialize\ good\ solution\ =\ M\ and\ sequence\ =\ [j = 1, \ldots, Job]$

$Step$ 2: $Descendingly\ sort\ sequence\ and\ Initialize\ n = 1, \ldots, Number\ of\ Test$

$Step$ 3: $Initialize\ t = 1, \ldots, Period, and\ j = sequence(1), \ldots., sequence(Job)$

$Step$ 4: $Determine\ solution\ for\ all\ j, t\ where\ j = 1, \ldots, Job\ and\ t = 1, \ldots, Period$

$Step$ 5: $If\ j = Job\ go\ to\ step\ 7, otherwise\ go\ to\ step\ 6$

$Step$ 6: $Set\ j = j + 1\ and\ go\ to\ step\ 4$

$Step$ 7: $If\ t = Period\ go\ to\ step\ 9, otherwise\ go\ to\ step\ 8$

$Step$ 8: $Set\ t = t + 1\ and\ go\ to\ step\ 4$

$Step$ 9: $If\ solution \leq good\ solution\ go\ to\ step\ 10, otherwise\ go\ to\ step\ 11$

$Step$ 10: $Set\ set\ good\ solution = solution\ and\ go\ to\ step\ 11$

$Step$ 11: $If\ n = Number\ of\ Test\ then\ go\ to\ step\ 15, otherwise\ go\ to\ step\ 12$

$Step$ 12: $Divide\ sequence\ into\ subgroups\ according\ to\ penalty\ cost$

$if\ penalty\ cost\ of\ job\ j \geq 30\ then\ add\ job\ j\ to\ subgroup\ 1$

$if\ penalty\ cost\ of\ job > 10\ and\ job\ j < 30\ then\ add\ job\ j\ to\ subgroup\ 2$

$if\ penalty\ cost\ of\ job \leq 10\ then\ add\ job\ j\ to\ subgroup\ 3$

$Step$ 13: $for\ A = 1\ to\ each\ subgroup$

$for\ x = 1\ to\ length(subgroupA)$

$y = round\big(((subgroupA - x) * rand\big) + x)$

$if\ x \neq y$

$TemporaryLocation = subgroupA(x)$

$subgroupA(x) = subgroupA(y)$

$$subgroupA(y) = TemporaryLocation$$

$$end\ if$$

$$next\ x$$

$$next\ A$$

$Step$ 14: $Set\ sequence = [subgroup1\ \ subgroup2\ \ subgroup3]\ and\ go\ to\ step$ 3

$Step$ 15: $Display\ good\ solution\ and\ stop$

In Step 1, a very big number is assigned as a good solution. Since this is a minimizing problem, heuristic tries to find a smaller solution than good solution. First sequence is provided by the user.

In Step 2, the heuristic algorithm sorts jobs in sequence according to their penalty costs from largest to smallest. The reason is that priorities of jobs are known and penalty costs define priority level of a job. This step puts having high priorities jobs into first spots of the production sequence.

In Step 3, the heuristic algorithm sets sequence of the first job as j is equal to 1. Also, it sets planning period t to 1.

In Step 4, problem is solved for job j and for all jobs and all planning periods.

Step 5 checks whether the problem is solved for all jobs or not solved. If it is solved, then Step 7 is followed, otherwise it goes to Step 6.

Step 6 moves the next job and postpones tardy jobs to next period. Then, Step 4 is followed.

Step 7 checks whether problem is solved for all periods or not solved. If it is solved then it goes to Step 9, otherwise Step 8 is followed.

Step 8 moves to the next period and postpones tardy jobs to next period. Then Step 4 is followed.

In Step 9, the heuristic algorithm checks current solution, if it is smaller than good solution then it goes to Step 10, otherwise Step 11 is followed.

In Step 10, good solution is updated. current solution is new good solution and next step is Step 11.

Step 11 controls whether problem is solved until maximum number of iterations is reached. If so, Step 15 is followed, otherwise Step 12 is followed.

In Step 12, the heuristic divides the sequence into three subgroups. Jobs having penalty costs more than 30 or equal to 30 are joined to subgroup 1, jobs having penalty costs below 10 are combined to subgroup 3, and the rest of jobs are combined to subgroup 2. Since penalty costs define priority levels of jobs, each subgroup keeps job having similar priority levels together.

In Step 13, the sequence each subgroup is altered randomly, and each alteration is different than each other. In step 14, these three subgroups are reunited to create a new sequence, and Step 3 is followed. Step 15 represents a good solution as closed to an optimum solution.

6.2. Pseudo-Code of The Heuristic Algorithm

This section represents the pseudo-code for the heuristic algorithm explained in the previous section. Figure 15 represents the pseudo-code of proposed heuristic algorithm. Complexity level of heuristic depends on number of orders, number of jobs, planning horizon and number of iterations.

Proposed heuristic method narrows the solution space by sequencing products according to their priorities. It considers narrowed solution space to obtain good solutions and it does not control entire solution space. Therefore, the algorithm may not find optimum solution.

```
initialize (big solution, good starting point)
sets (max_time, max_job, max_iteration, demand)
while number_of_time ≤ max_iteration
sequence= good starting point
while time ≤ max_time
        while job ≤ max_job
        solution = solution + problem_function (sequence, demand)
        job = job + 1
        end while
        time = time + 1
        if solution ≤ big solution then big solution = solution
end while
        while job ≤ max_job
        if penalty_cost(job) ≥ 30 then sequence_high(job) = job
        elseif penalty_cost(job) ≤ 10 then sequence_low(job) = job
        else sequence_medium(job) = job
              while a ≤ length(sequence_high)
              y= round(((sequence_high(a)) * rand) + a)
              if a ≠ y then
              {temp = sequence_high(a)
              sequence_high(y)= sequence_high(a)
              sequence_high(y)= temp}
              end while
              while a ≤ length(sequence_low)
              y= round(((sequence_low(a)) * rand) + a)
              if a ≠ y then
              {temp = sequence_low(a)
              sequence_low(y)= sequence_low(a)
              sequence_low(y)= temp}
              end while
              while a ≤ length(sequence_medium)
              y= round (((sequence_ medium (a)) * rand) + a)
              if a ≠ y then
              {temp = sequence_ medium (a)
              sequence_ medium (y)= sequence_ medium (a)
              sequence_ medium (y)= temp}
              end while
        sequence= sequence_high & sequence_medium & sequence_low
        end while
number_of_iteration= number_of_iteration + 1
end while
```

Figure 15: Pseudo-code of proposed heuristic method.

Chapter 7

Demonstrative Example

To verify the proposed heuristic method, a demonstrative example is solved by both the mathematical model and heuristic method. For this example, hypothetical data is used instead of real data. Section 7.1 explains the case study for after-sales production problem together with the data structures used for the application of mathematical modelling and heuristic method. Section 7.2 presents the results obtained by the mathematical model and the heuristic method.

7.1. A Case Study for After-sales Production

In this demonstrative example, planning horizon is four weeks, and number of products is chosen as three. Table 4 presents customer demands over planning horizon and penalty costs for three types of products. Numbers of these products are 30644624, 30644791 and 30644794. Raw materials can be shared among the products. Eight different raw materials are required for these products. Accordingly, Table 5 represents product number in rows and associated material number in columns. Numbers in Table 5 for a particular material and product type show the required quantities of raw materials for a product. Total number of required panels for production is two. The reason is that some products may belong to the same product family, so they may share the same production panel. Thus, each product has a unique product structure, and hence each requires its own technical drawing. Therefore, total number of drawings is three. The relationship between products, panels and drawings are given in Table 6. Besides, Table 6 shows process times of products. Accordingly, Table 6 represents the product number in rows and associated panel number, drawing number and process time in columns. The numbers demonstrate that the relationship between a product and associated panel and drawing. In other words, if there exists an associated panel or drawing for a product, it is 1, otherwise it is 0. Beginning inventories and ordered quantities over four weeks for each raw material are given in Table 7. Inventory availability of each panel and each drawing is shown in Tables 8 and 9. Available capacity is assumed to be 14 hours for each period.

Table 4: Customer demands over planning horizon and penalty costs for products.

Product No	Week No				
	1	2	3	4	
	Demand				Penalty Cost (€)
30644624	1	0	0	0	2
30644791	1	0	0	0	10
30644794	2	0	1	0	5

Table 5: Amount of required materials for product types.

Product No	Material No						
	M3569C03	M3569C07	M4165004	M4165015	M3324204	M3344008	M3344009
30644624	1	2	0	2	2	0	1
30644791	0	2	2	0	3	2	0
30644794	3	0	1	4	0	0	1

Table 6: Associated panel, drawing numbers and processing time for sample products.

Product No	Panel No		Drawing No			
	PNL 1	PNL 2	TD1	TD2	TD3	Process Time (h)
30644624	1	0	1	0	0	3
30644791	1	0	0	1	0	8
30644794	0	1	0	0	1	4

Table 7: Initial inventory levels and ordered quantities of raw materials

Material No		Week No			
		1	2	3	4
	Initial Inventory	Ordered Quantity			
M3569C03	5	0	3	0	0
M3569C07	5	0	0	0	0
M4165004	5	0	0	0	0
M4165015	25	0	0	0	0
M3324204	28	0	0	0	0
M3344008	33	0	0	0	0
M3344009	35	0	0	0	0
M3344125	32	0	0	0	0

Table 8: Stock availability of panels over planning horizon.

Panel No	Week No			
	1	2	3	4
	Stock Availability			
PNL 1	1	1	1	1
PNL 2	1	1	1	1

Table 9: Stock availabilities of drawings over planning horizon.

Drawing No	Week No			
	1	2	3	4
	Stock Availability			
TD 1	1	1	1	1
TD 2	1	1	1	1
TD 3	1	1	1	1

7.2. Results of the Example

In order to solve given example with above data, IBM ILOG CPLEX Optimization Studio software is used and the mathematical model is presented in Section 5.3. Screenshots of solutions are given in Figures 16, 17, 18, 19 and 20.

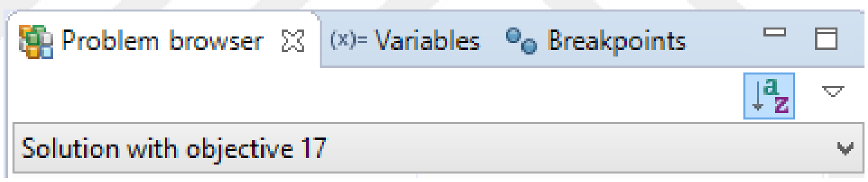

Figure 16: Results of example.

Figure 16 shows the optimum solution for this example which is 17 € (minimum total penalty cost of tardiness). The sequence of jobs according to time periods is found as Job 2 - Job 3 - Job 1 – Job 3. This sequence is also given in Figure 17. It is noted that each product type and its associated order is defined as a job. According to the solution in Figure 17, Job 2 and Job 3 are the first and second products to be produced in period 1. Then, Job 1 is to be produced in period 2. Remaining quantity of job 3 is to be produced last in period 2. Figure 18 displays number of tardy jobs for all planning horizon. According to Table 4 above and Figure 17, there is a demand of job 1 in period 1, however, it is scheduled in period 2 as a tardy job, there is a demand of 2 for job 3 in period 1, and demand of 1 in period 3. All these three jobs are tardy according to the solution. Accordingly, total number of tardy jobs is 4, and total cost of tardy jobs is calculated as the summation penalty cost of product 1 and three times penalty costs of product 3 that makes 2+5+5+5=17. Weekly material consumption is given in Figure 19. Weekly demand levels are represented in Figure 20.

Value for x

job (size 3)	period (size 4)			
	1	2	3	4
1	0	1	0	0
2	1	0	0	0
3	1	1	0	0

Figure 17: Amount of products to be produced over planning horizon.

Value for tardy

job (size 3)	1..NbPeriods (size 4)			
	1	2	3	4
1	1	0	0	0
2	0	0	0	0
3	1	0	1	1

Figure 18: Number of tardy jobs over planning horizon.

Value for Inventory

material (size 8)	period (size 4)			
	1	2	3	4
1	5	5	1	1
2	5	3	1	1
3	5	2	1	1
4	25	21	15	15
5	28	25	23	23
6	33	31	31	31
7	35	34	32	32
8	32	30	28	28

Figure 19: Raw material inventory level over planning horizon.

Value for NewDemands

job (size 3)	period (size 4) 1	2	3	4
1	1	1	0	0
2	1	0	0	0
3	2	1	1	1

Figure 20: Beginning demands over planning horizon.

The same example is solved with the developed heuristic method (see Section 6.1), in order to verify its performance. For this small problem, the proposed heuristic method finds the same optimum solution too. Figure 21 shows the tabulated results.

In Figure 21, 4th, 5th and 6th rows represent product number and column B, C, D and E represent planning period. Related numbers represent production quantity for each product in each period. 8th, 9th and 10th rows show total time capacity, used capacity and remaining capacity for each period. 15th, 16th and 17th rows represent customer demands. Pop-up excel message box displays solution and sequence for this problem.

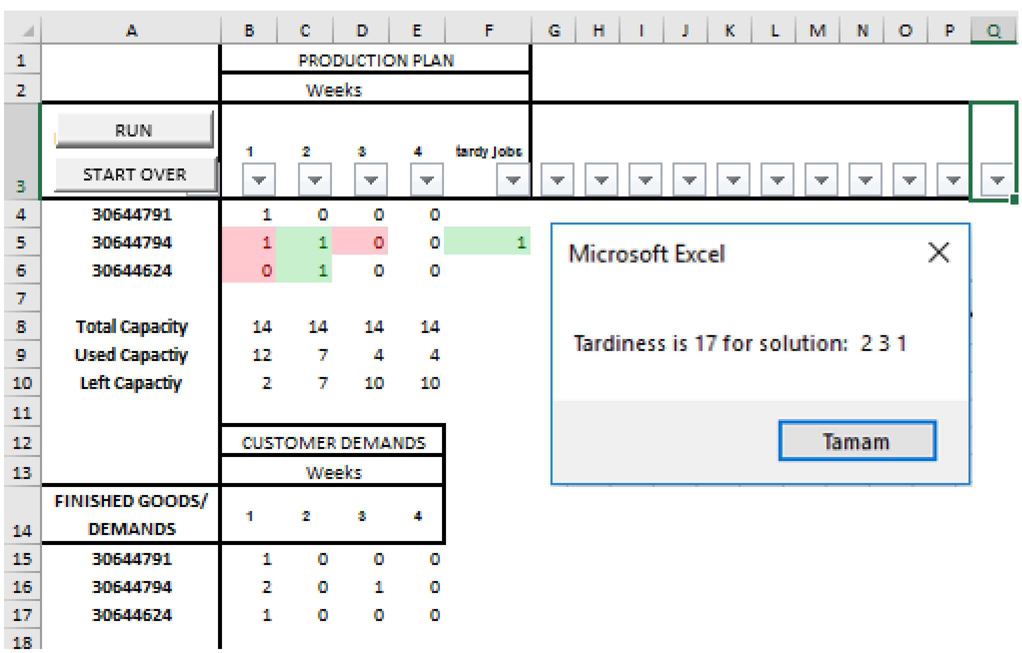

Figure 21: Results of proposed heuristic method.

7.3. Concluding Remarks

The reason of using a heuristic method is the long computation time when real data is applied to the problem. In addition, the problem is NP-hard (see Section 4.3). Mathematical model is further tested with the real data (see Section 5.1 and Appendices A, B, C and D). The optimization software runs more than 2 hours for the real data, and no result could be obtained. Since, this problem is a real-life problem, solving such a problem in actual planning environment requires quick results. Production plan should be provided before beginning of each shift and it should respond quickly when any problems exist. This results current plans to be infeasible for production periods. This is the reason that the software is interrupted and problem is considered as NP-Hard problem after two hours. For this reason; a heuristic method is proposed in this study. Chapter 8 presents the results obtained by the heuristic model implemented by a real set of data.

Chapter 8

Experimental Design and Results

Chapter 8 first presents the experimental design in Section 8.1. This section covers the description of problem instances created to test the proposed heuristic and also the description of alternative evaluation method. That is, the problem is adopted by one of the traditional metaheuristics called Simulated Annealing (SA). After, Section 8.2 reveals results of problem instances obtained by the heuristic method and also shows the results of SA. Then, the results obtained by these two methods are compared in Section 8.3.

8.1 Experimental Design

In this section, collected real data (see Section 5.1) is applied to the proposed heuristic method and Simulated Annealing (SA). Section 8.1 consists of two subsections. Section 8.1.1 describes problem instances generated and explains the differences among them. Section 8.1.2 explains application steps of SA algorithm and it provides a flow chart and the pseudo-code of SA algorithm.

8.1.1. Design of Problem Instances

Total 8 instances are generated for the experimental design. Each instance has a different initial sequence. A particular sequence represents the production sequence of products to be produced in the system. That is, the product which is placed into the first spot in the sequence, is produced as first and it consumes the limited resources first. Therefore, minimizing tardiness depends on a sequence. Due to different tardiness penalty costs and different demands of each product, each sequence has a different tardy cost. The reason is consumption of resources. Resources are shared among each product. Table 10 displays tardiness penalty costs. Table 11 shows sequences for each problem instances.

Table 10: Tardiness penalty cost for each product.

Product Number	Tardiness Penalty Cost (€)
30644624	40
30644791	38
30644794	36
31384342	33
31415546	33
31415563	33
31419516	32
31433050	31
31453587	30
31674022	22
31674791	22
31678731	22
31687005	16
3Q0 971 225 B	15
3G0 971 509 B	14
3G0 971 509 E	13
3G0 971 509 F	12
3Q0 971 013 C	11
3Q0 971 015 C	10
3Q0 971 237	10
3Q0 971 475	9
5G0 971 509 J	8
5G0 971 509 K	7
5G0 971 509 L	6
5Q0 971 015 F	5
5Q0 971 015 G	4
5Q0 971 015 H	3
5Q0 971 015 J	2
5Q0 971 449 A	2
5Q0 971 475 A	2
5Q0 971 483 A	2
8V0 971 509 E	2
8V0 971 509 F	1
8V0 971 509 H	1
8V0 971 509 K	1
A5E32526521011	1
A5E36172628001	1

Table 11: Problem instances and their starting sequences.

Instance No	Starting Sequence
1	1-2-3-4-5-6-7-8-9-10-11-12-13-14-15-16-17-18-19-20-21-22-23-24-25-26-27-28-29-30-31-32-33-34-35-36-37
2	2-33-37-13-1-19-24-25-23-22-36-28-12-3-32-11-15-21-26-10-6-27-8-31-35-20-9-18-7-29-30-17-16-4-14-5-34
3	8-5-7-30-9-21-4-20-24-3-13-37-16-19-10-12-32-28-22-18-25-15-35-23-26-11-6-17-29-31-14-1-2-27-34-36-33
4	28-2-33-17-6-4-19-24-36-20-26-12-9-22-11-30-32-25-35-5-1-3-27-8-14-23-13-18-31-37-10-21-15-7-16-34-29
5	13-25-27-37-24-1-5-8-20-21-12-32-11-6-23-19-34-3-30-36-29-17-4-7-35-14-15-2-26-28-16-10-9-18-31-33-22
6	13-32-10-17-8-26-37-9-14-6-28-11-27-12-25-31-20-4-22-30-15-29-23-35-21-7-19-16-18-5-33-24-1-36-3-34-2
7	12-16-21-18-27-1-20-36-4-25-28-37-24-34-32-30-31-10-13-19-33-8-22-9-26-15-29-23-35-5-7-17-11-3-6-14-2
8	16-7-22-11-35-23-20-29-26-14-30-9-31-19-15-37-21-17-12-24-28-1-32-5-25-33-2-18-10-3-27-36-34-8-4-13-6

It is assumed that the same demand profile is assumed for each problem instance. In other words, the demand for a particular product is the same in all instances. Each sequence represents a starting point in solution space. For one-piece demand from each product, size of solution space is 37!. Since both developed heuristic and simulated annealing are local search algorithms, both apply this initial sequence in each iteration to compare results. Except the first instance, starting sequences of each instance are created randomly. However, in the first instance, experiment aims to observe how both method performs under a good starting point. Therefore, sequence in the first instance is aligned from product with the largest penalty costs to the lowest since it is expected that result of this sequence is close to a good solution.

8.1.2. Simulated Annealing

Simulated annealing is chosen for this experiment since both algorithms are local search algorithms. Section 8.1.2 represents and explains steps of simulated annealing algorithm and provides a pseudo-code for it. Figure 22 represents the flow chart of simulated annealing algorithm. It is note that SA algorithm developed applies 2-opt neighborhood method. It generates a new solution by swapping positions of each job in the sequence (Euchi and Chabchoub, 2011, p 65).

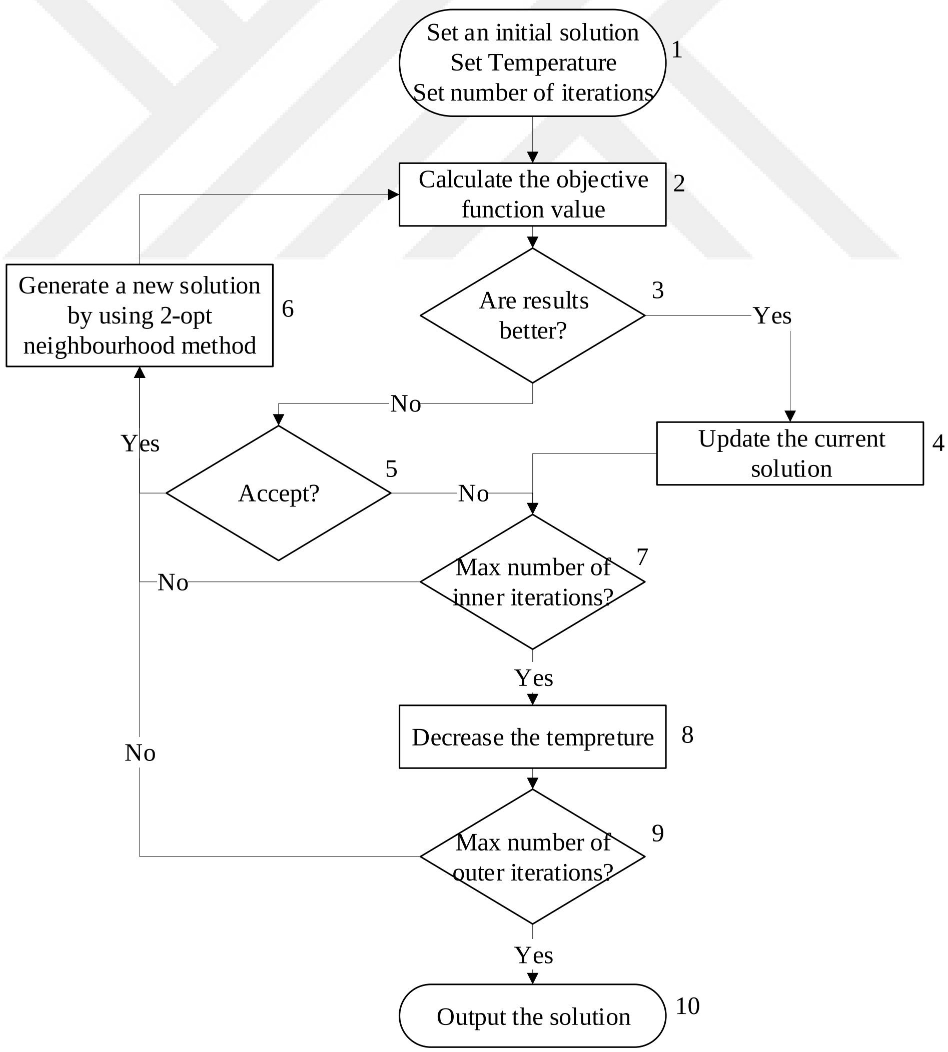

Figure 22: Flow chart of simulated annealing.

$Step$ 1: $Initialize\ initial\ solution\ and\ set\ tempreture\ and\ number\ of\ iterations$ $and\ go\ to\ step$ 2

$Step$ 2: $solve\ the\ problem\ by\ calling\ problem\ function\ and\ go\ to\ step$

$Step$ 3: $if\ new\ result\ is\ better\ than\ current\ solution\ then\ go\ to\ step$ 4 $otherwise\ go\ to\ step$ 5

$Step$ 4: $Update\ the\ current\ solution\ then\ go\ to\ step$ 7

$Step$ 5: $if\ higher\ total\ tardy\ cost\ is\ accepted\ based\ on\ acceptence\ function\ then$ $go\ to\ step$ 6 $otherwise\ go\ to\ step$ 7

$Step$ 6: $Generate\ a\ new\ solution\ by\ using$ $2 - opt\ and\ go\ to\ step$ 2

$Step$ 7: $if\ maximum\ number\ of\ inner\ iterations\ is\ reached\ then\ go\ to\ step$ 8 $otherwise\ go\ to\ step$ 6

$Step$ 8: $Decrease\ the\ temperature\ and\ go\ to\ step$ 9

$Step$ 9: $if\ maximum\ number\ of\ outer\ iterations\ is\ reached\ then\ go\ to\ step$ 10 $otherwise\ go\ to\ step$ 6

$Step$ 10: $display\ the\ final\ result$

Also, the pseudo-code of SA algorithm is given in Figure 23 in the following.

```
initialize (solution)
sets (outer_max_iteration, inner_max_iteration, temperature)
while outer iteration number ≤ outer_max_iteration
while inner iteration number ≤ inner_max_iteration
                create new solution with 2-opt
                if current result ≤ solution then solution = current
result
                else if random number ≤ exp(-ΔE) then accept the
solution
end while
          temperature= temperature*0,99
end while
```

Figure 23: Pseudo-code of SA algorithm.

8.2 Results

This section displays results of the experimental design. Next subsection presents results of the proposed heuristic method. Following subsection shows results of SA method. At the end, Section 8.2.3 compares results of both methods and discuss them.

8.2.1. Results of Proposed Heuristic Method

Real data is applied to the developed algorithm and it runs for 8 instances which is provided in Section 8.1.1. Each instance runs a hundred times. Results are given in Table 12 for each instance and Figure 24 visualizes the results with a bar chart. Figure 25 shows computation time of each instance. Average computation time is 181 seconds and average tardiness cost is found 141311.

Table 12: Results of developed heuristic method.

Sequence No	Starting Sequence	Tardiness costs (€)
1	1-2-3-4-5-6-7-8-9-10-11-12-13-14-15-16-17-18-19-20-21-22-23-24-25-26-27-28-29-30-31-32-33-34-35-36-37	140067
2	2-33-37-13-1-19-24-25-23-22-36-28-12-3-32-11-15-21-26-10-6-27-8-31-35-20-9-18-7-29-30-17-16-4-14-5-34	141532
3	8-5-7-30-9-21-4-20-24-3-13-37-16-19-10-12-32-28-22-18-25-15-35-23-26-11-6-17-29-31-14-1-2-27-34-36-33	141217
4	28-2-33-17-6-4-19-24-36-20-26-12-9-22-11-30-32-25-35-5-1-3-27-8-14-23-13-18-31-37-10-21-15-7-16-34-29	141615
5	13-25-27-37-24-1-5-8-20-21-12-32-11-6-23-19-34-3-30-36-29-17-4-7-35-14-15-2-26-28-16-10-9-18-31-33-22	142631
6	13-32-10-17-8-26-37-9-14-6-28-11-27-12-25-31-20-4-22-30-15-29-23-35-21-7-19-16-18-5-33-24-1-36-3-34-2	140603
7	12-16-21-18-27-1-20-36-4-25-28-37-24-34-32-30-31-10-13-19-33-8-22-9-26-15-29-23-35-5-7-17-11-3-6-14-2	141531
8	16-7-22-11-35-23-20-29-26-14-30-9-31-19-15-37-21-17-12-24-28-1-32-5-25-33-2-18-10-3-27-36-34-8-4-13-6	141298

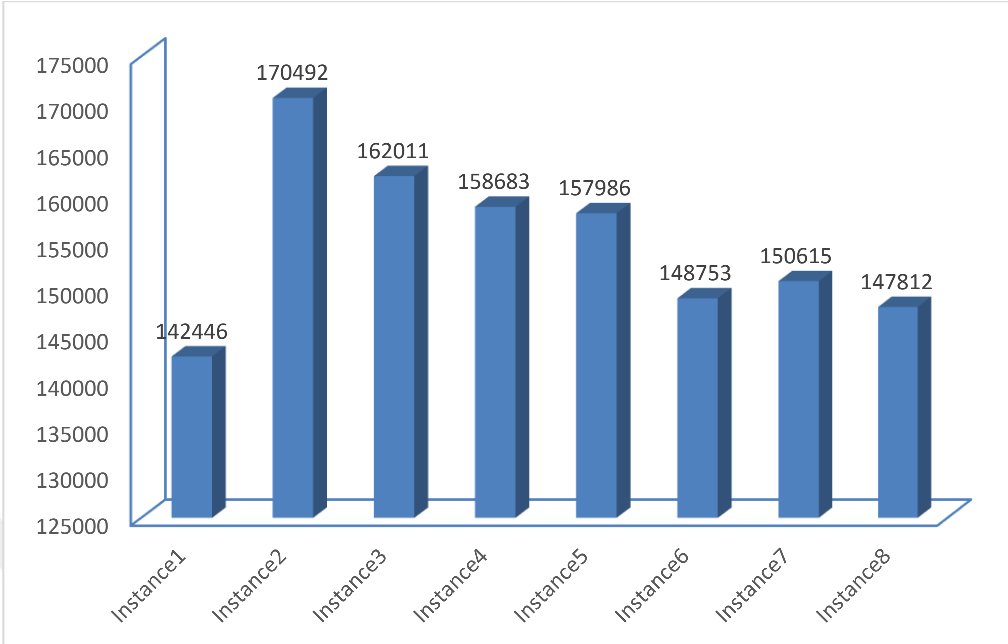

Figure 24: Bar chart of proposed heuristic method's results.

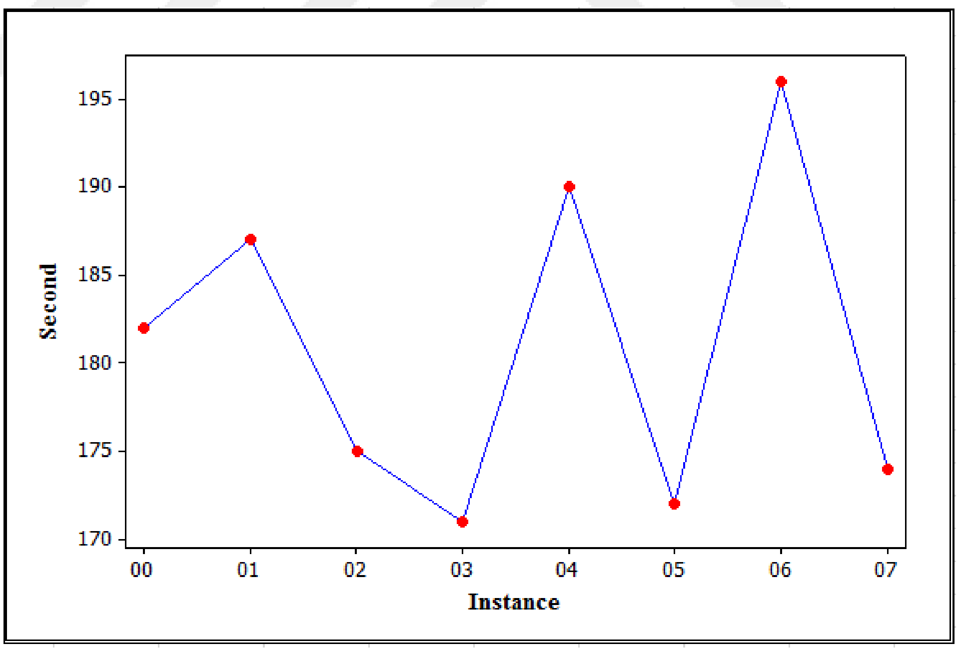

Figure 25: Computation time plot of developed heuristic.

8.2.2. Results of Simulated Annealing

The same data and the same sequences are also used for the SA method. Table 13 represents results of the SA algorithm. Heuristic searches solution space 10 times, and in each iteration, it looks for local minima 10 times (10x10) for all instances. The reason of 10x10 iteration is that algorithm runs more than one hour for only one instance after 15x15 iterations. Results are also presented with a bar chart graph in Figure 26.

Table 13: Results of simulated annealing.

Sequence No	Starting Sequence	Tardiness costs (€)
1	1-2-3-4-5-6-7-8-9-10-11-12-13-14-15-16-17-18-19-20-21-22-23-24-25-26-27-28-29-30-31-32-33-34-35-36-37	142446
2	2-33-37-13-1-19-24-25-23-22-36-28-12-3-32-11-15-21-26-10-6-27-8-31-35-20-9-18-7-29-30-17-16-4-14-5-34	170492
3	8-5-7-30-9-21-4-20-24-3-13-37-16-19-10-12-32-28-22-18-25-15-35-23-26-11-6-17-29-31-14-1-2-27-34-36-33	162011
4	28-2-33-17-6-4-19-24-36-20-26-12-9-22-11-30-32-25-35-5-1-3-27-8-14-23-13-18-31-37-10-21-15-7-16-34-29	158683
5	13-25-27-37-24-1-5-8-20-21-12-32-11-6-23-19-34-3-30-36-29-17-4-7-35-14-15-2-26-28-16-10-9-18-31-33-22	157986
6	13-32-10-17-8-26-37-9-14-6-28-11-27-12-25-31-20-4-22-30-15-29-23-35-21-7-19-16-18-5-33-24-1-36-3-34-2	148753
7	12-16-21-18-27-1-20-36-4-25-28-37-24-34-32-30-31-10-13-19-33-8-22-9-26-15-29-23-35-5-7-17-11-3-6-14-2	150615
8	16-7-22-11-35-23-20-29-26-14-30-9-31-19-15-37-21-17-12-24-28-1-32-5-25-33-2-18-10-3-27-36-34-8-4-13-6	147812

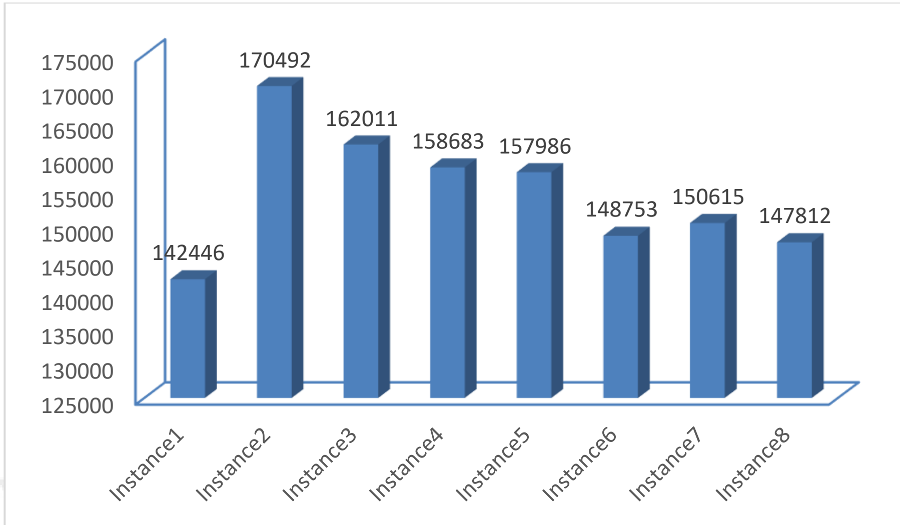

Figure 26: Bar chart of simulated annealing approach's results.

Figure 27 presents computation time of each instance. Average solution time is obtained as 1001 seconds and average tardiness cost is obtained as 154849.

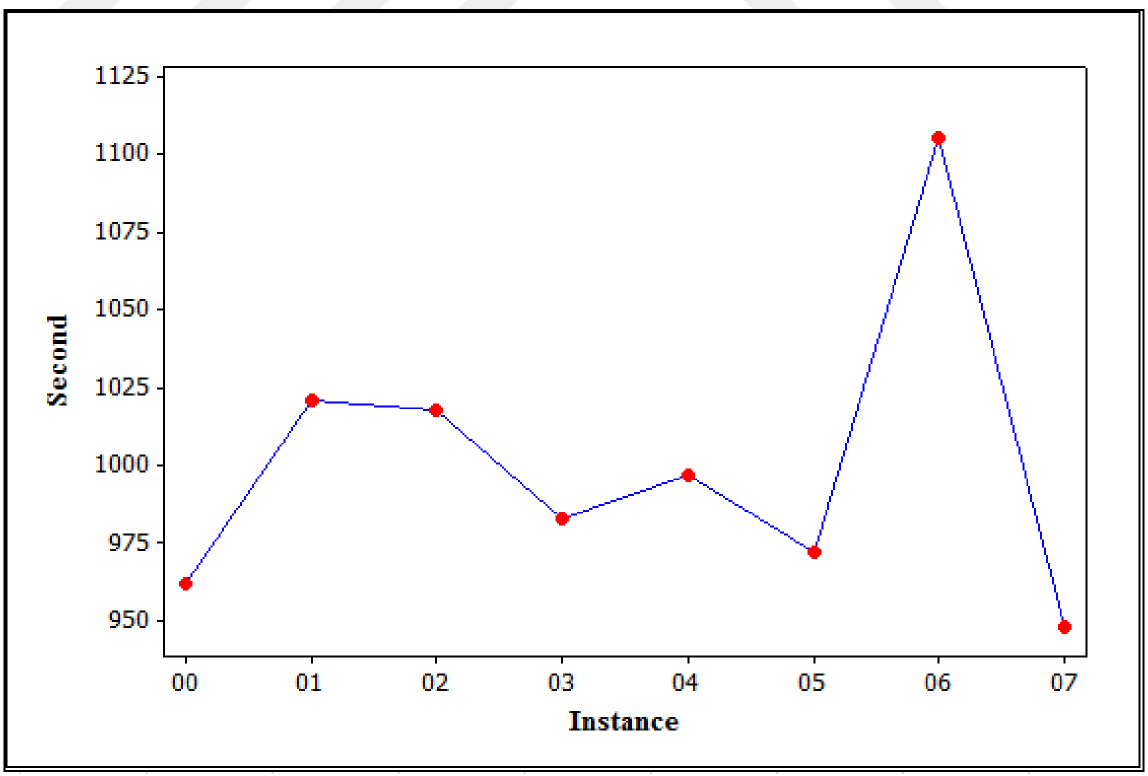

Figure 27: Computation time plot of simulated annealing.

Solution values are obtained by using MATLAB R2014b software for both algorithms. The tests are performed on the same computer with an INTEL® i5 – 5200U 1.40GHz clock speed.

8.2.3. Results of Comparison of Proposed Heuristic and Simulated Annealing

Table 14 presents results of both solutions for all instances. Results prove that the developed heuristic method solves problem five times faster and provides significantly better solution for real-life problem. Developed model is compared with the SA since both algorithms share some similar characteristics. That is, each algorithm searches the solution space randomly. Simulated annealing selects a random solution in entire solution space and it starts to look for local minima for that solution. Then, it escapes from the local minima and starts over until a maximum number of iterations is reached. In some cases, it gives worse solutions due to random selections, and it takes much time to reach a solution. The SA algorithm provides better solutions with higher number of iterations. Its performance is dependent on the number of iterations. The result of first instance as good as expected since the SA starts with the good sequence. However, results are still worse than the developed heuristic and computation time is five times higher.

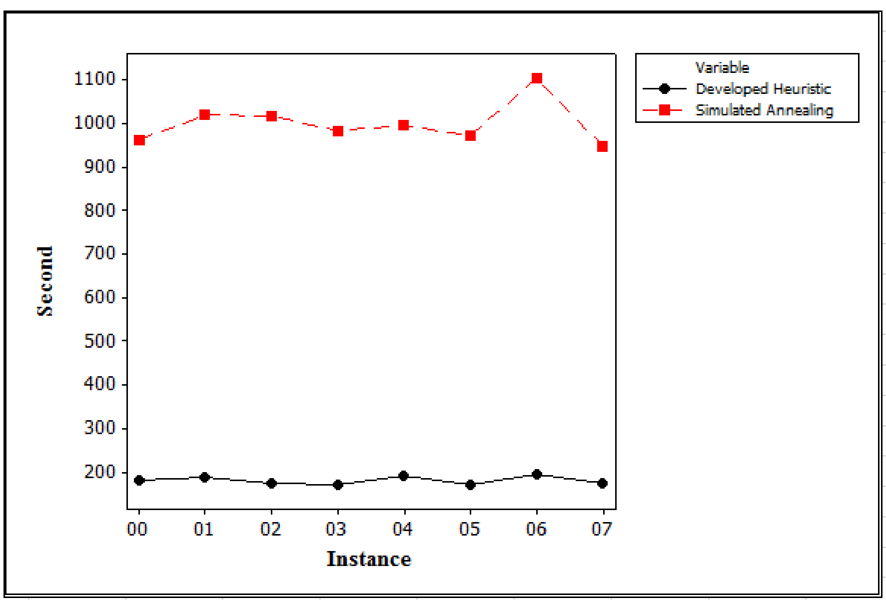

Figure 28: Comparison of computation time for both algorithms.

However, developed heuristic method provides a good solution in short time since it narrows solution space (see Table 14, Figures 28 and 29). Developed method generates sequence to solve the problem. It placed high priority jobs to beginning of the sequence and puts low priority jobs to the end of the sequence. This situation leads to produce high priority jobs at first. These priorities are already known and they are provided by the company. To define these priorities, tardiness penalty costs are used. Therefore, job with high penalty cost refers to high priority job.

The MATLAB is used to implement the both developed heuristic and SA methods. The minimum solution value is considered as lower bound ($MTPC_{ins}^{LB}$). The deviation ratio between the minimum tardiness penalty cost from a developed heuristic algorithm and that from the simulated annealing algorithm is employed to evaluate the performance of both algorithms (see Equation 20) (Chung et al, 2007; p. 447).

$$Deviation\ ratio = \frac{MTPC_{ins}^{H} - MTPC_{ins}^{LB}}{MTPC_{ins}^{LB}}\ x\ 100\% \tag{20}$$

where;

$MTPC_{ins}^{H} =$ The minimum tardiness penalty cost in instance ins obtained from heuristic

$MTPC_{ins}^{LB} =$ The minimum tardiness penalty cost in among all instances obtained from heuristic

Table 14: Comparison of deviation ratio (%) and computation time for both algorithm.

Sequence No	Developed Heuristic	Simulated Annealing	CT of Developed Heuristic (second)	CT of Simulated Annealing (second)
2	1.05	21.72	187	1021
3	0.82	15.67	175	1018
4	1.11	13.29	171	983
5	1.83	12.79	190	997
6	0.38	6.20	172	972
7	1.05	7.53	196	1105
8	0.88	5.53	174	948
Avg.	1.02	11.82	181.83	1006.28

Table 14 presents comparison of the results according to the deviation ratio for both algorithms and all problem instances. Developed heuristic algorithm has the better performance than simulated annealing algorithm with a least average computation time and a least average deviation ratio of 181.83 and 1.02, respectively. The reason for its good performance is that ideal loading for each process capability of each machine is estimated first and is used as an assignment reference.

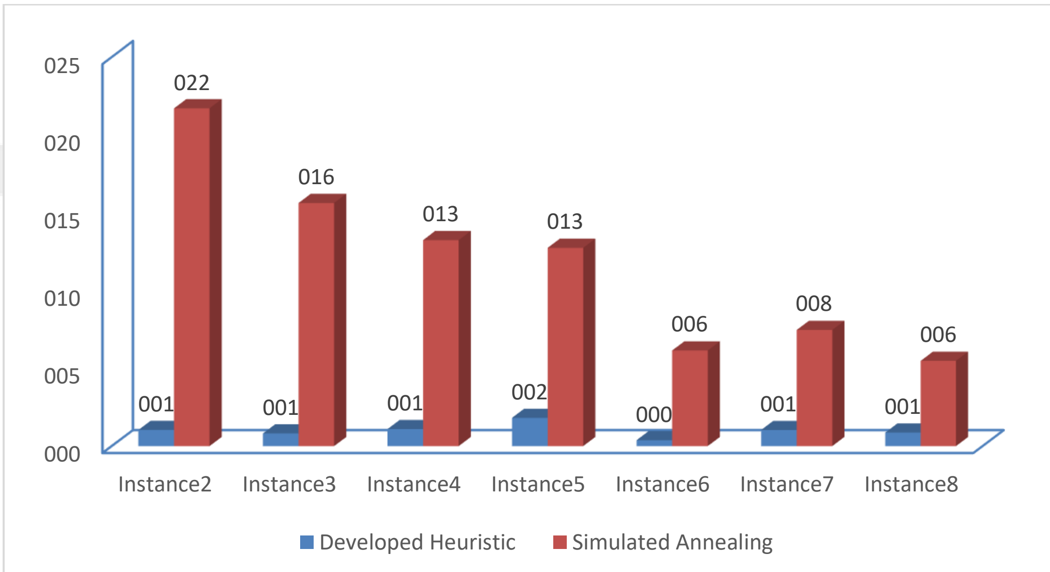

Figure 29: Bar chart of comparison of simulated annealing and developed heuristic method.

In each iteration, proposed heuristic alters sequences according to this priory concept, and it forces each sequence to stay in the narrowed solution space. In order to achieve that, heuristic divides the sequence into three groups according to priority level of jobs. These groups are called high, medium and low priority subsequences. Developed heuristic alters these subsequences separately and reunites them to generate a new sequence. This situation narrows the solution space.

The proposed heuristic may not find the optimum solution. The reason is that algorithm does not control entire solution space. It makes assumptions on the solution space and looks for a good solution. With regard to the application of such a method in the practice or in the company of interest, quick computation time is critical. Figures 28 and 29 justify that proposed algorithm can provide a good result within short period.

Chapter 9

An Application for Tardiness Minimization

This Chapter presents a tardiness minimization application using real data set to be applied in a production planning environment. Section 9.1 presents the black-box model of the application and Section 9.2 shows the created user-interface and how the application could be used in a real production-planning environment. Section 9.3 demonstrates results obtained by this application.

9.1. Structure of Tardiness Minimization Application

Figure 30 represents a black-box model of the application. Inputs are demands, bill of materials, inventory levels, capacity, technical drawings and production panels. These inputs are entered into the application by each department. Application outputs are tardy jobs and total cost of tardy jobs.

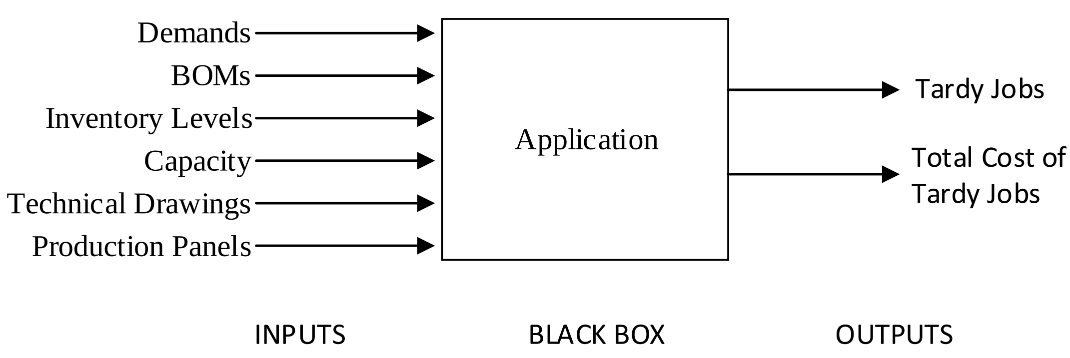

Figure 30: Black-Box model of the application.

9.2. User-Interface of Tardiness Minimization Application

This section demonstrates how to use the application. Figure 31 shows opening screen of application. Users have to login first. Application keeps login information such as the person, name of department, login date and time. Each department can only view and edit assigned sheets. Figure 31 displays login sheet in the following.

In order to login, users have to enter their user name, password and department information at the same time, otherwise application does not allow them to login. In Figure 31, user logins for production planning department, and the system opens the related sheet (see Figure 32). Except for the admin, nobody can view or edit the data (see Figure 33).

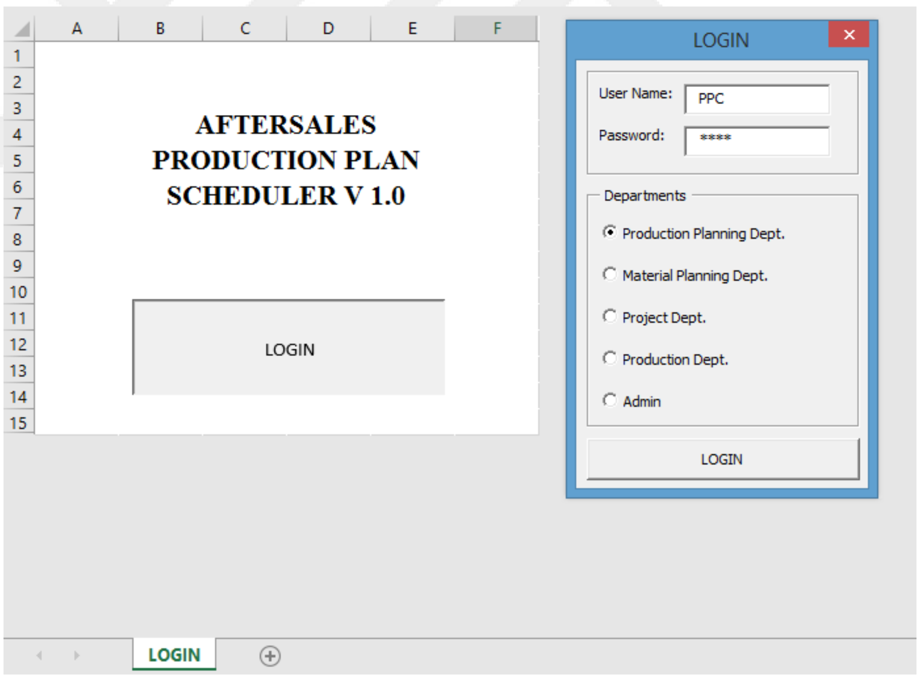

Figure 31: Start screen of the application.

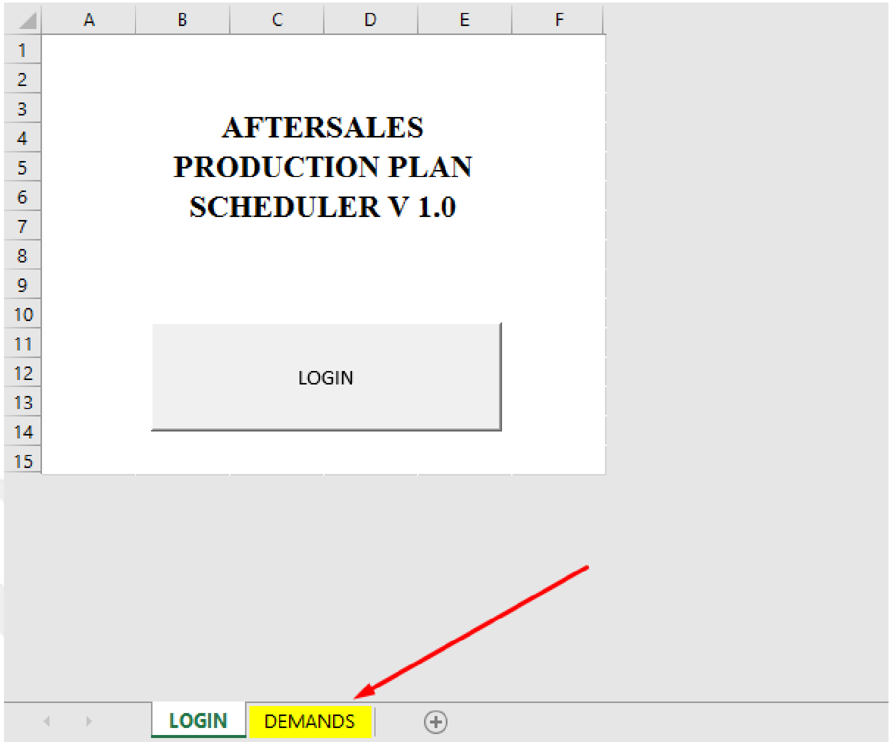

Figure 32: Screen shot of enabled “DEMANDS” sheet.

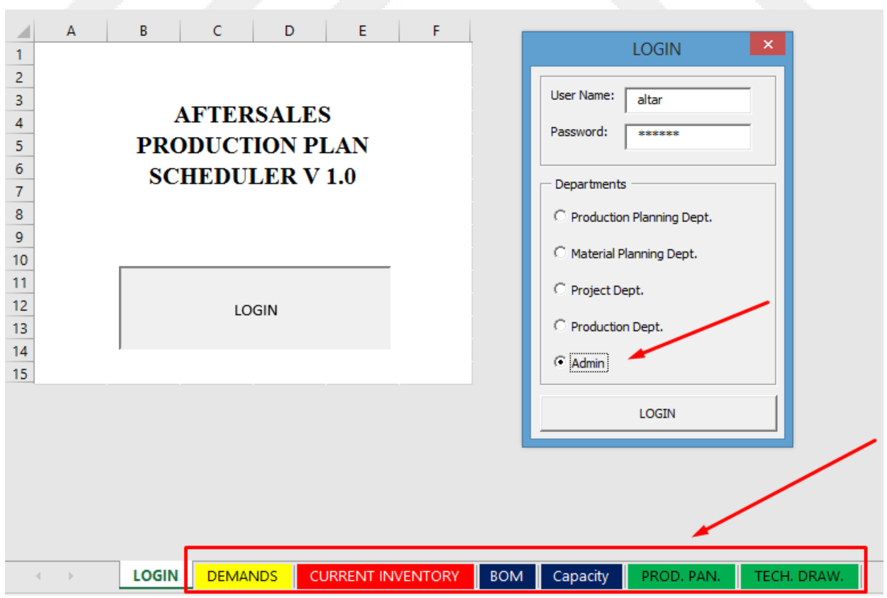

Figure 33: Screen shot of admin login.

In Figure 33, each color indicates different departments. Yellow is for the production planning, red is for the material planning, blue is for the project, and green is for the production departments. Each department logins and enters required data at the beginning of each week. Material planning department enters current stocks and scheduled orders. Project department enters BOMs and required capacity for each product. Production checks and updates the required production panel and technical drawings stock levels. At the end, production planner updates customer demands and clicks RUN button (see Figures 34 and 35).

9.3. Results of Tardiness Minimization Application

Figure 35 displays a production plan. White background numbers represent that finished good is produced as demands. Red background numbers indicate that production quantity is less than demand values. This means that jobs are tardy. Tardy jobs are postponed to next production period. Numbers in the green background represent goods that are produced more than the relevant period's order. The reason is that tardy jobs from previous periods are produced in this planning period as well. Tardy jobs can be producible in the following weeks if missing resources are ordered.

FINISHED GOODS/ DEMANDS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
30644624	11	0	0	25	15	0	0	0	20	0	0	0	0	0	20	0	10	0	0	0	0	0	0	0	0	0	5	5	9	0	0	0	0	0	0	0	0	0
30644791	14	0	0	30	0	0	31	0	0	0	19	16	0	0	0	0	8	4	4	0	0	0	0	0	16	0	0	0	0	0	12	0	0	0	20	0	0	0
30644794	0	3	0	0	1	16	18	0	0	0	0	0	0	0	13	0	0	0	0	5	10	0	0	0	0	14	8	1	0	0	0	9	11	0	0	0	0	0
31384342	13	12	5	0	1	13	0	0	0	0	0	0	0	0	0	15	0	0	0	0	0	0	0	0	0	0	0	6	0	3	0	0	0	0	0	0	0	0
31415546	15	0	5	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31415563	11	6	0	5	1	17	0	0	0	14	0	0	13	16	1	0	2	3	0	0	0	0	2	7	0	0	0	0	3	0	0	0	0	0	0	0	0	0
31419516	0	0	0	0	0	0	0	16	12	18	0	0	3	9	8	0	0	0	0	0	0	19	0	0	0	11	1	0	0	0	0	9	0	0	0	5	12	0
31433050	0	0	0	5	7	15	0	9	0	0	0	11	0	4	0	5	0	0	8	0	4	0	0	0	19	20	3	0	19	0	9	18	0	0	0	3	4	0
31453587	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0
31674022	0	0	0	0	4	3	20	19	1	2	18	3	0	0	5	0	15	1	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31674791	0	0	0	5	0	19	5	0	14	4	0	7	0	0	17	0	4	11	14	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
31678731	0	0	0	0	9	0	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	4	3	15	0	9	1	0	0	3	0	0	0	0
31687005	0	4	17	7	18	10	2	5	8	9	0	20	0	0	13	0	16	20	8	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
3Q0 971 225 B	0	0	0	0	0	4	0	0	13	0	0	0	4	0	6	17	0	9	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0	0
3G0 971 509 B	0	0	0	0	0	0	18	11	0	0	0	0	0	0	2	0	2	15	0	0	2	0	11	1	4	0	0	0	0	0	0	0	0	0	0	0	0	0
3G0 971 509 E	0	0	0	0	0	10	0	0	0	0	0	0	16	18	12	14	9	0	20	0	0	8	0	13	14	20	0	0	0	0	0	0	0	0	0	0	0	0
3G0 971 509 F	0	0	0	0	18	0	19	0	0	0	5	0	8	0	0	0	0	0	0	15	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3Q0 971 013 C	18	19	5	0	0	1	0	0	0	10	0	0	0	0	0	0	10	0	0	0	0	17	0	9	2	0	0	0	0	0	0	0	0	0	0	0	0	0
3Q0 971 015 C	0	16	7	2	1	15	3	0	2	0	0	0	0	8	0	0	20	0	0	0	0	12	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3Q0 971 237	18	0	6	0	7	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0
3Q0 971 475	11	11	0	8	0	0	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5G0 971 509 J	0	18	0	12	0	12	11	20	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	8	0	0	0
5G0 971 509 K	2	0	0	11	0	17	0	0	0	1	12	17	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5G0 971 509 L	1	5	4	0	0	0	4	18	0	0	0	0	0	0	0	0	0	0	0	0	18	2	12	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5Q0 971 015 F	18	10	18	20	0	0	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	14	0	0
5Q0 971 015 G	14	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	0
5Q0 971 015 H	0	17	0	1	0	0	0	10	10	0	0	0	10	0	19	0	0	0	0	0	0	0	12	0	0	0	0	0	10	15	0	0	0	0	0	7	0	0
5Q0 971 015 J	0	7	12	0	0	0	7	0	19	0	0	0	17	0	17	0	0	0	17	11	0	0	5	16	16	0	0	0	0	0	0	0	0	0	0	0	0	0
5Q0 971 449 A	0	0	18	8	15	5	7	13	0	2	4	18	0	0	0	5	12	11	5	13	6	13	11	2	11	18	2	17	14	0	0	0	0	13	3	10	0	0
5Q0 971 475 A	0	11	8	19	15	9	4	1	20	10	0	2	0	0	12	0	9	9	1	0	0	0	14	4	5	12	10	10	9	4	10	0	2	0	0	2	0	4
5Q0 971 483 A	0	0	0	0	0	2	0	5	12	0	12	17	2	0	0	5	0	7	0	0	0	0	0	0	0	0	0	0	12	0	7	0	0	0	0	0	0	8
8V0 971 509 E	0	0	0	0	0	0	0	0	0	0	0	17	10	0	9	3	15	0	0	0	0	14	3	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0
8V0 971 509 F	0	0	0	0	0	0	0	0	0	0	0	1	16	13	0	17	0	17	15	0	0	0	19	15	0	0	0	2	0	0	0	0	0	17	0	0	16	0
8V0 971 509 H	11	6	0	0	0	0	0	0	11	0	10	10	12	0	0	16	0	17	0	0	0	2	0	4	4	11	0	6	7	16	0	19	9	12	0	0	0	0
8V0 971 509 K	8	0	15	14	20	0	20	0	0	2	0	3	0	5	2	3	12	0	20	0	0	0	13	11	0	0	10	0	11	0	0	0	0	0	11	0	3	0
A5E32526521011	0	15	0	0	0	9	0	4	16	11	0	6	0	0	0	0	0	0	19	0	0	0	0	0	0	0	0	0	4	0	0	5	0	0	0	0	0	0
A5E36172628001	13	20	8	0	0	6	12	0	0	2	0	0	1	0	16	0	7	0	20	0	0	0	9	6	0	0	0	0	3	0	0	0	0	0	0	0	0	0

Figure 34: Screen shot of customer demands.

RUN RESTART	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	tardy jobs
30644624	11	0	0	25	0	0	15	0	0	0	20	0	0	0	0	0	30	0	0	0	0	0	0	0	0	0	5	5	0	0	0	0	0	0	0	0	0	0	9
30644791	14	0	0	30	0	0	31	0	0	0	19	0	0	0	0	0	24	0	8	0	0	0	0	0	16	0	0	0	0	0	12	0	0	0	20	0	0	0	
30644794	0	3	0	0	0	0	35	0	0	0	0	0	0	0	0	0	13	0	0	0	0	15	0	0	0	2	20	1	0	0	0	0	0	0	0	0	0	0	20
31384342	13	12	5	0	0	0	14	0	0	0	0	0	0	0	0	0	15	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	3
31415546	15	0	5	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
31415563	11	6	0	5	0	0	18	0	0	0	14	0	0	0	0	0	3	0	0	0	0	32	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	3
31419516	0	0	0	0	0	0	0	0	0	0	46	0	0	0	0	0	20	0	0	0	0	19	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	26
31433050	0	0	0	5	7	0	4	0	0	0	20	0	0	0	0	0	0	0	28	0	4	0	0	0	0	0	42	0	0	0	0	0	0	0	0	0	0	0	53
31453587	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	
31674022	0	0	0	0	4	0	23	0	0	0	40	0	0	0	0	0	23	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
31674791	0	0	0	5	0	0	5	0	0	0	37	0	0	0	0	0	0	0	0	0	0	53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
31678731	0	0	0	0	3	0	0	0	0	0	17	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0	19	15	0	0	0	0	0	0	0	0	0	0	13
31687005	0	4	17	7	0	0	0	0	0	0	40	0	0	0	0	0	0	0	89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
3Q0 971 225 B	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	50	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0	0	0	0	
3G0 971 509 B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	48	0	0	0	0	16	0	0	0	0	0	0	0	0	0	0	0	
3G0 971 509 E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60	0	0	0	0	21	73	0	0	0	0	0	0	0	0	0	0	
3G0 971 509 F	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0	0	33	0	0	0	0	0	0	0	0	0	1	18	0	0	0	0	0	0	0	0	0	0	
3Q0 971 013 C	18	19	5	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	47	0	0	0	0	0	0	0	0	0	0	
3Q0 971 015 C	0	16	7	2	0	0	0	0	0	0	0	0	0	0	0	0	47	0	0	0	0	14	0	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0	
3Q0 971 237	18	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	6	0	7	0	0	0	0	0	0	0	0	0	0	
3Q0 971 475	11	11	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0	0	0	
5G0 971 509 J	0	18	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	69	0	0	0	0	0	0	0	0	0	0	0	0	8
5G0 971 509 K	2	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	0	0	0	0	0	0	0	0	0	0	0	
5G0 971 509 L	1	5	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	41	0	0	0	0	0	0	0	0	0	0	0	
5Q0 971 015 F	18	10	18	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0	0	22
5Q0 971 015 G	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0	0	0	0	8
5Q0 971 015 H	0	17	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	79
5Q0 971 015 J	0	7	12	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	123
5Q0 971 449 A	0	0	18	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	231
5Q0 971 475 A	0	11	8	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	46	75	0	0	0	0	0	0	0	0	0	0	57
5Q0 971 483 A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	54	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27
8V0 971 509 E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	83
8V0 971 509 F	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	147
8V0 971 509 H	11	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	166
8V0 971 509 K	8	0	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	160
A5E32526521011	0	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	74
A5E36172628001	13	20	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	82
Capacity	1133	1425	1717	954	2082	2245	688	2260	2244	2228	2	2230	2216	2216	2192	2180	199	2232	790	2250	2210	166	2282	2282	2074	1447	482	873	2316	2296	2152	2236	2262	2262	2013	2253	2253	2253	
Capacity Usage	1267	975	683	1446	318	155	1712	140	156	172	2398	170	184	184	208	220	2201	168	1610	150	190	2234	118	118	326	953	1918	1527	84	104	248	164	138	138	387	147	147	147	
Total Capacity	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	

Figure 35: Screen shot of after sales production plan.

Since, the application generates a feasible production plan, production runs without having any line stoppages. This situation leads to increase in production efficiency. This efficiency rate is calculated as following equation, $\frac{Actual\ Production\ Quantity}{Target\ Quantity} x\ 100\%$. Application also displays how much capacity required for each planning period. This situation allows production team to plan the workforce allocation.

In addition, this production plan gives information about tardy jobs and their periods. This information is vital for production planner. The reason is that planner can contact to the customer as soon as he gets this plan and can postpone the due dates of tardy jobs. As a result of this situation, tardiness penalty cost is automatically be eliminated.

Chapter 10

Discussion and Conclusion

This thesis considers the real-life problem of determining the schedule of after-sales production in wire-harness industry by minimizing the tardiness and subject to resources capacity restrictions while satisfying the customer's demand for a given planning horizon. To represent the problem mathematically a mixed integer programing model with cost-based objective function and capacitated resource constraints are developed. The model considers penalty costs while allowing the demand for all products. Since this study desires to provide a user-friendly application besides the mathematical model, to be able to solve real size problems within acceptable computation times, a heuristic method is developed. The heuristic provides a scheduling and sequencing mechanism for all feasible jobs. Also, it provides infeasibility information at the beginning of the planning horizon which helps to avoid costs of tardy jobs. It should be emphasized that main contributions of this thesis are a new heuristic method, real-life problem with read-data, capacitated lot sizing on after-sales production area and an applicable user-friendly application.

To examine the effectiveness of the developed heuristic algorithm, numerical examples are constructed on the proposed method and traditional metaheuristic solution approaches. To the best of author's knowledge, this study is first to focus on real-life problem in after-sales production system with a heuristic method which considers resource capacity restrictions and allocation in production planning horizon with high product variety. Demonstrative example and real problem results showed that the proposed heuristic algorithm gives solutions which are close to the optimal solution within a very short amount of computation time. Since application can be used in industry, it should provide quick response within short time.

The application generated uses the proposed heuristic method and MS-Excel user interface. The heuristic method is coded in Visual Basic Application (VBA) language. The reasons of using MS-Excel interface are given as follows. First, company has own MS OFFICE applications. The second reason is MS-Excel has a user friendly interface. In addition, people knows how to use MS-Excel. However, the most important reason is that MS-Excel allows to enter the dynamic data entry. All data structures are dynamic. Authorized users can add new products, new bill of materials, new raw materials or new demands into application without recoding anything in VBA environments. Working principle of the algorithm is the same for all projects. When a new project arrives, only required process adds related data into related sheets and run the application. This makes the created application user friendly since user just needs to know how to use MS Excel.

As future research directions, this study can be extended in a number of ways. First, the developed heuristic algorithm can be compared with other existing heuristics or metaheuristic algorithms such as Genetic Algorithms. Results can be used to measure performance of the proposed heuristic method. Second, this study uses only the real data so hypothetical data can be used to investigate the stochastic environment. Finally, the application developed currently uses MS-Excel interface. This situation causes only one user edition on the application file. Therefore, more user friendly and server connected a desktop application can be coded. As a matter of fact, server and data tables are already created for this application.

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Appendices

Appendix A

Data for Customer Demands

Products/ Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13
30644624	11	0	0	25	15	0	0	0	20	0	0	0	0
30644791	14	0	0	30	0	0	31	0	0	0	19	16	0
30644794	0	3	0	0	1	16	18	0	0	0	0	0	0
31384342	13	12	5	0	1	13	0	0	0	0	0	0	0
31415546	15	0	5	20	0	0	0	0	0	0	0	0	0
31415563	11	6	0	5	1	17	0	0	0	14	0	0	13
31419516	0	0	0	0	0	0	0	16	12	18	0	0	3
31433050	0	0	0	5	7	15	0	9	0	0	0	11	0
31453587	0	0	0	0	0	0	0	0	0	0	0	0	0
31674022	0	0	0	0	4	3	20	19	1	2	18	3	0
31674791	0	0	0	5	0	19	5	0	14	4	0	7	0
31678731	0	0	0	0	9	0	19	0	0	0	0	0	0
31687005	0	4	17	7	18	10	2	5	8	9	0	20	0
3Q0 971 225 B	0	0	0	0	0	4	0	0	13	0	0	0	4
3G0 971 509 B	0	0	0	0	0	0	18	11	0	0	0	0	0
3G0 971 509 E	0	0	0	0	0	10	0	0	0	0	0	0	16
3G0 971 509 F	0	0	0	0	18	0	19	0	0	0	5	0	8
3Q0 971 013 C	18	19	5	0	0	1	0	0	0	10	0	0	0
3Q0 971 015 C	0	16	7	2	1	15	3	0	2	0	0	0	0
3Q0 971 237	18	0	6	0	7	0	0	4	0	0	0	0	0
3Q0 971 475	11	11	0	8	0	0	17	0	0	0	0	0	0
5G0 971 509 J	0	18	0	12	0	12	11	20	0	0	0	0	0
5G0 971 509 K	2	0	0	11	0	17	0	0	0	1	12	17	0
5G0 971 509 L	1	5	4	0	0	0	4	18	0	0	0	0	0
5Q0 971 015 F	18	10	18	20	0	0	17	0	0	0	0	0	0
5Q0 971 015 G	14	0	0	0	0	0	0	0	0	0	6	0	0
5Q0 971 015 H	0	17	0	1	0	0	0	10	10	0	0	0	10
5Q0 971 015 J	0	7	12	0	0	0	7	0	19	0	0	0	17
5Q0 971 449 A	0	0	18	8	15	5	7	13	0	2	4	18	0
5Q0 971 475 A	0	11	8	19	15	9	4	1	20	10	0	2	0
5Q0 971 483 A	0	0	0	0	0	2	0	5	12	0	12	17	2
8V0 971 509 E	0	0	0	0	0	0	0	0	0	0	0	17	10
8V0 971 509 F	0	0	0	0	0	0	0	0	0	0	0	1	16

8V0 971 509 H	11	6	0	0	0	0	0	0	11	0	10	10	12
8V0 971 509 K	8	0	15	14	20	0	20	0	0	2	0	3	0
A5E32526521011	0	15	0	0	0	9	0	4	16	11	0	6	0
A5E36172628001	13	20	8	0	0	6	12	0	0	2	0	0	1

Products/ Weeks	14	15	16	17	18	19	20	21	22	23	24	25	26
30644624	0	20	0	10	0	0	0	0	0	0	0	0	0
30644791	0	0	0	8	4	4	0	0	0	0	0	16	0
30644794	0	13	0	0	0	0	5	10	0	0	0	0	14
31384342	0	0	15	0	0	0	0	0	0	0	0	0	0
31415546	0	0	0	0	0	0	12	0	0	0	0	0	0
31415563	16	1	0	2	3	0	0	0	0	2	7	0	0
31419516	9	8	0	0	0	0	0	0	19	0	0	0	11
31433050	4	0	5	0	0	8	0	4	0	0	0	19	20
31453587	0	0	0	0	0	0	0	0	0	0	0	0	0
31674022	0	5	0	15	1	17	0	0	0	0	0	0	0
31674791	0	17	0	4	11	14	0	0	0	0	0	0	0
31678731	0	0	0	0	0	0	0	0	0	12	0	0	4
31687005	0	13	0	16	20	8	0	0	0	0	0	0	0
3Q0 971 225 B	0	6	17	0	9	0	0	0	0	0	0	13	0
3G0 971 509 B	0	2	0	2	15	0	0	2	0	11	1	4	0
3G0 971 509 E	18	12	14	9	0	20	0	0	8	0	13	14	20
3G0 971 509 F	0	0	0	0	0	0	15	0	0	0	4	0	0
3Q0 971 013 C	0	0	0	10	0	0	0	0	17	0	9	2	0
3Q0 971 015 C	8	0	0	20	0	0	0	0	12	13	0	0	0
3Q0 971 237	0	0	0	0	0	0	0	0	0	0	0	0	0
3Q0 971 475	0	0	0	0	0	0	0	0	0	0	0	0	0
5G0 971 509 J	0	0	0	12	0	0	0	0	0	0	14	0	0
5G0 971 509 K	3	0	0	0	0	0	0	0	0	0	0	0	0
5G0 971 509 L	0	0	0	0	0	0	0	18	2	12	5	0	0
5Q0 971 015 F	0	0	0	0	0	0	0	0	0	0	0	0	0
5Q0 971 015 G	0	0	0	0	0	0	7	0	0	0	0	0	0
5Q0 971 015 H	0	19	0	0	0	0	0	0	0	12	0	0	0
5Q0 971 015 J	0	17	0	0	0	17	11	0	0	5	16	16	0
5Q0 971 449 A	0	0	5	12	11	5	13	6	13	11	2	11	18
5Q0 971 475 A	0	12	0	9	9	1	0	0	0	14	4	5	12
5Q0 971 483 A	0	0	5	0	7	0	0	0	0	0	0	0	0
8V0 971 509 E	0	9	3	15	0	0	0	0	14	3	0	0	0
8V0 971 509 F	13	0	17	0	17	15	0	0	0	19	15	0	0
8V0 971 509 H	0	0	16	0	17	0	0	0	2	0	4	4	11
8V0 971 509 K	5	2	3	12	0	20	0	0	0	13	11	0	0
A5E32526521011	0	0	0	0	0	19	0	0	0	0	0	0	0
A5E36172628001	0	16	0	7	0	20	0	0	0	9	6	0	0

Products/ weeks	27	28	29	30	31	32	33	34	35	36	37	38
30644624	5	5	9	0	0	0	0	0	0	0	0	0
30644791	0	0	0	0	12	0	0	0	20	0	0	0
30644794	8	1	0	0	0	9	11	0	0	0	0	0
31384342	0	6	0	3	0	0	0	0	0	0	0	0
31415546	0	0	0	0	0	0	0	0	0	0	0	0
31415563	0	0	3	0	0	0	0	0	0	0	0	0
31419516	1	0	0	0	0	9	0	0	0	5	12	0
31433050	3	0	19	0	9	18	0	0	0	3	4	0
31453587	0	0	0	0	0	3	0	0	0	0	0	0
31674022	0	0	0	0	0	0	0	0	0	0	0	0
31674791	0	0	3	0	0	0	0	0	0	0	0	0
31678731	3	15	0	9	1	0	0	3	0	0	0	0
31687005	0	0	0	0	0	1	0	0	0	0	0	0
3Q0 971 225 B	0	0	0	0	0	0	0	0	0	0	0	0
3G0 971 509 B	0	0	0	0	0	0	0	0	0	0	0	0
3G0 971 509 E	0	0	0	0	0	0	0	0	0	0	0	0
3G0 971 509 F	0	0	0	0	0	0	0	0	0	0	0	0
3Q0 971 013 C	0	0	0	0	0	0	0	0	0	0	0	0
3Q0 971 015 C	0	0	0	0	0	0	0	0	0	0	0	0
3Q0 971 237	0	7	0	0	0	0	0	0	0	0	0	0
3Q0 971 475	0	0	0	0	0	0	0	0	0	0	0	0
5G0 971 509 J	0	0	0	0	0	0	0	0	8	0	0	0
5G0 971 509 K	0	0	0	0	0	0	0	0	0	0	0	0
5G0 971 509 L	0	0	0	0	0	0	0	0	0	0	0	0
5Q0 971 015 F	0	0	0	0	0	0	0	0	8	14	0	0
5Q0 971 015 G	0	0	0	0	0	0	8	0	0	0	0	0
5Q0 971 015 H	0	0	10	15	0	0	0	0	0	7	0	0
5Q0 971 015 J	0	0	0	0	0	0	0	0	0	0	0	0
5Q0 971 449 A	2	17	14	0	0	0	0	13	3	10	0	0
5Q0 971 475 A	10	10	9	4	10	0	2	0	0	2	0	4
5Q0 971 483 A	0	0	12	0	7	0	0	0	0	0	0	8
8V0 971 509 E	0	0	0	0	12	0	0	0	0	0	0	0
8V0 971 509 F	0	2	0	0	0	0	0	17	0	0	16	0
8V0 971 509 H	0	6	7	16	0	19	9	12	0	0	0	0
8V0 971 509 K	10	0	11	0	0	0	0	0	11	0	3	0
A5E32526521011	0	0	4	0	0	5	0	0	0	0	0	0
A5E36172628001	0	0	3	0	0	0	0	0	0	0	0	0

Appendix B

Data for Bills of Materials

COMPONENTS / FINISHED GOODS	30644624	30644791	30644794	31384342	31415546	31415563	31419516	31433050	31453587	31674022	31674791	31678731	31687005
M3569C03	1	0	3	2	3	1	4	1	2	1	3	1	2
M3569C07	2	2	0	4	1	0	1	3	0	1	3	0	3
M4165004	0	2	1	4	2	0	1	4	0	2	1	4	4
M4165015	2	0	4	0	4	0	1	1	4	2	3	0	4
M3324204	2	3	0	3	0	4	2	2	3	2	1	4	0
M3344008	0	2	0	0	2	2	3	3	0	1	3	1	2
M3344009	1	0	1	0	1	1	0	3	2	2	2	3	0
M3344125	0	0	2	1	3	0	0	1	2	0	2	4	4
M3344126	2	0	0	2	3	0	1	3	1	2	1	2	2
M3344167	2	2	1	0	1	4	0	2	3	4	0	0	0
M3344172	3	0	0	2	4	1	3	3	0	0	2	2	1
M3344173	0	4	0	1	3	4	1	4	4	3	3	0	4
M3344224	1	0	4	4	3	0	1	1	4	4	1	2	4
M3371004	4	1	2	1	0	2	0	0	3	2	2	2	3
M3371009	2	0	4	3	3	1	4	2	0	0	0	0	4
M3371042	2	0	0	2	1	2	0	3	4	4	2	2	2
12015798	2	5	6	0	6	0	6	0	2	1	5	3	3
12015858	6	1	4	4	4	2	1	4	6	4	6	6	3
12047682	1	0	0	4	3	2	0	4	3	3	4	0	1
12052643	1	4	4	0	2	2	0	2	6	0	6	6	6
12052848	6	2	1	2	5	0	0	4	4	6	5	3	2
12059181	4	5	3	1	0	5	3	0	0	0	0	0	0
12066681	3	0	1	1	1	6	6	4	0	5	2	5	2
12124819	4	3	2	0	0	0	3	0	0	0	6	4	3
12129787	6	4	1	0	0	0	0	5	5	6	0	0	0
12160437	0	4	4	4	6	2	1	4	2	0	5	0	0
13678636	1	0	6	4	1	4	4	0	0	6	6	0	0
15332142	0	2	1	4	4	0	0	5	0	0	0	1	0
15369260	6	0	1	4	0	5	2	2	5	3	0	0	5

15488183	4	0	0	0	2	0	6	6	1	1	4	1	1
15327501	6	4	1	4	6	4	0	6	0	5	5	4	0
12020807	3	0	0	3	3	1	0	5	2	1	3	3	3
12033731	2	3	4	0	6	1	5	6	2	3	1	5	0
12052850	4	1	1	5	0	2	3	5	0	0	0	6	5
12059185	1	0	0	0	6	6	4	1	5	3	6	2	5
12059450	2	2	6	4	1	4	5	3	1	0	5	0	0
12064752	1	0	6	4	0	2	6	2	6	0	3	4	2
12066176	2	4	3	0	0	5	3	3	0	0	3	6	0
12084924	0	1	2	0	0	0	1	6	0	3	4	4	0
12110250	0	0	0	4	3	5	2	4	6	3	0	3	2
13514575	4	0	0	3	0	5	3	4	3	6	3	2	2
13805375	6	0	0	2	5	0	3	4	2	3	0	6	5
15317832	0	5	3	5	0	4	1	6	3	2	3	2	4
15319799	3	2	2	3	6	2	2	1	1	4	4	3	5
15319801	1	0	0	6	2	6	6	2	6	4	0	5	0
15324070	4	5	5	3	4	6	5	3	0	0	4	0	6
15326059	1	1	4	1	0	5	0	0	3	4	6	0	0
15358639	0	6	3	5	0	6	0	3	3	2	6	2	6
15418415	1	3	2	6	0	0	6	0	0	2	2	4	4
15491363	4	5	5	0	0	1	2	2	3	6	3	0	0
15499124	4	3	0	1	1	1	5	4	1	3	3	5	0
10718190	3	0	0	1	1	6	0	4	1	1	3	1	0
10724596	6	0	6	2	0	0	0	4	0	1	0	2	0
10725808	5	0	3	0	0	1	0	0	6	4	3	0	0
10731371	0	0	4	2	1	6	0	2	1	3	5	0	0
10734087	0	0	6	4	3	6	0	1	6	1	4	3	1
10751583	0	0	1	2	5	0	0	5	6	6	5	4	0
10751584	0	1	1	0	1	6	0	2	2	2	0	2	1
10751585	5	1	4	6	6	6	2	0	0	0	5	1	6
10756523	1	2	5	4	0	0	0	1	1	0	1	0	0
10756524	5	1	5	5	0	0	2	6	0	0	0	6	4
10756527	2	4	4	4	2	0	5	4	5	1	0	4	1
10756531	1	1	0	0	1	6	3	5	5	3	5	2	0
10756533	1	6	6	6	2	6	1	1	0	0	1	5	6
10756534	2	5	2	0	0	0	2	5	0	6	6	0	0
10763182	4	1	5	5	3	0	4	0	4	0	0	4	3
10763185	6	3	2	0	3	0	0	0	0	0	4	0	0
10768667	0	4	4	0	3	0	3	0	5	1	0	0	4
10776148	6	2	6	3	0	4	0	0	6	1	4	4	0
10776325	6	4	6	1	6	1	0	5	5	4	3	3	5
10779004	0	1	4	0	0	0	2	5	4	6	6	4	0
10779162	4	4	1	2	1	2	6	2	0	2	0	2	2
10779593	0	1	6	2	4	0	2	4	0	1	0	1	0
10779598	0	2	1	5	6	2	0	0	3	0	0	0	3
10779751	0	3	3	0	0	0	0	5	0	1	0	5	0
10780235	0	5	0	6	1	6	1	5	6	6	0	1	0

10781054	0	6	0	1	3	6	2	3	1	1	0	0	0
10788769	0	3	0	0	0	2	0	0	4	1	4	4	0
10788770	3	5	0	0	2	4	4	6	6	6	1	4	0
10789065	0	2	0	0	5	0	3	5	2	0	5	0	0
10789197	1	2	0	0	6	0	1	5	1	0	0	1	5
10811280	1	1	0	0	5	0	3	2	5	2	3	0	4
10811281	0	1	1	0	1	0	4	3	1	0	0	6	6
10811290	0	0	5	6	0	0	0	0	5	4	4	1	6
10811966	3	0	5	1	0	0	0	0	0	3	5	6	0
10820502	1	0	4	0	0	0	0	0	1	5	2	2	3
10846768	2	0	0	5	0	0	0	0	1	3	2	5	6
10846959	2	0	6	3	0	6	0	0	1	4	3	2	3
10847167	1	0	5	6	0	6	0	0	6	0	6	3	3

COMPONENTS / FINISHED GOODS	3Q0971225B	3G0971509B	3G0971509 E	3G0971509 F	3Q0971013C	3Q0971015C	3Q0971237	3Q0971475	5G0971509 J	5G0971509K	5G0971509 L	5Q0971015 F
M3569C03	1	4	2	4	4	3	2	4	0	0	0	4
M3569C07	4	0	2	4	4	0	0	1	4	3	1	0
M4165004	2	3	3	2	3	3	4	3	1	3	2	0
M4165015	1	3	0	1	3	3	1	1	4	4	4	0
M3324204	0	1	2	2	3	1	0	0	2	3	1	1
M3344008	2	4	4	2	1	3	4	4	0	1	1	2
M3344009	0	0	3	1	3	0	2	1	2	4	3	1
M3344125	0	1	0	2	4	4	1	0	0	0	3	2
M3344126	3	4	0	3	4	3	4	4	1	3	0	3
M3344167	3	3	0	4	3	1	2	4	3	4	0	3
M3344172	0	0	4	3	2	0	2	4	4	1	1	3
M3344173	0	2	4	3	2	3	2	4	0	4	1	2
M3344224	0	0	0	0	0	1	4	1	1	4	3	0
M3371004	0	0	4	3	0	0	2	3	0	4	3	4
M3371009	4	4	3	0	0	0	0	1	1	4	4	3
M3371042	2	2	1	1	2	1	0	2	1	0	1	1
12015798	0	5	1	0	6	0	0	5	2	0	1	0
12015858	5	1	2	0	0	0	0	2	5	6	0	0
12047682	1	5	0	1	0	6	6	6	2	2	0	0
12052643	2	1	3	0	4	0	0	4	6	0	0	0
12052848	4	0	0	0	0	0	0	0	0	0	0	0
12059181	0	4	1	2	2	1	3	6	5	1	3	6
12066681	3	1	5	3	5	0	0	0	0	0	0	0

12124819	0	0	4	5	0	6	2	0	4	0	6	3
12129787	0	3	4	4	5	3	3	1	5	1	5	0
12160437	4	1	1	4	4	1	0	5	3	2	1	0
13678636	0	1	1	5	2	4	6	2	6	3	3	4
15332142	0	0	5	5	4	0	0	0	0	2	0	0
15369260	4	5	0	0	0	0	0	5	2	1	6	3
15488183	0	2	3	0	1	4	5	4	0	4	0	3
15327501	0	0	3	4	2	3	3	0	0	0	0	0
12020807	0	5	4	5	0	4	0	0	2	0	5	1
12033731	0	0	0	6	4	0	6	1	6	0	0	4
12052850	1	5	3	5	0	2	6	3	3	1	1	5
12059185	6	2	0	0	0	0	3	3	5	3	0	5
12059450	0	3	5	0	0	0	0	3	0	0	4	3
12064752	0	0	0	3	4	5	4	0	0	2	1	4
12066176	0	2	5	2	5	2	1	0	4	1	1	2
12084924	5	5	5	0	0	3	0	1	3	4	5	2
12110250	6	1	6	3	2	2	5	2	3	2	3	6
13514575	0	1	6	4	2	0	0	3	6	3	2	4
13805375	1	4	0	1	0	0	0	0	3	4	1	0
15317832	0	2	3	4	0	5	0	3	6	6	6	0
15319799	2	0	0	3	0	0	0	0	5	0	5	3
15319801	1	2	0	0	0	0	0	4	5	1	5	6
15324070	3	2	0	5	0	0	1	0	0	1	0	4
15326059	4	4	0	0	4	1	6	0	2	0	2	5
15358639	0	0	0	6	3	0	5	4	4	0	0	3
15418415	0	0	2	5	2	1	2	2	2	5	0	6
15491363	2	0	2	6	5	3	0	0	3	0	0	3
15499124	6	0	0	5	4	5	0	0	0	0	0	4
10718190	0	0	0	0	4	4	2	4	4	0	0	0
10724596	0	0	1	0	5	4	0	0	6	2	5	0
10725808	0	3	5	2	2	0	0	4	1	6	4	0
10731371	0	2	5	1	0	2	1	5	5	1	3	6
10734087	0	1	1	6	0	2	3	5	0	1	1	2
10751583	0	0	2	3	0	4	5	4	5	1	2	1
10751584	5	2	5	4	0	0	1	4	4	1	4	5
10751585	1	1	2	0	1	2	4	4	6	2	2	0
10756523	0	1	2	0	5	1	2	4	4	5	1	0
10756524	0	3	5	3	0	6	5	2	4	5	0	0
10756527	3	3	1	4	5	6	6	0	0	2	4	0
10756531	0	0	6	3	3	3	0	0	4	6	2	0
10756533	2	2	3	3	2	0	3	5	2	3	2	0
10756534	0	4	4	0	0	6	5	5	4	3	5	6
10763182	6	0	2	3	6	3	2	5	1	3	5	5
10763185	6	2	4	0	0	2	0	5	1	2	0	6
10768667	0	5	1	4	5	2	0	0	6	1	6	4
10776148	0	4	3	4	0	0	0	0	2	0	1	4
10776325	0	0	5	5	0	0	0	0	0	6	0	0

10779004	0	0	6	5	0	5	0	4	3	2	0	0
10779162	0	5	0	1	6	4	5	6	2	4	2	0
10779593	1	0	2	5	6	4	5	5	6	0	5	0
10779598	6	6	2	6	5	0	5	5	6	0	6	0
10779751	6	0	1	4	0	6	0	0	0	0	4	0
10780235	2	0	0	3	0	0	2	4	0	0	0	3
10781054	6	0	2	0	3	6	1	0	0	0	0	3
10788769	6	1	5	4	2	0	0	2	0	0	0	6
10788770	0	5	2	6	2	4	3	1	0	1	0	2
10789065	0	6	0	0	3	0	5	1	0	3	0	3
10789197	0	6	1	4	1	5	4	2	2	3	0	6
10811280	0	1	2	2	0	6	6	6	2	0	5	6
10811281	0	3	1	0	3	1	0	0	2	0	0	0
10811290	0	1	2	3	4	6	4	0	2	0	2	3
10811966	6	5	1	0	1	2	4	6	0	0	5	6
10820502	5	4	1	0	1	5	5	5	1	0	2	2
10846768	6	3	3	0	2	5	5	4	4	0	3	0
10846959	4	3	0	3	1	6	5	2	0	0	1	6
10847167	1	5	0	1	4	6	1	4	4	0	3	1

COMPONENTS / FINISHED GOODS	5Q0971015G	5Q0971015H	5Q0971015J	5Q0971449A	5Q0971475A	5Q0971483A	8V0971509E	8V0971509F	8V0971509H	8V0971509K	A5E32526521011	A5E36172628001
M3569C03	1	2	4	0	3	1	0	2	3	3	3	3
M3569C07	0	1	1	1	3	0	0	1	4	0	1	2
M4165004	2	4	4	3	3	3	1	4	4	4	4	4
M4165015	1	3	2	4	0	4	4	0	3	1	3	3
M3324204	0	3	1	2	2	3	0	2	4	4	1	3
M3344008	0	4	3	4	2	3	0	0	3	0	4	1
M3344009	3	2	1	1	2	2	3	3	0	4	1	3
M3344125	0	3	3	2	0	2	1	2	2	0	3	4
M3344126	1	1	4	0	4	3	2	2	2	0	0	0
M3344167	2	3	3	3	4	1	4	3	1	3	2	0
M3344172	3	2	2	4	0	4	2	1	1	4	3	0
M3344173	2	1	3	0	4	4	2	0	3	0	2	2
M3344224	4	1	1	0	2	2	4	3	1	4	4	3
M3371004	1	2	2	0	3	1	1	1	3	2	2	4
M3371009	1	2	1	0	1	3	2	3	2	3	0	3
M3371042	1	0	0	0	1	0	3	4	4	2	2	1
12015798	4	0	2	4	6	1	4	5	3	1	2	2
12015858	1	0	0	3	5	0	0	0	0	3	6	4

12047682	6	0	0	6	0	0	0	0	0	6	3	6
12052643	0	2	6	5	6	0	4	1	3	1	6	6
12052848	6	3	1	2	2	4	6	4	4	1	0	5
12059181	5	0	0	1	6	3	1	0	6	4	4	0
12066681	0	5	3	2	0	2	0	0	0	0	5	3
12124819	1	0	0	0	0	2	0	5	5	0	5	1
12129787	4	5	0	0	3	1	0	4	6	4	1	3
12160437	1	1	0	5	0	1	4	2	0	5	3	6
13678636	5	1	2	2	5	0	6	2	2	2	3	2
15332142	0	0	4	6	3	5	0	1	0	3	6	0
15369260	3	5	0	5	2	0	5	1	4	2	5	1
15488183	0	3	0	0	0	0	1	2	2	2	2	0
15327501	0	0	2	3	3	0	1	1	1	2	2	2
12020807	4	5	4	3	1	4	5	4	4	1	4	0
12033731	0	5	2	1	1	2	2	0	5	5	0	0
12052850	3	3	0	2	1	4	0	2	5	0	0	5
12059185	5	1	0	0	0	0	4	4	0	0	6	3
12059450	6	0	3	4	3	0	0	0	5	6	5	1
12064752	5	3	3	6	0	2	2	0	1	0	6	0
12066176	1	0	5	5	3	4	0	1	3	4	2	3
12084924	5	1	5	2	4	0	2	2	3	1	4	6
12110250	2	0	1	2	2	0	3	6	2	0	0	0
13514575	5	1	1	3	1	3	4	4	2	1	3	0
13805375	2	6	3	4	6	1	1	6	0	2	5	6
15317832	0	0	2	1	2	0	0	0	3	6	2	1
15319799	6	4	6	3	2	1	1	5	0	4	1	0
15319801	2	1	3	2	1	0	2	0	6	3	3	2
15324070	6	4	2	0	0	0	0	5	3	6	5	3
15326059	3	5	2	4	1	4	0	4	4	0	1	1
15358639	1	2	2	5	5	3	0	0	2	0	6	3
15418415	4	5	2	3	1	6	0	0	6	4	1	0
15491363	1	0	2	1	3	6	0	0	1	5	4	0
15499124	1	0	0	0	5	2	0	0	1	2	0	2
10718190	0	0	0	0	0	6	2	0	6	1	2	1
10724596	2	0	0	0	0	3	0	0	1	2	0	0
10725808	0	0	0	0	0	0	0	0	3	6	0	0
10731371	1	0	0	0	1	0	6	3	0	6	0	0
10734087	0	0	2	0	0	3	3	0	0	6	0	0
10751583	5	1	6	0	0	1	5	1	0	4	0	0
10751584	2	4	2	0	0	5	4	0	0	4	0	0
10751585	0	5	3	4	0	0	0	0	0	6	6	5
10756523	4	5	0	0	0	6	5	0	0	4	3	2
10756524	6	3	2	4	0	2	0	0	0	5	0	4
10756527	6	0	3	0	0	0	0	0	5	0	5	4
10756531	0	2	3	3	4	0	0	0	0	0	0	2
10756533	3	0	3	3	4	0	0	3	1	0	5	2
10756534	0	0	0	4	4	0	0	6	1	0	1	5

10763182	0	0	0	1	3	0	0	6	3	0	1	3
10763185	0	0	0	5	0	0	3	0	0	0	4	0
10768667	0	0	0	5	0	0	0	0	1	5	3	0
10776148	0	0	0	1	3	2	4	2	3	6	3	0
10776325	0	0	0	0	3	2	5	4	0	1	1	0
10779004	4	0	4	2	5	4	0	4	3	1	5	0
10779162	0	0	5	6	1	3	3	0	3	4	4	0
10779593	0	0	4	1	3	0	4	6	4	1	4	0
10779598	0	0	5	2	1	3	4	0	0	0	3	6
10779751	0	0	2	2	5	5	0	5	0	4	4	2
10780235	0	5	6	4	4	4	1	3	5	6	4	5
10781054	0	3	4	0	1	4	2	0	0	4	6	1
10788769	0	3	4	0	0	5	4	0	0	1	5	2
10788770	0	3	6	0	5	6	3	0	1	0	2	1
10789065	5	0	1	0	1	1	0	5	0	4	0	6
10789197	2	0	2	0	6	4	6	0	2	4	0	4
10811280	4	1	1	0	4	4	1	0	6	4	4	3
10811281	6	3	0	0	3	2	4	1	0	3	2	4
10811290	0	4	0	3	3	6	2	2	2	5	0	5
10811966	0	0	0	3	1	0	1	4	1	1	0	4
10820502	0	6	0	1	5	0	1	3	4	0	0	5
10846768	0	3	0	3	3	0	0	3	1	3	0	0
10846959	0	3	0	2	4	6	6	3	4	2	0	0
10847167	0	5	0	5	3	5	0	0	5	2	0	3

Appendix C

Data for Material Inventories

Components	Current Inventory	1	2	3	4	5	6	7	8	9	10	11	12
M3569C03	3000	0	3	0	0	0	0	828	0	0	0	651	0
M3569C07	3000	0	0	0	0	0	0	599	0	0	0	591	0
M4165004	3000	0	0	0	0	0	0	866	0	0	0	722	0
M4165015	3000	0	0	0	0	0	0	820	0	0	0	619	0
M3324204	3000	0	0	0	0	0	0	802	0	0	0	947	0
M3344008	3000	0	0	0	0	0	0	0	0	0	0	787	0
M3344009	3000	0	0	0	0	0	0	0	0	0	0	660	0
M3344125	3000	0	0	0	0	0	0	677	0	0	0	653	0
M3344126	3000	0	0	0	0	0	0	696	0	0	0	874	0
M3344167	3000	0	0	0	0	0	0	862	0	0	0	525	0
M3344172	3000	0	0	0	0	0	0	907	0	0	0	906	0
M3344173	3000	0	0	0	0	0	0	535	0	0	0	797	0
M3344224	3000	0	0	0	0	0	0	0	0	0	0	596	0
M3371004	3000	0	0	0	0	0	0	0	0	0	0	736	0
M3371009	3000	0	0	0	0	0	0	0	0	0	0	640	0
M3371042	3000	0	0	0	0	0	0	861	0	0	0	556	0
12015798	3000	0	0	0	0	0	0	606	0	0	0	901	0
12015858	3000	0	0	0	0	0	0	728	0	0	0	768	0
12047682	3000	0	0	0	0	0	0	779	0	0	0	693	0
12052643	3000	0	0	0	0	0	0	599	0	0	0	650	0
12052848	3000	0	0	0	0	0	0	727	0	0	0	783	0
12059181	3000	0	0	0	0	0	0	0	0	0	0	503	0
12066681	3000	0	0	0	0	0	0	0	0	0	0	695	0
12124819	3000	0	0	0	0	0	0	536	0	0	0	790	0
12129787	3000	0	0	0	0	0	0	693	0	0	0	851	0
12160437	3000	0	0	0	0	0	0	508	0	0	0	805	0
13678636	3000	0	0	0	0	0	0	0	0	0	0	521	0
15332142	3000	0	0	0	0	0	0	688	0	0	0	573	0
15369260	3000	0	0	0	0	0	0	773	0	0	0	890	0

15488183	3000	0	0	0	0	0	0	0	0	0	0	831	0
15327501	3000	0	0	0	0	0	0	0	0	0	0	827	0
12020807	3000	0	0	0	0	0	0	982	0	0	0	649	0
12033731	3000	0	0	0	0	0	0	671	0	0	0	770	0
12052850	3000	0	0	0	0	0	0	0	0	0	0	670	0
12059185	3000	0	0	0	0	0	0	911	0	0	0	605	0
12059450	3000	0	0	0	0	0	0	693	0	0	0	911	0
12064752	3000	0	0	0	0	0	0	0	0	0	0	797	0
12066176	3000	0	0	0	0	0	0	531	0	0	0	647	0
12084924	3000	0	0	0	0	0	0	877	0	0	0	655	0
12110250	3000	0	0	0	0	0	0	0	0	0	0	729	0
13514575	3000	0	0	0	0	0	0	810	0	0	0	929	0
13805375	3000	0	0	0	0	0	0	654	0	0	0	711	0
15317832	3000	0	0	0	0	0	0	547	0	0	0	606	0
15319799	3000	0	0	0	0	0	0	519	0	0	0	523	0
15319801	3000	0	0	0	0	0	0	724	0	0	0	560	0
15324070	3000	0	0	0	0	0	0	589	0	0	0	989	0
15326059	3000	0	0	0	0	0	0	633	0	0	0	671	0
15358639	3000	0	0	0	0	0	0	746	0	0	0	804	0
15418415	3000	0	0	0	0	0	0	583	0	0	0	757	0
15491363	3000	0	0	0	0	0	0	898	0	0	0	614	0
15499124	3000	0	0	0	0	0	0	644	0	0	0	893	0
10718190	3000	0	0	0	0	0	0	890	0	0	0	628	0
10724596	3000	0	0	0	0	0	0	776	0	0	0	543	0
10725808	3000	0	0	0	0	0	0	581	0	0	0	643	0
10731371	3000	0	0	0	0	0	0	518	0	0	0	698	0
10734087	3000	0	0	0	0	0	0	808	0	0	0	736	0
10751583	3000	0	0	0	0	0	0	539	0	0	0	612	0
10751584	3000	0	0	0	0	0	0	722	0	0	0	864	0
10751585	3000	0	0	0	0	0	0	919	0	0	0	822	0
10756523	3000	0	0	0	0	0	0	694	0	0	0	540	0
10756524	3000	0	0	0	0	0	0	827	0	0	0	671	0
10756527	3000	0	0	0	0	0	0	768	0	0	0	684	0
10756531	3000	0	0	0	0	0	0	525	0	0	0	568	0
10756533	3000	0	0	0	0	0	0	508	0	0	0	619	0
10756534	3000	0	0	0	0	0	0	747	0	0	0	949	0
10763182	3000	0	0	0	0	0	0	963	0	0	0	844	0
10763185	3000	0	0	0	0	0	0	904	0	0	0	941	0
10768667	3000	0	0	0	0	0	0	948	0	0	0	992	0
10776148	3000	0	0	0	0	0	0	870	0	0	0	810	0
10776325	3000	0	0	0	0	0	0	540	0	0	0	903	0
10779004	3000	0	0	0	0	0	0	885	0	0	0	711	0
10779162	3000	0	0	0	0	0	0	882	0	0	0	880	0
10779593	3000	0	0	0	0	0	0	695	0	0	0	675	0

10779598	3000	0	0	0	0	0	0	877	0	0	0	890	0
10779751	3000	0	0	0	0	0	0	646	0	0	0	825	0
10780235	3000	0	0	0	0	0	0	869	0	0	0	767	0
10781054	3000	0	0	0	0	0	0	586	0	0	0	747	0
10788769	3000	0	0	0	0	0	0	831	0	0	0	971	0
10788770	3000	0	0	0	0	0	0	723	0	0	0	737	0
10789065	3000	0	0	0	0	0	0	538	0	0	0	633	0
10789197	3000	0	0	0	0	0	0	777	0	0	0	995	0
10811280	3000	0	0	0	0	0	0	843	0	0	0	534	0
10811281	3000	0	0	0	0	0	0	639	0	0	0	543	0
10811290	3000	0	0	0	0	0	0	848	0	0	0	970	0
10811966	3000	0	0	0	0	0	0	634	0	0	0	890	0
10820502	3000	0	0	0	0	0	0	536	0	0	0	717	0
10846768	3000	0	0	0	0	0	0	990	0	0	0	556	0
10846959	3000	0	0	0	0	0	0	978	0	0	0	801	0
10847167	3000	0	0	0	0	0	0	950	0	0	0	853	0

Components	Current Inventory	13	14	15	16	17	18	19	20	21	22	23	24
M3569C03	3000	0	0	0	0	513	0	0	0	0	697	0	0
M3569C07	3000	0	0	0	0	819	0	0	0	0	872	0	0
M4165004	3000	0	0	0	0	706	0	918	0	0	964	0	0
M4165015	3000	0	0	0	0	0	0	844	0	0	936	0	0
M3324204	3000	0	0	0	0	961	0	517	0	0	544	0	0
M3344008	3000	0	0	0	0	661	0	949	0	0	640	0	0
M3344009	3000	0	0	0	0	555	0	825	0	0	799	0	0
M3344125	3000	0	0	0	0	692	0	934	0	0	585	0	0
M3344126	3000	0	0	0	0	779	0	817	0	0	809	0	0
M3344167	3000	0	0	0	0	0	0	832	0	0	953	0	0
M3344172	3000	0	0	0	0	0	0	961	0	0	954	0	0
M3344173	3000	0	0	0	0	0	0	630	0	0	547	0	0
M3344224	3000	0	0	0	0	913	0	825	0	0	970	0	0
M3371004	3000	0	0	0	0	645	0	860	0	0	542	0	0
M3371009	3000	0	0	0	0	927	0	525	0	0	917	0	0
M3371042	3000	0	0	0	0	744	0	1000	0	0	517	0	0
12015798	3000	0	0	0	0	511	0	590	0	0	869	0	0
12015858	3000	0	0	0	0	808	0	924	0	0	964	0	0
12047682	3000	0	0	0	0	0	0	802	0	0	851	0	0
12052643	3000	0	0	0	0	0	0	946	0	0	865	0	0
12052848	3000	0	0	0	0	936	0	512	0	0	832	0	0
12059181	3000	0	0	0	0	987	0	842	0	0	542	0	0
12066681	3000	0	0	0	0	505	0	0	0	0	866	0	0

12124819	3000	0	0	0	0	933	0	0	0	0	967	0	0
12129787	3000	0	0	0	0	776	0	591	0	0	693	0	0
12160437	3000	0	0	0	0	742	0	558	0	0	672	0	0
13678636	3000	0	0	0	0	629	0	0	0	0	926	0	0
15332142	3000	0	0	0	0	687	0	954	0	0	996	0	0
15369260	3000	0	0	0	0	709	0	0	0	0	885	0	0
15488183	3000	0	0	0	0	689	0	0	0	0	923	0	0
15327501	3000	0	0	0	0	776	0	674	0	0	591	0	0
12020807	3000	0	0	0	0	892	0	753	0	0	803	0	0
12033731	3000	0	0	0	0	807	0	584	0	0	979	0	0
12052850	3000	0	0	0	0	780	0	822	0	0	653	0	0
12059185	3000	0	0	0	0	0	0	875	0	0	869	0	0
12059450	3000	0	0	0	0	581	0	532	0	0	646	0	0
12064752	3000	0	0	0	0	979	0	645	0	0	987	0	0
12066176	3000	0	0	0	0	831	0	784	0	0	701	0	0
12084924	3000	0	0	0	0	0	0	824	0	0	509	0	0
12110250	3000	0	0	0	0	631	0	897	0	0	515	0	0
13514575	3000	0	0	0	0	0	0	534	0	0	850	0	0
13805375	3000	0	0	0	0	665	0	922	0	0	549	0	0
15317832	3000	0	0	0	0	865	0	951	0	0	657	0	0
15319799	3000	0	0	0	0	987	0	600	0	0	728	0	0
15319801	3000	0	0	0	0	540	0	863	0	0	608	0	0
15324070	3000	0	0	0	0	529	0	846	0	0	686	0	0
15326059	3000	0	0	0	0	527	0	956	0	0	501	0	0
15358639	3000	0	0	0	0	905	0	902	0	0	940	0	0
15418415	3000	0	0	0	0	822	0	737	0	0	681	0	0
15491363	3000	0	0	0	0	794	0	567	0	0	680	0	0
15499124	3000	0	0	0	0	794	0	614	0	0	743	0	0
10718190	3000	0	0	0	0	815	0	959	0	0	741	0	0
10724596	3000	0	0	0	0	717	0	834	0	0	676	0	0
10725808	3000	0	0	0	0	550	0	738	0	0	969	0	0
10731371	3000	0	0	0	0	812	0	852	0	0	715	0	0
10734087	3000	0	0	0	0	843	0	969	0	0	555	0	0
10751583	3000	0	0	0	0	719	0	756	0	0	593	0	0
10751584	3000	0	0	0	0	633	0	738	0	0	824	0	0
10751585	3000	0	0	0	0	629	0	882	0	0	582	0	0
10756523	3000	0	0	0	0	673	0	924	0	0	823	0	0
10756524	3000	0	0	0	0	643	0	600	0	0	800	0	0
10756527	3000	0	0	0	0	885	0	685	0	0	743	0	0
10756531	3000	0	0	0	0	913	0	977	0	0	888	0	0
10756533	3000	0	0	0	0	696	0	799	0	0	851	0	0
10756534	3000	0	0	0	0	602	0	948	0	0	884	0	0
10763182	3000	0	0	0	0	690	0	645	0	0	656	0	0
10763185	3000	0	0	0	0	879	0	952	0	0	885	0	0

10768667	3000	0	0	0	0	905	0	802	0	0	876	0	0
10776148	3000	0	0	0	0	700	0	999	0	0	559	0	0
10776325	3000	0	0	0	0	813	0	729	0	0	542	0	0
10779004	3000	0	0	0	0	932	0	597	0	0	614	0	0
10779162	3000	0	0	0	0	950	0	753	0	0	977	0	0
10779593	3000	0	0	0	0	905	0	639	0	0	568	0	0
10779598	3000	0	0	0	0	972	0	807	0	0	940	0	0
10779751	3000	0	0	0	0	688	0	799	0	0	660	0	0
10780235	3000	0	0	0	0	597	0	757	0	0	597	0	0
10781054	3000	0	0	0	0	662	0	599	0	0	828	0	0
10788769	3000	0	0	0	0	744	0	976	0	0	785	0	0
10788770	3000	0	0	0	0	707	0	962	0	0	584	0	0
10789065	3000	0	0	0	0	879	0	625	0	0	506	0	0
10789197	3000	0	0	0	0	677	0	764	0	0	642	0	0
10811280	3000	0	0	0	0	709	0	625	0	0	559	0	0
10811281	3000	0	0	0	0	621	0	969	0	0	563	0	0
10811290	3000	0	0	0	0	725	0	637	0	0	973	0	0
10811966	3000	0	0	0	0	723	0	868	0	0	977	0	0
10820502	3000	0	0	0	0	870	0	988	0	0	991	0	0
10846768	3000	0	0	0	0	633	0	960	0	0	692	0	0
10846959	3000	0	0	0	0	519	0	661	0	0	556	0	0
10847167	3000	0	0	0	0	768	0	531	0	0	890	0	0

Components	**Current Inventory**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**
M3569C03	3000	0	855	997	752	0	0	0	0	0	0	0	0
M3569C07	3000	0	692	0	799	0	0	0	0	0	0	0	0
M4165004	3000	0	0	934	953	0	0	0	0	0	0	0	0
M4165015	3000	0	637	904	848	0	0	0	0	0	0	0	0
M3324204	3000	0	928	681	0	0	0	0	0	0	0	0	0
M3344008	3000	0	0	567	972	0	0	0	0	0	0	0	0
M3344009	3000	0	586	548	575	0	0	0	0	0	0	0	0
M3344125	3000	0	766	766	0	0	0	0	0	0	0	0	0
M3344126	3000	0	0	736	539	0	0	0	0	0	0	0	0
M3344167	3000	0	515	907	737	0	0	0	0	0	0	0	0
M3344172	3000	0	512	710	0	0	0	0	0	0	0	0	0
M3344173	3000	0	985	951	759	0	0	0	0	0	0	0	0
M3344224	3000	0	0	737	649	0	0	0	0	0	0	0	0
M3371004	3000	0	722	922	779	0	0	0	0	0	0	0	0
M3371009	3000	0	502	0	684	0	0	0	0	0	0	0	0
M3371042	3000	0	604	841	806	0	0	0	0	0	0	0	0
12015798	3000	0	958	781	904	0	0	0	0	0	0	0	0

12015858	3000	0	875	909	960	0	0	0	0	0	0	0	0
12047682	3000	0	570	745	516	0	0	0	0	0	0	0	0
12052643	3000	0	995	715	846	0	0	0	0	0	0	0	0
12052848	3000	0	586	504	765	0	0	0	0	0	0	0	0
12059181	3000	0	513	996	713	0	0	0	0	0	0	0	0
12066681	3000	0	0	587	824	0	0	0	0	0	0	0	0
12124819	3000	0	875	917	573	0	0	0	0	0	0	0	0
12129787	3000	0	702	0	695	0	0	0	0	0	0	0	0
12160437	3000	0	561	774	549	0	0	0	0	0	0	0	0
13678636	3000	0	752	740	724	0	0	0	0	0	0	0	0
15332142	3000	0	767	933	0	0	0	0	0	0	0	0	0
15369260	3000	0	956	714	0	0	0	0	0	0	0	0	0
15488183	3000	0	0	925	895	0	0	0	0	0	0	0	0
15327501	3000	0	790	859	705	0	0	0	0	0	0	0	0
12020807	3000	0	943	0	811	0	0	0	0	0	0	0	0
12033731	3000	0	953	568	993	0	0	0	0	0	0	0	0
12052850	3000	0	735	608	695	0	0	0	0	0	0	0	0
12059185	3000	0	849	580	0	0	0	0	0	0	0	0	0
12059450	3000	0	891	512	780	0	0	0	0	0	0	0	0
12064752	3000	0	698	0	734	0	0	0	0	0	0	0	0
12066176	3000	0	0	532	945	0	0	0	0	0	0	0	0
12084924	3000	0	919	580	863	0	0	0	0	0	0	0	0
12110250	3000	0	891	782	907	0	0	0	0	0	0	0	0
13514575	3000	0	547	530	718	0	0	0	0	0	0	0	0
13805375	3000	0	816	959	614	0	0	0	0	0	0	0	0
15317832	3000	0	554	624	980	0	0	0	0	0	0	0	0
15319799	3000	0	608	867	518	0	0	0	0	0	0	0	0
15319801	3000	0	646	881	570	0	0	0	0	0	0	0	0
15324070	3000	0	774	641	751	0	0	0	0	0	0	0	0
15326059	3000	0	874	647	555	0	0	0	0	0	0	0	0
15358639	3000	0	704	602	599	0	0	0	0	0	0	0	0
15418415	3000	0	588	574	608	0	0	0	0	0	0	0	0
15491363	3000	0	794	992	632	0	0	0	0	0	0	0	0
15499124	3000	0	765	531	993	0	0	0	0	0	0	0	0
10718190	3000	0	793	578	710	0	0	0	0	0	0	0	0
10724596	3000	0	770	983	795	0	0	0	0	0	0	0	0
10725808	3000	0	708	504	803	0	0	0	0	0	0	0	0
10731371	3000	0	904	757	552	0	0	0	0	0	0	0	0
10734087	3000	0	692	850	681	0	0	0	0	0	0	0	0
10751583	3000	0	527	668	555	0	0	0	0	0	0	0	0
10751584	3000	0	886	582	590	0	0	0	0	0	0	0	0
10751585	3000	0	581	949	576	0	0	0	0	0	0	0	0
10756523	3000	0	791	613	692	0	0	0	0	0	0	0	0
10756524	3000	0	712	786	828	0	0	0	0	0	0	0	0

10756527	3000	0	629	715	517	0	0	0	0	0	0	0	0
10756531	3000	0	893	967	602	0	0	0	0	0	0	0	0
10756533	3000	0	582	973	550	0	0	0	0	0	0	0	0
10756534	3000	0	808	789	576	0	0	0	0	0	0	0	0
10763182	3000	0	855	563	911	0	0	0	0	0	0	0	0
10763185	3000	0	774	646	519	0	0	0	0	0	0	0	0
10768667	3000	0	882	953	1000	0	0	0	0	0	0	0	0
10776148	3000	0	896	791	584	0	0	0	0	0	0	0	0
10776325	3000	0	704	820	938	0	0	0	0	0	0	0	0
10779004	3000	0	650	529	885	0	0	0	0	0	0	0	0
10779162	3000	0	825	826	669	0	0	0	0	0	0	0	0
10779593	3000	0	961	744	505	0	0	0	0	0	0	0	0
10779598	3000	0	534	646	942	0	0	0	0	0	0	0	0
10779751	3000	0	892	612	617	0	0	0	0	0	0	0	0
10780235	3000	0	550	874	649	0	0	0	0	0	0	0	0
10781054	3000	0	677	918	893	0	0	0	0	0	0	0	0
10788769	3000	0	522	552	901	0	0	0	0	0	0	0	0
10788770	3000	0	838	975	913	0	0	0	0	0	0	0	0
10789065	3000	0	864	699	796	0	0	0	0	0	0	0	0
10789197	3000	0	835	664	708	0	0	0	0	0	0	0	0
10811280	3000	0	954	640	802	0	0	0	0	0	0	0	0
10811281	3000	0	538	680	995	0	0	0	0	0	0	0	0
10811290	3000	0	567	775	842	0	0	0	0	0	0	0	0
10811966	3000	0	884	571	824	0	0	0	0	0	0	0	0
10820502	3000	0	711	714	579	0	0	0	0	0	0	0	0
10846768	3000	0	540	851	594	0	0	0	0	0	0	0	0
10846959	3000	0	939	743	514	0	0	0	0	0	0	0	0
10847167	3000	0	785	744	891	0	0	0	0	0	0	0	0

Appendix D

Data for Process Times and Penalty Costs

Product	Process Time (Minute)	Tardiness Penalty Cost (Euro)
30644624	12	40
30644791	12	38
30644794	12	36
31384342	12	33
31415546	12	33
31415563	10	33
31419516	10	32
31433050	10	31
31453587	10	30
31674022	8	22
31674791	8	22
31678731	8	22
31687005	8	16
3Q0 971 225 B	6	15
3G0 971 509 B	6	14
3G0 971 509 E	6	13
3G0 971 509 F	6	12
3Q0 971 013 C	6	11
3Q0 971 015 C	5	10
3Q0 971 237	5	10
3Q0 971 475	5	9
5G0 971 509 J	5	8
5G0 971 509 K	4	7
5G0 971 509 L	4	6
5Q0 971 015 F	4	5
5Q0 971 015 G	4	4
5Q0 971 015 H	4	3
5Q0 971 015 J	4	2
5Q0 971 449 A	4	2
5Q0 971 475 A	4	2
5Q0 971 483 A	4	2
8V0 971 509 E	4	2

8V0 971 509 F	4	1
8V0 971 509 H	4	1
8V0 971 509 K	4	1
A5E32526521011	4	1
A5E36172628001	4	1

Appendix E

Developed Algorithm MATLAB Code

```
test=100;
PC=[   13  32  8   22  1   7   10  2   4   15  2   30  2   10  14  1   9   12  22  6   2   40  2   33
5   1   38  11  22  36  3   1   1   31  33  16  33  ];
sqn=[   16  7   22  11  35  23  20  29  26  14  30  9   31  19  15  37  21  17  12  24  28  1
32  5   25  33  2   18  10  3   27  36  34  8   4   13  6   ];


Goodsolution=99999999999999999999;

PC;
arr =PC;

    for i = 1:length(arr)
     for j = i + 1:length(arr)
        if (arr(i) < arr(j))
            SrtTemp = arr(j);
            SrtTemp2 = sqn(j);
            arr(j) = arr(i);
            sqn(j) = sqn(i);
            arr(i) = SrtTemp;
            sqn(i) = SrtTemp2;
        end
     end
```

```
        end

solution=PreProduction(sqn);
% disp(sqn)
% disp(solution)
% disp(arr)


for zz=1:test
a=1;
b=1;
c=1;

for i=1:length(arr)
   if(arr(i)>=30)
       groupA(a)=arr(i);
       groupAA(a)=sqn(i);
   a=a+1;
   end
   if(arr(i)<30 && arr(i)>10 )
       groupB(b)=arr(i);
       groupBB(b)=sqn(i);
       b=b+1;
   end
   if(arr(i)<=10)
       groupC(c)=arr(i);
       groupCC(c)=sqn(i);
       c=c+1;
   end
end
```

```
for i=1:length(groupA)
    j=round(((length(groupA)-i)*rand)+i);

        if (i~=j)

                Temp = groupA(i);
                Temp2 = groupAA(i);
                groupA(i) = groupA(j);
                groupAA(i) = groupAA(j);
                groupA(j) = Temp;
                groupAA(j) = Temp2;

        end
end

for i=1:length(groupB)
    j=round(((length(groupB)-i)*rand)+i);

        if (i~=j)

                Temp = groupB(i);
                Temp2 = groupBB(i);
                groupB(i) = groupB(j);
                groupBB(i) = groupBB(j);
                groupB(j) = Temp;
                groupBB(j) = Temp2;

        end
end
for i=1:length(groupC)
```

```
    j=round(((length(groupC)-i)*rand)+i);

        if (i~=j)

                Temp = groupC(i);
                Temp2 = groupCC(i);
                groupC(i) = groupC(j);
                groupCC(i) = groupCC(j);
                groupC(j) = Temp;
                groupCC(j) = Temp2;

        end
end
arr=[groupA groupB groupC];
sqn=[groupAA groupBB groupCC];

Solution=PreProduction(sqn);
if(Solution < Goodsolution)
  Goodsolution=Solution;
  Goodsqn=sqn;
end



% disp(sqn)
% disp(Solution)
end
disp(['Best solution: ',num2str(Goodsqn)])
disp(['Best objective: ',num2str(Goodsolution)])
```

Appendix F

Simulated Annealing MATLAB Code

```
tzero=100;
tfinal=1;
t=tzero;
m=20;
n=20;
alpha = 0.99;
xzero=[ 1   2   3   4   5   6   7   8   9   10  11  12  13  14  15  16  17  18  19  20  21  22  23
24  25  26  27  28  29  30  31  32  33  34  35  36  37];

x=zeros(n+1,37);
a=zeros(n,2);
x(1,:)=xzero;
xfinal=xzero;
xtemp=zeros(m+1,37);
xtemp(1,:)=xzero;

for i=1:n
    for j=1:m
        rng('shuffle')
    r=randperm(37);
    r=r(1:2);
    a(j,1)=r(1,1);
    a(j,2)=r(1,2);
```

```
    lastx=xtemp(j,:);
    swap=xtemp(j,a(j,1));
    xtemp(j,a(j,1))=xtemp(j,a(j,2));
    xtemp(j,a(j,2))=swap;
    xtemp(j+1,:)=xtemp(j,:);
    if PreProduction(xtemp(j,:))<=PreProduction(lastx)
    xtemp(j+1,:)=xtemp(j,:);
    else
        if rand()<= exp(-1*(PreProduction(xtemp(j,:))-PreProduction(lastx))/t);
                    xtemp(j+1,:)=xtemp(j,:);
        else
         xtemp(j+1,:)=lastx;
        end
    end

  if PreProduction(xtemp(j+1,:))<=PreProduction(xfinal)
        PreProduction(xtemp(j+1,:));
        xfinal=xtemp(j+1,:);
    x(i,:)=xfinal;
   end


   end
    xtemp(1,:)=xtemp(j+1,:);
    t = alpha * t;
end
disp(['Best solution: ',num2str(xfinal)])
disp(['Best objective: ',num2str(PreProduction(xfinal))])
```

Appendix G

Mathematical Model OPL Code

```
/*********************************************

 * OPL 12.8.0.0 Model

 * Author: Altar

 * Creation Date: 7 Nis 2018 at 11:56:08

 *********************************************/

//sets and indices


int Nbjob = ...;

range job = 1..Nbjob;//item number

int Nbpanel = ...;

range panel = 1..Nbpanel;//item number

int Nbmaterial = ...;

range material = 1..Nbmaterial;//item number

int Nbdrawing = ...;

range drawing = 1..Nbdrawing;//item number
```

```
int NbPeriods = ...;

range period = 1..NbPeriods;//period number


//parameters

int M=9999999999; //a very big number

float processtime[job]=...; //Process time

float demand[job][period]=...;//Customer Demand

float PenaltyCost[job]=...;//penalty cost of not satisfying one unit of item i


float BOM[job][material]=...;//BOM

float BomP[job][panel]=...; // relationship between job and panel

float BomD[job][drawing]=...;// relationship between job and drawing


float Inv0[material]=...;// Initial material Inventory

float Inv0P[panel]=...;// Initial material Inventory

float Inv0D[drawing]=...;// Initial material Inventory


float Capacity=...;//capacity

float MaterialOrder[material][period]=...;//ordered material in period t

float PanelInventory[panel][period]=...;// Is panel in stock at t or not?
```

```
float DrawingInventory[drawing][period]=...;//Is drawing in stock at t or not?

//decision variables

dvar int+ x[job][period]; // amount of produced goods
dvar int+ Inventory[material][period];// beginning inverntory at period t
dvar int+ InventoryP[panel][period];
dvar int+ InventoryD[drawing][period];

dvar int+ tardy[job][1..NbPeriods];// tardy jobs at period t
dvar int+ NewDemands[job][period];// total demand = customer demands at period t and
tardy jobs from period t-1

minimize sum (j in job, t in 1..NbPeriods) ((PenaltyCost[j])*(tardy[j][t]));

subject to {
//--------------------------------------t=1
forall (i in material, t in period: t==1){
            sum (j in job)(BOM[j][i]*x[j][t])<= Inventory[i][t];
```

```
Inventory[i][t]==Inv0[i];
Inventory[i][t]>=0;}

forall (m in panel, t in period: t==1){
    forall(j in job){BomP[j][m]*x[j][t]<= InventoryP[m][t];}
    InventoryP[m][t]==Inv0P[m];
    InventoryP[m][t]>=0;}

forall (h in drawing, t in period: t==1){
    forall(j in job){BomD[j][h]*x[j][t]<= InventoryD[h][t];}
    InventoryD[h][t]==Inv0D[h];
    InventoryD[h][t]>=0;}

forall (j in job, t in period: t==1){
    x[j][t]<= NewDemands[j][t];
    NewDemands[j][t]==demand[j][t];
    tardy[j][t]==NewDemands[j][t]-x[j][t];
    sum (j in job)(processtime[j]*x[j][t])<=Capacity;}

//---------------------------------t>1
```

```
forall (t in period: t>1)
	{	sum (j in job)(processtime[j]*x[j][t])<=Capacity;


		forall (i in material){
			Inventory[i][t]==Inventory[i][t-1]-sum(j in job)(BOM[j][i]*x[j][t-
1])+MaterialOrder[i][t];
			sum (j in job)(BOM[j][i]*x[j][t])<= Inventory[i][t];}


		forall (m in panel){
			InventoryP[m][t]==InventoryP[m][t-1]+PanelInventory[m][t];
			forall(j in job){BomP[j][m]*x[j][t]<= InventoryP[m][t];}}


		forall (h in drawing){
			InventoryD[h][t]==InventoryD[h][t-1]+DrawingInventory[h][t];
			forall(j in job){BomD[j][h]*x[j][t]<= InventoryD[h][t];}}


		forall (j in job){
			x[j][t]<= NewDemands[j][t];
			NewDemands[j][t]==demand[j][t]+tardy[j][t-1];}
```

```
forall (j in job) {
tardy[j][t]==NewDemands[j][t]-x[j][t];}
    }


}
/*********************************************
 * OPL 12.8.0.0 Data
 * Author: Altar
 * Creation Date: 7 Nis 2018 at 11:56:08
 *********************************************/
NbPeriods = 4;
Nbjob = 3;
Nbmaterial = 8;
Nbdrawing=3;
Nbpanel=3;
PenaltyCost = [2 10 5];
processtime = [3 8 4];
demand = [[ 1 0 0 0]
        [ 1 0 0 0]
        [ 2 0 1 0]];
```

```
BOM=[[1 2 0 2 2 0 1 0]
     [0 2 2 0 3 2 0 0]
     [3 0 1 4 0 0 1 2]];

BomP=[[1 0 0]
      [0 1 0]
      [0 0 1]];

BomD=[[1 0 0]
      [0 1 0]
      [0 0 1]];

Inv0 =[5 5 5 25 28 33 35 32];
Inv0P =[1 1 1];
Inv0D =[1 1 1];

MaterialOrder =[[0 3 0 0]
                [0 0 0 0]
```

```
[0 0 0 0]
[0 0 0 0]
[0 0 0 0]
[0 0 0 0]
[0 0 0 0]
[0 0 0 0]];

PanelInventory=[[ 0 0 0 0]
                [ 0 0 0 0]
                [ 0 0 0 0]];

DrawingInventory=[[0 0 0 0]
                  [0 0 0 0]
                  [0 0 0 0]];

Capacity=14;
```