A TWO STAGE APPROACH FOR HYBRID-ASSEMBLY LINE DESIGN

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DOĞUKAN ŞİMŞEK

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submitted by **DOĞUKAN ŞİMŞEK** in partial fulfillment of the requirements for the degree of **Master of Science in Industrial Engineering Department, Middle East Technical University** by,

Prof. Dr. Gülbin Dural Ünver
Dean, Graduate School of **Natural and Applied Sciences** _____

Prof.Dr. Murat Köksalan
Head of Department, **Industrial Engineering** _____

Prof.Dr. Ömer Kırca
Supervisor, **Industrial Engineering Dept., METU** _____

Examining Committee Members:
Prof.Dr. Meral Azizoğlu
Industrial Engineering Dept., METU _____

Prof.Dr. Ömer Kırca
Industrial Engineering Dept., METU _____

Prof. Dr. Haldun Süral
Industrial Engineering Dept., METU _____

Assoc. Prof. Dr. Cem İyigün
Industrial Engineering Dept., METU _____

Assoc. Prof. Dr. Ferda Can Çetinkaya
Industrial Engineering Dept., Çankaya University _____

Date: 03.12.2014

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Doğukan ŞİMŞEK

Signature :

ABSTRACT

A TWO STAGE APPROACH FOR HYBRID-ASSEMBLY LINE DESIGN

Şimşek, Doğukan
M.S., Department of Industrial Engineering
Supervisor: Prof. Dr. Ömer Kırca

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The aim of the study is to propose an approach for hybrid assembly line design in the make-to-order and mixed-model environment. In this context, the main goal is to reduce lead-time, which is one of the key concepts of competitive markets. A systematic approach was employed for designing of hybrid assembly line in order to achieve the goal. The line is divided into two parts in a hybrid system: while the first part of the line works as a closed-loop system for instant replenishment of Constant Work in Progress (CONWIP) supermarket, the second part of the line works for order fulfillment that starts the fulfillment by pulling semi-finished products from the CONWIP supermarket. At the first phase, a mathematical model was developed to identify the right station to install the CONWIP supermarket, which has an objective function forcing maximization of horizontal balancing of the line. The output of the model was the input for the second phase. Here, the CONWIP levels were identified for each product type using a simulation-embedded optimization tool, which retrieves the inputs from simulation runs in the simulation model of the proposed system. At the second phase, current serial assembly line and the proposed hybrid assembly line were compared considering optimized CONWIP levels, which were previously collected. The performance measures were set as lead-time, WIP level and throughput level. Comparison of the results revealed that hybrid system provides an opportunity for lead-time reduction at a reasonable WIP level.

Keywords: CONWIP, Hybrid Assembly Line, Mixed-model Assembly Line, Commonality, Supermarket, Make to Order, Assembly Line Balancing, Closed-loop Assembly Line, Horizontal Balancing

ÖZ

MELEZ MONTAJ HATTI TASARIMI İÇİN İKİ AŞAMALI BİR YAKLAŞIM

Şimşek, Doğukan
Yüksek Lisans, Endüstri Mühendisliği Bölümü
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Bu çalışma, siparişe göre karışık model üretimi yapan bir montaj hattının tasarımı üzerinedir. Çalışmadaki amaç, rekabete dayalı marketlerdeki en önemli performans ölçütlerinden olan teslim süresini azaltmaktır. Bu hedefi yakalamak amacıyla melez montaj hattı tasarımı için sistematik bir yaklaşım geliştirilmiştir. Montaj hattı ikiye bölünmüş: birinci bölüm kapalı çevrim olarak CONWIP süpermarketi besleyen bir yapıda tasarlanırken, hattın son bölümü ise sipariş ihtiyacına göre yarı-mamul halindeki ürünleri CONWIP süpermarketten çekip siparişleri karşılama hedefiyle çalışacak şekilde tasarlanmıştır. Yaklaşımın birinci aşamasında, basit montaj hattı dengeleme problemlerinde kullanılan klasik bir matematiksel model CONWIP süpermarketi kuracak doğru yeri bulmak amacıyla revize edilmiştir. Matematiksel modelin amaç fonksiyonu yatay dengelemeyi maksimize edecek şekilde tasarlanmıştır. Birinci aşamanın sonucu ikinci aşamada girdi olarak kullanılmıştır. İkinci aşamada benzetim modeline gömülü şekilde çalışan bir optimizasyon aracı sayesinde süpermarket için CONWIP stok seviyeleri belirlenmiştir. Mevcut sistem ve CONWIP stok seviyeleri ile çalışan önerilen sistem, performans ölçütleri (teslim süresi, stok seviyesi, üretim adedi) bazında kıyaslamaya sokulmuştur. Kıyaslama, önerilen sistemin mevcut sisteme göre daha kısa teslim süreleriyle müşteriye cevap verme fırsatını kabul edilebilir bir stok seviyesiyle ulaşılabileceğini ortaya koymuştur.

Anahtar Kelimeler: CONWIP, Melez Montaj Hattı, Karışık Model, Benzerlik, Süpermarket, Siparişe Göre Üretim, Montaj Hattı Dengelemesi, Kapalı Çevrim Montaj Hattı, Yatay Dengeleme

To my grandparents
&
To the trees

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CHAPTER 1

INTRODUCTION

Flow-oriented production systems are called as *assembly line*, in which the work resources are utilized to execute assigned tasks repeatedly at the assigned stations that are associated in a serial order (Boysen, Fliedner, and Scholl, 2007). The products are transported from one station "k" to another station "k+1" by a conveyor belt or another material handling equipment. Stations are the places that particular operations are done to produce final products using material resources and work resources. Figure 1.1 depicts an illustration of a standard serial assembly line.

The assembly line balancing problem (ALBP) has been studied by various researchers for years. The assembly lines are key factor to operate high volume of production in short delivery times. Customers need to receive their orders as soon as they placed the order. Considering the fact that customers only pay for the value added processes, the main challenge in the market is to minimize non-value added processes by reducing the lead-time.

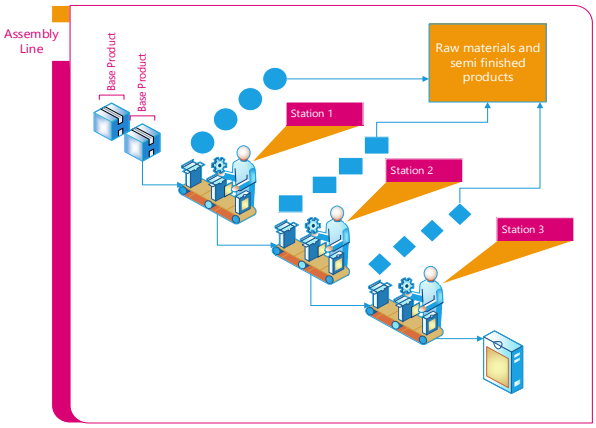


Figure 1.1 Assembly Line (Boysen, Fliedner, & Scholl, 2007)

A *task* is defined as the piece of the work. *Task* is the assigned operation, and the required time to complete the task is called *processing time.* The total elapsed time to move a unit of work from the beginning to the end of a station is called as *Cycle Time*. The total processing time of assigned tasks should be less than or equal to cycle time. The *workforce level* is defined as the number of final products completed in a unit period, and it depends on the cycle time. The assembly line balancing problem focuses on assigning tasks to the stations considering the *precedence relationship* of the tasks and workforce resources constraints. Here, the problem has an objective function mostly based on cycle time or workforce level optimization. Since the first mathematical formalization of Assembly Line Balancing Problem (ALBP) by Salveson et al. (1955), core of the problem determined as assigning the tasks to stations. However, due to technological or mechanical constraints of the tasks of models, some tasks depend on other tasks in order to be initiated. In the literature, such relations are called as *precedence relationship* of the tasks, and it constituted the core of the constraints for a feasible line balancing. Subset of the tasks, which must be completed before task *"j"* started, called as *predecessor of "j".* Subset of the tasks, which must start after task *"j"* completed, called *successor of "j".*

1.1 Characteristics of Assembly Line Systems

Since the first implementations of assembly line, number of developments are proposed, which presents evolutionary approaches about the environment of assembly lines. The assembly lines evolved into more flexible structures from strictly paced and straight single-model lines. In addition to that, there are lines with different characteristics in the market, such as Customer-Oriented Multi-Model or Mixed-Model lines, lines with parallel workstations or tasks, U-formed lines and asynchronous lines with transitional buffers (Becker and Scholl, 2006).

Assembly lines can be categorized into three groups with respect to the model variation being produced in the line. When a single product is assembled in the line, it is called as *single model assembly line,* and the optimization problems are called Single Model

Assembly Line Balancing (S-ALBP). These lines are used for products' demand for single model.

Two variants of the lines can be listed depending on the type of intermixing the products: (1) a *mixed model line* produces the units of different models in an arbitrarily inter-mixed sequence (Bukchin et al.,2002), whereas (2) a *multi-model line* produces a sequence of batches, which contains units of one model or a group of similar models, with intermediate setup operations (Becker and Sholl, 2006). It is a common issue that balancing and sequencing researches are linked to lot sizing problems (Burns and Daganzo, 1987; Dobson and Yano, 1994) when different models are assembled in the line; it is called as *multi-model assembly line*. The production is completed considering pre-determined lot sizes, and there may be setup processes between consecutive lots. In such cases of one lot size without setup, multi-model assembly lines are called as *mixed model assembly lines*. Mixed model assembly line are needed to be installed in order to cover mixed orders. Over the time, customer demands start to evolve into mixed type. In order to satisfy differentiated customer demands, mixed-model assembly lines are employed. Figure 1.2 represents different types of assembly lines, in which the models are symbolized by particular geometric shapes and letters.

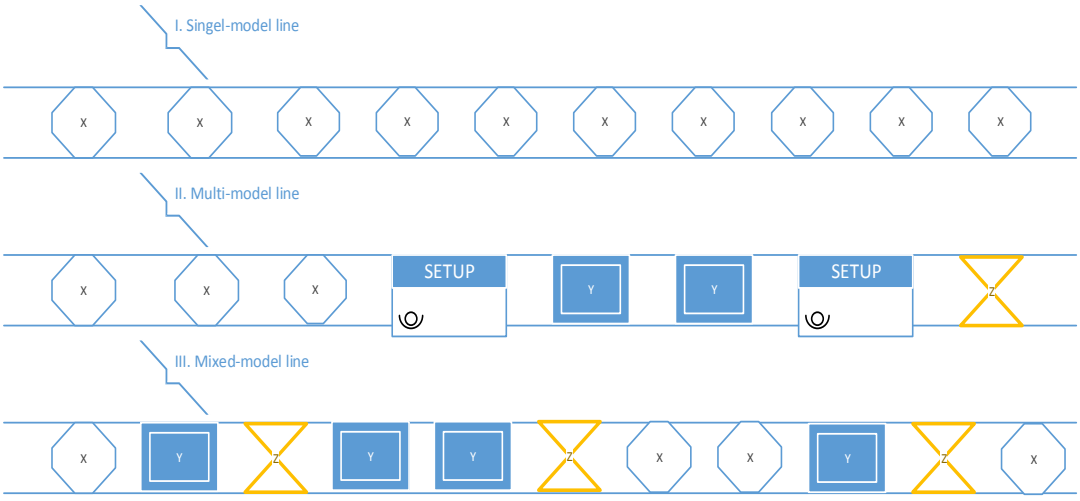


Figure 1.2 Types of Assembly Lines

Processing times is another characteristic for ALBP. Task times are categorized under *deterministic* class (Johnson, 1983) when the standard deviations of task times are small or negligible. These tasks are simple tasks, or they are fulfilled by highly reliable automated stations. Some of the tasks, which present inconsistencies with respect to differences in workloads, skills, and motivation as well as the failure of complex processes, require the use of *stochastic* task times (Buzacott and Mandelbaum, 1990; Robinson et al., 1990; Hillier et al., 1991; Hillier et al., 1993; Pike and Martin, 1994). Likewise, stochastic time differentiations and *dynamic variations* of processing times are categorized. These variations are the result of systematic simplifications such as *learning effects* or *consecutive advance* of the production process (Boucher, 1987; Chakravarty, 1988).

There can be a common cycle time, and every station is limited to the *cycle time c as* an upper bound for each station. The stations operate under a constant speed, and this type of lines called *paced assembly lines.* These lines have fixed production rate that are considered as the complement of the cycle time. Alternatively, all stations of the line operate at a specific speed. In this case, products are allowed to move from station "k" to successive "k+1", when the resources of k completed the assigned tasks.
Product can be queued before entering the next station and it may stay idle till the next product is completed. These problems can be suppressed by the buffers between stations. These cases are called as *unpaced or buffered assembly line,* and ALBP provides positioning and dimensioning buffers that may cause additional decision problems. (Buzacott, 1967; Suhail, 1983; Baker et al., 1990; Hillier et al., 1991; Hillier et al., 1993; Malakooti, 1994; Powell, 1994; Dolgui et al., 2002).

The flow of products and materials are influential factors for the layout of assembly line. On the other hand, there are also other layout options. An assembly line can be organized in serial manner called *serial assembly line,* where stations are line up on a straight line. These type of serial lines are much inflexible. The other type is *U-shaped Assembly Line, which* may deal with the disadvantages of inflexible serial line system.

The U-shaped Assembly Line Balancing Problem is introduced and modelled by Miltenburg and Wijngaard (1994). The assembly line is presented in Figure 1.3. Both ends of the line are forming closely together. Here, stations can be synchronized so that during the same cycle two or more work pieces at different stage of the line can be managed. Stations are called *crossover station* when the same work piece is processed in two distinct cycle c (station K1 in Figure 1.3). Furthermore, a U-line suits for better distribution of load to stations by task-station combinations, and it provides job enhancement and augmentation, (Miltenburg and Wijngaard, 1994; Monden, 1998; Scholl and Klein, 1999).

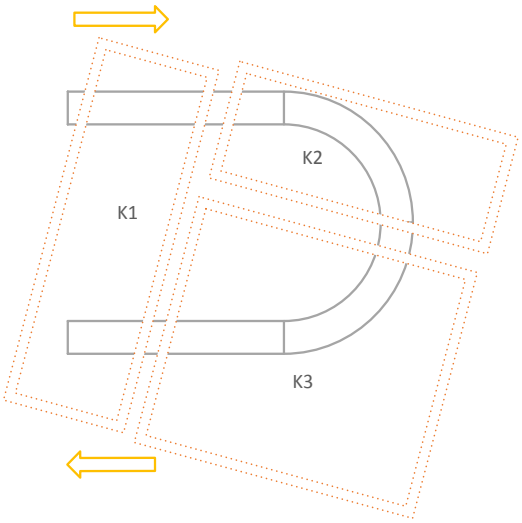


Figure 1.3 U-Shaped Assembly Line

Another important concept to improve line balancing is *parallelism*. Parallelism context can be applied to stations, lines, tasks, and work pieces. In multi-model context, grouping the models with a particular approach in order to present new product families may result in installing new lines. Each line is designed for one product or family is called *parallel lines*, which provides better line balances and productivity. On the other side, the ALBP brings the additional decision problems regarding the number of lines and work resources to be installed to lines (Geoffrion and Graves, 1976). The context parallelism can also be applied to the stations of which work resource is duplicated at the designated station “k”. Here, assigned work piece is

performed in order to reduce cycle time of station "k", which is called *parallel stations.* This context should especially applied in order to reduce common cycle time of the system when some of the task times are greater than desired cycle time (Buxey, 1973; Pinto et al., 1981; Sarker and Shanthikumar, 1983; Bard, 1989; Daganzo and Blumenfeld, 1994). Applying parallelism to the tasks can provide cycle time reduction, and this context is called as *parallel tasks*. A parallel task is assigned to more than one station, and they can be processed interchangeably by assigned stations (Pinto et al., 1975; Bukchin et al., 2002; Bukchin and Rabinowitch, 2006). In addition to that, *parallel work piece* can be applied by assigning same work piece to several workplaces in order to work simultaneously at different places. This concept ensures that they do not interfere each other (Falkenauer, 2005). *Parallel workplaces* are applied at the two-sided assembly lines where tasks can be done from left side and the right side of the station (Bartholdi, 1993; Kim et al., 2000a; Lee et al., 2001).

The balancing problem can be related to equipment or process selection problem if there are process alternatives being performed by different technology and/or equipment (Baybars, 1986; Pinto et al., 1983).

The common assumption of Simple Assembly Line Balancing approach is that all stations and all resources have capability to perform the assigned task. But in real world, there can be some restrictions about balancing the line. In some cases, all stations may not have capability to perform all tasks, whereas, technology related tasks have an appropriate station subset to assign, i.e. molding, welding, and dyeing operations (Kilbridge and Wester, 1961; Bukchin and Tzur, 2000). In addition to *station-related assignment restrictions* as mentioned above, there may be *task related restrictions*. First, Subset of tasks is expected to be linked/incompatible, so these tasks must/must not be assigned to the same stations. Second, minimum, and maximum time or distance space may be needed between a pair of tasks (Ignall, 1965; Deckro, 1989; Agnetis et al., 1995). Moreover, p*osition related constraints* exist for work pieces that are heavy, large-sized or fixed at a workplace. These tasks require a subset of stations

to be completed (Buxey and Sadjadi, 1976; Wang and Wilson, 1986). Last type of assignment related constraint is *operator related constraint*. It occurs because operators may have different levels of capability to perform tasks. In the bottom line, it can be argued that task's subset of work resource is needed to be introduced, and it is needed to be take into account in the process of balancing/optimizing the problem (Agrawal, 1985; Iskander and Chou, 1990).

Line Balancing Optimization problems may have different objectives. Boysen et al. (2007) defined that ALBP can be guided by some objective as evaluating the solutions. The objectives are categorized under sets and presented at Table 1.1.

Table 1.1 Detailed Classification of ALBP Objectives

Objective Direction	*Objective*	*Subject*	*Definition*
Min	Number of Stations "m"	Fixed Cycle Time or Production Rate	Given Data specifies Planning Horizon ALBP-1
Min	Cycle Time "c"	Fixed Number of Stations	ALBP-2
Max	Production Rate	Fixed Number of Stations	
Max	Efficiency "E"	Fixed Production Rate and/or Number of Stations	E: Productive Part of line capacity ALBP-E
Min	Cost		
Max	Profit		
Min	Idle Time of Stations		Station time differences over produced models are balanced for every single station. Horizontal balancing(Merenge et al., 1999)
Min	Idle Time of Line		Station times are balanced over all stations of the line. Vertical balancing (Rachamadugu and Talbot, 1991)
Min/Max	Score		Defined score may related to one or more component of the system that describes bottlenecks or further measures of efficiency. Such that required grip strengths, quality, or number of work piece position changes and so on.

1.2 Problem Definition and Solution Approach

Ulusoy Elektrik is a company in the Medium Voltage (MV) switchgear market. The company operates in both domestic and foreign market. In order to keep the competitive place in the market, it is important for the company to respond the customer needs as fast as possible. A dynamic, flexible, agile production system is needed to keep up the demand fluctuation and order customization. Thus, the purpose of this study is to propose an approach for modular hybrid assembly line design. The performance measure of design is defined in terms of lead-time reduction and throughput level. In Figure 1.4, simple value stream map of current make-to-order is presented. The characteristics of the system is serial, paced and mixed-model assembly line.

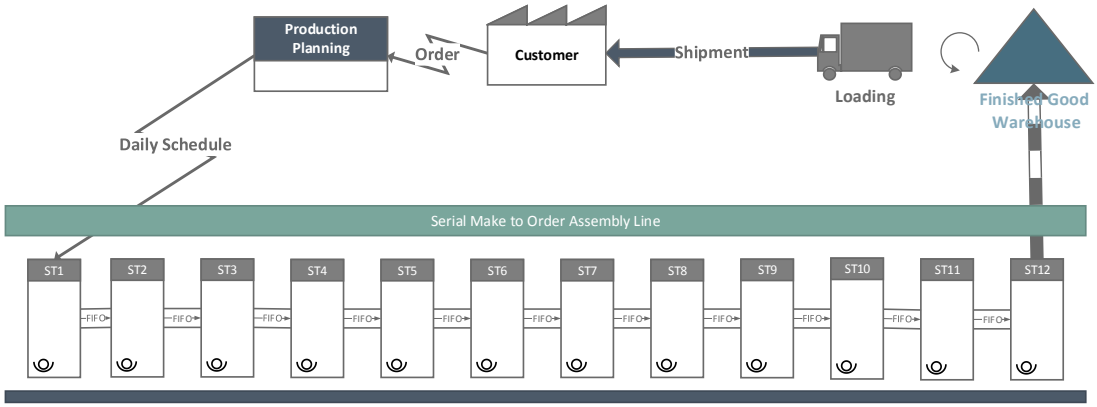


Figure 1.4 Base Serial Assembly Line

Customer places order, and production planning and scheduling are done in daily basis. Daily schedule is sent to the first station. A single order for one product is completed within minimum 120 minutes.

Due to competitive nature of the market, make-to-order (MTO) environment is a key characteristic for production to be flexible. Therefore, implementations of pull systems are appropriate for MTO systems. Moreover, production lead-time stands as a vital performance measure for producers who expect demand- responsiveness in a minimum time interval. In addition to that, WIP level is another key issue that should

be minimized, too. Maximization of the efficiency of mixed model assembly line is expected to be achieved by minimization of the horizontal and vertical balancing measures.

Spearman et al. (1990) proposed CONWIP systems as a pull alternative. He stated that the proposed system overwhelmed the Kanban systems in terms of wide range of application field and easiness to operate. Consequently, CONWIP Based Controlled Hybrid Assembly Line with a supermarket at station "k" (see Figure 1.5) is proposed.

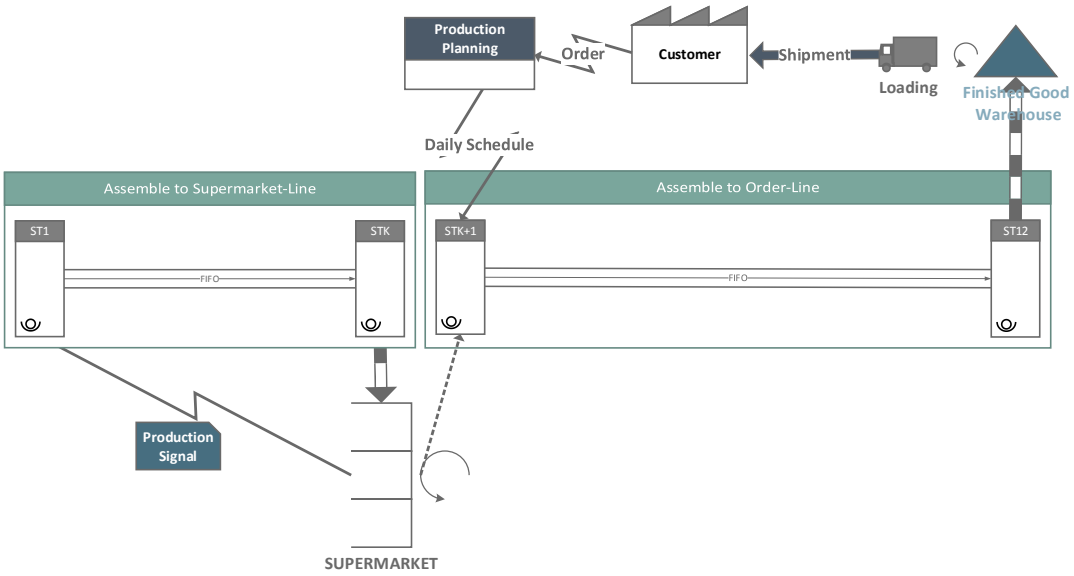


Figure 1.5 Proposed Hybrid Assembly Line

In order to construct a system as illustrated in Figure 1.5, there are three important questions to be answered:

a. Where the supermarket should be installed? (at which station)
b. What should the level of WIP be?
c. How should the performance of proposed system be? (in terms of performance measures)

Initially, a Mathematical Model was constructed to determine the right station “k” to install the supermarket. The validation of proposed mathematical models was done by employing the problem test beds in the literature. Afterwards, a simulation based optimization tool was employed for WIP level determination. Lastly, simulation models of current and proposed systems were constructed to compare the systems with respect to performance measures such as lead-time, WIP level and throughput level. The performance measures are analyzed by statistical analysis for verification and understanding in order to reveal the significant differences between scenarios. The remainder of this thesis is organized as follows:

In Chapter 2, a description of production system at a switchgear producer was presented.

In Chapter 3, a literature survey on assembly line balancing and CONWIP systems was presented.

In Chapter 4, a mathematical model was presented for the Mixed-Model Assembly Line Balancing Problem with an objective maximizing the horizontal balance as the first step of hybrid-assembly line design approach.

In Chapter 5, a simulation model was presented to test the robustness of proposed system. In addition to that, an embedded mathematical model was proposed to determine the CONWIP levels for minimizing lead times, and considering the validation step of hybrid assembly line design approach.

Lastly, in Chapter 6, the study was summarized including the findings, and some of the possible future research directions.

CHAPTER 2

DESCRIPTION OF PRODUCTION SYSTEM AT SWITCHGEAR PRODUCER

Ulusoy Elektrik A.Ş. is an engineering company in Turkish Electro-Mechanics Industry since 1985. Ulusoy Elektrik (UE) has been operating as a leading and innovative organization in its sector. It offers quality and notable products to its customers. Ulusoy Elektrik supplies products for many facilities such as industrial facilities, power distribution stations, cement factories, petro chemical factories, iron and steel plants, airports, harbors, railroads, shopping centers, hospitals and so on. Ulusoy Elektrik's products consist of switchgears and kiosks, which have variaties in an extensive range. Its main products are air-insulated-modular switchgears, metal-clad switchgears, gas-insulated-modular switchgears, automated closed blocker, medium tension cable accessories and mono-block concrete kiosks. The main product of the factory is named as "cell" in general, and daily production rate of the facility is 54 units of cell. Considering entire product families, Ulusoy Elektrik's main goal is running with maximum efficiency, making high profit to keep its leadership in its sector and meet its foreign and domestic customers' needs effectively with quality products. The order fulfillment process starts with receiving a customer order and ends with the delivery of product is summarized in Figure 2.1.

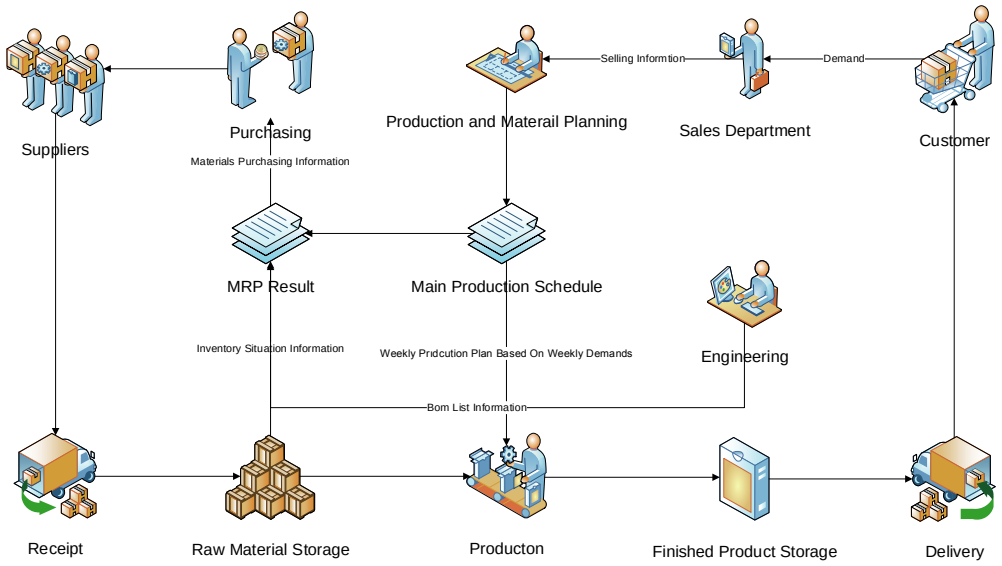


Figure 2.1 General Decision Process of Ulusoy Elektrik

2.1 Production System

When the plant is overviewed, it can be observed that there are many departments connected directly or indirectly. These departments are: Switchgear Assembly Line (SW-AL), Sheet Metal Processing (SMP), Dye house, Welding, Machining, Coating, Copper Processing, Resin Processing, Switch Assembly Line, Low Voltage Panel Assembly Line and Managerial Departments, involving Planning, Sales, Finances and Purchasing Department. SW-AL is the backbone of the facility, in which most of other production departments and Sub-assembly Lines are installed to feed the SW-AL Line.

Main components of the SW-AL System are inputs, outputs, major units, transformations and emergent properties. Inputs consist of directly supplied materials, semi-finished products and daily schedule. Major units are workers, supervisors, physical line, machines, daily schedule, semi-finished product storage area and material handling equipment, such as forklift, scrap boxes and so on. Outputs are switchgears as final products, on-time product delivery and completed tasks. Transformations can be listed as 300 individual tasks performed repeatedly at the

assigned station for the specified product. Promising features are quality of the final products and fulfilment of orders.

- Raw Material Input and Incoming Quality Control

Warehouse department manages delivery activities. The plan is to apply job shop production principle on each process in accordance with lean manufacturing principles The production is triggered by shipping.

All materials, which are needed for the production, enter into the workshop area from the open warehouse. After acceptance to the warehouse, materials are transferred to the quality control department for to control batches and functions.

Incoming quality control department is divided into two parts as acceptance and test laboratory departments. In the acceptance department, soft touch micrometer, calipers, and jigs are used for measurements. In test laboratory department, special testing equipment and three-dimensional measuring devices are used.

- Sheet Metal Processing and Dye house Departments

Large amounts of products are made of galvanized steel. Plate-shaped sheets retrieved from raw material supplier (according to production plan) are processed by punch press at first, following the incoming quality control (size and galvanizing thickness - 275 gr/m2). After drilling and cutting operations,if needed, they are processed by guillotine cutter and transferred to hydraulic press brake in order to finish the bending operations. Powder coating is applied in the cabin for the products, which were required to be painted according to the specification documents. Kanban System is unique to Ulusoy Elektrik, and it is applied between hydraulic press brake and punch press. Kanban System has been applied for metal sheet supply since 2012. Materials are formed and prepared by hydraulic press brake for manufacturing, and they are pulled by Assembly Line through Kanban. For manufacturing phase at the sheet-

processing department, Pulling the material by assembly line is required to trigger application of Kanban work-orders.

- Resin Processing

The most critical materials are produced by the injection Method in this department, which provides high electrical isolation to the product. The main raw material "resin" is prepared before injection. It is exposed to the oven drying and the cooling processes for curing after injection. Molds of all materials are produced by the tooling department of the company. The design of the injection presses are original products, and it belongs to the technical staff of Ulusoy Elektrik.125.000th switchgear has been manufactured in this department in May, 2013. Capacity has reached to 15,000 pcs / year by using to new mold investment.

- Switch Assembly Department

While upper and lower cover of switch, which come from resin processing, are assembled in the lines, operations of mechanism assembly, which run ignition inside and vertically to the shaft on Mechanism Assembly Line, are made. At the conjuction point of these lines, the mechanism is mounted to the separator, and the switch is filled with gas SF6 after it is vacuumed. SF6 gas is vital for operation of the system. If the contacts stay separate from each other under 36.000 volt, arc occurs at very high temperatures. SF6 gas is utilized to absorb this arc.

At the final step, SF6 gas leakage is controlled. Gas testing device works by sniffing method. It is guaranteed that the gas will not leak out of the inner surface of the material for twenty years. Since the beginning of 2010, Kanban Method is applied in this department. The department starts operating by pulling the switches from the Assembly Line. Too many interruptions and production losses were experienced due to synchronization problems between assembly line and this department before the application. Improvements have been made, and interruptions have been reduced at

sixty percent rate on Assembly Line after the application was put in use. The application is a genuine design produced according to the needs of Ulusoy Elektrik.

- Main Assembly Line

Materials provided from sheet processing, machining, resin manufacturing and sub-industry materials are assembled on this line to create the final product. One product comes out of the line in every 10 minutes. Small-scale visual Kanban at the next station is the first pulling system, which was activated in the company.

- Low-Voltage Panel Assembly Line, Copper Workshop and End of Assembly Line

There are two separate sub-assembly departments in order to form the copper materials used on product and to assemble the Low-Voltage Panel. Because the flow improvement on electric panel assemble has deformed in time, new improvement is applied on this department. Following that, pulling and flow applications are going to be activated for the copper production department until July.

Various tests are conducted during the products are on the assembly line. These tests include physical controls and electrical controls. Resistance values of the products affect the product performance. Therefore, for all of the products, the resistance values are measured and recorded. If there is any fault on the products, they are sent to product repair line. They are tested again after repairing. Eighty-seven percent of the products are manufactured correctly at their first time in this line.

At the end of the line, all of the products are exposed to 70000 voltage electric current for one minute. During this process, arc is not allowed. The products that pass the test successfully are packaged and delivered.

- Quality Assurance and High Frequency Test

Every day, one product is randomly selected among the final products and tested for customer use and different use conditions. Materials, which are produced in resin

processing and added to production directly, are subject to a discharge test a hundred percent on this department before going to Assembly Line. The products, which exceed specified value on partial discharge test, are returned to related department and corrective action request is created.

- Tooling and Machining Departments

The design and the manufacturing rights of all molds used in the factory belong to employees of this department. Two vertical machining centers, one Universal Lathe, one Milling Machine, and one Grinding Machine are intensively used for these purposes. Six pieces CNC Lathe Machines, one Drill, Saw, Universal Lathe, and 3 pieces Revolver Machine are available in the Machining Department. This department processes copper, brass and aluminum materials used in production. Overall machine efficiency is in the range of 70-75% in the Machining Department.

The overall production process of a switchgear product is presented in Figure 2.2. The figure is a representation of the detailed production process that previously mentioned

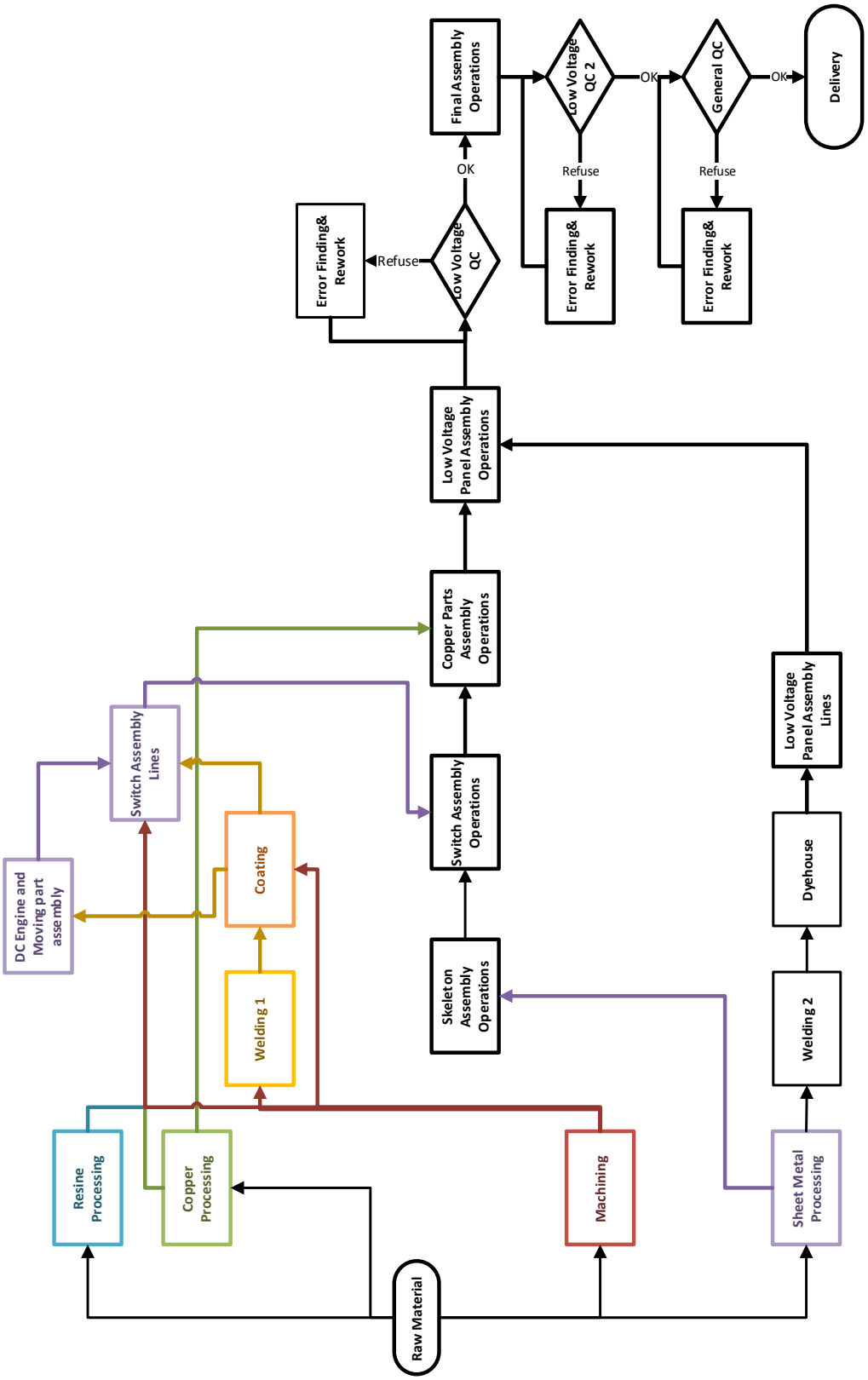


Figure 2.2 Flowchart of a Switchgear Production Process

2.2 Case with Numbers

The problem data of the case is presented in this section. As mentioned before, there are six main production families. The annual revenue earned from these product families in the last three years are presented in Table 2.1. It was summarized in the table that the largest amount of the actual revenue is earned from air insulated modular switchgear (71.88%) during the term.

Table 2.1 Actual Revenue of Ulusoy Elektrik According to Product Families

Year	31.12.11	31.12.12	31.12.13	30.6.14	Product Family Sub Total	Rate of family sub-total to grand total
Mono-block Concentrate Kiosks	9,714,944	15,074,251	15,745,154	7,289,135	47,823,484	8.01%
Gas Insulated Modular Switchgears	3,933,406	7,829,236	10,461,506	3,574,843	25,798,991	4.32%
Air Insulated Modular Switchgears	56,716,953	88,825,296	196,744,127	86,929,185	429,215,561	71.88%
Automated Closed Blockers	315,216	786,075	351,308	187,187	1,639,786	0.27%
Medium Tension Cable Accessories	877,977	1,227,746	1,984,212	548,406	4,638,341	0.78%
Metal Clad Switchgears	4,748,909	3,893,738	10,043,548	6,095,481	24,781,676	4.15%
Others	11,141,135	17,946,429	25,904,139	8,225,013	63,216,716	10.59%
Yearly Sub Total	87,448,540	135,582,771	261,233,994	112,849,250	597,114,555	

There are thousands of variations of air-insulated switchgear produced by considering customer-based specifications. In 2013, 13,200 products had been produced in 1,951 different configurations. Because of the high variation in a single line, the idea of simplification of the line (at least one part of the line) has been proposed as a solution

for lead-time reduction and preventing the effect of demand fluctuation. The detailed information about proposed system was presented in the introduction chapter. Total distinct model quantity, configuration quantity and total production quantity of 2011, 2012, 2013 and first 6 months of 2014 are presented in Table 2.2. In 2013, the firm produced 13200 pieces of switchgear, and the production is distributed on 37 different models with 1951 different configurations. Since, Ford produced the Model-T in early 1900s, the production demand has been evolved from mass production to mass customization. The natural result of changes on demand forced the players of the market to fulfil highly customized customer needs as far as possible. The term "configuration" has been proposed as the combination of product features to satisfy product requirements/ customer needs at this point. It was resulted as thousands of different configurations and thousands of changes in the bills of materials in the main models. These variations also caused changes in operation set of a model. Consequently, high variations of products are produced in a single line, and these changes negatively affect the line balancing issue.

Table 2.2 Production Quantity, Configuration, and Model Data of past years

Year	Distinct Model Number	Distinct Configuration Number	Total Production Quantity
2011	29	1,089	12,265
2012	34	1,570	13,091
2013	37	1,951	13,200
First half of 2014	28	1,111	7409

The detailed production information of the past years according to the models is presented in Table 2.3. It can be observed from the table that 82% of the production of past three and a half year distributed on four main models of 1, 2, 4 and 8 with the rate of 0.27, 0.17, 0.29 and 0.9, respectively. Eighteen percent of the production is distributed on the other models. These four models were selected to be used in hybrid line design approach. Here, only one configuration of these models is selected.

Table 2.3 Production Quantity According to Model per Year

Model	2011	2012	2013	First half of 2014	Total	Percentage	Cumulative Percentage
1	4506	3632	1853	2490	12.481	27%	27%
4	3265	4816	3569	1589	13.239	29%	56%
2	2429	2483	1502	1528	7.942	17%	73%
8	1218	784	1543	615	4.160	9%	82%
Others	847	1375	4732	1186	8.140	18%	100%
Total	12265	13091	13200	7409	45.965		

The configuration numbers used for production per year regarding to the models are presented in Table 2.4. While model 1 and 2 were produced under 142 configurations, rather complex products in model 4 and 8 were produced under 1389 configuration.

Table 2.4 Total Distinct Configuration Number According to the Models per Year

Model	2011	2012	2013	First half of 2014
1	17	15	19	24
4	495	714	861	427
2	61	93	123	89
8	336	433	528	365
Others	180	315	420	206
Total	1089	1570	1951	1111

Task information about selected products is represented in Table 2.5. Total number of operations that were executed to produce the related model is represented in the table. In addition to that, total task times to execute all tasks in the related subset of model were also presented in the table.

Table 2.5 Operation Summary of Products

Models	1	2	4	8
Total Number of tasks	111	134	154	134
Total Time to finish the product(mins)	57.42	67.80	108.46	100.94

The production process of any Switchgear Model involves some common operations. Here, the main purpose is to complete these common operations at the initial stations as soon as possible. Mostly, tasks for the models have identical relationships, and identical tasks are assigned for the models, too. The task/model matrix is presented in Table 2.6. If the task j used in model m, the related $A_{j\text{-}m}$ element is represented with 1, otherwise it is represented with 0.

Table 2.6 Common Operation Matrix over All Models

Task j	***1***	***2***	***4***	***8***	***Total Common Task Number Σ***
1	1	1	1	1	4
2	1	1	1	1	4
3	1	1	1	1	4
4	1	1	0	0	2
5	1	1	1	1	4
6	1	1	1	1	4
7	1	1	1	1	4
8	1	1	1	1	4
9	1	1	0	0	2
10	1	1	1	1	4
11	1	1	0	0	2
12	1	0	1	0	2
13	1	1	1	1	4
14	1	1	1	1	4
15	1	1	1	1	4
Remaining parts of the table is represented in Appendix A					

A representative set of common operations is demonstrated in Table 2.7, and the remaining set is given in Appendix A. The data is represented in two section, in first section of the table; common operations are represented in numbers according to operation ID. In the second section of the table, common operations are represented in numbers, while operation ID and task duration are remained the same for both of the model pairs.

Table 2.7 Total Common Operation for Model Pairs

	Models	1	2	4	8
Common Operations(CO)	**1**	-	98	71	58
	2		-	75	59
	4			-	75
	8				-
Common Operations with the Same Processing Time(COSPT)	**1**	-	81	40	28
	2		-	44	31
	4			-	67
	8				-

The specific operations are presented in Table 2.8 , which outlines the differences among the models. The difference among the models occurs as a result of task duration differences between one model "m" to another. Furthermore, specific tasks for the model features also show differences. For example, there are 81 common operations for m_1=01 and m_2=02 pair, and m_1=01 has 13 specific operations with respect to m_2=02. Similarly, m_2=02 has 36 specific operations th respect to m_1=01.

Table 2.8 Total Unique Operation for Model Pairs

Models	01	02	04	08
01	-	13	40	53
02	36	-	59	75
04	83	79	-	79
08	76	75	59	-

Detailed information about the task relationships and task times are given in Appendix A. Here, the task time units are given in minutes. The number of universal set of the tasks is 296, and particular subset of this universal set with different task times is used to produce four models. Cycle time of the lines is fixed at 10 minutes and maximum task time in the universal set is fixed at 3.97 minutes.

CHAPTER 3

LITERATURE REVIEW

In this chapter, literature review is presented in two sections. The first section includes the review of the studies about the general assembly line balancing problems. It was found that there are number of studies in the literature about this domain. The second section presents insight about the CONWIP systems.

3.1 Assembly Line Balancing Problem

First known study was conducted by Salveson (1955), who created an analytical approach for assembly line balancing problem (ALBP). His study can be categorized under a single model deterministic (SMD) assembly line as a new approach for simple assembly line balancing problems (SALBP-1). A linear formulation that estimates all possible task combinations was proposed. However, in many cases, linear approach can be infeasibile due to the task divisibility and , the interest of researchers on topic of assembly line balancing gradually increased.

3.1.1 General Assembly Line Balancing Problems

Jackson (1956) proposed a study to reveal an enumeration procedure in order to solve the cases that previously argued by Salveson (1955). He proposed the first algorithm for solving SALBP-1 a dynamic programming approach using tree notation. Jackson created his algorithm based on feasible assignment sets and their generation process. Jackson's algorithm initially generates all feasible assignments for the first station. Following that, it is generated for the second station considering the first station assignments. Afterwards, the combinations of first and second stations' assignments were created for third station assignment procedure, and so on. The procedure is replicated by adding a new station to each of the iteration. Jackson removed certain sets regarding to the dominant criterion, and duplicated solution sets were excluded in

his study. The optimal solution was formulated when all tasks were assigned. The final assignment set that had been generated in the last iteration, and it was proposed as a result for SALBP-1.

Baybars(1986) stated that Bowman (1960) was the first to provide a "non-divisibility" constraint, by changing the LP formulation of Salveson et al.(1955) about one of integer programming. Bowman proposed two mathematical formulations. In the first formulation, the main decision variable was created to hold the total assigned duration for a task *j* at a station *k.* In the second formulation, the start time record of a task *j was* defined as the main decision variable. On the other hand, the stations were not clearly indicated in the model. Moreover, a binary variable was introduced to avoid overlapping start times. The proposed model aimed to minimize the finishing time. Following that study, White (1961) modified Bowman's model by defining a decision variable (Equation 2.1).

$$X_{jk} = \begin{cases} 1 \; if \; task \; j \; is \; assigned \; to \; station \; k, \\ 0 \quad o/w, \end{cases} \forall \, j \in J \; and \; k \in K \tag{2.1}$$

Helgeson and Birnie (1961) proposed the first known heuristic procedure for SMD SALBP. They used a popular and well-known 'Ranked Positional Weight Method' for the problem. Tasks were weighted by an interrelated rank value. The Positional Weight (PW) of a task *j* was quantified by summation of its own processing time and processing times of task *j*'s successors. Firstly, tasks were listed in descending order with respect to their PW and assignments being done at the station *k.* This process was completed if the remaining time of station *k* was greater than the processing time of task *j* and/or there was no violation of precedence relationship exists. Otherwise, the task, which had subsequent biggest PW, was considered. If there was no further task to assign for station *k,* the next station *k+1* established and examined for the assignments. The authors also proposed finish-to-start assignment procedure with a reverse approach, which was called as "inverse positional weight". However, the approach has not guaranteed a near optimal solution.

An approach was developed and proposed primarily to provide balance among the lines without utilization of computer by Kilbridge and Wester (1961b). The procedure started with grouping tasks into columns in the precedence graph, in which tasks are positioned at the left-most side without violation of precedence relationships. In such diagram, a swap is done through tasks for each column and without violating the precedence relationship, and some tasks can be relocated in sequential columns at the right side of their current positions. To achieve the optimum balance, task relocation availability and swap options were exploited. The authors proposed a simple and successful technique particularly for the greater C, under the condition of having one station that crosses numerous columns. Conversely, for the lower C, which may need multiple stations, a reasonable amount of modification was necessary.

Shortest path concept was proposed by Gutjahr and Nemhauser (1964) for solving SALBP. They defined a feasible set as a subset of tasks that can be processed in any order by not violating the precedence relationship, and it was exempted from prior completion of any other task. The concept of "feasible subsets" was used by the authors. They started with producing a network N, which illustrated the precedence relationship, and the feasible subsets were symbolized as nodes. While the source node was the null set, the sink node was the set of all tasks. They defined $T_i$as the sum of the process times of the tasks, which were represented by node i. Besides, they symbolized the subset of tasks denoted by node *i* as S_i. Two nodes were coupled with a direct arc (i, j) if $S_i \subset S_j \quad and \quad T_j - T_i \leq T$. Consequently, an arc (i, j) depicted an assignment of all elements of subset *j*, that was denoted by S_j, but not the element of S_i. Thus, a coupled resemblance among source-sink paths and feasible assignments existed. Lastly, the optimum solution for shortest path in the network N was a counterpart to find the minimum number of stations for a SALBP. It should be mentioned that Ghosh and Gagnon (1989) indicated that since the ALBP problem fell into the NP hard class of combinatorial optimization problems (Gutjahr and Nemhauser, 1964), it has consistently challenged for the development of efficient algorithms in order to obtain optimal solutions.

Patterson and Albracht (1975) proposed a search method based on IP techniques, but it was specialized for SALBP. Sequences of 0-1 programs were examined for feasible solutions. They introduced the earliest and latest station concepts for each task; thus, number of variables to be checked for feasible solution were reduced. Furthermore, the incidence constraints are excluded by using conditional feasibility test for the precedence constraints and/or binary infeasibility test for cycle time constraints with limited combinations. Geoffrion (1967) enumeration process was reinforced for fathoming a partial solution, and the examination is summarized excluding the particular structure of the problem. The proposed search algorithm took into account a lower bound *[W/T]** generated for k*, where k was the station number. The authors generated the number of stations k according to equation 2.2 or 2.3, alternatively;

$$k_i = \left[{}^{W}/_{T}\right]^{*} - 1 + i, \qquad \forall\, i \in Z^{+} \tag{2.2}$$

$$k_i = \left[{}^{W}/_{T}\right]^{*} - 1 + F_i, \qquad \forall\, i \in Z^{+} \tag{2.3}$$

Here, F_i is the Fibonacci number until a feasible solution is found. A binary search procedure was conducted for locating the interval in order to reveal the optimal number of stations.

Multi-model deterministic (MMD) version of ALBP was the first mentioned model by Kilbridge and Wester (1962b). Balancing of mixed-model lines was a problem encountered within many industries, particularly in the automotive industry. Kilbridge and Wester (1962b) also proposed that, in addition to the task allocation problem, a model sequencing decision had to be optimized in MMD ALBP. (e.g., see Dar-El and Cother 1975, Dar-El and Cucuy 1977, Dar-El and Nadivi 1981).

3.1.2 Mixed-Model Assembly Line Balancing Problems

A new technique called `Computer Method of Sequencing Operations for Assembly Lines' (COMSOAL) was generated and proposed by Arcus (1966). He proposed the random generation of a feasible sequence as the main framework. Firstly, the approach

assigns the equivalent probability of assortment to the tasks without any remaining unassigned predecessor. The method completes the allocation of some idle times to work resources in order to deal with the processing time fluctuations. Station times were weighted based on randomly generated weights. Considering the assumption of unpaced assembly line, station times, which were transformed into distance measures, were taken. The proposed approach provides an increase in station times. However, if the line is sufficiently long, the solution can be applied, else, the solution stand academic until some of the following design alternatives done: (1) reducing the production rate (i.e. increasing cycle time), (2) elongating the line, (3) stopping the activity of the line, or (4) increasing the capacity of work resources by employing extra workers. Ghosh and Gagnon (1989) stated that Arthur' COMSOAL is the pioneering program in both MMD and MMS categories.

Thomopoulos (1967) proposed a heuristic procedure for MALBP by modifying Kibridge and Wester's (1961) study, which was developed for SMD. Thomopoulos proposed a new model that compromises consideration summation of the total time required for each model as a whole shift. Following that, the tasks were assigned to the stations on shift basis instead of cycle time basis. Three kind of inefficiencies named at the study are listed as follows: the work resource's capability of finishing the product before the next unit arrives into related station (work deficiency), incomplete task due to time shortage (utility of work or work congestion), and the idle work resources for the next product (idleness). The author computed the penalty costs of listed inefficiencies based on the sequencing of multi model, and he used the results to achieve the sequence of the models. However, the proposed method was a heuristic procedure; the author mentioned the near-optimal solutions generated from the robustness test by Monte Carlo methods.

Thomopoulos (1970) proposed a heuristic procedure for MALBP, which was similar to Hoffman's (1963) heuristic approach for SALBP. His technique presented a better solution in terms of balancing with the smoothness approach. The procedure assigned tasks to stations in a serial order. Until an assignment at a station time fell into a pre-

determined interval (acceptable combination) for each station k reached, a finite number of feasible combinations iterated. The smoothness of a specific balancing was measured by a specially formulated mathematical equation that was defined as an objective function (2.4). Here, the objective function aimed to minimize the absolute differences between the average station time of the model, which was denoted as follows: $AVGST_m = \sum_j^J p_{jm}/m\,,\ \forall\, m \in M$, and the models' actual station times $RST_{mk}\ \forall\, k \in K$.

$$Minimize\ \ smth = \sum_{k=1}^{K}\sum_{m=1}^{M}|RST_{mk} - AVGST_m|\,, \tag{2.4}$$

The procedure attempted to minimize fluctuations or to satisfy smoothness in station times horizontally among all models by selecting the feasible combination based on the objective function.

Roberts and Villa (1970) constructed an IP model, and the model was taken as the minimization of the total idle time. Because of the fact that the model contained extreme number of variables and constraints, the authors stated that the formulation was based on theoretical foundations instead of practical real-world interests. Moreover, authors of SMD (singe model deterministic) problem modified the network model of Gutjahr and Nemhauser (1964), in order to deal with the MMD (multi model deterministic) problem.

Macaskill (1972) proposed a paper that investigates MALBP. The pioneering formal definition of a combined precedence diagram was made in this study. The author constructed his balancing strategy on Thomopoulus (1970) paper. Tasks were assigned according to total available labor hour necessary to unit processing time and cycle time of respective model. The aim of study was not altering the Thomopolous procedure; he proposed an algorithm for selecting the next task from eligible task set for the related assignment. Similar to Helgeson and Birnie (1961), Macaskill also used

Ranked Positional Weight Method. In the study, the balancing procedure was completed by Thomopolous method with a computer-aided technique.

Gökçen and Erel (1997) proposed a binary goal-programming model for the mixed-model ALB problem. They defined the reason of selection of goal programming approach. The approach was stated as a natural modelling tool since it aims to achieve a reasonable assignment rather than the optimal solution while dealing with conflicting goals. Because of that, several goals, some may be conflicting ones, can be instantaneously measured. Here, the study offered a level of flexibility for the decision maker. They assumed that a task with different processing times among the models should be assigned to same station. This assumption was used in defining the decision variable as $V_{jk} = if\ task\ j\ assigned\ to\ station\ k\ \ 1,\ \ o/w\ 0$ without model index. Tasks were assigned to the fixed stations for all models. The primary goal was avoiding the violation of pre-determined upper bound in total number of stations. Secondary goal was determining the cycle time's upper bound for each model. Last goal, the least prioritized one, is adhering to zoning constraints. It was reported that the model was significantly superior to the model of Roberts and Villa (1970). Nevertheless, it was stated that, due to the excessive storage and computation requirements, both of the models, which were proposed by Roberts and Villa (1970) and Gökçen and Erel (1997), were far from to be applied in real-world cases.

Erel and Gökçen (1998) proposed the shortest-route formulation for the mixed-model assembly line balancing problem, based on Gutjahr and Nemhauser (1964) algorithm. The problem was modified into single-model from mixed-model by combined precedence diagram. They assumed that a task with common features among the models should be assigned to same station. They stated that their proposed network was significantly smaller than Roberts and Villa's (1970) shortest-route network.

Bukchin et al. (2002) proposed a new approach addressing the MALBP, which was developed by modifying the previous approaches with the new requirements of modern assembly organization. Workers of the proposed assembly environment were

suitable to perform all tasks. Such environments do not limit the assignment of tasks to any stations even though resources in these stations are available. Similarly, a smooth and less fluctuated assignment among stations can be gathered. Moreover, the tasks were clustered into two categories: one group was common for all models and it should be assigned to a single station, remaining group was the one that can be assigned to distinct stations for different models. Thus, three-step solution algorithm was executed. First, positions of the tasks of the first set were collected as a preliminary solution. Afterwards, each model was balanced individually by assigning tasks into the second cluster at the stations, following the positions of tasks being collected at preceding step. Lastly, the procedure was executed to enrich solutions by repositioning the first cluster tasks from recently assigned positions to the subsequent neighbor stations. Therefore, the handled problem was identified as MMS (multi model stochastic) nature, and the obtained results were evaluated by using Bukchin's (1998) bottleneck measure. At the time of reaching local optimum two-way decision: first, the solution was accepted; second, the solution was rejected and a new solution was iterated by incrementing the solution number.

Simaria and Vilarinho (2004) proposed a detailed study addressing MALBP. The authors organized their paper in two main section as mathematical model and the genetic algorithm based heuristic approach. The mathematical model was constructed as a binary formulation with a multi-objective approach. The first one was cycle time, and the remaining one was a binary indicator that shows how the task was assigned among the stations. Due to the excessive size of mathematical model, solution fell into NP-hard case. In the second part, a GA based heuristic procedure presented. Initially, lower bound for cycle time was generated. Right before proceeding to GA, a simple practical heuristic procedure was executed until collecting feasible solutions. Afterwards, GA was applied to the solution, which was collected from prior step. At this step, the one, which aims for cycle time minimization, incrementally decreased cycle time. Lastly, after collecting the results, a second GA was executed to minimize fluctuations of the assignments.

Bukchin and Rabinowitch (2006) proposed a branch-and-bound algorithm to deal with MALBP. They initially started with relaxation of task assignment constraint. In their model, the tasks could have been assigned to a single model for all stations or tasks could have been assigned to distinct stations for each model. They called these type of relaxations as "task duplication". Therefore, particular costs (cost of machinery and tool duplication, accompanying costs for line complexity and inventory management cost) associated with the assignment. Thus, the objective was to minimize the total cost associated with the assignments. Task cost and station cost formed the total cost factor. Station cost was relational to the number of stations in the line, and task cost included the supplementary cost of duplication. It should be noted here that relaxation of assignment, in other words application task duplication, has been previously employed in the studies of Roberts and Villa (1970) and Bukchin et al. (2002).

Emde et al. (2010) proposed a comprehensive computational study addressing MALBP for smoothing the actual workload, which may vary according to daily product mix in the line. Four objectives were defined under the study, one was for vertical and the remaining three objectives were for horizontal balancing. Afterwards, an evaluation was conducted on different distance measures for workload smoothing. They defined this objective function as the difference between the actual processing time of the model and the cycle time. In the study, superiority of the results over other procedures on *Manhattan distance metric* was argued.

Rabbani et al. (2012) proposed a study dealing with MALP with respect to two type of objectives: one was the minimum cycle time, and the second was the number of stations that was subject to horizontal and vertical balancing. The paper focuses on make-to-order environment assembly schedule, which was in more probabilistic nature since it was depended on customer request. Moreover, the study evaluated six multi objective evolutionary algorithm methods to determine the best fit for MALBP in make-to-order cases.

For further literature in ALBP, the readers are advised to see the survey studies which were proposed by Baybars (1986), Ghosh and Gagnon (1989), Erel and Sarin (1998), Becker and Scholl (2006), Boysen et al. (2007), and Boysen et al. (2009).

3.2 CONWIP Systems

Spearman et al. (1990) proposed a new pull-based system, named as Constant Work In Progress (CONWIP) as an alternative of Kanban. They developed the study over Hall (1981) findings, and it was pointed out that Kanban was fundamentally proposed for a repetitive manufacturing system'. They stated that it was not applicable for a shop controlled by job orders. The proposed system was applicable to a broader type of production environment while holding the benefits of Kanban. The author tested the robustness of the system while comparing it with a traditional push system and a Kanban system. A simulation method was utilized for the comparison. The findings revealed that CONWIP is superior to other mentioned systems for the cases of which customer demand is significantly over the capacity. Spearman pointed out that a further research should be conducted on WIP level optimization and a re-evaluation when the demand quantity is close to capacity level.

Spearman and Zazanis (1992) investigated the behavior of push and pull production systems in order to explain the performance superiority of pull systems. The authors defined three qualification to be monitored and examined: first one was that pull systems have less congestion, second one was that pull systems are fundamentally easier to operate, and last one was that the benefits of a pull environment depends on WIP more than the practice of "pulling" everywhere. The evaluation was completed with respect to the models. The study revealed that not only their deductions were valid but also the proposed hybrid control strategy had both push and pull characteristics that enabled a superior performance over pure push/pull systems. They merely

indicated that the effectiveness of pull systems was not a result of pull-triggered production but limiting WIP and its variability.

Duenyas (1995) addressed a problem as quoting customer lead times in a manufacturing environment under a variety of modelling assumptions. They examined under three cases: first case was that producer has infinite capacity, second case was that jobs are processing first-come first-served (FCFS), and the producer has finite capacity, and the last case was that jobs are processing in any order (producer may choose to produce any of order). For the first case, a closed form formulation was derived for lead-time quote optimization. For the second case, the author stated that different form of control policies were optimal for the cases where the lead-time was determined by customer, and where producers were qualified to the contest in terms of lead-time. For the third case, the author showed that the jobs should have been processed with respect to Earliest Due Date (EDD) principle under different policies (i.e. optimal lead-time quoting or order sequencing).

Hoop and Roof (1998) proposed a simple flexible production control method for setting WIP levels in a pull production operation by the CONWIP for meeting the target production rates. They used a method called as Statistical Throughput Control (STC) (Spearman et al. (1989), which was a modification of Statistical Process Control (SPC) method of Montgomery (1991). The method automatically adjusts WIP levels (via Kanban cards) with the real-time data captured from demand fluctuations. The authors merely indicated that the proposed model STC was designed to be executed for environmental changes (i.e. inductions were collected from kaizen efforts), not for a steady-state model. They evaluated the proposed model performance using simulation technique. They also conducted a sensitivity analysis by testing following environments: simple flow lines, single and multiple products, routings with shared resources and assembly systems. Consequently, they indicated that the proposed model (STC) was simply applicable, besides they also proposed WIP level determination approach that was previously pointed out as a further research by Spearman et al.(1990). Hoop and Roof's dynamic STC to determine the WIP level was

superior over a theoretical WIP level calculation at the beginning, while dealing with demand fluctuations. Because it is a simple production management tool, the model provides a great advantage as it incorporates with fluctuations dynamically, and it efficiently regulates WIP level appropriately.

Ayhan and Wortman (1999) investigated the relationship between average output and fixed WIP levels in CONWIP controlled shops, make-to-stock shops and assembly shops. The processing times were held in stochastic manner. An approach presented that calculates the expected mean output level under given fixed WIP level. A set of stochastic difference equations defined to characterize the system dynamics. A discrete index Markov chain on a continuous state space was employed to model system states. For collecting an estimated expression for the system mean output with the given WIP level, standard Markovian analysis was conducted, considering the discretization of state space.

Leitch (2001) used simulation technique to understand the effect of some characteristics of a pull production line on WIP. The author tried to reveal a case to provide a better understanding about the effect of following characteristics: lead time, capacity (capacity utilization) and stochastic environment. The previously listed parameters were selected since they were significant cost drivers of such dynamic environment. Because of the characteristics of the pull system, that was farther complex than the conventional push system applied at Reeve (1990) and Banker et al. (1988) studies. These cost drivers had interdependent effect on WIP level and output rate. Consequently, it was revealed that there were strategic trade-offs between these cost drivers to be handled by the management.

Ip et al. (2007) compared single-loop and multi-loop CONWIP for a lamp assembly line that produces wide variety of products with discrete distribution processing time and demands. They defined their performance measures by service level and WIP. They proposed a model regarding WIP as total cost and service level. Their aim was

to find the optimum parameter setting. For this purpose, a novel rule-based genetic algorithm (GA) approach was constructed. A rule was designed to alter the card number (WIP) of each loop for conducting sensitivity analysis. By interchanging the card number, the performance measures were tracked. They stated that single loop CONWIP system overwhelmed the multi-loop CONWIP system in terms of performance measures with zero shortage probability WIP level (total cost reduced).

Eng and Sin (2013) proposed discrete event simulation (DES) models for End of Line (EOL) assembly operations in a semiconductor manufacturing firm in order to evaluate the performance of CONWIP control mechanisms. They defined throughput, cycle time, and WIP level as performance measures. Considering these performance measures, an evaluation was conducted on simulation models for three-production design: first one was the base model, second one was the single loop CONWIP mechanism, and last one was the multi-loop CONWIP mechanism. The collected results presented in Table 3.1. The throughput rates (service level) were fixed to 193 to perform an appropriate comparison.

Table 3.1 The Collected Results from Eng and Sin (2013) study

	Throughput	*Average WIP*	*Cycle Time*
Base Model	193	575	3984.00
Single-loop CONWIP	193.0148	440 (⇧)	3264.62
Multi-loop CONWIP	193	443	3251.11 (⇧)

For the single-loop CONWIP control mechanism, there was 18.1% improvement from the base model in terms of cycle time, and there was 23.47% improvement from the base model in terms of WIP. For multi-loop CONWIP control mechanism, there was 18.4% improvement of the base model in terms of cycle time, and there was 22.95% improvement from the base model in terms of WIP. The results revealed that the CONWIP system overwhelmed the current system upon both of the performance measures, as expected, and this argument was supported by many previous studies. Secondly, the results revealed that multi-loop CONWIP performs slightly better than

single loop system in terms of cycle time. Single-loop CONWIP performed slightly better than multi-loop in terms of WIP level (total cost) similar to findings at Ip et al. (2007) study. Another important data collected from the results was the moral for both models. As more cards were presented to the system, it would result in expansion of buffer size that causes longer cycle times. For further literature in CONWIP systems, the readers are advised to read the survey study of Framinan, Gonzalez, and Ruiz-Usano (2003).

CHAPTER 4

MATHEMATICAL MODEL FOR MIXED-MODEL ASSEMBLY LINE BALANCING PROBLEM

In this chapter, mathematical formulation of the model as the first stage of the approach is presented. Solution methods for the mixed model balancing can be classified under two main sections. These are relaxed and un-relaxed procedures. The relaxation can be done by relaxing the fixed cycle time for all model assumption by defining different cycle time for each model, or by defining lower and upper bounds for cycle time. This type of approach is expected to reduce the line efficiency, because of compensation effects between the models. Deutsch (1971) presented a branch and bound algorithm for stochastic and deterministic versions of MALBP. Besides, Link (1992) proposed another modification of MALBP in terms of cycle time constraints. In order to acquire a job assignment free from a specific model mix, the author replaced the common cycle time constraint with upper and lower bounds for the station time of each model. A multi objective was used in the study. First objective was to minimize the maximal deviation between any station times T_{mk} from the average station time t_m of respective model m. Second objective was to align station loads.

Second relaxation approach is relaxing the "identical tasks have to be assigned to the same station for all models" assumption, which will result the decomposition of mixed model problem into M single model problem. Roberts and Villa (1970) presented a respective generalization of the shortest path formulation of SALBP-1. However, this type of assignment is not desired because of the following reasons: loss of specialization effects, complicated production control, and additional facility requirements. Görke (1978) proposed a study to solve successively the synchronization problem by fixing the task at the first assigned station for the remaining models. Macaskill (1969) also tried to cope with synchronization problems

at his thesis study. Relaxation of task assignment assumption is called as task duplication in the literature. Bukchin et al. (2002) proposed a new approach addressed to the MALBP by modifying the old approaches considering the new requirements of modern assembly organization. The proposed assembly environment workers were eligible to perform all tasks. Such environment did not limit the assignment of tasks to any stations regarding to the capacity of resources. Similarly, a smooth and less fluctuated assignment among stations can be collected. Moreover, the tasks were clustered into two categories, one covers the the tasks that are common for all models and should be assigned to a single station, second one covers the tasks that can be assigned to distinct stations for different models. Thus, three stepped solution algorithm was executed. Bukchin and Rabinowitch (2006) proposed a branch and bound algorithm to deal with MALBP. They initially started relaxation of task assignment constraint. In their model, tasks can be assigned to a single model for all stations, or tasks can be assigned to distinct stations for each model. They called this type of relaxations as task duplication. Therefore, some costs (cost of machinery and tool duplication, costs accompanying because of line complexity and inventory management cost) were associated with the assignment. Thus, the objective was to minimize the total cost associated with assignments.

Considering unrelaxed solution procedures of MALBP-1(Min station number) and MALBP-2(Min cycle time), in the literature, the MALBP was generally solved as some respective versions of SALBP. (Arcus, 1966; Macaskill, 1972). Methods for smoothed station loads were the approaches given above, however, they did not aim to equalize the station's utilization depending on the models. General approach for solution MALBP was to present a multi-objective approach. Along with classical objectives such as ALBP-1, ALBP-2, and ALBP-E that were coping with aggregate joint model, a secondary objective was released to cope with station times for different models. Consequently, it was found that a kind of SALBP could easily be applied to the corresponding kind of MALBP with an arbitrary secondary objective for equalizing the stations' utilization for each model.

Moreover, for exact procedures, some necessary modifications were needed to be done. Firstly, all optimal solutions were considered (Dar-El and Rubinovitch (1979)) with a branch and bound algorithm in order to eliminate the best solution over all stations. Secondly, station loads were searched considering secondary objective function. Thirdly, dominance and reduction procedures, in which only a single optimal solution was required for SALBP, had to be omitted or relaxed. When a solution that was correspondent to the obligatory solution with respect to the primary objective was collected, it was selected for the secondary objective. The optimal solutions were collected for the primary objective could also be checked simultaneously, according to the secondary objective in order to reduce compilation time.

Considering the studies in the literature, MALBP was solved according to three approaches. First, the assumption of assigning same tasks at same station was relaxed and decomposed the MALBP into "M" (4) different SALBP model. Second, a version of MALBP was constructed to solve the problem as SALBP. Different from first approach, the ALBP was executed for a combined model. In order to solve the problem, the precedence relationships of individual models were combined into a single combined precedence relationship. Last, a MALBP problem, which was specially designed for the goal, was constructed. The identical tasks assigned to the same station assumption also relaxed in this model. However, the assignment of identical tasks at same station was encouraged as far as precedence relationship allows with help of objective function.

A weighted multi-objective model was constructed to encourage assignment of common tasks to earlier stations as minimizing the total station number. This objective function was called as *commonality point* throughout the text. The objective of models was to maximize the commonality point to assemble four different type of models with a given station number and production rate i.e. cycle time. An iterative approach was applied for each k= {2, 3,…, 21} and fixed cycle time C = {10} in order to select the right station to construct the supermarket.

First, the terminology, assumptions and notations were introduced. In the following section, the models are presented together with the validation and the parametric testing of their performance.

4.1 Terminology, Assumptions and Notation

4.1.1 Terminology

Task: Indivisible work element.

Model: A product or one of its variants, i.e. a product that has a typical and unique combination of features making it different from other products.

Station: A workplace on the assembly line where some certain tasks are done recurrently.

Task Time: Time required to complete the task.

Cycle Time: Cycle Time is the total elapsed time to move a unit of work from the beginning of the station to the end.

Precedence Relations: Associations among tasks restricting the order of execution of tasks, defined by the environment of the tasks and the products assembled.

Precedence Graph: A network based illustration of precedence relations. Tasks are represented by nodes and an arc between nodes represents the precedence relation of two linked tasks. An example of a precedence graph for six-task system is illustrated below in Figure 4.1.

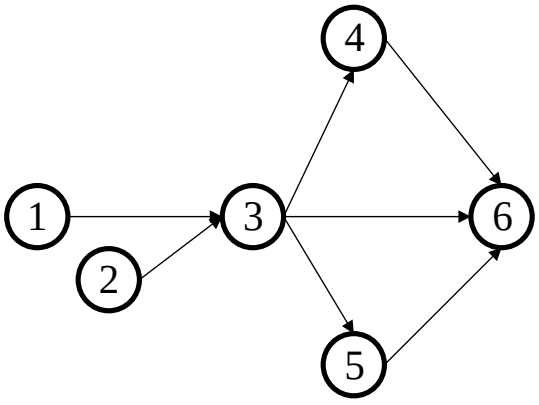


Figure 4.1 Sample Precedence Graph for ALBP

Predecessors of a Task: Set of tasks that must be completed before starting time of task "j". For example for above represented precedence relationship, the predecessors set of task 6 is {1, 2, 3, 4, 5}.

Immediate Predecessors of a Task: Set of tasks that must be completed immediately before the task j starts. For example for above represented precedence relationship, the immediate predecessors set of task 6 is {3, 4, 5}.

Successors of a Task: Set of tasks that cannot be processed before the completion time of the task j. For example for above represented precedence relationship, the successors set of task 2 is {3, 4, 5, 6}.

Immediate Successors of a Task: Set of tasks that cannot be processed immediately before the completion time of the task j. For example for above represented precedence relationship, the immediate successors set of task 2 is {3}.

Precedence Matrix: it is the illustration of the precedence relations in a Matrix Format. For a problem with N tasks, if precedence relationships does not differ from one model to another, N*N upper right Matrix formed. Else, Precedence Matrix must be constructed every model "m". A sample matrix is given in Table 4.1 for the precedence relation represented in Figure 4.1.

Matrix fulfilled with directions given below:

- If task i precedes j: Entry(i, j) is 1
- Otherwise: 0

Table 4.1 Sample Precedence Matrix for ALBP

Tasks	**1**	**2**	**3**	**4**	**5**	**6**
1	-		1			
2		-	1			
3			-	1	1	1
4				-		1
5					-	1
6						-

4.1.2 Assumptions

These assumptions are the common assumptions for Mathematical Models for ALBP. Further assumptions will be introduced when needed.

- All tasks are processed in a predetermined mode (no processing alternatives exist).
- The line is paced line with a fixed common cycle time according to a desired output quantity.
- The line is considered to be serial with no feeder lines or parallel elements.
- The processing sequence of tasks is subject to precedence relationships.
- Task times are deterministic (and integral). Same task may have different processing times for different models.
- There are no assignment restrictions of tasks besides precedence constraints.
- A task cannot be split among two or more stations.
- All stations are equally equipped, eligible, with respect to machines and workers.
- Several models of a product family produced at a single line. The models have many common tasks.

4.2 Mathematical Models

4.2.1 Single Assembly Line Balancing Approach Model

The mathematical model that is represented in this section is executed for two different approaches. Firstly, the model is executed for each individual product model “m” with independent precedence relationship. Secondly, the math-model is executed for an aggregate model with a joint precedence relationship. The construction of aggregate model will be represented at the end of the section. The remainder of this section is notation, model, and construction of aggregate model.

Notation:

The following notation is used throughout the text. Additional notations will be represented when needed.

Indices

i, j : $Task\ Indices$

k : $Station\ Index$

Sets

J : $Set\ of\ tasks\ over\ all\ models$

K : $Set\ of\ stations$

S_i : $Set\ of\ immediate\ successors\ of\ task\ i$

$A_j = Set\ of\ models\ common\ for\ task\ j$

$O = Set\ of\ common\ tasks\ |A_j| > 1$

$O' = Set\ of\ non - common\ tasks$

Parameters

$Kmax$: $Maximum\ station\ number$

G : $A\ big\ positive\ number$

C : $Common\ cycle\ time\ of\ stations$

C_k: $Cycle\ time\ of\ station\ = \begin{cases} C & k < Kmax \\ G & k = Kmax \end{cases}$

P_j: $Process\ time\ of\ task\ j\ for\ aggregate\ model$

w_1: $Weight\ of\ primary\ objective$

Decision Variables

Y_{jk}: $Task\ assingment\ indicator = \begin{cases} 1 & if\ Task\ j\ assigned\ to\ station\ k \\ 0 & o/w \end{cases}$

Objective Function

$$Max\ Z = w_1 * \sum_{j \in O} \sum_{k=1}^{Kmax-1} [Kmax - k] * |A_j| * Y_{jk} + \sum_{j \in O'} \sum_{k=1}^{Kmax-1} [Kmax - k] * Y_{jk} \quad (4.1)$$

Subject to

$$\sum_{k \in K} Y_{jk} = 1 \qquad \forall\ j \in J \quad (4.2)$$

$$\sum_{k \in K} Y_{ik} * k - \sum_{k \in K} Y_{jk} * k \leq 0 \qquad \forall\ i, j \in J\ ;\ j \in S_i \quad (4.3)$$

$$\sum_{j \in J} p_j * Y_{jk} \leq C_k \qquad \forall\ k \in K \quad (4.4)$$

The objective (4.1) constructed as a weighted multi objective in order to encourage primarily common task assignments and secondarily non-common task assignments (a version of SALBP-1). First part of objective, the assignment variable Y_{jk} valued with assigned station "k" and pre-calculated $|A_j|$ that is cardinality of set of common models for model j. This part calculated for stations lower than Kmax and tasks that are in set *O*. The second part of objective encourages the assignment of unique tasks that are used for just one model. A set *O'* has been constructed as set of non-common tasks. The primary objective was weighted by multiplying it with w_1 while the secondary objective remains same. Computational experiments during the determination of the respective weight are given under solution of the case study section.

Constraint (4.2) ensures that every task j can only be assigned at only one station over all stations. Constraint (4.3) constructed to satisfy precedence relationship. If a task "j" that is immediate successor of task "i", than assigned station of task "j" cannot be greater than assigned station of task "i". Constraint (4.4) ensures that total process time of the model at station "k" cannot exceed predetermined upper bounds of stations

as C_k. The summation cannot exceed pre-determined cycle time "C" for such stations that k < Kmax. While, the summation cannot exceed pre-determined cycle time "G" (a big number that should be greater than longest lead time) for station k=Kmax, to assign all remaining inappropriate tasks to station k=Kmax since that is determined as *bucket station*. It is fundamental for the iterative approach, while parametrically interchanging Kmax some tasks could not be assigned to normal stations (inappropriate tasks). In order to retrieve optimum solution these inappropriate tasks assigned to bucket station at respective Kmax alternation iteration. Note that Kmax alternation iteration is stopped when all tasks assigned to non-bucket stations (k<Kmax).

4.2.2 Mixed-Model Assembly Line Balancing Approach Model

Notation:

The following notations are used for MALBP approach are represented in this section. Additional notations are represented. The remainder of this section is notation, and model.

Indices

m : $Model\ Index$

Sets

M : $Set\ of\ models$

S_{im} : $Set\ of\ Immediate\ Successors\ of\ Task\ i\ for\ model\ m$

Parameters

P_{jm}: $Process\ time\ of\ task\ j\ for\ model\ m$

w_2: $Weight\ of\ primary\ objective$

Decision Variables

$$Y_{jk}^{m}: Task\ assingment\ indicator = \begin{cases} 1\ if\ model\ m's\ task\ j\ assigned\ to\ station\ k \\ 0 \qquad\qquad\qquad\qquad\qquad\qquad\qquad o/w \end{cases}$$

$$X_{jk}: Commonality\ index\ of\ a\ task\ j\ at\ station\ k \qquad\qquad for\ k<Kmax$$

$$XC_{jk}: Common\ assignment\ indicator =$$

$$\begin{cases} 1\ if\ Commonality\ index\ X_{jk}\ has\ a\ value\ with\ equal\ or\ greater\ than\ 2\ and\ k < Kmax \\ 0 \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad o/w \end{cases}$$

The assumption "identical tasks should be assigned at same stations for all models" has been relaxed, and the assignment of tasks executed independently. Nonetheless, a decision variable is represent which is called as commonality index, that indicates the assignment of identical tasks of models at same station, and this type of common assignments are encouraged by the objective function. Firstly, a single objective (non-weighted) model constructed, but the results were insufficient to decide the supermarket's station. Consequently, a weighted objective model is constructed which "common" assignments at initial stations are forced by primary objective, while all tasks' assignments to initial stations are forced by the secondary objective. The secondary objective can be classified as a version of MALB-1 (minimize station number).

Objective Function

$$Max\ Z = w_2 * \sum_{K=1}^{Kmax-1} \sum_{j \in J} XC_{jk} * (Kmax - k) + \sum_{K=1}^{Kmax-1} \sum_{j \in J} (X_{jk} - 1) * (Kmax - k) \qquad (4.5)$$

Subject to

$$\sum_{k \in K} Y_{jk}^{m} = 1 \qquad \forall\ j \in J, \forall\ m \in M \qquad (4.6)$$

$$\sum_{k \in K} Y_{ik}^{m} * k - \sum_{k \in K} Y_{jk}^{m} * k \leq 0 \qquad \forall\ i, j \in J\ ;\ j \in S_{im}\ ; \forall\ m \in M \qquad (4.7)$$

$$\sum_{j \in J} Y_{jk}^{m} * P_{jm} \leq C_k \qquad \forall\ k \in K\ ; \forall\ m \in M \qquad (4.8)$$

$$\sum_{m \in M} Y_{jk}^{m} = X_{jk} \qquad \forall j \in J ; for\ k < Kmax \tag{4.9}$$

$$X_{jk} \geq 2 * XC_{jk} \qquad \forall j \in J ; \forall k \in K \tag{4.10}$$

The objective (4.5) maximizes the commonality point. Commonality point constructed as summation of Equality 4.5.1 and Equality 4.5.2 as two different objectives. Because of the fact that Equation 4.5.1 is primary objective, it is weighted by multiplying with w_2 and Equation 4.5.2 is multiplied by one. Computational experiments during the determination of the weight are given under solution of the case study section.

$$w_2 * \sum_{K=1}^{Kmax-1} \sum_{j \in J} XC_{jk} * (Kmax - k) \tag{4.5.1}$$

$$\sum_{K=1}^{Kmax-1} \sum_{j \in J} (X_{jk} - 1) * (Kmax - k) \tag{4.5.2}$$

Equation (4.5.1) is constructed for encouraging the assignment of common operations to earlier stations. As defined above notations XC_{jk} is a binary variable that takes the value of 1, if a task "j" is assigned to station "k" for more than one model (for 2, 3, 4) and this type of assignment is called as *common assignment*. Now then, this variable will be called as *commonality indicator*. Summation of this binary variable over "j" and "k", while multiplying the difference between maximum station numbers Kmax, minus variable's cardinality of "k", satisfies the encouragement the assignment to earlier stations, since Kmax is constant the lower "k" results greater difference. Equation (4.5.2) is constructed for encouraging the assignment of operations to earlier stations. As defined above in notations X_{jk} is the summation of Y_{jk}^{m} over "m" that represents the cardinality of assigned model set for task "j" at station "k" and takes a value from subset S={0,1,2,3,4}. Now then, this variable will be called as *commonality index*. Similarly, $X_{jk} - 1$ statement is summing while multiplying the difference between maximum station numbers Kmax, and actual cardinality of "k", satisfies the encouragement of assignments to earlier stations. It should be mentioned that the lower

"k" (earlier station) results higher positive effect at objective function. There is another point to highlight that the single assignments or non-assignment of tasks at a station is penalized through subtracting one from *commonality index* ($X_{jk} - 1$).

Constraint (4.6) ensures that every task j on model m can only be assigned at only one station over all stations. Constraint (4.7) constructed to satisfy individual precedence relationships of models. If a task "j" is immediate successor of task "i" for model "m", than assigned station of "j" cannot be greater than assigned station of task "i" for model "m". This equation is valid when process times of task "j" of model "m" or processing time of task "i" of model "m" is greater than zero. Constraint (4.8) ensures that makespan of a model "m" at station "k" cannot exceed predetermined upper bounds of stations as C_k. The summation cannot exceed pre-determined cycle time "C" for such stations that k < Kmax. While, the summation cannot exceed pre-determined cycle time "G" (a big number that should be greater than longest lead-time) for station k=Kmax, to assign all remaining inappropriate tasks to station k=Kmax since that is determined as *bucket station*. It is fundamental for the iterative approach, while parametrically interchanging Kmax some tasks (inappropriate tasks) could not be assigned to *non-bucket stations*. In order to retrieve optimum solution these inappropriate tasks are assigned to bucket station at respective Kmax alternation iteration. Note that Kmax alternation iteration is stopped when all tasks assigned to non-bucket stations (k<Kmax).

Constraint (4.9) ensures the assignment of total common model "m" assignments for task "j" at station k is set to *commonality index* variable X_{jk} . The commonality index assigned to X_{jk} through summing Y_{jk}^{m} over all models. Constraint (4.10) ensures that the *commonality indicator* XC_{jk} takes value of one while X_{jk} is equals to {2,3,4}, and station *k* is lower than *Kmax* (non-bucket stations) otherwise XC_{jk} will take the value of zero.

Since the variables are identified as non-negative values by definition; Firstly, Y_{jk}^{m} and XC_{jk} are identified as *binary,* Secondly, X_{jk} is identified as *integer*. It is not necessary to force this by explicitly constructing an additional constraint.

Before advancing the subsequent section, it should be cited that these mathematical formulations are not first of their kind, at least in overall approach to the problem. There are other mathematical formulations suggested by a range of papers for the Mixed-Model ALBP. Current model based on binary design is joint formulation with numerous paper suggested before. Nevertheless, a general resemblance exists; the arrangement of constraints, particularly objective functions (4.1), (4.5) and commonality assignment constraints (4.9), and (4.10) are unique at this study. Any mathematical model suggested in the literature may have advantages and disadvantages compared to other formulations. However, making performance assessment with other models in the literature is not the concern of the study. Comprehensive comparisons for different MALBP approaches have been represented in this study.

4.3 Performance Measures

The performance measures evaluated throughout the models are defined below. All performance measures will be tested with cycle time C = {10} and maximum station number Kmax = {2,3,4,…,21}. On the other hand, it should be indicated that the tasks assigned to bucket station (last station) are exempt from calculation of performance measures.

Computational Time (CT): The total GAMS Cplex solver required to find the integer solution.

Total Commonality Index (TCI): This performance measure is defined for evaluating horizontal balance. This performance measure is summation of X_{jk} over all sets while the variable takes one of the value from subset S = {2,3,4}. The TCI measured for tasks that are assigned to a station for more than one model.

Idle Time (IT): This performance measure is defined for evaluating vertical balance. Idle time is the difference between the cycle time and the finish time of a model at some station *k.*

4.4 Validation of Mathematical Modeling Approaches

The validation of proposed mathematical models is verified through four selected literature problems. These problems are common problems for MALBP literature. First problem is adopted from Bowman's (1960) study, which is an 8-task problem. The second problem is adopted from Rosenberg und Ziegler's (1992) study that is a 25-task problem. The third problem is adopted from Kilbridge and Wester's (1961) study, which is a 45-task problem. The fourth and the last problem is adopted from Bartholdi's (1993) study that is 148-task problem. Table 4.2 summarizes the basic data on the test bed problems.

Table 4.2 Parameters of data sets that are employed for validation

Test-Bed Problems	**Bowman (1960)**	**Rosenberg und Ziegler (1992)**	**Kilbridge and Wester (1961)**	**Bartholdi (1993)**
Total Work Content (time units)	*75*	*158*	*568*	*6213*
Cycle Time (time units)	*34*	*32*	*116*	*766*
G (cycle time of bucket station)	*150*	*316*	*1136*	*12426*
Kmax-line length (stations)	*5*	*7*	*7*	*11*
Tasks	*8*	*25*	*45*	*148*
Models	*5*	*4*	*5*	*4*

For each problem, cycle times are set approximately two times of the maximum processing time among all tasks. Moreover, total work content is calculated through summation of all processing times of all tasks for associated problem.

The mathematical models are prerequisite an initial Kmax value with the intention of solving the problems. The initial Kmax is calculated through the formulation that is given below (see Equ. 4.11). Note that this value is an approximation for the minimum required Kmax to execute all tasks on the single line. However, this formulation does not take into account the effect of interference, thus greater Kmax may be required.

Under the condition of a presence of infeasibility, Kmax will be increased progressively until a feasible solution is gained. Note that "G", cycle times of bucket station, is set approximately twice time of the total work content.

$$LB_{Kmax} = \frac{\left[max_m\{\sum_{j \in J} p_{jm}\}\right]}{C} + 2 \tag{4.11}$$

Furthermore, the test beds are transformed into a joint model for validation of SALBP approach. The aggregate model construction processes is executed as follows. The processing times of the joint model's tasks are obtained by picking the maximum task duration through all models for each task (Equ. 4.12). The precedence relationships of model's tasks are obtained through taking the union of immediate successors of all models for each task (Equ. 4.13).

$$p_j = max_m(p_{jm}) \qquad \forall j \in J \tag{4.12}$$

$$S_j = \cup_{m \in M} S_{jm} \qquad \forall j \in J \tag{4.13}$$

Problems are formulated with GAMS 24.1.3 and solved with CPLEX 12.5.1 solver. Maximum solution time is set to 10800 seconds. Gap percentage is set to 0%. Gap percentage is the alteration between incumbent integer solution found and the current level of lower bound on optimal solution calculated by the branch and cut procedure of CPLEX algorithm. CPLEX efforts to increase the lower bound and catches better integer solutions concurrently. The procedure finishes when percentage difference between these two records is ensue to be zero else, the limit is grasped. Table 4.3 summarizes both statistics of problems and solutions for all data sets.

Table 4.3 Results of data sets that are employed for validation

	Test-Bed Problems	Bowman (1960)	Rosenberg and Ziegler (1992)	Kilbridge and Wester (1961)	Bartholdi (1993)
MALBP	Line Length	3	5	5	8
	Total # of Variables	305	1078	2240	9812
	Discrete # of Variables	280	1050	2205	9768
	Elapsed time (seconds)	0.11	1.5	10800	10800
	Absolute Gap	0	0	26.37	27.59
	Relative Gap	0	0	4.37%	6.79%
SALBP	Line Length	3	5	6	9
	Total # of Variables	45	182	322	1639
	Discrete # of Variables	40	175	315	1628
	Elapsed time (seconds)	1.29	1.55	1.67	611.65
	Absolute Gap	0	0	0	0
	Relative Gap	0	0	0	0

Solutions collected through the data sets verify that the mathematical formulations are correct and turn out solutions to the problems. However, for larger problems it takes longer time to collect an integer solution. The processing time and precedence relations data of employed data sets are represented in Appendix A while solution details are given in Appendix B.

4.5 Solution of the Case Study Problem

After market research, the management has decided to set the production rate as 54 units per day (one shift a day). A shift (08:00-18:00) lasts for 10 hours. On the other hand, one hour is released as grant for legal rights such as lunch and teatime. Consequently, remaining production time is 540 minutes per day. The cycle time calculated as C={10} according to $Cycle\ Time\ (C) = \frac{Daily\ Production\ Time}{Target\ Production\ Rate}$ equation, with given production rate of 54 units per day.

As it was mentioned previously, after determining the Cycle Time, the best station to install the supermarket have been searched by interchanging Kmax = {2,3,4,…,21}progressively till all tasks are assigned to non-bucket (k>Kmax) stations.

Four types of mathematical models are constructed and iteratively executed (Kmax alternation) for the first stage of the hybrid line design approach. These models are,

Mixed Model Assembly Line Balancing with non-weighted objective abbreviated as MALBPnw, Mixed Model Assembly Line Balancing with weighted objective abbreviated as MALBPwo, Single Model Assembly Line Balancing independent assignment abbreviated as SALBPia, Single Model Assembly Line Balancing joint assignment abbreviated as SALBPja. MALBPnw approach is the preliminary version of mathematical model that is given under Section 4.2.2, the Equation 4.5.2 was employed as the objective function of the respective model for this approach. Note that last version is given under Section 4.2.2, and the approach is abbreviated as MALBPwo.

$$\sum_{K=1}^{Kmax-1} \sum_{j \in J} (X_{jk} - 1) * (Kmax - k) \qquad (4.5.2)$$

Farther, there are two modeling approaches for single model ALBP case (SALBPia, SALBPja). For both approaches, the mathematical model, which is given under Section 4.2.1, is employed. Generation of these approaches conducted through data sets and execution method. Intended for SALBPia all version of products (models) are executed individually with respective SALBP approach. For SALBPja a joint aggregate model is generated before executing the mathematical model. Generated aggregate model's data set is employed for execution of respective SALBPja modeling approach. The aggregate model construction processes is executed as follows. The processing times of the joint model's tasks are obtained by picking the maximum task duration through all models for each task (Equ. 4.12). The precedence relationships of model's tasks are obtained through taking the union of immediate successors of all models for each task (Equ. 4.13). These instructions are also employed for generation of joint model for the test bed data which is employed for validation.

$$p_j = max_m(p_{jm}) \qquad \forall j \in J \qquad (4.12)$$

$$S_j = \cup_{m \in M} S_{jm} \qquad \forall j \in J \qquad (4.13)$$

The weights of objective functions that are represented at mathematical models may have important effect on the performance measures. Owing to this fact a parametrical analyses conducted for the approaches that have weighted objective function(SALBPia, SALBPja and MALBPwo). Determination of w_1 and w_2 is gathered through an experimental iterative computational analysis. Firstly, Kmax is set to eight, weight (w1 and w2) is iteratively increased starting from one, and the search procedure is ended when the weight is equal to four. The step size of the search was 0.5. Owing to obtained experimental results, setting the weight to 1.5, increase the primary performance measure TCI two additional score at MALBPwo approach. Iterative increase from that point does not result change at TCI score, while the competition time is increasing.

Table 4.4 Parametric Weight Analyses

	Objective Weight	TCI	CT (Seconds)	Idle Time of Weighted Aggregate Model
MALBPwo	1	292	35.82	6.31
	1.5	294	62.19	6.31
	2	294	226.40	6.12
	2.5	294	185.03	6.12
	3	294	168.99	6.31
	3.5	294	161.31	6.42
	4	294	132.19	6.42
SALBPja	1	182	13.07	40.16
	1.5	182	14.15	40.16
	2	182	10.29	40.39
	2.5	182	8.90	40.39
	3	182	10.01	40.16
	3.5	182	9.63	40.16
	4	182	9.43	40.39
SALBPia	1	126	15.40	6.31
	1.5	128	12.91	6.31
	2	128	13.87	6.31
	2.5	128	11.45	6.63
	3	128	10.93	6.63
	3.5	128	15.06	6.31
	4	128	13.08	6.31

Moreover, the experimental results reveal that, changing the weight does not result any change at the primary performance measure TCI score at SALBPja approach.

Consequently, SALBPja's weight is set to one. Note that the SALBPia approach represents a slightly better performance by incremental increase of the weight owing the fact that the respective approach represents the worst performance in terms of TCI score. However, the weight of primary objective is set to 1.5 for SALBPia approach. Selected weights 1.5, 1, and 1.5 are highlighted at the given Table 4.4 for their respective approaches MALBPwo, SALBPja and SALBPia. These weights are employed during the solution of the approaches for case study and test bed validation. The results, which have been obtained through these approaches, have been represented in the following sections.

4.6 Computational Experiments

Computational experiments are given under this section. GAMS win64 24.1.3 software package is employed for mathematical model computations. GAMSGDX option is utilized for reading the parameters and writing the solution outputs through excel. The solutions executed on a computer that has the following technical qualifications. Processor: Intel® Core™ i7-4700HQ CPU @2.40GHz, Random Access Memory (RAM): 16 GB, System Architecture: 64-Bit(x64), Operating System: Windows 8.1 Pro.

The computational experiments will be shortly talked, which have less priority for the one time execution case. It should be indicated that the effect of every alternation of Kmax by one that stepping procedure results 1500 binary and 300 integer variables released to system to be evaluated for MALBP approaches. Besides, 300 binary variables released to system to be evaluated for both SALBP approaches. Computational time of MALBP non-weighted objective model and SALBP individual assignment model, according to Kmax runs are represented in Figure 4.2. It can be said that as the Kmax increases the feasible region for the case, and the computational time for optimal solution search procedure also increases.

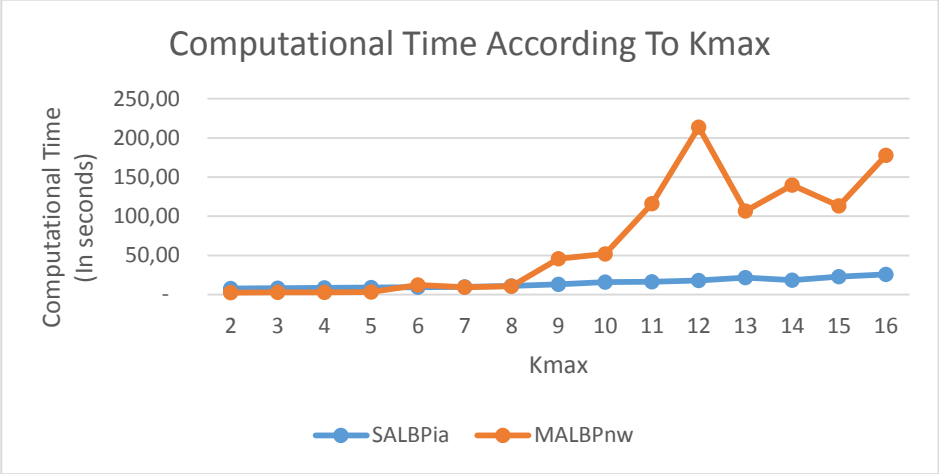


Figure 4.2 Computational time according to Kmax for SALBPia and MALBPnw

Distinct from prior cases the weighted objective MALBP and SALBP execution for joint model consumes significantly greater time for optimum solution search (see Figure 4.3). The solution times are logarithmically increasing as the multiplier Kmax increases. Because of the fact that, GAMS is searching the optimal value for objective functions among the feasible regions, the respective solution time gradually increases.

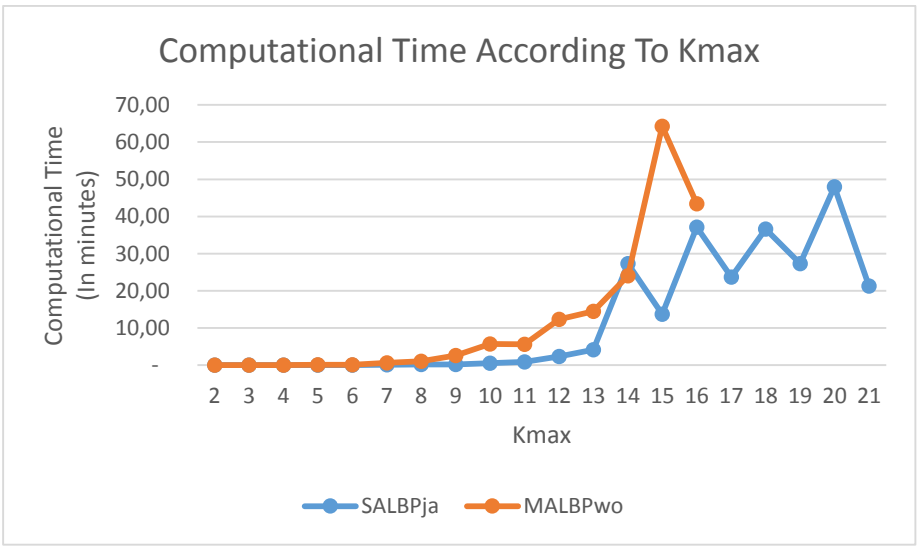


Figure 4.3 Computational time according to Kmax for SALBPja and MALBPwo

Besides, the optimum solution search along the possible solutions increase, because the trade-offs introduced by means of objective function to be checked are increasing.

4.7 Discussion of Results

In this section, the mathematical insights of models will be discussed to provide a better comparison and understanding. Initially, it should be indicated that all tasks are assigned to appropriate stations with respect to objective function and constraints while Kmax = 13 for MALBPnw, MALBPwo and SALBPia. According to SALBPja approach all tasks of joint model assigned when Kmax = 21. The highest TCI observed as 144,346,148 and 387 for respective modelling approaches MALBPnw, MALBPwo, SALBPia and SALBPja.

However, the TCI continued to fluctuate in a slight interval for MALBPnw and SALBPia but for both model all tasks are assigned at first twelve stations. Fluctuation of TCI at can be addressed to $(Kmax - k)$ multiplier at the objective functions, as Kmax increases, assignment of non-common tasks can provide similar or better improvement at objective function. In contrast to these two cases, MALBmo and SALBPja remain the performance measure same among remaining Kmax interchanges. Subsequently the best result is gathered at Kmax=13 for MALBPwo and Kmax=21 for SALBPja.

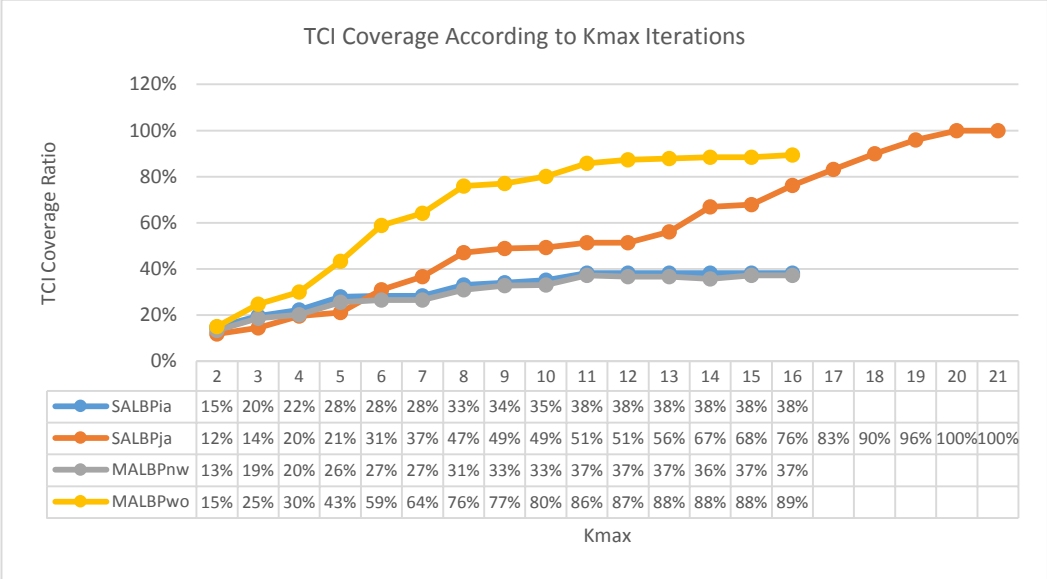
Now then, the assignments of mathematical models will be investigated in order to understand the assignment behavior of models. The TCI coverage rates of respective iterations for the Kmax (MALBPwo: 13, MALBPnw: 13, SALBPja: 21, SALBPia: 13) that all tasks assigned to non-bucket stations are represented in Figure 4.4. Four lines are represented and each stands for a modeling approach. Each approach is represented with universal abbreviations used throughout the text.

The MALBP non-weighted objective model (MALBPnw) and SALBP independent assignment approach (SALBPia) finishes all tasks at sixth station for model 2 and finishes all tasks at fifth station for model 1. However, more complicated models: MALBP weighted objective model (MALBPwo) and SALBP joint assignment approach (SALBPja) makes postponements in order to increase the TCI, the models

assign less tasks to first five stations according to MALBPnw and SALBPia and add the delayed tasks at the end of prior assignment. This is nearly similar to preemption application under parallel machine case.

Owing the fact that, model 1 and model 2 represents a pair in terms of task similarity while model 4 and model 8 also represents a pair in terms of task similarity (see Table 2.7 and Table 2.8), the MALBPwo model forces the assignment of same tasks at same stations especially for these pairs. Farther, assignment of same tasks at the same station is the nature of SALBPja, therefore best TCI scores gathered with this approach.

The MALBPwo model reduces the operation variation between these pairs, in other words, proposes a horizontally balanced assignment conducted for each pair of model achieved. The MALBPwo reaches higher TCI score by pairing the models with respect to their similarity. The horizontally balancing is done: firstly, among these pairs, then among all models. The model represents the behavior not because a special design conducted through parameters or indices but because proposed objective function (Equ. 4.5) which forces the assignment of tasks to same stations among the models as far as possible to gather higher TCI as a performance measure. In contrast to Gökçen and Erel(1997) approach which is done through variable indices under the assumption '*same tasks must be assigned to same stations which is valid for all models*', the MALBPwo model provides a horizontally balanced assignment thanks to objective function encouragement. Nevertheless, it can be observed that best solutions in terms of performance measures gathered through SALBPja, which is similar to Gökçen and Erel (1997) study. The results gathered from the Mathematical model executions are represented in Appendix B.



	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
SALBPia	15%	20%	22%	28%	28%	28%	33%	34%	35%	38%	38%	38%	38%	38%	38%					
SALBPja	12%	14%	20%	21%	31%	37%	47%	49%	49%	51%	51%	56%	67%	68%	76%	83%	90%	96%	100%	100%
MALBPnw	13%	19%	20%	26%	27%	27%	31%	33%	33%	37%	37%	37%	36%	37%	37%					
MALBPwo	15%	25%	30%	43%	59%	64%	76%	77%	80%	86%	87%	88%	88%	88%	89%					

Figure 4.4 Ratio of Gathered TCI to Max Available TCI for Kmax Runs

In Figure 4.4, the ratio represents the coverage of Best TCI score, in order to conduct a comparison between the models. Best TCI is gathered by calculation of following statement $\sum_{j\in J}|A_j|$, the final result of the calculation is 387. It could be easily gathered through the results that SALBP joint model approach represents the best performance while Kmax = {20, 21}. MALBP weighted objective approach (MALBPwo) succeeding SALBPja with 89% cover while Kmax = {16}.

Experimental results reveal that the horizontal balancing (TCI cover) has linear relationship with line length and idle time. As far as horizontal balance increase, the line length and idle time will also increase. In Table 4.5 the line length outputs of line balancing approaches are given.

Table 4.5 Line Length According to Solution Approach

	MALBPwo	**MALBPnw**	**SALBPja**	**SALBPia**
Line Length (Station #)	12	12	20	12

Observations through experimental results reveal that 11% additional TCI score improvement, which is gathered through MALBPwo to SALBPja method alternation,

costs eight additional station installation. It should also mentioned that SALBPja starts to represent better TCI scores than MALBPwo after Kmax = {18} iteration. As far as horizontal balance increase, the line length and idle time will also increase.

As the line length increases, the idle time according to model also increases. SALBPja model submit 100% coverage of TCI score with a cost of eighty additional idle time (in minutes) for each model (see Table 4.6). It can be said that selection of SALBPja the average idle time at stations will increase 1.91, 2.26, 3.62, and 3.36 additional minutes for respective models 1, 2, 4, and 8. Note that the idle time is same for MALBPwo, MALBPnw and SALBPia approaches for the reason that the line length is the function of total idle time. MALBPwo approach represents similar performance with MALBPnw and SALBPia approaches in terms of idle time, while the MALBPwo approach represents significantly better performance at maximization of commonality in other words TCI score coverage.

Table 4.6 Total Idle Time through the line According to Solution Approach

Model	MALBPnw	MALBPwo	SALBPia	SALBPja
1	62.58	62.58	62.58	142.58
2	52.20	52.20	52.20	132.20
4	11.54	11.54	11.54	91.54
8	19.06	19.06	19.06	99.06
Weighted	37.84	37.84	37.84	117.84

Comparing the best two approaches' performance, there is a tradeoff between idle time and TCI score. MALBPwo covers 89% of Best TCI score and stands second for this performance measure while SALBP cover 100% of Best TCI score. Nonetheless, application of SALBPja results eighty additional idle times for individual model and weighted aggregate model. Applying SALBPja instead of MALBPwo will result covering 41 additional TCI score, in other words increasing TCI cover rate 89% to 100%, will result 80 additional idle time for each model's production process. It should be indicated that the weighted model is calculated by multiplying the observed idle times of each model with their respective weight that are given in Table 4.7.

Table 4.7 Weight of the models

	Model#1	**Model#2**	**Model#4**	**Model#8**
Weight	0.3335	0.2074	0.3488	0.1102

Moreover, the idle times per stations according to solution approaches are given in Table 4.8. Note that Table 4.6 is the cumulative version of Table 4.8. Table 4.8 is given for satisfying a better understanding the distribution of idle times through the stations of the line. The Table 4.8 reveals that the idle times are observed especially at the end of the line for MALBPnw, MALBPwo, and SALBPia approaches while the idle times spread over the whole line, especially at the initial stations, for SALBPja approach which represents the worst performance in terms of idle time.

Table 4.8 Idle Times at Stations According to Modeling Approaches

	MALBPwo		**MALBPnw**		**SALBPja**		**SALBPia**	
Stations	Model#1	Model#2	Model#1	Model#2	Model#1	Model#2	Model#1	Model#2
1	1.53	0.21	0.04	0.21	5.72	5.40	0.01	0.21
2	3.50	0.22	0.01	0.22	6.97	7.04	0.15	0.22
3	2.92	0.31	0.08	0.31	9.28	8.20	0.02	0.31
4	2.85	0.12	0.11	0.12	10.00	10.00	0.04	0.12
5	0.35	0.16	0.78	0.16	4.83	3.97	0.03	0.16
6	0.21	0.56	1.57	0.56	8.41	5.14	2.33	0.32
7	1.21	0.64	10.00	0.64	3.17	3.50	10.00	0.87
8	10.00	10.00	10.00	10.00	10.00	5.18	10.00	10.00
9	10.00	10.00	10.00	10.00	9.58	10.00	10.00	10.00
10	10.00	10.00	10.00	10.00	8.86	6.74	10.00	10.00
11	10.00	10.00	10.00	10.00	10.00	9.80	10.00	10.00
12	10.00	10.00	10.00	10.00	6.26	7.36	10.00	10.00
13					7.30	7.30		
14					7.35	8.13		
15					6.93	6.83		
16					4.67	3.97		
17					5.93	6.44		
18					4.78	4.25		
19					2.56	2.94		
20					10.00	10.00		

	Model#4	Model#8	Model#4	Model#8	Model#4	Model#8	Model#4	Model#8
1	0.00	0.09	0.00	0.08	3.81	3.65	0.00	0.00
2	3.35	0.11	0.95	0.14	4.18	4.96	0.95	0.22
3	1.09	0.36	0.07	0.31	5.40	1.33	0.07	0.33
4	0.15	0.55	1.11	0.57	5.17	3.95	1.11	0.22
5	0.36	0.07	0.67	0.07	2.99	5.46	0.67	0.40
6	0.17	0.26	0.16	0.26	5.60	6.23	0.07	0.26
7	0.03	0.44	0.74	1.82	4.98	6.98	0.83	1.82
8	0.03	4.84	0.51	0.54	7.01	7.07	0.51	0.54
9	0.75	2.39	1.72	0.14	5.45	3.92	1.72	0.14
10	0.05	0.26	0.03	0.40	2.16	10.00	0.03	0.40
11	1.30	0.94	0.01	4.72	6.69	3.56	0.01	4.72
12	4.26	8.74	5.57	10.00	9.43	2.30	5.57	10.00
13					1.01	3.85		
14					5.85	3.47		
15					0.89	7.08		
16					1.12	1.12		
17					2.20	4.45		
18					3.34	2.94		
19					4.54	9.94		
20					9.72	6.80		

Lastly, Table 4.9 is represented for making a supermarket place determination. Note that the SALBPia and MALBPwo are representing poor performance in terms of TCI so this two method is eliminated for such decision making issue. MALBPwo and SALBPja approaches are selected with their respective TCI coverage performance (Figure 4.4). Subsequently, in order to achieve final output of the first stage of hybrid line design approach, TCI performance per Kmax step of the selected modeling approaches are analyzed. Table 4.9 is represented to illustrate the actual TCI improvement with achieving that step i.e. for MALBPwo approach the TCI score is increased 18.5% by stepping from Kmax seven to Kmax eight. Owing to these results for the MALBPwo approach, the search should be stopped achieving 75% of best TCI and farther steps are not attractive to execute while Kmax is equals to eight. On the other hand, for the SALBPja approach, similar 295 TCI score to MALBPwo could be achieved while Kmax is equal to sixteen with a 12.2% actual improvement according to prior step. Respective selected steps are highlighted at Table 4.9.

Table 4.9 TCI Change for Kmax Step for Modeling Approaches

Kmax	SALBPia	SALBPja	MALBPnw	MALBPwo
3	33.3%	21.7%	38.5%	65.5%
4	13.2%	35.7%	8.3%	20.8%
5	25.6%	7.9%	26.9%	44.8%
6	1.9%	46.3%	4.0%	35.7%
7	0.0%	18.3%	0.0%	8.8%
8	16.4%	28.2%	16.5%	18.5%
9	3.1%	3.8%	5.8%	1.4%
10	3.0%	1.1%	0.8%	4.0%
11	8.8%	4.2%	12.5%	7.1%
12	0.0%	0.0%	-1.4%	1.8%
13	0.0%	9.0%	0.0%	0.6%
14	0.0%	19.4%	-2.8%	0.6%
15	0.0%	1.5%	4.3%	0.0%
16	0.0%	12.2%	0.0%	1.2%
17		9.2%		
18		8.1%		
19		6.6%		
20		4.3%		
21		0.0%		

Consequently, with regard to MALBP weighted objective approach results, the line length must be determined as twelve station and the CONWIP Supermarket must be installed at station seven (Kmax=8) where increasing the Kmax does not provide a significant improvement in terms of TCI. On the other hand, with regard to selected second approach SALBP joint assignment approach results, the line length must be determined as twenty stations and the CONWIP supermarket must be installed at station fifteen (Kmax = 16) where the possible yield is not sufficient to step up.

CHAPTER 5

SIMULATION MODEL AND VERIFICATION

Model of a system in order to analyze determining the problems may be complicated in some cases, furthermore understanding and numerically analyzing the constructed model may also be complicated (Halaç, 1995). Simulation is widely used for modelling real-world representation. The widest definition of simulation has been made by (Erkut and Baskak, 1997): They defined the *simulation technique* as construction and experiment conduction of the defined computer model of the system, in order to understand the process and evaluate the effects of different parameters.

Simulation is a modelling tool similar to mathematical model, which is especially employed at modelling a wide variety of complex stochastic systems. The simulation technique provides a powerful tool as an opportunity to be utilized aimed at system analyzing. Simulation has been applied at a wide variety of fields such as healthcare, marketing, supply chain, military and so on. The modelling technique has an important role particularly, evaluation of operational performance and design of manufacturing systems. Many successful applications of simulation technique in a wide range of fields had been researched in literature. The researches have proved its prosperity in many practical real-world problems.

Simulation technique and the use of its software packages have been subjected in various books (i.e. Kelton et al. (2011), Sokolowski et al. (2009), Ross (2006)). Numerous studies and papers in the literature about simulation technique; researching different characteristics of the modelling technique such as verification and validation of models, and conducting and analyzing simulation experiments have been published. Smith and Negahban (2014) provided a comprehensive review of discrete event simulation publications.

Particularly, simulation technique employed at balancing problems (Reeve and Thomas (1973); Buxey et al. (1976); Driscolla and Abdel-Shafi (1985); Moberly and Wyman (1973)). Moreover, similar to the case Ip et al. (2007) and Eng and Sin (2013) employed simulation technique to evaluate the performance of CONWIP systems

Some of the fields of simulation applications are represented below:

- Design and analysis of Production Systems
- Assembly Line Balancing
- Workforce Planning
- Analysis the Effect of Stock Policy at an Inventory System
- Design of Distribution Channels

Pros and cons of Simulation Technique:

Advantages

- A flexible solution approach
- Easy to understand according to other system model techniques
- Successful and efficient at big complicated problem solutions that cannot be solved or modelled by Classic Approach
- Application can be done phase by phase
- Results can be gathered in a short period while real-time observation of system behavior may take a long time.
- Researcher have full control on the model i.e. she/he can start/stop the system anytime required.

Disadvantages:

- The technique does not guarantee proposing the optimum solution.
- Every simulation is idiosyncratic
- Easiness of application may result ignorance of the analytical solutions
- Faults done during modelling and analyze may have provide, wrong results.

The experiments and results of robustness test of proposed Hybrid Assembly Line are represented in this chapter. Firstly, Current Assembly Line constructed as a *base model* (Figure 5.1) to compare the proposed systems (Figure 5.2) results. Afterwards proposed system with integrated CONWIP Level Optimization Model had been constructed.

Firstly, input analyze of uncontrollable parameters are represented which are interarrival time and batch size of orders. Afterwards, assumptions that are taken into account while modelling the system will be represented. Then, Serial Assembly Line as *base model* and Hybrid Assembly Line as *proposed model* will be defined and detailed. Lastly, solutions of models under different scenarios and discussion of the results will be represented.

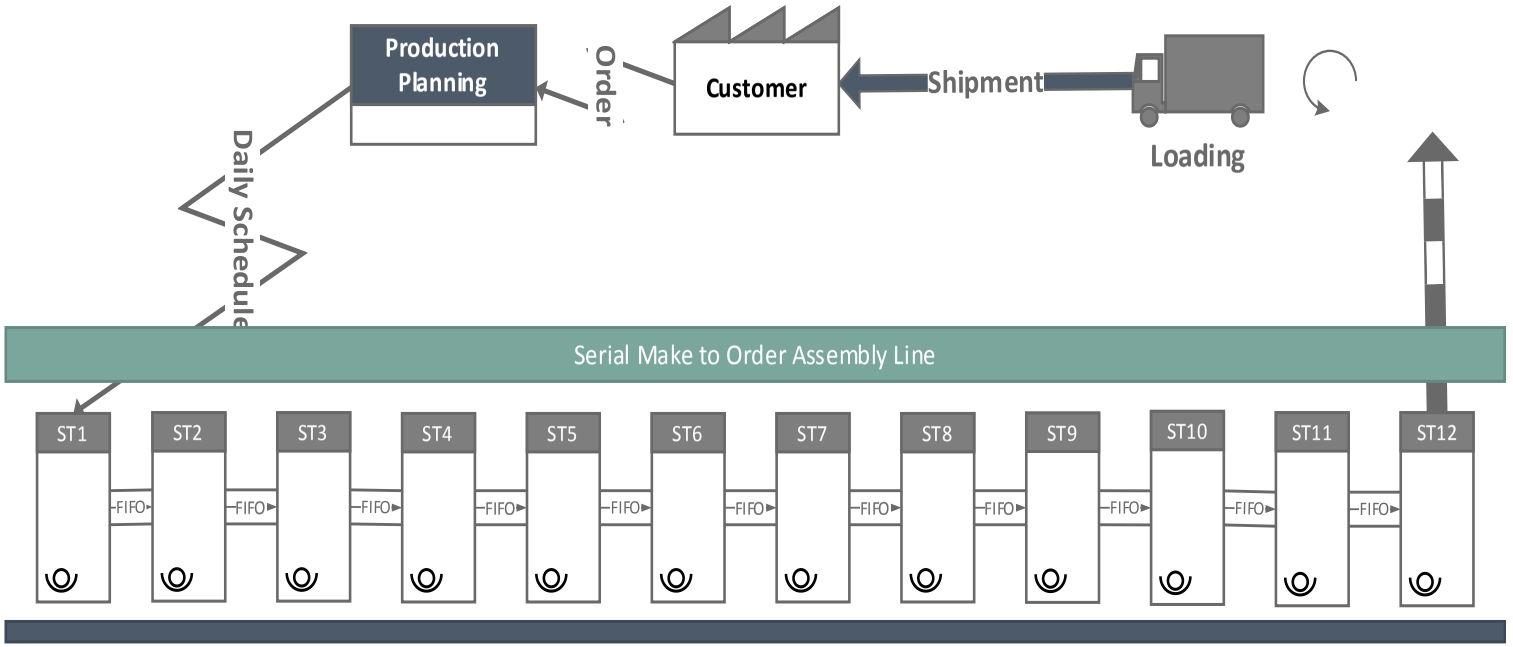


Figure 5.1 Base Model (Current Serial Assembly Line)

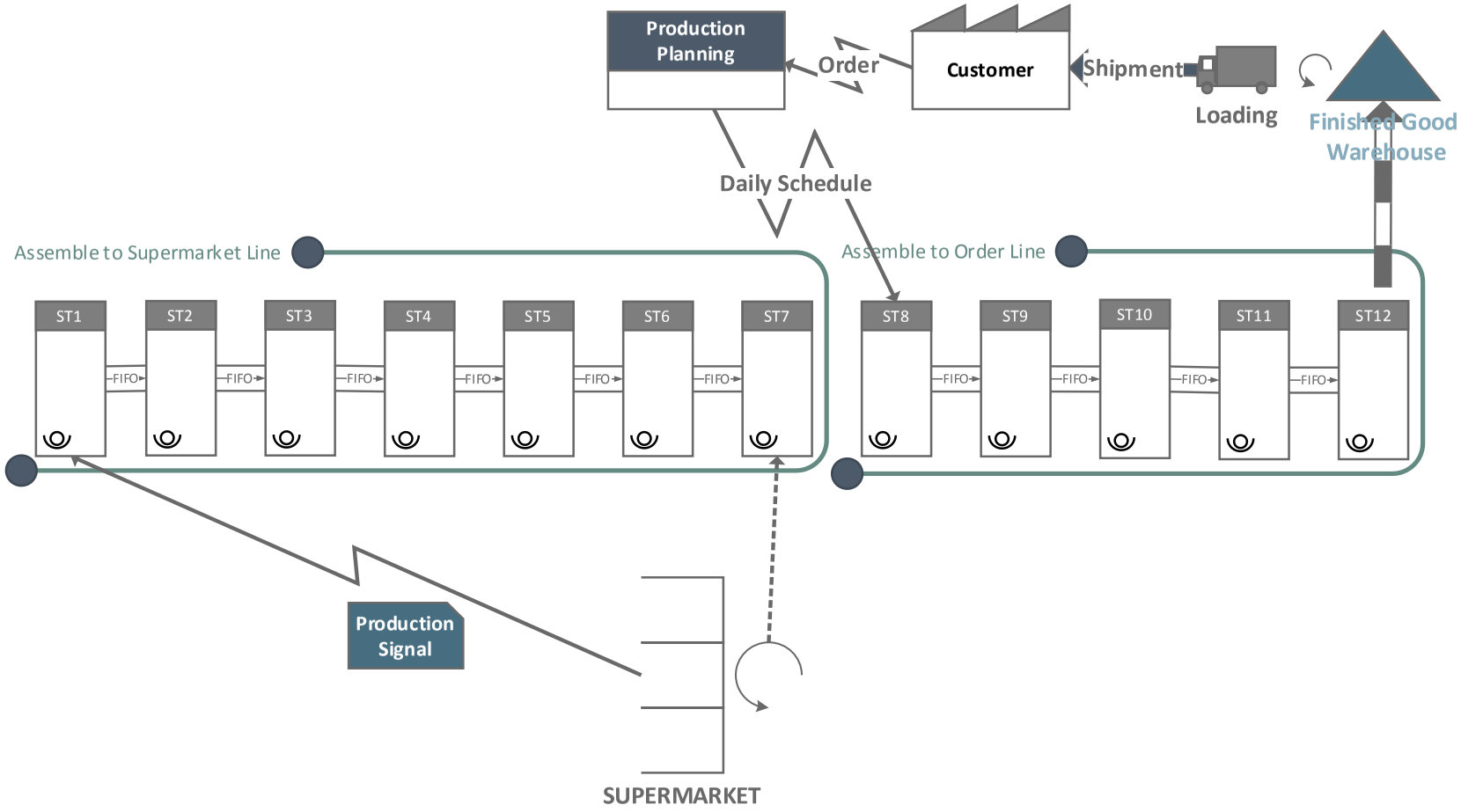


Figure 5.2 Proposed Model (Hybrid Assembly Line)

In order to test robustness the simulation model of current system and proposed system conducted and executed on a simulation software. The parameters that are alternated are listed below. In the last section, we will represent a sensitivity analysis to understand the effectiveness of proposed system.

i. Distribution of Order Size,(Gamma or Exponential)
ii. Cycle Time or Line Length
(C=5,K=24;C=10,K=12;C=10,K=20;C=5,K=8)

Arena 13.5 Software Package used for modelling the designs. The package presents the visual programming standards, siman codes occur behind while the user visually construct model within modules, block, elements and transfers and link them to each other to represent the relationship of the system components. Because of reporting and modelling superiority, Arena Software Package is employed for constructing the simulation models of *base system* and *proposed system*.

5.1 Input Analyze

The input analyze of used data will be represented throughout the section. There are three data defined to be distributed according to a distribution. Arena input analyzer is utilized to find the best-fit distribution to related data. The model distributions , interarrival times, and order sizes of data are tested. Order data had been retrieved from ERP database of the switchgear producer with a horizon of one year. Retrieved data prepared for distribution testing. Firstly, the orders are pivot according to create date and time than the interarrival time between two adjacent order pairs are calculated. Calculated order size and interarrival times had been put on test on Arena. Tested order data is represented in Appendix C.

5.1.1 Interarrival Time

After testing the order data, the best-fit distribution is found as a version of beta distribution. According to analysis results fits with a version of beta distribution that the distribution fits with 0.000826 square error. Gathered expression (5.1) will be defined as interarrival time distribution at simulation models for random time generation of adjacent entity creation.

$$Interarrival\ time(t) = 0.999 + 838*BETA(0.383, 5.12) \quad (5.1)$$

Related results of analysis and the best-fit distribution behavior comparing with actual data histogram are represented in Appendix C.

5.1.2 Order Size

Another stochastic parameter of the model is order size. Two of best-fit distributions is selected and used for parametric sensitivity analysis. After testing the order data, the best-fit distribution is set at a version of exponential distribution. The analysis results are revealed that the distribution fits with 0.000339 square error. Gathered expression (5.2) will be defined as order size distribution at simulation models for random generation of batch size of orders.

$$Order\ size(t) = 0.999 + EXPO(3.23) \quad (5.2)$$

Consequently, the second best fit distribution found as *gamma distribution*. The analysis results are revealed that the distribution fits with 0.121783 square error. Gathered expression (5.3) will be defined as order size distribution at simulation models for random generation of batch size of orders.

$$Order\ size(t) = 0.999 + GAMMA(8.76, 0.369) \quad (5.3)$$

Related results of analysis and the best-fit distribution behavior comparing with actual data histogram are represented in Appendix C.

5.1.3 Distribution of Models

Last parameter as the distribution of model data is represented. The distribution according to product type represented in Table 5.1, which is gathered from order data. After entity creation, the entities are constantly divided into product types with regard to following values.

Table 5.1 Constant Distribution Rate of Products

	Model#1	Model#2	Model#4	Model#8
Distribution	0.3335	0.2074	0.3488	0.1102

These distributions of models will also used for weighting the performance measures

5.2 Assumptions

These assumptions are the common assumptions for simulation models. Further assumptions will be introduced when needed.

- All tasks are processed in a predetermined mode (no processing alternatives exist),
- Paced line with a fixed common cycle time according to a desired output quantity,
- Deterministic (and integral) station times for all models. Paced assembly line. Buffer will not allowed,
- Decision processes for work orders done with zero or negligible time,
- No breakdown or any other interruption to production process allowed,
- Deterministic (and integral) model distribution with respect to Table 5.1 for all models.

5.3 Model

5.3.1 Base Model

The model details of serial, paced assembly line, which is defined as *base system* is given under this section. As previously mentioned the aim of construction of this base model is to compare the proposed system in terms of performance measures, which are selected to construct a comprehensive comparison. The illustration of the system is represented in Figure 5.1.

The union of three sub-models that are listed below compromised the Base Model.

- Order Creation Sub-model,
- Assembly Process Sub-model,
- Order Fulfilment Sub-model.

The relationship of these sub-models is represented in Figure 5.3. The details of sun-models are given below under sub-sections.

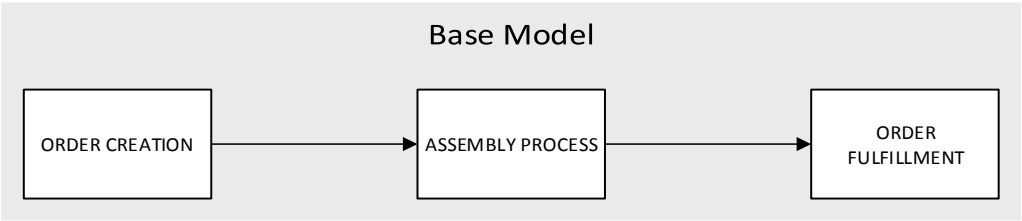


Figure 5.3 Base Model Simulation Model Flowchart

5.3.1.1 Order Creation Sub-model

This sub-model consists of two type of modules. There is one create and one assign module. Create Module used for creation of entities to system subject to stochastic interarrival times and order sizes to represent the customer behavior. The other module assigns used for assigning the product type to the entities according to cumulative discrete distribution of the products that gathered at data analyze. Moreover, the arrival time of products in terms of product type has been registered with an attribute, which is defined under this module. This attribute records the actual simulation time of the

related entity as soon as arrived at the system. That will be used for calculation of lead-time. After assigning the entity type, this sub-model links to Assembly Process Sub-model.

5.3.1.2 Assembly Process Sub-model

This sub-model consists of one type of module. There are twelve processes module to represent the stations. Process Modules worked under seize delay release principle. Delay time is defined with a constant value that to represent the Cycle Time. Entities are coming from Order Creation sub-model and leaving this sub-model links to Order Fulfilment Sub-model.

5.3.1.3 Order Fulfilment Sub-model

This sub-model consists of three type of modules. There are four records, one is decide, and the other is dispose module. Decide module used to separate, by checking arrived entity type of that comes from the last station as finished products, to the records before dispose operation for recording the leaving/fulfilment time. There are four record module constructed to hold the leaving time for each entity type by defining arrive attribute under each record. Last module dispose is representing the leaving of the product from the system.

5.3.2 Proposed Model

The simulation model is constructed for representation of the *proposed system* that is illustrated in Figure 5.2. Moreover, an embedded tool, which is constructed for CONWIP level optimization, is also represented. The aim is to determine the best CONWIP levels while minimizing the average weighted lead-time. The details of CONWIP level optimization tool represented under section 5.3.3 in detail.

The union of five sub-models that are listed below compromised the proposed model.

- Order Creation sub-model,
- Assembly to Supermarket sub-model,

- Assembly to Order sub-model,
- Supermarket loading/unloading sub-model,
- Order fulfilment sub-model.

The decision process and relationship of these sub-models represented in Figure 5.4. Firstly, order will arrive from customer to the system. Immediately right after the arrival of order, initially supermarket controlled in terms of level for each product type. If the order can be satisfied from supermarket, then it is sent as a work order to launch station of *order to assembly-line* and the semi-finished products pulled from the *supermarket* to launch station of *assembly to order-line* as an unloading procedure. Meanwhile, an order also sent as a *CONWIP order* to launch station of *assembly to supermarket-line*. If the order cannot be satisfied through supermarket, then order sent as a *product work order* to launch station of *assembly to supermarket-line*. A decide procedure run at the end of the *assembly to supermarket-line* checks the work order type if it is *CONWIP order* semi-finished product sent to supermarket for loading, else as a *product work order* semi-finished product sent to assembly to order-line. Lastly, *product order* completed at *assembly to order-line* and the finished product proceed to order fulfilment process. The details of employed sub-models are given in following sections.

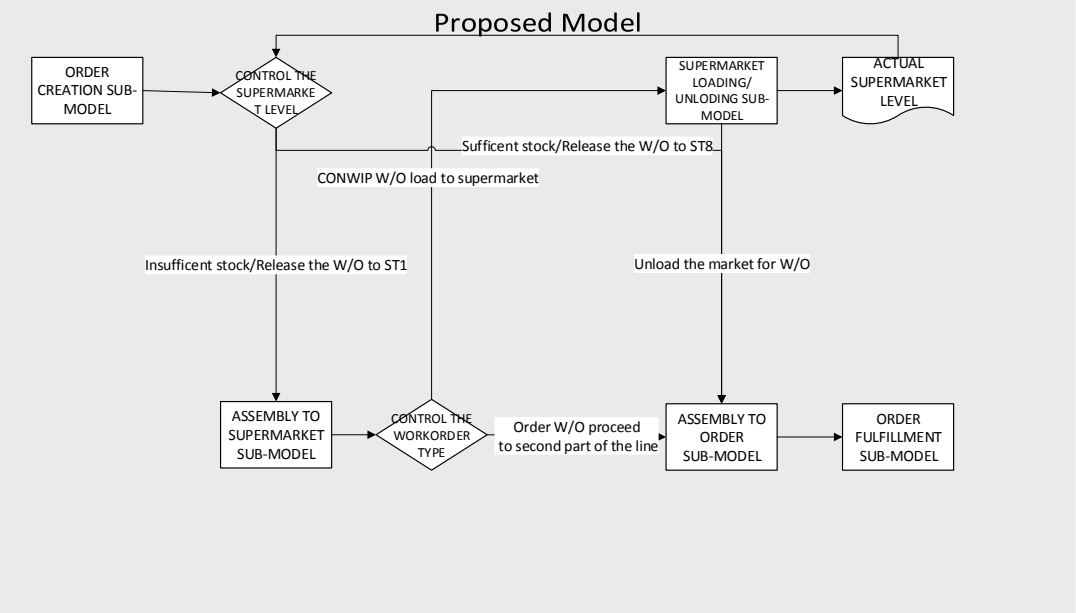


Figure 5.4 Proposed System Simulation Model Flowchart

5.3.2.1 Order Creation Sub-model

This sub-model consists of five type of modules. There are one create, two assign, five decide, four record and four hold module. Create module used for creation of entities to system subject to stochastic interarrival times and order sizes to represent the customer behavior. The other module assign used for assigning the product type to the entities according to cumulative discrete distribution of the products that gathered at data analyze. After assigning the entity type, it proceeds to decide module and separated to four-route option according to their type (01, 02, 04, and 08). The module route is fixed for each of the entity type (product type). Firstly, product held in hold module until batch queue of related entity type is equals to zero under *supermarket loading/unloading sub-model* done by defining a condition, than released with batch size one. Record module logs the stock level recording under *supermarket loading/unloading sub-model* as soon as the entity released from hold module. Lastly entities proceed to decide modules to evaluate the stock level: if the level equals to zero the entity proceed to the first station as a work order, else entity triggered the pull operation to *supermarket loading/unloading sub-model* or it can be called unloading procedure while entity sent as pull signal. Entities that their production starts from first

station proceed to assign module. This module tag two attributes to the entities these are arrival time and production type. Production type attribute defined to differ the work orders processed at *assembly to supermarket-line* from CONWIP work orders. Moreover, the arrival time of products in terms of product type has been registered with this attribute, which is defined under this module. This attribute records the actual simulation time of the entity type as soon as arrived at the system. That will be used for calculation of lead-time. The arena model of sub-model is represented in Figure 5.5.

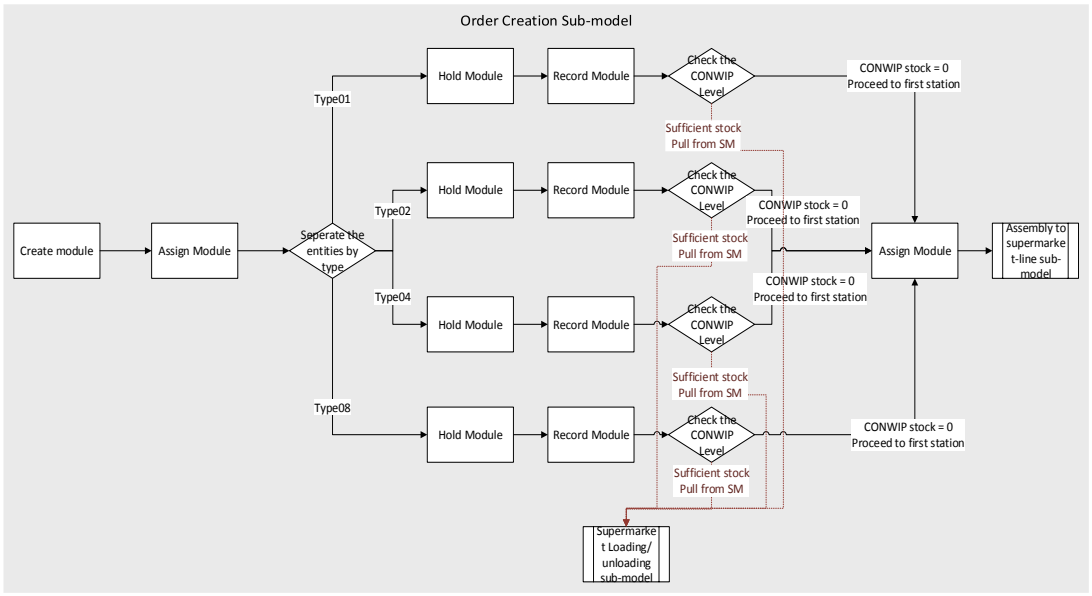


Figure 5.5 Order Creation Sub-model for Proposed System

5.3.2.2 Assembly to Supermarket Sub-model

This sub-model consists of two of modules. There are seven process modules to represent the stations and two decide module. Process modules worked under seize delay release principle. Delay time is defined with a constant value that to represent the cycle time. Decide modules installed for two different purposes: First decide module determine the leaving production type of semi-finished product according to assigned attribute (that is assigned immediately before leaving the *order creation sub-model*). If the semi-finished is tagged as order work order, it is released to *assembly to order-line sub-model* else released to second decide module.

Second, decide module checks and assigns the semi-finished products to four different route with regard to pre-defined entity type (product type). These routes defined to represent the loading movement to *supermarket loading/unloading sub-model*. Entities are coming from *order creation sub-model* or *supermarket loading/unloading sub-model*s work order and leaving this sub-model links to *supermarket loading/unloading sub-model* or *assembly to order-line sub-model* as semi-finished product. The arena model of sub-model is represented in Figure 5.6.

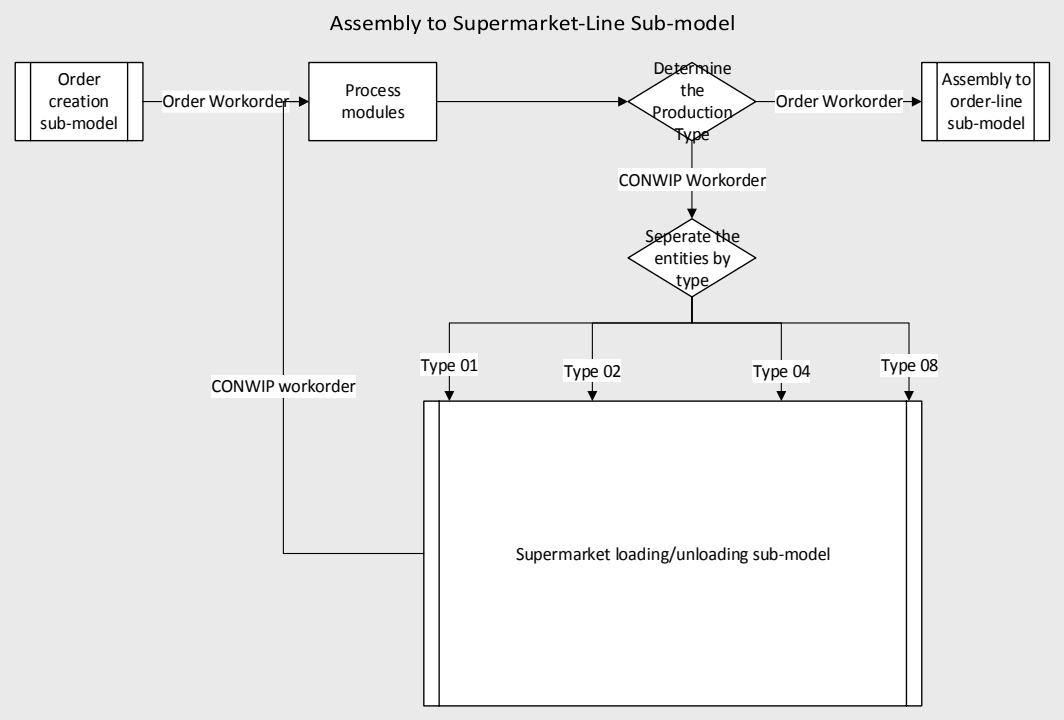


Figure 5.6 Assembly to Supermarket Sub-model for Proposed System

5.3.2.3 Supermarket Loading/unloading Sub-model

This sub-model consists eight type of modules. There are five assign, four create, four separate, four store, four hold, four unstore, four batch and four separate module in this sub-model. Create modules installed for first load of CONWIP stock of each product types. This module worked at the beginning to fill the related slots of products with a size of one. Afterwards the four separate modules, where each works for same purpose, separate is multiplexing the first created entities according to variables(x1,

x2, x4, x8) levels which are input from variable design. The created embedded math model searches the best combination of these variables while minimizing the average lead-time (section 5.3.3). After multiplexing procedure at separate module entity arrives, first four assign module. These modules tagging the entity types that are born without identity at related create module. Then the entities proceed to store module are tagged that they are stored, there are two routes feed this module, one is create-separate-assign route that works one time, at the start of simulation with zero time. The second route is coming from *assembly to supermarket-line sub-model*s semi-finished product. This route is continuously feed the supermarket with semi-finished products to related slots of supermarket that they are pulled with CONWP work orders previously. Hold module is installed to keep semi-finished products until batch module satisfies the pulling condition with a zero queue. Afterwards, when hold module release the semi-finished products, the system tagged that they are unloaded from the supermarket. After this module unloading procedure starts, the entities proceed to batch modules. Batch module waits until the entity size reach two. One of the entities represents the semi-finished product and the other entity that comes from *order creation sub-model* represents pull signal. When this two entity enters module stick this two entity together and sends only one entity to separate module. Separate module multiplex the arriving entity, one sent to *assembly to supermarket sub-model* as a CONWIP work order, the other is sent to last assign module as semi-finished product. Last, assign module logs the actual arrival time of semi-finished product that will be used for lead-time calculation. After leaving, the entity proceeds to *assembly to order sub-model* as a semi-finished product. Entities are coming from *assembly to supermarket-line sub-model* as semi-finished product or order creation sub-model as pull signal and they are leaving this sub-model linked to *assembly to order sub-model* as semi-finished product. The arena model of sub-model is represented in Figure 5.7.

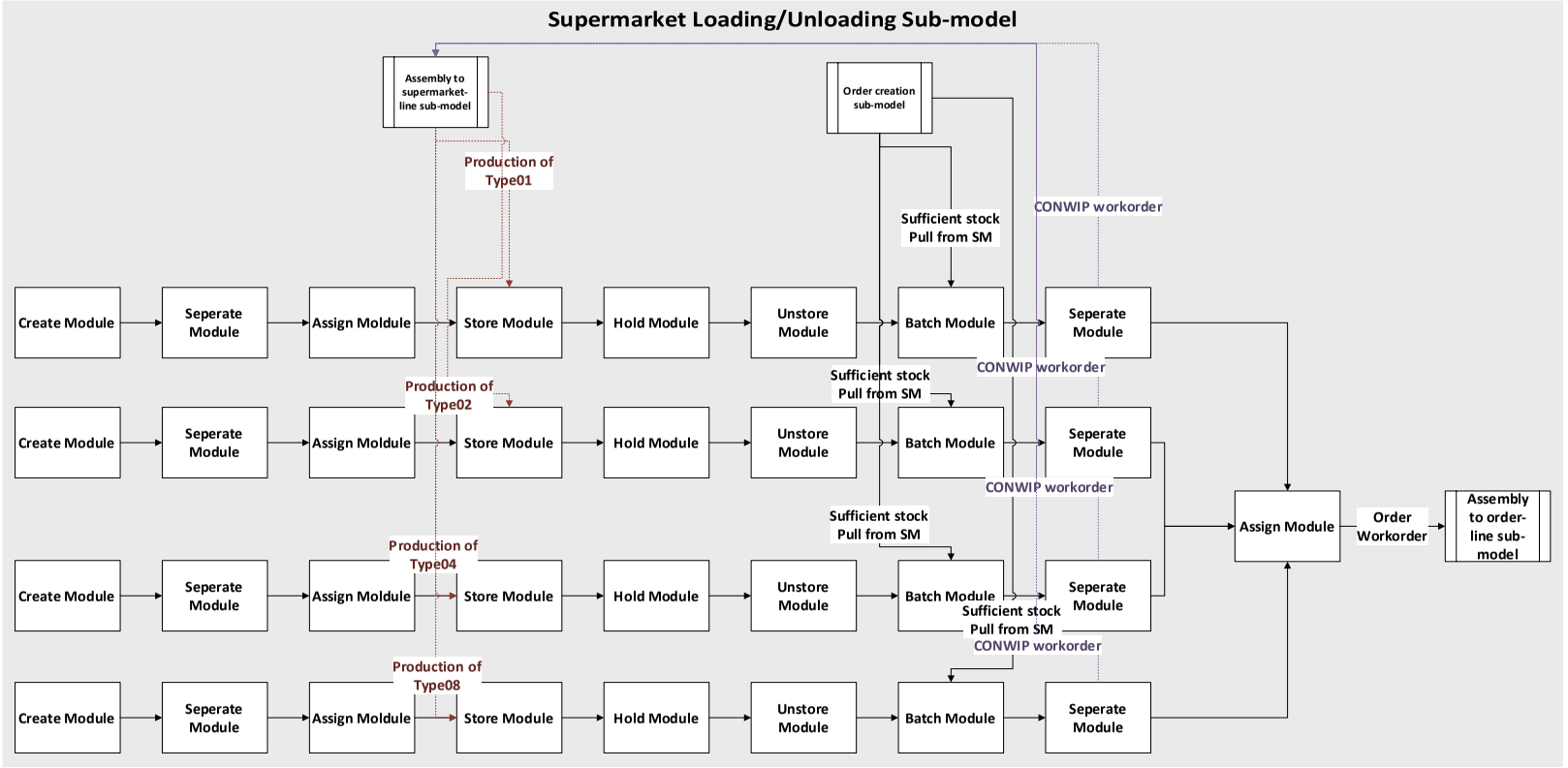


Figure 5.7 Supermarket Loading/unloading Sub-model for Proposed Syste

5.3.2.4 Order Fulfilment Sub-model

This sub-model consists of five type of modules. There are eight assign, four record, one decide and one dispose module. Decide module used to separate, by checking arrived entity type of that comes from the last station as finished products, to the assign modules before dispose operation for recording the leaving/fulfilment time. The first four assign modules holds number of entity arrived, lead-time of the entity (Actual time – arrival time to the system), cumulative lead-time. There are four record module constructed to hold the leaving time for each entity type by defining arrive attribute under each record. Second, four assign modules average lead-time of each entity according to Equation 5.4 where the $leadtime_{mn}$ represents the actual lead time of model *m* of entity *n* and *N* represents the set of entities. Last module dispose is represents the leaving of the product from the system. The arena model of sub-model is represented in Figure 5.8.

$$Avgleadtime_m = \frac{\sum_{n \in N} leadtime_{mn}}{Total\ entity\ disposed_m} \tag{5.4}$$

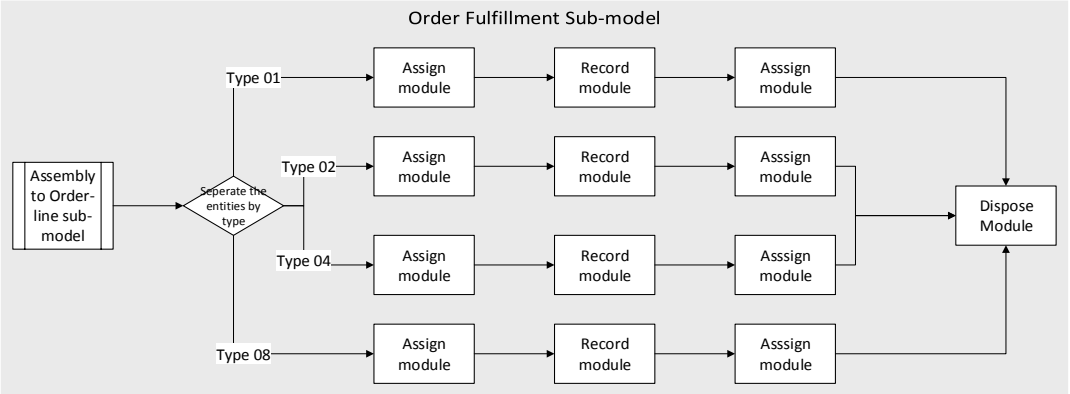


Figure 5.8 Order Fulfillment Sub-model for Proposed System

5.3.2.5 Assembly to Order Sub-model

This sub-model consist one type of module. There are five process modules to represent the station. Process modules worked under seize delay release principle. Delay time is defined with a constant value that to represent the cycle time. Entities are coming from *assembly to supermarket-line sub-model* or *supermarket loading/unloading sub-model* as semi-finished product and they are leaving this sub-model linked to *order fulfilment sub-model* as finished product. The arena model of sub-model is represented in Figure 5.9.

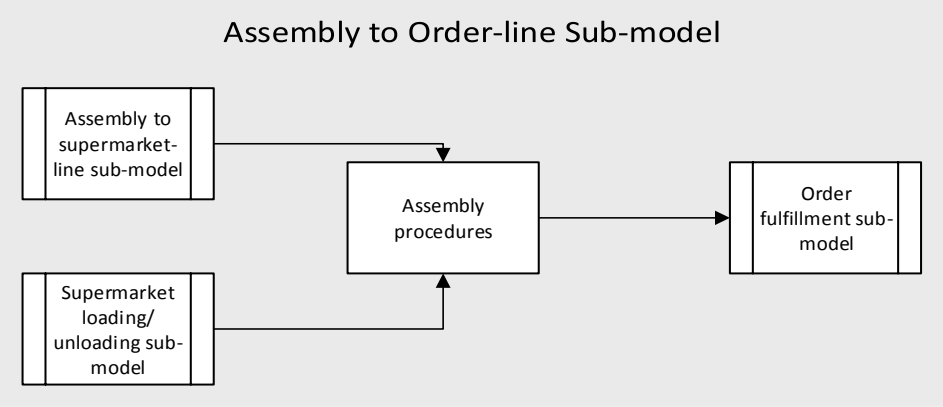


Figure 5.9 Assembly to Order-line Sub-model for Proposed System

5.3.3 CONWIP Level Optimization

The mathematical representation defined under Optquest[tm] tool of Arena software. The optimization procedure done with respect to following steps: First simulation model of proposed system constructed under Arena software, consequently mathematical model constructed under defined tool. Lastly, the optimization done under Optquest[tm] tool owing to simulation model constructed beforehand. When the tool is launched, it checks the Arena model and loads information from the model, including the defined controls and responses, into its own database. Afterwards definition of the optimization problem using Optquest[tm]‘s interface is proceeded.

When the optimization runs:

- Optimization tool feeds a potential solution into the Arena model by setting the control values.
- Arena runs one replication to evaluate the solution.
- The tool takes the resulting response values from Arena.
- The tool analyzes the results of the simulation and uses its intelligent search procedures to generate a new potential solution, which it then sends to Arena.
- The tool repeats this process, running multiple simulations. Its ultimate goal is to find the solution that optimizes (minimizes) the value of the model's objective (5.5).
- Once the tool exits, the controls in the Arena model are returned to their original default values. The Arena model is completely unaffected by the tool.

The following notation is used for mathematical representation of CONWIP level optimization.

Parameters

W_m: $weight\ of model\ m$

UB_m: $COWIP\ level's\ upper\ bound\ of\ model\ m$

Decision Variables

Z : $Average\ weighted\ lead\ time$

X_m: $CONWIP\ level\ of\ model\ m\ that\ will\ be\ held\ under\ supermarket$

$Avleadtime_m(X_m)$:

$observed\ lead\ time\ of\ model\ m\ on\ simulation\ replications,$

$as\ a\ function\ of\ X_m\ values$

Objective Function

$$Max\ Z = \sum_{m=1}^{M} Avleadtime_m(X_m) * W_m \quad (5.5)$$

Constraint

$$X_m \leq UB_m \qquad for\ \forall\ m \in M \quad (5.6)$$

The objective (5.5) is constructed to maximize average weighted lead-time. Calculated objective function is performance measure of the simulation runs. Besides, the decision variable average lead-time ($Avleadtime_m$) calculated with respect to every tested CONWIP level X_m under each simulation replication. ($Avleadtime_m$) is a function of X_m that the determined CONWIP levels directly effects the average lead time of the products. So, the optimization tool employed for best combination of X_m levels. The output will be compared to base model results. The products are weighted according to parameters represented at Table 5.1. The entities entered to system separated according to rates represented below, these rates are set as weight.

Table 5.2 Upper Bound Determination for Simulation Optimization Model

	Width(mm)	***Depth(mm)***	***Footprint(m^2)***	***Determined Upper-Bound Level***	***Required Space(m^2)***
1	750	1,400	1.05	35	36.75
2	750	1,400	1.05	25	26.25
4	1,000	1,400	1.40	35	49.00
8	1,000	1,400	1.40	15	21.00
	Upper bound calculation			Total Net required space	133.00
				Extra space for conveyor belts	13.30
				Total Space required	146.30

Constraint (5.6) constructed to limit the WIP level. The calculation of upper bounds represented in Table 5.2. First and main motivation behind this calculation is available space that is 150 meter square. The levels are empirically determined by executing independent simulation runs with respect to their weights (see Table 5.1). This allocation does not exceed the maximum available space as calculated in Table 5.2. Moreover the upper-bounding will provides narrowing down the feasible region while

limiting redundant runs, reduce Computational times; limit the total cost to bear. It should be re-indicated that the Optimization Tool searches the best combination of WIP levels by interchanging the X_m values among possible combinations with a step size of one. Detailed results gathered from Embedded Optimization Tool (Optquest) represented in Appendix E.

5.4 Performance Measures

Three type of performance measures is de1termined. These measures are average weighted lead-time, total throughput level, and WIP level of proposed system. Firstly, average weighted lead-time of a product is calculated by multiplying each avgleadtime of model "m" (calculated at Equ. 5.4) with respective weights which was previously given in Table 5.1. (see Equ. 5.7). This performance measure is held for observing lead-time differentiation through scenarios as a primary aim of system design.

Indices

s : $Scenario\ index$

a : $Alternative\ system\ index$

Sets

S : $Set\ of\ scenarios$

A : $Set\ of\ alternative\ systems\ \{base, proposed\}$

Parameter

w_m : $Weight\ of\ model\ m$ {0.335, 0.2074, 0.3488, 0.1102 }

$$Average\ weighted\ lead\ time_{sa} = \sum_{m \in M} Avgleadtime_m * w_m \qquad \forall s \in S; a \in A \qquad (5.7)$$

Secondly, the throughput rate is held for measuring the service level. Thirdly, average WIP level at the supermarket is held just for proposed model to understand the total cost to bear for such system. These measures will be tested for eight different scenarios, which are executed both for proposed model and for based model.

5.5 Verification of Simulation Model Results

There is an issue of randomness and thus statistical analysis with any random inputs. This part of the study represented for statistical test and verification of the simulation outputs. For terminating simulations such as the proposed models the number of independent replication number is an essential issue for variance reduction. Since the confidence intervals of performance measures, should represent an acceptable range for conduction of performance comparison through the scenarios. Firstly, the simulation models are executed for five replications (n_0) and gathered results are tested for a projected 95% confidence interval half width. For each scenario and each performance measure, the following statistical parameters are calculated. Mean (μ), standard deviation(s), 95% confidence interval half width (h). Using these parameters projected half width and new replication number has been calculated for all scenarios' base and proposed system. The sample calculation Table 5.3 is given for lead-time performance measure for model one. Projected half width is calculated by multiplying the mean of five-time replication with 0.04 that the interval of the variance should not highly varied through samples in order to conduct statistical comparisons of performance measures. By using the projected half width we have used Kelton's (2009) approximate sample size formulation (see Equ. 5.8) where "s" denotes the scenario index, "a" denotes the alternative system index, "p" denotes the performance measure index.

$$n_{sap} \cong n_0 \frac{{h_0}^2}{h^2} \qquad \forall\ s \in S;\ a \in A;\ p \in P \qquad (5.8)$$

The new replication number "n" calculated for all performance measures and for all scenarios. Maximum of calculated values are selected as new replication number of related scenario (see Equ. 5.9).

$$n_{sa} = \left[max_m\{n_{sap}\}\right] \qquad \forall\ p\ \in P \tag{5.9}$$

Table 5.3 New replication number calculation for variance reduction

Scenario	***Statistical Parameters***	***Flow time of model#1 @Base System***	***Flow time of model#1 @Alternative System***
Scenario 1	Average (μ)	236.98	174.23
Scenario 1	Std. Dev. (s)	21.06	20.22
Scenario 1	Half Width (h_0)	26.15	25.10
Scenario 1	Square Error	0.11	0.14
Scenario 1	Projected Half Width (h)	9.48	6.97
Scenario 1	New Replication # (n)	38.04	64.87

Remaining parts of the table is given in Appendix D

Remaining parts of calculation table is given in Appendix D. The calculated new replication numbers for each simulation model as the final result of previous calculation process is given in Table 5.4.

Table 5.4 New replication number for each scenario

	Replication Number	
Scenarios	**Base System**	**Proposed System**
Scenario 1	39	154
Scenario 2	30	71
Scenario 3	16	17
Scenario 4	11	86
Scenario 5	3623	4407
Scenario 6	1239	1295
Scenario 7	22	73
Scenario 8	19	66

The given replication number of each simulation scenario for base and proposed system are set as new replication number and the simulation models are executed respectively. Subsequently the performance measures have been put in statistical analysis in order to understand the represented mean differences are significantly

different from each other. One-way ANOVA test has been conducted for verification of outputs.

The One-Way ANOVA procedure produces a one-way analysis of variance for a quantitative dependent variable by a single factor (independent) variable. Analysis of variance is used to test the hypothesis that the means of performance measures for each scenario are equal. Besides, test of homogeneity of variance test is used to test the hypothesis that the variances of each group are homogenous. Respective hypothesizes are given below.

Hypotheses for variance homogeneity test:

Hv_0: Scenario variances are homogenous with 95% confidence,

$Hv_{1:}$ Scenario variances are not homogenous with 95% confidence

Hypotheses for one-way variance analysis test:

Hm_0: There is no significant difference between scenarios' means with 95% confidence,

$Hm_{1:}$ There is significant difference between scenarios' means with 95% confidence

In addition to determining that differences exist among the means, a test should be executed to determine which groups means differ. There are two types of tests for comparing means: a priori contrasts and post hoc tests. Contrasts are tests set up before running the experiment and post hoc tests are run after the experiment has been conducted. Post-hoc test is examined for detailed scenario comparison. There are two assumption options under this test: first assumption is variances are equal and the second the variances are not equal. Two test Tukey and Tamhane has been selected to represent the respective assumptions and the significance level has been set as 0.05. The selection of method will be done according to analysis of homogeneity test; if the variances are homogenous Tukey test should be selected and analyzed, else Tamhane should be analyzed for individual scenario comparison. The statistical tests have been

executed for each performance measure and each scenarios. The scenarios and used parameters are given below at Table 5.5.

Table 5.5 Parameters according to scenarios

System ID	***Alternative System***	***Order size Dist.***	***Line Length***	***Supermarket Station***	***Cycle Time***	***Scenario***
1	Base	Exponential	12	7	10.00	Scenario 1
2	Proposed	Exponential	12	7	10.00	Scenario 1
3	Base	Gamma	12	7	10.00	Scenario 2
4	Proposed	Gamma	12	7	10.00	Scenario 2
5	Base	Exponential	24	7	5.00	Scenario 3
6	Proposed	Exponential	24	7	5.00	Scenario 3
7	Base	Gamma	24	7	5.00	Scenario 4
8	Proposed	Gamma	24	7	5.00	Scenario 4
9	Base	Exponential	8	7	15.00	Scenario 5
10	Proposed	Exponential	8	7	15.00	Scenario 5
11	Base	Gamma	8	7	15.00	Scenario 6
12	Proposed	Gamma	8	7	15.00	Scenario 6
13	Base	Exponential	20	15	10.00	Scenario 7
14	Proposed	Exponential	20	15	10.00	Scenario 7
15	Base	Gamma	20	15	10.00	Scenario 8
16	Proposed	Gamma	20	15	10.00	Scenario 8

Statistical analyses reveal that the means of performance measures are significantly differs from each other. In some scenario-to-scenario comparisons the means do not statistically significantly differ from each other, and that cases will be given at the end of this section. It should be noted that the odd IDs represent base systems and the even IDs represent the proposed systems.

5.5.1 Average Weighted Lead-Time Verification

Firstly, the statistical results of weighted average weighted lead-time performance measure's statistical analysis are represented below. The descriptive statistics of related performance measure is given at Table 5.6 for each alternative system. It should be noted that the N as the sample size that is the input of previous variance reduction step, which the results were given at Table 5.4.

Table 5.6 Descriptive statistics of weighted average lead-time

ID	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean: Lower Bound	95% Confidence Interval for Mean: Upper Bound	Minimum	Maximum
1	39	238.01	14.63	2.34	233.27	242.76	207.19	271.22
2	154	168.60	14.08	1.13	166.36	170.84	137.23	220.02
3	30	297.89	22.87	4.18	289.35	306.43	243.28	362.06
4	71	226.66	25.49	3.03	220.63	232.70	173.40	319.79
5	16	142.75	1.85	0.46	141.76	143.74	138.79	146.43
6	17	112.73	1.80	0.44	111.80	113.66	108.79	116.48
7	11	160.63	4.57	1.38	157.56	163.70	152.01	166.52
8	86	129.08	3.71	0.40	128.29	129.88	121.19	137.14
9	3,623	1,177.39	571.41	9.49	1,158.78	1,196.00	457.06	6,288.04
10	4,407	1,070.03	576.99	8.69	1,052.99	1,087.07	328.67	6,155.93
11	1,239	1,786.93	1,028.04	29.21	1,729.63	1,844.23	512.20	8,122.05
12	1,239	1,676.40	1,022.45	29.05	1,619.41	1,733.39	407.58	7,951.87
13	22	317.96	14.97	3.19	311.32	324.60	287.20	351.24
14	22	168.25	15.04	3.21	161.59	174.92	137.46	201.78
15	19	381.26	26.68	6.12	368.40	394.12	323.31	442.13
16	22	226.23	25.25	5.38	215.04	237.43	170.93	287.78

Table 5.7 shows that the output of the ANOVA analysis and whether there is statistically significant difference between scenarios' means. The significance level is 0.00 (p = .000), which is below 0.05 and, therefore, there is a statistically significant difference in the mean weighted average lead-time. The Hm_1 hypothesis is accepted.

Table 5.7 Test of ANOVA for weighted average lead-time

	Sum of Squares	*df*	*Mean Square*	*F*	*Sig.*
Between Groups	1,296,437,973.58	15.00	86,429,198.24	181.03	-
Within Groups	5,252,220,151.32	11,001.00	477,431.16		
Total	6,548,658,124.90	11,016.00			

This is great to know, but the differentiation between specific groups should be known for further scenario comparison. Luckily, it can be found out in the multiple comparisons table, which contains the results of post-hoc tests. As mentioned previously in this section selection of post-hoc test is accompanied with homogeneity test, which is given in Table 5.8.

Table 5.8 Test of homogeneity of variances for weighted average lead-time

Levene Statistic	*df1*	*df2*	*Sig.*
90.97	15.00	11,001.00	0.00

Table 5.8 shows that the output of the test of homogeneity analysis and whether the variances of scenarios are homogenous. The significance level is 0.00 (p = .000), which is below 0.05 and, therefore, the weighted average lead-time variance of scenarios are not homogenous. The Hv_1 hypothesis is accepted. The post-hoc test should be executed under the assumption of equal variances not assumed. For this type of assumption, Tamhane test has been selected. Table 5.9 represents the means of systems are not significantly differ from each other, remaining pairs represent statistically significantly different means. Because of the size of the table, the remaining parts of the table are given in Appendix D. The results will be used for comparison of systems at subsequent sections.

Table 5.9 Test of Tamhane mean differences for weighted average lead-time

					95% Confidence Interval	
(I) System	**(J) System**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**Upper Bound**	**Lower Bound**
1	4	11.35	3.83	0.36	-2.56	25.26
1	16	11.78	5.87	1.00	-11.55	35.11
2	14	0.35	3.40	1.00	-13.33	14.03
4	1	-11.35	3.83	0.36	-25.26	2.56
4	16	0.43	6.18	1.00	-23.58	24.44
7	14	-7.63	3.49	0.99	-21.59	6.34
11	12	110.53	41.19	0.59	-34.77	255.83
12	11	-110.53	41.19	0.59	-255.83	34.77
14	2	- 0.35	3.40	1.00	-14.03	13.33
14	7	7.63	3.49	0.99	-6.34	21.59
16	1	-11.78	5.87	1.00	-35.11	11.55
16	4	-0.43	6.18	1.00	-24.44	23.58

Remaining parts of the Table is given in Appendix D

5.5.2 Wip Level Verification

Secondly, the statistical results of WIP level performance measure's statistical analysis are represented below. The descriptive statistics of related performance measure is given at Table 5.10 for each alternative system. It should be noted that the N as the

sample size that is the input of previous variance reduction step, which the results were given at Table 5.4. It should be mentioned again that this performance measure held just for proposed alternative systems.

Table 5.10 Descriptive statistics of WIP level

ID	N	Mean	Std. Deviation	Std. Error	*95% Confidence Interval* Lower Bound	Upper Bound	Minimum	Maximum
2	154	55.76	1.32	0.11	55.55	55.96	51.71	58.60
4	71	65.30	1.96	0.23	64.83	65.76	58.03	68.97
6	17	84.96	0.40	0.10	84.76	85.17	84.18	85.67
8	86	94.99	0.54	0.06	94.87	95.10	93.21	96.05
10	4407	22.61	4.99	0.08	22.46	22.76	4.97	36.37
12	1295	47.66	12.54	0.35	46.98	48.35	9.74	76.53
14	73	72.71	1.69	0.20	72.31	73.10	68.04	76.11
16	66	70.29	1.99	0.24	69.80	70.78	66.10	74.31

Table 5.11 shows that the output of the ANOVA analysis and whether there is statistically significant difference between scenarios' means. The significance level is 0.00 (p = .000), which is below 0.05 and, therefore, there is a statistically significant difference in the mean WIP level. The Hm_1 hypothesis is accepted.

Table 5.11 Test of ANOVA for WIP level

Levene Statistic	*df1*	*df2*	*Sig.*
380.63	7.00	6,161.00	-

This is great to know, but the differentiation between specific groups should be known for further scenario comparison. Luckily, it can be found out in the multiple comparisons table, which contains the results of post-hoc tests. As mentioned previously in this section selection of post-hoc test is accompanied with homogeneity test, which is given in Table 5.12.

Table 5.12 Test of homogeneity of variances for WIP level

	Sum of Squares	*df*	*Mean Square*	*F*	*Sig.*
Between Groups	1,476,956.81	7.00	210,993.83	4,133.11	-
Within Groups	314,517.23	6,161.00	51.05		
Total	1,791,474.04	6,168.00			

Table 5.12 shows that the output of the test of homogeneity analysis and whether the variances of scenarios are homogenous. The significance level is 0.00 (p = .000), which is below 0.05 and, therefore, the WIP level variance of scenarios are not homogenous. The Hv_1 hypothesis is accepted. The post-hoc test should be executed under the assumption of equal variances not assumed. For this type of assumption, Tamhane test has been selected. Table 5.13 represents the means of systems are significantly differ from each other, remaining pairs are also representing statistically significantly different means. Because of the size of the table, the remaining parts of the table are given in Appendix D. The results will be used for comparison of systems at subsequent sections. It should be mentioned that all systems' means are statistically significantly differs from each other for this WIP level performance measure.

Table 5.13 Test of Tamhane mean differences for WIP level

					95% Confidence Interval	
(I) System	**(J) System**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**Upper Bound**	**Lower Bound**
2	4	-9.54240(*)	0.26	-	-10.36	-8.73
2	6	-29.20729(*)	0.14	-	-29.67	-28.74
2	8	-39.23296(*)	0.12	-	-39.61	-38.85
2	10	33.14718(*)	0.13	-	32.74	33.56
2	12	8.09224(*)	0.36	-	6.95	9.23
2	14	-16.95206(*)	0.22	-	-17.67	-16.24
2	16	-14.53554(*)	0.27	-	-15.39	-13.68
4	2	9.54240(*)	0.26	-	8.73	10.36
4	6	-19.66489(*)	0.25	-	-20.47	-18.86
4	8	-29.69056(*)	0.24	-	-30.46	-28.92
4	10	42.68958(*)	0.24	-	41.90	43.47
4	12	17.63464(*)	0.42	-	16.32	18.95

**The mean difference is significant at the .05 level*

Remaining parts of the Table is given in Appendix D

5.5.3 Throughput Level Verification

Lastly, the statistical results of throughput level performance measure's statistical analysis are represented below. The descriptive statistics of related performance measure is given at Table 5.14 for each alternative system. It should be noted that the N as the sample size that is the input of previous variance reduction step, which the results were given at Table 5.4.

Table 5.14 Descriptive statistics of throughput level

					95% Confidence Interval			
ID	**N**	**Mean**	**Std. Deviation**	**Std. Error**	**Lower Bound**	**Upper Bound**	**Minimum**	**Maximum**
1	39	9,019.15	348.80	55.85	8,906.09	9,132.22	8,227.00	9,838.00
2	154	8,991.86	326.48	26.31	8,939.88	9,043.83	8,238.00	9,849.00
3	30	9,074.00	319.38	58.31	8,954.74	9,193.26	8,585.00	9,781.00
4	71	9,084.27	338.25	40.14	9,004.20	9,164.33	8,218.00	9,976.00
5	16	9,039.50	414.33	103.58	8,818.72	9,260.28	8,237.00	9,845.00
6	17	9,046.88	401.45	97.37	8,840.48	9,253.29	8,242.00	9,855.00
7	11	9,158.45	425.14	128.18	8,872.84	9,444.07	8,600.00	9,781.00
8	86	9,077.14	331.19	35.71	9,006.13	9,148.15	8,218.00	9,983.00
9	3623	8,893.08	253.89	4.22	8,884.81	8,901.35	8,068.00	9,497.00
10	4407	8,901.51	256.64	3.87	8,893.93	8,909.08	7,892.00	9,508.00
11	1239	8,941.35	297.12	8.44	8,924.79	8,957.91	7,731.00	9,497.00
12	1295	8,953.49	297.36	8.26	8,937.27	8,969.70	7,737.00	9,508.00
13	22	9,039.23	360.46	76.85	8,879.41	9,199.05	8,219.00	9,830.00
14	73	8,986.93	357.38	41.83	8,903.55	9,070.31	8,238.00	9,849.00
15	19	9,121.42	347.17	79.65	8,954.09	9,288.75	8,580.00	9,773.00
16	66	9,069.26	305.12	37.56	8,994.25	9,144.27	8,298.00	9,851.00

Table 5.15 shows that the output of the ANOVA analysis and whether there is statistically significant difference between scenarios' means. The significance level is 0.00 (p = .000), which is below 0.05 and, therefore, there is a statistically significant difference in the mean WIP level. The Hm_1 hypothesis is accepted.

Table 5.15 Test of ANOVA for throughput level

Levene Statistic	***df1***	***df2***	***Sig.***
11.63	15	11,152.00	-

This is great to know, but the differentiation between specific groups should be known for further scenario comparison. Luckily, it can be found out in the multiple comparisons table, which contains the results of post-hoc tests. As mentioned previously in this section selection of post-hoc test is accompanied with homogeneity test, which is given in Table 5.16.

Table 5.16 Test of homogeneity of variances for throughput level

	Sum of Squares	***df***	***Mean Square***	***F***	***Sig.***
Between Groups	15,968,375.68	15.00	1,064,558.38	14.55	-
Within Groups	815,716,830.46	11,152.00	73,145.34		
Total	831,685,206.13	11,167.00			

Table 5.16 shows that the output of the test of homogeneity analysis and whether the variances of scenarios are homogenous. The significance level is 0.00 (p = .000), which is below 0.05 and, therefore, the throughput level variance of scenarios are not homogenous. The Hv_1 hypothesis is accepted. The post-hoc test should be executed under the assumption of equal variances not assumed. For this type of assumption, Tamhane test has been selected. Table 5.17 represents the means of systems are significantly differ from each other, remaining pairs are not representing statistically significantly different means. Because of the size of the table, the remaining parts of the table are given in Appendix D. The results will be used for comparison of systems at subsequent sections.

Table 5.17 Test of Tamhane mean differences throughput level

					95% Confidence Interval	
(I) System	**(J) System**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**Upper Bound**	**Lower Bound**
2	9	98.78069(*)	26.64	0.03	2.93	194.63
4	9	191.19115(*)	40.36	0.00	42.05	340.33
4	10	182.76250(*)	40.33	0.00	33.73	331.79
8	9	184.06308(*)	35.96	-	52.36	315.77
8	10	175.63443(*)	35.92	0.00	44.05	307.22
8	11	135.79167(*)	36.70	0.04	1.80	269.78
9	2	-98.78069(*)	26.64	0.03	-194.63	-2.93
9	4	-191.19115(*)	40.36	0.00	-340.33	-42.05
9	8	-184.06308(*)	35.96	-	-315.77	-52.36
9	11	-48.27141(*)	9.44	-	-81.57	-14.97
9	12	-60.40926(*)	9.28	-	-93.14	-27.67
9	16	-176.18112(*)	37.79	0.00	-316.32	-36.04
10	4	-182.76250(*)	40.33	0.00	-331.79	-33.73
10	8	-175.63443(*)	35.92	0.00	-307.22	-44.05
10	11	-39.84276(*)	9.28	0.00	-72.61	-7.08
10	12	-51.98061(*)	9.12	-	-84.17	-19.79
10	16	-167.75247(*)	37.76	0.00	-307.78	-27.72
11	8	-135.79167(*)	36.70	0.04	-269.78	-1.80
11	9	48.27141(*)	9.44	-	14.97	81.57
11	10	39.84276(*)	9.28	0.00	7.08	72.61
12	9	60.40926(*)	9.28	-	27.67	93.14
12	10	51.98061(*)	9.12	-	19.79	84.17
16	9	176.18112(*)	37.79	0.00	36.04	316.32
16	10	167.75247(*)	37.76	0.00	27.72	307.78

**The mean difference is significant at the .05 level*

5.6 Solution of the Case Study Problem

The results are gathered for eight different scenarios, in order to understand the effects of parameters on performance measures. The determined parameters according to scenarios were given in Table 5.5. The supermarket place has been set at seventh station for MALBPwo approach's performance testing. In addition, the supermarket place has been set at fifteenth station for SALBPja approach's performance testing. The models are executed for different cycle times C = {5, 10, 15} under two different order size distribution (exponential, gamma) related distribution analysis given under input analysis section (see Sec. 5.1.2). The interarrival time is not alternated and directly best-fit beta distribution is used. Farther, deterministic distribution is used for model variation and it is fixed for all scenarios. The simulation models are executed for 264 days, and replicated for respective calculated replication numbers (see Table 5.4).

It should be mentioned that the mathematical models are constructed and parametrically analyzed while the cycle time equals to ten, so first, second, seventh, and eighth scenarios are using the optimized supermarket place and line length, which are gathered through first step of the hybrid assembly line design approach. Scenario one and two are generated according to MALBPwo approaches' input parameters. On the other side, scenario seven and eight are generated according to SALBPja approaches' input parameters. Because of the insufficient performance of MALBPnw and SALBPia approaches at step one, respective simulation models have not constructed for them.

5.7 Discussion of Results

Performance comparison according to scenario parameters will be represented throughout this section. As previously mentioned scenario 1 (C=10, K=12, Order size distribution=Expo, Supermarket station=7) and scenario 2 (C=10, K=12, Order size distribution=Gamma, Supermarket station=7) are best fit for MALBPwo. Besides, scenario 7 (C=10, K=20, Order size distribution=Expo, Supermarket station=20) and

scenario 8 (C=10, K=20 Order size distribution=Gamma, Supermarket station=20) are best fit for SALBPja. Rest is executed for sensitivity analysis. Outputs of simulation models in terms of performance measures are given at Table 5.18.

Table 5.18 Summary of performance measures according the scenarios

ID	System Def.	Order Size Distribution	Alternative System	Mean of Average Weighted lead time	Mean of WIP level	Mean of Through put level	Scenarios
1	C=10,K=12	Exponential	Base	238.01		9,019.15	Scenario 1
5	C=5,K=24	Exponential	Base	142.75		9,039.50	Scenario 3
9	C=15,K=8	Exponential	Base	1,177.39		8,893.08	Scenario 5
13	C=10,K=20	Exponential	Base	317.96		9,039.23	Scenario 7
3	C=10,K=12	Gamma	Base	297.89		9,074.00	Scenario 2
7	C=5,K=24	Gamma	Base	160.63		9,158.45	Scenario 4
11	C=15,K=8	Gamma	Base	1,786.93		8,941.35	Scenario 6
15	C=10,K=20	Gamma	Base	381.26		9,121.42	Scenario 8
2	C=10,K=12	Exponential	Proposed	168.60	55.76	8,991.86	Scenario 1
6	C=5,K=24	Exponential	Proposed	112.73	84.96	9,046.88	Scenario 3
10	C=15,K=8	Exponential	Proposed	1,070.03	22.61	8,901.51	Scenario 5
14	C=10,K=20	Exponential	Proposed	168.25	72.71	8,986.93	Scenario 7
4	C=10,K=12	Gamma	Proposed	226.66	65.30	9,084.27	Scenario 2
8	C=5,K=24	Gamma	Proposed	129.08	94.99	9,077.14	Scenario 4
12	C=15,K=8	Gamma	Proposed	1,676.40	47.66	8,953.49	Scenario 6

Lead-time results as the most important performance measure for different scenarios will be talked about. Respective performance measure's representation will be done according to scenarios. Firstly, for C = 5 the MALBPwo model executed for single run by changing parameters as C = 5 and Kmax=25. Optimum line length must be twenty-four for such cycle time. As a natural result, simulation is modelled for twenty-four stations. The scenario constructed to understand the behavior of assembly lines that have longer assembly to order line (second part of the line). The supermarket is constructed at station seven that is previously optimized at the first stage of hybrid assembly line design approach. Thus, assembly to supermarket-line (closed-loop system) theoretically feeds the supermarket thirty-five minutes after CONWIP signal placed as CONWIP work order at the first station. Moreover, it can be obviously seen from the Figure 5.10 that the lead-time improvement according to base model is nearly thirty minutes.

Secondly, the case data has been optimized for C=10 with MALBPwo approach. Optimum line length must be twelve for MALBPwo approach. Subsequently, simulation is modelled for twelve stations. Besides, the supermarket is constructed at station seven that is the previously optimized station place at the first stage of hybrid assembly line design approach. Thus, assembly to supermarket-line (closed-loop system) feeds the supermarket seventy minutes after CONWIP signal placed as CONWIP work order at the first station. Furthermore, it can be obviously seen from the Figure 5.10 that the lead-time improvement according to base model is nearly seventy minutes.

Thirdly, for C=15 the gams model executed for single run by changing parameters as C=15 and Kmax=8. Optimum line length must be eight for such cycle time. Subsequently, simulation is modelled for eight stations. The scenario constructed to understand the behavior of assembly lines that have longer assembly to CONWIP market line (first part of the line). The supermarket is constructed at station seven that is the previously optimized station place. Thus, assembly to supermarket-line (closed-loop system) feeds the supermarket one hundred and five minutes after CONWIP signal placed as CONWIP work order at the first station. Moreover, it can be observed from the Figure 5.10 that the lead-time improvement according to base model is slightly over one hundred five minutes. Two point thirty six extra minutes gained in scenario 5. Note that the scenario 6 data is not given in the figure because the statistical analysis reveals that there is no significance difference between base and proposed system (see Table 5.9).

Lastly, for C=10 the case data has been optimized for C=10 with SALBPja approach. Optimum line length must be twenty for SALBPja approach. Subsequently, simulation is modelled for twenty stations. Moreover, the supermarket is constructed at station fifteen that is the previously optimized station place at first stage of hybrid assembly line design approach. Thus, assembly to supermarket-line (closed-loop system) feeds the supermarket one hundred fifty minutes after CONWIP signal placed as CONWIP

work order at the first station. Furthermore, it can be observed from the Figure 5.10, the lead-time improvement according to base model is nearly 150 minutes.

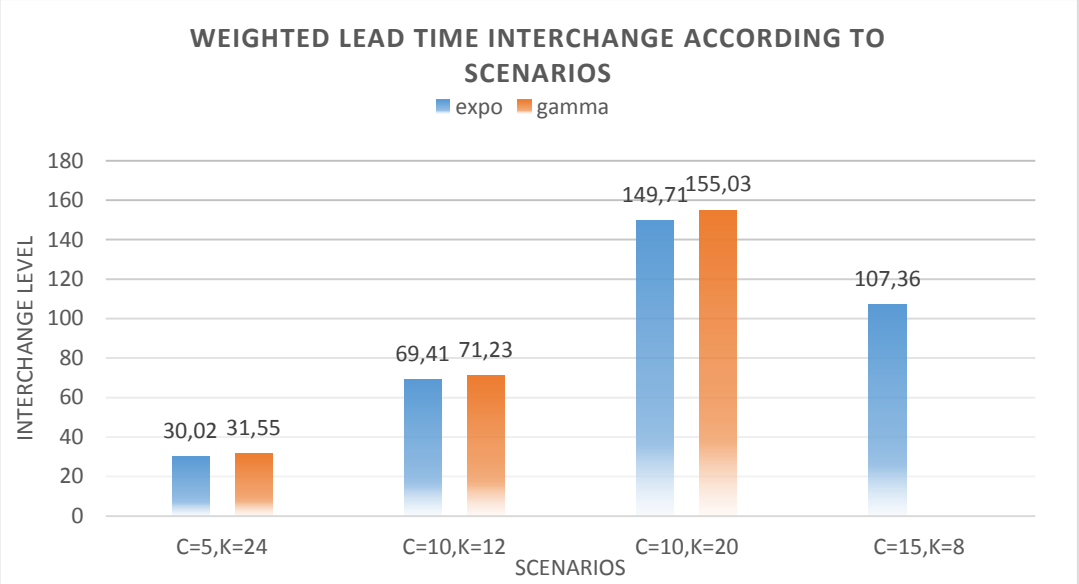


Figure 5.10 Weighted Lead Time Improvement According to Base Model for Different Scenarios

Owing to these results, it can be said that as the length of assembly to CONWIP supermarket line increases, the lead-time reductions gathered through proposed system would also increase. However, further investigations must be done for understanding the lead-time reduction behavior according to supermarket installed station distance to the initial station. It should be also re-indicated that those scenarios 3,4,5,6 are not optimized in terms of supermarket station decision. Station seven is selected as supermarket station for these respective scenarios through MALBPwo model's output.

At this instant, Figure 5.10 is insufficient to compare the performance of MALBPwo's C=10; K=12 scenario with SALBPja's C=10; K20 scenario. According to Figure 5.10 SALBPja represents a superior performance in terms of lead-time reduction. This quote contradicts with theoretical approach that as the line length increases average lead-time should also increase. It can be observed from Table 5.19 that SALBPja's respective scenarios' scenario seven and scenario eight's base model average

lead-time performances are worse than MALBPwo's respective scenarios scenario one and scenario two's base model. This is suitable with the quote. Installing the supermarket reduces the average lead-time of both models' scenarios to 168 minutes for expo distributed order size and 226 minutes for gamma distributed order size. The statistical analyses which were given at Table 5.9 reveals that there is no significant difference between proposed systems 2(C=10;K=12;Order Size Dist=Expo)-14(C=10;K=20;Order Size Dist=Expo) and 4(C=10;K=12;Order Size Dist=Expo)-16(C=10;K=20;Order Size Dist=Gamma). In summary, the performances of proposed systems are performing similar for same parameters in terms of lead-time. Nevertheless, owing the fact that the average weighted lead-times of scenario 7 and scenario 8's base systems are higher, subsequently higher reduction is observed. The disadvantage of the longer line length is cleared in terms of lead-time by constructing such hybrid assembly line. Note that the means of average weighted lead-time significantly differs between base and proposed system for each scenario (see Table 5.19).

Table 5.19 Summary of Average weighted lead-time according the scenarios and alternative systems

System Def.	**Order Size Distribution**	**Base**	**Proposed**
C=5,K=24	Exponential	142.75	112.73
C=10,K=12	Exponential	238.01	168.6
C=10,K=20	Exponential	317.96	168.25
C=15,K=8	Exponential	1177.39	1070.03
C=5,K=24	Gamma	160.63	129.08
C=10,K=12	Gamma	297.89	226.66
C=10,K=20	Gamma	381.26	226.23
C=15,K=8	Gamma	1786.93	1676.4

As a last performance measure, WIP level results will be discussed for respective scenarios. The Figure 5.11 indicates that as the supermarket distance from last station, in other words the length of the assembly to order-line increases, the system need to stand greater amount of WIP in order to response customer demands.

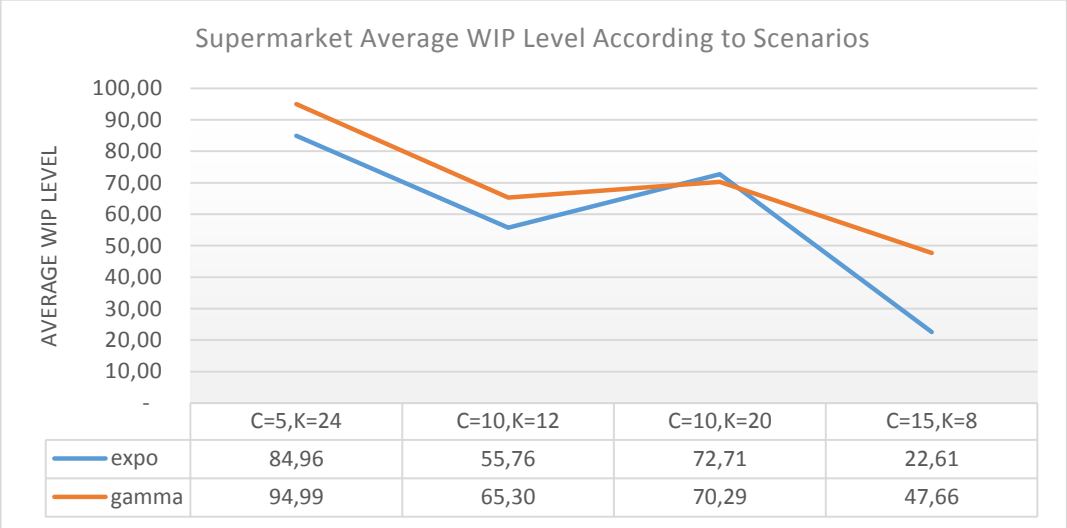


Figure 5.11 Total WIP level of Supermarket for Different Scenarios

Before proceeding the performance evaluation, turning back to statistical analysis of related performance measure, the scenarios are significantly differs from each other (see Table 5.13). The detailed analysis of WIP level and parameters given in Table 5.20 that average WIP level of CONWIP supermarket has a strong relationship between the line lengths of second part of the line. As the assembly to order line length increases, average WIP level of supermarket will also increase. Average WIP Level is greater at Scenario 4 vs Scenario 8. Moreover, order size distribution also has effect on this performance measure. The producer will held higher WIP which order sizes are gamma distributed, than exponential distributed order size circumstances. Average WIP Level is greater at Scenario 4 than Scenario 3. Lastly, whole line length has positive effect on average WIP level quantity. Average WIP Level is greater at Scenario 7 than Scenario 1. Note that the WIP level means statistically significantly differs from each other from each alternative system (see Table 5.20).

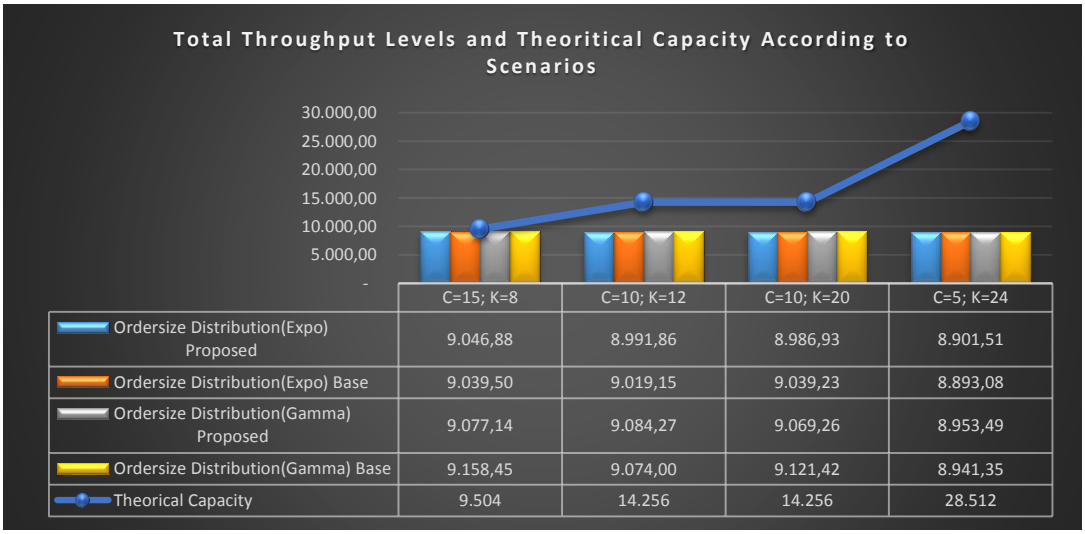
Table 5.20 Average WIP Level and Line Length of Scenarios

	Length				
Scenario	**Line (Stations)**	**Assembly to order line (Stations)**	**Assembly to supermarket line (Stations)**	**Average WIP level (Products)**	**Stock/ Day (Days)**
Scenario 4, C=5; K=24; Order Size Distribution (Gamma)	24	17	7	94.99	1.70
Scenario 3, C=5; K=24; Order Size Distribution (Expo)	24	17	7	84.96	1.52
Scenario 7, C=10; K=20; Order Size Distribution (Expo)	20	5	15	72.71	1.30
Scenario 8, C=10; K=20; Order Size Distribution (Gamma)	20	5	15	70.29	1.26
Scenario 2, C=10; K=12; Order Size Distribution (Gamma)	12	5	7	65.30	1.17
Scenario 1, C=10; K=12; Order Size Distribution (Expo)	12	5	7	55.76	1.00
Scenario 6, C=15; K=8; Order Size Distribution (Gamma)	8	1	7	47.66	0.85
Scenario 5, C=15; K=8; Order Size Distribution (Expo)	8	1	7	22.61	0.40
**Sorted According to Avg. WIP level in Descending Order*					

Coming the throughput levels observed during the scenarios, as the least important performance measure. Respective performance measure's representation will be done according to scenarios. Briefly, it can be said that the service level or throughput stands same. Going back to statistical analyses of the related performance measure it can be observed from Table 5.17 that there is no significance difference between proposed and base systems for each scenario. The results reveal that the throughput level remains same or the increases are negligible. As a consequence of the fact that the system designed as a make to order system and the identified distributions of interarrival time and order size remains same for all scenarios, the level does not significantly change. The proposed system does not have any effect on the performance measure according to base system.

Moreover, total throughput level under different scenarios and theoretical capacities are represented in Figure 5.12. When C=5 demand is significantly under theoretical capacity. When C=10 demand is slightly under theoretical capacity. When C=15 demand is almost equals to theoretical capacity. The previous studies reveal that the

CONWIP system represents a superior performance under over-capacity cases. However, the results reveal that the system represents an acceptable performance when the demand distributes under-capacity or equal to capacity. Because of the fact that the proposed model for all scenarios works according to make-to-order principle, higher demand results higher throughput (see Figure 5.12). The underlying reason can be identified that the order demand closes the gap between theoretical capacity and the throughput level under gamma distributions. It should be pointed out that a further research on behavior of performance measures upon over-capacity cases should be conducted.



	C=15; K=8	C=10; K=12	C=10; K=20	C=5; K=24
Ordersize Distribution(Expo) Proposed	9.046,88	8.991,86	8.986,93	8.901,51
Ordersize Distribution(Expo) Base	9.039,50	9.019,15	9.039,23	8.893,08
Ordersize Distribution(Gamma) Proposed	9.077,14	9.084,27	9.069,26	8.953,49
Ordersize Distribution(Gamma) Base	9.158,45	9.074,00	9.121,42	8.941,35
Theorical Capacity	9.504	14.256	14.256	28.512

Figure 5.12 Total Throughput Levels and Theoretical Capacity According to Scenarios

Consequently, significant improvements are observed on the average weighted lead-time while maintaining or improving service level (throughput) with a reasonable WIP level (total cost). For scenario 1, the total WIP level should be held as daily capacity. In other words, customer service level will remain same; lead-time will reduce while holding a daily stock of semi-finished CONWIP. The WIP level is equal to daily capacity for scenario 1 that is the second step of MALBPwo approach. For scenario 7, 1.30 daily stock should be deal with for such improvements on performance measures. Whereas customer service level remains same, average weighted lead-time can be

reduced while holding reasonable semi-finished CONWIP, which is slightly higher than daily capacity for scenario 7, is the second step of SALBPja approach.

The simulation execution setup is set for 264 days and 9 hours a day under these parameters the simulation models are executed for different replication numbers for each system (see Table 5.4) and the average of performance measures, which were observed through these replications, are represented as performance measures in current and prior sections.

CHAPTER 6

CONCLUSION

In this study, re-design of a Make-to-Order Mixed-Model Assembly Line is focused with an aim to reduce the lead-time. Hybrid assembly line is proposed that the first part of the line will work according to CONWIP principle as a closed loop system while the end of the line will work according to Make-to-Order principle. For such design, a two-staged approach is proposed that aims to provide a tool to determine the critical parameters such as CONWIP level and Best Station for installing the Supermarket for the decision makers.

Initially, modifications of traditional SALBP and MALBP mathematical models are constructed aiming to understand the line and model behaviors. Supermarket station is determined according to a commonality point, which is representing the common assignment of task "j" at station "k" for more than one models. The line divided into two parts, and tasks that are common through more than one models are assigned at the first part of the line and the less common operations in other words, tasks that cause the configuration, are assigned at the second part of the line. Four mathematical models are designed for parametric analysis and it is observed that the Single Assembly Line Balancing approach with a joint model (SALBPja) and Mixed Model Assembly Line Balancing approach with a weighted objective(MALBPwo) are representing better performance in terms of horizontal balancing. Note that both of the models' are maximizing horizontal balance while making concessions from vertical balance, allowing idle times. MALBPwo represents better performance in terms of vertical balance. Objective functions especially constructed to encourage the assignment of common tasks at prior stations. The disadvantage of the proposed MALBPwo model is computational time increase.

Nonetheless, SALBPja model's disadvantage is significant idle times increase in consequence of increase in line length. Owing the fact that the model is designed for one time execution, MALBPwo model's disadvantage can be ignored. However, SALBPja model's disadvantages that should be accompanied with operating cost that are serious obstacle for implementation. Lastly, the proposed mathematical models put in validation process by executing them with literature problems' data sets. Important observation obtained from the experimental procedure that as the problems get larger, the computational times required achieving an optimal solution by the mathematical models exponentially increase.

Afterwards, a simulation model is proposed for evaluating the performance and robustness of the hybrid system. Moreover, an embedded CONWIP level optimization procedure is represented owing the fact that the value of CONWIP is vital on critical performance measures (lead-time, WIP level, Throughput) (Ip et al. (2007)). As a result, the requirement of best combination of CONWIP levels for models can be achieved through an optimization model. It should be indicated that, manual alternation procedure of CONWIP levels is far from reaching optimum result and it would be time consuming. Owing the fact that, employment of an embedded dynamic optimization tool (Optquest) on simulation model would provide better results for such stochastic process rather than a static deterministic mathematical model. The optimization tool iteratively tested the CONWIP level combinations aiming to find best combination that minimizes average lead-time, which is observed from related simulation executions that are executed with respect to dynamically alternated CONWIP levels through optimization tool. The outputs of the optimization tool are used as input parameters at proposed system simulation runs. The base model and proposed model executed on Arena and the outputs of the executions are compared. Obtained results are put in statistical analyses in order to observe whether there is a significance difference between compared scenarios. Moreover, different scenarios are also created in order the test reliability of the system under different conditions. Order size distribution and line length (cycle time) are alternated for scenario creation.

When the simulation results of respective scenarios of the MALBPwo and SALBPja mathematical models are compared, it is observed that there is no significant difference between average weighted lead-time performance of the systems. Besides, the system constructed with respect to SALBPja approach necessitates to be operated with significantly higher WIP level than MALBPwo's systems required.

To sum up, an approach is proposed for hybrid assembly line design, which positive results are gathered in the environment. The literature in this problem is still limited. There are limited studies conducted for CONWIP level optimization. However, there are few studies adapted a dynamic approach for determining the CONWIP levels of the models. Farther, proposed mathematical models also provide a method that address ALBP with an objective function forces horizontal balance. Various studies in the literature especially addresses the cycle time reduction or work resources reduction. New type of objectives are provided that result better horizontal balancing. General approach for maximizing horizontal balance is solving the MALBP as a version of SALBP (Gökçen and Erel, 1997). However, SALBP method gives higher horizontal balance, while the length of the line and idle times for stations are significantly increasing. Customer demands force the producers to offer high-varied products with minimum waiting. Important observation obtained from the experimental results that the implementation of SALBP approach for high-varied multi product families (the products significantly differ from each other) results significant increase of the line length and idle times, that results worse performance on vertical balance of the line. There are also studies trying to solve the horizontal balance with MALBP approach. Roberts and Villa (1970), Bukchin et al. (2002) and Bukchin and Rabinowitch (2006) proposed heuristic procedures aiming to maximize horizontal balance. It should be mentioned that, under such circumstances that a product family -highly varied- should be produced at single line, the proposed MALBPwo approach should be employed. The study revealed that the proposed MALBPwo model could cope with such circumstances just with mathematical modeling approach for 300 tasks, 16 stations, and 4 models case.

For further studies, relaxation of assumptions should be tested. The performance of proposed method should especially tested for unpaced assembly lines, different order size distributions(especially for overcapacity cases) or stochastic processing times. The shape of the line is also another important concept for assembly line design for the related case. Hence, aiming to maximize horizontal balance and minimize idle time, the application of parallel lines or "Y" type line should be considered, hence the proposed line design approach should be modified for this type of parametric shape alternation. Moreover, a study comparing the performance of single line, parallel lines and "Y" type line should be conducted for hybrid assembly line design approach.

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APPENDIX A

PROBLEM DATA USED AT MATHEMATICAL MODELS

Case study data

Table A.1 Precedence Relationship of Tasks for Models

Task j	IP of 01	IP of 02	IP of 04	IP of 08	IP of Joint
1	0	0	0	0	
2	0	1, 14	1, 14	1, 14	1, 14
3	1, 14	2	2	2	2
4	2	3	0	0	3
5	3	3	3	3	3
6	3	3	3	3	3
7	3	4, 5, 6, 8, 9, 13, 104, 111	5, 6, 8, 13, 104, 150, 151	5, 6, 8, 13, 104, 150, 241, 250	4, 5, 6, 8, 9, 13, 104, 111, 150, 151, 241, 250
8	3	3	3	3	3
9	3	3	0	0	3
10	3	4, 5, 6, 8, 9, 13, 104, 111	5, 6, 8, 13, 104, 150, 151	5, 6, 8, 13, 104, 150, 241, 250	4, 5, 6, 8, 9, 13, 104, 111, 150, 151, 241, 250
11	3	7, 10, 112	0	0	7, 10, 112
12	4, 5, 6, 8, 9, 13, 104	0	153, 154, 155, 156	0	11, 153, 154, 155, 156
13	4, 5, 6, 8, 9, 13, 104	3	3	3	3
14	7, 10	0	0	0	
15	11	113, 114	153, 154, 155, 156	155, 242, 244, 245, 246, 248, 252	11, 113, 114, 153, 154, 155, 156, 242, 244, 245, 246, 248, 252
16	11	15, 115	153, 154, 155, 156	155, 242, 244, 245, 246, 248, 252	11, 15, 115, 153, 154, 155, 156, 242, 244, 245, 246, 248, 252
17	11	16	12, 15, 16, 157, 158, 159, 162	15, 16, 113, 158, 159, 243, 247	12, 15, 16, 32, 113, 157, 158, 159, 162, 243, 247
18	11	16	167, 198	198, 255	255, 12, 15, 16, 32, 167, 198
19	12, 15, 16, 32	17, 18	18, 168, 199, 200	18, 199, 200	17, 18, 168, 199, 200
20	12, 15, 16, 32	19, 45	0	0	19, 45
21	17, 18	19, 45	0	0	19, 45
22	17, 18	19, 45	46, 186	19, 201	19, 45, 46, 186, 201

Table A.1 Continued

Task j	IP of 01	IP of 02	IP of 04	IP of 08	IP of Joint
23	19, 45	20, 21, 22, 46, 122, 123	22, 47, 48, 170, 171, 172, 187	22, 171, 172	20, 21, 22, 46, 47, 48, 122, 123, 170, 171, 172, 187
24	19, 45	20, 21, 22, 46, 122, 123	0	0	20, 21, 22, 46, 122, 123
26	19, 45	25, 40, 125, 140	174	23, 173, 174, 257	257, 23, 25, 40, 49, 125, 140, 173, 174
27	19, 45	25, 40, 125, 140	174	23, 173, 174, 257	257, 23, 25, 40, 49, 125, 140, 173, 174
28	20, 21, 22, 38, 46	26, 27, 126	26, 27	26, 27, 258	258, 26, 27, 126
29	20, 21, 22, 38, 46	28, 41, 120, 127, 260	28, 41, 42, 260	28, 42, 260	260, 28, 41, 42, 43, 120, 127
30	20, 21, 22, 38, 46	29, 42, 121	29	29	29, 42, 44, 121
31	0	0	0	0	
32	20, 21, 22, 38, 46	0	0	0	11
33	23, 24, 39, 47, 48	0	0	0	30
34	23, 24, 39, 47, 48	30	29	0	29, 30
35	23, 24, 39, 47, 48	30	29	0	29, 30
36	25, 40, 49	34, 35, 116, 117	30, 34, 35	0	30, 33, 34, 35, 116, 117
37	25, 40, 49	34, 35, 116, 117	30, 34, 35	0	30, 33, 34, 35, 116, 117
38	26, 27	0	0	0	19, 45
39	26, 27	20, 21, 22, 46, 122, 123	0	0	20, 21, 22, 46, 122, 123
40	26, 27	23, 24, 39, 47, 48, 124	0	0	23, 24, 39, 47, 48, 124
41	26, 27	26, 27, 126	26, 27	0	26, 27, 126
42	28, 41, 43, 260	28, 41, 120, 127, 260	26, 27	26, 27, 258	258, 260, 26, 27, 28, 41, 43, 120, 127
43	28, 41, 43, 260	0	0	0	26, 27
44	28, 41, 43, 260	0	0	0	260, 28, 41, 43
45	29, 42, 44	17, 18	18, 168, 199, 200	0	17, 18, 168, 199, 200
46	30	19, 45	19, 45, 185, 201	0	19, 45, 185, 201

Table A.1 Continued

Task j	IP of 01	IP of 02	IP of 04	IP of 08	IP of Joint
47	30	20, 21, 22, 46, 122, 123	46, 186	0	20, 21, 22, 46, 122, 123, 186
48	30	20, 21, 22, 46, 122, 123	46, 186	0	20, 21, 22, 46, 122, 123, 186
49	33, 34, 35	0	22, 47, 48, 170, 171, 172, 187	0	22, 23, 24, 39, 47, 48, 170, 171, 172, 187
50	33, 34, 35	139	0	280	280, 36, 37, 139
51	36, 37	50, 54, 55, 141	0	283	283, 50, 54, 55, 56, 141
52	36, 37	50, 54, 55, 141	0	283	283, 50, 54, 55, 56, 141
53	36, 37	51, 52, 60	0	283	283, 51, 52, 57, 60
54	36, 37	139	180, 182, 193	0	36, 37, 139, 180, 182, 193
55	50, 54, 55, 56	139	180, 182, 193	0	36, 37, 139, 180, 182, 193
56	50, 54, 55, 56	0	0	0	36, 37
57	50, 54, 55, 56	0	0	0	50, 54, 55, 56
58	51, 52, 57	0	0	0	51, 52, 57
59	51, 52, 57	0	0	0	53, 58, 60
60	51, 52, 57	50, 54, 55, 141	0	0	50, 51, 52, 54, 55, 57, 141
61	53, 58, 60	51, 52, 60	54, 55, 134, 183, 194, 195	283	283, 51, 52, 54, 55, 59, 60, 134, 183, 194, 195
62	59	53, 61	203	283	283, 53, 61, 203
63	61	62	62, 204	283	283, 62, 204
64	62	63	0	0	63
65	63	64, 72, 73, 74	72, 73, 74, 205, 206, 207, 209	0	64, 72, 73, 74, 205, 206, 207, 209
66	63	64, 72, 73, 74	72, 73, 74, 205, 206, 207, 209	72, 73, 74, 207	64, 72, 73, 74, 205, 206, 207, 209
67	63	64, 72, 73, 74	72, 73, 74, 205, 206, 207, 209	72, 73, 74, 207	64, 72, 73, 74, 205, 206, 207, 209
68	63	64, 72, 73, 74	0	0	64, 72, 73, 74
69	64, 72, 73, 74	64, 72, 73, 74	0	72, 73, 74, 207	64, 72, 73, 74, 207
70	64, 72, 73, 74	0	0	0	64, 72, 73, 74
71	64, 72, 73, 74	64, 72, 73, 74	0	0	64, 72, 73, 74
72	64, 72, 73, 74	63	63	51, 52, 53, 61, 62, 63, 204	51, 52, 53, 61, 62, 63, 204

Table A.1 Continued

Task j	IP of 01	IP of 02	IP of 04	IP of 08	IP of Joint
73	64, 72, 73, 74	63	63	51, 52, 53, 61, 62, 63, 204	51, 52, 53, 61, 62, 63, 204
74	64, 72, 73, 74	63	63	51, 52, 53, 61, 62, 63, 204	51, 52, 53, 61, 62, 63, 204
75	64, 72, 73, 74	76	220	76, 217, 286	286, 76, 217, 220
76	65, 66, 67, 68, 69, 70, 71	65, 66, 67, 68, 69, 71	65, 66, 212, 213, 214, 215, 216, 217, 67	66, 67, 69, 285	285, 65, 66, 67, 68, 69, 71, 212, 213, 214, 215, 216, 217
77	76	76	0	0	76
78	76	76	75, 221	76, 217, 286	286, 75, 76, 217, 221
79	76	75, 77, 78, 221	78	75, 78, 221	75, 77, 78, 221
80	75, 77, 78, 221	75, 77, 78, 221	78	75, 78, 221	75, 77, 78, 221
81	75, 77, 78, 221	75, 77, 78, 221	78	0	75, 77, 78, 221
82	75, 77, 78, 221	79, 80, 81	79, 80, 81	0	79, 80, 81
83	79, 80, 81	82	82	79, 80	79, 80, 82
84	82	83	83	83	83
85	83	84	84	84	84
86	84	85	85	0	85
87	85	85	85	85	85
88	85	85	85	85	85
89	85	85	85	85	85
90	85	86, 87, 88, 89, 144	85	85	85, 86, 87, 88, 89, 144
91	85	90, 145, 146	224, 225	225	86, 87, 88, 90, 145, 146, 224, 225
92	86, 87, 88, 89, 90	91	91	91, 289	289, 91
93	91	91	0	0	91
94	91	92, 93, 147	92, 147, 226	92, 226	92, 93, 147, 226
95	92, 93	92, 93, 147	230	94, 227	92, 93, 94, 147, 227, 230
96	92, 93	94, 95	0	0	94, 95
97	94, 95	96, 99, 100, 101	0	0	10, 96, 99, 100, 101
98	94, 95	96, 99, 100, 101	0	0	10, 96, 99, 100, 101
99	94, 95	94, 95	0	94, 227	94, 95, 227
100	94, 95	94, 95	95, 232	95, 99, 290	290, 94, 95, 99, 232
101	94, 95	94, 95	95, 232	95, 99, 290	290, 94, 95, 99, 232
102	96, 99, 100, 101, 103	96, 99, 100, 101	0	0	10, 96, 99, 100, 101
103	96, 99, 100, 101, 103	96, 99, 100, 101	95, 232	0	94, 95, 96, 99, 100, 101, 232
104	96, 99, 100, 101, 103	3	3	3	3

Table A.1 Continued

Task j	IP of 01	IP of 02	IP of 04	IP of 08	IP of Joint
105	96, 99, 100, 101, 103	0	0	0	10, 96, 99
106	96, 99, 100, 101, 103	97, 98, 102, 103, 148	0	0	10, 96, 97, 98, 99, 102, 103, 148
107	96, 99, 100, 101, 103	97, 98, 102, 103, 148	100, 101, 103	0	10, 96, 97, 98, 99, 100, 101, 102, 103, 148
108	96, 99, 100, 101, 103	97, 98, 102, 103, 148	0	0	10, 96, 97, 98, 99, 102, 103, 148
109	97, 98, 102, 105, 106, 107, 108	106, 107, 108	0	0	10, 97, 98, 106, 107, 108
110	97, 98, 102, 105, 106, 107, 108	106, 107, 108	0	0	10, 97, 98, 106, 107, 108
111	0	3	0	0	3
112	0	4, 5, 6, 8, 9, 13, 104, 111	0	0	4, 5, 6, 8, 9, 13, 104, 111
113	0	11	0	155, 242, 244, 245, 246, 248, 252	11, 155, 242, 244, 245, 246, 248, 252
114	0	11	0	0	11
115	0	113, 114	0	0	113, 114
116	0	30	30, 34, 35	0	30, 34, 35
117	0	30	30, 34, 35	0	30, 34, 35
118	0	34, 35, 116, 117	36, 37, 116, 117	0	34, 35, 36, 37, 116, 117
119	0	36, 37, 118, 128	118	0	36, 37, 118, 128
120	0	26, 27, 126	0	0	26, 27, 126
121	0	28, 41, 120, 127, 260	0	0	260, 28, 41, 120, 127
122	0	19, 45	0	0	19, 45
123	0	19, 45	0	0	19, 45
124	0	20, 21, 22, 46, 122, 123	0	0	20, 21, 22, 46, 122, 123
125	0	23, 24, 39, 47, 48, 124	0	0	23, 24, 39, 47, 48, 124
126	0	25, 40, 125, 140	0	0	25, 40, 125, 140
127	0	26, 27, 126	0	0	26, 27, 126
128	0	34, 35, 116, 117	0	0	34, 35, 116, 117
129	0	36, 37, 118, 128	0	0	36, 37, 118, 128
130	0	119, 129	0	0	119, 129
131	0	130	0	0	130
132	0	131	0	0	131
133	0	132	0	0	132

Table A.1 Continued

Task j	IP of 01	IP of 02	IP of 04	IP of 08	IP of Joint
134	0	133	180, 182, 193	0	133, 180, 182, 193
135	0	134	0	0	134
136	0	135	0	0	135
137	0	135	0	0	135
138	0	135	0	0	135
139	0	136, 137, 138	0	0	136, 137, 138
140	0	23, 24, 39, 47, 48, 124	0	0	23, 24, 39, 47, 48, 124
141	0	139	0	0	139
142	0	0	0	0	
143	0	0	0	0	
144	0	85	0	0	85
145	0	86, 87, 88, 89, 144	0	0	86, 87, 88, 89, 144
146	0	86, 87, 88, 89, 144	0	0	86, 87, 88, 89, 144
147	0	91	91	0	91
148	0	96, 99, 100, 101	0	0	96, 99, 100, 101
149	0	0	0	0	
150	0	0	3	3	3
151	0	0	3	0	3
152	0	0	5, 6, 8, 13, 104, 150, 151	0	5, 6, 8, 13, 104, 150, 151
153	0	0	7, 10, 152	0	7, 10, 152
154	0	0	7, 10, 152	0	7, 10, 152
155	0	0	7, 10, 152	7, 10, 251	7, 10, 152, 251
156	0	0	7, 10, 152	0	7, 10, 152
157	0	0	153, 154, 155, 156	0	153, 154, 155, 156
158	0	0	153, 154, 155, 156	155, 242, 244, 245, 246, 248, 252	153, 154, 155, 156, 242, 244, 245, 246, 248, 252
159	0	0	153, 154, 155, 156	155, 242, 244, 245, 246, 248, 252	153, 154, 155, 156, 242, 244, 245, 246, 248, 252
160	0	0	12, 15, 16, 157, 158, 159, 162	15, 16, 113, 158, 159, 243, 247	12, 15, 16, 113, 157, 158, 159, 162, 243, 247
161	0	0	17, 160, 163, 164	17, 160, 249	17, 160, 163, 164, 249
162	0	0	153, 154, 155, 156	0	153, 154, 155, 156
163	0	0	12, 15, 16, 157, 158, 159, 162	0	12, 15, 16, 157, 158, 159, 162

Table A.1 Continued

Task j	IP of 01	IP of 02	IP of 04	IP of 08	IP of Joint
164	0	0	12, 15, 16, 157, 158, 159, 162	0	12, 15, 16, 157, 158, 159, 162
165	0	0	17, 160, 163, 164	0	17, 160, 163, 164
166	0	0	161, 165	0	161, 165
167	0	0	166, 197	0	166, 197
168	0	0	167, 198	0	167, 198
169	0	0	0	0	
170	0	0	46, 186	0	46, 186
171	0	0	46, 186	19, 201	19, 46, 186, 201
172	0	0	46, 186	19, 201	19, 46, 186, 201
173	0	0	22, 47, 48, 170, 171, 172, 187	22, 171, 172	22, 47, 48, 170, 171, 172, 187
174	0	0	23, 49, 173	22, 171, 172	22, 23, 49, 171, 172, 173
175	0	0	118	0	118
176	0	0	118	0	118
177	0	0	119, 175, 176, 188, 189	0	119, 175, 176, 188, 189
178	0	0	119, 175, 176, 188, 189	0	119, 175, 176, 188, 189
179	0	0	119, 175, 176, 188, 189	0	119, 175, 176, 188, 189
180	0	0	177, 178, 179, 190, 191, 192	0	177, 178, 179, 190, 191, 192
181	0	0	0	0	
182	0	0	177, 178, 179, 190, 191, 192	0	177, 178, 179, 190, 191, 192
183	0	0	180, 182, 193	0	180, 182, 193
184	0	0	54, 55, 134, 183, 194, 195	0	54, 55, 134, 183, 194, 195
185	0	0	18, 168, 199, 200	0	18, 168, 199, 200
186	0	0	19, 45, 185, 201	0	19, 45, 185, 201
187	0	0	46, 186	0	46, 186
188	0	0	118	0	118
189	0	0	118	261, 262, 263, 264, 265	261, 262, 263, 264, 265, 118
190	0	0	119, 175, 176, 188, 189	0	119, 175, 176, 188, 189
191	0	0	119, 175, 176, 188, 189	0	119, 175, 176, 188, 189
192	0	0	119, 175, 176, 188, 189	0	119, 175, 176, 188, 189
193	0	0	177, 178, 179, 190, 191, 192	0	177, 178, 179, 190, 191, 192
194	0	0	180, 182, 193	0	180, 182, 193
195	0	0	180, 182, 193	0	180, 182, 193
196	0	0	54, 55, 134, 183, 194, 195	0	54, 55, 134, 183, 194, 195
197	0	0	161, 165	161, 253	161, 165, 253
198	0	0	166, 197	197, 254	166, 197, 254
199	0	0	167, 198	198, 255	255, 167, 198
200	0	0	167, 198	198, 255	255, 167, 198
201	0	0	18, 168, 199, 200	18, 199, 200	18, 168, 199, 200
202	0	0	54, 55, 134, 183, 194, 195	0	54, 55, 134, 183, 194, 195
203	0	0	61, 184, 196, 202	0	61, 184, 196, 202
204	0	0	203	283	283, 203
205	0	0	63	0	63
206	0	0	63	0	63
207	0	0	63	51, 52, 53, 61, 62, 63, 204	51, 52, 53, 61, 62, 63, 204

Table A.1 Continued

Task j	IP of 01	IP of 02	IP of 04	IP of 08	IP of Joint
208	0	0	0	0	
209	0	0	63	0	63
210	0	0	0	0	
211	0	0	0	0	
212	0	0	72, 73, 74, 205, 206, 207, 209	0	72, 73, 74, 205, 206, 207, 209
213	0	0	72, 73, 74, 205, 206, 207, 209	0	72, 73, 74, 205, 206, 207, 209
214	0	0	72, 73, 74, 205, 206, 207, 209	0	72, 73, 74, 205, 206, 207, 209
215	0	0	72, 73, 74, 205, 206, 207, 209	0	72, 73, 74, 205, 206, 207, 209
216	0	0	72, 73, 74, 205, 206, 207, 209	0	72, 73, 74, 205, 206, 207, 209
217	0	0	72, 73, 74, 205, 206, 207, 209	66, 67, 69, 285	285, 66, 67, 69, 72, 73, 74, 205, 206, 207, 209
218	0	0	0	0	
219	0	0	76	0	76
220	0	0	219	0	219
221	76	76	220	76, 217, 286	286, 76, 217, 220
222	0	0	0	0	
223	0	0	0	0	
224	0	0	86, 87, 88, 89, 90	0	86, 87, 88, 89, 90
225	0	0	86, 87, 88, 89, 90	87, 88, 89, 90, 288	288, 86, 87, 88, 89, 90
226	0	0	91	91, 289	289, 91
227	0	0	92, 147, 226	92, 226	92, 147, 226
228	0	0	92, 147, 226	0	92, 147, 226
229	0	0	92, 147, 226	0	92, 147, 226
230	0	0	94, 227, 228, 229	0	94, 227, 228, 229
231	0	0	0	0	
232	0	0	230	0	230
233	0	0	0	0	
234	0	0	0	0	
235	0	0	100, 101, 103	100, 101, 291	291, 100, 101, 103
236	0	0	0	0	
237	0	0	100, 101, 103	0	100, 101, 103
238	0	0	100, 101, 103	0	100, 101, 103
239	0	0	0	0	
240	0	0	107, 235, 237, 238	0	107, 235, 237, 238
241	0	0	0	3	3
242	0	0	0	7, 10, 251	7, 10, 251
243	0	0	0	155, 242, 244, 245, 246, 248, 252	155, 242, 244, 245, 246, 248, 252
244	0	0	0	7, 10, 251	7, 10, 251
245	0	0	0	7, 10, 251	7, 10, 251
246	0	0	0	7, 10, 251	7, 10, 251
247	0	0	0	155, 242, 244, 245, 246, 248, 252	155, 242, 244, 245, 246, 248, 252

Table A.1 Continued

Task j	IP of 01	IP of 02	IP of 04	IP of 08	IP of Joint
248	0	0	0	7, 10, 251	7, 10, 251
249	0	0	0	15, 16, 113, 158, 159, 243, 247	15, 16, 113, 158, 159, 243, 247
250	0	0	0	3	3
251	0	0	0	5, 6, 8, 13, 104, 150, 241, 250	5, 6, 8, 13, 104, 150, 241, 250
252	0	0	0	7, 10, 251	7, 10, 251
253	0	0	0	17, 160, 249	17, 160, 249
254	0	0	0	161, 253	161, 253
255	0	0	0	197, 254	197, 254
256	0	0	0	0	
257	0	0	0	22, 171, 172	22, 171, 172
258	0	0	0	23, 173, 174, 257	257, 23, 173, 174
259	0	0	0	29	29
260	20, 21, 22, 38, 46	26, 27, 126	26, 27	26, 27, 258	258, 26, 27, 126
261	0	0	0	30, 259	259, 30
262	0	0	0	30, 259	259, 30
263	0	0	0	30, 259	259, 30
264	0	0	0	30, 259	259, 30
265	0	0	0	30, 259	259, 30
266	0	0	0	261, 262, 263, 264, 265	261, 262, 263, 264, 265
267	0	0	0	261, 262, 263, 264, 265	261, 262, 263, 264, 265
268	0	0	0	261, 262, 263, 264, 265	261, 262, 263, 264, 265
269	0	0	0	189, 266, 267, 268	266, 267, 268, 189
270	0	0	0	189, 266, 267, 268	266, 267, 268, 189
271	0	0	0	189, 266, 267, 268	266, 267, 268, 189
272	0	0	0	269, 270, 271	269, 270, 271
273	0	0	0	272	272
274	0	0	0	272	272
275	0	0	0	273, 274	273, 274
276	0	0	0	275	275
277	0	0	0	276	276
278	0	0	0	276	276
279	0	0	0	277, 278	277, 278
280	0	0	0	279	279
281	0	0	0	280	280
282	0	0	0	280	280
283	0	0	0	50, 281, 282	281, 282, 50
284	0	0	0	0	
285	0	0	0	72, 73, 74, 207	72, 73, 74, 207
286	0	0	0	66, 67, 69, 285	285, 66, 67, 69
287	0	0	0	0	
288	0	0	0	85	85
289	0	0	0	225	225
290	0	0	0	94, 227	94, 227
291	0	0	0	95, 99, 290	290, 95, 99

Table A.1 Continued

Task j	IP of 01	IP of 02	IP of 04	IP of 08	IP of Joint
292	0	0	0	100, 101, 291	291, 100, 101
293	0	0	0	100, 101, 291	291, 100, 101
294	0	0	0	100, 101, 291	291, 100, 101
295	0	0	0	100, 101, 291	291, 100, 101
296	0	0	0	100, 101, 291	291, 100, 101

Table A.2 Processing times of respective models

Task j	1	2	4	8	joint	Task j	1	2	4	8	joint
1	0.34	0.34	0.44	0.44	0.44	39	0.39	0.39	0	0	0.39
2	0.2	0.2	0.36	0.36	0.36	40	0.77	0.77	0	0	0.77
3	0.37	0.37	0.65	0.65	0.65	41	0.16	0.16	0.16	0	0.16
4	0.56	0.56	0	0	0.56	42	0.32	0.32	0.32	0.32	0.32
5	0.68	0.68	0.68	0.68	0.68	43	1.32	0	0	0	1.32
6	0.34	0.34	1.14	1.14	1.14	44	0.65	0	0	0	0.65
7	0.68	0.68	1.59	1.59	1.59	45	0.45	0.45	0.45	0	0.45
8	0.04	0.04	0.04	0.04	0.04	46	0.48	0.48	0.48	0	0.48
9	1.11	1.11	0	0	1.11	47	0.72	0.72	0.72	0	0.72
10	0.5	0.5	0.5	0.5	0.5	48	0.19	0.19	0.19	0	0.19
11	0.88	0.88	0	0	0.88	49	0.12	0	0.26	0	0.26
12	0.7	0	0.7	0	0.7	50	0.57	0.57	0	0.6	0.6
13	0.44	0.44	0.44	0.44	0.44	51	0.44	0.44	0	0.64	0.64
14	0.1	0.1	0.1	0.1	0.1	52	0.14	0.17	0	0.14	0.17
15	0.25	0.25	0.25	0.25	0.25	53	0.31	0.35	0	0.22	0.35
16	0.21	0.21	0.21	0.21	0.21	54	0.33	0.34	0.62	0	0.62
17	0.26	0.26	0.26	0.26	0.26	55	0.81	0.81	0.68	0	0.81
18	0.7	0.7	0.7	0.7	0.7	56	0.42	0	0	0	0.42
19	0.55	0.55	0.88	1.05	1.05	57	0.55	0	0	0	0.55
20	0.53	0.54	0	0	0.54	58	0.13	0	0	0	0.13
21	0.13	0.13	0	0	0.13	59	0.48	0	0	0	0.48
22	0.13	0.13	0.13	0.13	0.13	60	0.54	0.54	0	0	0.54
23	0.2	0.17	0.13	0.13	0.2	61	0.57	0.57	0.57	0.57	0.57
24	0.9	0.9	0	0	0.9	62	0.3	0.3	0.32	0.32	0.32
25	0.16	0.16	0	0	0.16	63	0.56	0.56	3.03	3.03	3.03
26	1.26	1.26	1.09	1.09	1.26	64	0.21	0.21	0	0	0.21
27	0.34	0.34	0.34	0.34	0.34	65	0.18	0.18	0.15	0	0.18
28	0.47	0.47	0.47	0.47	0.47	66	0.2	0.2	0.18	0.18	0.2
29	0.06	0.06	0.06	0.06	0.06	67	0.37	0.37	0.19	0.44	0.44
30	0.19	0.19	0.19	0.19	0.19	68	1.87	1.87	0	0	1.87
31	0	0	0	0	0	69	0.31	0.31	0	0.31	0.31
32	0.28	0	0	0	0.28	70	0.78	0	0	0	0.78
33	0.22	0	0	0	0.22	71	0.16	0.16	0	0	0.16
34	0.56	0.56	0.56	0	0.56	72	0.18	0.18	0.18	0.18	0.18
35	0.58	0.58	0.58	0	0.58	73	0.1	0.1	0.1	0.1	0.1
36	0.17	0.35	0.35	0	0.35	74	0.14	0.14	0.14	0.14	0.14
37	0.55	0.55	0.55	0	0.55	75	0.17	0.26	0.17	0.17	0.26
38	0.17	0	0	0	0.17	76	0.37	0.37	0.54	0.54	0.54

Table A.2 Continued

Task j	1	2	4	8	joint	Task j	1	2	4	8	joint
77	0.38	0.38	0	0	0.38	126	0	0.66	0	0	0.66
78	1.2	1.2	1.79	1.79	1.79	127	0	0.14	0	0	0.14
79	0.07	0.07	0.07	0.07	0.07	128	0	0.58	0	0	0.58
80	0.04	0.04	0.04	0.04	0.04	129	0	0.18	0	0	0.18
81	0.35	0.35	0.35	0	0.35	130	0	0.96	0	0	0.96
82	0.17	0.17	0.17	0	0.17	131	0	1.38	0	0	1.38
83	0.28	0.28	3.25	3.25	3.25	132	0	0.69	0	0	0.69
84	1.44	1.44	1.44	1.44	1.44	133	0	0.22	0	0	0.22
85	1.69	1.69	2.27	2.27	2.27	134	0	0.46	0.15	0	0.46
86	0.09	0.09	0.09	0	0.09	135	0	0.28	0	0	0.28
87	0.92	0.92	0.92	0.92	0.92	136	0	0.35	0	0	0.35
88	0.46	0.46	0.46	0.46	0.46	137	0	0.35	0	0	0.35
89	0.45	0.45	0.45	0.45	0.45	138	0	0.35	0	0	0.35
90	1.04	0.98	0.98	0.98	1.04	139	0	0.32	0	0	0.32
91	1.62	0.92	0.92	0.92	1.62	140	0	0.12	0	0	0.12
92	0.6	0.6	0.6	0.6	0.6	141	0	0.2	0	0	0.2
93	0.44	0.41	0	0	0.44	142	0	0	0	0	0
94	0.37	0.45	0.45	0.45	0.45	143	0	0	0	0	0
95	0.8	0.8	1.46	1.46	1.46	144	0	0.1	0	0	0.1
96	0.42	0.42	0	0	0.42	145	0	0.1	0	0	0.1
97	0.59	0.59	0	0	0.59	146	0	0.5	0	0	0.5
98	0.16	0.16	0	0	0.16	147	0	0.2	0.49	0	0.49
99	0.81	0.81	0	0.81	0.81	148	0	0.46	0	0	0.46
100	1.61	1.65	1.76	1.76	1.76	149	0	0	0	0	0
101	1.38	1.41	1.59	1.59	1.59	150	0	0	0.7	0.7	0.7
102	0.04	0.04	0	0	0.04	151	0	0	0.96	0	0.96
103	1.31	1.31	1.31	0	1.31	152	0	0	0.62	0	0.62
104	0.1	0.1	0.06	0.06	0.1	153	0	0	0.15	0	0.15
105	0.46	0	0	0	0.46	154	0	0	0.15	0	0.15
106	2.04	2.04	0	0	2.04	155	0	0	0.88	0.88	0.88
107	1.87	1.92	2.38	0	2.38	156	0	0	0.54	0	0.54
108	0.8	0.8	0	0	0.8	157	0	0	0.92	0	0.92
109	0.09	0.11	0	0	0.11	158	0	0	0.33	0.33	0.33
110	0.3	0.3	0	0	0.3	159	0	0	0.34	0.34	0.34
111	0	0.31	0	0	0.31	160	0	0	2.16	2.16	2.16
112	0	0.73	0	0	0.73	161	0	0	0.75	0.75	0.75
113	0	0.8	0	0.8	0.8	162	0	0	0.39	0	0.39
114	0	0.18	0	0	0.18	163	0	0	1.05	0	1.05
115	0	0.28	0	0	0.28	164	0	0	0.3	0	0.3
116	0	0.13	0.29	0	0.29	165	0	0	0.98	0	0.98
117	0	0.13	0.13	0	0.13	166	0	0	1.42	0	1.42
118	0	0.7	1.19	0	1.19	167	0	0	0.97	0	0.97
119	0	0.11	0.11	0	0.11	168	0	0	0.36	0	0.36
120	0	0.57	0	0	0.57	169	0	0	0	0	0
121	0	0.88	0	0	0.88	170	0	0	1.5	0	1.5
122	0	0.14	0	0	0.14	171	0	0	0.3	0.56	0.56
123	0	0.7	0	0	0.7	172	0	0	0.53	0.81	0.81
124	0	0.55	0	0	0.55	173	0	0	0.9	0.9	0.9
125	0	2.08	0	0	2.08	174	0	0	0.44	0.44	0.44

Table A.2 Continued

Task j	1	2	4	8	joint	Task j	1	2	4	8	joint
175	0	0	0.3	0	0.3	224	0	0	0.56	0	0.56
176	0	0	1.24	0	1.24	225	0	0	0.33	0.33	0.33
177	0	0	0.34	0	0.34	226	0	0	0.21	0.21	0.21
178	0	0	0.33	0	0.33	227	0	0	1.22	1.22	1.22
179	0	0	0.36	0	0.36	228	0	0	0.81	0	0.81
180	0	0	0.57	0	0.57	229	0	0	1.23	0	1.23
181	0	0	0	0	0	230	0	0	1.73	0	1.73
182	0	0	2.1	0	2.1	231	0	0	0	0	0
183	0	0	0.99	0	0.99	232	0	0	0.12	0	0.12
184	0	0	0.99	0	0.99	233	0	0	0	0	0
185	0	0	0.16	0	0.16	234	0	0	0	0	0
186	0	0	0.12	0	0.12	235	0	0	0.06	0.06	0.06
187	0	0	0.15	0	0.15	236	0	0	0	0	0
188	0	0	0.15	0	0.15	237	0	0	0.31	0	0.31
189	0	0	1.08	1.08	1.08	238	0	0	1.41	0	1.41
190	0	0	1.22	0	1.22	239	0	0	0	0	0
191	0	0	1.22	0	1.22	240	0	0	0.28	0	0.28
192	0	0	1.22	0	1.22	241	0	0	0	0.65	0.65
193	0	0	2.5	0	2.5	242	0	0	0	0.19	0.19
194	0	0	0.55	0	0.55	243	0	0	0	0.92	0.92
195	0	0	0.63	0	0.63	244	0	0	0	1.5	1.5
196	0	0	1.14	0	1.14	245	0	0	0	0.6	0.6
197	0	0	0.41	0.41	0.41	246	0	0	0	0.6	0.6
198	0	0	0.35	0.35	0.35	247	0	0	0	1.19	1.19
199	0	0	0.9	0.9	0.9	248	0	0	0	0.7	0.7
200	0	0	0.33	0.33	0.33	249	0	0	0	1.87	1.87
201	0	0	1.08	1.08	1.08	250	0	0	0	0.2	0.2
202	0	0	1.05	0	1.05	251	0	0	0	0.89	0.89
203	0	0	0.33	0	0.33	252	0	0	0	0.69	0.69
204	0	0	0.96	0.96	0.96	253	0	0	0	0.41	0.41
205	0	0	0.12	0	0.12	254	0	0	0	1.6	1.6
206	0	0	0.5	0	0.5	255	0	0	0	1.01	1.01
207	0	0	0.49	0.49	0.49	256	0	0	0	0	0
208	0	0	0	0	0	257	0	0	0	0.6	0.6
209	0	0	0.1	0	0.1	258	0	0	0	0.6	0.6
210	0	0	0	0	0	259	0	0	0	0.9	0.9
211	0	0	0	0	0	260	0.15	0.15	0.25	0.28	0.28
212	0	0	2.56	0	2.56	261	0	0	0	1.2	1.2
213	0	0	0.09	0	0.09	262	0	0	0	0.55	0.55
214	0	0	0.07	0	0.07	263	0	0	0	2.6	2.6
215	0	0	2.23	0	2.23	264	0	0	0	0.61	0.61
216	0	0	0.18	0	0.18	265	0	0	0	0.87	0.87
217	0	0	3.97	3.97	3.97	266	0	0	0	0.64	0.64
218	0	0	0	0	0	267	0	0	0	0.56	0.56
219	0	0	0.19	0	0.19	268	0	0	0	0.56	0.56
220	0	0	0.69	0	0.69	269	0	0	0	0.6	0.6
221	0.32	0.32	0.32	0.32	0.32	270	0	0	0	0.6	0.6
222	0	0	0	0	0	271	0	0	0	0.6	0.6
223	0	0	0	0	0	272	0	0	0	0.8	0.8

Table A.2 Continued

Task j	1	2	4	8	joint	Task j	1	2	4	8	joint
273	0	0	0	0.33	0.33	287	0	0	0	0	0
274	0	0	0	0.5	0.5	288	0	0	0	0.09	0.09
275	0	0	0	0.62	0.62	289	0	0	0	0.83	0.83
276	0	0	0	0.39	0.39	290	0	0	0	0.84	0.84
277	0	0	0	0.2	0.2	291	0	0	0	0.16	0.16
278	0	0	0	1.25	1.25	292	0	0	0	0.36	0.36
279	0	0	0	1.62	1.62	293	0	0	0	0.07	0.07
280	0	0	0	1.95	1.95	294	0	0	0	1.2	1.2
281	0	0	0	0.48	0.48	295	0	0	0	1	1
282	0	0	0	1.02	1.02	296	0	0	0	1	1
283	0	0	0	0.47	0.47	297	0	0	0	0	0
284	0	0	0	0	0	298	0	0	0	0	0
285	0	0	0	2	2	299	0	0	0	0	0
286	0	0	0	0.56	0.56	300	0	0	0	0	0
273	0	0	0	0.33	0.33	287	0	0	0	0	0
274	0	0	0	0.5	0.5	288	0	0	0	0.09	0.09
275	0	0	0	0.62	0.62	289	0	0	0	0.83	0.83
276	0	0	0	0.39	0.39	290	0	0	0	0.84	0.84
277	0	0	0	0.2	0.2	291	0	0	0	0.16	0.16
278	0	0	0	1.25	1.25	292	0	0	0	0.36	0.36
279	0	0	0	1.62	1.62	293	0	0	0	0.07	0.07
280	0	0	0	1.95	1.95	294	0	0	0	1.2	1.2
281	0	0	0	0.48	0.48	295	0	0	0	1	1
282	0	0	0	1.02	1.02	296	0	0	0	1	1
283	0	0	0	0.47	0.47						
284	0	0	0	0	0						
285	0	0	0	2	2						
286	0	0	0	0.56	0.56						

Table A.3 Commonality Matrix of Tasks for Models

Task j	***1***	***2***	***4***	***8***	***Total Common Task Number |Aj|***	***Task j***	***1***	***2***	***4***	***8***	***Total Common Task Number |Aj|***	***Task j***	***1***	***2***	***4***	***8***	***Total Common Task Number |Aj|***
1	1	1	1	1	4	45	1	1	1	0	3	89	1	1	1	1	4
2	1	1	1	1	4	46	1	1	1	0	3	90	1	1	1	1	4
3	1	1	1	1	4	47	1	1	1	0	3	91	1	1	1	1	4
4	1	1	0	0	2	48	1	1	1	0	3	92	1	1	1	1	4
5	1	1	1	1	4	49	1	0	1	0	2	93	1	1	0	0	2
6	1	1	1	1	4	50	1	1	0	1	3	94	1	1	1	1	4
7	1	1	1	1	4	51	1	1	0	1	3	95	1	1	1	1	4
8	1	1	1	1	4	52	1	1	0	1	3	96	1	1	0	0	2
9	1	1	0	0	2	53	1	1	0	1	3	97	1	1	0	0	2
10	1	1	1	1	4	54	1	1	1	0	3	98	1	1	0	0	2
11	1	1	0	0	2	55	1	1	1	0	3	99	1	1	0	1	3
12	1	0	1	0	2	56	1	0	0	0	1	100	1	1	1	1	4
13	1	1	1	1	4	57	1	0	0	0	1	101	1	1	1	1	4
14	1	1	1	1	4	58	1	0	0	0	1	102	1	1	0	0	2
15	1	1	1	1	4	59	1	0	0	0	1	103	1	1	1	0	3
16	1	1	1	1	4	60	1	1	0	0	2	104	1	1	1	1	4
17	1	1	1	1	4	61	1	1	1	1	4	105	1	0	0	0	1
18	1	1	1	1	4	62	1	1	1	1	4	106	1	1	0	0	2
19	1	1	1	1	4	63	1	1	1	1	4	107	1	1	1	0	3
20	1	1	0	0	2	64	1	1	0	0	2	108	1	1	0	0	2
21	1	1	0	0	2	65	1	1	1	0	3	109	1	1	0	0	2
22	1	1	1	1	4	66	1	1	1	1	4	110	1	1	0	0	2
23	1	1	1	1	4	67	1	1	1	1	4	111	0	1	0	0	1
24	1	1	0	0	2	68	1	1	0	0	2	112	0	1	0	0	1
25	1	1	0	0	2	69	1	1	0	1	3	113	0	1	0	1	2
26	1	1	1	1	4	70	1	0	0	0	1	114	0	1	0	0	1
27	1	1	1	1	4	71	1	1	0	0	2	115	0	1	0	0	1
28	1	1	1	1	4	72	1	1	1	1	4	116	0	1	1	0	2
29	1	1	1	1	4	73	1	1	1	1	4	117	0	1	1	0	2
30	1	1	1	1	4	74	1	1	1	1	4	118	0	1	1	0	2
31	0	0	0	0	0	75	1	1	1	1	4	119	0	1	1	0	2
32	1	0	0	0	1	76	1	1	1	1	4	120	0	1	0	0	1
33	1	0	0	0	1	77	1	1	0	0	2	121	0	1	0	0	1
34	1	1	1	0	3	78	1	1	1	1	4	122	0	1	0	0	1
35	1	1	1	0	3	79	1	1	1	1	4	123	0	1	0	0	1
36	1	1	1	0	3	80	1	1	1	1	4	124	0	1	0	0	1
37	1	1	1	0	3	81	1	1	1	0	3	125	0	1	0	0	1
38	1	0	0	0	1	82	1	1	1	0	3	126	0	1	0	0	1
39	1	1	0	0	2	83	1	1	1	1	4	127	0	1	0	0	1
40	1	1	0	0	2	84	1	1	1	1	4	128	0	1	0	0	1
41	1	1	1	0	3	85	1	1	1	1	4	129	0	1	0	0	1
42	1	1	1	1	4	86	1	1	1	0	3	130	0	1	0	0	1
43	1	0	0	0	1	87	1	1	1	1	4	131	0	1	0	0	1
44	1	0	0	0	1	88	1	1	1	1	4	132	0	1	0	0	1

Table A.3 Continued

Task j	***1***	***2***	***4***	***8***	***Total Common Task Number |Aj|***	***Task j***	***1***	***2***	***4***	***8***	***Total Common Task Number |Aj|***	***Task j***	***1***	***2***	***4***	***8***	***Total Common Task Number |Aj|***
133	0	1	0	0	1	177	0	0	1	0	1	221	1	1	1	1	4
134	0	1	1	0	2	178	0	0	1	0	1	222	0	0	0	0	0
135	0	1	0	0	1	179	0	0	1	0	1	223	0	0	0	0	0
136	0	1	0	0	1	180	0	0	1	0	1	224	0	0	1	0	1
137	0	1	0	0	1	181	0	0	0	0	0	225	0	0	1	1	2
138	0	1	0	0	1	182	0	0	1	0	1	226	0	0	1	1	2
139	0	1	0	0	1	183	0	0	1	0	1	227	0	0	1	1	2
140	0	1	0	0	1	184	0	0	1	0	1	228	0	0	1	0	1
141	0	1	0	0	1	185	0	0	1	0	1	229	0	0	1	0	1
142	0	0	0	0	0	186	0	0	1	0	1	230	0	0	1	0	1
143	0	0	0	0	0	187	0	0	1	0	1	231	0	0	0	0	0
144	0	1	0	0	1	188	0	0	1	0	1	232	0	0	1	0	1
145	0	1	0	0	1	189	0	0	1	1	2	233	0	0	0	0	0
146	0	1	0	0	1	190	0	0	1	0	1	234	0	0	0	0	0
147	0	1	1	0	2	191	0	0	1	0	1	235	0	0	1	1	2
148	0	1	0	0	1	192	0	0	1	0	1	236	0	0	0	0	0
149	0	0	0	0	0	193	0	0	1	0	1	237	0	0	1	0	1
150	0	0	1	1	2	194	0	0	1	0	1	238	0	0	1	0	1
151	0	0	1	0	1	195	0	0	1	0	1	239	0	0	0	0	0
152	0	0	1	0	1	196	0	0	1	0	1	240	0	0	1	0	1
153	0	0	1	0	1	197	0	0	1	1	2	241	0	0	0	1	1
154	0	0	1	0	1	198	0	0	1	1	2	242	0	0	0	1	1
155	0	0	1	1	2	199	0	0	1	1	2	243	0	0	0	1	1
156	0	0	1	0	1	200	0	0	1	1	2	244	0	0	0	1	1
157	0	0	1	0	1	201	0	0	1	1	2	245	0	0	0	1	1
158	0	0	1	1	2	202	0	0	1	0	1	246	0	0	0	1	1
159	0	0	1	1	2	203	0	0	1	0	1	247	0	0	0	1	1
160	0	0	1	1	2	204	0	0	1	1	2	248	0	0	0	1	1
161	0	0	1	1	2	205	0	0	1	0	1	249	0	0	0	1	1
162	0	0	1	0	1	206	0	0	1	0	1	250	0	0	0	1	1
163	0	0	1	0	1	207	0	0	1	1	2	251	0	0	0	1	1
164	0	0	1	0	1	208	0	0	0	0	0	252	0	0	0	1	1
165	0	0	1	0	1	209	0	0	1	0	1	253	0	0	0	1	1
166	0	0	1	0	1	210	0	0	0	0	0	254	0	0	0	1	1
167	0	0	1	0	1	211	0	0	0	0	0	255	0	0	0	1	1
168	0	0	1	0	1	212	0	0	1	0	1	256	0	0	0	0	0
169	0	0	0	0	0	213	0	0	1	0	1	257	0	0	0	1	1
170	0	0	1	0	1	214	0	0	1	0	1	258	0	0	0	1	1
171	0	0	1	1	2	215	0	0	1	0	1	259	0	0	0	1	1
172	0	0	1	1	2	216	0	0	1	0	1	260	1	1	1	1	4
173	0	0	1	1	2	217	0	0	1	1	2	261	0	0	0	1	1
174	0	0	1	1	2	218	0	0	0	0	0	262	0	0	0	1	1
175	0	0	1	0	1	219	0	0	1	0	1	263	0	0	0	1	1
176	0	0	1	0	1	220	0	0	1	0	1	264	0	0	0	1	1

Table A.3 Continued

Task j	***1***	***2***	***4***	***8***	***Total Common Task Number |Aj|***	***Task j***	***1***	***2***	***4***	***8***	***Total Common Task Number |Aj|***	***Task j***	***1***	***2***	***4***	***8***	***Total Common Task Number |Aj|***
265	0	0	0	1	1	276	0	0	0	1	1	287	0	0	0	0	0
266	0	0	0	1	1	277	0	0	0	1	1	288	0	0	0	1	1
267	0	0	0	1	1	278	0	0	0	1	1	289	0	0	0	1	1
268	0	0	0	1	1	279	0	0	0	1	1	290	0	0	0	1	1
269	0	0	0	1	1	280	0	0	0	1	1	291	0	0	0	1	1
270	0	0	0	1	1	281	0	0	0	1	1	292	0	0	0	1	1
271	0	0	0	1	1	282	0	0	0	1	1	293	0	0	0	1	1
272	0	0	0	1	1	283	0	0	0	1	1	294	0	0	0	1	1
273	0	0	0	1	1	284	0	0	0	0	0	295	0	0	0	1	1
274	0	0	0	1	1	285	0	0	0	1	1	296	0	0	0	1	1
275	0	0	0	1	1	286	0	0	0	1	1						

Test bed data

Table A.4 Data set of Bowman

	Task Time					
Task j	**1**	**2**	**4**	**8**	**9**	**IP of Task j**
1	11	10	10	10	10	-
2	17	16	15	15	18	1
3	9	8	9	9	9	2
4	5	5	5	4	5	2
5	8	7	7	8	8	3
6	12	12	12	12	11	3,4
7	10	9	10	10	10	5
8	3	2	3	2	2	6

Table A.5 Data set of Rosenberg und Ziegler

	Task Times						Task Times				
Task j	**1**	**2**	**4**	**8**	**IP of Task j**	**Task j**	**1**	**2**	**4**	**8**	**IP of Task j**
1	4	4	3	6	-	14	14	3	3	2	5
2	3	3	3	3	-	15	15	6	4	5	2
3	9	9	9	9	1,2	16	16	3	3	4	1
4	6	4	4	4	3	17	17	11	15	16	13
5	7	11	12	9	4	18	18	6	4	4	4
6	4	4	4	4	5	19	19	2	2	2	2
7	10	6	5	8	6	20	20	2	4	5	2
8	7	7	6	9	4	21	21	5	9	9	9
9	5	5	4	7	8	22	22	6	4	3	6
10	1	1	1	1	6,9	23	23	4	2	2	2
11	2	4	4	4	7,8	24	24	12	4	2	8
12	1	1	1	1	7	25	25	4	4	4	4
13	7	3	3	3	9,11						

Table A.5 Data set of Kilbridge and Wester

	Task Times						Task Times						
Task j	**1**	**2**	**4**	**8**	**9**	**IP of Task j**	**Task j**	**1**	**2**	**4**	**8**	**9**	**IP of Task j**
1	9	9	8	8	9	-	11	10	9	10	10	9	-
2	9	8	9	8	9	-	12	11	11	10	9	11	-
3	10	9	9	10	10	1	13	6	5	6	6	6	11,12
4	10	9	9	10	9	2	14	22	23	23	21	22	7,8
5	17	17	15	18	18	3	15	11	10	9	10	11	13
6	17	15	17	15	15	4	16	19	20	17	20	18	15
7	13	13	13	13	12	1	17	12	12	12	12	11	14
8	13	13	12	11	13	2	18	3	2	3	2	2	15
9	20	18	21	21	21	5,7	19	7	7	7	7	7	16,18
10	20	18	19	19	20	6,8	20	4	3	4	3	4	19

Table A.5 Continued

	Task Times							Task Times					
Task j	1	2	4	8	9	IP of Task j	Task j	1	2	4	8	9	IP of Task j
21	55	50	58	49	53	20	34	3	3	2	2	2	33
22	14	15	13	15	14	21	35	7	6	6	7	6	33
23	27	25	28	29	25	15	36	9	9	9	8	9	33
24	29	26	27	30	26	15	37	4	4	4	4	4	12
25	26	27	27	24	26	14	38	7	7	6	6	6	26,28
26	6	5	6	5	6	17,25	39	5	5	5	4	5	-
27	5	4	5	5	5	17	40	4	3	4	3	3	35,38
28	24	24	22	25	26	22,27	41	21	22	20	20	19	10,29
29	4	4	4	4	4	14	42	12	12	11	13	11	41
30	5	5	5	4	5	14	43	6	6	6	5	5	37
31	7	6	7	7	6	14	44	5	5	4	5	5	42
32	4	3	4	3	4	14	45	5	5	4	5	5	42
33	15	14	14	15	15	19,23							

Table A.6 Data set of Bartholdi

	Task Times						**Task Times**				
Task j	**1**	**2**	**4**	**8**	**IP of Task j**	**Task j**	**1**	**2**	**4**	**8**	**IP of Task j**
1	16	16	16	16	-	27	10	12	13	10	23,24
2	30	30	30	30	-	28	24	26	28	22	23,24
3	5	9	10	7	2	29		22	22	22	27,28
4	45	49	50	47	3	30	29	29	29	29	-
5	25	33	35	29	1,3	31	30	20	18	24	29
6	8	8	7	10	1,3	32	20				-
7	38	40	40	40	1,3	33	14	14	12	18	-
8	35	39	40	37	1,4	34	41	41	39	45	32
9	30	34	33	36	6	35	42	42	44	38	33
10	26	32	33	30	8	36	47	47	47	47	34,35
11	15	19	20	17	-	37	7	7	7	7	36
12	11	11	11	11	11	38	80	80	80	80	37
13	34	30	30	30	12	39	5	9	10	7	38
14	15	15	15	15	9,10	40	40	42	44	38	39
15	50	56	58	52	14	41	45	49	50	47	40
16	50	56	58	52	14	42	10	22	23	20	-
17	10	6	5	8	15,16	43	32	32	32	32	42
18	22	26	28	22	17	44	60	72	70	76	43
19	22	26	28	22	17	45	82	78	79	76	37
20	8	8	8	8	18,19	46	7	7	7	7	45
21	7	7	7	7	20	47	40	42	42	42	46
22	10	6	5	8	20	48	10	16	18	12	40,47
23	15	13	11	17	20	49	50	44	46	40	47
24	15	11	10	13	20	50	30	36	35	38	-
25	10	10	10	10	23,24	51	36	32	30	36	50
26	30	20	20	20	23,24	52	11	11	11	11	-

Table A.6 Continued

	Task Times						Task Times				
Task j	**1**	**2**	**4**	**8**	**IP of Task j**	**Task j**	**1**	**2**	**4**	**8**	**IP of Task j**
53	118	118	118	118	51,52	99	45	57	60	51	65
54	20	30	32	26	40,47	100	39	39	39	39	99
55		14	14	14	54	101	40	20	18	24	95,98
56	26	30	30	30	-	102	21	31	32	29	101
57		24	24	24	-	103	13	13	13	13	101
58	52	52	50	56	-	104	40	50	50	50	96
59	28				-	105	60	56	60	48	91
60	3	3	3	3	-	106	25	31	32	29	84
61	3	3	3	3	-	107	8	8	8	8	106
62	16				61	108	383	383	383	383	107
63	16	16	18	12	62	109	45	35	30	45	108
64	30	36	38	32	-	110	35	33	30	39	109
65	6	10	10	10	64	111	20	26	30	18	90
66	20	16	20	8	65	112	150	174	180	162	111
67	10	10	10	10	63,66	113	11	11	11	11	112
68	10	18	20	14	67	114	10	28	30	24	113
69	30	26	24	30	51	115	10	18	20	14	114
70	11	11	11	11	-	116	31	31	31	31	113
71	116	120	120	120	64,70	117	30	34	34	34	116
72	20	30	31	28	54,64	118	30	22	22	22	117
73	40	40	40	40	56	119	65	45	40	55	105
74	40	40	40	40	-	120	31	31	31	31	113
75	96	106	110	92	59,74	121	30	34	34	34	120
76	10				54	122	30	22	20	26	121
77	32	24	22	28	76	123	19	19	19	19	113
78	10	6	5	8	77	124	7	21	22	19	123
79	281	281	281	281	69	125	19	19	19	19	115,124
80	14				79	126	40	56	60	48	118,122
81	22	30	32	26	80	127	60	50	50	50	102,103
82	10	10	10	10	78,81	128	16				113
83	16	26	27	24	82	129	11	11	11	11	128
84	30	22	20	26	83	130	27	27	27	27	129
85	20	20	20	20	79	131	16	20	21	18	130
86	20	22	22	22	58,73	132	32	40	39	42	-
87	42	52	50	56	86	133	25	21	20	23	55
88	20	26	27	24	58,73	134	20	20	20	20	72
89	10	16	18	12	59,73	135	50	42	40	46	133,134
90	19	19	19	19	73,75	136	64	64	64	64	135
91	99	131	135	123	-	137	20	24	22	28	130
92	40	30	26	38	-	138	10	20	20	20	-
93	26	26	26	26	-	139	39	29	30	27	138
94	45	47	49	43	-	140	24	20	20	20	139
95	10	30	31	28	68	141	121	181	190	163	-
96	31	31	31	31	73	142	150	146	150	138	141
97	19	19	19	19	75	143	71	57	50	71	79,142
98	30	38	40	34	68	144	170	170	170	170	-

Table A.6 Continued

	Task Times						Task Times				
Task j	**1**	**2**	**4**	**8**	**IP of Task j**	**Task j**	**1**	**2**	**4**	**8**	**IP of Task j**
145	150	124	120	132	144	147	78	78	78	78	142,145
146	60	68	70	64	79,142	148	78	78	78	78	142,145

APPENDIX B

DETAILS OF SOLUTIONS OBTAINED WITH MATHEMATICAL MODELS

Case Study Results

Table B.1 Task assignments according to SALBPia approach

Model	Station	Assigned Tasks
Model#1	1	1 2 3 4 6 7 8 10 11 12 13 14 15 16 17 18 19 20 21 22 23 32 39 45 46 48 104
	2	24 25 26 27 28 29 30 33 34 35 36 37 40 41 42 43 44 49 50 54 260
	3	51 52 53 55 56 57 58 59 60 61 62 63 64 65 66 67 72 73 74 75 76 77 78 79 80 81 82 83 221
	4	5 47 69 71 84 85 86 87 88 89 91 92 93 94
	5	38 90 95 96 97 98 99 100 101 102 103 105 108 109 110
	6	9 68 70 106 107
Model#2	1	1 2 3 4 5 6 7 8 9 10 11 13 14 15 16 18 104 111 112 113 114 115
	2	17 19 20 21 22 23 24 25 27 39 40 45 46 47 48 122 123 124 125 140
	3	26 28 29 30 34 35 36 37 41 42 116 117 118 119 120 121 126 127 128 129 130 260
	4	50 51 52 53 54 55 60 61 62 63 64 72 73 74 131 132 133 134 135 136 137 138 139 141
	5	65 66 67 68 69 71 75 76 77 78 79 80 81 82 83 84 85 86 144 221
	6	87 88 89 90 91 92 93 94 95 96 99 100 145 146 147
	7	97 98 101 102 103 106 107 108 109 110 148
Model#4	1	1 2 3 5 6 7 8 10 13 14 104 150 151 152 153 154 155 156
	2	12 15 16 17 157 158 159 160 161 162 163 164 165 197
	3	18 19 22 45 46 47 48 166 167 168 172 185 186 187 198 199 200 201
	4	23 26 27 28 29 30 34 35 36 37 41 42 49 116 117 170 171 173 174 260
	5	118 119 175 176 177 178 179 180 188 189 190 191 192
	6	54 55 61 134 182 183 193 194 195 196
	7	62 63 65 66 67 72 73 74 184 202 203 204 205 206 207 209 213 214 216
	8	76 212 215 217 219
	9	75 78 79 80 81 82 83 84 220 221
	10	85 86 87 88 89 90 91 92 94 147 224 225 226 229
	11	95 100 101 103 227 228 230 232
	12	107 235 237 238 240
Model#8	1	1 2 3 5 6 7 8 10 13 14 104 150 155 241 250 251 252
	2	15 16 17 113 158 159 242 243 244 245 246 247 248 249
	3	18 19 160 161 197 198 199 200 253 254 255
	4	22 23 26 27 28 29 30 42 171 172 173 174 201 257 258 259 260 265
	5	189 261 262 263 264 266 267 268 269 270 271
	6	50 272 273 274 275 276 277 278 279 280 281 282
	7	51 52 53 61 62 63 66 67 69 72 73 74 204 207 283

Table B.1 Continued

Model	Station	Assigned Tasks
Model#8	8	75 76 78 79 80 217 221 285 286
	9	83 84 85 87 88 89 90 288
	10	91 92 94 95 99 100 225 226 227 289 290 291
	11	101 235 292 293 294 295 296

Table B.2 Task assignments according to SALBPja approach

Model	Station	Assigned Tasks
Joint	1	1 2 3 4 5 6 8 9 13 14 104 111 150 151 152 241 250 251
	2	7 10 11 12 32 112 114 153 154 155 156 157 162 242 245 246 252
	3	15 16 17 113 115 158 159 160 163 243 244 247 248
	4	161 164 165 166 167 197 249 253 254 255
	5	18 19 20 21 22 24 39 45 46 47 48 122 123 168 185 186 187 198 199 200 201
	6	23 25 27 40 49 124 125 126 140 170 171 172 173 174 257
	7	26 28 29 30 33 34 35 36 37 38 41 42 43 44 116 117 120 121 127 258 260
	8	118 119 128 129 130 131 132 133 175 176 188 259 262 264 265
	9	56 177 178 179 189 191 192 261 263 266 268
	10	54 55 134 135 136 137 138 139 180 182 190 193
	11	141 183 194 195 196 267 269 270 271 272 273 274 275 276 277 278
	12	50 51 52 53 57 58 59 60 61 279 280 281 282 283
	13	62 63 64 65 66 67 69 71 72 73 74 184 202 203 204 205 206 207 209 213 214
	14	68 70 216 217 285 286
	15	75 76 77 78 79 80 81 82 212 215 219 220 221
	16	83 84 85 86 87 88 89 144 145 146 288
	17	90 91 92 93 94 147 224 225 226 227 228 229 289
	18	95 96 98 99 100 101 102 148 230 232 290 291 292 293
	19	97 103 105 106 107 108 109 110 235 237 238
	20	240 294 295 296
Model#1	1	1 2 3 4 5 6 8 9 13 14 104
	2	7 10 11 12 32
	3	15 16 17
	4	
	5	18 19 20 21 22 24 39 45 46 47 48
	6	23 25 27 40 49
	7	26 28 29 30 33 34 35 36 37 38 41 42 43 44 260
	8	
	9	56
	10	54 55
	11	
	12	50 51 52 53 57 58 59 60 61
	13	62 63 64 65 66 67 69 71 72 73 74
	14	68 70
	15	75 76 77 78 79 80 81 82 221
	16	83 84 85 86 87 88 89
	17	90 91 92 93 94
	18	95 96 98 99 100 101 102
	19	97 103 105 106 107 108 109 110
	20	1 2 3 4 5 6 8 9 13 14 104
Model#2	1	1 2 3 4 5 6 8 9 13 14 104 111
	2	7 10 11 112 114

Table B.2 Continued

Model	Station	Assigned Tasks
Model#2	3	15 16 17 113 115
	4	
	5	18 19 20 21 22 24 39 45 46 47 48 122 123
	6	23 25 27 40 124 125 126 140
	7	26 28 29 30 34 35 36 37 41 42 116 117 120 121 127 260
	8	118 119 128 129 130 131 132 133
	9	
	10	54 55 134 135 136 137 138 139
	11	141
	12	50 51 52 53 60 61
	13	62 63 64 65 66 67 69 71 72 73 74
	14	68
	15	75 76 77 78 79 80 81 82 221
	16	83 84 85 86 87 88 89 144 145 146
	17	90 91 92 93 94 147
	18	95 96 98 99 100 101 102 148
	19	97 103 106 107 108 109 110
	20	1 2 3 4 5 6 8 9 13 14 104 111
Model#4	1	1 2 3 5 6 8 13 14 104 150 151 152
	2	7 10 12 153 154 155 156 157 162
	3	15 16 17 158 159 160 163
	4	161 164 165 166 167 197
	5	18 19 22 45 46 47 48 168 185 186 187 198 199 200 201
	6	23 27 49 170 171 172 173 174
	7	26 28 29 30 34 35 36 37 41 42 116 117 260
	8	118 119 175 176 188
	9	177 178 179 189 191 192
	10	54 55 134 180 182 190 193
	11	183 194 195 196
	12	61
	13	62 63 65 66 67 72 73 74 184 202 203 204 205 206 207 209 213 214
	14	216 217
	15	75 76 78 79 80 81 82 212 215 219 220 221
	16	83 84 85 86 87 88 89
	17	90 91 92 94 147 224 225 226 227 228 229
	18	95 100 101 230 232
	19	103 107 235 237 238
	20	240
Model#8	1	1 2 3 5 6 8 13 14 104 150 241 250 251
	2	7 10 155 242 245 246 252
	3	15 16 17 113 158 159 160 243 244 247 248
	4	161 197 249 253 254 255
	5	18 19 22 198 199 200 201
	6	23 27 171 172 173 174 257
	7	26 28 29 30 42 258 260
	8	259 262 264 265
	9	189 261 263 266 268
	10	
	11	267 269 270 271 272 273 274 275 276 277 278
	12	50 51 52 53 61 279 280 281 282 283

Table B.2 Continued

Model	Station	Assigned Tasks
Model#8	13	62 63 66 67 69 72 73 74 204 207
	14	217 285 286
	15	75 76 78 79 80 221
	16	83 84 85 87 88 89 288
	17	90 91 92 94 225 226 227 289
	18	95 99 100 101 290 291 292 293
	19	235
	20	294 295 296

Table B.3 Task assignments according to MALBPnw approach

Model	Station	Assigned Tasks
Model#1	1	1 2 3 4 7 8 10 11 12 14 15 16 17 18 19 20 21 22 23 24 25 32 38 39 45 48 104
	2	6 13 26 27 28 29 30 33 34 35 36 37 40 41 42 43 44 49 50 54 56 260
	3	46 51 52 53 55 57 58 59 60 61 62 63 64 65 66 67 71 72 73 74 75 76 77 78 79 80 81 82 221
	4	69 83 84 85 86 87 88 89 91 92 93 94 95 96
	5	5 9 47 70 97 98 99 101 102 103 105 108 109 110
	6	68 90 100 106 107
Model#2	1	1 2 3 4 5 6 7 8 9 10 11 13 14 15 16 18 104 111 112 113 114 115
	2	17 19 20 21 22 23 24 25 27 39 40 45 46 47 48 122 123 124 125 140
	3	26 28 29 30 34 35 36 37 41 42 116 117 118 119 120 121 126 127 128 129 130 260
	4	50 51 52 53 54 55 60 61 62 63 64 72 73 74 131 132 133 134 135 136 137 138 139 141
	5	65 66 67 68 69 71 75 76 77 78 79 80 81 82 83 84 85 86 144 221
	6	87 88 89 90 91 92 93 94 95 96 99 101 145 146 147
	7	97 98 100 102 103 106 107 108 109 110 148
Model#4	1	1 2 3 5 6 7 8 10 13 14 104 150 151 152 153 154 155 156
	2	12 15 16 17 157 158 159 160 161 162 163 164 165 197
	3	18 19 22 45 46 47 48 166 167 168 172 185 186 187 198 199 200 201
	4	23 26 27 28 29 30 34 35 36 37 41 42 49 116 117 170 171 173 174 260
	5	118 119 175 176 177 178 179 180 188 189 190 191 192
	6	54 55 61 134 182 183 193 194 195 202
	7	62 63 65 66 67 72 73 74 184 196 203 204 205 206 207 209 213 214 216
	8	76 212 215 217 219
	9	75 78 79 80 81 82 83 84 220 221
	10	85 86 87 88 89 90 91 92 94 147 224 225 226 229
	11	95 100 101 103 227 228 230 232
	12	107 235 237 238 240
Model#8	1	1 2 3 5 6 7 8 10 13 14 104 150 241 242 245 248 250 251
	2	15 16 17 113 155 158 159 243 244 246 247 249 252
	3	18 160 161 197 198 199 200 201 253 254 255
	4	19 22 23 26 27 28 29 30 42 171 172 173 174 257 258 259 260 262
	5	189 261 263 264 265 266 267 268 269 270 271
	6	50 272 273 274 275 276 277 278 279 280 281 282
	7	51 52 53 61 62 63 66 67 69 72 73 74 204 207 283
	8	75 76 78 79 80 217 221 285 286
	9	83 84 85 87 88 89 90 288

Table B.3 Continued

Model	Station	Assigned Tasks
Model#8	10	91 92 94 95 99 100 225 226 227 289 290 291
	11	101 235 292 293 294 295 296

Table B.4 Task assignments according to MALBPwo approach

Model	Station	Assigned Tasks
Model#1	1	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 18 32 104
	2	17 19 20 21 22 23 24 25 27 38 39 40 45 46 47 48 49
	3	26 28 29 30 33 34 35 36 37 41 42 43 44 56 260
	4	50 51 52 53 54 55 57 58 59 60 61 62 63 64 70 72 73 74
	5	65 66 67 68 69 71 75 76 77 78 79 80 81 82 83 84 85 86 221
	6	87 88 89 90 91 92 93 94 95 96 99 101 105
Model#2	1	1 2 3 4 5 6 7 8 9 10 11 13 14 15 16 18 104 111 112 113 114 115
	2	17 19 20 21 22 23 24 25 27 39 40 45 46 47 48 122 123 124 125 140
	3	26 28 29 30 34 35 36 37 41 42 116 117 118 119 120 121 126 127 128 129 130 260
	4	50 51 52 53 54 55 60 61 62 63 64 72 73 74 131 132 133 134 135 136 137 138 139 141
	5	65 66 67 68 69 71 75 76 77 78 79 80 81 82 83 84 85 86 144 221
	6	87 88 89 90 91 92 93 94 95 96 99 101 145 146 147
	7	97 98 100 102 103 106 107 108 109 110 148
Model#4	1	1 2 3 5 6 7 8 10 13 14 104 150 151 152 153 154 155 156
	2	12 15 16 157 158 159 160 162 163 164
	3	17 18 19 45 161 165 166 167 168 185 197 198 199 200
	4	22 23 26 27 28 29 30 41 42 46 47 48 49 170 171 172 173 174 186 187 201 260
	5	34 35 36 37 116 117 118 119 175 176 177 178 188 189 190 192
	6	54 55 134 179 180 182 183 191 193 195
	7	61 62 63 72 73 74 184 194 196 202 203 204 205 207
	8	65 66 67 206 209 212 213 215 217
	9	75 76 78 79 80 81 82 83 84 214 216 219 220 221
	10	85 86 87 88 89 90 91 92 94 147 224 225 226 227
	11	95 100 101 228 229 230 232
	12	103 107 235 237 238 240
Model#8	1	1 2 3 5 6 7 8 10 13 14 104 150 155 241 245 250 251
	2	15 16 113 158 159 160 242 243 244 246 247 248 252
	3	17 18 19 161 197 198 199 200 249 253 254 255
	4	22 23 26 27 28 29 30 42 171 172 173 174 201 257 258 259 260 262
	5	189 261 263 264 265 266 267 268 269 270 271
	6	50 272 273 274 275 276 277 278 279 280 281 282
	7	51 52 53 61 62 63 69 72 73 74 204 207 283 285
	8	66 67 217 286
	9	75 76 78 79 80 83 84 221
	10	85 87 88 89 90 91 92 94 225 226 227 288 289
	11	95 99 100 101 290 291 292 293 295 296

*Because of the size of the results, just the final Kmax steps of respective approaches are represented. The results gathered through weight analyses are given at CD as Appendix B.

Test Bed Results

Table B.5 Task assignments according to approaches for Bowman's data set

Solution Approach	Station	Model1	Model2	Model4	Model8	Model9	Joint
MALBPwo	1	1 2 4	1 2 3	1 2 4	1 2 3	1 2 4	
	2	3 5 6 8	4 5 6 7	3 5 6 8	4 5 6 7	3 5 6 8	
	3	7	8	7	8	7	
SALBPja	1						1 2 4
	2						3 5 6 8
	3						7

Table B.6 Task assignments according to approaches for Rosenberg und Ziegler's data set

Solution Approach	Station	Model1	Model2	Model4	Model8	Joint
MALBPwo	1	1 2 3 4 5	1 2 3 4 8 9	1 2 3 4 8 9	1 2 3 4 5	
	2	6 7 12 15 17	5 6 7 10 11 13 14	5 6 7 10 11 13 14	6 7 12 15 17	
	3	8 9 10 11 13 14 16 23	12 15 19 20 21 22 24	12 15 16 19 20 21 22 24	8 9 10 11 13 14 23	
	4	19 20 21 22 24	16 17 18 23 25	17 18 23 25	16 19 20 21 22 24	
	5	18 25			18 25	
SALBPja	1					1 2 3 4
	2					5 6 8 9
	3					7 10 11 12 13 14 19
	4					15 16 20 21 22
	5					17 18 23 25
	6					24

Table B.7 Task assignments according to approaches for Kilbridge and Wester's data set

Approach	Model	Station	Assigned Tasks
MALBPwo	Model#1	1	1 2 3 7 8 12 14 29 30 31 32 37 39
		2	4 6 11 13 15 16 17 18 19 20 27 43
		3	10 23 33 34 35 41 42 44 45
		4	5 9 24 25 26 36
		5	21 22 28 38 40
	Model#2	1	11 12 13 15 16 18 19 23 33 34 37 43
		2	1 2 3 4 7 8 14 20 29 30 31 32 35 39
		3	5 6 10 17 36 41 42 44 45
		4	21 24 25 26 27
		5	9 22 28 38 40

Table B.7 Continued

Approach	Model	Station	Assigned Tasks
MALBPwo	Model#4	1	1 2 4 7 8 14 17 27 29 30 31 32 39
		2	3 6 10 11 12 13 37 41 42 44 45
		3	5 15 16 18 19 20 23 33 34 35 36
		4	9 24 25 26 43
		5	21 22 28 38 40
	Model#8	1	1 2 3 4 7 8 11 14 17 27 29 39
		2	6 10 12 13 15 18 32 37 41 42 43 44 45
		3	16 19 20 23 25 26 30 33 34 35
		4	5 21 22 28 38 40
		5	9 24 31 36
	Model#9	1	11 12 13 15 16 18 19 23 33 34 37 43
		2	1 2 7 8 14 17 20 27 29 30 31 32 35 39
		3	4 6 10 25 26 41 42 44 45
		4	21 22 28 36 38 40
		5	21 22 28 36 38 40
SALBPja	Joint	1	1 2 3 11 12 13 15 16 18 19 20 37 39 43
		2	4 6 7 8 14 17 27 29 30 31 32
		3	10 23 33 34 35 41 42 44
		4	5 9 24 25 26 36 45
		5	21 22 28 38 40

Table B.8 Task assignments according to approaches for Bartholdi's data set

Approach	Model	Station	Assigned Tasks
MALBPwo	Model#1	1	1 3 5 6 9 10 11 12 14 18 19 20 21 30 37 39 40 42 47 48 54 56 62 64 65 68 72 76 78 80 81 82 83 93 95 96 98 101 102 103 106 107
		2	2 13 22 23 24 25 26 27 28 31 33 46 50 52 58 59 60 61 63 66 67 69 70 73 74 84 85 86 88 89 97 133 134 138 139 140
		3	32 43 75 77 90 92 111 112 113 114 115 116 117 118 120 121 122 123 124 125 128 129 130 131 137
		4	4 7 8 15 16 17 35 41 44 49 51 87 94 99 100 104 126 132
		5	34 36 91 105 119 127 135 136 141 142
		6	38 53 71 144 145 147
		7	45 79 143 146 148
		8	108 109 110
	Model#2	1	2 13 22 23 24 25 26 27 28 29 31 33 43 46 52 55 57 60 61 63 66 67 69 73 77 78 81 82 84 85 89 92 129 130 131 133 134 137 138 139 140
		2	1 3 6 9 10 11 12 14 18 19 20 21 30 37 39 40 42 47 48 51 56 65 68 70 83 93 95 96 97 98 101 102 103 106 107
		3	4 5 7 8 15 16 17 34 35 49 50 54 58 64 72 74 86 88 132 135
		4	36 75 87 90 111 112 113 114 115 116 117 118 120 121 122 123 124 125 127
		5	38 41 44 45 53 94 99 100 104 126 136
		6	91 105 108 109 110 119
		7	71 141 142 144 145
		8	79 143 146 147 148

Table B.8 Continued

Approach	Model	Station	Assigned Tasks
MALBPwo	Model#4	1	2 9 10 12 13 14 21 22 23 24 25 26 27 28 29 30 31 33 37 46 52 55 56 57 60 61 65 69 70 77 84 85 92 93 96 97 129 130 131 133 134 137
		2	1 3 6 11 18 19 20 39 40 42 47 48 50 51 63 66 67 68 73 78 81 82 83 89 95 98 101 102 103 106 107 138 139 140
		3	4 5 7 8 15 16 17 34 35 43 49 54 58 64 72 74 86 88 132 135
		4	36 44 75 90 111 112 113 114 115 116 117 118 120 121 122 123 124 125
		5	38 41 87 91 94 99 100 104 105 119 126 127
		6	53 71 108 109 110 136
		7	45 141 142 144 145
		8	79 143 146 147 148
	Model#8	1	1 3 5 6 11 18 19 20 39 40 42 43 47 48 54 55 63 64 66 67 68 70 72 73 83 89 95 97 98 101 102 103 106 107 138 139 140
		2	2 9 10 12 13 14 21 22 23 24 25 26 27 28 30 31 33 37 46 52 56 58 60 61 65 69 74 78 81 82 84 85 86 88 93 96 133 134
		3	50 75 77 90 92 111 112 113 114 115 116 117 118 120 121 122 123 124 125 129 130 131 137
		4	4 7 8 15 16 17 29 35 41 49 51 57 94 99 100 104 126 127 132
		5	34 36 44 45 53 87 135 141 142
		6	38 91 105 119 136 144 145 147
		7	71 79 143 146 148
		8	108 109 110
SALBPja	Joint	1	1 3 6 9 10 11 12 14 18 19 20 21 22 23 24 25 27 30 33 37 39 42 46 52 56 60 61 63 65 66 67 68 70 78 81 82 83 85 93 97 106 107 133 134 138
		2	2 26 28 29 31 40 43 47 48 54 55 57 64 69 72 73 77 84 95 98 101 102 103 139 140
		3	59 74 75 76 80 89 90 96 111 112 113 114 115 116 120 123 124 125 128 129 130 131 137
		4	4 5 7 8 13 15 16 17 34 35 51 58 86 88 92 117 118 121 122 132
		5	36 41 44 49 50 62 87 94 99 100 104 126 127 135 136
		6	32 38 45 53 91 105 119 144
		7	71 141 142 145 147 148
		8	79 108 109 110
		9	143 146

Gams code of MALBPnw approach

$onecho > shinjiru.txt

par=p Rng=a1 Dim=2

par=pd Rng=a319 Dim=3

$offecho

Sets

J Set of operations /1*300/

K Set of stations /1*16/

M Set of models /1,2,4,8/

alias (j,i);

$CALL GDXXRW.EXE shinjiru.xlsx @shinjiru.txt

$GDXIN shinjiru.gdx

Parameters

p(j,m) Process time of job j for model m

pd(m,i,j) Precedence relationship

C Common cycle time /10/

Kmax Bucket station number /16/

G Big positive number /150/ ;

$LOAD p pd

$GDXIN

Variables

totaltime(k,m)	Total proccess time assigned at station k for model m
z	Objective function var.
X(j,k)	TC Index;

Integer variables

X(j,k);

Binary variables

Y(j,k,m)	Task boolean assignment indicator for every model and station;

Equations

Obj	Constructed to encourage to assign common operations at earlier stations
c1(j,m,k)	Tasks with zero processing time should not be assigned to any station
c2(j,m)	For every task j on model m can only be assigned only one station ove all stations only for the jobs has value that are greater than zero
c3(i,j,m)	This constraint constructed in order to satisfy precedence relationship in terms of stations
c4(j,k)	This constraint sums the assignment indicator over all models in order calculate TC Index
c5(j,k)	TC index should take the value of zero for the tasks have assigned to bucket station
c6(k,m)	This constraint sums the process time of job j's which are assigned to station k for evey model and assign the value to total time variable
c7(k,m)	Total time of each model at normal stations must not be great than cycle time

c8(k,m) Total time of each model at bucket station must not be great than a big number "G";

```
obj.. z =e=  sum((j,k), (X(j,k)-1)*(Kmax-ord(k)))  ;
c1(j,m,k)$(p(j,m)=0).. Y(j,k,m) =e= 0;
c2(j,m)$(p(j,m)>0).. sum((k),Y(j,k,m)) =e= 1;
c3(i,j,m)$(pd(m,i,j)=1 and p(j,m)>0 and p(i,m)>0)..  sum((k),ord(k)*Y(i,k,m)) =l=
sum((k),ord(k)*Y(j,k,m));
c4(j,k)$(ord(k)<Kmax).. sum((m),Y(j,k,m))  =e= X(j,k) ;
c5(j,k)$(ord(k)=Kmax)..  0 =e= X(j,k);
c6(k,m)..sum((j),Y(j,k,m)*p(j,m)) =e= totaltime(k,m)  ;
c7(k,m)$(ord(k)<Kmax).. totaltime(k,m) =l= C;
c8(k,m)$(ord(k)=Kmax).. totaltime(k,m) =l= G;
```

Model shinjiru /all/;

```
Option optcr=0;
Option optca=0;
Option reslim=10800;

Solve shinjiru using MIP max z;
display Y.l;
display totaltime.l;
display z.l;
execute_unload 'shinjiru.gdx', y,totaltime, z;
execute 'gdxxrw.exe shinjiru.gdx O=shinjiru.xlsx var=y.l rng=sayfa3!a1';
execute 'gdxxrw.exe shinjiru.gdx O=shinjiru.xlsx var=totaltime.l rng=sayfa3!u1 rdim
= 1 cdim = 1' ;
execute 'gdxxrw.exe shinjiru.gdx O=shinjiru.xlsx var=z.l rng=sayfa3!aa5';
```

Gams code of MALBPwo approach

$onecho > shinjiru.txt

par=p Rng=a1 Dim=2

par=pd Rng=a319 Dim=3

$offecho

Sets

J	Set of operations /1*300/
K	Set of stations /1*16/
M	Set of models /1,2,4,8/

alias (j,i);

$CALL GDXXRW.EXE shinjiru.xlsx @shinjiru.txt

$GDXIN shinjiru.gdx

Parameters

p(j,m)	Process time of job j for model m
pd(m,i,j)	Precedence relationship
C	Common cycle time /10/
Kmax	Bucket station number /16/
G	Big positive number /150/ ;

$LOAD p pd

$GDXIN

Variables

totaltime(k,m)	Total process time assigned at station k for model m
z	Objective function var.
X(j,k)	TC Index
Xc(j,k)	Boolean TCI indicator;

Integer variables

X(j,k);

Binary variables

Y(j,k,m)	Task boolean assignment indicator for every model and station
Xc(j,k)	Boolean TCI indicator;

Equations

Obj	Constructed to encourage to assign common operations at earlier stations
c1(j,m,k)	Tasks with zero processing time should not be assigned to any station
c2(j,m)	For every task j on model m can only be assigned only one station over all stations only for the jobs has value that are greater than zero
c3(i,j,m)	This constraint constructed in order to satisfy precedence relationship in terms of stations
c4(j,k)	This constraint sums the assignment indicator over all models in order calculate TC Index
c5(j,k)	TC index should take the value of zero for the tasks have assigned to bucket station
c6(j,k)	This constraints assign the value of one if TC index is greater than one
c7(k,m)	This constraint sums the process time of job j's which are assigned to station k
c8(k,m)	Total time of each model at normal stations must not be great than cycle time for every model and assign the value to total time variable
c9(k,m)	Total time of each model at bucket station must not be great than a big number "G";

```
obj.. z =e= 1.5*sum((j,k),xc(j,k)*(Kmax-ord(k)))+ sum((j,k), (X(j,k)-1)*(Kmax-ord(k)));
c1(j,m,k)$(p(j,m)=0).. Y(j,k,m) =e= 0;
c2(j,m)$(p(j,m)>0).. sum((k),Y(j,k,m)) =e= 1;
c3(i,j,m)$(pd(m,i,j)=1 and p(j,m)>0 and p(i,m)>0).. sum((k),ord(k)*Y(i,k,m)) =l= sum((k),ord(k)*Y(j,k,m));
c4(j,k)$(ord(k)<Kmax).. sum((m),Y(j,k,m)) =e= X(j,k) ;
c5(j,k)$(ord(k)=Kmax).. 0 =e= X(j,k);
c6(j,k)..X(j,k) =g= 2*Xc(j,k);
c7(k,m).. sum((j),Y(j,k,m)*p(j,m)) =e= totaltime(k,m);
c8(k,m)$(ord(k)<Kmax).. totaltime(k,m) =l= C;
c9(k,m)$(ord(k)=Kmax).. totaltime(k,m) =l= G;
```

Model shinjiru /all/;

```
Option optcr=0;
Option optca=0;
Option reslim=10800;

Solve shinjiru using MIP max z;
display Y.l;
display totaltime.l;
display z.l;
execute_unload 'shinjiru.gdx', y,totaltime, z;
execute 'gdxxrw.exe shinjiru.gdx O=shinjiru.xlsx var=y.l rng=sayfa3!a1';
execute 'gdxxrw.exe shinjiru.gdx O=shinjiru.xlsx var=totaltime.l rng=sayfa3!u1 rdim = 1 cdim = 1' ;
execute 'gdxxrw.exe shinjiru.gdx O=shinjiru.xlsx var=z.l rng=sayfa3!aa5';
```

Gams code of SALBPja and SALBPia approach

$onecho > kir.txt

par=p Rng=a2:b301 rDim=1

par=pd Rng=b319 Dim=2

set=o Rng=a625 rdim=1

set=oprime Rng=e625 rdim=1

par=akar Rng=s2:t301 Rdim=1

$offecho

$CALL GDXXRW.EXE kirca.xlsx @kir.txt

$GDXIN kirca.gdx

Sets

J	Set of operations /1*300/
K	Set of stations /1*16/
o(*)	Set of common operations
oprime(*)	Set of non-common operations

alias (j,i);

$LOAD o oprime

$GDXIN

$CALL GDXXRW.EXE kirca.xlsx @kir.txt

$GDXIN kirca.gdx

Parameters

p(j)	Process time of job j for model m
pd(i,j)	Precedence relationship
akar(j)	Cardinality of common models for operation j
C	Common cycle time /10/

Kmax	Bucket station number /16/
G	Big positive number /200/ ;
$LOAD p pd akar	
$GDXIN	

Variables

totaltime(k)	Total process time assigned at station k for model m
z	Objective function var. ;

Binary variables

Y(j,k)	Task boolean assignment indicator for every model and station;

Equations

Obj	Constructed to encourage to assign common operations at the earlier stations
c1(j,k)	Tasks with zero processing time should not be assigned to any station
c3(j)	For every task j on model m can only be assigned only one station over all stations only for the jobs has value that are greater than zero
c4(i,j)	This constraint constructed in order to satisfy precedence relationship in terms of stations
c5(k)	This constraint sums the process time of job j's which are assigned to station k for every model and assign the value to total time variable
c6(k)	Total time of each model at normal stations must not be great than cycle time

c7(k) Total time of each model at bucket station must not be great than a big number "G";

obj.. z =e= sum((o(j),k)$(ord(k)<Kmax),(Kmax-ord(k))*akar(j)*y(j,k)) +
sum((oprime(j),k)$(ord(k)<Kmax),(Kmax-ord(k))*y(j,k)) ;
c1(j,k)$(p(j)=0).. Y(j,k) =e= 0;
c3(j)$(p(j)>0).. sum((k),Y(j,k)) =e= 1;
c4(i,j)$(pd(i,j)=1 and p(j)>0 and p(i)>0).. sum((k),ord(k)*Y(i,k)) =l= sum((k),ord(k)*Y(j,k));
c5(k).. sum((j),Y(j,k)*p(j)) =e= totaltime(k) ;
c6(k)$(ord(k)<Kmax).. totaltime(k) =l= C;
c7(k)$(ord(k)=Kmax).. totaltime(k) =l= G;

Model shinjiru /all/;
Option optcr=0;
Option optca=0;
Option reslim=10800;

Solve shinjiru using MIP max z;
display Y.l;
display totaltime.l;
display z.l;
execute_unload 'kirca.gdx', y,totaltime,z;
execute 'gdxxrw.exe kirca.gdx O=kirca.xlsx var=y.l rng=sayfa3!a1';
execute 'gdxxrw.exe kirca.gdx O=kirca.xlsx var=totaltime.l rng=ttltime!a1' ;
execute 'gdxxrw.exe kirca.gdx O=kirca.xlsx var=z.l rng=sayfa3!aa1';

APPENDIX C

PROBLEM DATA USED AT SIMULATION MODELLING

Input Analyze

```
       Distribution Summary

Distribution:   Beta
Expression:     0.999 + 838 * BETA(0.383, 5.12)
Square Error:   0.000826

Chi Square Test
  Number of intervals   = 19
  Degrees of freedom    = 16
  Test Statistic        = 35.6
  Corresponding p-value < 0.005

Kolmogorov-Smirnov Test
  Test Statistic        = 0.0633
  Corresponding p-value < 0.01

       Data Summary

Number of Data Points   = 2719
Min Data Value          = 1
Max Data Value          = 839
Sample Mean             = 59.3
Sample Std Dev          = 83.6

       Histogram Summary

Histogram Range         = 0.999 to 839
Number of Intervals     = 40
```

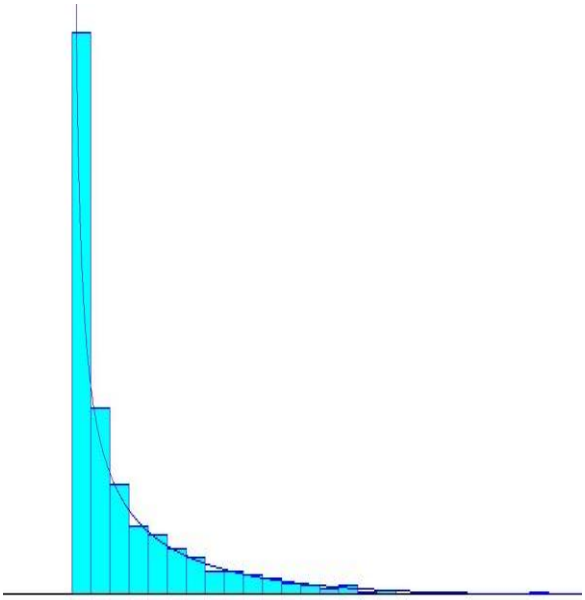


Figure C.1 Outputs of input analyze for interarrival time

```
        Distribution Summary

Distribution:   Exponential
Expression:     0.999 + EXPO(3.23)
Square Error:   0.000339

Chi Square Test
  Number of intervals   = 2
  Degrees of freedom    = 0
  Test Statistic        = 128
  Corresponding p-value < 0.005

Kolmogorov-Smirnov Test
  Test Statistic        = 0.0999
  Corresponding p-value < 0.01

        Data Summary

Number of Data Points   = 2719
Min Data Value          = 1
Max Data Value          = 645
Sample Mean             = 4.23
Sample Std Dev          = 13.8

        Histogram Summary

Histogram Range         = 0.999 to 645
Number of Intervals     = 40
```

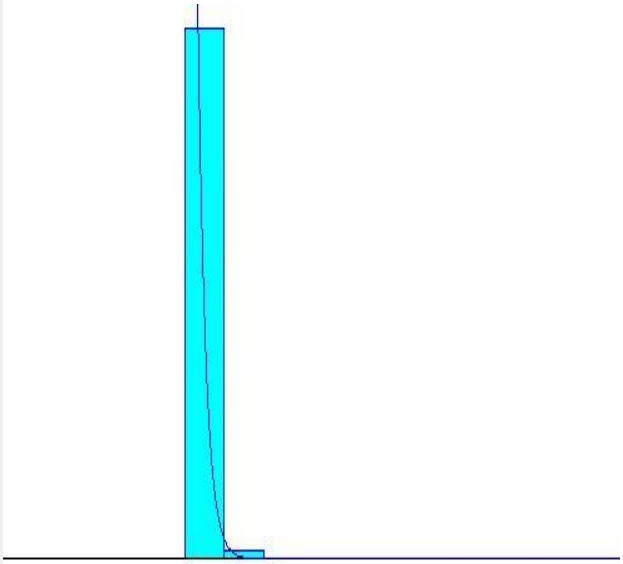


Figure C.2 Outputs of input analyze for order size (Best Fit)

```
        Distribution Summary

Distribution:   Gamma
Expression:     0.999 + GAMM(8.76, 0.369)
Square Error:   0.121783

Chi Square Test
  Number of intervals   = 3
  Degrees of freedom    = 0
  Test Statistic        = 560
  Corresponding p-value < 0.005

Kolmogorov-Smirnov Test
  Test Statistic        = 0.937
  Corresponding p-value < 0.01

        Data Summary

Number of Data Points   = 2719
Min Data Value          = 1
Max Data Value          = 645
Sample Mean             = 4.23
Sample Std Dev          = 13.8

        Histogram Summary

Histogram Range         = 0.999 to 645
Number of Intervals     = 40
```

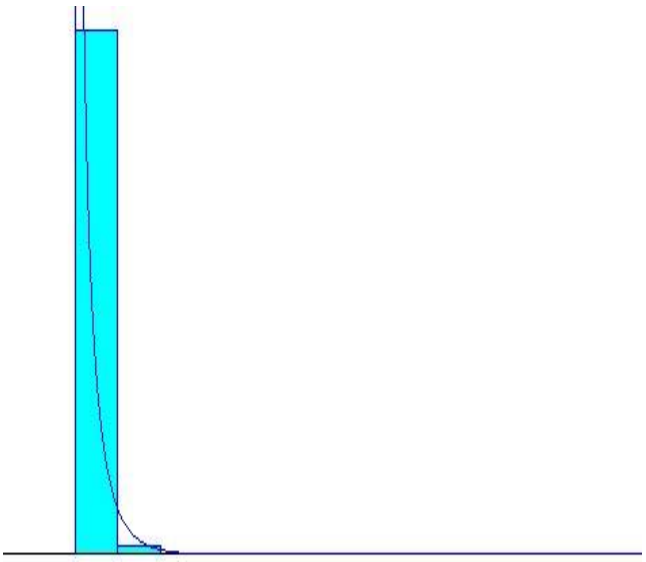


Figure C.3 Outputs of input analyze for order size (Second Best Fit)

*Because of the size of the details, the data tables are given at CD as Appendix C.

*The arena models are given at CD as Appendix C.

APPENDIX D

DETAILS OF SOLUTIONS OBTAINED WITH SIMULATION MODEL

Descriptive Statistics of Simulation Performance Measures

Table D.1 Descriptive statistics of weighted average lead-time

					95% Confidence Interval for Mean			
ID	**N**	**Mean**	**Std. Deviation**	**Std. Error**	**Lower Bound**	**Upper Bound**	**Minimum**	**Maximum**
1	39	238.01	14.63	2.34	233.27	242.76	207.19	271.22
2	154	168.60	14.08	1.13	166.36	170.84	137.23	220.02
3	30	297.89	22.87	4.18	289.35	306.43	243.28	362.06
4	71	226.66	25.49	3.03	220.63	232.70	173.40	319.79
5	16	142.75	1.85	0.46	141.76	143.74	138.79	146.43
6	17	112.73	1.80	0.44	111.80	113.66	108.79	116.48
7	11	160.63	4.57	1.38	157.56	163.70	152.01	166.52
8	86	129.08	3.71	0.40	128.29	129.88	121.19	137.14
9	3,623	1,177.39	571.41	9.49	1,158.78	1,196.00	457.06	6,288.04
10	4,407	1,070.03	576.99	8.69	1,052.99	1,087.07	328.67	6,155.93
11	1,239	1,786.93	1,028.04	29.21	1,729.63	1,844.23	512.20	8,122.05
12	1,239	1,676.40	1,022.45	29.05	1,619.41	1,733.39	407.58	7,951.87
13	22	317.96	14.97	3.19	311.32	324.60	287.20	351.24
14	22	168.25	15.04	3.21	161.59	174.92	137.46	201.78
15	19	381.26	26.68	6.12	368.40	394.12	323.31	442.13
16	22	226.23	25.25	5.38	215.04	237.43	170.93	287.78

Table D.2 Descriptive statistics of WIP level

					95% Confidence Interval			
ID	**N**	**Mean**	**Std. Deviation**	**Std. Error**	**Lower Bound**	**Upper Bound**	**Minimum**	**Maximum**
2	154	55.76	1.32	0.11	55.55	55.96	51.71	58.60
4	71	65.30	1.96	0.23	64.83	65.76	58.03	68.97
6	17	84.96	0.40	0.10	84.76	85.17	84.18	85.67
8	86	94.99	0.54	0.06	94.87	95.10	93.21	96.05
10	4407	22.61	4.99	0.08	22.46	22.76	4.97	36.37
12	1295	47.66	12.54	0.35	46.98	48.35	9.74	76.53
14	73	72.71	1.69	0.20	72.31	73.10	68.04	76.11
16	66	70.29	1.99	0.24	69.80	70.78	66.10	74.31

Table D.3 Descriptive statistics of throughput level

					95% Confidence Interval			
ID	**N**	**Mean**	**Std. Deviation**	**Std. Error**	**Lower Bound**	**Upper Bound**	**Minimum**	**Maximum**
1	39	9,019.15	348.80	55.85	8,906.09	9,132.22	8,227.00	9,838.00
2	154	8,991.86	326.48	26.31	8,939.88	9,043.83	8,238.00	9,849.00
3	30	9,074.00	319.38	58.31	8,954.74	9,193.26	8,585.00	9,781.00
4	71	9,084.27	338.25	40.14	9,004.20	9,164.33	8,218.00	9,976.00
5	16	9,039.50	414.33	103.58	8,818.72	9,260.28	8,237.00	9,845.00
6	17	9,046.88	401.45	97.37	8,840.48	9,253.29	8,242.00	9,855.00
7	11	9,158.45	425.14	128.18	8,872.84	9,444.07	8,600.00	9,781.00
8	86	9,077.14	331.19	35.71	9,006.13	9,148.15	8,218.00	9,983.00
9	3623	8,893.08	253.89	4.22	8,884.81	8,901.35	8,068.00	9,497.00
10	4407	8,901.51	256.64	3.87	8,893.93	8,909.08	7,892.00	9,508.00
11	1239	8,941.35	297.12	8.44	8,924.79	8,957.91	7,731.00	9,497.00
12	1295	8,953.49	297.36	8.26	8,937.27	8,969.70	7,737.00	9,508.00
13	22	9,039.23	360.46	76.85	8,879.41	9,199.05	8,219.00	9,830.00
14	73	8,986.93	357.38	41.83	8,903.55	9,070.31	8,238.00	9,849.00
15	19	9,121.42	347.17	79.65	8,954.09	9,288.75	8,580.00	9,773.00
16	66	9,069.26	305.12	37.56	8,994.25	9,144.27	8,298.00	9,851.00

Table D.4 Tamhane post-hoc test results of average weighted lead-time

Scenario					95% Confidence Interval	
(I)	**(J)**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**Upper Bound**	**Lower Bound**
1	2	69.41	2.60	-	59.67	79.15
1	3	-59.88	4.79	0.00	- 78.04	- 41.72
1	4	11.35	3.83	0.36	- 2.56	25.26
1	5	95.27	2.39	-	86.11	104.42
1	6	125.28	2.38	-	116.14	134.43
1	7	77.39	2.72	-	67.09	87.68
1	8	108.93	2.38	-	99.80	118.05
1	9	- 939.38	9.78	-	- 973.86	- 904.89
1	10	- 832.01	9.00	-	- 863.76	- 800.27
1	11	- 1,548.92	29.30	-	- 1,652.41	- 1,445.43
1	12	- 1,438.39	29.14	-	- 1,541.32	- 1,335.46
1	13	-79.94	3.96	-	- 95.06	- 64.82
1	14	69.76	3.97	-	54.59	84.93
1	15	- 143.25	6.55	-	- 170.11	- 116.38
1	16	11.78	5.87	1.00	- 11.55	35.11
2	1	-69.41	2.60	-	- 79.15	- 59.67
2	3	- 129.29	4.33	-	- 146.21	- 112.37
2	4	-58.06	3.23	-	- 69.88	- 46.24
2	5	25.86	1.23	-	21.45	30.26
2	6	55.87	1.22	-	51.50	60.25
2	7	7.97	1.79	0.01	0.82	15.13
2	8	39.52	1.20	-	35.20	43.83
2	9	-1,008.79	9.56	-	-1,042.49	-975.08
2	10	-901.42	8.77	-	-932.32	-870.52
2	11	-1,618.33	29.23	-	-1,721.57	-1,515.09
2	12	-1,507.80	29.07	-	-1,610.48	-1,405.12
2	13	-149.35	3.39	-	-162.98	-135.73
2	14	0.35	3.40	1.00	-13.33	14.03
2	15	-212.66	6.23	-	-239.08	-186.23
2	16	-57.63	5.50	0.00	-80.27	-35.00
3	1	59.88	4.79	0.00	41.72	78.04
3	2	129.29	4.33	-	112.37	146.21
3	4	71.23	5.16	-	52.01	90.45
3	5	155.14	4.20	-	138.49	171.80
3	6	185.16	4.20	-	168.52	201.81
3	7	137.26	4.40	-	120.13	154.40
3	8	168.81	4.19	-	152.17	185.45
3	9	-879.50	10.37	-	-916.17	-842.83
3	10	-772.14	9.64	-	-806.26	-738.01
3	11	-1,489.04	29.50	-	-1,593.24	-1,384.84
3	12	-1,378.51	29.35	-	-1,482.16	-1,274.86
3	13	-20.07	5.26	0.04	-39.92	-0.22
3	14	129.64	5.26	-	109.76	149.52
3	15	-83.37	7.41	0.00	-112.28	-54.46
3	16	71.66	6.81	0.00	45.63	97.68

D.4 Continued

Scenario					95% Confidence Interval	
(I)	**(J)**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**Upper Bound**	**Lower Bound**
4	1	-11.35	3.83	0.36	-25.26	2.56
4	2	58.06	3.23	-	46.24	69.88
4	3	-71.23	5.16	-	-90.45	-52.01
4	5	83.92	3.06	-	72.62	95.21
4	6	113.94	3.06	-	102.65	125.22
4	7	66.04	3.32	-	53.80	78.27
4	8	97.58	3.05	-	86.31	108.85
4	9	-950.72	9.96	-	-985.86	-915.59
4	10	-843.36	9.20	-	-875.82	-810.91
4	11	-1,560.27	29.36	-	-1,663.98	-1,456.56
4	12	-1,449.74	29.20	-	-1,552.89	-1,346.59
4	13	-91.29	4.40	-	-107.68	-74.91
4	14	58.41	4.41	-	41.98	74.84
4	15	-154.60	6.83	-	-181.94	-127.25
4	16	0.43	6.18	1.00	-23.58	24.44
5	1	-95.27	2.39	-	-104.42	-86.11
5	2	-25.86	1.23	-	-30.26	-21.45
5	3	-155.14	4.20	-	-171.80	-138.49
5	4	-83.92	3.06	-	-95.21	-72.62
5	6	30.02	0.64	-	27.50	32.54
5	7	-17.88	1.45	0.00	-24.82	-10.94
5	8	13.66	0.61	-	11.32	16.01
5	9	-1,034.64	9.50	-	-1,068.15	-1,001.13
5	10	-927.28	8.70	-	-957.96	-896.60
2	16	-57.63	5.50	0.00	-80.27	-35.00
5	11	-1,644.18	29.21	-	-1,747.36	-1,541.01
5	12	-1,533.65	29.05	-	-1,636.27	-1,431.04
5	13	-175.21	3.23	-	-188.58	-161.84
5	14	-25.51	3.24	0.00	-38.93	-12.08
5	15	-238.51	6.14	-	-264.87	-212.16
5	16	-83.49	5.40	0.00	-105.99	-60.98
6	1	-125.28	2.38	-	-134.43	-116.14
6	2	-55.87	1.22	-	-60.25	-51.50
6	3	-185.16	4.20	-	-201.81	-168.52
6	4	-113.94	3.06	-	-125.22	-102.65
6	5	-30.02	0.64	-	-32.54	-27.50
6	7	-47.90	1.45	0.00	-54.85	-40.95
6	8	-16.36	0.59	-	-18.60	-14.11
6	9	-1,064.66	9.50	-	-1,098.17	-1,031.15
6	10	-957.30	8.70	-	-987.98	-926.62
6	11	-1,674.20	29.21	-	-1,777.38	-1,571.03
6	12	-1,563.67	29.05	-	-1,666.28	-1,461.06
6	13	-205.23	3.22	-	-218.59	-191.86
6	14	-55.52	3.24	0.00	-68.95	-42.10
6	15	-268.53	6.14	-	-294.89	-242.18
6	16	-113.51	5.40	0.00	-136.01	-91.00
7	1	-77.39	2.72	-	-87.68	-67.09

D.4 Continued

Scenario					95% Confidence Interval	
(I)	**(J)**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**Upper Bound**	**Lower Bound**
7	2	-7.97	1.79	0.01	-15.13	-0.82
7	3	-137.26	4.40	-	-154.40	-120.13
7	4	-66.04	3.32	-	-78.27	-53.80
7	5	17.88	1.45	0.00	10.94	24.82
7	6	47.90	1.45	0.00	40.95	54.85
7	8	31.54	1.44	0.00	24.59	38.50
7	9	-1,016.76	9.59	-	-1,050.59	-982.93
7	10	-909.40	8.80	-	-940.43	-878.37
7	11	-1,626.30	29.24	-	-1,729.58	-1,523.03
7	12	-1,515.77	29.08	-	-1,618.49	-1,413.06
7	13	-157.33	3.48	-	-171.25	-143.41
7	14	-7.63	3.49	0.99	-21.59	6.34
7	15	-220.63	6.27	-	-247.13	-194.14
7	16	-65.61	5.56	0.00	-88.35	-42.86
8	1	-108.93	2.38	-	-118.05	-99.80
8	2	-39.52	1.20	-	-43.83	-35.20
8	3	-168.81	4.19	-	-185.45	-152.17
8	4	-97.58	3.05	-	-108.85	-86.31
8	5	-13.66	0.61	-	-16.01	-11.32
8	6	16.36	0.59	-	14.11	18.60
8	7	-31.54	1.44	0.00	-38.50	-24.59
8	9	-1,048.30	9.50	-	-1,081.81	-1,014.80
8	10	-940.94	8.70	-	-971.61	-910.27
8	11	-1,657.85	29.21	-	-1,761.02	-1,554.68
8	12	-1,547.32	29.05	-	-1,649.93	-1,444.71
8	13	-188.87	3.22	-	-202.23	-175.51
8	14	-39.17	3.23	0.00	-52.58	-25.75
8	15	-252.18	6.13	-	-278.53	-225.82
8	16	-97.15	5.40	0.00	-119.65	-74.65
9	1	939.38	9.78	-	904.89	973.86
9	2	1,008.79	9.56	-	975.08	1,042.49
9	3	879.50	10.37	-	842.83	916.17
9	4	950.72	9.96	-	915.59	985.86
9	5	1,034.64	9.50	-	1,001.13	1,068.15
9	6	1,064.66	9.50	-	1,031.15	1,098.17
9	7	1,016.76	9.59	-	982.93	1,050.59
9	8	1,048.30	9.50	-	1,014.80	1,081.81
9	10	107.36	12.87	-	62.00	152.72
9	11	-609.54	30.71	-	-717.96	-501.12
9	12	-499.01	30.56	-	-606.90	-391.12
9	13	859.43	10.02	-	824.07	894.80
9	14	1,009.14	10.02	-	973.75	1,044.52
9	15	796.13	11.30	-	755.67	836.59
9	16	951.15	10.91	-	912.32	989.99
10	1	832.01	9.00	-	800.27	863.76
10	2	901.42	8.77	-	870.52	932.32
10	3	772.14	9.64	-	738.01	806.26

D.4 Continued

Scenario					95% Confidence Interval	
(I)	(J)	Mean Difference (I-J)	Std. Error	Sig.	Upper Bound	Lower Bound
10	4	843.36	9.20	-	810.91	875.82
10	5	927.28	8.70	-	896.60	957.96
10	6	957.30	8.70	-	926.62	987.98
10	7	909.40	8.80	-	878.37	940.43
10	8	940.94	8.70	-	910.27	971.61
10	9	-107.36	12.87	-	-152.72	-62.00
10	11	-716.91	30.47	-	-824.49	-609.32
10	12	-606.37	30.32	-	-713.42	-499.32
10	13	752.07	9.26	-	719.36	784.78
10	14	901.77	9.26	-	869.05	934.50
10	15	688.77	10.63	-	650.52	727.01
10	16	843.79	10.22	-	807.31	880.27
11	1	1,548.92	29.30	-	1,445.43	1,652.41
11	2	1,618.33	29.23	-	1,515.09	1,721.57
11	3	1,489.04	29.50	-	1,384.84	1,593.24
11	4	1,560.27	29.36	-	1,456.56	1,663.98
11	5	1,644.18	29.21	-	1,541.01	1,747.36
11	6	1,674.20	29.21	-	1,571.03	1,777.38
11	7	1,626.30	29.24	-	1,523.03	1,729.58
11	8	1,657.85	29.21	-	1,554.68	1,761.02
11	9	609.54	30.71	-	501.12	717.96
11	10	716.91	30.47	-	609.32	824.49
11	12	110.53	41.19	0.59	-34.77	255.83
11	13	1,468.97	29.38	-	1,365.20	1,572.75
11	14	1,618.68	29.38	-	1,514.90	1,722.45
11	15	1,405.67	29.84	-	1,300.26	1,511.08
11	16	1,560.70	29.70	-	1,455.80	1,665.60
12	1	1,438.39	29.14	-	1,335.46	1,541.32
12	2	1,507.80	29.07	-	1,405.12	1,610.48
12	3	1,378.51	29.35	-	1,274.86	1,482.16
12	4	1,449.74	29.20	-	1,346.59	1,552.89
12	5	1,533.65	29.05	-	1,431.04	1,636.27
12	6	1,563.67	29.05	-	1,461.06	1,666.28
12	7	1,515.77	29.08	-	1,413.06	1,618.49
12	8	1,547.32	29.05	-	1,444.71	1,649.93
12	9	499.01	30.56	-	391.12	606.90
12	10	606.37	30.32	-	499.32	713.42
12	11	-110.53	41.19	0.59	-255.83	34.77
12	13	1,358.44	29.22	-	1,255.23	1,461.66
12	14	1,508.15	29.22	-	1,404.93	1,611.37
12	15	1,295.14	29.69	-	1,190.27	1,400.01
12	16	1,450.17	29.54	-	1,345.82	1,554.51
13	1	79.94	3.96	-	64.82	95.06
13	2	149.35	3.39	-	135.73	162.98
13	3	20.07	5.26	0.04	0.22	39.92
13	4	91.29	4.40	-	74.91	107.68
13	5	175.21	3.23	-	161.84	188.58

D.4 Continued

Scenario					95% Confidence Interval	
(I)	**(J)**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**Upper Bound**	**Lower Bound**
13	6	205.23	3.22	-	191.86	218.59
13	7	157.33	3.48	-	143.41	171.25
13	8	188.87	3.22	-	175.51	202.23
13	9	-859.43	10.02	-	-894.80	-824.07
13	10	-752.07	9.26	-	-784.78	-719.36
13	11	-1,468.97	29.38	-	-1,572.75	-1,365.20
13	12	-1,358.44	29.22	-	-1,461.66	-1,255.23
13	14	149.70	4.52	-	132.40	167.01
13	15	-63.30	6.90	0.00	-90.96	-35.65
13	16	91.72	6.26	0.00	67.30	116.14
14	1	-69.76	3.97	-	-84.93	-54.59
14	2	-0.35	3.40	1.00	-14.03	13.33
14	3	-129.64	5.26	-	-149.52	-109.76
14	4	-58.41	4.41	-	-74.84	-41.98
14	5	25.51	3.24	0.00	12.08	38.93
14	6	55.52	3.24	0.00	42.10	68.95
14	7	7.63	3.49	0.99	-6.34	21.59
14	8	39.17	3.23	0.00	25.75	52.58
14	9	-1,009.14	10.02	-	-1,044.52	-973.75
14	10	-901.77	9.26	-	-934.50	-869.05
14	11	-1,618.68	29.38	-	-1,722.45	-1,514.90
14	12	-1,508.15	29.22	-	-1,611.37	-1,404.93
14	13	-149.70	4.52	-	-167.01	-132.40
14	15	-213.01	6.91	-	-240.68	-185.34
14	16	-57.98	6.27	0.00	-82.42	-33.54
15	1	143.25	6.55	-	116.38	170.11
15	2	212.66	6.23	-	186.23	239.08
15	3	83.37	7.41	0.00	54.46	112.28
15	4	154.60	6.83	-	127.25	181.94
15	5	238.51	6.14	-	212.16	264.87
15	6	268.53	6.14	-	242.18	294.89
15	7	220.63	6.27	-	194.14	247.13
15	8	252.18	6.13	-	225.82	278.53
15	9	-796.13	11.30	-	-836.59	-755.67
15	10	-688.77	10.63	-	-727.01	-650.52
15	11	-1,405.67	29.84	-	-1,511.08	-1,300.26
15	12	-1,295.14	29.69	-	-1,400.01	-1,190.27
15	13	63.30	6.90	0.00	35.65	90.96
15	14	213.01	6.91	-	185.34	240.68
15	16	155.03	8.15	-	123.52	186.54
16	1	-11.78	5.87	1.00	-35.11	11.55
16	2	57.63	5.50	0.00	35.00	80.27
16	3	-71.66	6.81	0.00	-97.68	-45.63
16	4	-0.43	6.18	1.00	-24.44	23.58
16	5	83.49	5.40	0.00	60.98	105.99
16	6	113.51	5.40	0.00	91.00	136.01
16	7	65.61	5.56	0.00	42.86	88.35

D.4 Continued

Scenario					95% Confidence Interval	
(I)	(J)	Mean Difference (I-J)	Std. Error	Sig.	Upper Bound	Lower Bound
16	8	97.15	5.40	0.00	74.65	119.65
16	9	-951.15	10.91	-	-989.99	-912.32
16	10	-843.79	10.22	-	-880.27	-807.31
16	11	-1,560.70	29.70	-	-1,665.60	-1,455.80
16	12	-1,450.17	29.54	-	-1,554.51	-1,345.82
16	13	-91.72	6.26	0.00	-116.14	-67.30
16	14	57.98	6.27	0.00	33.54	82.42
16	15	-155.03	8.15	-	-186.54	-123.52

Table D.5 Tamhane post-hoc test results of WIP level

Scenario					95% Confidence Interval	
(I)	(J)	Mean Difference (I-J)	Std. Error	Sig.	Upper Bound	Lower Bound
2	4	-9.54	0.26	-	-10.36	-8.73
2	6	-29.21	0.14	-	-29.67	-28.74
2	8	-39.23	0.12	-	-39.61	-38.85
2	10	33.15	0.13	-	32.74	33.56
2	12	8.09	0.36	-	6.95	9.23
2	14	-16.95	0.22	-	-17.67	-16.24
2	16	-14.54	0.27	-	-15.39	-13.68
4	2	9.54	0.26	-	8.73	10.36
4	6	-19.66	0.25	-	-20.47	-18.86
4	8	-29.69	0.24	-	-30.46	-28.92
4	10	42.69	0.24	-	41.90	43.47
4	12	17.63	0.42	-	16.32	18.95
4	14	-7.41	0.30	-	-8.38	-6.44
4	16	-4.99	0.34	-	-6.06	-3.92
6	2	29.21	0.14	-	28.74	29.67
6	4	19.66	0.25	-	18.86	20.47
6	8	-10.03	0.11	-	-10.41	-9.64
6	10	62.35	0.12	-	61.95	62.76
6	12	37.30	0.36	-	36.17	38.43
6	14	12.26	0.22	-	11.55	12.96
6	16	14.67	0.26	-	13.82	15.52
8	2	39.23	0.12	-	38.85	39.61
8	4	29.69	0.24	-	28.92	30.46
8	6	10.03	0.11	-	9.64	10.41
8	10	72.38	0.09	-	72.08	72.68
8	12	47.33	0.35	-	46.22	48.43
8	14	22.28	0.21	-	21.62	22.94
8	16	24.70	0.25	-	23.88	25.51
10	2	-33.15	0.13	-	-33.56	-32.74
10	4	-42.69	0.24	-	-43.47	-41.90
10	6	-62.35	0.12	-	-62.76	-61.95

Table D.5 Continued

Scenario					95% Confidence Interval	
(I)	(J)	Mean Difference (I-J)	Std. Error	Sig.	Upper Bound	Lower Bound
10	8	-72.38	0.09	-	-72.68	-72.08
10	12	-25.05	0.36	-	-26.17	-23.94
10	14	-50.10	0.21	-	-50.78	-49.42
10	16	-47.68	0.26	-	-48.51	-46.86
12	2	-8.09	0.36	-	-9.23	-6.95
12	4	-17.63	0.42	-	-18.95	-16.32
12	6	-37.30	0.36	-	-38.43	-36.17
12	8	-47.33	0.35	-	-48.43	-46.22
12	10	25.05	0.36	-	23.94	26.17
12	14	-25.04	0.40	-	-26.30	-23.79
12	16	-22.63	0.43	-	-23.96	-21.29
14	2	16.95	0.22	-	16.24	17.67
14	4	7.41	0.30	-	6.44	8.38
14	6	-12.26	0.22	-	-12.96	-11.55
14	8	-22.28	0.21	-	-22.94	-21.62
14	10	50.10	0.21	-	49.42	50.78
14	12	25.04	0.40	-	23.79	26.30
14	16	2.42	0.31	-	1.42	3.42
16	2	14.54	0.27	-	13.68	15.39
16	4	4.99	0.34	-	3.92	6.06
16	6	-14.67	0.26	-	-15.52	-13.82
16	8	-24.70	0.25	-	-25.51	-23.88
16	10	47.68	0.26	-	46.86	48.51
16	12	22.63	0.43	-	21.29	23.96
16	14	-2.42	0.31	-	-3.42	-1.42

Table D.6 Tamhane post-hoc test results of throughput level

Scenario					95% Confidence Interval	
(I)	(J)	Mean Difference (I-J)	Std. Error	Sig.	Upper Bound	Lower Bound
1	2	27.30	61.74	1.00	-203.92	258.51
1	3	-54.85	80.74	1.00	-354.67	244.97
1	4	-65.11	68.78	1.00	-318.48	188.25
1	5	-20.35	117.68	1.00	-500.24	459.55
1	6	-27.73	112.25	1.00	-478.14	422.68
1	7	-139.30	139.82	1.00	-779.56	500.96
1	8	-57.99	66.29	1.00	-303.16	187.19
1	9	126.08	56.01	0.98	-89.87	342.03
1	10	117.65	55.99	0.99	-98.24	333.54
1	11	77.81	56.49	1.00	-139.30	294.91
1	12	65.67	56.46	1.00	-151.38	282.71
1	13	-20.07	95.00	1.00	-383.11	342.96
1	14	32.22	69.78	1.00	-224.36	288.81
1	15	-102.27	97.28	1.00	-479.76	275.23

Table D.6 Continued

Scenario					95% Confidence Interval	
(I)	(J)	Mean Difference (I-J)	Std. Error	Sig.	Upper Bound	Lower Bound
1	16	-50.10	67.31	1.00	-298.78	198.57
2	1	-27.30	61.74	1.00	-258.51	203.92
2	3	-82.14	63.97	1.00	-326.99	162.71
2	4	-92.41	48.00	1.00	-265.88	81.06
2	5	-47.64	106.87	1.00	-513.53	418.24
2	6	-55.03	100.86	1.00	-487.04	376.99
2	7	-166.60	130.86	1.00	-819.14	485.95
2	8	-85.28	44.36	1.00	-244.60	74.03
2	9	98.78	26.64	0.03	2.93	194.63
2	10	90.35	26.59	0.10	-5.32	186.02
2	11	50.51	27.63	1.00	-48.60	149.62
2	12	38.37	27.58	1.00	-60.56	137.30
2	13	-47.37	81.23	1.00	-374.79	280.05
2	14	4.93	49.41	1.00	-173.71	183.56
2	15	-129.56	83.88	1.00	-476.63	217.50
2	16	-77.40	45.86	1.00	-243.16	88.36
3	1	54.85	80.74	1.00	-244.97	354.67
3	2	82.14	63.97	1.00	-162.71	326.99
3	4	-10.27	70.79	1.00	-274.93	254.40
3	5	34.50	118.87	1.00	-448.59	517.59
3	6	27.12	113.49	1.00	-427.04	481.28
3	7	-84.45	140.82	1.00	-725.08	556.17
3	8	-3.14	68.38	1.00	-260.37	254.09
3	9	180.92	58.46	0.40	-51.20	413.05
3	10	172.49	58.44	0.52	-59.58	404.57
3	11	132.65	58.92	0.98	-100.39	365.69
3	12	120.51	58.89	1.00	-112.47	353.50
3	13	34.77	96.47	1.00	-334.19	403.73
3	14	87.07	71.76	1.00	-180.55	354.68
3	15	-47.42	98.71	1.00	-430.37	335.52
3	16	4.74	69.36	1.00	-255.66	265.14
4	1	65.11	68.78	1.00	-188.25	318.48
4	2	92.41	48.00	1.00	-81.06	265.88
4	3	10.27	70.79	1.00	-254.40	274.93
4	5	44.77	111.09	1.00	-424.40	513.94
4	6	37.39	105.32	1.00	-399.58	474.35
4	7	-74.19	134.32	1.00	-719.31	570.94
4	8	7.13	53.73	1.00	-186.51	200.76
4	9	191.19	40.36	0.00	42.05	340.33
4	10	182.76	40.33	0.00	33.73	331.79
4	11	142.92	41.02	0.09	-8.19	294.03
4	12	130.78	40.98	0.22	-20.21	281.78
4	13	45.04	86.70	1.00	-294.13	384.21
4	14	97.34	57.97	1.00	-111.81	306.48
4	15	-37.15	89.19	1.00	-393.62	319.31
4	16	15.01	54.97	1.00	-183.56	213.58

Table D.6 Continued

Scenario					95% Confidence Interval	
(I)	(J)	Mean Difference (I-J)	Std. Error	Sig.	Upper Bound	Lower Bound
5	1	20.35	117.68	1.00	-459.55	500.24
5	2	47.64	106.87	1.00	-418.24	513.53
5	3	-34.50	118.87	1.00	-517.59	448.59
5	4	-44.77	111.09	1.00	-513.94	424.40
5	6	-7.38	142.16	1.00	-568.57	553.80
5	7	-118.95	164.80	1.00	-805.44	567.53
5	8	-37.64	109.57	1.00	-505.28	430.00
5	9	146.42	103.67	1.00	-319.18	612.02
5	10	137.99	103.65	1.00	-327.61	603.60
5	11	98.15	103.92	1.00	-367.39	563.70
5	12	86.01	103.91	1.00	-379.53	551.56
5	13	0.27	128.98	1.00	-511.10	511.64
5	14	52.57	111.71	1.00	-417.28	522.42
5	15	-81.92	130.66	1.00	-600.47	436.63
5	16	-29.76	110.18	1.00	-498.03	438.52
6	1	27.73	112.25	1.00	-422.68	478.14
6	2	55.03	100.86	1.00	-376.99	487.04
6	3	-27.12	113.49	1.00	-481.28	427.04
6	4	-37.39	105.32	1.00	-474.35	399.58
6	5	7.38	142.16	1.00	-553.80	568.57
6	7	-111.57	160.97	1.00	-786.11	562.96
6	8	-30.26	103.71	1.00	-465.08	404.56
6	9	153.81	97.46	1.00	-276.74	584.36
6	10	145.38	97.44	1.00	-285.17	575.93
6	11	105.53	97.73	1.00	-325.05	536.12
6	12	93.40	97.72	1.00	-337.19	523.98
6	13	7.66	124.04	1.00	-478.81	494.12
6	14	59.95	105.97	1.00	-377.94	497.85
6	15	-74.54	125.79	1.00	-568.98	419.90
6	16	-22.38	104.36	1.00	-458.09	413.34
7	1	139.30	139.82	1.00	-500.96	779.56
7	2	166.60	130.86	1.00	-485.95	819.14
7	3	84.45	140.82	1.00	-556.17	725.08
7	4	74.19	134.32	1.00	-570.94	719.31
7	5	118.95	164.80	1.00	-567.53	805.44
7	6	111.57	160.97	1.00	-562.96	786.11
7	8	81.32	133.07	1.00	-566.08	728.71
7	9	265.38	128.25	1.00	-395.36	926.11
7	10	256.95	128.24	1.00	-403.83	917.72
7	11	217.11	128.46	1.00	-442.88	877.10
7	12	204.97	128.45	1.00	-455.06	865.00
7	13	119.23	149.46	1.00	-528.73	767.18
7	14	171.52	134.84	1.00	-472.77	815.82
7	15	37.03	150.91	1.00	-614.51	688.58
7	16	89.20	133.57	1.00	-557.27	735.66
8	1	57.99	66.29	1.00	-187.19	303.16
8	2	85.28	44.36	1.00	-74.03	244.60

Table D.6 Continued

Scenario					95% Confidence Interval	
(I)	**(J)**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**Upper Bound**	**Lower Bound**
8	3	3.14	68.38	1.00	-254.09	260.37
8	4	-7.13	53.73	1.00	-200.76	186.51
8	5	37.64	109.57	1.00	-430.00	505.28
8	6	30.26	103.71	1.00	-404.56	465.08
8	7	-81.32	133.07	1.00	-728.71	566.08
8	9	184.06	35.96	-	52.36	315.77
8	10	175.63	35.92	0.00	44.05	307.22
8	11	135.79	36.70	0.04	1.80	269.78
8	12	123.65	36.66	0.12	-10.21	257.52
8	13	37.91	84.74	1.00	-296.66	372.48
8	14	90.21	55.00	1.00	-108.00	288.41
8	15	-44.28	87.29	1.00	-396.93	308.37
8	16	7.88	51.83	1.00	-178.99	194.75
9	1	-126.08	56.01	0.98	-342.03	89.87
9	2	-98.78	26.64	0.03	-194.63	-2.93
9	3	-180.92	58.46	0.40	-413.05	51.20
9	4	-191.19	40.36	0.00	-340.33	-42.05
9	5	-146.42	103.67	1.00	-612.02	319.18
9	6	-153.81	97.46	1.00	-584.36	276.74
9	7	-265.38	128.25	1.00	-926.11	395.36
9	8	-184.06	35.96	-	-315.77	-52.36
9	10	-8.43	5.72	1.00	-28.59	11.74
9	11	-48.27	9.44	-	-81.57	-14.97
9	12	-60.41	9.28	-	-93.14	-27.67
9	13	-146.15	76.97	1.00	-467.15	174.85
9	14	-93.86	42.04	0.97	-248.99	61.28
9	15	-228.34	79.76	0.71	-571.21	114.52
9	16	-176.18	37.79	0.00	-316.32	-36.04
10	1	-117.65	55.99	0.99	-333.54	98.24
10	2	-90.35	26.59	0.10	-186.02	5.32
10	3	-172.49	58.44	0.52	-404.57	59.58
10	4	-182.76	40.33	0.00	-331.79	-33.73
10	5	-137.99	103.65	1.00	-603.60	327.61
10	6	-145.38	97.44	1.00	-575.93	285.17
10	7	-256.95	128.24	1.00	-917.72	403.83
10	8	-175.63	35.92	0.00	-307.22	-44.05
10	9	8.43	5.72	1.00	-11.74	28.59
10	11	-39.84	9.28	0.00	-72.61	-7.08
10	12	-51.98	9.12	-	-84.17	-19.79
10	13	-137.72	76.95	1.00	-458.70	183.26
10	14	-85.43	42.01	1.00	-240.46	69.60
10	15	-219.92	79.74	0.79	-562.77	122.94
10	16	-167.75	37.76	0.00	-307.78	-27.72
11	1	-77.81	56.49	1.00	-294.91	139.30
11	2	-50.51	27.63	1.00	-149.62	48.60
11	3	-132.65	58.92	0.98	-365.69	100.39
11	4	-142.92	41.02	0.09	-294.03	8.19

Table D.6 Continued

Scenario					95% Confidence Interval	
(I)	**(J)**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**Upper Bound**	**Lower Bound**
11	5	-98.15	103.92	1.00	-563.70	367.39
11	6	-105.53	97.73	1.00	-536.12	325.05
11	7	-217.11	128.46	1.00	-877.10	442.88
11	8	-135.79	36.70	0.04	-269.78	-1.80
11	9	48.27	9.44	-	14.97	81.57
11	10	39.84	9.28	0.00	7.08	72.61
11	12	-12.14	11.81	1.00	-53.80	29.53
11	13	-97.88	77.31	1.00	-419.30	223.54
11	14	-45.58	42.67	1.00	-202.61	111.45
11	15	-180.07	80.09	0.99	-523.16	163.01
11	16	-127.91	38.49	0.16	-270.12	14.30
12	1	-65.67	56.46	1.00	-282.71	151.38
12	2	-38.37	27.58	1.00	-137.30	60.56
12	3	-120.51	58.89	1.00	-353.50	112.47
12	4	-130.78	40.98	0.22	-281.78	20.21
12	5	-86.01	103.91	1.00	-551.56	379.53
12	6	-93.40	97.72	1.00	-523.98	337.19
12	7	-204.97	128.45	1.00	-865.00	455.06
12	8	-123.65	36.66	0.12	-257.52	10.21
12	9	60.41	9.28	-	27.67	93.14
12	10	51.98	9.12	-	19.79	84.17
12	11	12.14	11.81	1.00	-29.53	53.80
12	13	-85.74	77.29	1.00	-407.14	235.66
12	14	-33.45	42.64	1.00	-190.37	123.48
12	15	-167.94	80.07	1.00	-511.01	175.14
12	16	-115.77	38.46	0.35	-257.87	26.33
13	1	20.07	95.00	1.00	-342.96	383.11
13	2	47.37	81.23	1.00	-280.05	374.79
13	3	-34.77	96.47	1.00	-403.73	334.19
13	4	-45.04	86.70	1.00	-384.21	294.13
13	5	-0.27	128.98	1.00	-511.64	511.10
13	6	-7.66	124.04	1.00	-494.12	478.81
13	7	-119.23	149.46	1.00	-767.18	528.73
13	8	-37.91	84.74	1.00	-372.48	296.66
13	9	146.15	76.97	1.00	-174.85	467.15
13	10	137.72	76.95	1.00	-183.26	458.70
13	11	97.88	77.31	1.00	-223.54	419.30
13	12	85.74	77.29	1.00	-235.66	407.14
13	14	52.30	87.50	1.00	-288.76	393.36
13	15	-82.19	110.68	1.00	-508.83	344.44
13	16	-30.03	85.54	1.00	-366.53	306.47
14	1	-32.22	69.78	1.00	-288.81	224.36
14	2	-4.93	49.41	1.00	-183.56	173.71
14	3	-87.07	71.76	1.00	-354.68	180.55
14	4	-97.34	57.97	1.00	-306.48	111.81
14	5	-52.57	111.71	1.00	-522.42	417.28

Table D.6 Continued

Scenario					95% Confidence Interval	
(I)	(J)	Mean Difference (I-J)	Std. Error	Sig.	Upper Bound	Lower Bound
14	6	-59.95	105.97	1.00	-497.85	377.94
14	7	-171.52	134.84	1.00	-815.82	472.77
14	8	-90.21	55.00	1.00	-288.41	108.00
14	9	93.86	42.04	0.97	-61.28	248.99
14	10	85.43	42.01	1.00	-69.60	240.46
14	11	45.58	42.67	1.00	-111.45	202.61
14	12	33.45	42.64	1.00	-123.48	190.37
14	13	-52.30	87.50	1.00	-393.36	288.76
14	15	-134.49	89.96	1.00	-492.54	223.56
14	16	-82.33	56.21	1.00	-285.32	120.67
15	1	102.27	97.28	1.00	-275.23	479.76
15	2	129.56	83.88	1.00	-217.50	476.63
15	3	47.42	98.71	1.00	-335.52	430.37
15	4	37.15	89.19	1.00	-319.31	393.62
15	5	81.92	130.66	1.00	-436.63	600.47
15	6	74.54	125.79	1.00	-419.90	568.98
15	7	-37.03	150.91	1.00	-688.58	614.51
15	8	44.28	87.29	1.00	-308.37	396.93
15	9	228.34	79.76	0.71	-114.52	571.21
15	10	219.92	79.74	0.79	-122.94	562.77
15	11	180.07	80.09	0.99	-163.01	523.16
15	12	167.94	80.07	1.00	-175.14	511.01
15	13	82.19	110.68	1.00	-344.44	508.83
15	14	134.49	89.96	1.00	-223.56	492.54
15	16	52.16	88.06	1.00	-302.09	406.41
16	1	50.10	67.31	1.00	-198.57	298.78
16	2	77.40	45.86	1.00	-88.36	243.16
16	3	-4.74	69.36	1.00	-265.14	255.66
16	4	-15.01	54.97	1.00	-213.58	183.56
16	5	29.76	110.18	1.00	-438.52	498.03
16	6	22.38	104.36	1.00	-413.34	458.09
16	7	-89.20	133.57	1.00	-735.66	557.27
16	8	-7.88	51.83	1.00	-194.75	178.99
16	9	176.18	37.79	0.00	36.04	316.32
16	11	127.91	38.49	0.16	-14.30	270.12
16	12	115.77	38.46	0.35	-26.33	257.87
16	13	30.03	85.54	1.00	-306.47	366.53
16	14	82.33	56.21	1.00	-120.67	285.32
16	15	-52.16	88.06	1.00	-406.41	302.09

*Because of the size of the details, new replication number calculation tables are given at CD as Appendix D.

APPENDIX E

CONWIP OPTIMIZATION OPTQUEST RESULTS

Best Solutions Stopped due to the Auto Stop option.

Best Solutions

Select	Simulation	Objective Value	Status	x1	x2	x4	x8
☐	122	1,689803E+006	Feasible	18	25	19	5
☐	148	1,689803E+006	Feasible	18	24	19	5
☐	157	1,689803E+006	Feasible	18	22	19	5
☐	161	1,689803E+006	Feasible	18	21	19	5
☐	166	1,689803E+006	Feasible	18	23	19	5
☐	217	1,689803E+006	Feasible	18	17	19	5
☐	225	1,689803E+006	Feasible	18	20	19	5
☐	247	1,689803E+006	Feasible	18	19	19	5
☐	248	1,689803E+006	Feasible	18	18	19	5
☐	69	1,689811E+006	Feasible	18	25	20	5

Figure E.1 Optquest results for C=10 Order Size Distribution=Expo (Scenario 1)

Best Solutions Stopped due to the Auto Stop option.

Best Solutions

Select	Simulation	Objective Value	Status	x1	x2	x4	x8
☐	154	2,251324E+006	Feasible	35	25	14	4
☐	232	2,251332E+006	Feasible	35	24	14	4
☐	173	2,251334E+006	Feasible	34	25	14	4
☐	255	2,251339E+006	Feasible	35	23	14	4
☐	253	2,251341E+006	Feasible	34	24	14	4
☐	398	2,251347E+006	Feasible	35	22	14	4
☐	261	2,251348E+006	Feasible	33	25	14	4
☐	259	2,251349E+006	Feasible	34	23	14	4
☐	377	2,251356E+006	Feasible	34	22	14	4
☐	403	2,251362E+006	Feasible	32	25	14	4
☐	252	2,251363E+006	Feasible	33	23	14	4
☐	262	2,251370E+006	Feasible	32	24	14	4
☐	530	2,251371E+006	Feasible	33	22	14	4
☐	94	2,251374E+006	Feasible	35	25	16	4
☐	257	2,251376E+006	Feasible	35	21	14	4
☐	236	2,251376E+006	Feasible	31	25	14	4
☐	256	2,251377E+006	Feasible	32	23	14	4
☐	57	2,251378E+006	Feasible	35	25	17	4
☐	102	2,251381E+006	Feasible	35	24	16	4
☐	174	2,251383E+006	Feasible	34	25	16	4
☐	93	2,251386E+006	Feasible	35	24	17	4
☐	66	2,251388E+006	Feasible	35	25	15	4
☐	88	2,251389E+006	Feasible	35	23	16	4
☐	468	2,251390E+006	Feasible	30	25	14	4
☐	84	2,251393E+006	Feasible	35	23	17	4

Figure E.2 Optquest results for C=10 Order Size Distribution=Gamma (Scenario 2)

Best Solutions Stopped due to the Auto Stop option.

Best Solutions

Select	Simulation	Objective Value	Status	x1	x2	x4	x8
☐	145	1,143293E+006	Feasible	16	23	35	15
☐	148	1,143293E+006	Feasible	16	25	35	15
☐	155	1,143293E+006	Feasible	16	24	35	15
☐	156	1,143293E+006	Feasible	16	24	34	15
☐	159	1,143293E+006	Feasible	16	24	33	15
☐	160	1,143293E+006	Feasible	16	23	34	15
☐	163	1,143293E+006	Feasible	16	22	31	15
☐	168	1,143293E+006	Feasible	16	25	31	15
☐	169	1,143293E+006	Feasible	16	25	33	15
☐	226	1,143293E+006	Feasible	16	15	32	15

Figure E.3 Optquest results for C=5 Order Size Distribution=Expo (Scenario 3)

Best Solutions Stopped due to the Auto Stop option.

Best Solutions

Select	Simulation	Objective Value	Status	x1	x2	x4	x8
☐	25	1,283587E+006	Feasible	35	25	35	5
☐	54	1,283587E+006	Feasible	35	24	34	5
☐	68	1,283587E+006	Feasible	35	24	35	5
☐	69	1,283587E+006	Feasible	35	25	34	5
☐	72	1,283587E+006	Feasible	34	24	34	5
☐	77	1,283587E+006	Feasible	34	25	35	5
☐	81	1,283587E+006	Feasible	34	25	34	5
☐	100	1,283587E+006	Feasible	34	24	35	5
☐	132	1,283587E+006	Feasible	32	24	35	5
☐	135	1,283587E+006	Feasible	34	20	32	5
☐	137	1,283587E+006	Feasible	32	24	34	5
☐	140	1,283587E+006	Feasible	34	23	31	5
☐	144	1,283587E+006	Feasible	27	23	30	5
☐	150	1,283587E+006	Feasible	32	22	33	5
☐	151	1,283587E+006	Feasible	33	24	34	5
☐	152	1,283587E+006	Feasible	32	25	35	5
☐	153	1,283587E+006	Feasible	31	25	35	5
☐	154	1,283587E+006	Feasible	32	24	32	5
☐	155	1,283587E+006	Feasible	34	20	34	5
☐	156	1,283587E+006	Feasible	31	25	34	5
☐	158	1,283587E+006	Feasible	34	21	33	5
☐	161	1,283587E+006	Feasible	34	22	33	5
☐	164	1,283587E+006	Feasible	33	23	34	5
☐	177	1,283587E+006	Feasible	32	25	33	5
☐	180	1,283587E+006	Feasible	35	25	31	5

Figure E.4 Optquest results for C=5 Order Size Distribution=Gamma (Scenario 4)

Best Solutions Stopped due to the Auto Stop option.

Best Solutions

Select	Simulation	Objective Value	Status	x1	x2	x4	x8
☐	565	7,252911E+006	Feasible	12	21	15	4
☐	564	7,253092E+006	Feasible	12	21	16	4
☐	499	7,253268E+006	Feasible	12	21	17	4
☐	243	7,253399E+006	Feasible	12	21	18	4
☐	566	7,253432E+006	Feasible	12	21	14	4
☐	309	7,253537E+006	Feasible	12	21	19	4
☐	654	7,253578E+006	Feasible	12	22	15	4
☐	659	7,253592E+006	Feasible	13	21	15	4
☐	483	7,253847E+006	Feasible	12	22	17	4
☐	328	7,253961E+006	Feasible	12	22	18	4

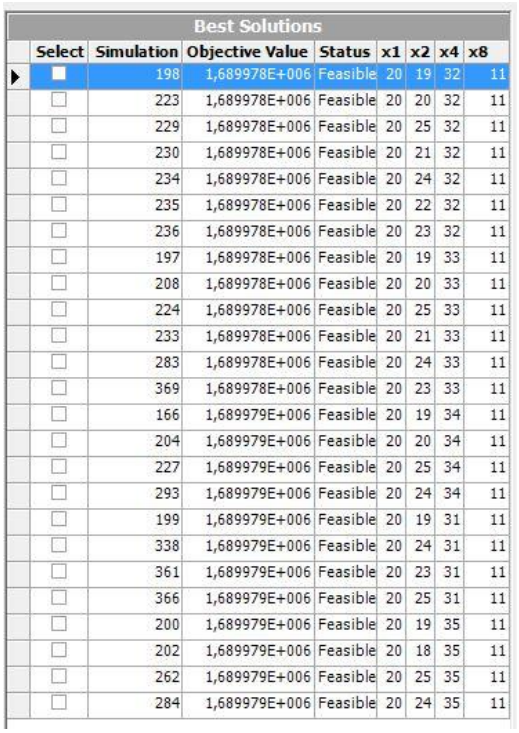
Figure E.5 Optquest results for C=15 Order Size Distribution=Expo (Scenario 5)

Best Solutions Stopped due to the Auto Stop option.

Best Solutions

Select	Simulation	Objective Value	Status	x1	x2	x4	x8
☐	29	1,284414E+007	Feasible	35	25	35	5
☐	117	1,284450E+007	Feasible	34	25	35	5
☐	51	1,284474E+007	Feasible	35	25	35	4
☐	183	1,284487E+007	Feasible	33	25	35	5
☐	182	1,284487E+007	Feasible	35	24	35	5
☐	329	1,284511E+007	Feasible	34	25	35	4
☐	193	1,284523E+007	Feasible	34	24	35	5
☐	490	1,284524E+007	Feasible	32	25	35	5
☐	262	1,284549E+007	Feasible	35	24	35	4
☐	186	1,284560E+007	Feasible	35	23	35	5
☐	330	1,284560E+007	Feasible	33	24	35	5
☐	477	1,284563E+007	Feasible	31	25	35	5
☐	52	1,284565E+007	Feasible	35	25	34	5
☐	303	1,284585E+007	Feasible	34	24	35	4
☐	465	1,284600E+007	Feasible	30	25	35	5
☐	112	1,284601E+007	Feasible	34	25	34	5
☐	59	1,284621E+007	Feasible	35	25	34	4
☐	188	1,284621E+007	Feasible	35	23	35	4
☐	492	1,284636E+007	Feasible	31	24	35	5
☐	240	1,284638E+007	Feasible	35	22	35	5
☐	191	1,284638E+007	Feasible	33	25	34	5
☐	160	1,284638E+007	Feasible	35	24	34	5
☐	336	1,284658E+007	Feasible	34	25	34	4
☐	215	1,284673E+007	Feasible	35	25	35	2
☐	478	1,284674E+007	Feasible	30	24	35	5

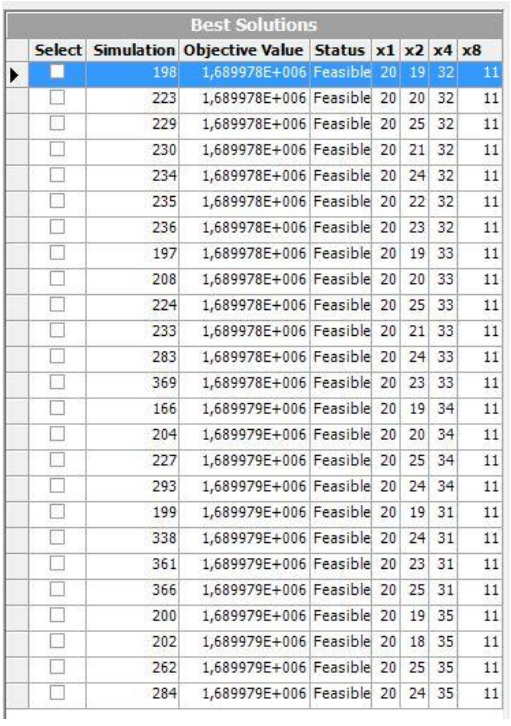
Figure E.6 Optquest results for C=15 Order Size Distribution=Gamma (Scenario 6)



Best Solutions

Select	Simulation	Objective Value	Status	x1	x2	x4	x8
☐	198	1,689978E+006	Feasible	20	19	32	11
☐	223	1,689978E+006	Feasible	20	20	32	11
☐	229	1,689978E+006	Feasible	20	25	32	11
☐	230	1,689978E+006	Feasible	20	21	32	11
☐	234	1,689978E+006	Feasible	20	24	32	11
☐	235	1,689978E+006	Feasible	20	22	32	11
☐	236	1,689978E+006	Feasible	20	23	32	11
☐	197	1,689978E+006	Feasible	20	19	33	11
☐	208	1,689978E+006	Feasible	20	20	33	11
☐	224	1,689978E+006	Feasible	20	25	33	11
☐	233	1,689978E+006	Feasible	20	21	33	11
☐	283	1,689978E+006	Feasible	20	24	33	11
☐	369	1,689978E+006	Feasible	20	23	33	11
☐	166	1,689979E+006	Feasible	20	19	34	11
☐	204	1,689979E+006	Feasible	20	20	34	11
☐	227	1,689979E+006	Feasible	20	25	34	11
☐	293	1,689979E+006	Feasible	20	24	34	11
☐	199	1,689979E+006	Feasible	20	19	31	11
☐	338	1,689979E+006	Feasible	20	24	31	11
☐	361	1,689979E+006	Feasible	20	23	31	11
☐	366	1,689979E+006	Feasible	20	25	31	11
☐	200	1,689979E+006	Feasible	20	19	35	11
☐	202	1,689979E+006	Feasible	20	18	35	11
☐	262	1,689979E+006	Feasible	20	25	35	11
☐	284	1,689979E+006	Feasible	20	24	35	11

Figure E.7 Optquest results for C=10 Order Size Distribution=Expo (Scenario 7)



Best Solutions

Select	Simulation	Objective Value	Status	x1	x2	x4	x8
☐	198	1,689978E+006	Feasible	20	19	32	11
☐	223	1,689978E+006	Feasible	20	20	32	11
☐	229	1,689978E+006	Feasible	20	25	32	11
☐	230	1,689978E+006	Feasible	20	21	32	11
☐	234	1,689978E+006	Feasible	20	24	32	11
☐	235	1,689978E+006	Feasible	20	22	32	11
☐	236	1,689978E+006	Feasible	20	23	32	11
☐	197	1,689978E+006	Feasible	20	19	33	11
☐	208	1,689978E+006	Feasible	20	20	33	11
☐	224	1,689978E+006	Feasible	20	25	33	11
☐	233	1,689978E+006	Feasible	20	21	33	11
☐	283	1,689978E+006	Feasible	20	24	33	11
☐	369	1,689978E+006	Feasible	20	23	33	11
☐	166	1,689979E+006	Feasible	20	19	34	11
☐	204	1,689979E+006	Feasible	20	20	34	11
☐	227	1,689979E+006	Feasible	20	25	34	11
☐	293	1,689979E+006	Feasible	20	24	34	11
☐	199	1,689979E+006	Feasible	20	19	31	11
☐	338	1,689979E+006	Feasible	20	24	31	11
☐	361	1,689979E+006	Feasible	20	23	31	11
☐	366	1,689979E+006	Feasible	20	25	31	11
☐	200	1,689979E+006	Feasible	20	19	35	11
☐	202	1,689979E+006	Feasible	20	18	35	11
☐	262	1,689979E+006	Feasible	20	25	35	11
☐	284	1,689979E+006	Feasible	20	24	35	11

Figure E.8 Optquest results for C=10 Order Size Distribution=Gamma (Scenario 8)