System Design and Analysis Using Simulation for Hybrid Cellular Manufacturing Systems in Labor-intensive Industry

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ABSTRACT

System Design and Analysis Using Simulation for Hybrid Cellular Manufacturing Systems in Labor-Intensive Industry

Li Ju, Huang

This research investigates the problems of system design in a hybrid cellular manufacturing (CM) system with loop layout. A hybrid CM system comprises a cellular layout and a functional layout. In labor-intensive industry, the functional layout is organized into production modules. The operator of every module is able to perform different kinds of tasks for one specific function. However, each operator is assigned to only one of the operations. This manufacturing system has emerged due to the high product variety in fashion industry that is usually highly labor-intensive. This study presents a new approach for system design to improve system performance. A three-phased simulation model is derived. The bottleneck machines of a cell are located in the first phase, and the cell workload and system workload are balanced in the second and third phase. Incorporating simulation models and optimum seeking procedure, the appropriate values of controllable parameters are proposed according to the objective of the production. The three-phased method is applied to the hybrid CM system of a footwear factory.

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CHAPTER 1

INTRODUCTION

1.1 Background

In order to minimize the production expense and time, applications of Group Technology and cellular manufacturing (CM) systems have been introduced to various manufacturing industries and service industries. Even though the fundamental idea of this conversion retains the flexibility of job shops, CM encounters more obstacles to improve the flexibility once the physical layout is set. The principle of one complete part produced in a cell restrains the development of flexibility. However, flexibility is crucial for a company to meet the market needs. To adapt to the competitive environment, a manufacturing system must be capable of producing products of diverse designs with a high level of productivity and quality.

Over the last decade manufacturing industry has been relentlessly adapting to customer needs, looking for better ways to produce a myriad of products. The change of the market trend has made great impact on labor-intensive factories whose products are usually of short life-cycles. Despite the fact that a number of innovative solutions on manufacturing system designs were proposed, researchers showed little interest in labor-intensive industry. For instance, both Flexible Cellular Manufacturing System and Virtual Cellular Manufacturing System require programmable equipments, CNC operators, integrated manufacturing, and material handling systems, which are not suitable for some functions in labor-intensive production. In the meantime, the concept of Hybrid Cellular

Manufacturing System emerges and allows the presence of cells in a functional layout. Then, hybrid CM seems to be a solution for labor-intensive industry.

1.2 Motivation

Cellular Manufacturing technology has been intensively studied through simulation studies and surveys. Implementing CM provides the benefits of the reductions in setup time, lot size, work-in-process (WIP) inventory, material handling costs, flow time and production time. It also outputs products with higher quality. This methodology has been very successful and increasingly popular among manufacturers. They have implemented CM technology in various forms. However, to meet today's market expectations, CM technology seems to be in a difficult position to achieve a flexible production without modifications. Its lack of flexibility makes it vulnerable to the changes of product design.

A number of companies adopted CM technology but later reversed back to functional layouts. The return to functional layout was a day-to-day transformation that led to the presence of manufacturing cells within a functional layout that seems to accommodate managers. They could keep CM technology advantages while enhancing flexibility of their layout. It then became a Hybrid Cellular Manufacturing (HCM), whose layout is not clearly defined; all it needs are cells within a functional layout. The HCM is available to companies who felt they have lost too much flexibility when they switched from functional to CM and decided to incorporate cells with their original layout. There are also functional factories that intended to take the advantages of CM and create a beneficial trade-off of flexibility for productivity.

1.3 Design HCM Using Computer Simulation

Research has been conducted on HCM with different analytical tools such as mathematical programming and computer simulation. Since such systems are normally very complicated and involve many system operation functions, computer simulation is more effective and widely used. Using simulation, researchers showed that implementing HCM may yield significant savings for some companies in certain industry. In addition, it was shown that HCM could outperform CMS when higher flexibility is required. It was also shown that HCM may outperform Job Shop (JS) layouts in many practical applications.

1.4 Research Objectives

Prominent manufacturing system features, such as machine sharing problems and material transportation system problems, have not received enough attention from researchers. Moreover, the problems are less studied in hybrid CM research. Most studies focus on other HCM characters such as batch size, set-up time, scheduling, or cell formation. The principle objective of this research is to present a general approach to improve system performance with proper selections of critical operational characters under various system constraints for HCM system in labor-intensive industries. To solve practical problems, integrated simulation models are developed to study HCM system design. An integrated approach with a three-phase analysis method is developed to propose a strategy for system design. In real-life situation, a factory that seeks for improvement may not prepare to implement an entire system reconfiguration due to the economical, practical and temporal considerations. In view of this, the performance improvement will be evaluated in terms of work-in-process inventory level, the average material handling cost and time and total throughput.

1.5 Outline

In this research a three-phase approach is proposed using simulation models. In Chapter 2, an overview of the literature is given. Chapter 3 presents the problem definition and system description. The dependent and independent variables are also introduced. The detailed information of modeling is presented in Chapter 4. The results and their analysis are given in Chapter 5. Optimization and sensitivity analysis is conduced in order to provide solutions for proper system design. Chapter 6 illustrates an application of the developed method. Finally, conclusions are drawn in Chapter 7.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Companies are continually evaluating their manufacturing systems in light of increasing market competition either for the purpose of growth or, in some cases, simply for survival. Over the years a number of different plant organizations have been used to meet this challenge. Productivity and flexibility were to be taken into consideration while the same level of quality had to be ensured. In a CM layout components are grouped into families based on similarities in the production process. Machines are grouped in cells accordingly in order to produce these components. It reduces WIP flow times and increases productivity. To respond to the demand that constantly fluctuates, higher flexibility is required from today's organizations.

CM systems are usually designed based on product lines, group technology, or part routings. A CM system designed on product lines is a focused factory approach. Manufacturing cell design is based on group technology requiring the use of GT classification and coding system to code all the products and an additional procedure to form part families from the products based on their GT codes (Lioa *et al.*,1996). Routing based procedures achieve CM design using a variety of cell formation algorithms. GT-oriented and routing-based procedures are popular for low discrete part production. Various forms and their prominent features are summarized in figure 2.1

The advantage is that the time required for the set-up changes between similar components is shorter, and it in turn reduces components flow times, lowers WIP

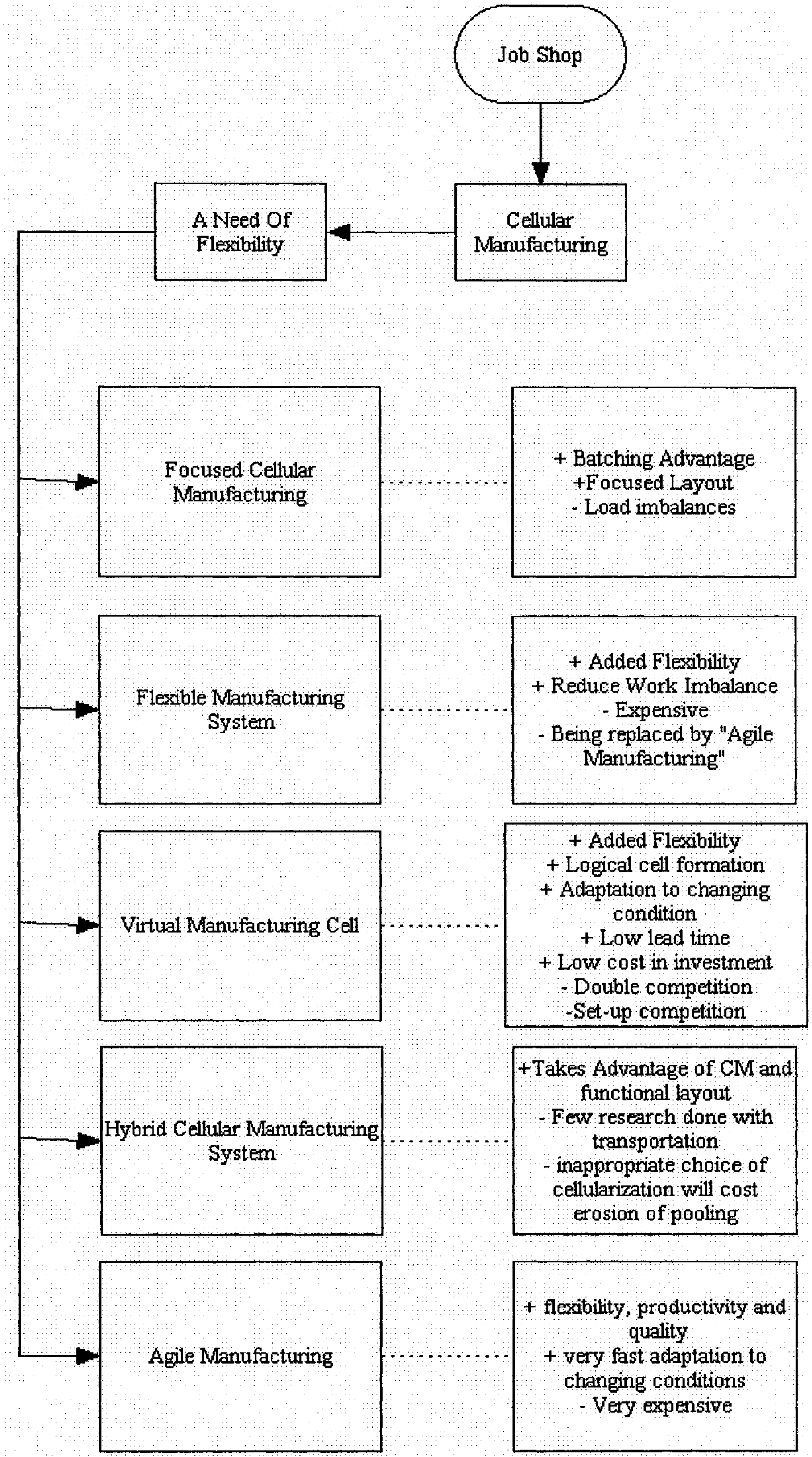


Figure 2.1: Summary of CM Innovations

inventories, and increases productivity for machines. The major disadvantage of this scheme is that it fails to meet the competitive need toward flexibility. Skinner (1974) suggested that batch processing factories would benefit if they were focused. Schoberger (1982) suggested organizing processing plants by end-items. Al-Mubarak *et al.* (2003) stated that additional research was desired on a more focused type of CM factory in order to improve its flexibility.

Over the years, many companies have changed to product layout for the complete production processes. They removed workshops and introduced manufacturing cells, mostly with remarkable success. Nevertheless, some enterprises recognized that they lost more flexibility than expected and others have not even been able to set-up a product oriented organization. Permanent manufacturing cells are not as flexible as workshops. In 1960, the idea of flexibility was proposed under the name "System 24", a flexible machining process able to operate without any human operators 24 hours a day, under computer control. From the beginning the emphasis was on automation rather than on "reorganization of workflow".

Considering dynamic market, several enterprises hesitated to introduce manufacturing cells. Furthermore, the contradiction between high investment and low capacity utilization makes manufacturing cells relatively unattractive. A way to overcome those restrictions is to implement Virtual Cellular Manufacturing (VCM). Production teams are responsible for a complete manufacturing process of products; however, in contradiction to permanent manufacturing cells, there is no need to change the existing workshop layout. Cost savings and higher flexibility are the main advantages of this concept.

In the middle of 1960s, market competition became more intense; cost was the primary concern, then quality. As the market became more complex, the speed of delivery grew more important to customers. The innovation of Flexible Manufacturing System (FMS) is to gain the competitive edge. It aims at producing reasonably priced customized products of high quality that can be quickly delivered to costumers. FMS concept is nowadays called Agile Manufacturing (AM).

Agile Manufacturing system was investigated to easily cope with, in a flexible and economical way, the diversified needs of consumers, the unpredictability of market demand and the reduced life cycles of products. The goal is to achieve flexibility and productivity simultaneously (Zhang *et al.*,1999). Agile manufacturing system successfully reconfigures manufacturing cells and integrates many disparate elements contained in the cells.

Shafer and Charnes (1996) stated that CM seeks to achieve many of the benefits associated with mass production. Cellular manufacturing is applied to production by GT principles. Model-based studies, have discerned that CM was not uniformly superior to functional layouts, and in several instances the adoption of CM was detrimental to shop performance. There are three possible explanations:

- Firstly, CM might not be appropriate to the model based production
- Secondly, the model based study did not include characteristics that provide the important benefits associated with CM;
- Thirdly, CM may not have assessed the situation accurately.

One of the major advantages of the functional layout is the routeing flexibility, engendered from the ability of substituting the machines for one another in a functional department. An investigation on a variety of operating environments allows examining if additional characteristics of CM can offset the loss in flexibility that occurs during the transition from a functional to a cellular layout. One proposal was to transform functional departments into cells gradually. This follows the actual practice of many firms that set up a pilot cell for preliminary investigation of CM. If the shop performance improves, the additional cells might be created to become a hybrid layout. This concept is realistic for many of companies, and it draws the strengths from both CM and functional layouts to be competitive for nowadays constant changing market.

2.2 Focused Cellular Manufacturing (FCM)

Al-Mubarak *et al.* (2003) discussed focused layout schemes according to process, product line or order factors. In their research, they decided to group components based on end-items and form cells accordingly. This is called focused cellular manufacturing (FCM). The major advantage of FCM is to reduce completion times for assembled end-items and WIP inventories while maintaining certain level of flexibility. Also, it is easy to install in a company where few end-items produced in large annual volumes and many end-items produced in small volumes. The disadvantage of FCM, however, is load imbalances that may develop as different product markets grow at different rates.

By using simulation, they made a comparison between FCM and JS, as well as FCM and CM. The results indicated that FCM scheme had a batching advantage. This advantage dominated the balance machine utilization benefit of the job shop layout scheme. The JS was only able to overcome the batching advantage when there were small batch sizes or large setup time magnitudes. The same batching advantage outweighed the set-up time reduction advantage of the cellular manufacturing scheme for average end-item completion times and average WIP inventory levels. Al-Mubarak *et al.* (2003) suggested that further research on the behavior of focused cellular manufacturing layouts is necessary.

2.3 Virtual Cellular Manufacturing (VCM)

In the past several years, industry has strived to make batch production more efficient and adapt to changes in demand and advanced technology. JS is a favored environment for batch production due to its flexibility. The frequency of set-ups incurred in those shops, however, resulted in either a significant reduction in capacity or increased batch sizes. Manufacturing cells dedicated to families of parts that considerably lessened the problem of set-up time. CM compromises the routing flexibility and ability of JS to respond to the changes. It became evident that dedicating machines to specific parts could not respond to short-term changes in demand. Kannan and Ghosh (1996) suggested that, under those circumstances, CM systems have poorer performance than job shops.

By virtue of the incapability of CM in responding to changes, the idea of implementing higher flexibility in a traditional CM layout was generated. Saad (2003) and Kannan and Ghosh (1996) suggested that machines could be temporarily assigned to families by scheduling a functionally organized shop using rules that recognized the existence of part families. When a machine becomes available, it can be assigned to a family rather than an individual job. As machines from different process departments are ‘dedicated’ to a family, a sequence of machines develops through the shop similar to that obtained in traditional cells. While machines remain dedicated to a family, parts from that family are routed to the corresponding machines. The only difference is that machines are not necessarily adjacent to one another to be part of the same family. Since the machine is already set up for the family, the need for additional set-ups is greatly reduced. When a family does not need a machine anymore due to the change of conditions, the machine can be re-assigned to another family. In this way, one cell contracts while another expands. Cells, as a result, learn to adapt to changing conditions. Unlike CM that has permanent cells and families, this new design is made of temporary cells and logical cells. Those are virtual cells. They are flexible routing mechanisms, having such cells taking advantages of JS and CM while being less affected by their weaknesses.

Kannan and Ghosh (1996) used a simulation model with different shop configuration, set-up times and part mix variability to identify conditions under which VCM is a more appropriate mode of small batch production than traditional process and cellular layout methods. The authors demonstrated the effectiveness of VCM and showed that it outperformed CM over a wide range of conditions. Mertins *et al.* (2000) observed the following advantages and problems of VCM:

- Advantages: low investment, low lead time, low WIP, high flexibility.
- Problems: team formation, team spirit in distributed teams, set-up conditions, double competition

They focused on a new approach, applying lot size harmonization, to solve one of the problems -- double competition. The concept is to limit the occupation time of capacity units while altering the access to resources by the production teams to ensure a defined order sequence. Through the application of simulation, this concept has been proved to be feasible. It provides a clear access mechanism for the teams to the resources; a minimized lead time is achieved. Because of the harmonized lot sizes, an alternating access to resources is possible.

2.4 Flexible Manufacturing Systems (FMS) in CM Layout

In the design and operation of a CMS, flexibility can reduce the risks associated with uncertainty. Among the several types of flexibility, routing flexibility has the ability to use alternative routes inside a cell or to route parts to cells offering the same process. It can strongly affect CMS performance. Routing flexibility is capable of responding to a changing environment; so that switching products to different cells in case of market changes do not dramatically affect the system performance (Albino and Garavelli., 1999). Flexible manufacturing systems often are organized into a cellular architecture for ease of operations. These cells are usually treated as an extension of the conventional cell-formation problem. Kochikar and Narendran (1998) argued that owing to the existence of flexible routing and transfer capabilities it should be treated as a distinct problem. They developed several cell formation methods based on maximizing flexibility.

Many studies have focused on the advantages of either cellular or process organizations in different contexts. In particular, demand variability and resource dependability can make a strong impact on the performance of a CMS stressing the routing flexibility benefits that can balance the additional flexibility costs. A trade-off between productivity and flexibility needs to be investigated.

Lee and Kim (2000) discussed operations of a flexible manufacturing system. A number of decisions have to be made before the FMS begins to produce parts. Such decision problems include those of selecting subsets of part types for immediate and simultaneous production, the partitioning of machines of each type into machine groups, determining relative ratios at which the selected part types are produced, allocating operations and associated cutting tools to machines or machine groups, and allocating pallets and fixtures to the selected part types. They further considered machine grouping and loading problems for a given set of selected part types. The decision-making on machine grouping constitutes the environment for the loading problem. Such decisions on machine grouping are related to the number of machine groups and the number of machines in each group as well as how the machines are grouped.

Albino and Garavelli (1999) proposed a simulation model to investigate some effects of demand variability, resource dependability and routing flexibility on CMS performance. The use of routing flexibility is analyzed focusing on tactical problems of route design. Their study focusing on economic considerations is to investigate the relationships between limited flexibility and system performance. Simulation study shows that the effect of demand variability and resource dependability require optimal CMS configurations.

2.5 Agile Manufacturing (AM) in a CM Layout

Agile manufacturing is an emerging concept to be more flexible and responsive to the changing market needs. The basis of agile manufacturing is to reconfigure the manufacturing cell and to integrate disparate elements contained in cells. The manufacturing cell consists of physical equipment such as material handling devices, computer hardware, machine tools, robots and computer hardware and required software for the integration of those devices. Therefore the cell control system must be generated and modified in a rapid and efficient manner. Kirk and Tebaldi (1997) defined agile manufacturing as the achievement of full mass customization at low cost and high volume. It requires more of the simple flexibility or the implementation of FMS. A true agile manufacturing system will not only be capable of providing a structural requirements but will have the ability to cope with the variables in joint type and configuration, within a specific variant and on a mixed model production line. Each different sub-assembly process requires variations in assembly sequence, and different programs and sets of parameters in the controllers (Watanabe and Kwintiana., 2004). This requires far more from the control system than a traditional manufacturing system. While agile manufacturing offers many advantages for companies competing in the industrial field where production life cycles are very short, it can also be applied to niche markets in more traditional industries.

2.6 Hybrid Cellular Manufacturing (HCM)

It is clear that most firms do not convert from functional to cellular layouts in short period of time. Hybrid layouts are often the solution for factories. HCM needs to be investigated to seek optimum trade-off between functional and cellular layouts.

Burgess *et al.* (1993) compared a factory structured as a traditional job shop with the same factory structured as a hybrid factory containing a cellular manufacturing unit. The performance is evaluated in terms of flow times and delays for the hybrid factory and in a normal factory. The authors noted that the hybrid factory with a manufacturing cell performed better than the traditional job shop. The productivity gains from the cellular manufacturing were combined with an appropriate allocation of resources between the cell and after work centres. The productivity gains allowed the hybrid factory to achieve lower optimum flow times than the traditional JS when the cell was operated at a relatively high operating level than the non-cell work canters.

The same comparison was done by Shambu and Suresh (2000). Unlike most of the past research in group technology, their work examined the entire shop floor, in which the CM systems had cells and another workshop as a functional layout. The performance measures used were flow time, work-in-process inventory, machine utilization and flow ratio. They showed this part family-oriented system significantly outperformed job shop.

Delaney *et al.* (1995) presented a method to design hybrid cellular/functional system. This method is to minimize inter-cell material handling and to maximize intra-cell directional flow. Furthermore, it develops a shop redesign plan that maximizes the net benefit obtained from the facility rearrangement. The facility redesign process encompasses three stages: cell formation, intra-cell layout and time-phased implementation plan.

2.7 Transportation

Material flow in a cellular manufacturing systems is usually supported by a series of materials handling subsystems for intercell and intracell material handling (Schmidt and Jackman, 1999). Automated guided vehicle systems may be used to move unit loads between manufacturing cells as well as conveyer belts. It is important to determine which handling system is adequate to a corresponding layout. Costs, load transfer cycle time, and buffer of outgoing unit are basic factors in selecting an AVG handling system or conveyer system. A conveyer system may be the best compromise between cost and efficiency due to its storage capabilities and easiness to implement. Polajnar *et al.* (1995) proposed a comparison between automated guided vehicle (AGV), automated rail-guided vehicle (ARV) and automated conveyor system (CS) using a simulation model with the program package SIMFACTORY II.5. The authors noticed the flow times and the costs of the belts are lower and the simulation study has shown that the highest productivity of the system is achieved when using automatic conveyor belts as a material handling device.

2.8 Simulation

Simulation plays important roles in designing various production facilities. It can be applied in many different areas ranging from strategic market prediction and business process simulation at the management level of the control hierarchy, to the production cell and process control level. In any case, simulation helps in predicting future behavior of the observed system and can be used as a testing environment for systems that are being designed. Applying simulation can reduce risk and investment on the one hand, and shorten throughput time and lower operating costs on the other (Mušic and Matko, 1999).

Eldabi and Ray (1997) stated that since 1990 the use of simulation programs in manufacturing has mushroomed. This phenomenon can be explained by the following three causes. First, simulation has grown to be the only feasible means that is able to analyze the factories with increasing complexity. Indeed, in order to become more competitive, most factories laid more emphasis on automation to improve productivity and quality and to reduce the costs. Those changes have made most factories' operation more dynamic and complicated, and in turn made simulation the best candidate in analyzing the factories. Second, nowadays the cost of computer hardware required to run simulation programs is very low compared to several years ago. Third, the simulation programs can be understood and operated by managers and manufacturing engineers who may not be simulation specialists.

In 1991, Law and Kelton (1991) presented features desired in simulation software summarized as followed:

- Generating random numbers from uniform probability distribution
- Generating random values from a specified probability distribution
- Advancing simulation time
- Determining the next event from the event list and passing control to the appropriate block of code

- Adding records to or deleting records from a list
- Collecting and analyzing data
- Reporting the results
- Detecting error conditions

There are three types of simulation software: program generators, data-driven simulators and general purpose simulation languages such as ARENA, GPSS, SLAM, SIMSCRIPT and Q-GERT. Data Driven simulators are computer packages that allow modeling systems with little or no programming. They are domain-specific and used to model systems with specific features. Program generators are also used to make simulation more accessible to non-computer specialists. A program generator is a computer program that generates another program. This generated source code may then be compiled or interpreted to present computable simulation model (Eldabi and Ray, 1997).

The main advantage of the general purpose simulation languages over the other two is its capability to model different types of systems with different characteristics. Besides, some simulation languages are developed in an attempt to solve handling manufacturing problems. They have features such as forklifts, conveyors and carts. Program generators and data-driven simulators serve as an approximation of a design (Rogers, 2002). Whereas simulations language may help to optimize design and control under a wide range of variables.

Simulation is considered as a very important computer aid in design process. It is crucial to determine the capability of different simulation software in order to decide the most appropriate software for a simulation project. Kannan and Ghosh (1995) devolved a simulation model for repetitive lots scheduling to improve the set-up efficiency in process layouts. Albino and Garavelli (1999) also conducted a simulation study with limited flexibility in cellular manufacturing. A Matlab simulation model was defined to analyze the system performance over several periods. This model was designed to analyze the level of flexibility for the best trade-offs between productivity and flexibility. They concluded that partial flexibility is the most profitable manufacturing layout of cost and system performances.

Huq *et al.* (2001) conducted a simulation analysis for factors influencing the flow time and through-put performance of functional and cellular layouts. The simulation experiment used the metrics through-put and flow time to contrast performance of a cellular-layout with a functional layout system. The experiment assumed a high level of cell independence and a given part is processed completely within one cell. The full simulation experiment involved 64 combinations of the two input factors, wherein a number of cellular modes with varying set-up time reduction factors are compared with a fixed functional set up time across varying lot sizes. The results suggested that, the performance of a cellular system is worse than a functional system under certain conditions.

Goyal *et al.* (1995) conducted a simulation for analysis of scheduling rules for a flexible manufacturing system. The purpose was to analyze various combinations of scheduling rules in the FMS system and the effect of different scheduling rules at the input loading buffer of the system.

There are numerical technical and research articles reporting development and applications of simulation in manufacturing and service systems. They appear in the *Journal of Simulation* and in *the proceedings of the annual Winter Simulation Conference.*

CHAPTER 3

SYSTEM DESIGN

3.1 Problem Statement

Despite the fact that there are a large number of simulation studies in manufacturing system design with GT technology, very few of the available approaches mainly deal with labor-intensive industry. Among the various types of industries, labor-intensive industries mostly exist in fashion market that requires simultaneous production of a myriad of products. In addition, the production processes usually involve continuous and repetitive operations, and in turn the control of material handling system becomes crucial in production planning. In order to cope with today's competitive markets, the traditional manufacturing system has been replaced by CMS gradually. However, the characteristics of labor-intensive industries seem to be the noises for adopting CMS.

3.1.1 Adaptation of CMS

CM technology is considered as a breakthrough in production management at the time when it was introduced into the industrial environment. A significant improvement in terms of time flow, production expenses and manufacturing system performance attracted production planners to practice this technology in their plants. This strategy, however, may not fit for all types of industries.

Nowadays, many factories in CMS encounter difficulties in adopting the short life cycles of product designs. These difficulties involve common production characters such as batch size, buffer size, set-up time, work-in-process inventory level, and cost. Once a new product design is released into a system, the characteristics of the production process or resource required may not suit the production planning pre-set. As a result, the workload unbalancing problem exists between machines or/and cells. Bottlenecks then emerge along with buffers. Indeed, the performance of CMS deteriorates due to lack of flexibility of adopting customer requirements.

In the past decade, colossal devotion on modifying the originate natures of CMS was proposed to retain the performance of CMS. However, CMS was invented based on the tradeoffs between performance and flexibility. Since 1980, more than 60% of the manufacturing industries in the United States are fully or partially in CM environment (Wemmerlov and Hyer, 1989). It appears that companies tend to retain their physical layouts for possible increments upon the levels of flexibility. Particularly, it becomes thorny while there are designs of material handling systems involved. The limitations of primordial physical layout are likely to generate inevitable hindrance to production planning. An astronomical expense is otherwise required for total reconfigurations or changeovers of manufacturing systems. Furthermore, performance should be kept unscathed. Hence, similar to most research efforts, the problem to be managed under this study is to improve steady-state output rate. Instead of endeavoring to adjust cell formation, however, the physical design of entire system remains the same.

3.1.2 Obstacles in Labor-Intensive Manufacturing

The most common innovation upon CMS is Virtual Cellular Manufacturing (VCM) system. VCM expects the installations of multi-functional or computerized equipments that were customized based on the needs of specific production. Despite the efficiency provided, it is more beneficial for most labor-intensive industries to retain lower level automation than many other industries. There are two causes leading to this fact. First, due to the high-levels of shop-floor employee involvement in production processes, the manufacturers tend to take advantages of lower labor cost in some developing countries. In those countries, the principal problem is the long learning curve on operating computer-controlled machines. Learning new computer skills or developing new programs, however, may be necessary to cater to various customer interests in today's markets. Therefore, long learning curve leads to long lead time. Second, the production procedures that require intensive labor work are usually the similar or repetitive operations with different processes or sequences, such as sewing function in apparel industry. To perform this one type of task, the essential skills could vary depends on product types. Automating this function will minimize the flexibility of this operation.

The advantages of CM technology, however, have attracted their attention that many manufacturers have recognized the importance of introducing the concept into their original system. On the other hand, CM technology disturbs the entire manufacturing process and affects the system performance. Alternatively, each operator from the labor-intensive sector is trained to broaden their skills and work as a team. A team is organized into a manufacturing module. Since the functions of every workstation in a module are identical, the modules could be considered as functional cells. The remaining production sectors could be grouped with CM technology. In fact, many of the labor-intensive industries employ hybrid cellular manufacturing systems.

The main thrust of this research is to derive an approach to implement partial flexibility into a hybrid cellular manufacturing system pre-set. The approach comprises two distinct stages. At the first stage, a three-phase method is introduced to balance workloads and to establish proper level of flexibility. At the second stage, a comparative experiment is carried out to complete the investigation. The effects of production characters are selectively studied in order to maximize the benefits from implementation of this methodology. To perform the analysis, several comprehensive hybrid CMS models are developed using SIMAN/ARENA discrete event simulation environment.

3.2 Hybrid CMS Environment

In this section, hybrid CMS environments are created to ensure that the characteristics and configurations of the manufacturing systems are sufficient to perform the proposed simulation study. The experimental environment has two aspects: the main characteristics of the model and the selections of the experimental factors.

3.2.1 System Description

The hybrid CMS under study is composed of 5 machine-cells, 1 assembly line and 1 packaging line. The machine-cells include three GT cells, Cells 1, 2 and 3, and two functional modules, Cells 4 and 5. The number of machines to form a manufacturing cell is ranging from 4 to 8. Each cell has been dedicated to process part families grouped due to the similarity of machine requirements and production procedures. Three types of products including total 12 different parts are produced. Table 3.1 lists the simulation parameters and code names. They are characteristics of the investigated system. Note that the code names generated are also applied for simulation modeling. Each part is processed consecutively through the workstations according to the pre-set sequence. The settings of operation sequences are diversified because it reflects the variety of product routings. Rapid change of product designs enforces CMS to adopt their diversity of manufacturing processes.

Table 3.1 Simulation Parameters and Code Names

simulation's constant	description	value
N	cell index	n = 1,2,3,4,5
C_n	cell	
M_{nx}	machine x in cell n	n = 1, x = 1,...,5
		n = 2, x = 1,...,6
		n= 3, x = 1,...,4
		n = 4, x = 1,...,7
		n = 5, x = 1,...,8
PA_i	Part i of product A	i = 1,2,3
PB_j	Part j of product B	j = 1,2,3,4
PC_k	Part k of product C	k = 1,2,3,4,5

Based on the former findings, conveyors are suggested for CMS. Because conveyors are the most dedicated material handling system, a proper design of conveyors in the cells leads to significant improvement on system performance (Polajnar, 1995). Moreover, the most common type of conveyor is the unidirectional network system, also known as unidirectional loop conveyor. Accordingly, the cellular layout with unidirectional flow is studied. Every cell is served by a single loop conveyor with machines surrounding. In case of inter-cell movements with batch flow, 4 free-path transporters are prepared to deliver parts between any cell pairs. The specifications and layouts of material handling systems are fixed. Likewise, the settings of transferring speed are constant throughout the production time (Li, 2003).

Buffer storage spaces are also one of the main characteristics of CMS. The principle buffers arise frequently in three locations in a cell. The first buffer is at the input/output station of a cell. Secondly, since the parts are transported with conveyor in a cell, the intermediate space between each pair of workstations is considered as the storage buffer. (Spedding *et al.*, 1998). At last, the buffering is also incurred at the input/output area of each machine. The buffering spaces are indicated in the Figure 3.1.

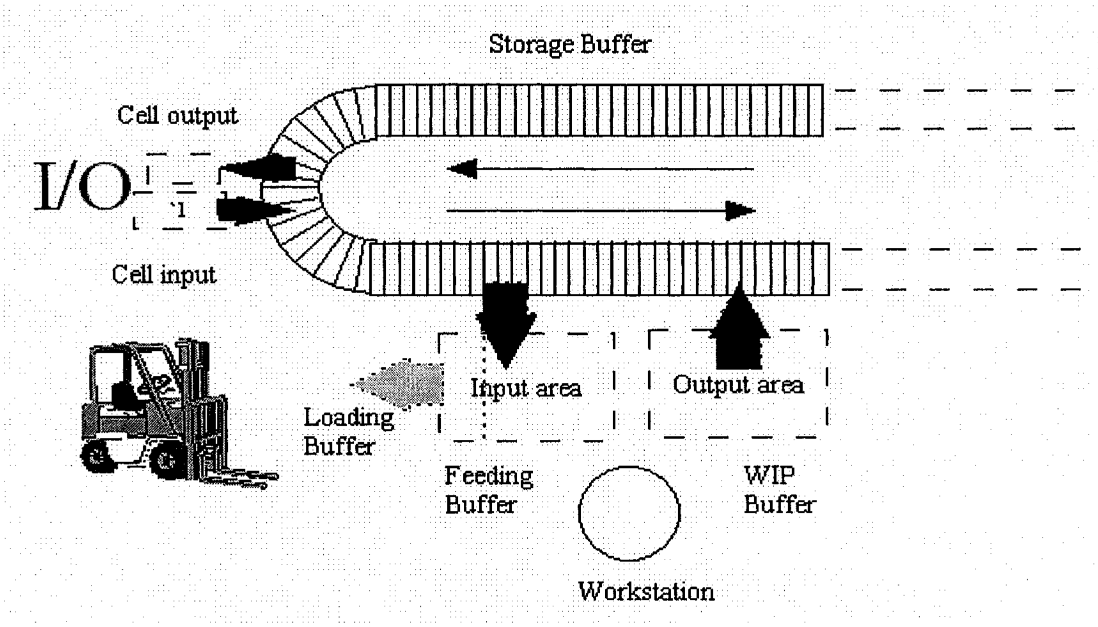


Figure 3.1: Buffering Spaces

The layout of the system is sketched in Fig 3.2. Jobs are launched into the system in the receiving department and removed from the system after terminating the process in the packaging department. The production process includes assembly and packaging. In the assembly cell, there is one workstation at each assembly level. For example, it requires two workstations, one for sub-assembly and the other for final assembly, to assemble a product with a 2-level structure. In the packaging department, there are two workstations that operate in parallel.

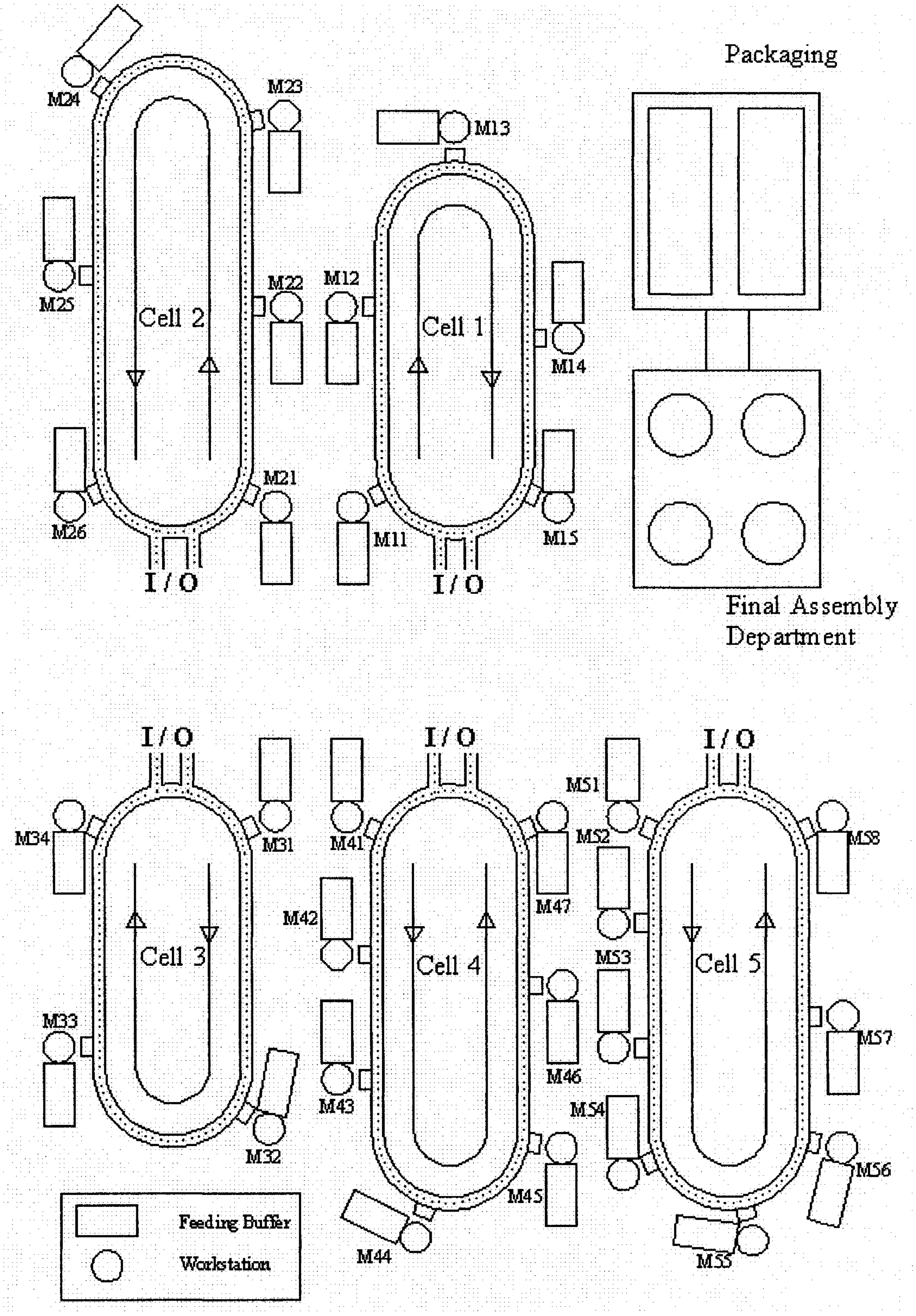


Figure 3.2: Layout of Manufacturing System

3.2.2 Performance Measurement Criteria

The purpose of this study is to show how simulation can be applied to improve a cellular manufacturing system performance without reconfiguring its physical layout. The fundamental principle is to logically rearrange the production system that underlies a flexibility-based approach. In an attempt to compare the performances of the existing CMS with different levels of flexibilities, the study is designed to pursue a dual objective. For one thing, various key inputs, such as layout and number of manufacturing cells, number of machines in each cell, the specifications of material handling system, the number of parts, number and sequences of operations for cell formation are retained the same throughout the whole investigation. For another, in order to carry out a comparable experimentation, a number of experimental factors that may affect the system behaviors vary.

For an experimental simulation model, independent variables affect system performance. Their individual effect may couple with other independent variables and behave additive effects of changes in these variables. Therefore, they are the inputs of simulation models. In this research, nine independent variables are used in order to conduct a comparable experiment for investigation. They are demand pattern, inter-arrival rate, product structure, batch size, set-up factor, set-up ratio, feeding buffer size, subcontracting buffer size, and priority dispatching rule. Their values are set either in a range or in different levels. On the other hand, variables that respond to sways of the independent variables are called dependent variables. Dependent variables may be either process variable or cost-effective outputs.

3.2.2.1 Independent Variables

1. *Demand Pattern*

To respond to market change, most factories are required to introduce more than one product into their production system. The distribution of the different products creates a demand pattern. It has been studied that how demand pattern makes impact on production process and the performance of each machine-cell. Basically, it demonstrates the variability of product mix requirements. It is modeled as product mix level. Previous studies of CMS performance have shown that demand variability is one of the reasons causing bottlenecks and load imbalance. Thereafter, adaptability of different demand patterns is one of the main focuses of organizing CMS and managerial practices. In this study, three different products are considered. Each of them has different level of complexity and has orders in different frequencies.

2. *Inter-arrival Rate*

The discussion of effects of inter-arrival rate on system performance is usually absent in many research reports in this area. Since the inter-arrival process occurs in the very first stage of production process, it determines the machine utilization, MHS availability and WIP inventory levels during entire process. Therefore, ideally, the inter-arrival rate is to be constant to minimize the influence upon system performance. Inter-arrival rate changes, however, depends on various factors, such as customer demand, system capacity and production control. To observe the dynamics of its effects, different patterns of inter-arrival rates are tested.

3. *Product Structure*

Since the manufacturing process is primarily concerned with locating bottlenecks in this study, it is important to determine the impact of product structure on system performance. Product structure is the bond of end-items and spare parts. The sequence to produce or assemble components varies from product to product. The change of sequences may result in additional production time. Product structure is considered to be one of the independent variables in this study.

4. *Batch Size* (Bh)

Cellular manufacturing is also known as batch manufacturing. The original concept of CMS allows small batch production to maintain the flexibility of job shop system. Small batch sizes often result in an inordinately high total setup time. The system becomes instable because the number of jobs launched into system exceeds the throughput rate. In order to diminish this impact on the system, large batch sizes cut down the setup times but lead to high levels of WIP inventory and unstable system performance. Large batch sizes and frequent set-ups result in long manufacturing lead times and less adaptability to customer demand. Accordingly, both of batch size and setup time are used as independent variables in the experiment.

5. *Set-up Magnitude*

The impact of set-up time on system performance drew the attention of many researchers in the past years. The importance of set-up magnitude has been highlighted when investigating cell or system capacities. It has been concluded that the setup magnitude can be controlled with two parameters: set-up factor (*d*) and the set-up ratio (*r*). To study the effect of set-up time, both parameters were considered.

The set-up factor involves a major and a minor set-up. The ratio of minor to major set-up defines the *d*. Major set-ups take place when two consecutive operations processed on a machine belong to the batches from different part families. On the other hand, if the succeeding job belongs to the same part family of the former job, minor set-ups incurred due to the set-up time reduction. The *r* is the ratio of set-up time to batch run time. The batch run time was obtained by multiplying the mean processing time of a job by the batch size. Set-up time is the preparation time for a machine to process the entire batch of parts.

6. *Buffer Size*(Br)

Buffer size is another vital independent variable to examining system performance especially when the design of material handling system is included (Hurley and Whybark, 1999). Generally, there is no central storage resource involved in a CMS for placing semi-finished products or WIP inventory. It is rather to transfer parts to visit every workstation in sequence directly. Therefore, the small buffer storage resources are found between individual workstations, the queue lines before and after serving, and input/output stations of each cell. The capability of this storage resource is known as buffer size. It is defined as the upper bound on the number of products that can be stored in an inventory.

Studying this variable aims to observe the impact of buffer size on a CMS. The resource of buffer storage has dual functions. On one hand, it is considered as a safety stock. The system performance can be influenced by the unexpected breakdowns or idleness at a workstation. This risk can be diminished by having proper buffers. On the other hand, it is also considered as WIP inventory. This inventory engages expensive floor space and forces a longer flow time. In the meantime it provides buffering, and it burdens the system with numbers of semi-finished products physically and economically. Obviously, the selection of the buffer size is a crucial management polices for overall system performance. Two types of buffers allocated to the station input area are considered. One is the feeding buffer, related to the length of the queue line. The other is the subcontracting buffer, existing at each bottleneck machine. It indicates the start-up of inter-cell movements. Once the queue length hits its upper bound, the incoming parts have to be processed by alternative machines in other cells.

7. *Priority Dispatching Rules*

Dispatching rules play a significant role on production planning in which it responds to the changes of demands, particularly in dynamic environments. With the help of priority dispatching rules, proper arrangement of job sequence shortens the lead time. It is, however, challenging to find optimal rules to meet the overall objectives of a system. In this study, material handling system problem and buffering problem at workstations are the principle subjects. Parts accumulate in the queues to be loaded on conveyors and make machines available. The sequence to release a part from a queue becomes crucial for final assembling. Therefore, priority dispatching rule is considered as an independent variable.

3.2.2.2 Dependent Variables

Dependent variables numerically indicate the measurements of system performance. They vary with independent variables. Three primary performance measures are used in this study collected: total throughput, average WIP inventory level and average transfer cost. Furthermore, two secondary measures are used: the number of inter-cell movement and cell output. Performance measurements are summarized in Table 3.2. The results will suggest better combinations of CMS characteristics in real world applications.

Table 3.2: Summary of Performance Measurements

Performance measure	Description
Total Throughput (TT)	total number of finishing goods
Average Transfer Cost(ATC)	average cost spent in transfers (transporters and conveyors) per part
Average WIP Inventory(AWIP)	average number of parts in the system
Cell Output(CO)	total output of a cell
Number of Inter-Cell Movements (NM)	the frequency of traveling between cells

CHAPTER 4

MODEL DEVELOPMENT AND THREE-PHASE METHOD

4.1 Development of the Simulation Model

A simulation model based on the CMS model described in Chapter 3 was developed using ARENA simulation package. ARENA is a general purpose simulation language. Manufacturing system design process commonly involves many parameters and assumptions. Simulation is a useful tool to helping such process. In this research, modeling for the proposed CMS is completed with ARENA. Furthermore, three specific tools, *Output Analyzer*, *Process Analyzer*, and *OptQuest for Arena*, along with ARENA have been used for different purposes. They provide sufficient resources for a better understanding of different "what if" scenarios, interaction between independent and dependent variables, as well as to find optimized solutions. Also, they help perform verification and validation to ensure the correctness of the model and to improve the manufacturing system design.

For this research, a pre-set CMS layout was modeled to solve the problem. A three-phase method is derived throughout the simulation modeling. Initially, the CMS model was built with all machines in each dedicated manufacturing cell. The production time was attached to a specific machine. Accordingly, machine utilizations indicate the candidate bottleneck machine if there is any. Thereafter, partial flexibility is introduced into the system. In the second phase, the workload on the bottleneck machine was reduced by sharing with the adjacent machine in the direction of product flow. In the third phase, considering the entire system as a colossal cell, the bottlenecks are located based on the performances of machine-cells. In this way, inter-cell travel is allowed to balance the workloads between the cells. The significance of this approach emphasizes on solving critical bottlenecks in order to balance workloads. The final model may not be optimal due to the limited flexibility. The design process tends to keep flexibility in a proper level to minimize the possible intra-cell and inter-cell movements.

4.1.1 Constrains and Assumptions

The basic assumptions used to build the model are:

1. Raw materials are available at the instant of order release.
2. Each part requires load, unload and processing time at each station it visits.
3. Each batch requires a set-up time.
4. Set-up times are constant at each station of each cell.
5. Capability of each machine is fixed.
6. Each part is assigned a strictly ordered operation sequence.
7. The operation sequence is assigned at the beginning of the simulation at any given instance. No additional jobs allowed; no parts are rejected.
8. Resources are reliable. No material handling system or machine breakdowns.
9. A material handling device performs only intra-cell or only inter-cell transfers.
10. A machine is allowed to be revisited more than once if necessary.

4.1.2 Input Parameters

4.1.2.1 Job Arrivals

Three different products (Product A, Product B, and Product C) could be produced in this system. It was assumed that the demands were equally distributed and each order comes with two products. The probability of a part type took place in an order varies depending on the complexity of the products. The number of components that comprise Products A, B, and C were 3, 4, and 5, respectively. Thus the population of the part types was 12 (3 PA_i, 4 PB_j, and 5 PC_k). Their product structures were all single-level. The interarrival times were random. Then, a stream of new jobs arrived in a system was assumed to be distributed exponentially with mean interarrival time of 22 minutes. Exponential distributions are suitable to model independent random arrival processes in simulation. They are used in testing the model developed in this research.

4.1.2.2 Processing of Jobs

Jobs vary in terms of process sequences, number of operations, and processing times. The matrices of process sequences and processing times are provided in Appendix I. The job processing times for operations on all machines were given with triangular distribution. Once a new job arrived, a set of operation sequence it was assigned. Only PC_5 can be produced exclusively in one cell, C_5. All the other parts visit two or more cells to complete the process. In contrast to the design process aiming at cell formation, part assignment is required in this research. Thus the part families can be drawn from process characteristics, such as operation sequence and machine types. The part families are shown in Table 4.1.

Table 4.1: Part Families

Part Family	Parts		
1	PA_1	PA_2	PB_2
2	PB_3	PB_4	
3	PC_3	PC_4	PC_5
4	PA_3	PB_1	PC_1

4.1.2.3 Material Handling System

As described in Section 3.2.1, the unidirectional loop manufacturing system was considered in this study. Each cell is served by a single conveyor. Between the cells, there are 4 transporters prepared for forced inter-cell movements. The material handling speed settings were 60 distance units per minute for each conveyor and 295 distance units per minute for each transporter. Since each part has a fixed routeing sequence, machines were located around a circular conveyor belt loop to reduce material handling cost. Every loop has one input/output (I/O) station. The workstations were arranged for a downstream flow. Excessive transferring movements may be required. If a part goes through downstream workstations ahead of upstream workstations, or the repeating operations are needed at the different time, the part is forced to pass the I/O station more than once. For all machines, loading and unloading time were set to be 0.1 minute and 0.08 minute, respectively, in this simulation study.

4.1.2.4 Simulation Run

The system was simulated for 10 replications. In each simulation run, a different stream of randomized seeds was reset after a 9600-minute start-up period. Pilot runs were performed to determine the length of warm-up periods to reach a steady state. A

2000-minute warm-up run was allocated during the data collection.

4.2 Proposed Solution Approach: Three-Phase Method

4.2.1 Phase I- Dedicated Machines and Bottlenecks Locating

Create Jobs

The first creation happened at the beginning of each simulation run and the machines were immediately available. The orders were released in a lot of two. At any given instance, as long as a new order was introduced into the system, it was assigned the necessary entity data or attributes. The aim of assignments was to facilitate further modeling process and the collection of statistical results. One entity could be a complete product or an individual part. An order was broken down into parts at the initial stage of production. Therefore, the entity indicated here is a part. Entity data given at this point includes part identification and unit holding cost. The number of parts and number of part types were defined with attributes of part distribution and part index. Subsequently, each part must follow an operation sequence. The part, finally, starts to seek the I/O station of the first cell in the sequence.

Dummy Machines

The I/O station was represented with two dummy machines: dummy station 0 for Input and dummy station 1 for Output. Parts look for the dummy station 0 of a candidate cell and load on the conveyor belonging to the cell. To exit the loop, a decision making must be processed. If a part already accomplishes the last step of operation in this cell, it will be sent to dummy station 1 and then exit the loop. Otherwise, the part travels to the next workstation in sequence. Therefore, to define operation sequences, dummy stations 0 and 1 were included. The logic was presented in the flowchart of production flow as shown in Figure 4.1.

Workstations

There are six possible resource states at a station. They are processing, starved, blocked, failed, waiting for setup, and setup. The situations of blocked and failed were not taken into consideration in this study. While a unit is conveyed to a workstation, ARENA decides if the unit should be unloaded from the conveyor depending on the number of parts waiting in queue for operations. This feeding buffer size was assumed to be 30 units for all workstations. If the space on the queue line is all occupied, the unit takes the advantage of the storage space on the conveyor. Otherwise, the unit enters the queue line to wait for its turn. The dispatching rule was First-In-First-Out (FIFO). The flow diagram is shown in Figure 4.2. The entering unit then was assigned the resource state of waiting for setup. An operator was seized for set up. After a delay of set up time, the operator was released and available for processing. The set up times are normally distributed with a mean 2.5 of minutes with a variance of 0.3 minute. The distribution was chosen because it is consistent with earlier hybrid CM studies (Burgess *et al.*, 1993). The processing time for a batch depends on the part types. The operator considered as a resource now was released for the next task. The post-operation buffer locating between the machine and the conveyor is a loading area. Afterward, the parts were delayed for loading on the conveyor. In addition, non-accumulating loop conveyors were incorporated into this manufacturing system. Whenever there were any loading or unloading activities, the conveyor temporarily stopped for the duration set for loading time or unloading time.

The total time an item spent at a workstation is displayed in Figure 4.3. The values are shown in Appendix II. The total time was the sum of average service time, average queue time and other time. The other time is the time a unit stayed on the conveyor waiting to be served at the machine assigned. The experimental results show that the bottleneck machines are M_{11}, M_{13} for C_1, M_{24}, M_{26} for C_2, M_{32}, M_{34} for C_3, M_{43}, M_{47} for C_4 and M_{54}, M_{55} for C_5. As pointed out in the recent research (Sheikhzadeh *et al.*, 1998), to improve cell productivities, the workloads of these bottleneck machines should be balanced with higher system flexibility

4.2.2 Phase II - Workload Balancing within a Cell

To balance the workload in a cell, a partial flexibility was relaxed for production. The intra-cell machine sharing was then allowed under the condition that the first downstream machine of a bottleneck machines was not busy. The jobs for the bottleneck machine can be sent to the workstation of either the one scheduled or the neighboring one. ARENA selects it based on the queue lengths of the two workstations. The queue with fewer units waiting has the priority. However, the jobs for the first downstream machine remained the same. Minor changes were added on the model of the first phase as Figure 4.4 shows. Therefore, the machine sharing is paired as $\{M_{11}, M_{12}\}$, $\{M_{13}, M_{14}\}$, $\{M_{24}, M_{25}\}$, $\{M_{26}, M_{21}\}$, $\{M_{32}, M_{33}\}$, $\{M_{34}, M_{31}\}$, $\{M_{43}, M_{44}\}$, $\{M_{47}, M_{41}\}$, and $\{M_{55}, M_{56}\}$. The outcomes of Phase II are shown in Figure 4.5. It can be seen that the average time a unit spent at the busy machines was reduced dramatically. Moreover, the workload within each cell was balanced but not for the entire manufacturing system.

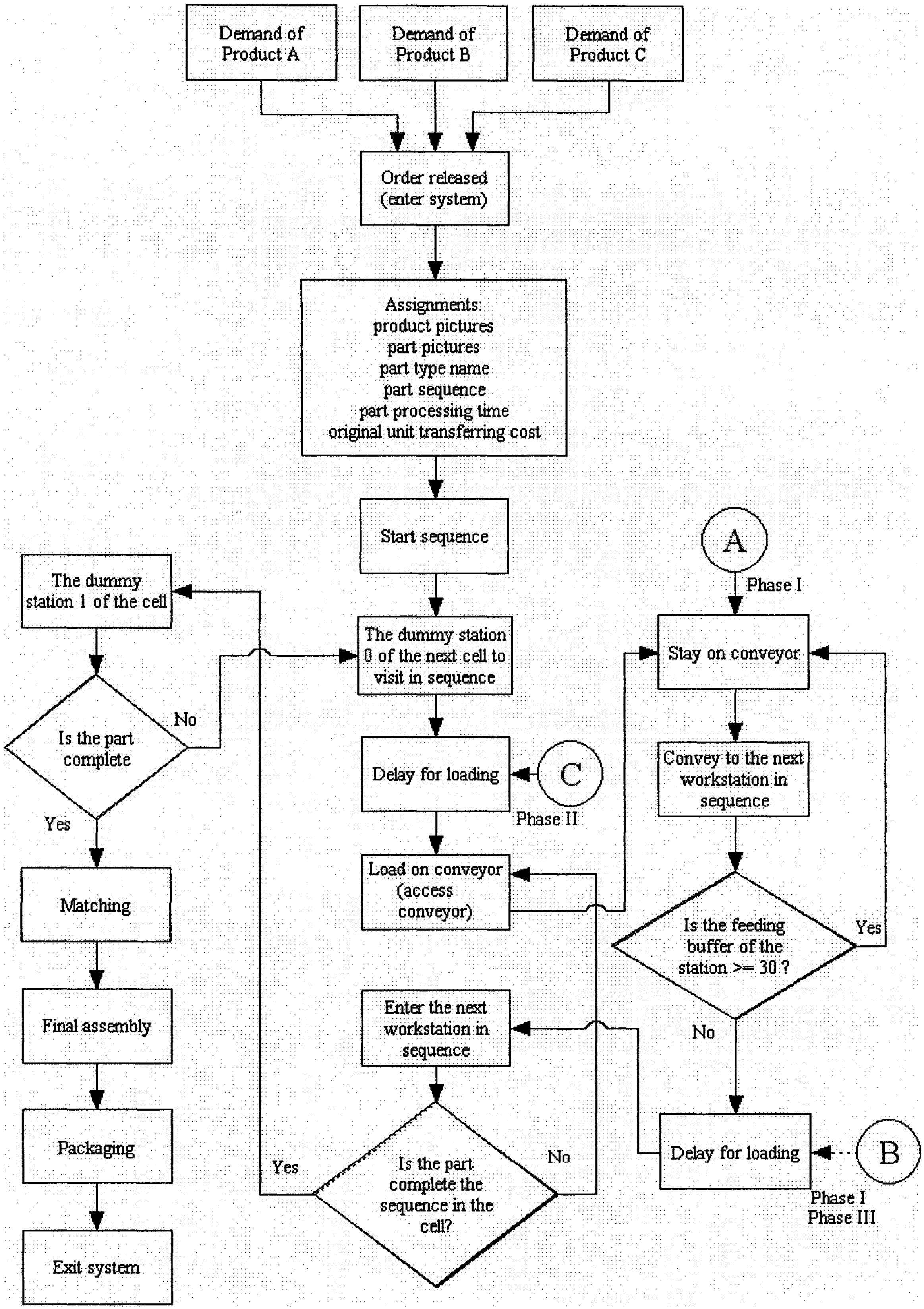


Figure 4.1: Production Flow

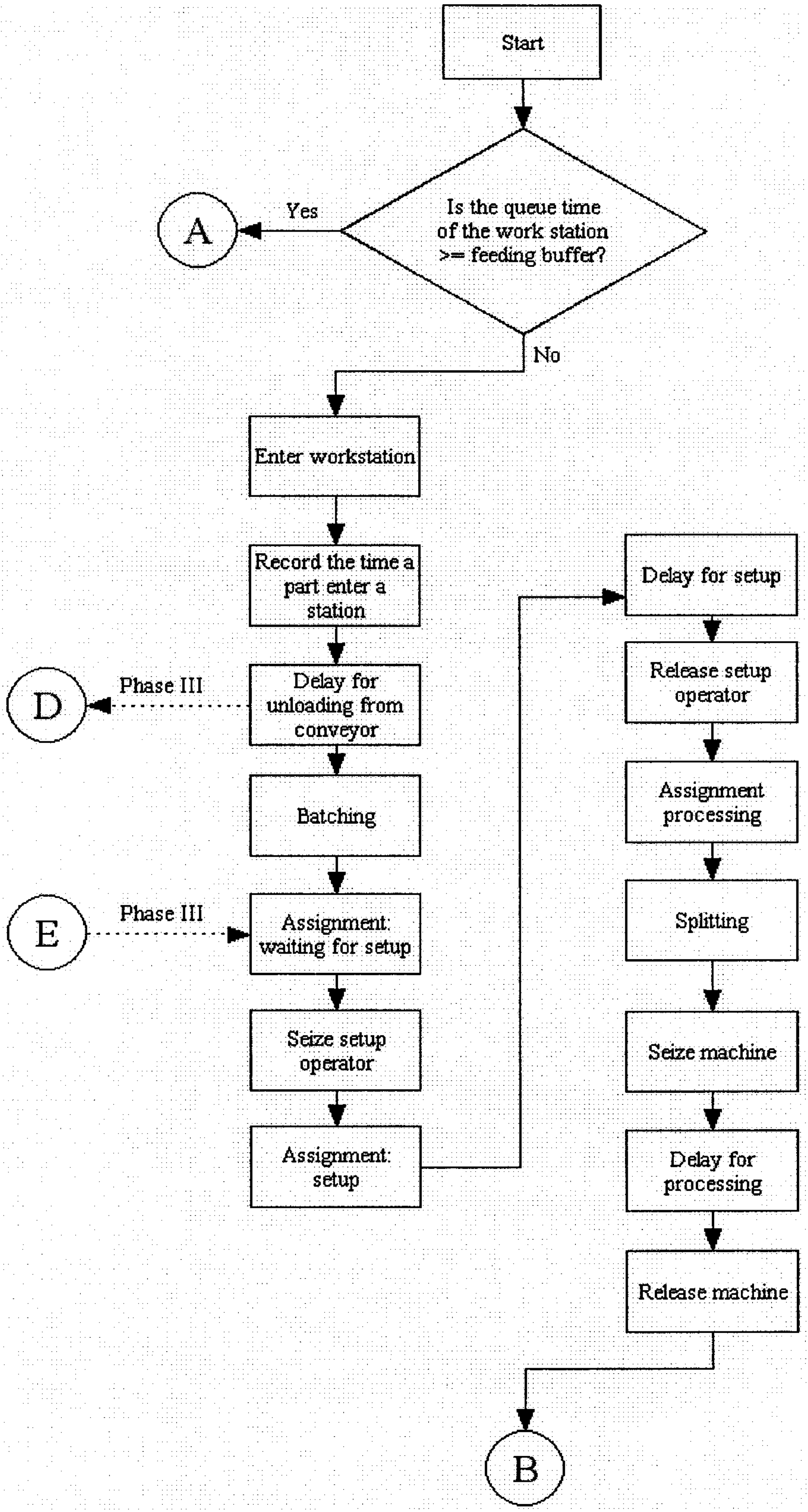


Figure 4.2: The Logic of Phase I Experiment

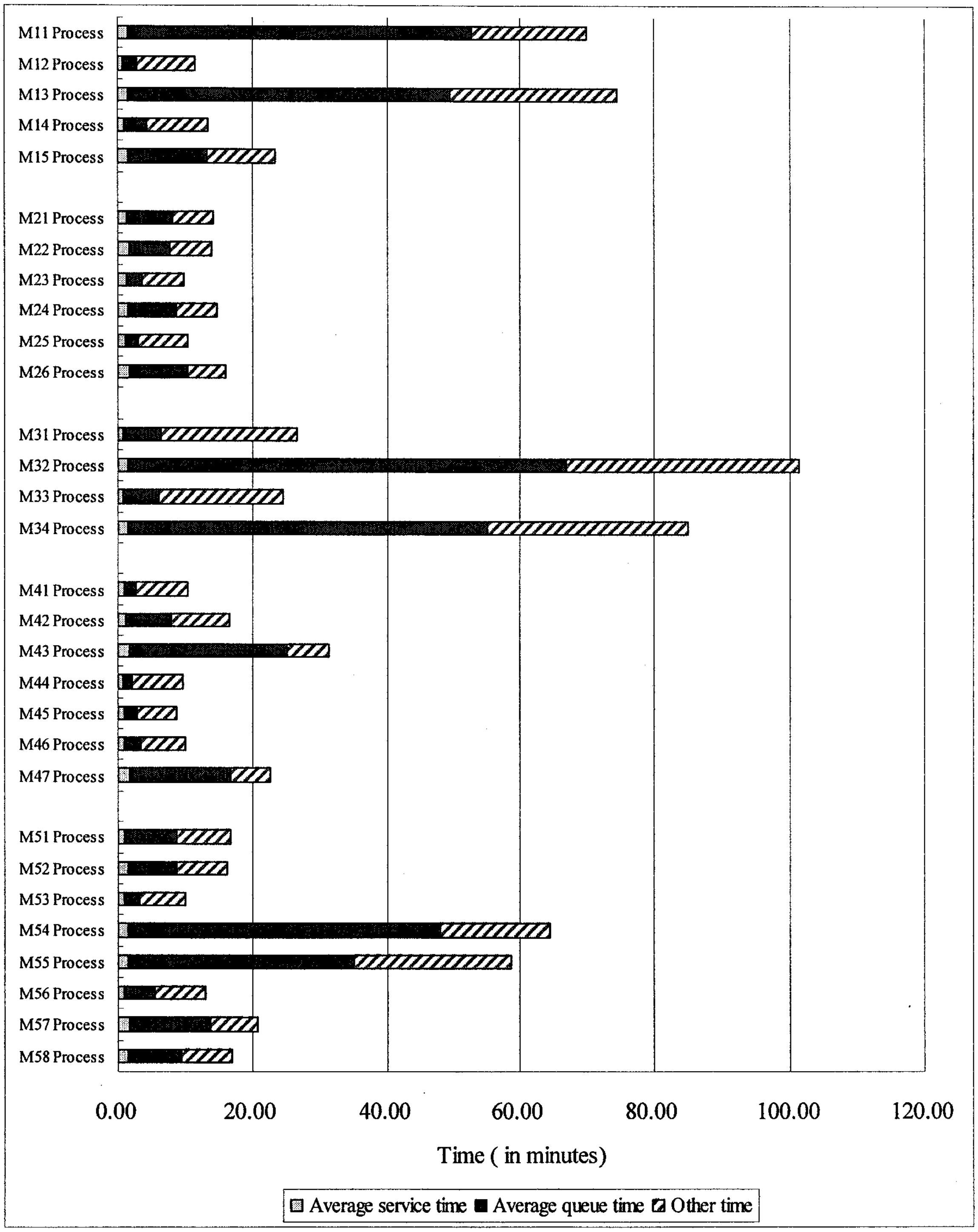


Figure 4.3: The Results of Phase I Experiment

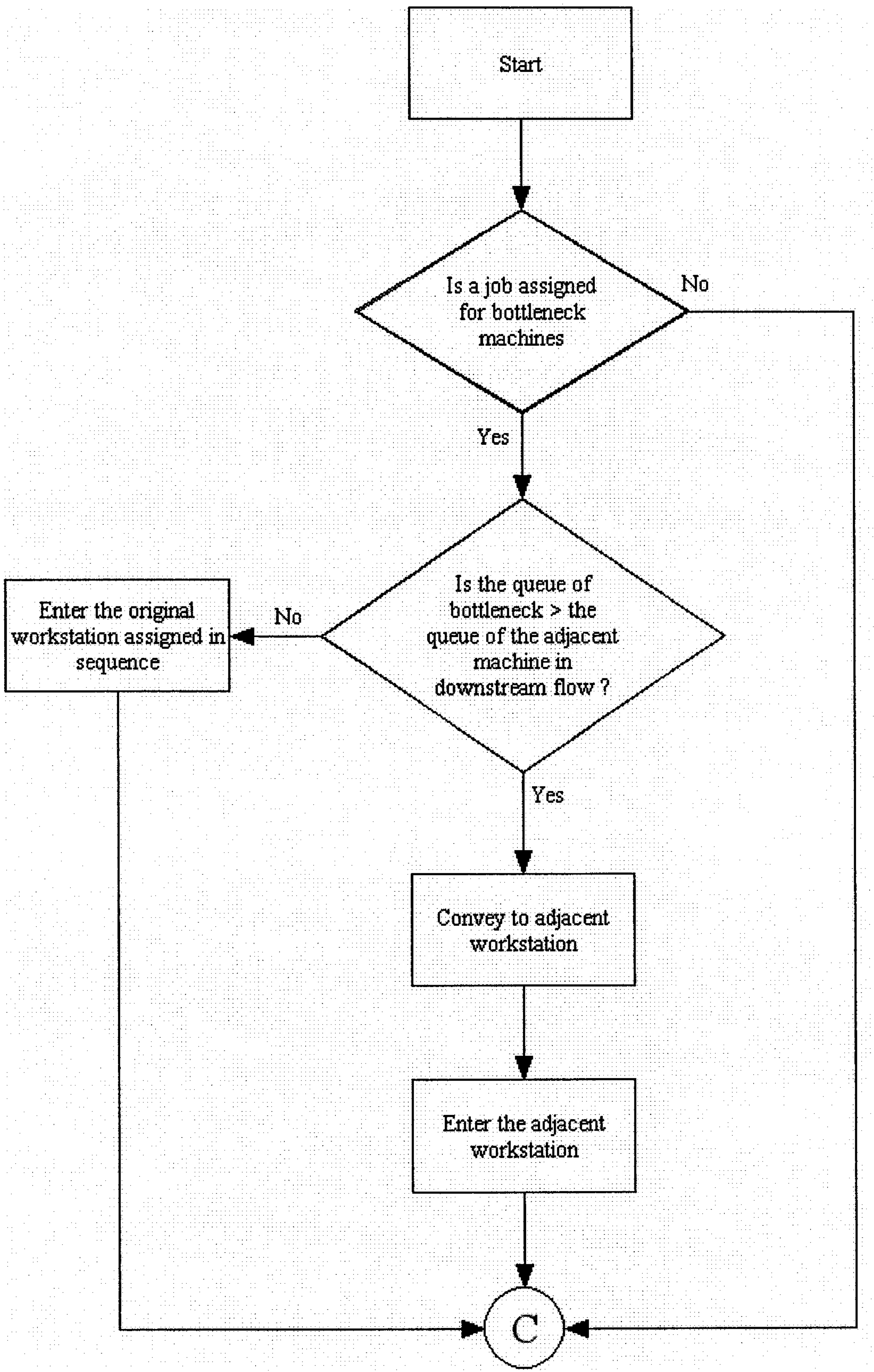


Figure 4.4: The Logic of Phase II Experiment

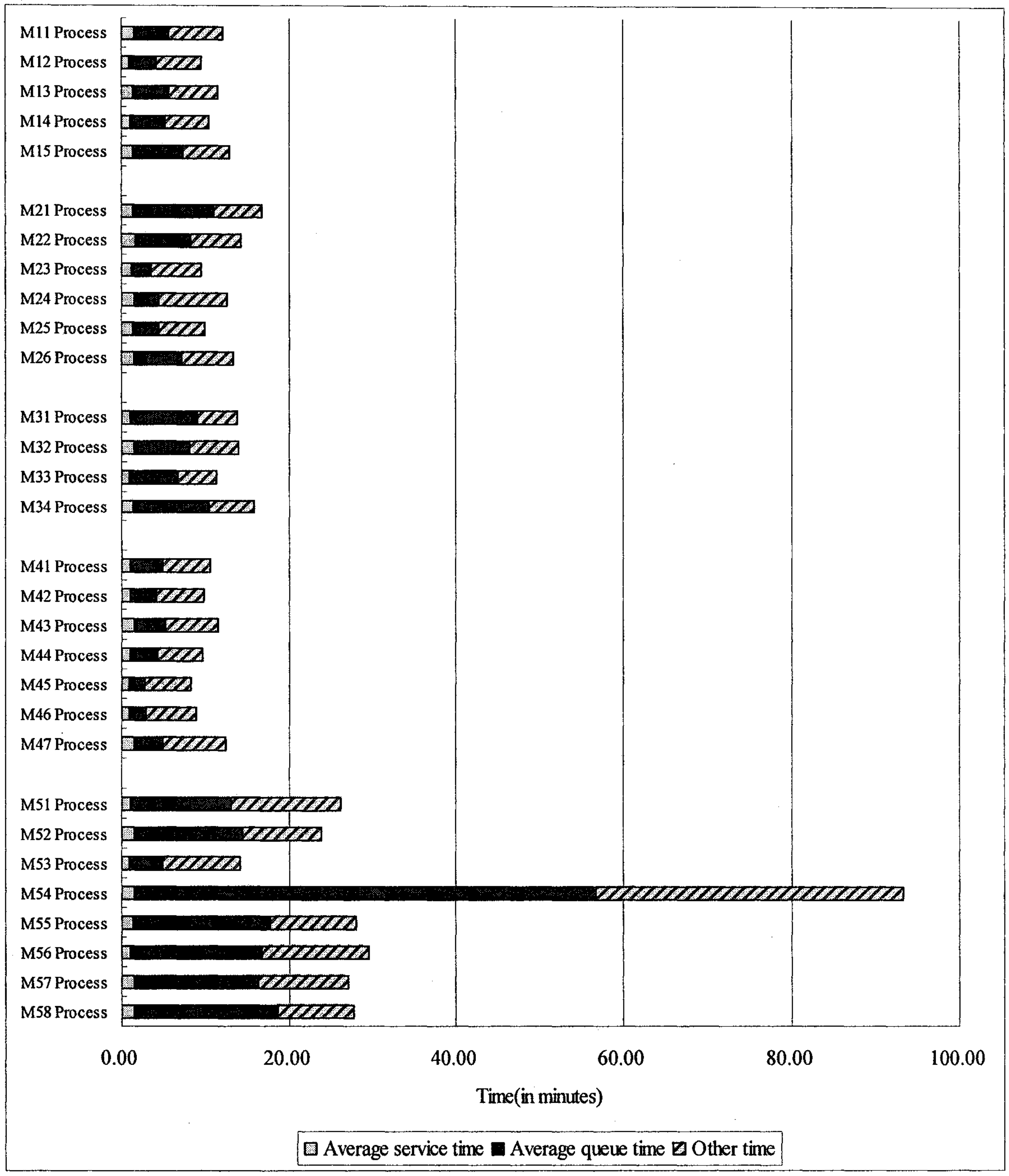


Figure 4.5: The Results of Phase II Experiment

4.2.3 Phase III - Workload Balancing within the System

The performance of individual cell improved based on the solution of the second phase. Not all of the parts, however, were able to complete their sequence in a cell. In a system, a cell that has more workloads is likely to affect overall production flow. In Phase III, the goal was to improve the productivity of the entire system. In Phase II, the average queue time at every workstation of cell 5 was quite long. This is due to the lack of flexibility at M_{54}. In Phase II, M_{54} was not allowed to share with M_{55} since M_{55} was also a bottleneck machine. Due to the delay at M_{54}, the succeeding operations cannot be processed. In view of this, the unit that is also required to visit other workstations had to wait a considerable amount of time.

To balance workload between manufacturing cells, the concept of virtual cellular manufacturing system was applied. A virtual cell is generated by logically reforming a cell without physical reconfiguration. Inter-cell transferring was allowed. The selection of the candidate machines for sharing the jobs of the bottleneck machines should be based on the qualities of cells. According to the hybrid CMS system investigated in this study, the personnel in cell 4 and cell 5 were trained for multi-task skills to form a cell as a module. In this way, any operations in these two cells can mutually support or cooperate, and, meanwhile, they were capable of sharing the workload of other production cells. In addition, the machines in cells 1, 2 and 3 were able to perform secondary tasks if necessary. According to the system layout, M_{54} can share workloads to M_{45}. The set up time for the jobs from external cells were assumed to be higher. They were normally distributed with a mean of 4.2 minutes with a variance of 0.5 minute. To maximize the productivity, three more pairs of inter-cell sharing were also assigned. They were {M_{15},

M_{46}}, {M_{12}, M_{21}} and {M_{42}, M_{31}}. Each pair of machine sharing was assigned a transporter, and in turn resulted in additional delay for loading and unloading work pieces from the material handling device.

Two flow diagrams are presented as below. Figure 4.6 shows the flow of the parts from the original cell to the other cell and back to continue the sequence. The size of feeding buffer of those busy machines, M_{15}, M_{21}, M_{31} and M_{54}, were assumed to be 20, 20, 20 and 10, respectively. The smaller size for M_{54} was for generating more frequently inter-cell flows. If one of their queue lines is full, the transporter will come to deliver a batch over the supporting machine. The transferring batch size was four, same as the processing size. Once the batch entered the other cell, the units were easy to mix with the jobs of the supporting cell. Therefore, all jobs were affixed with attribute names and a higher unit transferring cost before they left the original cell. In the meantime, new set-up times were assigned for those external jobs. After processing, the jobs were collected according to their attributes. Every activity of transferring was recorded to calculate the number of inter-cell movements. Figure 4.6 also shows the flowchart of receiving the jobs from other cells, and sending them back to their original cells. Some of the experimental results of this system are shown in Figure 4.7.

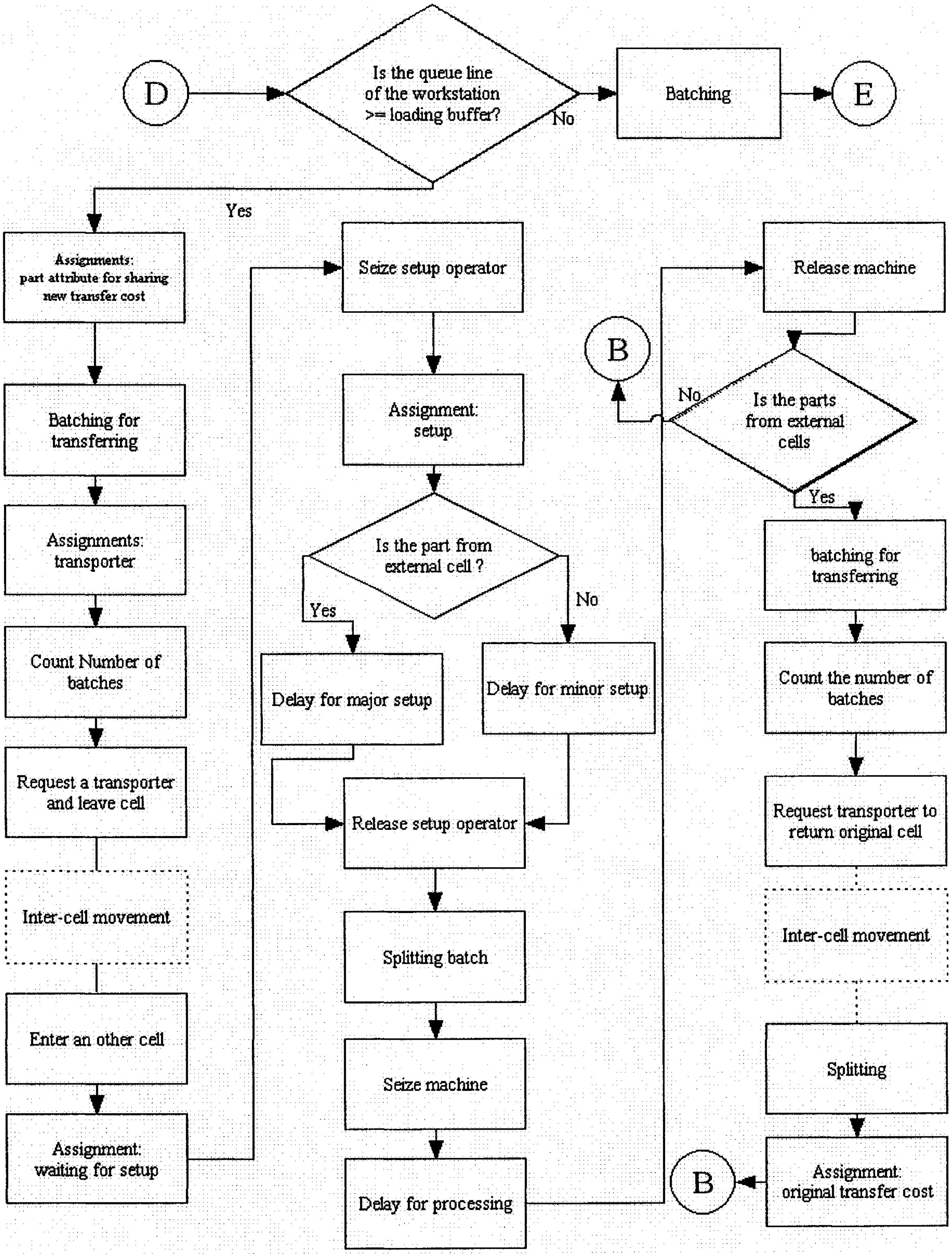


Figure 4.6: The Logic of Phase III Experiment

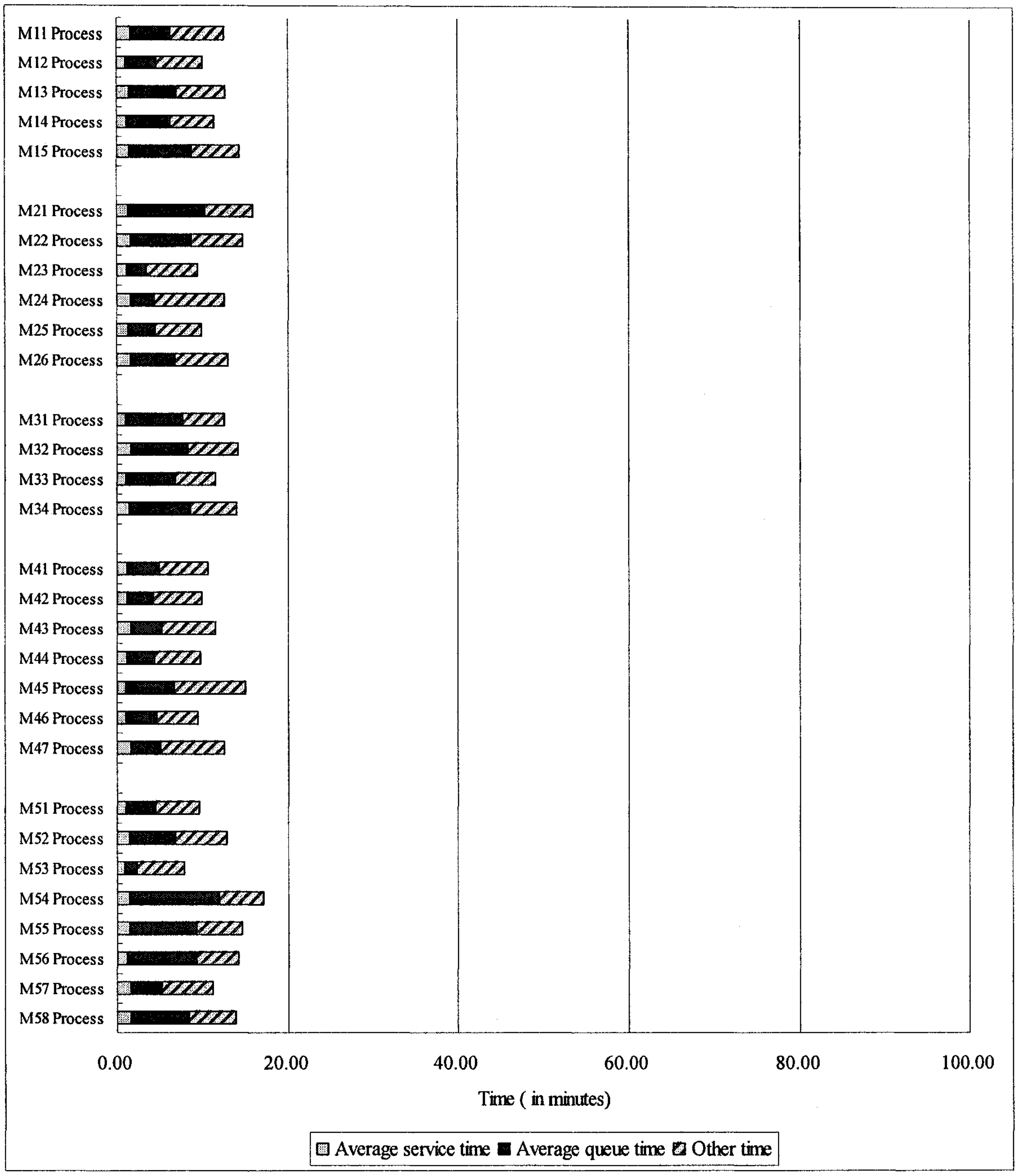


Figure 4.7: The Results of Phase III Experiment

CHAPTER 5

SIMULATION RESULT AND ANALYSIS

Output analyses of statistical results are presented in this chapter. The analyses were performed with an experimental design with 60 different production scenarios. The features of the system were investigated by comparing the performances of every scenario. However, since each simulation result was generated from a different random number stream, the output data of simulation exhibited random variations due to input variability. The first issue, therefore, was to reduce the effect of bias caused by this unrealistic initial condition. Multiple comparison tests were employed to confirm the statistically significant differences among the simulation results of the three phases. In order to conduct experimental simulation analyses, nine independent variables were used. Next, correlation tests were conducted for both independent and dependent variables. Different combinations of independent variables were compared to observe system behaviors under different scenarios. Finally, the optimization function of OptQuest was utilized to seek for better system features. The obtained sub-optimal solutions can suggest more appropriate production plans and better system performances.

5.1 Warm-up Conditions

The simulation models of this study were considered as non-terminating systems. To facilitate statistical analyses, the starting and stopping conditions are essential; therefore, it is crucial to minimize startup bias. In a steady-state simulation, however, the input variability can simply be worn off by running a long simulation time. Yet, the bias stays present for non-terminating simulations. For this reason, the data collected during the empty-and-idle state was dropped and considered as a warm-up stage of a simulation run. To estimate the length of the warm-up period, 100 of WIP levels were monitored as a signal for detecting biased effect. Figure 5.1 shows the resulting plot of the WIP across the simulations. Each simulation initiated with a buffer with no work in the system and appeared to stabilize when the jobs move further down the operation sequences. The warm-up period then is estimated to be 1500 minutes from the curves of 100 replications superimposed. To be more conservative, the duration has been rounding up to be 2000 minutes. Figure 5.2 plots the trends when the biased effect of the artificial initial condition has worn up. Evidently WIP levels turned to be consistent throughout simulation runs and cross replications.

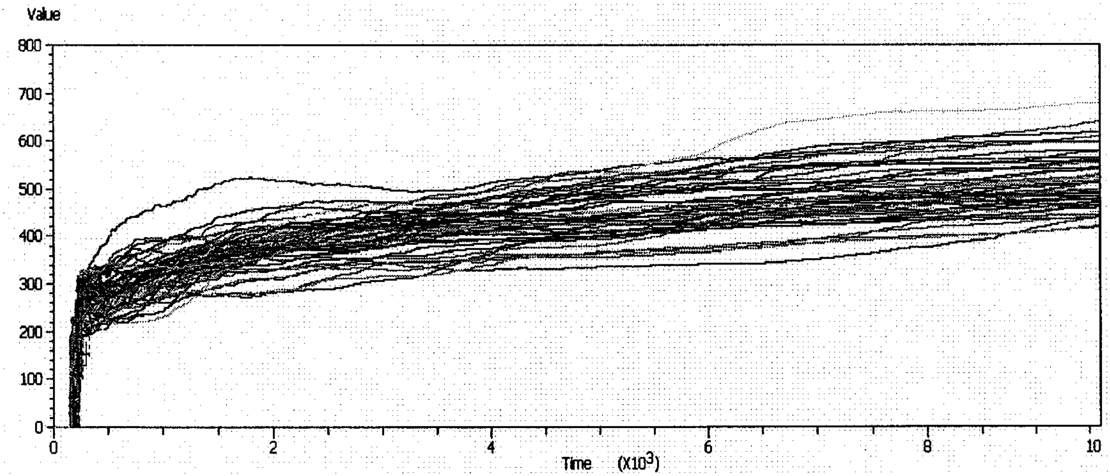


Figure 5.1: Within-Run WIP Level Plots

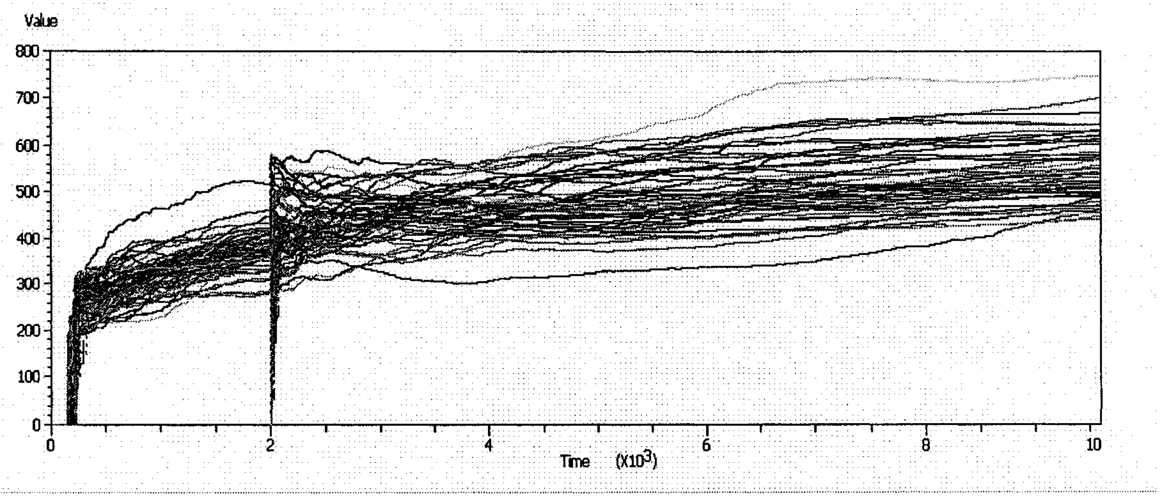


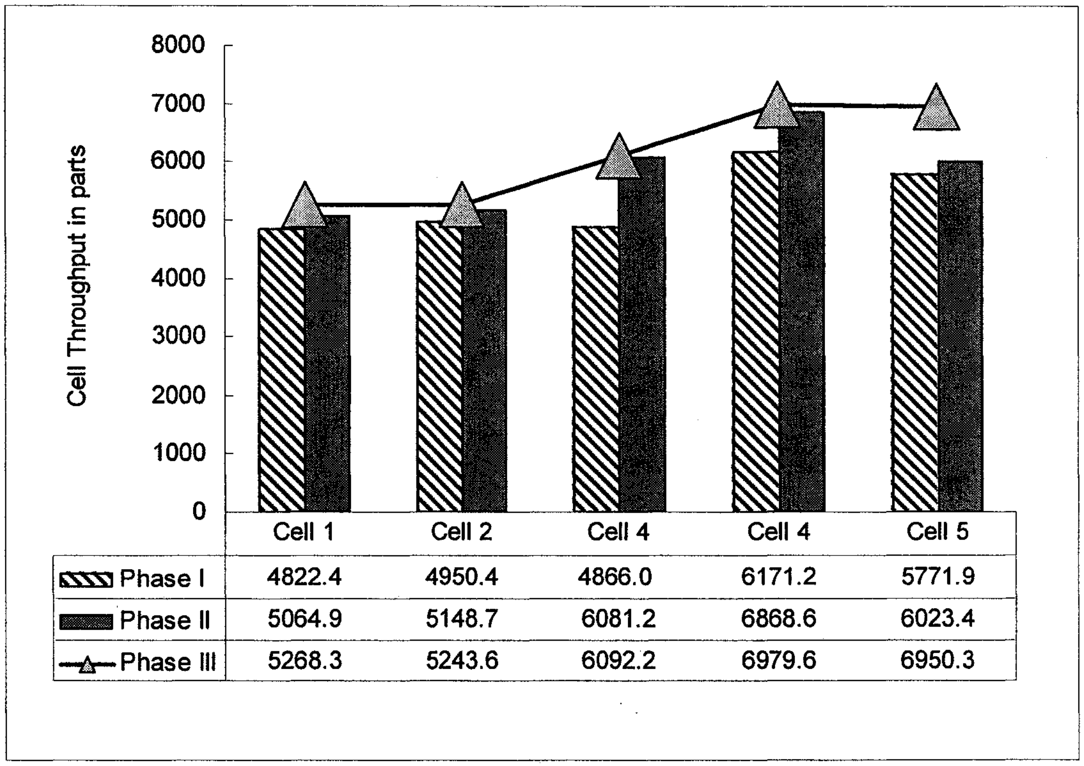
Figure 5.2: Within-Run WIP Level Plots with Warm-up Period Specified

5.2 Performance Improvements

When a degree of flexibility is relaxed, the effect upon performance is the first issue raised for further investigation. Performance can be observed by focusing on a certain cell or considering the whole production system. The production planning can be different depending on what aspect of performance is interested. Cell performance and system performance are both discussed throughout the three phases of the simulation study.

5.2.1 Cell Performance

For each phase, the output of each cell was shown in Figure 5.3. A significant cell improvement occurs in Phase II experiment but not in Phase III. The improvement mainly resulted from intra-cell machine sharing. In Phase III experiment, the greater flexibility provided by possible inter-cell transferring did not have much impact on cell performances. However, for C_5, the rate of increase in Phase II - Phase III is much larger than the rate of increase in Phase I - Phase II. This explained that while intra-cell machine sharing was not applicable to a cell, inter-cell machine sharing then brought into effect. It can be concluded that the selection of partial flexibility should be based on the behavior of the cell. Similarly to other research (Potts and Whitehead, 2001), a proper level of partial flexibility could improve the performance of the cells.

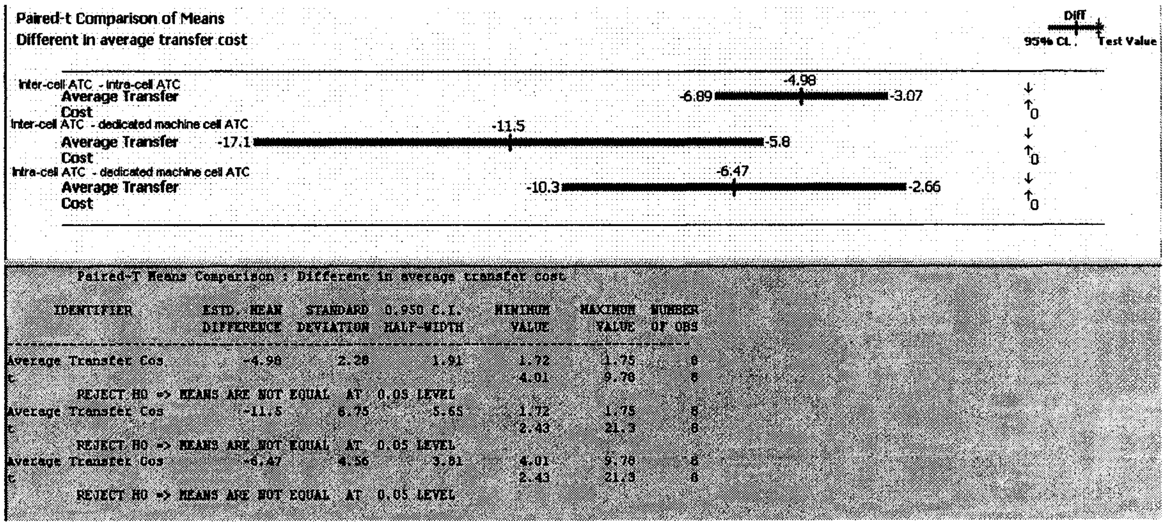


	Cell 1	Cell 2	Cell 4	Cell 4	Cell 5
▨ Phase I	4822.4	4950.4	4866.0	6171.2	5771.9
■ Phase II	5064.9	5148.7	6081.2	6868.6	6023.4
△ Phase III	5268.3	5243.6	6092.2	6979.6	6950.3

Figure 5.3: Cell Outputs

5.2.2 System Performance

A Tukey's multiple comparison procedure is performed to test the significances of performance improvements in total throughput, average transfer cost and average WIP. It is also known as Tukey's honestly significant difference (HSD) test. Tukey's test compares the differences between each pair of means. Pair-wise test is a statistical test that determines whether there is a significant difference between the two means. The results are presented as a confidence interval. The Output Analyzer provides the results with a 95% confidence interval on the expected difference. In this simulation study, the differences between the results of every two phases were of the observers' interest. The basic idea behind a t-test was to run a two-sided hypothesis test. The null hypothesis is that all means across different models are the same. When the null hypothesis of equality is rejected, there is indeed a significant statistical difference. Figure 5.4, Figure 5.5 and Figure 5.6 provide the results of comparison tests crossing all phases for total throughputs, average transfer costs, and average WIP, respectively. They all showed that the confidence intervals missed zeros. The Phase III model was substantially improved compared to previous two phases since the subtractions of intervals were all far away from zero. If the interval is too close to zero, it may be treated as random noise, which represents insignificant difference in comparison.



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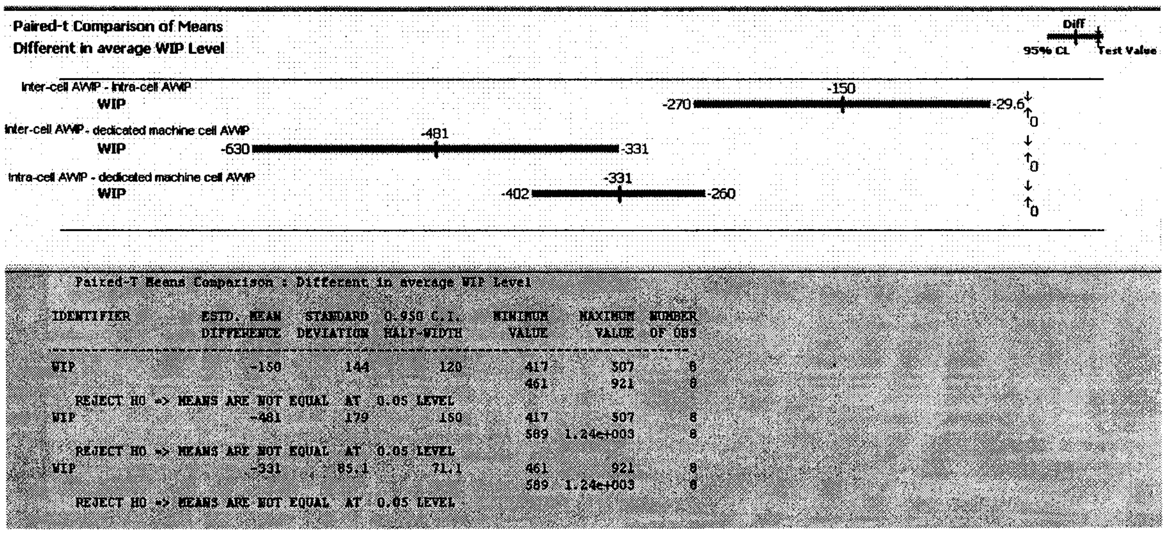
        Paired-T Means Comparison : Different in average transfer cost

    IDENTIFIER            ESTD. MEAN   STANDARD  0.950 C.I.     MINIMUM     MAXIMUM  NUMBER
                          DIFFERENCE  DEVIATION  HALF-WIDTH       VALUE       VALUE  OF OBS
-------------------------------------------------------------------------------------------
Average Transfer Cos           -4.98       2.28        1.91        1.72        1.75       8
t                                                              4.01        9.78       8
        REJECT H0 => MEANS ARE NOT EQUAL  AT  0.05 LEVEL
Average Transfer Cos           -11.5       6.75        5.65        1.72        1.75       8
t                                                              2.43        21.3       8
        REJECT H0 => MEANS ARE NOT EQUAL  AT  0.05 LEVEL
Average Transfer Cos           -6.47       4.56        3.81        4.01        9.78       8
t                                                              2.43        21.3       8
        REJECT H0 => MEANS ARE NOT EQUAL  AT  0.05 LEVEL
```

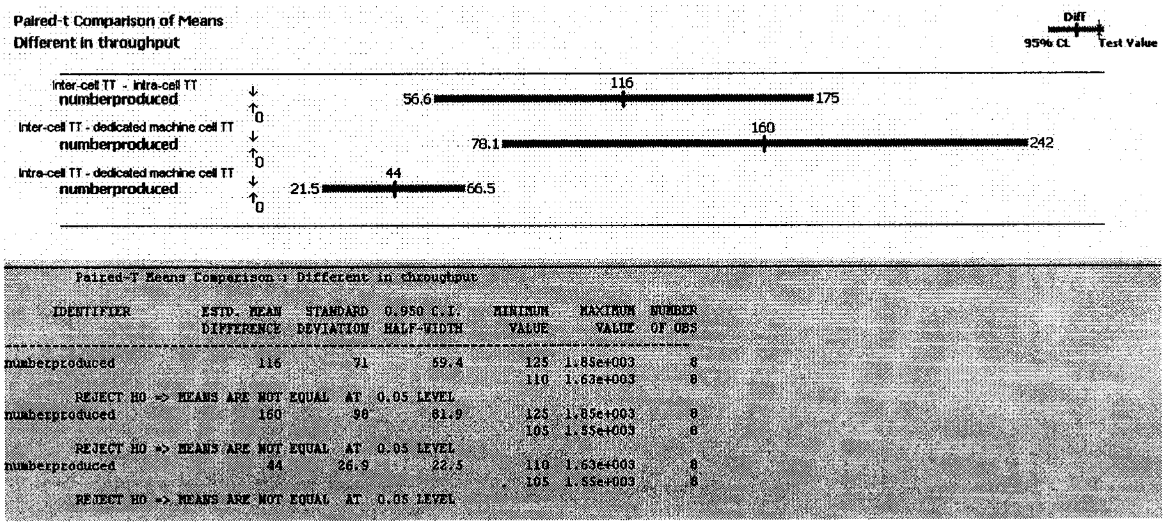
Figure 5.4: Paired-t Comparisons on the Expected Difference in ATC



```
   Paired-T Means Comparison : Different in average WIP Level

 IDENTIFIER          ESTD. MEAN  STANDARD  0.950 C.I.    MINIMUM    MAXIMUM  NUMBER
                     DIFFERENCE  DEVIATION HALF-WIDTH      VALUE      VALUE  OF OBS
 -------------------------------------------------------------------------------
 WIP                       -150        144        120        417        507       8
                                                             461        921       8
   REJECT H0 => MEANS ARE NOT EQUAL  AT  0.05 LEVEL
 WIP                       -481        179        150        417        507       8
                                                             589  1.24e+003       8
   REJECT H0 => MEANS ARE NOT EQUAL  AT  0.05 LEVEL
 WIP                       -331       85.1       71.1        461        921       8
                                                             589  1.24e+003       8
   REJECT H0 => MEANS ARE NOT EQUAL  AT  0.05 LEVEL
```

Figure 5.5: Paired-t Comparisons on the Expected Difference in AWIP



```
   Paired-T Means Comparison : Different in throughput

  IDENTIFIER          ESTD. MEAN  STANDARD  0.950 C.I.    MINIMUM    MAXIMUM  NUMBER
                      DIFFERENCE  DEVIATION HALF-WIDTH      VALUE      VALUE  OF OBS
-------------------------------------------------------------------------------
numberproduced               116         71       59.4        125  1.85e+003       8
                                                              110  1.63e+003       8
    REJECT H0 => MEANS ARE NOT EQUAL  AT  0.05 LEVEL
numberproduced               160         98       81.9        125  1.85e+003       8
                                                              105  1.55e+003       8
    REJECT H0 => MEANS ARE NOT EQUAL  AT  0.05 LEVEL
numberproduced                44       26.9       22.5        110  1.63e+003       8
                                                              105  1.55e+003       8
    REJECT H0 => MEANS ARE NOT EQUAL  AT  0.05 LEVEL
```

Figure 5.6: Paired-t Comparisons on the Expected Difference in TT

5.3 Post-Experiment Discussion

After the simulation model was developed through the three-phase method, an experimental design was performed to measure the system performance for different scenarios. The key issue to process this experiment is to seek the preferable values of the controllable parameters in order to maximize the system performance.

5.3.1 Factor Setting

The parameters chosen for simulation modeling are based on the hybrid CMS environment described. If an input parameter is an individual variable, its value will be set in respect of the ranges or specified levels.

Demand Pattern

Three different product mix levels are used to investigate the influence on overall system performance. The demand distributions for all part types are shown in Table 5.1. The differences on each level are determined by the distribution of the products with different complexity. The degree of product complexity is defined by the number of components or sub-assemblies required to make each end-item.

Three products are the parent items with the number of sub-assemblies of three, four and five. Under balanced product mix conditions, each product has one-third probability of releasing order into the system. The demand pattern is equally distributed. It is thus referred as equal product distribution (EPD). On the other hand, there are two cases considered under unbalanced product mix conditions. The first case has the three-sub-assembly products cover a larger portion of demand than that of the five-sub-assembly products. For example, product A accounts for 50% of the total demand and product C 16%. Product B covers 34% of the demand. This pattern is referred as simple product distribution (SPD). Conversely, the demand distribution is inverted to the opposite way. The most complicate product, product C, has the highest portion among the three. This distribution is referred as complex product distribution (CPD). This allocation of demand is similar to that used by Al-Mubarak *et al.* (2003).

Table 5.1: Demand Distributions

Product type	Number of sub-assemblies	Average number operations per part	Demand distribution		
			SPD	EPD	CPD
A	3	13.8	50%	33%	16%
B	4	15.3	34%	34%	34%
C	5	18.0	16%	33%	50%
Average	4	15.7			

Inter-arrival Rate

Inter-arrival rate plays a significant role in production process. Two types of inter-arrival rates, random and constant, were included. In most of the cases, the variety of the inter-arrival rate provides persistent fluctuation. Random inter-arrival rate, therefore, was set to observe the possible changes in production performance. However, the duration to launch a new order is controllable so that it can be fixed based on lead times of products on schedule. Constant inter-arrival rate was also considered.

Product Structure

For each product, a complete product structure is specified on a bill of materials (BOM). An end item is divided into different levels. It starts by level 0 of the end item, level 1 of sub-assemblies and followed by level 2 of components. The number of levels goes on if more components are required. Two types of product structures are set to perform the experiment. One is the single-level product structure. This type of product simply assembles all the parts in production. The multi-level product is to be processed in more than one level. The levels used in this research are two and three.

Batch Size

The batch sizes are related to the number of components of the product. Two levels of batch sizes used are 4 and 12. The smaller batch size is the average part numbers for one product, as shown in Table 5.1. The larger batch size is the total number of parts to be produced when each of the three products is equally processed. The range of batch sizes is based on the expectation of the output rate at each workstation. The operation at a workstation involves processing a batch of similar parts that may belong to the same or different products. The average number of operations per part is listed in Table 5.1.

Set-up Magnitude

Setup times are given by normal distribution. The mean (μ) values are specified in Table 5.2 with a variance of ±1% of the mean. The ratio of minor to major set-up defines the set-up factor (d). Major setups occur for each inter-cell movement when the system allows the machine to share between cells. Minor setups occur only inside a machine-cell. Three levels of d were considered: 0.2, 0.6, and 0.8. The higher level of d represents the lower degree of setup reduction.

The set-up ratio (r) is the ratio of set-up time to batch run time. The batch run time was derived from the part processing time and the batch size. The processing times in this experiment were created using triangular distribution over the interval of 20 to 120 seconds with mode value ranged between 25 and 110 seconds. Such distributions were commonly used when the actual distribution is unknown but the most likely values, minimum and maximum values of the process can be estimated. For each production, a common set-up time was selected from a normal distribution. Since the set-up time is a variable in this experiment, the processing time is pre-set with its mode value of 76.5 seconds or 1.3 minutes. Therefore, the mean batch run time can be defined by 5.2 minutes for small batch size and 15.6 minutes for large batch size. Two levels of the set-up ratio, small and large, were evaluated. The value of the set-up ratio is 0.5 at lower level and 0.9 at higher level.

The above distributions and parameters were established based on the findings or settings of previous cellular manufacturing studied (Burgress et al., 1992; Kannan, 1995, Shambu and Suresh, 2000). The values of parameters, *r* and *d*, employed to study the effect of setup magnitudes on system performance are shown in Table 5.2.

Buffer Size

In this model, different scenarios are investigated to determine the buffer sizes. In the first scenario, the system forbids the workload to be shared with other cells when the buffer size has reached the upper bound. During the whole process, all parts belonging to the machine-cell stay in the cell; in other words, the parts are either kept in queue or on conveyor belts. The buffer size discussed under this scenario is basically the capacity of the queue lines in input and output areas. Input area holds the parts that are unloaded from a conveyor and waiting for processing. By the same token, the parts stayed in the output area are already finished with the jobs assigned to the station and wait to return to conveyors. This is the feeding buffer size to be the first threshold for entering the workstation. It was chosen to range between 30 and 100 units. Unlike the first case, the second scenario allows the inter-cell machine sharing. If a machine is occupied for most of the production time, it may generate a potential bottleneck. When this situation appears, another buffer size is used as a second threshold. It means that when a part is about to enter this workstation, it has to be screened by the feeding buffer. If the part is permitted to enter the queue of the input area, it is unloaded from the conveyor. The buffering situation is then examined by the loading buffer size. If the size of queue reaches the upper bound of the loading buffer size, this part is delivered to be processed in another cell.

Table 5.2: Set-up Magnitudes

Batch size(Bh)	Set-up ratio (*r*)	Minor setup (minutes)	Set-up factor (*d*)	Major setup (minutes)
Small Bh	0.5	2.6	0.2	13.0
			0.6	4.3
(batch size = 4 units)			0.8	3.3
(batch run time = 5.2 minutes)	0.9	4.7	0.2	23.4
			0.6	7.8
			0.8	5.9
Large Bh	0.5	7.8	0.2	39.0
			0.6	13.0
(batch size = 12 units)			0.8	9.8
(batch run time=15.6 minutes)	0.9	14	0.2	46.8
			0.6	23.4
			0.8	17.6

Priority Dispatching Rules

Three priority dispatching rules were employed: FIFO (First in First Out), Highest Attribute Value and Lowest Attribute Value. The FIFO rule is consistently addressed as a prime scheduling rule compared to others in the past CMS studies (Shambu and Suresh, 2000). Highest Attribute Value has similar characters as FIFO. It also includes other comparable attributes of the parts. Two attributes, waiting time and transportation time, are taken into account. It was noted as Highest Waiting Time (HWT).The parts that have the longest waiting time or transportation time have priority to be processed. For the Lowest Attribute Value one, the attribute to be used was the processing time. It is also known as Shortest Processing Time (SPT).

The nine independent variables discussed above take different values for investigation using simulation experiments. As summarized in Table 5.3, there are two or three levels for variables. Scenarios used for testing in the experiments were generated with combinations of these factors.

Table 5.3: Summary of Independent Variables

Number	Independent variable	Number of levels	Levels
1	Demand Pattern	3	SPD, EPD,CPD
2	Inter-arrival Rate	2	random, constant
3	Product Structure	2	single-level, multi-level
4	Batch Size	2	4,12
5	Set-up Factor	3	0.2,0.6,0.8
6	Set-up Ratio	2	0.5,0.9
7	Feeding Buffer	2	small(S), large(L)
8	Loading Buffer	2	small(S), large(L)
9	Priority Dispatching Rule	3	FIFS, SPT, HWT

5.3.2 Correlation Tests

The nine independent variables were placed in 3 groups to observe 60 different scenarios. The three groups are shown in Table 5.4. Experimental results of 60 simulation tests are shown in Table 5.7, Table 5.8, and Table 5.9. It is to analyze the results to discover possible correlations or the presence of a possible common trend.

Table 5.4: Three Groups of Independent Variables

Group Number	1	2	3
Group Name	Demand	Set-up	Buffering
Independent Variables	Demand Pattern Inter-arrival Rate Product Structure Batch Size	Set-up Factor Set-up Ratio Batch Size	Feeding Buffer Size Loading Buffer Size Priority Dispatching Rule Batch Size

5.3.2.1 Analysis of Variance

The analysis of variance is given in Table 5.5. One-way ANOVA test was conducted to investigate how a dependent variable varies with an independent variable. The interaction effect is presented with F-test statistics. The variation is represented with the F-ratio. If the F-ratio equals to one, the dependent variables do not change with the independent variable. As the difference between the variables increases, the F-ratio values tend to increase. In this analysis, a 95% confidence interval was used to verify the variance. In Table 5.5, F is the value of the F-ratio. The probability represents the significance level of variation. The null hypothesis will not be rejected if the probability is greater than the chosen value, 0.05. The rejected cases are in boldface. As shown in Table 5.1, set-up time does not affect the transfer cost since set-up is only required at workstation, not by the transferring process. For average WIP, the variation of set-up ratio (r) has direct influence on WIP but no effect on set-up factor (*d*). *r* is related to batch size run time which is considered as a major factor if WIP can be reduced. It seems that the total throughput is less affected by the selected independent variables. One of the reasons is that the finished product, not the individual parts are counted in data collection. Mathematical simulation models may provide better solutions for producing multi-component products (Chen, 2001). It can also be noticed that the set-up factor hardly influences the overall performance. This is due to the limited flexibility in sharing workloads with other cells. The inter-cell transfer was minimized by controlling the feeding buffer size and loading buffer size.

Table 5.5: Correlation between Individual Independent and Dependant Variables

Dependent Variables	ATC		AWIP		TT	
Independent Variables	F	Prob.	F	Prob.	F	Prob.
Demand Pattern	6.73	0.007	46.7	<0.0001	57.24	<0.0001
Inter-arrival Rate	5.087	0.043	12.41	0.004	3.9	***0.072***
Product Structure	8.32	0.014	15.5	0.002	0.03	***0.867***
Batch Size	10.09	0.019	32.84	0.001	1.38	***0.285***
Set-up Factor	0.667	***0.54***	1.615	***0.257***	1.733	***0.237***
Set-up Ratio	1.5	***0.266***	32.91	0.0012	33.661	0.0011
Feeding Buffer Size	5.52	0.046	6.29	0.036	5.78	0.043
Loading Buffer Size	6.26	0.037	6.83	0.031	6.1	0.039
Priority Dispatching Rule	8.033	0.022	2.102	***0.185***	0.024	***0.88***

ATC: Average Transfer Cost
AWIP: Average WIP level
TT: Total Throughput

5.3.2.2 Correlations between Dependant Variables

In this section, the possible correlations between dependant variables will be discussed using Pearson's correlation coefficient test. The correlation matrix for the three system performances is shown in Table 5.6. This test is used to measure the strength of the linear relationship between the two variables. It is presented with Pearson's correlation coefficient ranging from -1.0 to 1.0. This test was done also with $\alpha = 0.05$. Considering the negative effect of TT and AWIP in all groups, the productivity reduces as average WIP increases no matter which independent variable may change during production. In Group 3, the buffering group, the total throughput is negatively correlated with ATC. The magnitude of the relationship is high. High transferring cost occurs while the queue lines are long. In a system, long waiting lines simply deteriorate overall performance. Therefore, ATC has a positive effect on AWIP. To avoid system congestions, the dependent variables were investigated with different buffer sizes for control the inter-cell material movement. Consequently, higher AWIP results in higher ATC.

Table 5.6: Correlation Matrix for Observed Dependant Variables

	Group 1			**Group 2**			**Group 3**		
Dependant variables	ATC	AWIP	TT	ATC	AWIP	TT	ATC	AWIP	TT
ATC	1	0.650	-0.560	1	-0.180	0.407	1.000	**0.896**	**-0.960**
AWIP		1	**-0.800**		1	**-0.940**		1	**-0.898**
TT			1			1			1

5.4 Interaction Effects

In the following subsections, the interaction effects of the experimental factors on the system performance will be discussed. In addition, statistical analyses are carried out to draw conclusions for different scenarios. The procedure to select the best scenario is based on the statistical method developed by Nelson *et al.* (2001). To investigate the performance measurements of each scenario, a box and whisker chart is plotted to observe the distribution of the data collected by ARENA. ARENA automatically computes the across-replications for 95% confidence intervals. Pair-wise comparisons of any two scenarios in a group were conduced to observe the significance of differences. The details were shown in Appendices III, IV, and V for Groups 1, 2 and 3, respectively. Next, the best scenarios will be identified with 95% confidence. An error tolerance is provided to control the amount that is small enough to be neglected. Usually, it is applied to the measurements whose magnitude of the results cannot be estimated.

The experiment results for groups 1 to 3 are summarized in Table 5.7 to Table 5.9, respectively. They show the total number of the inter-cell movement, ATC, AWIP, and TT. For the results in each table, there are three individual box and whisker charts to demonstrate 95% confidence intervals for the population mean of ATC, AWIP and TT, respectively. For each group, the independent variables covered are tested with all possible combinations. One combination was considered as a scenario on the test bed. Ten replications were performed for each scenario. The 95% confidence intervals for the ATC measurement were narrowed down to be within ±10%. Consequently, the value of ATC could vary in a larger range. Meanwhile, the scale used to measure the unit cost is small. Since the value was sensible, it became problematic to specify the value expected to fall within the interval width. Rather, the half width of the confidence interval was modified to be no more than 10% of the mean. The error tolerance was also specified to be 0.10. However, the magnitude for AWIP and TT are more distinguishable. The tolerances were set to be 0 for both. In all three tables, the values in boldface are the best scenarios with 95% confidence following the Nelson selection procedure (Kelton, 2002).

5.4.1 Demand Group

The experimental factors included in Group I are demand pattern, the variability of inter-arrival rate, product structure and batch size. These factors were considered to investigate as a group because they define the initial conditions. The results are shown in Table 5.7. The box and whisker plots of ATC, AWIP and TT are shown in Figure III-1, Figure III-2 and Figure III-3 separately in Appendix III. According to the table and the figures, the following observations can be drawn:

1. *There was very small difference in ATC among SPD and EPD when producing single level products:* The best ATC measurements suggested were all under 2.0 unit cost per part. The capacity of the material handling systems is sufficient to accommodate under the condition of SPD and EPD. For multi level products, it costs less in transportation by controlling the demand distribution to be EPD. For CPD, the increase of the ATC is related to the increase in the number of parts to be produced. Each part spends longer in queues, and therefore more inter-cell movements occur. Furthermore, parts may be required to travel around the conveyors since more workstations are available to perform more work. To handle the CPD conditions, however, small batch is recommended for producing multi level products and large batch for single level products. ATC, AWIP and TT deteriorate with increasing complexity in product structures. In general, it can be concluded that constant inter-arrival-rate with small batch size results in lower ATC.

2. *The values of ATC are similar for both random and constant inter-arrival rates with very different numbers of inter-cell movements.* Even though the parts cost more to be

Table 5.7: Simulation Results of Demand Group

Demand Pattern	Batch size(Bh)	Inter-arrival rate	Product Structure	Scenarios (#~ notation)	Total number of inter-cell movement	Average transfer cost (ATC)	Average WIP(AWIP)	Total throughput (TT)
SPD	Small Bh	Random	Single-level	1 ~ SPD 4 (random + single)	549	**1.763**	**468.880**	**2023**
			Multi-level	2 ~ SPD 4 (random + multi)	571	15.615	534.129	**2020**
		Constant	Single-level	3 ~ SPD 4 (constant + single)	50	**1.614**	**421.383**	**2022**
			Multi-level	4 ~ SPD 4 (constant + multi)	48	2.910	**483.680**	**2018**
	Large Bh	Random	Single-level	5 ~ SPD 12 (random + single)	376	**1.949**	681.152	**2020**
			Multi-level	6 ~ SPD 12 (random + multi)	382	19.903	750.975	**2032**
		Constant	Single-level	7 ~ SPD 12 (constant + single)	376	**1.949**	681.152	**2020**
			Multi-level	8 ~ SPD 12 (constant + multi)	273	11.642	734.599	**2022**
					---	---	---	---
EPD	Small Bh	Random	Single-level	9 ~ EPD 4 (random + single)	484	**1.717**	**508.049**	**2047**
			Multi-level	10 ~ EPD 4 (random + multi)	450	7.115	557.297	**2029**
		Constant	Single-level	11 ~ EPD 4 (constant + single)	287	**1.719**	**452.257**	**2024**
			Multi-level	12 ~ EPD 4 (constant + multi)	282	5.081	**509.527**	**2025**
	Large Bh	Random	Single-level	13 ~ EPD 12 (random + single)	298	**1.777**	717.991	**2011**
			Multi-level	14 ~ EPD 12 (random + multi)	298	14.350	783.067	**2036**
		Constant	Single-level	15 ~ EPD 12 (constant + single)	214	**1.724**	673.457	**2015**
			Multi-level	16 ~ EPD 12 (constant + multi)	214	8.778	745.092	**2029**
					---	---	---	---
CPD	Small Bh	Random	Single-level	17 ~ CPD 4 (random + single)	1167	7.425	1017.439	1857
			Multi-level	18 ~ CPD 4 (random + multi)	1092	81.581	977.411	1847
		Constant	Single-level	19 ~ CPD 4 (constant + single)	827	4.753	802.610	1863
			Multi-level	20 ~ CPD 4 (constant + multi)	805	48.271	837.770	1852
	Large Bh	Random	Single-level	21 ~ CPD 12 (random + single)	425	4.802	1015.931	1887
			Multi-level	22 ~ CPD 12 (random + multi)	459	117.094	1199.154	1888
		Constant	Single-level	23 ~ CPD 12 (constant + single)	351	5.670	991.894	1872
			Multi-level	24 ~ CPD 12 (constant + multi)	355	87.510	1029.190	1870

transferred with transporters than with conveyors, the number of inter-cell movements was not represented by the material handling costs. High variability of inter-arrival rates can cause imbalance of cell workloads and trigger more inter-cell activities.

3. *The combinations of small batch and constant inter-arrival rate with different product structures result in similar AWIP and TT.* For instance, the scenarios suggested for lower AWIP are those processed with fixed inter-arrival rate and small batch size. The overall productivities, therefore, were improved since AWIP and TT were negatively correlated with a strong magnitude. This benefit of this combination is also explained from the number of inter-cell movements. Very few inter-cell machine sharing activities were required. Obviously, constant inter-arrival rate provides a smoother production flow.

5.4.2 Setup Group

The setup group investigates set-up ratio, *r*, and set-up factor, *d*. In addition, since one set-up was required for one batch production, the batch size was also covered. The interaction effects of these three variables versus three dependant variables, ATC, AWIP and TT were plotted in Figure IV-1, Figure IV-2, and Figure IV-3 of Appendix IV, respectively. The values are shown in Table 5.8. There were two findings on the system performances:

1. *The influence of the set-up time on its ATC performances was insignificant. However, the ATC decreases as the number of the inter-cellular movements increases.* As

Table 5.8: Simulation Results of Set-up Group

Batch size(Bh)	Set-up ratio (r)	Set-up factor (d)	Scenarios (#~ notation)	Total number of inter-cell movement	Average transfer cost (ATC)	Average WIP(AWIP)	Total throughput (TT)
Small Bh	0.5	0.2	25 ~ 4 (0.5 X 0.2)	456	***1.722***	***494.728***	***2006***
		0.6	26 ~ 4 (0.5 X 0.6)	449	1.772	***488.651***	***2026***
		0.8	27 ~ 4 (0.5 X 0.8)	462	***1.720***	***512.237***	***2033***
	0.9	0.2	28 ~ 4 (0.9 X 0.2)	282	***1.741***	1289.042	1682
		0.6	29 ~ 4 (0.9 X 0.6)	286	1.750	1221.809	1703
		0.8	30 ~ 4 (0.9 X 0.8)	287	***1.741***	1261.678	1715
				---	---	---	---
Large Bh	0.5	0.2	31 ~ 12 (0.5 X 0.2)	351	1.883	908.054	***1995***
		0.6	32 ~ 12 (0.5 X 0.6)	332	1.806	841.308	***2034***
		0.8	33 ~ 12 (0.5 X 0.8)	326	1.804	826.447	***2013***
	0.9	0.2	34 ~ 12 (0.9 X 0.2)	157	1.763	1918.898	1432
		0.6	35 ~ 12 (0.9 X 0.6)	222	1.763	1418.066	1763
		0.8	36 ~ 12 (0.9 X 0.8)	209	1.764	1379.017	1747

shown in Figure IV-1, the range of 95% confidence intervals for each scenario has very little difference in ATC measurements. The ability to exploit setup similarities was to complete job sequences within a cell.

2. *The improvement of productivity was related to the set-up magnitude.* For instance, for *r* of 0.5 and *d* of 0.8, the TT was high compared to other scenarios with low AWIP. It means that when minor set-up time and major set-up time were similar, the overall production flow became similar to those in the cells. In the hybrid cellular manufacturing system, it can lower the degree of cellularization. Productivity was improved since the inter-cell sharing improved production flow. Moreover, the overall performance was affected by *r*.

5.4.3 Buffering Group

For a study involved with material handling system, buffer size was the key factor to performances. Usually, the buffering occurs in a queue line. The two buffers related cases studied here were feeding buffer and loading buffer at each workstation. The priority dispatching rules are important to manage the queues. Batch size was included since the transfer batch size may affect the system performances. To study all combinations of the 4 factors, 24 simulations were conducted. The results were summarized in Table 5.9. The box and whisker plots of the three dependant variables were shown in Figure V-1, Figure V-2 and Figure V-3 of Appendix V. The observations are listed below:

Table 5.9: Simulation Results of Buffering Group

Priority Dispatching rule	Batch size(Bh)	Feeding Buffer	Loading Buffer	Scenarios (#~ notation)	Total number of inter-cell movement	Average transfer cost (ATC)	Average WIP(AWIP)	Total throughput (TT)
FIFO	Small Bh	100	70	37~ FIFO 4-LL	0	10.473	1242.903	1610
			20	38 ~ FIFO 4-LS	486	***1.719***	***493.111***	***2039***
		30	21	39 ~ FIFO 4-SL	364	***2.143***	***525.663***	***1982***
			6	40 ~ FIFO 4-SS	1599	***1.853***	***518.819***	***2039***
	Large Bh	100	70	41 ~ FIFO 12-LL	0	9.498	1302.441	1649
			20	42 ~ FIFO 12-LS	238	***1.727***	695.867	***2019***
		30	21	43 ~ FIFO 12-SL	214	***2.165***	744.558	***2032***
			6	44 ~ FIFO 12-SS	1206	2.292	714.988	***2008***
					---	---	---	---
SPT	Small Bh	100	70	45 ~ SPT 4-LL	0	9.961	1095.516	1658
			20	46 ~ SPT 4-LS	444	***1.717***	***522.515***	***2025***
		30	21	47 ~ SPT 4-SL	371	***1.756***	***515.443***	***2025***
			6	48 ~ SPT 4-SS	1286	***1.807***	***482.508***	***2014***
	Large Bh	100	70	49 ~ SPT 12-LL	0	8.894	1260.375	1577
			20	50 ~ SPT 12-LS	194	***1.725***	718.674	***2031***
		30	21	51 ~ SPT 12-SL	195	***1.906***	706.171	***2048***
			6	52 ~ SPT 12-SS	1088	2.114	708.948	***2017***
					---	---	---	---
HWT	Small Bh	100	70	53 ~ HWT 4-LL	0	9.098	953.402	1698
			20	54 ~ HWT 4-LS	389	***1.703***	***497.7***	***2030***
		30	21	55 ~ HWT 4-SL	332	***1.714***	***513.298***	***1998***
			6	56 ~ HWT 4-SS	1493	***1.804***	***497.35***	***2021***
	Large Bh	100	70	57 ~ HWT 12-LL	0	8.139	1112.063	1696
			20	58 ~ HWT 12-LS	193	***1.725***	734.483	***1970***
		30	21	59 ~ HWT 12-SL	205	***1.813***	735.971	***2044***
			6	60 ~ HWT 12-SS	1215	2.371	750.283	***2008***

1. *ATC, AWIP and TT deteriorated with increased size of feeding buffer and smaller reduction of loading buffer. The behavior of this combination created a similar pattern for all system performance measures in this study.* It seems that large feeding buffer was not an appropriate choice for this system. However, the 30% reduction applied on loading buffer made the deterioration even more pronounced. For a steady-state system, the loading buffer was too large to provide agility. No inter-cell material flows were required. It thus leads to poor performance with high ATC, high AWIP and low throughput.

2. *Proper choices of buffer size have a positive effect on output. Two possible suggestions: Larger feeding buffer with 80% reduction on loading buffer and smaller feeding buffer with 30% reduction on loading buffer.* According to Nelson's selection procedure, except the one with large feeding buffer size and loading buffer size, the other scenarios seem to be the best. However, for the alternative small buffer sizes, the flexibility may be too large. The inter-cell movements, thus, became very dynamic and resulted in a high expense on transportation.

3. *Priority dispatching rules should be chosen based on the selection of batch size.* To consider overall performances, according to the three figures provided, there was no best priority dispatching rule among the all. However, each rule with proper batch size entails the improvement of productivity, i.e. FIFO and HWT should be applied with small Bh and SPT should be used with large Bh.

5.5 Optimum-Seeking Simulation

After the investigations on different scenarios, the optimal system performance was the primary interest. Typically, the greatest impediment was to select the best sets of values of controllable parameters to solve the optimization problem. We used the built-in optimization functions of the simulation software to search for optimal parameter values for better system performance. For each of the dependant variables, a post-experiment sensitivity analysis was performed to determine the best values of the controllable parameters. The set of the controllable parameters focuses on loading buffer sizes and inter-cell transfer batch sizes of the bottleneck machines (M_{15}, M_{21}, M_{31} and M_{54}). In addition, processing batch size and inter-arrival time were also included to complete a system design. Finding the best feasible alternative solutions for three performance measurements were considered as three different constrained optimization problems. Their objective functions were programmed independently to minimize ATC and AWIP and maximize TT. However, each model was subject to the same set of constrains as followed:

Loading Buffer < Feeding Buffer

30 parts =< Feeding Buffer =< 100 parts

6 parts =< Loading Buffer =< 70 parts

4 parts =< transfer batch size =< 12 parts

4 parts =< processing batch size =<12 parts

15 minutes =< inter-arrival time =< 25 minutes

5.5.1 Minimizing the Average Transfer Cost

The results of the optimization were shown in Table 5.10. The best values of controllable parameters were listed in the second column from the left. The ones with larger standard deviations have smaller impact on the objective function. It is evident that the buffer sizes were less influential. However, the change in the feeding buffer is commonly accompanied by the change in the loading buffer. The coupling has a prominent influence on the number of inter-cell transferring and the time a part stays on conveyors. The feeding buffer was a threshold to control the workload for each station. It may affect the dynamic of material handing activates. The loading buffer was more relevant to this measurement. On the other hand, transferring batch size should remain at 7 or 8 to have a lower ATC. For this reason, if a production planner wants to reduce the transfer cost, the transfer batch size should be the element that has to be primarily modified.

Table 5.10: The Sub-optimal Solution of Minimizing ATC

Name	**Best**	Minimum	Average	Maximum	Standard Deviation
Average Transfer Cost	**1.67011**	1.67011	1.71666	1.75361	1.81E-02
M_{15} loading buffer size	**15**	6	18.6042	70	8.62454
M_{15} transfer batch size	**7**	4	8.32176	12	2.12801
M_{21} loading buffer size	**45**	6	43.4838	70	14.7512
M_{21} transfer batch size	**8**	5	8.80324	12	1.60026
M_{31} loading buffer size	**25**	6	21.0347	70	9.64923
M_{31} transfer batch size	**7**	4	6.40509	12	1.5591
M_{54} loading buffer size	**19**	6	17.4699	30	5.23601
M_{54} transfer batch size	**7**	4	8.03704	12	2.24609
feeding buffer size	**54**	30	65.3542	100	17.2016
processing batch size	**5**	4	7.66204	12	2.46956
inter-arrival rate	**20**	19	21.9884	25	1.55675

5.5.2 Minimizing the Average WIP Inventory

As shown in Table 5.11, a small batch size was kept to transfer the jobs at M_{54}. M_{54} was the bottleneck of C_5 after Phase II and it also causes the unbalanced workload in the system. Generally, small transfer batch size improves flexibility of the system. As a result, the system would make inter-cell delivery as many batches as possible. This also explained the small standard deviation of the loading buffer of M_{54}. It remained the minimum value of the constraint. In addition, small processing batch size was preferred. It in turn costs the system less time on batching but might also produce fewer products. More set-up time was required when the number of batches increased. Furthermore, the inter-arrival rate was suggested to launch one order every 25 minutes, the maximum assumed. In this way, there were fewer jobs accumulated in the system.

Table 5.11: The Sub-optimal Solution of Minimizing AWIP

Name	**Best**	Minimum	Average	Maximum	Standard Deviation
Average WIP	**379.311**	379.311	384.826	396.29	5.80229
M_{15} loading buffer size	**9**	6	13.3359	70	9.83371
M_{15} transfer batch size	**9**	9	9.50965	12	1.12659
M_{21} loading buffer size	**30**	24	35.9305	70	13.252
M_{21} transfer batch size	**8**	8	8.58687	12	1.33673
M_{31} loading buffer size	**21**	6	20.2896	70	8.03979
M_{31} transfer batch size	**4**	4	4.00386	5	6.20E-02
M_{54} loading buffer size	**10**	6	9.32046	10	1.50212
M_{54} transfer batch size	**4**	4	4	4	0
feeding buffer size	**30**	30	40.6641	100	19.4916
processing batch size	**4**	4	4	4	0
inter-arrival rate	**25**	25	25	25	0

5.5.3 Maximizing the Total Throughput

The controllable parameters in maximizing the TT have similar behaviors in minimizing AWIP. The results of the optimization were presented in Table 5.12. TT and AWIP have opposite values as shown in Table 5.6. It represents the correlation matrix for observed dependant variables. The high standard deviations of buffer sizes of M_{15}, M_{21}, and M_{31} implied that they were considered as bottlenecks but less busy than M_{54}. In other words, they have less impact on the system performance. Transfer batch size of M_{54}, processing batch size, and inter-arrival rate, however, were the critical variables for overall system performance.

Table 5.12: The Sub-optimal Solution of Maximizing TT

Name	**Best**	Minimum	Average	Maximum	Standard Deviation
Total Throughput	**2313.33**	2198.5	2237.36	2313.33	26.1
M_{15} loading buffer size	**14**	6	12.3304	70	6.51139
M_{15} transfer batch size	**7**	4	5.9764	12	1.81587
M_{21} loading buffer size	**30**	6	24.4897	70	14.1289
M_{21} transfer batch size	**6**	4	5.61652	12	1.66886
M_{31} loading buffer size	**21**	6	23.4838	70	8.8282
M_{31} transfer batch size	**5**	4	5.33333	12	1.60506
M_{54} loading buffer size	**9**	6	9.37758	29	3.33997
M_{54} transfer batch size	**6**	4	5.80826	12	1.73676
feeding buffer size	**45**	30	42.8083	100	12.5968
processing batch size	**5**	4	5.37168	12	1.70819
inter-arrival rate	**19**	18	18.8289	20	0.509719

5.6 Summary of Findings

The findings presented in this chapter proposed several scenarios for successful implementations of the three-phase method along with simulation experiments for production system analysis. The hybrid manufacturing system was treated as a non-terminating system to perform simulation analysis. The *Output Analyzer* of ARENA was used in the initial stage of the analysis. The system performance was measured in terms of average transfer cost (ATC), average work-in-process inventory (AWIP), and total throughput (TT). To provide reasonable analysis for the effects of nine independent variables on the three dependent variables, post-experiment analyses were carried out with *Process Analyzer*, and *OptQuest*, attached to ARENA. With the help of *Process Analyzer*, 60 different scenarios were run and the best alternatives were suggested with 95% certainty.

As shown in Table 5.5, the correlation between independent and dependant variables was drawn with one-way ANOVA test. The set-up factor influences overall performance with minimum significance. The total throughput was less likely affected by the independent variables. The nine independent variables were divided into three groups: demand group, set-up group and buffering group. Based on the division, the correlations between dependent variables were tested with Pearson's correlation coefficient. The AWIP and TT were negatively affected by all of the three groups. In the buffering group, ATC had close linear relationships with AWIP in positive effect and with TT in negative effect. For each individual group, the interaction effects of the experimental factors on the dependent variables were also investigated.

1. For the demand group, simple product distribution (SPD) or equal product distribution (EPD) with single product structure were suggested to be the best scenarios. Small batch size makes the production of complicated production easier. Also, ATC was found to be indifferent to inter-arrival rate. It was resulted from different numbers of inter-cell flows. Moreover, the combination of small batch size and constant inter-arrival rate improved AWIP and TT regardless the product structure.

2. Two main findings were observed from the set-up group. The influence of set-up time variability is minor on ATC measurements. However, for certain combinations of the set-up magnitude, overall performance could be optimized. For set-up ratio of 0.5, the best performance is reached with set-up factor of 0.8. In general, performance deteriorates at higher set-up ratio.

3. In the buffering group, overall system performance decreases with increased size of the feeding buffer, especially with small loading buffer sizes. This finding suggests that a larger feeding buffer requires 80% of reduction on loading buffer. On the other hand, smaller feeding buffer was better to accompany a 30% of reduction on loading buffer. In addition, the selection of the batch size depends on the priority dispatching rules employed.

An optimum-seeking simulation analysis was demonstrated with *OptQuest* in the last subsection. Using the output of the simulation models, a sensitivity analysis was performed. The inputs then were evaluated and tested for the three performance measurements. As shown in Table 5.10, Table 5.11, and Table 5.12, four critical factors made significant effects on all of the three objectives. They are the loading buffer and the transferring batch size of M_{54}, the global processing batch size and the inter-arrival rate. Their best values are summarized in Table 5.13. Therefore, during decision making process, they are the main indications for system planning.

Table 5.13: Production Plans for three Different Objectives

Objective	Control Parameters			
	loading buffer (parts) of M_{54}	M_{54} transfer batch size (parts)	global processing size (parts)	inter-arrival rate (minutes)
Minimizing ATC	7	7	5	20
Minimizing AWIP	10	4	4	25
Maximizing TT	9	6	5	19

CHAPTER 6

APPLICATION IN THE APPAREL INDUSTRY

6.1 Introduction

This section demonstrates that the three-phase model is applied to a real world hybrid cellular manufacturing (HCM) system. One of the objectives of the study is to determine the optimal production plan to yield maximum productivity during a high season of an apparel company. The simulation experiments were conducted in a footwear firm located in the capital city of Indonesia.

Footwear industry is one of the apparel industries. In today's apparel market, the high variability of orders increases the competitiveness of the industry. The HCM system is the current configuration used by the company. It was undergoing a process of reconfiguration from Job Shop (JS) to Cellular Manufacturing System (CMS). As in most firms, hybrid layout was a product of day-to-day reality in intermittent manufacturing (Shambu and Suresh, 2000). Some machines remain to be grouped in functional cells to cope with the most critical phase of production, sewing. It will be lack of flexibility if the system is fully converted to CMS. However, it has become more difficult to maximize the pooling synergy in a HCM system. Production planning has to be systematically investigated as it becomes more complicated. This problem triggered the motivation of this study aiming to improve the system efficiency of the footwear factory.

6.2 Nature of the Apparel Industry

With the advantage of today's advanced technology, many production procedures are improved with higher level of atomization and computerization. The production plant considered in this research is also supported with more advanced facilities and equipments. Despite such progresses, the apparel industry has remained significantly less automated than many other manufacturing industries (Bureau of Labor Statistics, 2004). Therefore, apparel industry is still very labor-intensive. Traditionally, most workers perform repetitive manufacturing processes in an assembly line, such as cutting and sewing. Every worker is specialized in one function. In order to quickly respond to the changing market, modular manufacturing is preferred. Workers are assigned to work as a team, also known as a production *module.* Each worker has been cross-trained to be skillful and familiar with the several tasks assigned to the team.

Footwear industry is one of representatives in the apparel industry. The main feature of this industry is the great number of operations in stitching functions. This function involves many different operations in an assembly process. While simultaneously manufacturing manifold designs of shoes, the production procedures became excessively detailed. Production sequence and processing time of each operation may be similar for some designs, but not necessary exactly the same (Costa and Ferreia, 1999). Even though workers were trained to perform multi-functional tasks, they usually specialize in a certain task and were assigned to be responsible for that task only. Failing to assign a worker to take care of a certain function can be detrimental and the long set-up times could deteriorate the module efficiency. Therefore, parts may visit stitching machines in a module in different sequences depending on product designs. In fact, this critical phase of production has been designed to be a functional cell. The HCM, for this reason, is built by the coexistences of manufacturing cells and stitching modules.

6.3 Example of Footwear Industry

The size of the whole manufacturing system in this footwear firm is too large for this case study. The HCM system investigated was an epitome of the existing production system. The production process can be abstractly separated into two phases: vamp production and outsole. Outsole was not included in this study since its process time was relatively short. It is infrequent to find a bottleneck in a finishing line where outsoles were completed. Therefore, the vamp production was the focus to develop system analyses with the three-phase approach. It involves mainly two functions: cutting and stitching.

6.3.1 System Description and Inputs

The system consists of three GT cells (C1, C2 and C3) and two functional modules (F1 and F2). The machines assigned for each cell or module are presented in Table 6.1. Three products are manufactured. They are men leather boots, ladies suede sneakers and kids sneakers. The number of parts per product and the part names are shown in Table 6.2. Part processing sequences and processing times of each part are shown in Appendix VI. Kids sneakers seem to be more complicated and require longer production time. Indeed, the size of the product made the stitching and cutting processes more challenging.

Demand Distribution

Time series model for demands is used. Demand is an independent variable and is represented by inter-arrival rates over a certain period of time. If the inter-arrival rate is constant, it would make the process and workload control much easier. However, the reality is the high variety of product designs and customer demands. The time-ordered list of inter-arrival rate displays seasonality and a general tendency of increase or decrease. In this study, the data of one month period in the end of summer was used. The demand distributions displayed different patterns depending on the market needs of each product type during that period. The demand forecast is shown in Table 6.3. It is based on the historical data of the company.

Table 6.1: Machines Assigned for Each Cell or Module

Cell	C1	C2	C3	F1	F2
Workstations	Cutting 1 Cutting 2 QC 1 Matching Printing 1	Splitting Cutting 3 QC 2 Edge grinding Skiving Flatting	Embroidery 1 Printing 2 Hyfrequency Embroidery 2	Stitching 1 Stitching 2 Stitching 3 Stitching 4 Stitching 5 Stitching 6 Stitching 7	Stitching 8 Stitching 9 Stitching 10 Stitching 11 Stitching 12 Stitching 13 Stitching 14 Stitching 15

Table 6.2: Three Product Types

Product Types	Product Codes	Number of Parts	Part Codes				
Men Leather Boots	M	3	PM1	PM2	PM3		
Ladies Suede Sneakers	L	4	PL1	PL2	PL3	PL4	
Kids Sneakers	K	5	PK1	PK2	PK3	PK4	PK5

Table 6.3: Demand Variability

Product	Day																													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
M	96	115	154	173	173	192	192	211	230	230	250	307	326	326	326	326	326	346	365	365	365	365	384	384	384	403	403	422	422	442
L	179	256	256	307	333	384	384	384	410	410	461	461	512	512	512	512	512	486	435	435	358	358	333	282	256	256	230	205	205	102
K	704	640	608	576	576	544	544	512	512	512	480	480	480	448	416	416	384	384	352	352	320	320	288	288	256	224	192	160	128	128

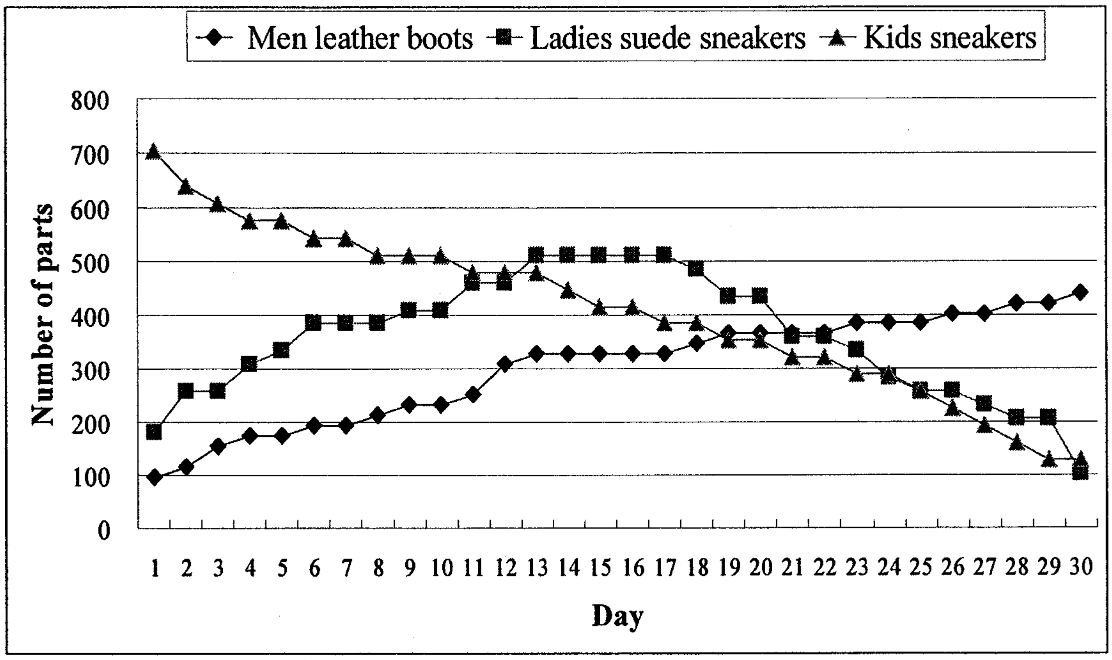


Figure 6.1: Daily Demand of a Month

The orders of men leather boots suggest an increasing trend to meet the needs in the fall. The demand pattern of ladies suede sneakers has a small peak throughout the month. The orders of this product type were usually random in small quantities. Thus, they require certain amount of production resource for a very short period of time. After the back-to-school time, the orders for kids sneakers decrease in the end of summer since most of the orders have been shipped out by then.

Other Considerations

For every cell or module, there was a single loop conveyor. All parts visit the workstations according to their sequences of operations. Transporters were assigned for every necessary inter-cell movement. The unit inter-cell and intra-cell material handling costs are shown in Table 6.4. Ten pairs of shoes were considered as a batch. A forced delay of setup time for every batch, the major setup time for transfer batch and the intra-cell setup time for batch operation are presented in Table 6.4. The machine sharing activities have setup times following normal distributions. Minor setup time follows NORM (μ, σ) distribution with μ= 0.4 min and σ= 0.05 min. The distribution was generated based on the setup time data from the current production system.

Table 6.4: The Unit Material Handing Cost and Set-up Times

	Unit M.H. Cost ($)	Set-up Time (mins)
Intra-cell	0.4	NORM (0.4, 0.05)
Inter-cell	1.8	NORM (3.2, 1.0)

6.3.2 Application

Applying Phase I of the simulation approach identifies yield bottleneck machines in every cell or module. The two most occupied machines for each cell were identified. The possible machines in the downstream direction of the busy workstation are shown in Table 6.5. After machine sharing was introduced in Phase II, two bottleneck cells, C3 and F2 were identified. For C3, the critical machine was found to be Embroidery 1 and the candidate sharing machine was Stitching 2. These two different machines can both perform sewing functions. In F2, the capability of Stitching 11 is too small for the assigned workload. The Stitching 5 of F1 then shared the workload of F2 since it was close to Stitching 11 and less busy. The sizes of the feeding buffer and the loading buffer were temporarily assumed to be 40 parts and 15 parts, respectively. The transfer batch size was remained the same as the operation size. Phase III of the simulation model was then applied for the final design for the footwear HCM system.

Table 6.5: Intra- cell Machine Sharing

Busy Workstation	Sharing Workstation
Cutting 1	Cutting 2
Quality Control	Matching
Splitting	Cutting 3
Edge grinding	Skiving
Embroidery 1	Embroidery 2
Printing	Hyfrequency
Stitching 3	Stitching 4
Stitching 7	Stitching 1
Stitching 8	Stitching 9
Stitching 12	Stitching 13

6.3.3 Performance Observations

To observe the system performances, some measurement criteria were used as shown in Table 6.6. In this industry, customer expects a variety of fashion styles and low prices, along with fast delivery and high quality. Therefore, AWIP was studied for not only saving production cost, but also better quality. Quality is higher if WIP level is lower. During the manufacturing processes, the shoes are easily deformed without protections. Minimizing WIP level yields better products. In addition, high total throughput shortened the lead time. In addition to improving the overall productivity of the system, throughputs of the three types of products were also tested separately.

Table 6.6: Measurements and Parameters

Code	Name
AWIP	average work-in-process inventory level (parts)
AUTC	average unit transfer cost ($)
TT	total throughput (products)
MT	throughput of leather boots (products)
LT	throughput of ladies suede sneakers (products)
KT	throughput of kids sneakers (products)
Ue	unit inter-cell transfer batch size for workstation Embroidery 1 (parts)
Us	unit inter-cell transfer batch size for workstation Stitching 11 (parts)

The system performance improvements are summarized in Table 6.7. A significant improvement from Phase I to Phase II was observed. The AUTC provided the greatest percentage of improvement. Obviously, the Phase II model reduced one cycle of the conveyor loops that a part had to travel. By comparing Phase II and Phase III, however, AUTC was higher in Phase III by 24.03%. At the same time, AWIP and TT were improved by 6.65% and 3.83%, respectively. This explains that the inter-cell flows occurred frequently and balanced the workload. Thus, with an improvement in productivity, the transferring cost increased.

6.3.4 Optimization

The case study used an optimization procedure to select best system configurations. The optimization procedure was undertaken with five controllable parameters. They were the loading buffer and inter-cell transfer size of Embroidery 1 and Stitching 11. The optimization results were summarized in Table 6.8. The upper portion of Table 6.8 suggests the values of the selected controllable parameters to meet the objectives; the lower portion presents the outcomes of measurements. The loading buffer and the Us value have no major effect upon TT. However, for the throughput of each product, the reduced values of these two factors lead to throughput maximization.

Table 6.7: Performance Improvements

Measurement	AWIP	AUTC	TT
Phase I	1692.588	10.797	5085
Phase II	819.087	3.907	5384
Phase III	764.625	4.846	5590
Phase I vs. Phase II	51.61%	63.81%	5.88%
Phase II vs. Phase III	6.65%	-24.03%	3.83%

6.4 Conclusions

A HCM system of a footwear factory was modeled and several production plans were proposed. It is challenging to produce according to the demand that fluctuates frequently.

When a new product is introduced, the production plan may require some adjustments. The daily change of demand distribution reflects the production in the real world of the footwear industry. There was more than one optimal solution proposed for this HCM system. The urgent orders can be taken care in advance with proper production planning. Although the given example was not complicated, it highlighted the main characteristics of the three-phase model.

Table 6.8: The Results of Optimizations

	Workstation				
	Embroidery 1		Stitching 11		All
Objective Measurement	loading buffer size (parts)	Ue (parts)	loading buffer size (parts)	Us(parts)	Operation batch size (parts)
Initial estimation	25	5	20	15	10
Minimize AWIP	11	5	8	5	5
Minimize AUTC	31	10	18	20	5
Maximize TT	14	15	39	25	5
Maximize MT	19	5	13	5	10
Maximize LT	19	5	31	20	15
Maximize KT	14	5	29	15	15

Objective Measurement	AWIP	AUTC	TT	MT	LT	KT
Initial estimation	764.63	4.85	5590	1564	2030	1996
Minimize AWIP	503.26	4.48	5512	1665	1944	1903
Minimize AUTC	655.44	3.42	5178	1443	1878	1857
Maximize TT	747.33	4.60	5728	1590	2080	2058
Maximize MT	670.33	4.30	5468	1788	1815	1865
Maximize LT	1010.46	6.62	5505	1471	2168	1866
Maximize KT	1041.94	11.15	5636	1572	1956	2108

CHAPTER 7

CONCLUSIONS AND FUTURE DEVELOPMENT

Short life cycle of today's manufactured products design demands flexibility of manufacturing systems. Cellular Manufacturing System (CMS) has less flexibility than functional manufacturing systems but higher productivity and shorter flow time. Over the past years, the impact of product diversification on the productivity of cellular manufacturing system seemed to be more pronounced. Customers' needs and demands have grown diverse. Those changes have significant influence on labor-intensive industry. The level of flexibility of CMS is insufficient to meet the customers' demands. Since there is no guarantee that a CMS will outperform a functionally organized system, many managers change their systems back to process oriented system. Consequently, hybrid manufacturing systems emerge while researchers seek new philosophies of GT.

This research proposes an approach to manage the unbalanced workloads between manufacturing cells in a CMS to improve system performance. It also suggests proper choices of production characters for maximum system efficiency. A model is derived for a hybrid CM system to conduct a simulation experiment. Each cell in the system is served with a unidirectional conveyor belt loop. By introducing a proper level of flexibility, the intra-cell and inter-cell material movements become the main factors to improve the overall system performance. Meanwhile, it demonstrates the interrelationships among other production characters. Optimal solutions are found with the synergy of optimization and sensitivity analysis. A case study was conducted by applying the three-phase approach to hybrid CM system in a footwear company. There are the major considerations of this research.

This study may be extended to solving production planning problems using simulation. By cooperating with the three-phased approach, production planning for a hybrid manufacturing system can be done by considering the forecasted demands, scheduling, inventory control and resource planning. Moreover, although many production characteristics are considered in this study, some other important factors, such as the possibility of machine breakdowns, are not yet taken into consideration. In the real world, however, many crucial factors cannot be ignored. More research that investigates other important factors is to be carried out using more effective methods.

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Appendix I: Part Process Sequences and Process Time (given in minutes)

Product Type		Product A					
Part Type (Seq.)		PA_1 (C1-C3-C4-C2)			PA_2 (C2-C3)		
Cell no.	Op.	1	2	3	1	2	3
1	M11	(92,96,98)	—	—	—	—	—
	M12	—	(40,41,43)	—	—	—	—
	M13	(90,98,104)	(78,85,92)	—	—	—	—
	M14	—	(34,36,39)	—	—	—	—
	M15	(68,77,84)	(85,88,90)	—	—	—	—
2	M21	—	—	(98,102,108)	(76,84,88)	—	—
	M22	—	—	(100,108,112)	(88,91,95)	—	—
	M23	—	—	(62,66,70)	(90,93,98)	—	—
	M24	—	—	—	—	(96,99,104)	—
	M25	—	—	(83,88,95)	(78,86,99)	—	—
	M26	—	—	(98,105,109)	—	(106,112,115)	—
3	M31	—	(67,69,71)	—	—	—	(37,39,41)
	M32	—	(98,107,115)	—	—	(89,92,95)	(103,108,117)
	M33	—	(49,50,52)	—	—	—	(48,49,50)
	M34	—	(85,87,89)	—	—	(92,98,101)	(82,84,85)
4	M41	—	—	—	—	—	—
	M42	—	(106,110,117)	—	—	—	—
	M43	—	(97,103,110)	—	—	—	—
	M44	—	—	—	—	—	—
	M45	—	—	—	—	—	—
	M46	—	(58,61,67)	—	—	—	—
	M47	—	—	—	—	—	—
5	M51	—	—	—	—	—	—
	M52	—	—	—	—	—	—
	M53	—	—	—	—	—	—
	M54	—	—	—	—	—	—
	M55	—	—	—	—	—	—
	M56	—	—	—	—	—	—
	M57	—	—	—	—	—	—
	M58	—	—	—	—	—	—

Product Type					Product B		
Part Type (Seq.)		PA$_3$ (C2-C3-C4-C5)			PB$_1$ (C1-C5-C2)		
Cell no.	Op.	1	2	3	1	2	3
1	M11	—	—	—	(102,108,111)	(86,99,91)	—
	M12	—	—	—	—	(62,69,76)	—
	M13	—	—	—	(93,96,99)	—	—
	M14	—	—	—	—	(86,95,100)	—
	M15	—	—	—	(84,87,90)	—	—
2	M21	(62,66,68)	—	—	—	—	(55,58,60)
	M22	(94,98,102)	—	—	—	—	—
	M23	—	(81,89,96)	—	—	—	(33,39,43)
	M24	(85,96,100)	(93,98,101)	—	—	—	—
	M25	—	—	—	—	—	(54,58,63)
	M26	(82,84,97)	(92,98,102)	—	—	—	(92,95,98)
3	M31	—	(53,60,64)	—	—	—	—
	M32	—	(98,102,109)	—	—	—	—
	M33	—	(42,46,48)	—	—	—	—
	M34	—	—	—	—		—
4	M41	—	—	—	—	—	—
	M42	—	—	—	—	—	—
	M43	—	(89,96,100)	—	—	—	—
	M44	—	(56,62,70)	—	—	—	—
	M45	—	(79,86,90)	—	—	—	—
	M46	—	—	—	—	—	—
	M47	—	(98,106,110)	—	—	—	—
5	M51	—	—	(90,95,109)	—	(102,109,114)	—
	M52	—	(48,58,66)	—	—	—	—
	M53	—	—	(67,69,71)	—	(43,49,55)	—
	M54	—	—	(92,96,98)	—	(99,103,113)	—
	M55	—	—	(93,99,105)	—	—	—
	M56	—	(88,92,98)	(60,64,71)	—	(55,57,63)	—
	M57	—	(96,98,102)	—	—	—	—
	M58	—	(100,106,113)	—	—	(91,95,98)	

Product Type							
Part Type (Seq.)		PB$_2$ (C2-C1-C4-C3)			PB$_3$ (C4-C1-C5)		
Cell no.	Op.	1	2	3	1	2	3
1	M11	—	(93,99,105)	—	—	(97,99,102)	—
	M12	—	(20,25,27)	—	—	(39,42,45)	—
	M13	—	(80,87,89)	—	—	(66,76,88)	(77,84,96)
	M14	—	(62,64,68)	—	—	—	(29,34,36)
	M15	—	—	—	—	(81,86,89)	—
2	M21	(69,72,74)	—	—	—	—	—
	M22	(93,95,98)	—	—	—	—	—
	M23	—	—	—	—	—	—
	M24	(25,27,29)	—	—	—	—	—
	M25	(89,97,108)	—	—	—	—	—
	M26	—		—	—	—	—
3	M31	—	—	(30,35,40)	—	—	—
	M32	—	—	—	—	—	—
	M33	—	—	(48,55,60)	—	—	—
	M34	—	—	(99,101,104)	—	—	—
4	M41	—	—	—	(90,93,96)	—	—
	M42	—	(85,96,102)	—	—	—	—
	M43	—	(96,100,106)	—	—	—	—
	M44	—	(29,33,37)	—	(38,41,42)	—	—
	M45	—	—	—	(60,63,68)	—	—
	M46	—	—	—	(90,100,108)	—	—
	M47	—	(89,97,100)	—	(70,73,77)		—
5	M51	—	—	—	—	—	(46,48,51)
	M52	—	—	—	—		—
	M53	—	—	—	—	—	(35,39,43)
	M54	—	—	—	—	—	(80,86,93)
	M55	—	—	—	—	—	(90,93,98)
	M56	—	—	—	—	—	—
	M57	—	—	—	—	—	(88,93,96)
	M58	—	—	—	—	—	—

Product Type		Product B			Product C		
Part Type (Seq.)		PB$_4$ (C4-C5-C1)			PC$_1$ (C1-C3-C5)		
Cell no.	Op.	1	2	3	1	2	3
1	M11	—	—	(88,91,93)	(68,70,72)	—	—
	M12	—	—	—	—	(42,43,45)	—
	M13	—	—	(81,85,99)	(76,83,88)	—	—
	M14	—	—	(61,62,65)	—	—	—
	M15	—	—	(98,105,109)	(82,89,94)	—	—
2	M21	—	—	—	—	—	—
	M22	—	—	—	—	—	—
	M23	—	—	—	—	—	—
	M24	—	—	—	—	—	—
	M25	—	—	—	—	—	—
	M26				—	—	—
3	M31	—	—	—	—	—	(37,39,45)
	M32	—	—	—	—	—	(66,78,85)
	M33	—	—	—	—	(30,32,34)	—
	M34	—	—	—	—	(57,61,63)	(81,88,96)
4	M41	(31,37,38)	—	—	—	—	—
	M42	(20,22,30)	—	—	—	—	—
	M43	—	(87,89,93)	—	—	—	—
	M44	—	—	—	—	—	—
	M45	—	(32,33,36)	—	—	—	—
	M46	(56,57,58)	—	—	—	—	—
	M47	(98,105,110)	(98,108,117)	—	—	—	—
5	M51	—	(33,35,36)	—	—	—	(63,65,71)
	M52	—	—	—	—	—	—
	M53	—	—	—	—	—	(50,55,58)
	M54	—	(78,86,94)	—	—	—	—
	M55	—	(92,96,99)	—	—	—	(83,88,95)
	M56	—		—	—	—	—
	M57	—	(92,96,99)	—	—	—	—
	M58	—	—	—	—	—	—

Product Type							
Part Type (Seq.)		PC$_2$ (C2-C3-C4)			PC$_3$ (C3-C4-C5)		
Cell no.	Op.	1	2	3	1	2	3
1	M11	—	—	—	—	—	—
	M12	—	—	—	—	—	—
	M13	—	—	—	—	—	—
	M14	—	—	—	—	—	—
	M15	—	—	—	—	—	—
2	M21	(85,90,96)	—	—	—	—	—
	M22	—	(95,102,107)	—	—	—	—
	M23	(73,80,82)	—	—	—	—	—
	M24	(83,88,97)	—	—	—	—	—
	M25	—	—	—	—	—	—
	M26	—	(101,105,109)	—	—	—	—
3	M31	—	—	(27,35,39)	(69,73,80)	—	—
	M32	—	(70,78,84)	(86,88,94)	(97,106,110)	—	—
	M33	—	—	(50,51,52)	(36,39,42)	—	—
	M34	—	(92,99,106)	(67,70,77)	(91,98,104)	—	—
4	M41	—	—	—	—	(35,36,38)	—
	M42	—	—	(44,45,46)	(40,41,42)	—	—
	M43	—	—	(96,98,103)	—	(91,97,104)	—
	M44	—	—	—	(50,52,59)	—	—
	M45	—	—	(36,38,43)	—	(46,50,54)	—
	M46	—	—	—	(30,31,34)	—	—
	M47	—	—	—	—	(89,95,98)	—
5	M51	—	—	—	—	—	—
	M52	—	—	—	—	—	(89,93,99)
	M53	—	—	—	—	—	—
	M54	—	—	—	—	(83,85,95)	—
	M55	—	—	—	—	—	(74,79,86)
	M56	—	—	—	—	(30,35,39)	—
	M57	—	—	—	—	(85,94,97)	—
	M58	—	—	—	—	—	—

Product Type		Product C					
Part Type (Seq.)		PC_4 (C4-C5)			PC_5 (C5)		
Cell no.	Op.	1	2	3	1	2	3
1	M11	—	—	—	—	—	—
	M12	—	—	—	—	—	—
	M13	—	—	—	—	—	—
	M14	—	—	—	—	—	—
	M15	—	—	—	—	—	—
2	M21	—	—	—	—	—	—
	M22	—	—	—	—	—	—
	M23	—	—	—	—	—	—
	M24	—	—	—	—	—	—
	M25	—	—	—	—	—	—
	M26	—	—	—	—	—	—
3	M31	—	—	—	—	—	—
	M32	—	—	—	—	—	—
	M33	—	—	—	—	—	—
	M34	—	—	—	—	—	—
4	M41	(34,37,39)	—	—	—	—	—
	M42	(80,84,90)	—	—	—	—	—
	M43	—	(86,90,96)	—	—	—	—
	M44	—	—	—	—	—	—
	M45	—	(30,33,38)	—	—	—	—
	M46	(30,31,37)	—	—	—	—	—
	M47	—	—	—	—	—	—
5	M51	—	—	—	(30,32,38)	(45,49,52)	—
	M52	—	—	(91,99,109)	(100,110,118)	—	(89,98,108)
	M53	—	(41,43,44)	—	—	—	(51,56,60)
	M54	—	(90,93,96)	—	(90,92,96)	—	(78,85,90)
	M55	—	—	(68,76,82)	—	(86,89,95)	(93,96,98)
	M56	—	—	(41,43,45)	(76,80,86)	(47,50,52)	(48,51,54)
	M57	—	—	(75,82,88)	(98,107,111)	—	—
	M58	—	(80,83,87)	—	(92,94,97)	—	(89,91,93)

Appendix II: Time s Unit Spent At a Workstation

Table II.-1: Time a Unit Spent at a Workstation of Phase I Experiment

	Average service time	Average queue time	Other time	Time spend at the workstation
M11 Process	1.55	51.15	17.35	70.05
M12 Process	0.73	2.02	8.80	11.54
M13 Process	1.44	48.06	24.98	74.48
M14 Process	0.97	3.29	9.07	13.32
M15 Process	1.44	11.74	10.17	23.35
M21 Process	1.30	6.71	6.10	14.10
M22 Process	1.64	6.09	6.11	13.84
M23 Process	1.24	2.30	6.25	9.79
M24 Process	1.59	7.15	5.98	14.73
M25 Process	1.14	1.94	7.19	10.27
M26 Process	1.60	8.77	5.62	15.99
M31 Process	0.82	5.56	20.05	26.44
M32 Process	1.58	65.35	34.51	101.44
M33 Process	0.77	5.31	18.44	24.52
M34 Process	1.46	53.72	29.83	85.00
M41 Process	0.86	1.84	7.60	10.31
M42 Process	1.12	6.87	8.60	16.59
M43 Process	1.60	23.36	6.32	31.29
M44 Process	0.77	1.38	7.35	9.50
M45 Process	0.98	1.83	5.76	8.57
M46 Process	0.99	2.39	6.53	9.91
M47 Process	1.61	15.11	5.76	22.48
M51 Process	1.03	7.58	8.17	16.78
M52 Process	1.53	7.17	7.39	16.09
M53 Process	0.85	2.42	6.63	9.90
M54 Process	1.52	46.48	16.49	64.50
M55 Process	1.44	33.52	23.66	58.62
M56 Process	1.01	4.38	7.63	13.02
M57 Process	1.61	12.13	6.88	20.62
M58 Process	1.56	7.86	7.54	16.97

*Unit : minutes

Table II - 2: Time a Unit Spent at a Workstation of Phase II Experiment

server	Average service time	Average queue time	Other time	Time spend at the workstation
M11 Process	1.55	4.17	6.41	12.13
M12 Process	1.00	3.20	5.32	9.51
M13 Process	1.44	4.24	5.80	11.48
M14 Process	1.13	4.13	5.14	10.41
M15 Process	1.43	5.95	5.52	12.90
M21 Process	1.37	9.75	5.61	16.72
M22 Process	1.64	6.67	5.97	14.28
M23 Process	1.23	2.31	6.03	9.57
M24 Process	1.59	2.83	8.18	12.60
M25 Process	1.32	3.19	5.44	9.96
M26 Process	1.60	5.59	6.19	13.38
M31 Process	1.02	7.97	4.86	13.85
M32 Process	1.58	6.62	5.76	13.96
M33 Process	1.00	5.71	4.64	11.35
M34 Process	1.45	8.94	5.38	15.77
M41 Process	1.15	3.72	5.67	10.53
M42 Process	1.11	3.10	5.56	9.77
M43 Process	1.61	3.60	6.33	11.54
M44 Process	1.11	3.21	5.41	9.72
M45 Process	0.97	1.79	5.48	8.23
M46 Process	0.96	1.92	6.10	8.97
M47 Process	1.61	3.33	7.54	12.47
M51 Process	1.04	11.97	13.14	26.15
M52 Process	1.52	12.90	9.38	23.80
M53 Process	0.86	4.02	9.25	14.13
M54 Process	1.52	55.32	36.38	93.23
M55 Process	1.43	16.23	10.36	28.03
M56 Process	1.12	15.67	12.70	29.48
M57 Process	1.61	14.70	10.74	27.05
M58 Process	1.58	16.96	9.07	27.61

Table II - 3: Time a Unit Spent at a Workstation of Phase III Experiment

server	Average service time	Average queue time	Other time	Time spend at the workstation
M11 Process	1.55	4.17	6.41	12.13
M12 Process	1.00	3.20	5.32	9.51
M13 Process	1.44	4.24	5.80	11.48
M14 Process	1.13	4.13	5.14	10.41
M15 Process	1.43	5.95	5.52	12.90
M21 Process	1.37	9.75	5.61	16.72
M22 Process	1.64	6.67	5.97	14.28
M23 Process	1.23	2.31	6.03	9.57
M24 Process	1.59	2.83	8.18	12.60
M25 Process	1.32	3.19	5.44	9.96
M26 Process	1.60	5.59	6.19	13.38
M31 Process	1.02	7.97	4.86	13.85
M32 Process	1.58	6.62	5.76	13.96
M33 Process	1.00	5.71	4.64	11.35
M34 Process	1.45	8.94	5.38	15.77
M41 Process	1.15	3.72	5.67	10.53
M42 Process	1.11	3.10	5.56	9.77
M43 Process	1.61	3.60	6.33	11.54
M44 Process	1.11	3.21	5.41	9.72
M45 Process	0.97	1.79	5.48	8.23
M46 Process	0.96	1.92	6.10	8.97
M47 Process	1.61	3.33	7.54	12.47
M51 Process	1.04	11.97	13.14	26.15
M52 Process	1.52	12.90	9.38	23.80
M53 Process	0.86	4.02	9.25	14.13
M54 Process	1.52	55.32	36.38	93.23
M55 Process	1.43	16.23	10.36	28.03
M56 Process	1.12	15.67	12.70	29.48
M57 Process	1.61	14.70	10.74	27.05
M58 Process	1.58	16.96	9.07	27.61

*Unit :minutes

Appendix III: ATC, AWIP and TT of Demand Group

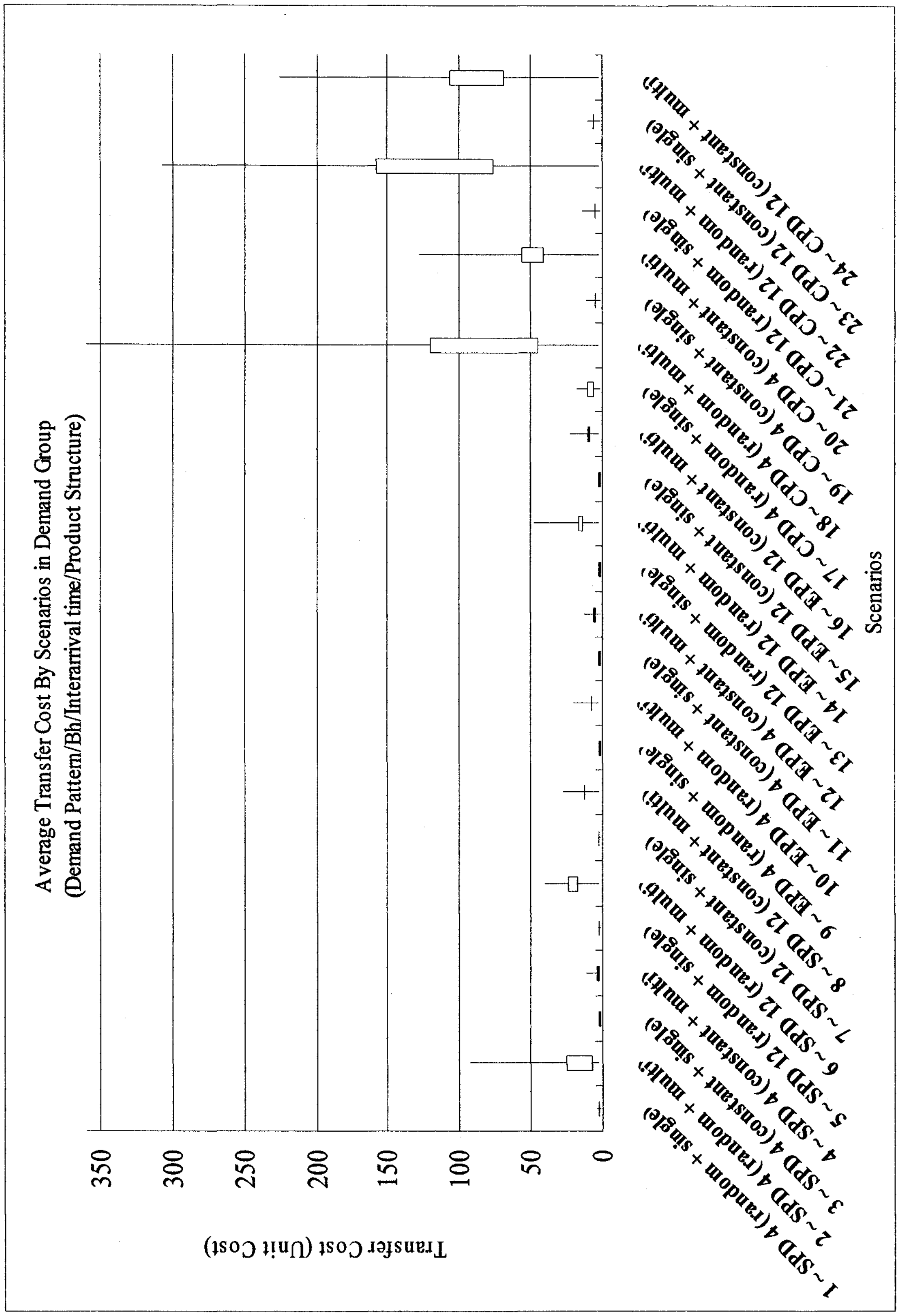

Figure III-1: ATC of Demand Group

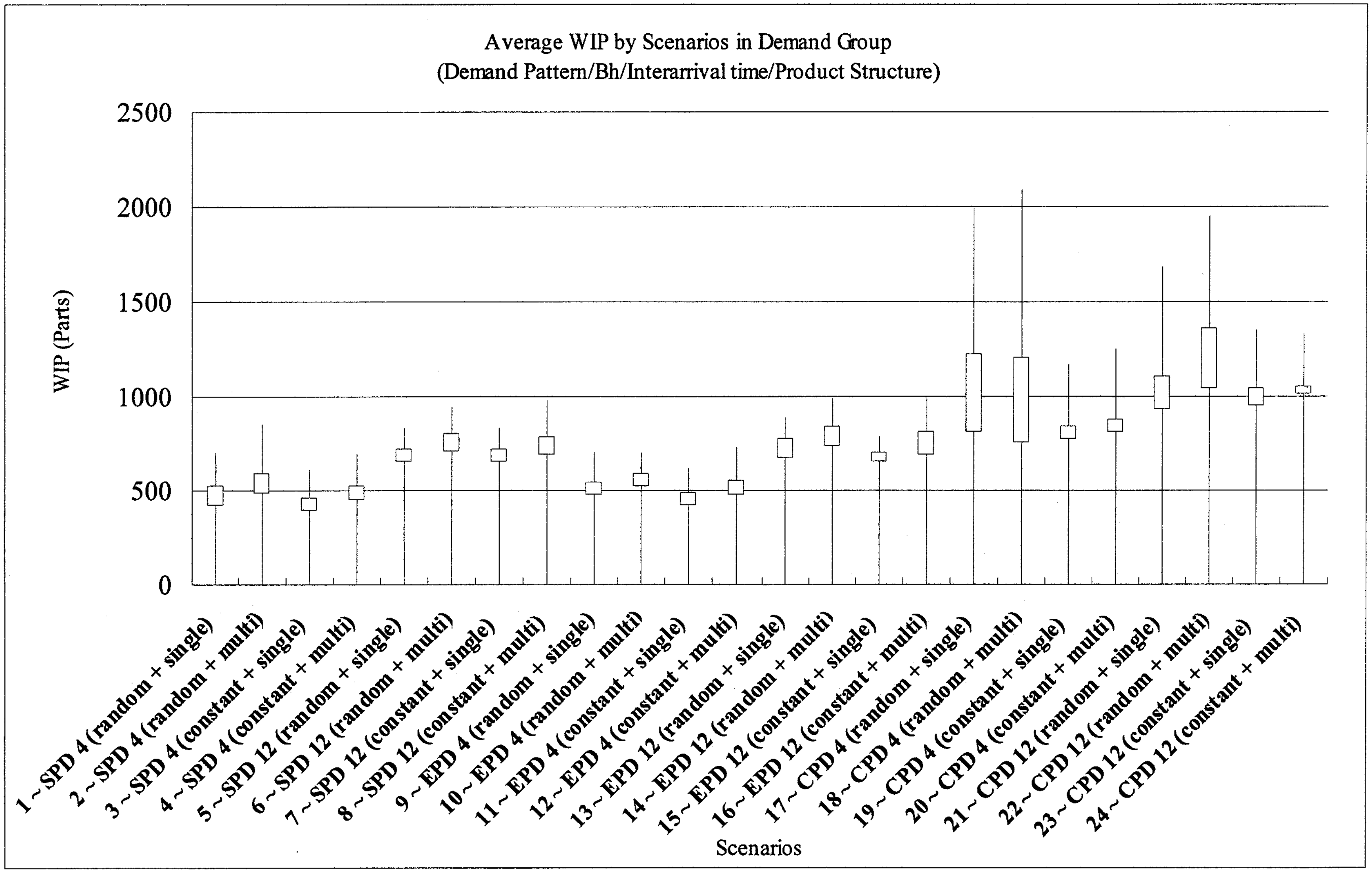

Figure III-2: WIP of Demand Group

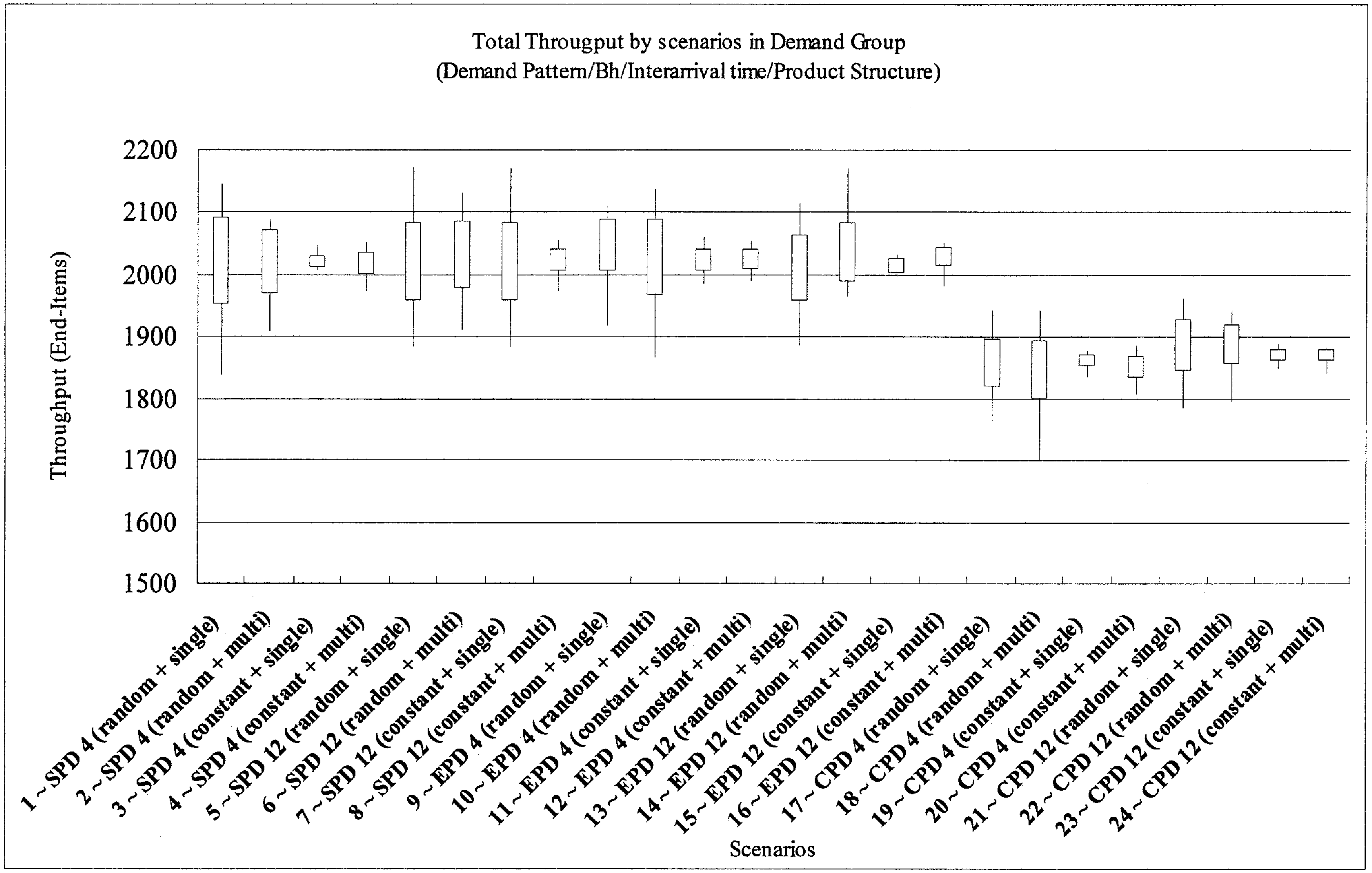

Figure III-3: TT of Demand Group

Appendix IV: ATC, AWIP and TT of Setup Group

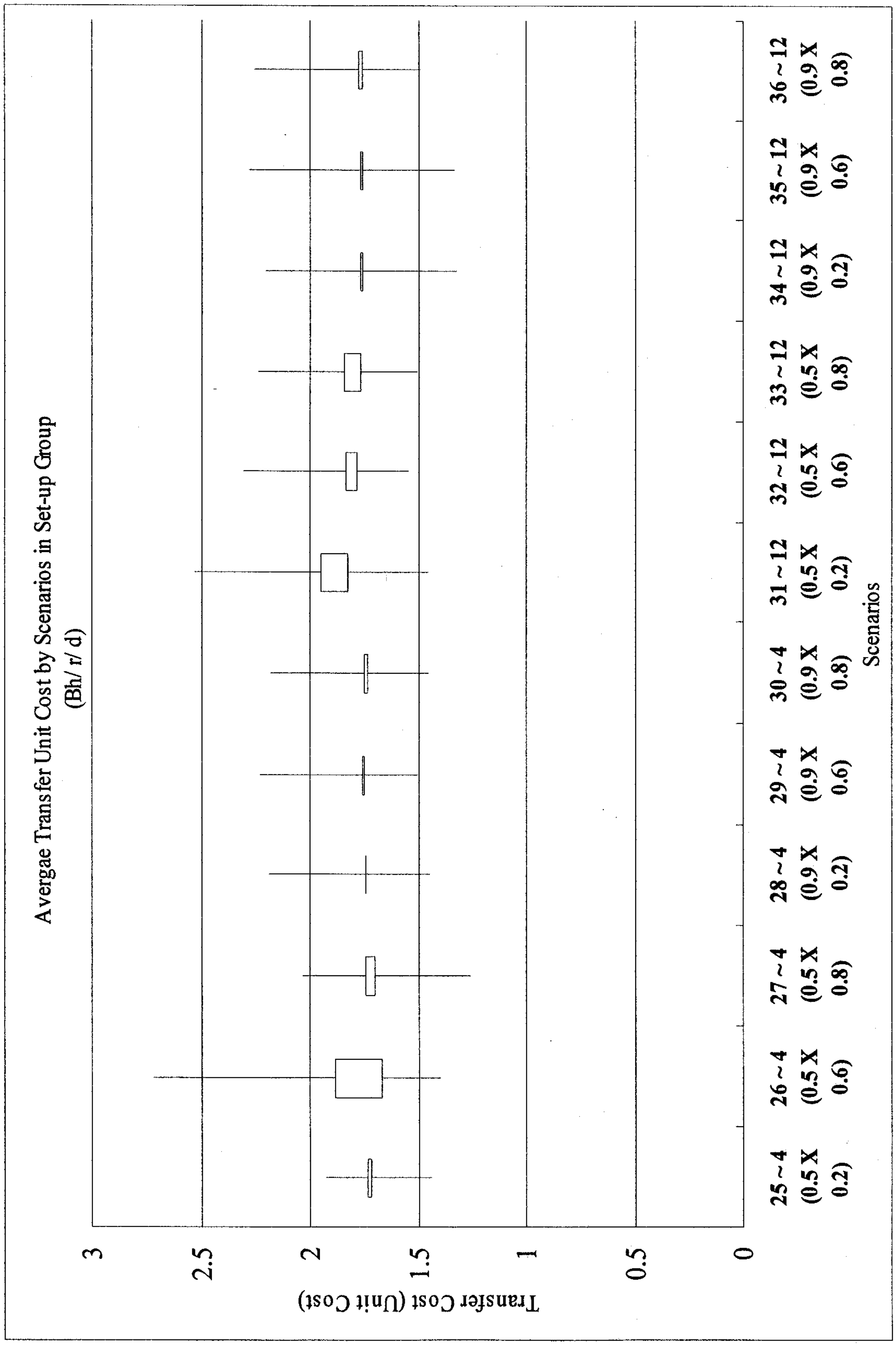

Figure IV-1: ATC of Set-up Group

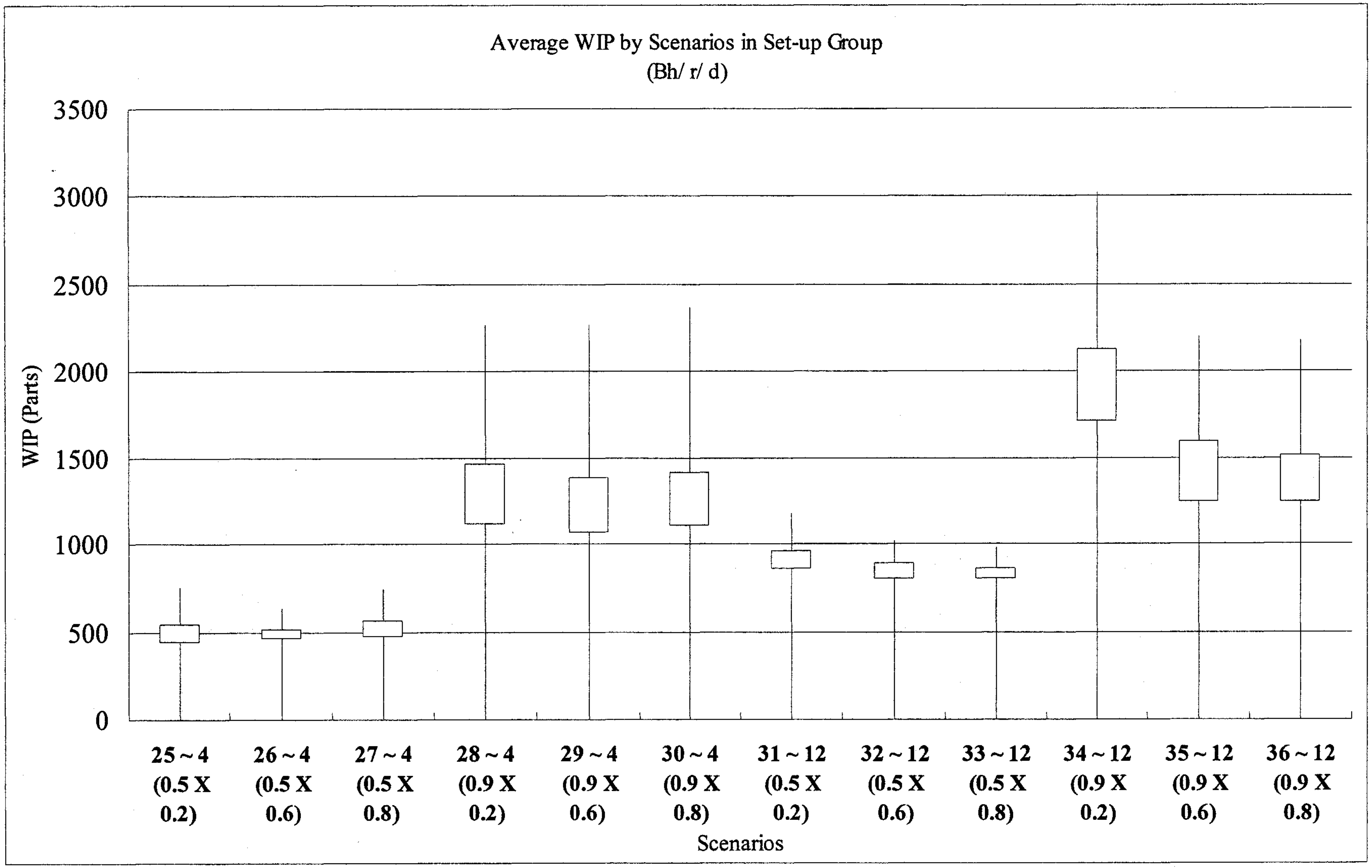

Figure IV-2: AWIP of Set-up Group

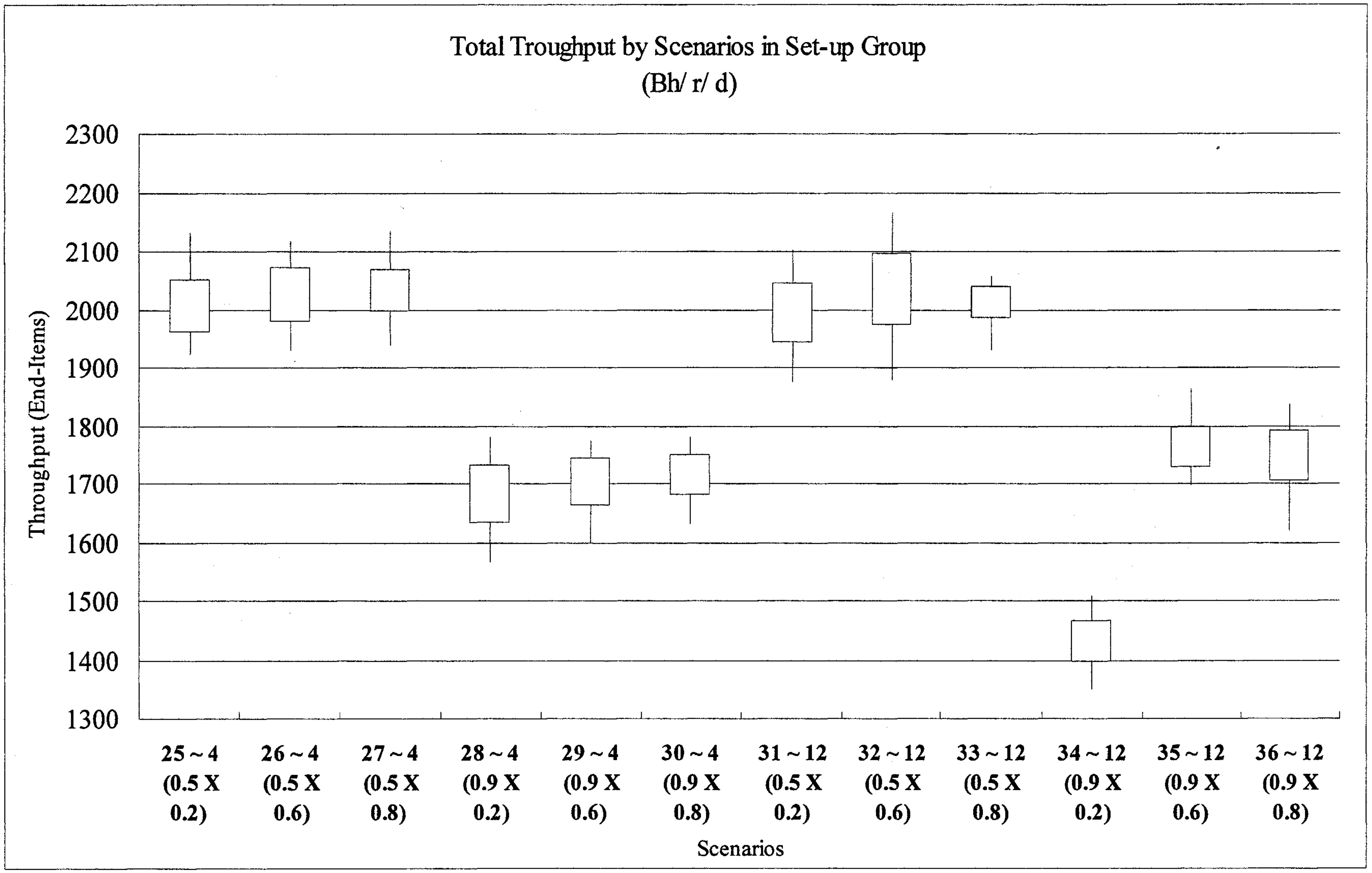

Figure IV-3: TT of Set-up Group

Appendix V: ATC, AWIP and TT of Buffering Group

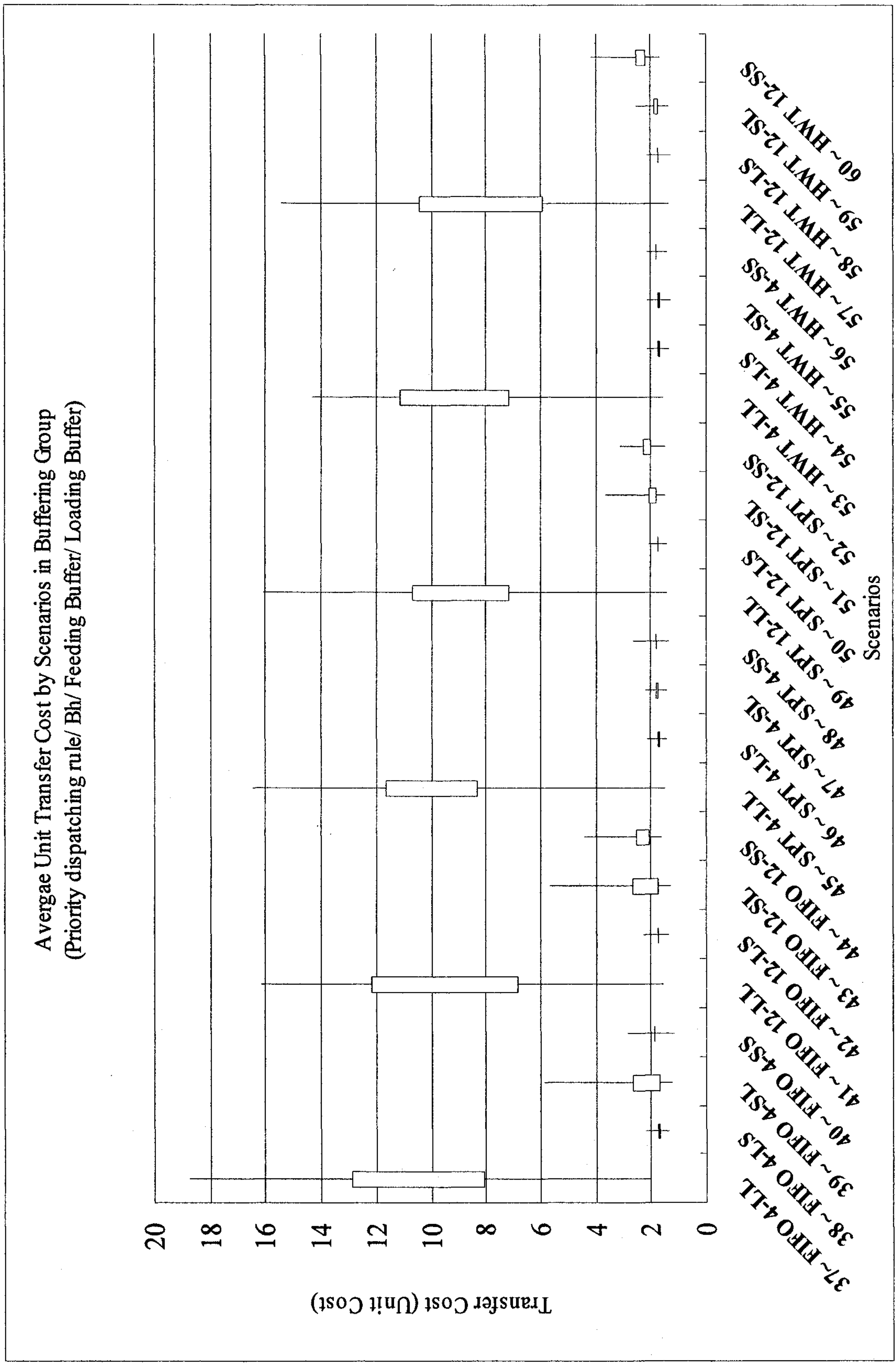

Figure V-1: ATC of Buffering Group

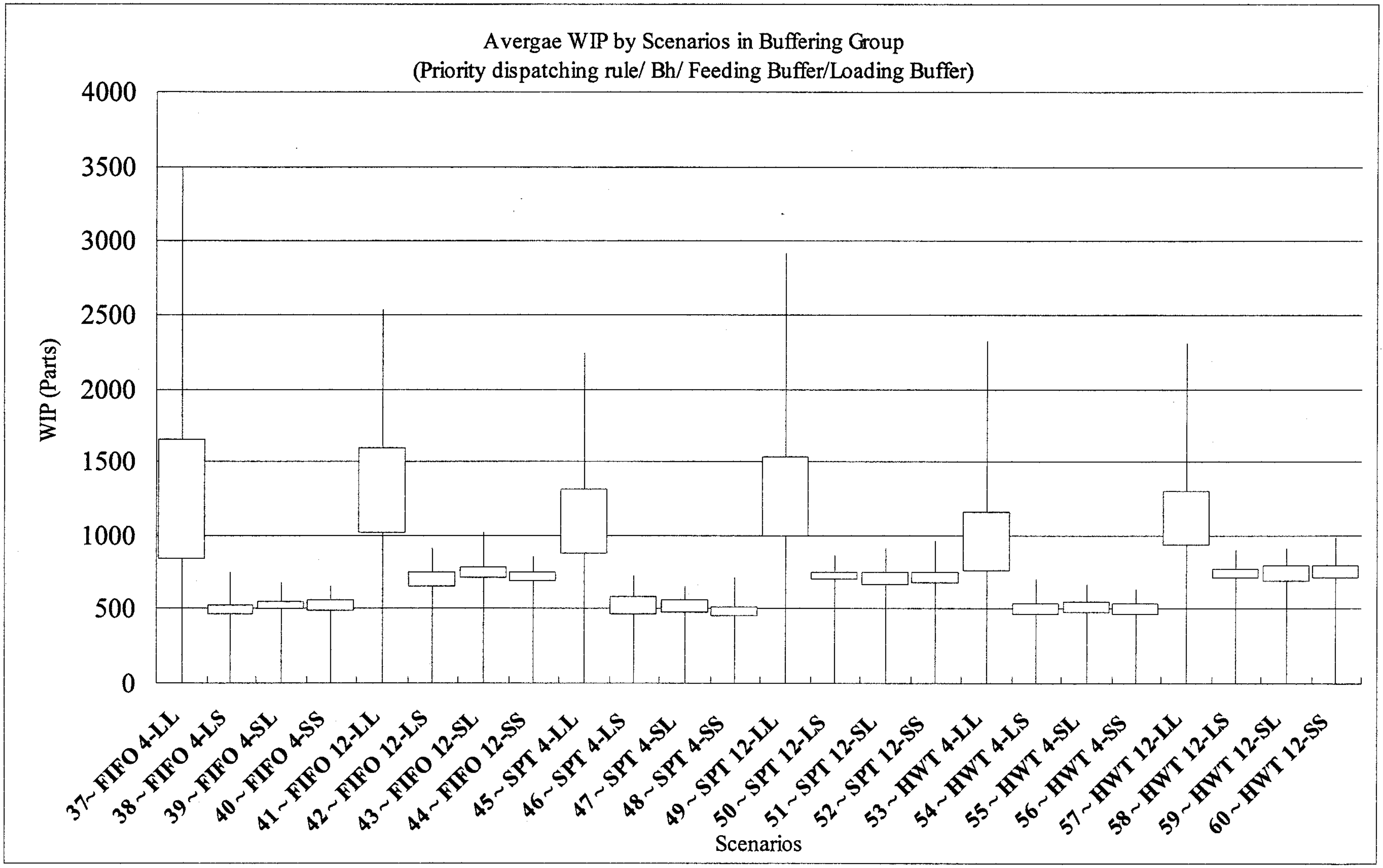

Figure V-2: AWIP of Buffering Group

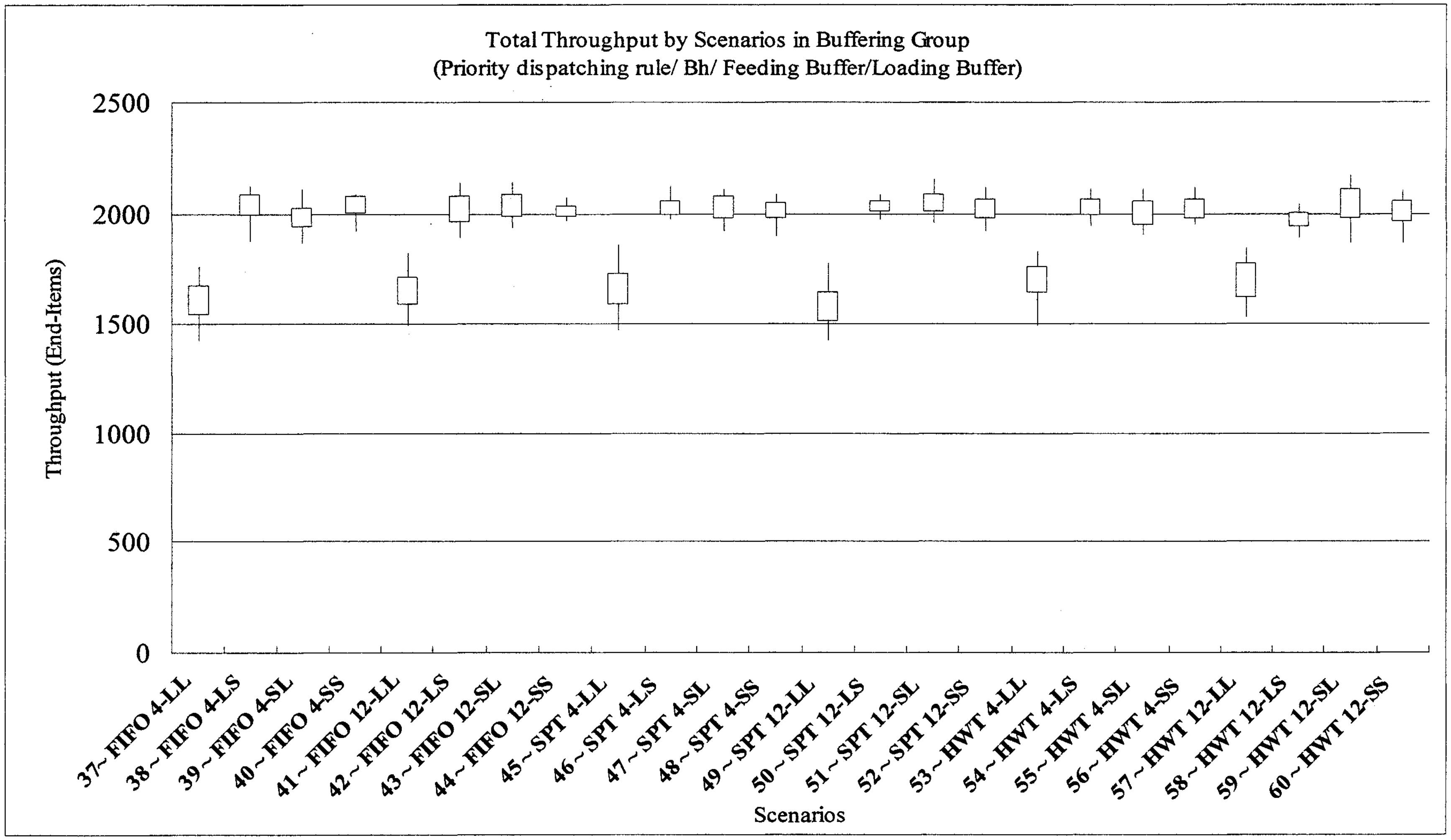

Figure V-3: TT of Buffering Group

Appendix VI: Part Process Sequences and Process Times of a Footwear Company

Product Type		**Product M: Men leather boots**					
Part Number		**PM1**			**PM2**		
cell	**Operation (mins)**	**1**	**2**	**3**	**1**	**2**	**3**
C1	Cutting 1	(19,20,24)	—	—	—	—	—
	Cutting 2	—	(20,21,23)	—	—	—	—
	Quality control 1	(10,11,13)	(39,41,43)	—	—	—	—
	Matching	—	(14,16,19)	—	—	—	—
	Printing 1	(13,16,18)	(25,28,30)	—	—	—	—
C2	Splitting	—	—	(21,25,29)	(36,40,43)	—	—
	Cutting 3	—	—	(15,19,23)	(18,21,25)	—	—
	Quality control 2	—	—	(24,28,31)	(14,18,23)	—	—
	Edge grinding	—	—	—	—	(35,38,41)	—
	Skiving	—	—	(37,38,42)	(30,33,37)	—	—
	Flatting	—	—	(27,30,33)	—	(20,22,28)	—
C3	Embroidery 1	—	(27,29,31)	—	—	—	(17,19,21)
	Printing 2	—	(11,13,16)	—	—	(9,12,15)	(28,30,33))
	Hyfrequency	—	(9,10,12)	—	—	—	(18,19,20)
	Embroidery 2	—	(30,40,45)	—	—	(22,24,27)	(32,34,35)
F1	Stitching 1	—	—	—	—	—	—
	Stitching 2	—	(22,24,28)	—	—	—	—
	Stitching 3	—	(25,31,36)	—	—	—	—
	Stitching 4	—	—	—	—	—	—
	Stitching 5	—	—	—	—	—	—
	Stitching 6	—	(37,38,40)	—	—	—	—
	Stitching 7	—	—	—	—	—	—
F2	Stitching 8	—	—	—	—	—	—
	Stitching 9	—	—	—	—	—	—
	Stitching 10	—	—	—	—	—	—
	Stitching 11	—	—	—	—	—	—
	Stitching 12	—	—	—	—	—	—
	Stitching 13	—	—	—	—	—	—
	Stitching 14	—	—	—	—	—	—
	Stitching 15	—	—	—	—	—	—

Product Type					**Product L: Ladies suede sneakers**		
Part Number		**PM3**			**PL1**		
cell	**Operation (mins)**	**1**	**2**	**3**	**1**	**2**	**3**
C1	Cutting 1	___	___	___	(25,26,29)	(36,39,41)	___
	Cutting 2	___	___	___	___	(17,21,25)	___
	Quality control 1	___	___	___	(20,24,26)	___	___
	Matching	___	___	___	___	(22,29,32)	___
	Printing 1	___	___	___	(34,37,40)	___	___
C2	Splitting	(32,36,38)	___	___	___	___	(35,38,40)
	Cutting 3	(24,26,29)	___	___	___	___	___
	Quality control 2	___	(12,18,22)	___	___	___	(33,39,43)
	Edge grinding	(31,35,39)	(41,46,49)	___	___	___	___
	Skiving	___	___	___	___	___	(14,18,23)
	Flatting	(12,14,21)	(22,27,30)	___	___	___	(22,25,28)
C3	Embroidery 1	___	(32,35,37)	___	___	___	___
	Printing 2	___	(27,29,30)	___	___	___	___
	Hyfrequency	___	(42,46,48)	___	___	___	___
	Embroidery 2	___	___	___	___		___
F1	Stitching 1	___	___	___	___	___	___
	Stitching 2	___	___	___	___	___	___
	Stitching 3	___	(36,39,44)	___	___	___	___
	Stitching 4	___	(16,20,27)	___	___	___	___
	Stitching 5	___	(6,15,18)	___	___	___	___
	Stitching 6	___	___	___	___	___	___
	Stitching 7	___	(8,12,15)	___	___	___	___
F2	Stitching 8	___	___	(15,17,20)	___	(33,36,38)	___
	Stitching 9	___	(35,40,43)	___	___	___	___
	Stitching 10	___	___	(10,16,20)	___	(43,49,55)	___
	Stitching 11	___	___	(27,30,36)	___	(22,27,32)	___
	Stitching 12	___	___	(40,41,42)	___	___	___
	Stitching 13	___	(29,31,33)	(18,20,25)	___	(15,17,23)	___
	Stitching 14	___	(10,13,15)	___	___	___	___
	Stitching 15	___	(35,38,42)	___	___	(42,45,49)	

Product Type							
Part Number		**PL2**			**PL3**		
cell	**Operation (mins)**	**1**	**2**	**3**	**1**	**2**	**3**
C1	Cutting 1	—	(19,22,25)	—	—	(41,45,47)	—
	Cutting 2	—	(20,25,27)	—	—	(8,13,16)	—
	Quality control 1	—	(30,31,34)	—	—	(44,49,50)	(37,38,41)
	Matching	—	(12,14,18)	—	—	—	(29,34,36)
	Printing 1	—	—	—	—	(21,26,29)	—
C2	Splitting	(39,42,44)	—	—	—	—	—
	Cutting 3	(10,12,16)	—	—	—	—	—
	Quality control 2	—	—	—	—	—	—
	Edge grinding	(25,27,29)	—	—	—	—	—
	Skiving	(24,27,29)	—	—	—	—	—
	Flatting	—		—	—	—	—
C3	Embroidery 1	—	—	(32,36,40)	—	—	—
	Printing 2	—	—	—	—	—	—
	Hyfrequency	—	—	(28,29,30)	—	—	—
	Embroidery 2	—	—	(29,38,46)	—	—	—
F1	Stitching 1	—	—	—	(25,27,28)	—	—
	Stitching 2	—	(19,21,25)	—	—	—	—
	Stitching 3	—	(33,37,41)	—	—	—	—
	Stitching 4	—	(29,33,37)	—	(38,41,42)	—	—
	Stitching 5	—	—	—	(14,16,19)	—	—
	Stitching 6	—	—	—	(31,33,36)	—	—
	Stitching 7	—	(34,38,40)	—	(12,13,18)		—
F2	Stitching 8	—	—	—	—	—	(46,48,51)
	Stitching 9	—	—	—	—		—
	Stitching 10	—	—	—	—	—	(15,20,29)
	Stitching 11	—	—	—	—	—	(32,36,40)
	Stitching 12	—	—	—	—	—	(43,46,48)
	Stitching 13	—	—	—	—	—	—
	Stitching 14	—	—	—	—	—	(38,39,42)
	Stitching 15	—	—	—	—	—	—

Product Type		**Product L**			**Product K: Kids sneakers**		
Part Number		**PL4**			**PK1**		
cell	**Operation (mins)**	**1**	**2**	**3**	**1**	**2**	**3**
C1	Cutting 1	—	—	(31,34.39)	(28,30,32)	—	—
	Cutting 2	—	—	—	—	(22,23,25)	—
	Quality control 1	—	—	(30,35,39)	(11,12,15)	—	—
	Matching	—	—	(21,22,25)	—	—	—
	Printing 1	—	—	(40,44,46)	(33,35,38)	—	—
C2	Splitting	—	—	—	—	—	—
	Cutting 3	—	—	—	—	—	—
	Quality control 2	—	—	—	—	—	—
	Edge grinding	—	—	—	—	—	—
	Skiving	—	—	—	—	—	—
	Flatting				—	—	—
C3	Embroidery 1	—	—	—	—	—	(37,39,45)
	Printing 2	—	—	—	—	—	(9,10,12)
	Hyfrequency	—	—	—	—	(30,32,34)	—
	Embroidery 2	—	—	—	—	(17,21,23)	(21,23,28)
F1	Stitching 1	(11,17,18)	—	—	—	—	—
	Stitching 2	(20,22,30)	—	—	—	—	—
	Stitching 3	—	(24,25,29)	—	—	—	—
	Stitching 4	—	—	—	—	—	—
	Stitching 5	—	(32,33,36)	—	—	—	—
	Stitching 6	(29,39,47)	—	—	—	—	—
	Stitching 7	(34,38,40)	(27,28,29)	—	—	—	—
F2	Stitching 8	—	(33,35,36)	—	—	—	(30,35,38)
	Stitching 9	—	—	—	—	—	—
	Stitching 10	—	—	—	—	—	(50,55,58)
	Stitching 11	—	(25,29,32)	—	—	—	—
	Stitching 12	—	(40,43,46)	—	—	—	(20,28,34)
	Stitching 13	—		—	—	—	—
	Stitching 14	—	(20,26,31)	—	—	—	—
	Stitching 15	—	—	—	—	—	—

Product Type					**Product K**		
Part Number		**PK2**			**PK3**		
cell	**Operation (mins)**	**1**	**2**	**3**	**1**	**2**	**3**
C1	Cutting 1	—	—	—	—	—	—
	Cutting 2	—	—	—	—	—	—
	Quality control 1	—	—	—	—	—	—
	Matching	—	—	—	—	—	—
	Printing 1	—	—	—	—	—	—
C2	Splitting	(31,35,38)	—	—	—	—	—
	Cutting 3	—	(25,30,33)	—	—	—	—
	Quality control 2	(22,27,32)	—	—	—	—	—
	Edge grinding	(33,35,36)	—	—	—	—	—
	Skiving	—	—	—	—	—	—
	Flatting	—	(22,24,28)	—	—	—	—
C3	Embroidery 1	—	—	(27,35,39)	(36,39,41)	—	—
	Printing 2	—	(39,42,45)	(18,26,30)	(21,22,25)	—	—
	Hyfrequency	—	—	(18,19,20)	(36,39,42)	—	—
	Embroidery 2	—	(32,34,37)	(36,40,42)	(40,41,43)	—	—
F1	Stitching 1	—	—	—	—	(35,36,38)	—
	Stitching 2	—	—	(44,45,46)	(20,21,22)	—	—
	Stitching 3	—	—	(26,32,38)	—	(27,29,33)	—
	Stitching 4	—	—	—	(20,22,29)	—	—
	Stitching 5	—	—	(36,38,43)	—	(26,30,34)	—
	Stitching 6	—	—	—	(30,31,34)	—	—
	Stitching 7	—	—	—	—	(19,25,28)	—
F2	Stitching 8	—	—	—	—	—	—
	Stitching 9	—	—	—	—	—	(24,30,39)
	Stitching 10	—	—	—	—	—	—
	Stitching 11	—	—	—	—	(43,45,47)	—
	Stitching 12	—	—	—	—	—	(41,47,49)
	Stitching 13	—	—	—	—	(30,35,39)	—
	Stitching 14	—	—	—	—	(26,29,31)	—
	Stitching 15	—	—	—	—	—	—

Product Type							
Part Number		**PK4**			**PK5**		
cell	**Operation (mins)**	**1**	**2**	**3**	**1**	**2**	**3**
C1	Cutting 1	—	—	—	—	—	—
	Cutting 2	—	—	—	—	—	—
	Quality control 1	—	—	—	—	—	—
	Matching	—	—	—	—	—	—
	Printing 1	—	—	—	—	—	—
C2	Splitting	—	—	—	—	—	—
	Cutting 3	—	—	—	—	—	—
	Quality control 2	—	—	—	—	—	—
	Edge grinding	—	—	—	—	—	—
	Skiving	—	—	—	—	—	—
	Flatting	—	—	—	—	—	—
C3	Embroidery 1	—	—	—	—	—	—
	Printing 2	—	—	—	—	—	—
	Hyfrequency	—	—	—	—	—	—
	Embroidery 2	—	—	—	—	—	—
F1	Stitching 1	(14,17,19)	—	—	—	—	—
	Stitching 2	(20,22,25)	—	—	—	—	—
	Stitching 3	—	(22,23,27)	—	—	—	—
	Stitching 4	—	—	—	—	—	—
	Stitching 5	—	(30,33,38)	—	—	—	—
	Stitching 6	(40,42,45)	—	—	—	—	—
	Stitching 7	—	—	—	—	—	—
F2	Stitching 8	—	—	—	(30,32,38)	(45,49,52)	—
	Stitching 9	—	—	(39,44,48)	(22,26,28)	—	(41,46,49)
	Stitching 10	—	(41,43,44)	—	—	—	(21,26,30)
	Stitching 11	—	(23,28,30)	—	(51,53,55)	—	(33,34,38)
	Stitching 12	—	—	(44,45,46)	—	(36,38,40)	(53,58,61)
	Stitching 13	—	—	(14,17,21)	(16,17,19)	(26,30,35)	(31,34,39)
	Stitching 14	—	—	(5,8,12)	(21,24,28)	—	—
	Stitching 15	—	(30,33,37)	—	(31,32,37)	—	(15,19,23)