A SIMULATION STUDY OF THE EFFECTS OF APPLYING JIT MANUFACTURING TECHNIQUES IN A JOB SHOP ENVIRONMENT WITH KANBAN-BASED PRODUCTION CONTROL

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ABSTRACT

Just-in-Time (JIT) manufacturing has long been considered effective for improving the performance of job shop manufacturing. For application in a job shop environment, the most often suggested JIT techniques include: cellular manufacturing, processing and transporting parts one at a time (i.e. single-unit production and conveyance), demand-pull production control with the Kanban (i.e. a visual signal), employing faster material handling facilities, and reducing the variability of setup / processing time.

However, how and to what extent these suggested JIT techniques can affect the performance of job shop manufacturing is still not well explored. Accordingly, the motivation behind this study was to gain more understanding of the effects of implementing the suggested JIT techniques on the production performance in a job shop environment. Two simulation experiments were carried out to investigate the effects of five influential factors that are related to the application of the JIT techniques in a job shop.

The findings through this study show that functional layout was more suitable for a Kanban-controlled job shop when the achievable amount of setup time reduction through the use of cellular manufacturing was small. On the other hand, if a large setup time reduction was achievable through cellular manufacturing, cellular layout should be adopted. As for a medium amount of setup time reduction achievable through cellular manufacturing, the performances for the two layouts were similar, except that cellular layout was more suitable with a medium to low setup time variability.

Although the use of single-unit production and conveyance (SUPC) in cellular layout had been emphasised by many JIT proponents, we found that SUPC was only suitable for a Kanban-controlled job shop with unidirectional intra-cell production flow and a large amount of setup time reduction achievable through cellular manufacturing.

The effects of material handling speed and variability of setup / processing time were not as essential as those of other influential factors. Therefore, to attain better performance for job shop manufacturing with Kanbans, employing faster material handling facilities and reducing setup / processing time variability should only be considered after the selection of appropriate shop layout and production flow patterns.

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CHAPTER 1

INTRODUCTION

Among the various types of manufacturing, job shop manufacturing is often adopted for producing products having low volume and large varieties, and requiring diversified processing sequences. However, the characteristics of job shop manufacturing can easily lead to poor production performance. In the face of today's competitive market, there is a need for reforming job shop manufacturing to achieve better shop performance. Several Just-in-Time (JIT) manufacturing techniques were often suggested as effective tools for improving the performance of job shop manufacturing. In this research project, we investigated the effects of applying these suggested JIT techniques in a job shop environment, and arrived at several practical guidelines on the effective use of these JIT techniques in job shop environments.

In the following sections, we will describe the characteristics of job shop manufacturing, the need for reforming job shop manufacturing, the JIT techniques for reforming job shop manufacturing and the purposes of this research project.

1.1 Characteristics of Job Shop Manufacturing

As given by Grunwald *et al.* (1989) and Cheng and Podolsky (1993: 17), manufacturing environments can be classified into two broad categories: continuous production, and intermittent production. Continuous production typically involves the production of one or a few families of products in large volume with only a minimal amount of interruption in the process flow. On the other hand, intermittent production is usually used for producing a larger number of product families. Therefore, changeovers of the production system for producing different part families are often required for intermittent production.

The intermittent production can be further classified into job shop manufacturing and repetitive manufacturing. Job shop manufacturing is distinguished from repetitive manufacturing by the complexity of product routings. In summary, job shop manufacturing is characterised by low and irregular volume of demand, high product variety and complex product routings through the production processes.

It is important to note that the 'job shop' as defined above is different from a 'project shop' (or a jobbing shop) where each job is 'made-to-design' (i.e. a one off) and a specific product is rarely repeated. On the other hand, in a job shop environment, the range of products to be produced is known and therefore, a specific product may be repeated for different job orders. However, in a job shop environment, because of the low and irregular volume of demand, it is not cost effective to set up flow lines as for repetitive manufacturing or mass production where the same product mix is repeated over and over again for a extended period of time.

As a result, job shop manufacturing often happens in small to medium size companies, which are more likely to have too small markets to adopt flow lines to achieve economies of scale as in large companies. In New Zealand this aspect is particularly important as most manufacturers would be considered small on an international scale. In New Zealand, a manufacturer employing less than 50 people is generally considered a small enterprise.

The definition of job shop does not necessarily restrict consideration of the application of the principles studied in this project to individual companies only. Job shops may exist as part of a large company as well (e.g. the machining shop of an automotive company). Discussions regarding the production strategies for job shop manufacturing are presented in the following sections and the next chapter.

1.2 The Need for Reforming Job Shop Manufacturing

In this study, the work to be accomplished on a machine for processing a batch of parts is composed of two components: the work for setting up the machine (e.g. change of tools and fixtures, adjustment, etc.) and the work actually performed on parts (e.g. cutting, machining, inspection, etc.). The time required for setting up a machine for processing a batch of parts was referred to as a 'setup time', while the time required for completing the work actually performed on a part was referred to as a 'processing time'.

As pointed out by Schonberger (1986: 6), the characteristics of job shop manufacturing often contribute to its lower production efficiency when compared with that of other manufacturing environments. Because of the variable demand and product variety, frequent machine changeovers (i.e. setups) are often required to process different products. When setup times are long, frequent setups will unavoidably lead to long production lead times. Traditionally, in job shop environments, manufacturers try to reduce the number of setups by increasing lot sizes. However, since all other parts in a lot have to wait in the queue while any part of the same lot is being processed, large lot sizes will increase the waiting time (i.e. delay by lot conveyance), and may eventually offset the lead time reduction brought about by the reduction in the number of machine setups (Monden 1983: 73, Shingo 1989: 34).

In addition, with large lot sizes, the accumulation of parts during machine setups will cause high work-in-process (WIP) inventory. The situation will be even worse with long setup times. Large lot sizes also extend the horizon of production planning and lead to slower response to changes in demand. Consequently, the finished good inventory (FGI) will increase and the level of customer satisfaction will be decreased with larger lot sizes. The above discussion shows that carrying out efficiently frequent machine setups is critical for improving the production performance of job shop manufacturing. Considering the adverse effects brought about by larger lot sizes, effort should be devoted to reducing setup times instead of increasing lot sizes.

Furthermore, traditional job shops are arranged in the so called 'functional layout' where machines of a similar function are grouped into a department. Parts are routed around the plant for different operations at different departments. Since product routings are more complicated for job shop manufacturing, the production flow in a traditional job shop is not as smooth as that in a flow shop (i.e. a repetitive manufacturing shop). As a result, production control is made more difficult in traditional job shops (Vakharia and Selim 1994).

Although the production performance in traditional job shop environments is usually lower than that of continuous production and repetitive manufacturing, job shop manufacturing is often necessary for producing products with lower and highly diversified demand. However, in today's changing and competitive market, job shop manufacturing firms do face the pressure to shorten production lead times and to keep a fast response to demand changes, without sacrificing product quality and increasing the production cost. Therefore, the traditional type of job shop manufacturing needs to be reformed and effective techniques for achieving better production performance in job shop environments should be adopted.

1.3 JIT Techniques for Reforming Job Shop Manufacturing

Among the available approaches for reforming job shop manufacturing, JIT manufacturing techniques have long been considered as effective tools for achieving better production performance in job shop environments. For application in job shop environments, the most suggested JIT manufacturing techniques include:

(1) Converting the traditional functional layout into cellular layout (i.e. adopting cellular manufacturing).
(2) Transporting a part to the succeeding workstation immediately after the operation at the preceding workstation is completed (i.e. single-unit production and conveyance).
(3) Employing faster material handling facilities.

(4) Implementing demand-pull production control with visual signals (i.e. 'Kanbans' in Japanese).
(5) Reducing the variability of setup and processing times.

The effectiveness of these suggested JIT manufacturing techniques in increasing the production performance of job shop manufacturing had been reported by several JIT proponents. The advantages of applying these JIT manufacturing techniques in job shop environments will be further illustrated in the next chapter.

1.4 Purposes of this Research Project

Although effective JIT manufacturing techniques for reforming job shop manufacturing had been reported, how to implement them effectively in job shop environments is still not well understood. Most of the reports on the implementation of JIT manufacturing focused on the continuous production or repetitive manufacturing environments, where JIT manufacturing techniques were first developed. Far less attention has been given to the application of JIT manufacturing in job shop environments. In particular, how, and to what extent these suggested JIT techniques can affect the production performance of job shop manufacturing is still not well explored.

Because of the lack of practical guidelines on the correct use of those suggested JIT manufacturing techniques in job shop environments, job shop manufacturing firms will be eventually prevented from applying these useful techniques. Accordingly, in order to support the use of JIT manufacturing techniques in job shop environments, this project was aimed at achieving the following purposes:

(1) to investigate the effects of applying those suggested JIT manufacturing techniques on the production performance of job shop manufacturing, and
(2) to provide manufacturers with practical guidelines on effective use of the those suggested JIT manufacturing techniques in job shop environments.

We designed a shop environment which possessed the typical characteristics of job shop manufacturing. Demand-pull production control with Kanbans (one of the suggested JIT techniques for job shop manufacturing) was adopted in the designed shop environment. The designed shop environment was then implemented as a simulation model.

We identified five influential factors related to the effectiveness of applying those suggested JIT techniques in job shop environments with Kanban-based production control. Two groups of simulation experiments were carried out by operating the developed simulation model to investigate the effects of the five influential factors on the performance of the experimental job shop.

In the first set of experiments, we investigated the effects of four influential factors, namely: shop layout, production flow patterns, the amount of setup time reduction achievable by adopting cellular manufacturing and increasing material handling speed.

It is important to recognise that in these experiments the term “layout” refers to specific changes from functional to cellular with certain restriction in the case of cellular layout. It is not concerned with detailed machine placement within a cell or cell layout within the factory. These changes can improve the performance of a job shop but are not the specific area for study in this program. The aim of the simulation experiments in this study is to compare the effects of changing from the broad categories of cellular layout with backtracking flow allowed, cellular layout with unidirectional flow and functional layout, and to identify the conditions under which these layouts can improve the performance of a job shop.

In the second set of experiments, the first three influential factors studied were made the same as for the first set of experiments, but material handling speed was replaced as a variable by coefficients of variation for setup and processing times. Graphical and statistical methods were employed to interpret and analyse the results obtained from the two sets of experiments and conclusions based on our findings were arrived at.

The following chapters are organised as follows. In Chapter 2, to justify the use of the five suggested JIT techniques in job shop environments, we will describe their advantages in detail. In Chapter 3, we will then review the literature related to the application of the Kanban-based production control in job shop environments. As mentioned earlier, Kanban-based production control was adopted in our experimental shop environment as well. By reviewing the information reported in previous studies of this field, we were able to identify the way to carry out our study so that the information that was lacking in previous studies could be revealed. In Chapter 4, we further clarify the purposes of this research project by specifying the research questions to be answered.

Two sets of simulation experiments were carried out to answer the specified research questions. The design of the experimental system for both sets of experiments is presented in Chapter 5. Details regarding the first group of experiments are presented in Chapters 6-8. The design of this set of experiments is presented in Chapter 6. In Chapter 7, we will describe the development and operation of the simulation model for the experiments. The analyses and discussions of the simulation results for this set of experiments are given in Chapter 8.

The details regarding the second group of experiments are given in Chapters 9-10. The design and execution of this set of experiments are presented in Chapter 9. The analyses and discussions of the simulation results for these experiments are given in Chapter 10. Finally, conclusions from the findings of our study, and managerial implications and recommendations are presented in Chapters 11 and 12, respectively.

CHAPTER 2

ADVANTAGES OF ADOPTING JIT MANUFACTURING TECHNIQUES IN JOB SHOP ENVIRONMENTS

Since the Just-in-Time (JIT) manufacturing techniques were perfected at Toyota production plants in the early 1970's, JIT has been adopted by many manufacturers not only in Japan, but also in countries around the world. The potential of JIT manufacturing in improving quality and production efficiency has been widely reported and drawn world-wide attention. A recent empirical study (Nakamura *et al.* 1998), which investigated 40 U.S. manufacturing plants, reported that implementation of JIT did lead to significant improvements in various plant performances, such as machine downtime, product quality, cycle time, production lead time and inventory levels.

The objective of JIT manufacturing is to produce the quantities of products needed, at the time they are needed and with the qualities needed. To produce the products at exactly the time they are required, it is essential to achieve smooth production flow (i.e. with no or few interruptions in production processes). Smoother production flow leads to stable production lead times, which are essential for ordering the materials and shipping the final products at the right time.

Because of the prerequisite of smooth production flow for achieving JIT production, the implementation of JIT manufacturing has mainly taken place in continuous production or repetitive manufacturing environments (e.g. automotive, home appliance, electronic industries), where smooth production flow is easier to be achieved. On the other hand, the implementation of JIT manufacturing techniques in job shop environments is not as easy as in the other manufacturing environments. The characteristics of job shop manufacturing, such as irregular demand and complex product routings (See Section 1.1) make it more difficult to achieve smooth production flow. This should explain why most reports on the implementation of JIT manufacturing focused on continuous production and repetitive manufacturing.

Although several investigators (Kelleher 1986, Schonberger 1986, Gravel and Price 1988, Lee *et al*. 1994) reported that job shop manufacturing firms are able to benefit from the JIT concepts as well, it is not likely that the whole of the JIT manufacturing concepts is as applicable in job shop environments as in repetitive and continuous manufacturing environments. Therefore, before we can study the effectiveness of implementing JIT manufacturing in job shop environments, it is essential to identify those core JIT manufacturing techniques useful for improving the production performance of job shop manufacturing.

The ultimate goal of JIT manufacturing is complete elimination of waste where waste is defined as covering no rejects, no delays, no stock piles, no queues, no idleness and no useless motion. The fundamental JIT precept to achieve this goal is to expose wastes so that they can be 'visually' identified and then eliminated immediately (Monden 1983, Cheng and Podolsky 1993, Schonberger 1986). By reviewing previous reports, we identified five JIT techniques essential for achieving this fundamental principle in job shop environments and therefore, improving the production performance. They are:

(1) Converting the traditional functional layout into cellular layout (i.e. adopting cellular manufacturing).
(2) Transporting a part to the succeeding workstation immediately after the operation at the preceding workstation is completed (i.e. single-unit production and conveyance).
(3) Employing faster material handling facilities.
(4) Implementing demand-pull production control with visual signals (i.e. 'Kanbans' in Japanese).
(5) Reducing the variability of setup and processing times.

These techniques will be described in detail in the following sections.

2.1 Adopting Cellular Manufacturing

Several investigators (Monden 1983: 67, Kelleher 1986, Schonberger 1986: 9 and Cheng and Podolsky 1993: 18) emphasised the importance of transforming the traditional functional layout into the so called ‘cellular layout’ (i.e. adopting cellular manufacturing). To convert the functional layout in traditional job shops into the cellular layout, parts are first grouped into several part families of similar operation sequences. Then machines are grouped into cells, with each cell being dedicated to the production of a family of parts. In a cellular layout, parts requiring similar operations are grouped into individual part families processed by dedicated cells. The benefits brought about by adopting cellular manufacturing in job shop environments include: smoother production flow, setup time reduction and flexible assignment of workers.Cellular manufacturing is essential for achieving smoother production flow in job shop environments. For continuous production and repetitive manufacturing, smooth production flow is achieved by repetitive production of the same product and the same product mix, respectively. With cellular manufacturing, the similar repetition is emulated by producing the same product family in a cell. As emphasised previously, smooth production flow is essential for visual identification of wastes (e.g. build-up of inventory) so that actions can be taken to eliminate the wastes immediately.

Another benefit brought about by cellular manufacturing is reduction in setup time by capitalising on the similarity among the operation sequences (i.e. routings) of the parts to be produced.Since parts with similar operation sequences may share some common setup up operations, these setup operations can be avoided when a family of parts are processed in a dedicated cell. As a result, setup times can be reduced with cellular manufacturing. The survey by Wemmerlöv and Hyer (1989) showed that an average of 41% reduction in setup time can be achieved through cellular manufacturing. Vakharia and Selim (1994) also reported that setup costs can be decreased by 20% to 60% with cellular layout.

In this study, we particularly addressed the aspect of cellular manufacturing in setup time reduction because as discussed in Section 1.2, it is crucial for improving the performance of job shop manufacturing. Although setup time reduction can be achieved by other measures (e.g. improving setup operations) as well, we focused on setup time reduction brought about by cellular manufacturing since this study was concerned with determining what level of performance improvement can be gained in the three performance indicators chosen by changing to a cellular layout which gives a specified level of setup time reduction.

A direct effect of setup up time reduction is the decrease in production lot sizes. As discussed in Section 1.2, the frequent machine setups required in job shop environments may lead to larger lot sizes. Consequently, the extended planning horizons brought about by larger lot sizes will deteriorate the accuracy of production schedules (Kelleher 1986; Schonberger 1986: 9) and lead to slow responses to demand changes. Therefore, the smaller lot sizes brought about by setup time reduction will enable fast response to demand changes, and thus improve the level of customer satisfaction. Monden (1983: 74) also emphasised that ultimately Toyota's ideal of small-lot production finally rests upon the crucial prerequisite of setup time reduction.

Another benefit brought about by cellular manufacturing is the flexibility in worker assignment (Monden 1983: 100-111). The machines in a JIT cell are usually arranged in a U-shaped loop. These machines are operated by multi-skilled workers with each worker being capable of operating several machines. Such U-shapes cell layout with multi-skilled workers allows the flexibility of quickly altering the number of workers and allocating operations among workers to adapt to variation in demand. However, as stated above, in this study, we focused on the effect of setup time reduction by adopting cellular layout rather than the effect of worker flexibility or other ways of achieving reduction in setup times.

2.2 Employing Single-unit Production & Conveyance and Faster Material Handling Facilities

Single-unit production and conveyance is made possible by the adoption of cellular manufacturing. Since machines for processing the same family of parts are grouped close together in a cell, parts can be transferred immediately to the succeeding machine as soon as the operation on the preceding machines is finished. Such a production method of achieving flow of one part at a time in a cell was termed single-unit production and conveyance at Toyota (Monden 1983: 68). It was believed that the delay by lot conveyance (See Section 1.2) can be eliminated and production lead times, substantially reduced with single-unit production and conveyance.

However, with single-unit production and conveyance, the problem of increased frequency of part movement also arises. It was therefore suggested that more efficient material handling facilities (e.g. conveyors, chutes, etc.) be employed to reduce part conveyance time.

2.3 Implementing Demand-pull Production Control with Kanbans

In the traditional job shop environment, production control is normally carried out based on estimated production schedules. Production of parts is initiated or materials are supplied at the requirement date less the standard production (or delivery) lead times. When the processing of a batch of parts is completed at a workstation, they are shipped to the next location, where they will wait in a queue until they gain the priority for processing or shipment. This production control mechanism is termed a 'push system' since it depends on the system to 'push' the material through the production processes according to the predetermined production schedules. However, in a job shop environment, some problems may arise due to the adoption of the push system:

- The proper operation of the push system ultimately relies on the assumption that the generated schedules can be correctly executed, and generation of correct schedules in turn relies on the accuracy of the estimated standard lead times. However, in a job shop environment, since the parts handled by a workstation may involve considerably different operations, substantial variations in setup and / or processing times may exist and cause severe variations in lead times. Furthermore, in the functional layout, the variable waiting times and conveyance times as parts go through different departments for different operations make the accurate estimation of lead times even more difficult (Schonberger 1986: 172). Consequently, to compensate for the lead time inaccuracy, safety factors have to be introduced in generating schedules, and excess inventory build-up will occur if materials are supplied or parts are completed earlier than required.

- In the push system, correct initiation and tracking of job orders require that inventory data and schedules be constantly updated to reflect the conditions on the shop floor. Since disturbances like rework on defective products, changes of customer orders, engineering design changes, machine breakdown, etc. are fairly common on the shop floor, procedures for securing correct inventory transactions with the presence of disturbances must be available to make the system function as planned. (Vollmann *et al.* 1992: 43-47). However, the attributes of product variety and routing complexity of job shop manufacturing may require more facilities (e.g. clerks, computer systems, etc.) and strict procedures to keep the inventory data up to date.

On the other hand, one of the important aspects of JIT manufacturing is the 'demand-pull' production control system using the Kanban. The word, Kanban, is the Japanese name for the signboard of a store. But for JIT manufacturing, it means any visual signal (e.g. a card, an empty space, a lighting signal, etc.) used for authorising part processing and movement.

For example, in a two-card Kanban system, each workstation is affiliated with an input buffer area for storing materials or parts waiting to be processed and an output buffer area for storing processed parts. A conveyance Kanban is attached to each container stored in the input buffer. The conveyance Kanban indicates the name and amount of parts carried in a specific container and the preceding workstation from which these parts are withdrawn. A production Kanban, which shows the name and amount of processed parts carried, is attached to each container at the output buffer.

When the facilities in a workstation are available for processing a container in the input buffer, the container is removed from the input buffer for processing and the conveyance Kanban on the container is detached. The detached conveyance Kanban is then used to acquire another container filled with parts to be processed from the preceding workstation. If an filled container, which contains the parts specified by the conveyance Kanban, is present at the output buffer of the preceding workstation, the conveyance Kanban is attached to this filled container. With a conveyance Kanban attached, this filled container is authorised to be moved to the succeeding workstation.

If any container in the output buffer of a workstation is withdrawn by the succeeding workstation, the production Kanban attached on the container is removed and sent to the process area of the workstation. Holding a production Kanban, the workstation is authorised to produce a container of parts designated by the production Kanban. The associated production Kanban will be attached to the container filled with processed parts. Detailed descriptions of the operations of the Kanban-based system were given by Monden (1983: 13-33), Esparrago, Jr.(1988) and Shingo (1989: 182-189).

As opposed to the push system, the Kanban-based production control constitutes a 'demand-pull' mechanism. As illustrated above, parts can only be moved from a preceding workstation to a succeeding workstation with the authorisation of conveyance Kanbans, which indicate the demand for parts at the succeeding workstation. After a filled container is shipped to the succeeding workstation, the production at the preceding workstation will then be triggered by a production Kanban. Ultimately, the production and movement of parts in a demand-pull system is controlled by the actual demand at the final workstation.

By adopting the demand-pull production control system with Kanbans, the difficulties in achieving effective production control in job shop environments can be resolved. Because parts are produced according to the actual demand represented by Kanbans instead of production schedules based on estimated lead times, the unnecessary inventory built-up due to incorrect lead time estimation can be avoided. In addition, in a Kanban-based production control system, production control is embedded in the shop operations co-ordinated by the visual Kanban signals. When disturbances happen at the shop floor, they can be identified immediately through the status of Kanban flow (e.g. A workstation is idle because of the shortage of production Kanbans.) and measures can be taken to remedy the problems. It is not necessary to depend on another control facilities, such as computer systems, for tracking transactions and therefore, production control is simplified and made effective.

The potential of Kanban-based production control in increasing the production performance of job shop manufacturing was reported by several investigators (Sandras 1985, Gravel and Price 1988, Martin-Vega *et al*. 1989, Lee *et al*. 1994). Benefits that Kanban-based production control can bring about in manufacturing shops include reduced inventory, reduced product defect rate, improved productivity, etc. (Gravel and Price 1988). Furthermore, the production control with Kanbans was also considered one of the important JIT techniques for driving continuous improvement activities in job shop environments (Sandras 1985, Stockton and Lindley1995). Various problems on the shopfloor can be exposed by lowering inventory levels (through reducing the number of Kanbans), and then problem solving techniques (e.g. Total Quality Management) can be employed to eliminate the problems.

In Subsection 5.5.2, we will describe in detail the Kanban-based production control mechanism employed in the shop model for this study.

2.4 Reducing the Variability of Setup and Processing Times

Both Shingo (1989: 141-148) and Monden (1983: 85-86) stressed the importance of standardised operations, which lead to lower setup and processing time variability, in achieving JIT production. Reduced setup and processing time variability brings about two benefits. First, because wasteful motions in setup and processing operations are eliminated, productivity can be increased. Second, low setup and processing time variability avoids the fluctuation of production flow among workstations. When the variability of setup and processing times is too high, the throughputs of different workstations tend to be more variable. As a result, higher work-in-process inventory is necessary to buffer the fluctuation of production flow caused by less balanced throughputs among workstations. Therefore, by reducing setup and processing time variability (i.e. standardising setup and processing operations), the level of the fluctuation in production flow can be decreased and excessive work-in-process inventory, eliminated.

In addition, the smooth production flow brought about by reduction in setup and processing variability is essential for successful implementation of the Kanban-based production control. Kimura and Terada (1981) and Villeda *et al.* (1988) both reported that fluctuations in some part of a Kanban-based system can be easily transmitted (and even amplified) to the entire system. Since setup and processing times tend to be more variable in traditional job shops, reducing setup and processing time variability is more important for realising the benefits of Kanban system in this case.

In this chapter, we have described the benefits of five essential JIT manufacturing techniques useful for improving the production performance of job shop manufacturing. In the next chapter, we will review previous reports regarding the application of JIT manufacturing in job shop environments and, in particular, look for the evidence supporting the effectiveness of applying the five suggested JIT manufacturing techniques in job shop environments. Since our study focuses on the job shop environment with Kanban-based production control, which plays an important role in reforming job shop manufacturing, we will review those reports related to the implementation of JIT manufacturing in job shop environments with Kanban-based production control.

CHAPTER 3

IMPLEMENTATION OF THE KANBAN SYSTEM IN JOB SHOP ENVIRONMENTS

In this chapter, we will present the review of previous reports related to the implementation of JIT manufacturing in job shop environments with Kanban-based production control. Through the review of previous reports, we sought to find out the ways in which these suggested JIT manufacturing techniques should be implemented in job shop environments so that their benefits can be realised.

The first implementation of the Kanban technique in a Hewlett Packard's low volume, complex product line was reported by Sandras (1985). The effectiveness of Kanban and TQC techniques in improving process performance were highlighted. However, since the detailed shop conditions, such as product routings, features of production (e.g. the operations involved), the type of shop layout (e.g. cellular or functional) were not reported, little information regarding successful implementation of JIT techniques in a Kanban-controlled job shop could be derived.

Philipoom *et al.* (1987) presented a simulation approach for determining the initial number of Kanbans at a workcenter through a hypothetical job shop and the effect of less-than-ideal production factors on the number of Kanbans was also examined. They developed a hypothetical job shop environment with Kanban-based production control. Their shop model was based on a functional layout with six workstations. Two products were produced in their shop environment. Their findings supported the importance of reducing processing time variability for realising the benefits of using Kanbans in a job shop environment, but the influence of setup time variability was not investigated in their study. Furthermore, their study did not answer whether the influence of setup and processing time variability was as significant in a job shop environment with cellular layout as with functional layout. Furthermore, because of the small size of their shop model, it is doubtful that their findings reflect the real situation in a larger job shop.

Gravel and Price (1988) carried out a pilot study in which the Kanban-based production control was used for producing one outdoor garment product. Their pilot shop comprised eight workstations arranged in functional layout. Some benefits like improved quality control, less in-process stock, shortened production lead time, increased throughput capacity, reduced floor space, and relieving some boredom previously experienced by workers were identified.

Since only one product was manufactured in their pilot study, it was unclear whether the same benefits could be achieved if Kanbans were used for producing all other products throughout the plant. If the Kanban system was to be applied to the whole shop, the problem of what layout (functional layout vs. cellular layout) to be adopted would arise. It is also noteworthy that the nearly negligible machine setup times of their pilot shop had little influence on the shop performance. This condition did not reflect the situations in the majority of job shops.

Martin-Vega *et al.* (1989) applied the Kanban demand-pull concept to wafer fabrication. They emphasised that to realise the benefits of demand-pull system with Kanbans, it is essential to achieve several JIT principles, such as housekeeping, layout changes, lot size reduction, setup time reduction and improved operator flexibility. Their finding regarding the importance of layout changes, lot size reduction and setup time reduction agrees with our discussion in Section 2.1. Since they had successfully applied the demand-pull production control with Kanbans in an actual shop (instead of a pilot shop), their empirical study provided valuable information on successful implementation of the Kanban system in job shop environments. However, they did not investigate the degrees of influence for those factors influencing the performance of a Kanban system (e.g. the effects of different levels of setup time reduction on the shop performance). Furthermore, their study did not examine the effects of applying those five JIT techniques identified in Chapter 2.

Lee *et al.* (1994) implemented a hybrid demand-pull system with Kanbans in a make-to-order job shop with the cellular manufacturing concept. A functional layout was adopted in their shop. The machines required for manufacturing a family of twenty-six highly demanding products were identified. Instead of grouping these machines into a cell, this family of parts were routed through these specific machines without physically rearranging the shop layout.

Their study was one of the few addressing the effects of applying the cellular manufacturing concept in a job shop environment with Kanban-based production control. They attempted to shorten the production lead times for those highly demanding products by utilising the similarities among the operation sequences of these products. However, their study had a number of deficiencies. As illustrated in Section 2.1, the adoption of cellular manufacturing is not only to reduce setup times by grouping parts into families, but also to reduce part movement by physically grouping machines for processing a family of parts into a cell. Since they did not actually group machines into cells, it was not likely that the full potential of cellular manufacturing could be realised. Furthermore, because some workcentres were not dedicated to the processing of the part family (i.e. the highly demanding parts), the difficulty of prioritising the part family and other parts at shared workcentres arose.

The results of trial runs showed that their approach simplified the production scheduling task and the decision logic used by operators to control material flow, and shortened the flow times of those highly demanding parts. However, they also pointed out that the operation of their Kanban system suffered from disruptions caused by frequent arrivals of orders with very short lead times. To a large extent, this problem arose because production lead times at their shop were too long due to the large production lot sizes caused by substantially long machine setup times at some workcentres. Therefore, it may reflect that the amount of setup time reduction achieved by sequencing the highly-demanded parts through the specific workcentres was too small to justify the adoption of their approach.

From the above review of literature, we can reveal some deficiencies in those previous studies of the implementation of the Kanban system in job shop environments:

(1) The shop sizes employed in some studies (Philipoom *et al.*, Gravel and Price) were too small to represent a typical job shop environment. Therefore, the conclusions derived from these studies do not necessarily hold true when larger shop sizes are considered.

(2) All the previous reports, except for that by Philipoom *et al.*, studied the shop performance under only the conditions of the specific shop environments investigated. In other words, the shop performances in most of the previous studies were not investigated under different combinations of shop conditions (i.e. scenarios). Consequently, it is doubtful whether their conclusions can be extended to job shop environments with different shop conditions (e.g. different shop layouts, material handling methods, etc.)

(3) Although five essential JIT techniques, as discussed in Chapter 2, had been suggested by several investigators as effective tools for improving the performance of job shop manufacturing, the effects of applying these suggested JIT techniques were not investigated in those previous studies reviewed. On the contrary, several studies (Flynn 1987, Flynn and Jacobs 1987, Morris and Tersine 1990) did show that cellular layout is not necessarily superior to traditional job shop (functional) layout. Hence it is necessary to investigate if the same argument holds true in a job shop environment with Kanban-based production control.

In summary, the previous reports did not answer how, and to what extent the JIT techniques suggested in Chapter 2 can affect the performance of job shop manufacturing. Therefore, in our study, we investigated the effects of five influential factors, which were related to the five suggested JIT techniques, on the performance of a job shop environment with Kanban-based production control. In the next chapter, we will present the specific research questions to be answered by this study.

CHAPTER 4

RESEARCH QUESTIONS TO BE ANSWERED BY THIS STUDY

As discussed in the last chapter, the previous reports on the implementation of JIT techniques in job shop environments with the Kanban system did not investigate the effects of applying the five JIT techniques identified in Section 1.3 under different shop conditions. The purpose of this project was therefore to fill in this gap in the research for the application of JIT manufacturing.

In order to express the objectives of this project more specifically, we will address the effects of applying the suggested JIT techniques in job shop environments by answering the following four corresponding research questions:

Research questions 1: Do shop layout and part flow patterns have any influence on the performance of a job shop with Kanban-based production control ? This research question addresses the effects of two JIT techniques: cellular manufacturing and single-unit production and conveyance.

Note that one of the objectives of this study is to investigate the effects of applying the selected JIT manufacturing techniques on the production performance of job shop manufacturing (See Section 1.4). As indicated in Section 2.1, layout change is the most often suggested JIT approach for improving the performance of job shop manufacturing.

In this study, we investigated the performances of different 'types' of shop layout, instead of different 'methods of shop layout design'. In particular the types of layout studied are functional and cellular with single-unit or batch production and cellular with backtracking flow allowed or unidirectional flow. Layout design today can be highly sophisticated using specialist computer programmes such as FactoryFLOW, CRAFT (Computerised Relative Allocation of Facilities Technique), ALDEP (Automated

Layout Design Program) or simulation software such as PROMODEL. However, this is not the focus of this study.

To compare the performances of different shop layouts, research question 1 can be further addressed by four subsections:

> Sub-question 1.1: For the cellular layout shops with batch production and conveyance (as opposed to single-unit production and conveyance), is there any difference between the performances of shop with backtracking intra-cell flow (*backtracking flow* hereafter) allowed and the shop with unidirectional intra-cell flow (*unidirectional flow* hereafter) ? Note that in this study, comparison of shop performance was based on three performance measures: average work-in-process inventory, average flow time and the average setup to processing time ratios, which are further described in Section 6.2.
>
> Sub-question 1.2: Similar to Sub-question 1.1, but for the cellular layout shops with single-unit production and conveyance.
>
> Sub-question 1.3: Among the shops with cellular layout, are those with batch production and conveyance different from those with single-unit production and conveyance in their performances?
>
> Sub-question 1.4: Is there any difference between functional layout and cellular layout in terms of shop performance ?

Research question 2: How does the amount of setup time reduction achievable through the use of cellular manufacturing affect the performances of the Kanban-controlled job shops with the various layouts and production flow patterns ? This research question addresses the effect of adopting cellular manufacturing.

Research question 3: How does material handling speed affect the performances of the Kanban-controlled job shops with the various layouts and production flow patterns ?

This research question addresses the effect of employing faster material handling facilities.

Research question 4: To what extent does the variability of setup and processing times influence the performances of the Kanban-controlled job shops with the various layouts and production flow patterns ? This research question addresses the JIT concept of reducing setup and processing time variability.

Hypotheses corresponding to the four research questions were formulated (to be illustrated in Chapters 6 and 9). Two sets of simulation experiments were carried out to collect the statistics on the shop performance required for testing the hypotheses. The research questions were then answered by investigating the results from testing the proposed hypotheses. In the next chapter, we will illustrate the design of the job shop environment, which was the basis of developing the simulation model for the experiments.

CHAPTER 5

DESIGN OF THE EXPERIMENTAL SYSTEM

The major objective of the experimental system design is to develop a manufacturing environment which exhibits the characteristics of job shop manufacturing and enables us to investigate the system behaviour under different system configurations and parameter settings. Accordingly, to fulfil the above objective, the experimental system design involves the following stages:

(1) Design of the operation sequences of the parts manufactured
(2) Cell configuration design for the cellular layouts
(3) Configuration design for the functional layout
(4) Design of the shop layout
(5) Design of the shop operations

These stages will be illustrated in details in the following sections.

5.1 Design of the Operation Sequences of the Parts Manufactured

In this study, an 'operation' was defined as the work to be accomplished on a machine of a workstation for processing a part. A workstation consisted of one or more identical and exchangeable machines. A machine could handle only one operation (for one part) at a time. An 'operation sequence' or 'routing' stands for the sequence of machines that a part has to visit to complete all its operations.

The operation sequences of different part types were taken from those given by Vakharia and Wemmerlöv (1990). This set of data was chosen because it had been used in another study (Irani and Ramakrishnan 1995) for studying cell formation as well and reasonable number of cells with similar sizes can be created from the data. In addition, in comparison with the routing data used in some previous simulation studies (Villeda *et* *al.* 1988, Morris and Tersine 1990, Yavuz and Satir 1995), this set of data is sufficient to distinguish the difference in the complexity of product routings between repetitive manufacturing and job shop manufacturing. Another advantage of using this set of routing data is that it is suitable for creating cells with or without inter-cell part movement, as required for this study. The operation sequences and demands of the different part types are summarised in Table 5.1. The shop environment consists of twenty-eight machines of twelve types and nineteen part types in total. The available numbers of machines for individual machine types are given in Table 5.2.

It is noted that though we have striven to select a suitable set of part routing data, different part routing data will lead to different shop designs. Although the sensitivity of experimental results to the different shop designs resulting from different part routing data is not the focus of this study, it is an issue deserving further study for future work.

When the shop was arranged in a functional layout, machines were grouped into 12 functional **departments**, with each department consisting of one or more identical and interchangeable machines. Parts were routed through different departments in the sequences specified by the routing data for operations required on specific machine types.

When the shop was arranged in a cellular layout, the different part types were grouped into several part families. There were more than one manufacturing cells in the shop, with each cell being dedicated to processing a family of parts. Each cell comprised one or more workstations with a workstation having one or more identical and interchangeable machines. In the functional layout, parts were transported among departments in lots (batches). In the cellular layout, once parts entered a cell, they were routed through various workstations according to the routing data.

Table 5.1 Operation sequences and demands of part types

Part type	Operation sequence (in sequence of machine types)	Portion of total number of parts manufactured annually (%)
1	1 - 4 - 8 - 9	3.27
2	1 - 4 - 7 - 4 - 8 - 7	2.97
3	1 - 2 - 4 - 7- 8 - 9	3.53
4	1 - 4 - 7 - 9	5.18
5	1 - 6 - 10 - 7 - 9	5.77
6	6 - 10 -7 - 8 - 9	2.89
7	6 - 4 - 8 - 9	2.75
8	3 - 5 - 2 - 6 - 4 - 8 - 9	4.26
9	3 - 5 - 6 - 4 - 8 - 9	4.51
10	4 - 7 - 4 - 8	3.70
11	6	3.96
12	11 - 7 - 12	11.43
13	11 - 12	7.38
14	11 - 7 - 10	14.81
15	1 - 7 - 11 - 10 - 11 - 12	2.58
16	1 - 7 - 11 - 10 - 11 - 12	2.58
17	11 - 7 - 12	8.83
18	6 - 7 - 10	6.43
19	12	3.17

Since it is quite common in practice that because of the complexity of routines, cells are sometimes dedicated to partial operation sequences rather than to the processing of complete parts (Flynn and Jacobs 1987), parts were allowed to visit more than one cell (i.e. Inter-cell part movement was allowed.). While parts were transported among cells in lots, they were moved among workstations in a cell one at a time for single-unit production and conveyance and in lots for batch production and conveyance.

Table 5.2 Available number of machines for individual machine types

Machine Type	1	2	3	4	5	6	7	8	9	10	11	12
Number of Machines Available	2	2	1	3	1	3	4	3	3	3	2	1

5.2 Cell Configuration Design for the Cellular Layouts

The objective of the cell configuration design process was to group the various part types into part families. Then machines were assigned to several cells, with each cell being dedicated to processing a part family. Considering the benefits brought about by the U-loop cell layout , as discussed in Chapter 2, the cell configuration design process in this study was aimed at creating flow line cells arranged in U-shape loops.

Two basic types of cellular layouts were investigated in this study: the cellular layout with backtracking flow allowed and the cellular layout with unidirectional flow. In the cellular layout with backtracking flow allowed, parts were allowed to move in both forward and backward directions along the U-loop in a cell. On the other hand, in the cellular layout with unidirectional flow, parts were only allowed to move in the forward direction along the U-loop in a cell. The configuration design of the two basic types of cellular layouts was illustrated individually in the following subsections.

5.2.1 Cell configuration design for the cellular layout with backtracking flow allowed

The cell configuration design for the cellular layout with backtracking flow allowed, involved three steps: formation of cells/part families, allocating machines to individual cells, and arrangement of the sequences of machines in individual cells. They are described as follows.

(1) Formation of cells/part families

Cells / part families can be formed based on either 'part design' (e.g. the part coding system) or 'part operations' (e.g. Production Flow Analysis). The part design method is appropriate where a coding system is available for classifying the shapes of parts. In addition, the part design method requires considerable manpower and time for carrying out the coding of parts. On the other hand, the part operations method is used for grouping part families without altering the existing part operations. This method is particularly suitable for modifying an existing layout quickly with much less cost than using the part design method. For this study, since we intended to form cells / part families from the part operation sequences shown in Table 5.1, the part operations method was employed.

For the cellular layout with backtracking flow allowed, Production Flow Analysis (Burbidge 1989) was used for identifying part families and forming cells. First, the processing requirements of part types on machines were represented by a machine-part matrix, as shown in Table 5.3. An 'x' appearing at the intersection of row i and column j of the machine-part matrix indicates that machine j was required for processing part i. For example, machine types 1, 2, 4, 7, 8, 9 were required to process part type 3. Note that in the matrix, the machine types required for processing individual part types are not necessarily in the order of corresponding operation sequences.

In order to allocate machine types to cells, and part types to part families, the order of the rows and columns of the initial machine-part matrix must be rearranged to find a block diagonal form of the 'x' entries in the matrix. Table 5.4 shows the machine-part matrix in a block diagonal form presented by Irani and Ramakrishnan (1995). They generated the final matrix by using the Facility Layout module in the STORM software package (Emmons *et al.* 1992). As shown in Table 5.4, four part families/cells could be identified (indicated by the broad grey lines). For example, Cell 1, which was composed of machine types 5, 3, 2, 6, 8, 4, 9, was dedicated to processing the part family of part types 11, 8, 9, 7.

Table 5.3 Initial machine-part matrix for the cellular layout with backtracking flow allowed

Part Type	Machine type											
	1	2	3	4	5	6	7	8	9	10	11	12
1	x			x				x	x			
2	x			x			x	x				
3	x	x		x			x	x	x			
4	x			x			x		x			
5	x					x	x		x	x		
6						x	x	x	x	x		
7				x		x		x	x			
8		x	x	x	x	x		x	x			
9			x	x	x	x		x	x			
10				x			x	x				
11						x						
12							x				x	x
13											x	x
14							x			x	x	
15	x						x			x	x	x
16	x						x			x	x	x
17							x				x	x
18						x	x			x		
19												x

Table 5.4 Final machine-part matrix in a block diagonal form for the cellular layout with backtracking flow allowed

Part Type	Machine type											
	5	3	2	6	8	4	9	1	7	10	11	12
11				X								
8	X	X	X	X	X	X	X					
9	X	X		X	X	X	X					
7	CELL 1			X	X	X	X					
1					X	X	X	X				
3			X		X	X	X	X	X			
10					X	X			X			
2					X	X		X	X			
4			CELL 2			X	X	X	X			
6				X	X		X		X	X		
5				X			X	X	X	X		
18				X	CELL 3				X	X		
15								X	X	X	X	X
16								X	X	X	X	X
14									X	X	X	
17									X		X	X
12									X		X	X
13											X	X
19									CELL 4			X

(2) Allocating machines to individual cells

At this step, the numbers of instances of the required machine types for individual cells were decided. The required number of machines for individual cells can be expressed as follows:

$$N_{ik} = \mathrm{INT}[TL_{ik} / (TC_i \times U_i)] \qquad (5.1)$$

where

N_{ik} = number of machines of type i in cell k.

TL_{ik} = required loading (hours per year) for machine type i in cell k.

$U_i =$ maximum utilisation rate for machine type $i = 0.9$ for all i.

$TC_i =$ available annual capacity for each machine of type i

However, since the lot sizes for individual part types would affect TL_{ik} (Smaller lot sizes will result in more production lots (batches), and therefore more machine loading time has to be spent in setting up the machines), it is necessary to incorporate lot sizing in the allocation of machines. Accordingly, we extended the formula presented by South (1986) so that the order (Kanban) lot sizes for individual part types could be taken into account in calculating the required machine loading in a cellular layout. In this study, an order lot size was defined as the number of parts in each batch (lot) of production (i.e. for one machine setup). Order lot sizes were the same as the Kanban lot sizes for individual part types. In other words, the number of parts carried in a standard container was equal to the order (Kanban) lot size of that specific part type.

Assuming that the shop was operated on two 6-hour shifts per working day with 5 working days per week, the available capacity for each machine would be 3120 hours for a year of 52 weeks. Therefore, given that the instances of a specific machine type in a cell are contained in one and only one workstation (Note: This restriction is needed to avoid the complexity associated with parallel operations when two or more identical machines are available in a cell for processing a given part.), the deterministic model of the required machine loading in each cell can be expressed as follows:

$$TL_{ik} = \sum_{j=1}^{p} [\, \mathrm{INT}(D_j / L_j) \times r_{jik} \times TS_{jik} + D_j \times TP_{jik} \,] \qquad (5.2)$$

and

$$TL_{ik} \leq U_i \times N_{ik} \times TC_i \qquad (5.3)$$

$$\sum_{k=1}^{c} N_{ik} = N_i, \text{ for } i = 1, 2, \ldots, m \qquad (5.4)$$

where

TL_{ik} = required loading (hours per year) for machine type i in cell k.

D_j = demand of part type j (number of parts per year).

L_j = order (Kanban) lot size of part type j.

r_{jik} = number of operations required by part type j on machine type i in cell k.

TS_{jik} = setup time for part type j on machine type i in cell k (hours per batch)

TP_{jik} = processing time for part type j on machine type i in cell k (hours per part)

U_i = maximum utilisation rate for machine type $i = 0.9$ for all i.

N_{ik} = number of machines of type i in cell k.

TC_i = available annual capacity for each machine of type $i = 3120$ hours for all i

p = total number of part types

N_i = total available number of machines of type i

c = total number of cells

m = total number of machine types

The lot sizes for the nineteen part types were individually adjusted to achieve as high as possible loading for individual machines, provided the constraints specified by (5.3) and (5.4) were satisfied. At the same time, the loading of individual machines and machine capacities allocated to individual part types in a cell were kept as even as possible. The final allocation of machines for the cellular layout with backtracking flow allowed is shown in Table 5.5. Table 5.6 shows the resulting order lot sizes and annual demands (in lots) for individual part types.

Note that the annual lot demands derived from the configuration design for both the cellular and functional layouts were preliminary. To achieve reasonable shop loads, the preliminary demands were further fine-tuned by adjusting the mean job inter-arrival time values for the individual shop configurations. However, the percentages of the total annual lot demand for individual part types were not changed. The setting of the mean job inter-arrival time values is described in Subsection 5.5.1.

Table 5.5 Allocation of machines for the cellular layout with backtracking flow allowed

Cell	Allocated Number of Machine Type											
No.	1	2	3	4	5	6	7	8	9	10	11	12
1	0	1	1	1	1	1	0	1	1	0	0	0
2	1	1	0	2	0	0	1	1	1	0	0	0
3	1	0	0	0	0	2	2	1	1	2	0	0
4	0	0	0	0	0	0	1	0	0	1	2	1
Total	2	2	1	3	1	3	4	3	3	3	2	1

Table 5.6 Order (Kanban) lot sizes and annual lot demands for the cellular layout with backtracking flow allowed

Part type	Order (Kanban) lot sizes	Annual demand in lots*
1	3	273
2	4	186
3	3	295
4	6	216
5	2	722
6	2	362
7	3	230
8	3	355
9	4	282
10	5	185
11	4	248
12	16	179
13	10	185
14	19	195
15	5	129
16	4	162
17	15	148
18	2	804
19	14	57
Total		5,213

* Based on D_j = 2,500, TS_{jik} = 2.1 and TP_{jik} = 0.1.

Since backtracking flow was allowed in cells, inter-cell part movement was kept to a minimum. Only part types 15 and 16, whose demand accounted for 5.16% of the total number of parts manufactured annually, required inter-cell movement. This was due to the limitation of the available number of machine type 1, which was required for processing part type 15 and 16. Therefore, part types 15 and 16 had to be processed on the machine type 1 in cell 3, and then moved to cell 4 for the rest of the operations.

(3) Arrangement of the sequences of machines in individual cells

The heuristic procedure proposed by Vakharia and Wemmerlöv (1990) was utilised to determine the machine sequences in the flow line cells by minimising backtracking flows. The resulting travel charts for the four cells are given in Tables 5.7 through 5.10. Each row and column of the travel chart represents a machine type that is required for processing the family of parts assigned to the cell. The sequences of machines have been arranged according to the procedure proposed by Vakharia and Wemmerlöv (1990) so that backtracks in cells were minimised. In addition to the machines required, an input and output sections were added to each cell. Each entry, x_{kl}, at row k and column l of the travel chart is defined as:

x_{kl} = total number of batches (in percentage of total number of batches produced annually) which flow from machine type 'k' to machine type 'l' per year for the part family manufactured by the cell. The values of x_{kk} (i.e. the diagonal entries) are not defined.

The *flow parameter* (FP) which is the ratio of the number of backtracks of batches (weighted by the 'distances' between operations) to the number of forward moves of batches, was used as a measure of backtracking movements of parts in a cell.

Table 5.7 Travel chart for Cell 1

Unit: % of total batches per year

from	to								
	in	3	5	2	6	4	8	9	out
in	-	0.122			0.092				
3		-	0.122						
5			-	0.068	0.054				
2				-	0.068				
6					-	0.166			0.048
4						-	0.166		
8							-	0.166	
9								-	0.166
out									-

FP = 0

Table 5.8 Travel chart for Cell 2

Unit: % of total batches per year

from	to							
	in	1	2	4	8	7	9	out
in	-	0.186		0.036				
1		-	0.057	0.130				
2			-	0.057				
4				-	0.124	0.169		
8					-	0.036	0.109	0.036
7				0.071	0.057	-	0.041	0.036
9							-	0.150
out								-

FP = 0.31

Table 5.9 Travel chart for Cell 3

Unit: % of total batches per year

from	to							
	in	1	6	10	7	8	9	out
in	-	0.194	0.224					
1		-	0.139					0.056
6			-	0.208	0.154			
10				-	0.208			0.154
7				0.154	-	0.069	0.139	
8						-	0.069	
9							-	0.208
out								-

FP = 0.14

Table 5.10 Travel chart for Cell 4

unit: % of total batches per year

	to					
from	in	11	7	10	12	out
in	-	0.136	0.056		0.011	
11		-	0.100	0.056	0.091	
7		0.056	-	0.037	0.063	
10		0.056		-		0.037
12					-	0.165
out						-

FP = 0.38

The smaller the FP, the lower was the amount of backtracking movement in a cell. It was defined as:

$$\mathrm{FP} = \Big[\sum_{k=1}^{K} \sum_{\substack{l=1 \\ l<k}}^{L} x_{kl} \; (k - l) \Big] / \Big[\sum_{k=1}^{K} \sum_{\substack{l=1 \\ k \to l}}^{L} x_{kl} \Big] \tag{5.5}$$

where:

x_{kl} = as defined previously.

$k \to l$ = operation 'k' immediately precedes operation 'l'.

$K = L$ = number of rows (or columns) in the travel chart.

The final cell configurations of the cellular layout with backtracking flow allowed are summarised in Table 5.11. The 'machine sequence' in the table indicates the types of machines assigned to a cell, and the sequence in which they were arranged along the U-shape loop.

Table 5.11 Cell configurations of the cellular layout with backtracking flow allowed

Cell No.	Part family members	Machine sequence	FP value
1	7, 8, 9, 11	3 - 5 - 2 - 6 - 4 - 8 - 9	0
2	1, 2, 3, 4, 10	1 -2 - 4 - 8 - 7 - 9	0.31
3	5, 6, 15, 16, 18	1 - 6 - 10 - 7 - 8 - 9	0.14
4	12, 13, 14, 15, 16, 17, 19	11 - 7 - 10 - 12	0.38

5.2.2 Cell configuration design for the cellular layout with unidirectional flow

Cell configuration design for the cellular layout with unidirectional flow consisted of two steps. The first step was formation of cells/part families and arrangement of the sequences of machines in individual cells. The second step involved allocating machines to individual cells. They are illustrated below.

(1) Formation of cells/part families and arrangement of the sequences of machines in individual cells

Because Production Flow Analysis was not appropriate for creating flow-line cells with unidirectional flows, an alternate of the heuristic procedure presented by Vakharia and Wemmerlöv (1990) was adopted to identify part families and form cells for the cellular layout with unidirectional flow. By following the procedure, the sequences of machines along the U-loops in individual cells were also determined while cells/part families were created. As opposed to the strategy for configuring the cellular layout with backtracking flow allowed, inter-cell part movement was created where necessary to maintain the unidirectional flows in cells. The first step was composed of the following three stages: preliminary part analysis, part grouping, and combination of part groups and cell formation

Stage 1: Preliminary part data analysis

At this stage, parts were classified into three mutually exclusive sets as follows:

(a) Set Φ_1 consists of part types 11, 13 and 19. These are the part types with single or dual operations.
(b) Set Φ_2 consists of part types 2, 10, 15, 16. These part types have backtracking in their operation sequences.
(c) Set Φ_3 consists of part types 1, 3-9, 12, 14, 17 and 18. There is no backtracking in the sequences of operations for these part types.

Stage 2: Part grouping

At the second stage, part groups consisting of the part types in sets Φ_2 and Φ_3 with identical operation sequences, were created. For example, the operation sequences for part types 1, 3 and 4 are {1,4,8,9}, {1,2,4,7,8,9} and {1,4,7,9}, respectively (See Table 5.1). Since both the operation sequences of part types 1 and 4 are contained in that of part type 3, the three part types can be merged to form a part group with the composite operation sequence, {1,2,4,7,8,9}. Sets Φ_2 and Φ_3 were treated separately. Table 5.12 gives the part groups created and their operation sequences, OR^1.

Stage 3: Combination of part groups and cell formation

Part groups were merged and cells were formed in this stage. A similarity matrix, *SO* (Vakharia and Wemmerlöv 1990) was first computed for the part groups without backtracks (Group *p*). Then the part groups were merged to form larger groups with composite operation sequences based on the similarity measures among the part groups. Finally parts with single or dual operations and with backtracks (Group *g* and *r*) were allocated to the composite operation sequences and cells were formed.

Table 5.12 Preliminary part grouping for the cellular layout with unidirectional flow

Set Φ_1: Part types with single or dual operations

Group (*g*)	Part type (*j*)	OR^1_g
1	11	{6}
2	13	{11,12}
3	19	{12}

Set Φ_4: Part types with backtracking and more than two operations in their operation sequences

Group (*r*)	Part type (*j*)	OR^1_r
4	2,10	{1,4,7,4,8,7}
5	15,16	{1,7,11,10,11,12}

Set Φ_4: Part types without backtracking and having more than two operations in their operation sequences

Group (*p*)	Part type (*j*)	OR^1_p
6	7-9	{3,5,2,6,4,8,9}
7	14	{11,7,10}
8	18	{6,7,10}
9	12, 17	{11,7,12}
10	5	{1,6,10,7,9}
11	6	{6,10,7,8,9}
12	1, 3, 4	{1,2,4,7,8,9}

Table 5.13 shows the SO matrix for the seven part groups without backtrack. Each entry, SO_{pq} in the matrix at row p, column q is defined as follows:

$$SO_{pq} = 0.5\ \{[(\sum_{i \in C_{pq}} A_{ip}) / (\sum_{i=1}^{M} A_{ip})] + [(\sum_{i \in C_{pq}} A_{iq}) / (\sum_{i=1}^{M} A_{iq})]\}$$

where:

SO_{pq} = similarity measure between part groups 'p' and 'q'

i = $(1, \cdots, M)$ = machine type index

$$A_{ip} = \begin{cases} 1 & \text{if machine type } 'i' \text{ is required to process parts in part group } 'p' \\ 0 & \text{otherwise} \end{cases}$$

C_{pq} = set of machine types whose members appear in both OR^1_p and OR^1_q in the same relative order.

Table 5.13 SO matrix for the part groups without backtracks (Group *p*)

	6	7	8	9	10	11	12
6	-						
7	0	-					
8	0	0.67	-				
9	0	0.67	0	-			
10	0.34	0	0.53	0	-		
11	0.51	0	0.53	0	0.80	-	
12	0.62	0	0	0	0.37	0.55	-

SO_{pq} measures the proportion of machine types used by two part groups '*p*' and '*q*' in the same order. The Vakharia and Wemmerlöv's procedure involves an iterative process of clustering part groups in descending order of their *SO* measures. However, their procedure unavoidably may lead to greatly different cell sizes. In addition, since they allocated all part groups with backtracks to a single cell, their procedure is not sufficient for creating pure unidirectional flow line cells required for this study. Thus instead, a modified procedure was adopted in this study for cell formation.

First, by examining the *SO* matrix, we decided that the three clusters of the part groups, {10,11}, {7,8,9} and {6,12} were merged to form three basic composite groups because of their larger *SO* measures. The unidirectional composite operation sequences for the three basic composite part groups are:

$OR^2_{(10+11)} = \{1,6,10,7,8,9\}$,

$OR^2_{(7+8+9)} = \{11,6,7,10,12\}$, and

$OR^2_{(6+12)} = \{3,5,1,2,6,4,7,8,9\}$

Then the part groups with backtracking, and with single and dual operations were allocated to the three basic composite part groups. To accommodate the part groups with single and dual operations, and with backtracking, the operation sequences of the preliminary parts groups in Table 5.12 were broken down into sub-sequences where necessary to achieve unidirectional part flow. Since the way of breaking the operation sequences of the preliminary part groups would affect the loading of individual machines, this procedure of breaking operation sequences and the next step, allocating machines to individual cells were actually performed iteratively to meet the constraint of available numbers of individual machine types and to achieve as even cell sizes as possible.

The resulting reorganised part grouping is presented in Table 5.14. Both part groups 6 and 11 were broken down into two groups because both OR_{6b}^{2} and OR_{11b}^{2} could be contained in other groups. The operation sequences of the part groups with backtracking were broken down into sub-groups without backtracking. Note that two machines of type 11 were used in the sequence, OR_{5b}^{2} to avoid backtracking. The reorganised part groups in Table 5.14 were then merged to form part families and cells.

The final cell formation and composite part groups are shown in Table 5.15. The operation sequences shown in Table 5.15 were the arrangement of the sequences of machines along the U-loops in individual cells.

As shown in Table 5.15, five cells (part families) were created for the cellular layout with unidirectional flow. Eight part types, whose demand accounted for 26% of the total number of parts manufactured annually, required inter-cell movement. Since no intra-cell backtracking was allowed, the FP values for all cells were, therefore, zero.

Table 5.14 Re-organised part grouping for the cellular layout with unidirectional flow

Set Φ_1: Part types with single or dual operations

Group (g)	Part type (j)	OR_g^2
1	11	{6}
2	13	{11,12}
3	19	{12}

Set Φ_4: Part types with backtracking and more than two operations in their operation sequences

Group (r)	Part type (j)	OR_r^2
4a	2,10	{1,4,7}
4b	2,10	{4,8}
4c	2	{7}
5a	15,16	{1,7}
5b	15,16	{11,10,11,12}

Set Φ_4: Part types without backtracking and having more than two operations in their operation sequences

Group (p)	Part type (j)	OR_p^2
6a	7-9	{3,5,2,6}
6b	7-9	{4,8,9}
7	14	{11,7,10}
8	18	{6,7,10}
9	12, 17	{11,7,12}
10	5	{1,6,10,7,9}
11a	6	{6,10,7}
11b	6	{8,9}
12	1, 3, 4	{1,2,4,7,8,9}

(2) Allocating machines to individual cells

As for the cellular layout with backtracking flow allowed, equations (5.2), (5.3) and (5.4) were used to determine the order lot sizes for individual part types, and number of machines required for individual cells. The resulting machine allocation for individual cells is shown in Table 5.16. Table 5.17 shows the order lot sizes and annual demand (in lots) for the cellular layout with unidirectional flow. The final cell configurations are summarised in Table 5.18.

Table 5.15 Final cell formation for the cellular layout with unidirectional flow

Cell No.	Composite part group	Operation sequence
1	(1+5a +10+11a)	{1,6,10,7,9}
2	(4a+4c+11b+12)	{1,2,4,7,8,9}
3	(2+3+5b +7+8+9)	{11,6,7,10,11,12}
4	6a	{3,5,2,6}
5	(4b+6b)	{4,8,9}

Table 5.16 Allocation of machines for the cellular layout with unidirectional flow

Cell	Allocated Number of Machine Type											
No.	1	2	3	4	5	6	7	8	9	10	11	12
1	1	0	0	0	0	1	1	0	1	1	0	0
2	1	1	0	1	0	0	1	1	1	0	0	0
3	0	0	0	0	0	1	2	0	0	2	2	1
4	0	1	1	0	1	1	0	0	0	0	0	0
5	0	0	0	2	0	0	0	2	1	0	0	0
Total	2	2	1	3	1	3	4	3	3	3	2	1

Table 5.17 Order (Kanban) lot sizes and annual lot demands for the cellular layout with unidirectional flow

Part type	Order (Kanban) lot sizes	Annual demand in lots*
1	3	273
2	5	149
3	3	295
4	7	185
5	3	481
6	2	362
7	3	230
8	3	355
9	2	564
10	6	155
11	4	248
12	16	179
13	10	185
14	19	195
15	5	129
16	4	162
17	15	148
18	2	804
19	14	57
Total		5,156

* Based on D_j = 2,500, TS_{jik} = 2.1 and TP_{jik} = 0.1.

Table 5.18 Cell configurations of the cellular layout with unidirectional flow

Cell No.	Part family members	Machine sequence	FP value
1	5, 6, 11, 15, 16	1 - 6 - 10 - 7 - 9	0
2	1, 2, 3, 4, 6, 10	1 - 2 - 4 - 7 - 8 - 9	0
3	12, 13, 14, 15, 16, 17, 18, 19	11 - 6 - 7 - 10 - 11 - 12	0
4	7, 8, 9	3 - 5 - 2 - 6	0
5	2, 7, 8, 9, 10	4 - 8 - 9	0

5.3 Configuration Design for the Functional Layout

When the shop was configured in a functional layout, it was equivalent to there being only a single cell in the shop. All machines of the same type were allocated in a functional department. Therefore the functional departments of the functional layout were regarded as large workstations grouped in a cell. The only task required for configuring the functional layout was to determine the order lot sizes for individual part types so that the constraint of available machine capacity was satisfied. As for the cellular layouts, equations (5.2), (5.3) and (5.4) were used to determine the appropriate order lot sizes. The order lot sizes and annual demand (in lots) for the functional layout is given in Table 5.19.

Table 5.19 Order (Kanban) lot sizes and annual lot demands for the functional layout

Part type	Order (Kanban) lot sizes	Annual demand in lots*
1	3	395
2	4	270
3	2	640
4	6	313
5	3	698
6	2	524
7	3	333
8	3	515
9	3	545
10	5	269
11	3	479
12	21	198
13	12	223
14	9	597
15	4	234
16	3	312
17	17	189
18	2	1166
19	12	96
Total		7,996

* Based on $D_j = 36,250$, $TS_{jik} = 0.97$ and $TP_{jik} = 0.1$.

5.4 Design of the Shop Layout

The purpose of the shop layout design process was to position the departments / cells in the available shop floor area to achieve as few inter-department/cell part movements as possible. As illustrated in Chapter 4, one of the research questions to be answered through this research project was whether different shop layouts (functional layout and various cellular layouts) made any difference in the performance of job shop manufacturing with Kanbans. To correctly investigate the influence of shop layout, it was essential that the relative positions among departments / cells were carefully designed because different relative positions would lead to different part movement distance and in turn, different shop performance.

In the shop modelled, each machine (including the input and output buffers, and auxiliary facilities) had a footprint of 14 feet by 14 feet. The total available shop floor area was 84 feet by 84 feet. In addition to functional departments / manufacturing cells, a receiving and a shipping departments were added to all layouts. All jobs were initiated in the receiving department and terminated in the shipping department. The methods of Systematic Layout Planning (Muther 1973) were employed to allocate the functional departments / manufacturing cells to the available shop floor area. The procedure of Systematic Layout Planning involved three steps. At the first step, Flow relationship diagrams, which were based on the intensity of flows among cells / departments, were constructed to determine the importance of closeness among cells / departments. At the next step, space relationship diagrams were prepared by individually placing the areas of cells / departments in the shop floor area according to the information provided by the flow relationship diagrams. Finally, the resulting space relationship diagrams were then used to determine the travelling distances of part movement among workstations as well as among cells / departments. The three steps of the shop layout design are individually illustrated below.

5.4.1 Preparation of the flow relationship diagrams

To construct the flow relationship diagrams for the three basic shop layouts (i.e. the cellular layout with unidirectional flow, the cellular layout with backtracking flow allowed and the functional layout), the 'from-to charts' for the various shop layouts had to be prepared first. Table 5.20 shows the from-to chart for the cellular layout with unidirectional flow. Each entry, x_{ij}, at row i and column j of the from-to chart indicates the total number of batches of parts which flow from cell / department i to cell / department j per year. For example, as shown in Table 5.20, there were 304 batches of parts flowing from cell 2 to cell 5 annually. The from-to charts for all the three basic layouts are given in Appendix 1.

Table 5.20 From-to chart for the cellular layout with unidirectional flow

unit: batches per year

From (Cell)	To (Cell)						
	In	1	2	3	4	5	Out
In*	--	1382	1057	1568	1149		
1		--	362	291			729
2			--			304	1264
3				--			1859
4					--	1149	
5			149			--	1304
Out*							--

* "In" represents the receiving department, and "Out", the shipping department.

Next, from the from-to charts, the total annual number of batches travelling between each pair of cells / departments in both directions (i.e. flow-of-material intensity) was calculated for each shop layout. The flow-of-material intensity values for each shop layout were then tabulated in a descending order. The range between the upper and lower limits of the values was evenly divided into five intervals corresponding to five categories, ranged from 'most important' to 'unimportant'. Each flow-or-material intensity value was then assigned to one of the five categories according to the interval which it lies in. The flow-of-material intensity values for the cellular layout with unidirectional flow is given in Table 5.21 as an example.

Table 5.21 Flow-of-material intensity for the cellular layout with unidirectional flow

Between pair of cells	Flow-of-material intensity value (batches per year)	Upper and lower limits of category interval	Importance of relationship rating
3 -- Out	1859	1859 to 1545	1*
In -- 3	1568		
In -- 1	1382	1545 to 1232	2
5 -- Out	1304		
2 -- Out	1264		
In -- 4	1149	1232 to 918	3
4 -- 5	1149		
In -- 2	1057		
1 -- Out	729	918 to 605	4
2 -- 5	453	605 to 291	Unimportant
1 -- 2	362		
1 -- 3	291		

* An *importance of relationship rating* of '1' indicates that closeness between the pair of cells / departments is the most essential. The larger the number of rating is, the less important is the closeness.

For example, as shown in Table 5.21, there were 1149 batches of parts flowing (in both directions) between cell 4 and cell 5. Since this flow-of-material intensity value lies in the interval between 1232 and 918, the importance of closeness between cell 4 and cell

5 was classified as '3'.The flow-of-material intensities for the three basic shop layouts are listed in Appendix 2.

The importance of relationship ratings for the three basic shop layouts were then presented in the form of flow relationship diagrams. As an example, Figure 5.1 shows the resulting flow relationship diagram for the cellular layout with unidirectional flow.

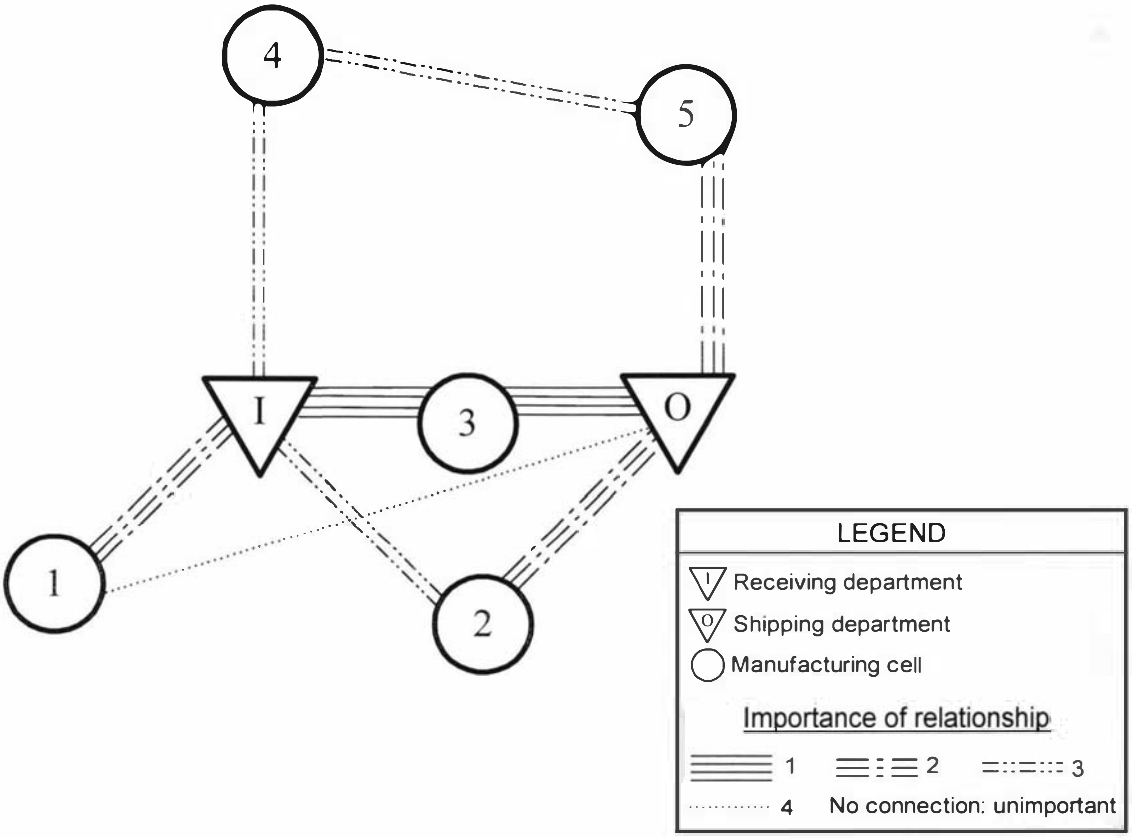


Figure 5.1 Flow relationship diagram for the cellular layout with unidirectional flow

By presenting the relationship between cells / departments in graphic symbols, the importance of closeness between each pair of cells / departments was more easily recognised visually through the flow relationship diagrams. The flow relationship diagrams for all the three basic shop layouts were presented in Appendix 3. These resulting flow relationship diagrams constituted the basis for preparing the space relationship diagrams in the following subsection.

5.4.2 Preparation of the space relationship diagrams

The space relationship diagram shows the exact relative positions among cells / departments in the available shop floor area. The space relationship diagrams were constructed by inserting the 'blocks' representing the required areas for cells/ departments into the available shop floor area. The blocks for cells / departments were inserted one pair at a time, beginning from the pair with the highest importance of closeness (i.e. the pair(s) with importance of relationship rating of '1') through the ones with 'unimportant' ratings. In the process of inserting blocks, the orientation and relative positions of inserted blocks were adjusted when necessary to fit into the confines of the available shop floor area.

As an example, the space relationship diagram for the cellular layout with unidirectional flow is presented in Figure 5.2. From Figure 5.1, we knew that the closeness between cell 3 and the receiving department, and between cell 3 and the shipping department was the most important. Therefore, the area blocks for cell 3, the receiving department and the shipping department were inserted in the shop floor area first. Note that the receiving and the shipping departments were both placed next to cell 3 to shorten the travelling distances of parts between the two departments and cell 3.

After positioning the cells / departments with the most important relationships, we then looked at the relationships with next importance ratings (i.e. the rating '2'). From Figure 5.1, we knew that the importance of the relationships for the three pairs, cell 1 - receiving department, cell 2 - shipping department and cell 5 - shipping department was rated '2'. Therefore, the block for cell 1 was inserted next to the receiving department. Then the blocks for cell 2 and cell 5 were positioned next to the shipping department.

Finally, cell 4 was placed at a position as close to the receiving department and cell 5 as possible, since the importance of the relationships between cell 4 and the receiving department, and between cell 4 and cell 5 was rated '3'. However, the closeness of cell 4 to the receiving department and cell 5 was not as essential as that of previously considered relationships.

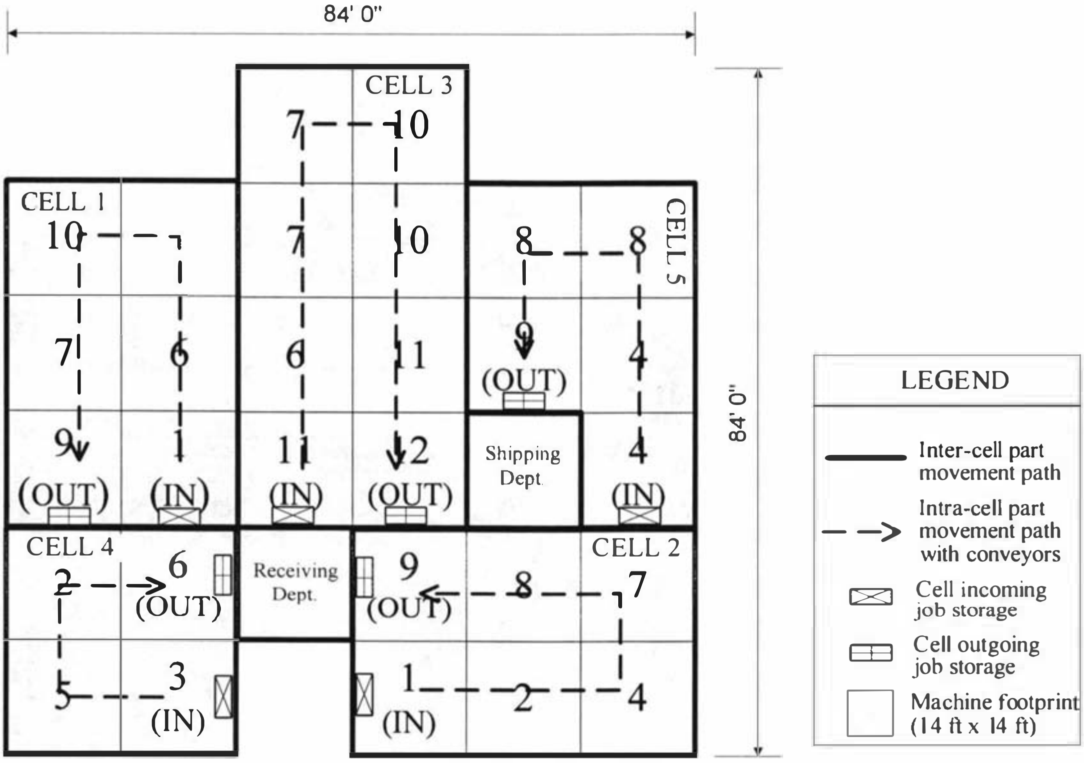


Figure 5.2 Space relationship diagram for the cellular layout with unidirectional flow

By following the procedure, pairs of cells / departments with more important relationship ratings were placed closer to each other and eventually, a reasonably arranged shop layout could be obtained. Possible alternative orientations and positions of cells were also considered in the procedure to achieve better results. The same procedure was followed to prepare the space relationship diagrams for other layouts. The completed space relationship diagrams for the three basic shop layouts were given in Appendix 4.

5.4.3 Determination of the inter-cell / department and intra-cell travelling distances.

After the space relationship diagrams were created, the travelling distances of parts between workstations / cells / departments could then be obtained by directly measuring these distances on the diagrams. The travelling distance between two workstations was measured between their centre points. In this study, we also took into account the possibility that different material handling methods could lead to different intra-cell travelling distances.

We will take cell 1 in Figure 5.2 as an example. If parts are moved from machine type 1 to machine type 9 by a worker, who can move directly between the centre points of the machines, the travelling distance is 14 feet. However, if parts are moved by a conveyor in the cell, parts at machine type 1 have to travel along the U-loop (i.e. through machine types 6, 10, 7) before reaching machine type 9. The travelling distance in this case will be 70 feet. Therefore, for each cell, the intra-cell distance matrices for both manual material handling and material handling by a conveyor were constructed.

As an example, Table 5.22 gives the intra-cell travelling distance matrix with material handling by a conveyor for cell 1 of the cellular layout with unidirectional flow. The intra-cell travelling distance matrix for the same cell, but with manual material handling is presented in Table 5.23. The differences in the intra-cell travelling distances because of the different material handling methods can be distinguished between the two matrices. The complete intra-cell travelling distances matrices are given in Tables A5.1 through A5.18 in Appendix 5.

The travelling distance between two cells / departments was measured from the outgoing storage of the preceding cell / department to the incoming storage of the succeeding cell / department. Inter-cell / department distance matrices for the three basic shop layouts are given in Tables A5.19 through A5.21 in Appendix 5. The travelling distance matrices were later incorporated in the simulation model of the shop environment, and used for calculating travelling times of part movements during simulation runs.

Table 5.22 Intra-cell distance matrix for Cell 1 with unidirectional flow (material handling by a conveyor)

unit: feet

From Workstation No./ Machine type	To Workstation No./Machine Type						
	In	1/1	2/6	3/10	4/7	5/9	Out
In	--	7	21	49	63	77	84
1/1		--	14	42	56	70	77
2/6			--	28	42	56	63
3/10				--	14	28	35
4/7					--	14	21
5/9						--	7
Out							--

Table 5.23 Intra-cell distance matrix for Cell 1 with unidirectional flow (manual material handling)

unit: feet

From Workstation No./ Machine type	To Workstation No./Machine Type						
	In	1/1	2/6	3/10	4/7	5/9	Out
In	--	7	35	49	35	21	--
1/1		--	28	42	28	14	21
2/6			--	28	14	28	35
3/10				--	28	42	49
4/7					--	28	35
5/9						--	7
Out							--

5.5 Design of the Shop Operations

In the shop model, the shop operations included the following four elements:

- arrival of jobs: introducing new jobs into the system,
- production control: routing jobs through the shop,
- processing of jobs, and
- material handling speed settings.

For the design of the shop operations, we defined the algorithms and parameters regarding the four elements. The design of the four elements are described in detail in the following subsections.

5.5.1 Arrival of jobs

To simulate the irregular demand pattern of a job shop environment, the inter-arrival times of jobs were assumed to be exponentially distributed. In order to have a fair comparison of the shop performance across difference shop configurations and parameters, the mean values of job inter-arrival time were manipulated so that the same amount of each part type was manufactured annually for all the three basic shop layouts (i.e. functional layout, cellular layout with unidirectional flow and cellular layout with backtracking flow allowed). The mean job inter-arrival time for a specific basic layout was calculated as the total working hours per year divided by the total number of lots produced per year:

$$\mathrm{TMJI} = \mathrm{WH} \,/ \sum_{j=1}^{p} \mathrm{INT}(\mathrm{D}_j \,/\, \mathrm{L}_j) \tag{5.6}$$

where

TMJI = mean job inter-arrival time

WH = working hours per year = 3120 hours

D_j = demand of part type j (number of parts per year).

L_j = order (Kanban) lot size of part type j.

p = total number of part types = 19

As mentioned above, D_j was the same for all the three basic layouts. Since $L_j, j = 1, 2, \ldots, p$, were different for the three basic layouts, one mean job inter-arrival time value was needed for each basic layout. In addition, the job inter-arrival time for a specific basic layout was also affected by the part family setup reduction factor (PFSRF) used in this study (See Subsection 5.5.3). The PFSRF represents the portion of the standard setup time required when consecutive jobs processed on a machine belong to the same part family. As the part family setup reduction factor became smaller, the machine loading was lower because less time was spent for setting up machines. Consequently, more parts can be produced by the shop at lower PFSRFs (i.e. D_j was larger at lower PFSRFs). Since three PFSRF levels, 0.7, 0.5 and 0.2 were used in this study (See Section 6.1.), a set of job inter-arrival time values was needed for each level of the PFSRF.

To obtain the suitable mean job inter-arrival time values, preliminary simulation runs were performed for the cellular layout with backtracking flow allowed and single unit production & conveyance, at each of the three part family setup reduction factor levels, to find out the annual demand level, D_j at which the average bottleneck machine utilisation reached about 66%. One set of D_j was therefore obtained for each level of PFSRF. The three sets of D_j for the three PFSRF levels were then used in equation (5.6) to calculate the mean job inter-arrival time values for the three basic layouts. The mean job inter-arrival time values are summarised in Table 5.24. In total, nine mean job inter-arrival time values (3 basic layouts at three levels of part family setup reduction factor) were used.

Upon the arrival of a job, the probability of a specific part type being assigned to the job is given in Table 5.25. The probability value for a part type was obtained by calculating the percentage of total batches of parts produced for that part type.

Table 5.24 List of mean job inter-arrival time values

Level of PFSRF	Shop layout	Mean job inter-arrival time (hrs)	Average annual total number of parts manufactured (pcs)
0.7	Functional layout	0.7069	20000
	CLUF*	0.7564	20000
	CLBF**	0.7481	20000
0.5	Functional layout	0.5953	23750
	CLUF	0.6370	23750
	CLBF	0.6300	23750
0.2	Functional layout	0.3900	36250
	CLUF	0.4173	36250
	CLBF	0.4128	36250

* Cellular layout with unidirectional flow
** Cellular layout with backtracking flow allowed

For example, as shown in Table 5.6 of Subsection 5.2.1, through the process of allocating machines to individual cells for the cellular layout with backtracking flow allowed, we arrived at the total number of batches (lots) of parts manufactured per year was 5213. In addition, among these annual total batches manufactured, the total number of batches manufactured for part type 1 was 273. Accordingly, the probability value for part type 1 for the cellular layout with backtracking flow allowed was 273/5213 = 0.0524 or 5.24%, as shown in Table 5.25. In other words, in the long run, 5.24% out of the total batches of parts produced by the shop belonged to part type 1.

Once the part type for an arriving job was decided, the lot size for the part type (as given in Table 5.6, 5.17 or 5.19, according to the basic shop layout investigated) was assigned to the job, and a container of parts with the specified part type and lot size was then launched into the system.

Table 5.25 Probability of part types to be assigned to an arriving job

Part type	Functional layout	Cellular layout with unidirectional flow	Cellular Layout with backtracking flow allowed
1	0.0494	0.0529	0.0524
2	0.0338	0.0289	0.0357
3	0.0800	0.0572	0.0566
4	0.0391	0.0359	0.0414
5	0.0873	0.0933	0.1385
6	0.0655	0.0702	0.0694
7	0.0416	0.0446	0.0441
8	0.0644	0.0689	0.0681
9	0.0682	0.1094	0.0541
10	0.0336	0.0301	0.0355
11	0.0599	0.0481	0.0476
12	0.0248	0.0347	0.0343
13	0.0279	0.0359	0.0355
14	0.0747	0.0378	0.0374
15	0.0293	0.0250	0.0247
16	0.0390	0.0314	0.0311
17	0.0236	0.0287	0.0284
18	0.1459	0.1559	0.1543
19	0.0120	0.0111	0.0109

5.5.2 Production control using a hybrid push/pull Kanban system

To apply the Kanban-based production control method to the job shop environment, a hybrid push/pull Kanban system instead of a ‘pure’ Kanban system was adopted in this study. The pure demand-pull Kanban system is the typical Kanban system used for repetitive manufacturing environments, where demand (both in volume and product types) is much more stable than that of job shop environments. Smooth operation of such Kanban system, where component replenishment is triggered by the demand at the final assembly line requires that:

(1) Fixed and limited stock of parts is kept at each stage for the consumption by the succeeding stage, and

(2) Signals are issued for replenishment of parts to be stocked at each stage when necessary.

However, these requirements are not likely to be attainable in the job shop environment. Since job shop environments are usually characterised by irregular demand patterns (in volume and/or product mixes), it is not cost-effective to keep a fixed stock of all the part types manufactured. Besides, without a uniformly sequenced final assembly schedule, there is no consumption of parts at the next higher assembly level to signal the need for replenishment (Kelleher 1986, Stockton and Lindley 1995).

Therefore, to adapt the Kanban-based production control method to the job shop environment, a hybrid push/pull Kanban system (Gravel and Price 1988, Lee *et al.* 1994, Li and Nahavandi 1997) was used instead for production control.

As shown in Figure 5.3, in the hybrid system, each cell (department) was assigned an incoming storage area for keeping containers carrying materials or parts to be processed and an outgoing storage area where containers holding processed parts to be transported to other cells (departments) were stocked. A specific number of empty container/conveyance Kanban sets (denoted by ① and ②) were allocated in the outgoing storage area for each part type produced in a cell (department).

Empty containers served as production Kanbans as well as storage spaces for holding processed parts. Each container was associated with a conveyance Kanban that authorises the moving of the container to the succeeding cell (department) designated by the Kanban. When a job order was released to the shop, the required materials or parts were launched to the incoming storage area of the first cell (department) on its routing. However, the job could only be processed when there was an available empty container (production Kanban) (denoted by ③) for storing the processed parts. Processed parts were stored in a container (denoted by ④) and kept in the outgoing storage until an available conveyance Kanban (denoted by ⑤) authorising the movement of the specific container was present. The conveyance Kanban was then attached to the container (denoted by ⑥), which was transported to the incoming storage area of the succeeding cell (department) specified by the Kanban.

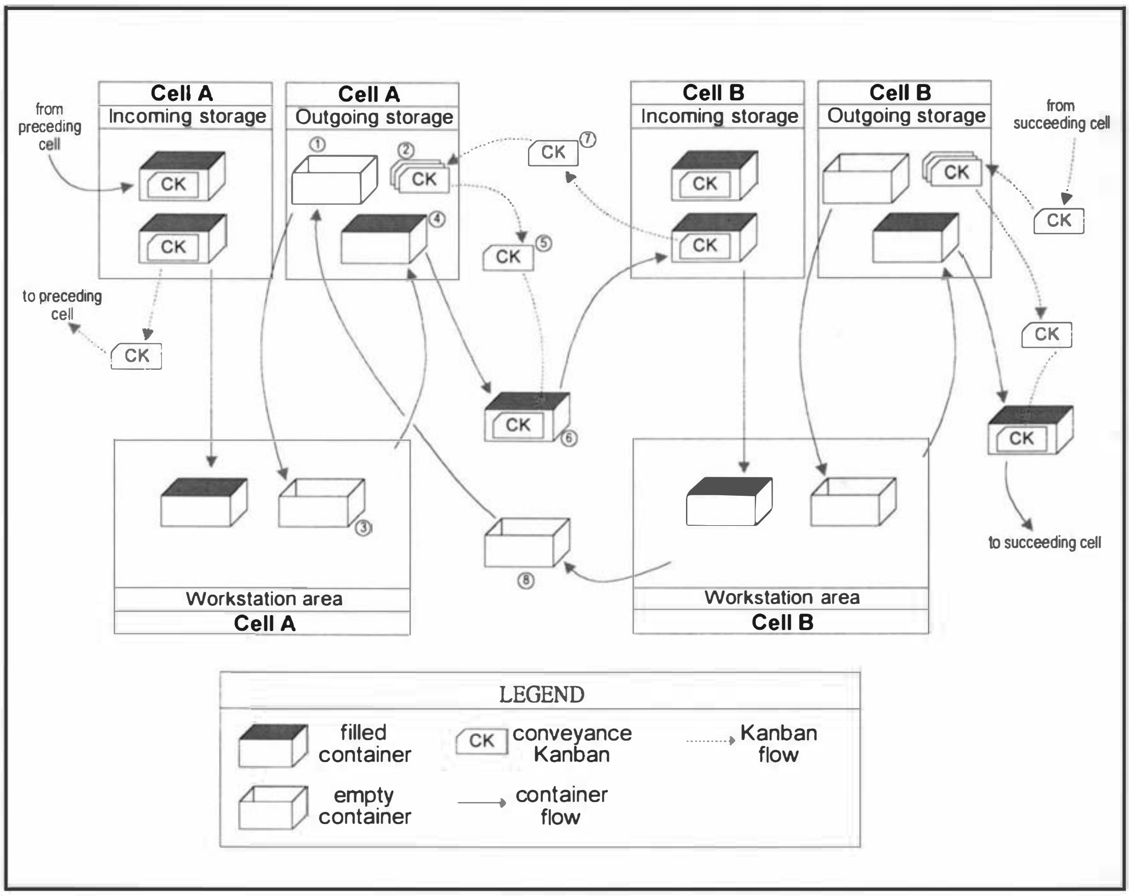


Figure 5.3 Operation of the hybrid push/pull Kanban system among cells

When parts in a container at the incoming storage began to be processed, the attached conveyance Kanban (denoted by ⑦) was removed and sent back to the preceding cell (department). A container was sent back to the outgoing storage of the preceding cell (department) when emptied (denoted by ⑧). The procedure was thus continued until the job was completed. In such a system, instead of being triggered by the requirement at the final assembly line, the production process was initiated by 'pushing' materials or parts into the system, and then parts were 'pulled' through cells (departments) according to Kanban signals.

The operation of the hybrid push/pull Kanban system among workstations within a cell is presented in Figure 5.4. The incoming and outgoing storage areas of cells are now replaced by the input and output buffer of workstations, respectively. Containers and Kanbans were circulated among workstations in the same manner as that among cells. The functional departments of the functional layout were regarded as workstations in a single cell.

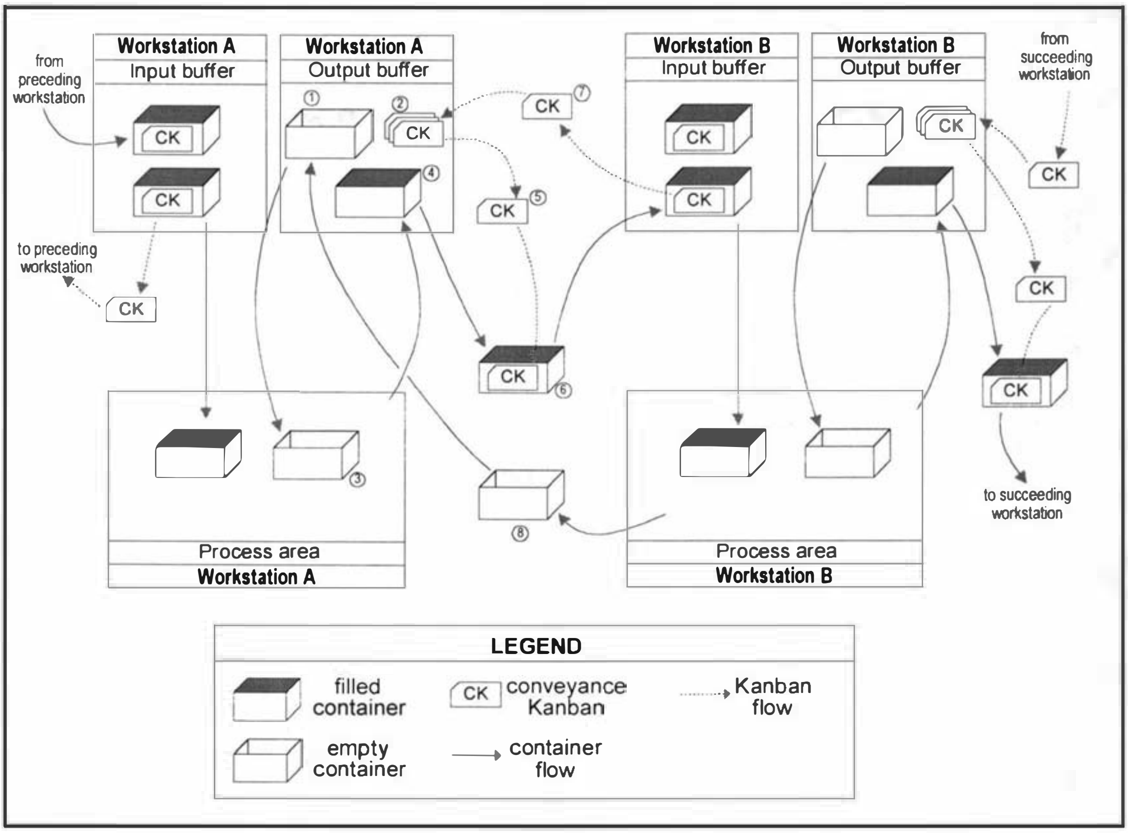


Figure 5.4 Operation of the hybrid push/pull Kanban system among workstations

5.5.3 Processing of jobs

Once a job (representing a container filled with parts of a specific part type) was launched into the shop, it would be routed through and processed at various cells / departments and workstations according to its operation sequence. In our shop model, two aspects were related to the processing of jobs: the setup and processing times for processing parts, and the scheduling of jobs.

(a) Setup and processing times for processing parts

As defined in Section 1.2, the time required to accomplish the work for processing a batch of parts on a machine at a workstation comprises two components: the setup time and the processing time.

Operations on all machines required the same mean processing time of 0.1 hours per part and the actual processing time values of individual operations were derived from the gamma distribution with a shape parameter, $\alpha = 3$. The gamma distribution was chosen because the histogram of service time data often has a shape similar to that of its density function (Law and Kelton 1991).

Sequence-dependent setup times were employed in this study. If a job to be processed on a machine was not in the same part family as the preceding completed job, a full setup would be required. If two consecutive jobs were of the same part family but different part types, only a partial setup was incurred. If the succeeding job was of exactly the same part type as that of the preceding job, no setup was required at all.

For each setup operation, a major setup time value was generated from the gamma distribution with an α value of 2 and a mean of 2 hours. The major setup time was then multiplied by a part family setup reduction factor (PFSRF) to obtain the partial setup time if applicable. Therefore, the lower the PFSRF, the larger is the amount of setup time reduction achieved by adopting cellular manufacturing. The α value of 2 was used because setup times are usually more variable than processing times in a job shop environment. Consequently, in a cellular layout, the setup times incurred were either partial or zero since only the same family of parts were processed in a cell, while in a functional layout, setup times could be full, partial or zero.

(b) Scheduling of jobs

As depicted in Subsection 5.5.2, the hybrid push / pull Kanban system was adopted for the production control in the shop model. When a job (i.e. a container filled with parts) arrived at the incoming storage area of a cell and there was an available empty container (i.e. production Kanban) for storing the completed parts at the outgoing storage area, parts in the container would be moved to the input buffer of the first workstation on their routing if storage space was available. Parts were moved in lots for batch production and conveyance, and one piece by one piece for single-unit production and conveyance. If either an empty container at the outgoing storage area of the cell or storage space in the input buffer (signified by a conveyance Kanban) of the workstation was not available, the job would be queued in the incoming storage area until both were available.

After a job was transferred to the input buffer of a workstation, it could only be processed when there were both an available empty container (i.e. production Kanban) for keeping processed parts in the output buffer and an available machine, or it would be queued in the input buffer until both were available. If more than one machines were available for processing a job, the one having the most similar setup to that required for the job would be selected. If all machines had the same setup, the machine to process the part was selected at random. When any machine in a workstation became idle, both a queue selection heuristic and a job selection rule were executed to select a job from those queued in the input buffer. The queue selection heuristic based on the 'repetitive lots' procedure (Flynn 1987) was performed first to search for a job of the same part type as that of the last processed job. If any one was found, the first one by order of arrival was selected. This procedure took advantage of sequence-dependent setup times and attempted to further minimise setups by not switching to another part type until all jobs of the same part type were completed. If no such matched part type was found, a job was selected for processing based on the shortest processing time (SPT) job selection rule. In circumstances when the SPT rule was not able to break ties among jobs, the first-come-first-serve (FCFS) rule was applied to break the ties. As depicted in the last section, transferring of jobs among workstations was authorised by the conveyance Kanban signals.

The functional departments of the functional layout operated in the same way as that of the workstations of a cellular layout as if there had been only one cell in the shop. However, since jobs processed by a department could be of different part families, the execution of the queue selection heuristic was a little different. If a job of the same part type could not be located, searching for a job of the same part family as that of the last completed job would be attempted. If still no matched job was found, the procedure was then reverted to the shortest processing time job selection rule. In this manner, the benefit of setup time reduction brought about by cellular manufacturing could still be realised indirectly in the functional layout by the adoption of the queue selection heuristic without physically grouping machines into cells.

5.5.4 Material handling speed settings

Since material handling speed had been claimed to be one of the essential factors for realising the benefits of cellular manufacturing (Monden 1983: 74, Shingo 1989: 37), both inter-cell (department) and intra-cell material handling speeds were explicitly incorporated in the shop model to examine their effects on the shop performance. The settings of material handling speed were derived from the data given by Apple (1963) and Apple (1972). Both high and low settings were investigated for all speeds. Considering the times for loading and unloading parts (stored in containers) with different sizes and weights may vary significantly, the loading and unloading times were uniformly distributed.

The material handling speed settings for inter-cell / department part movement are summarised in Table 5.26. Parts were transported in batches (lots) for inter-cell / department movement. The high speed setting was based on that of a fork lift truck. The travelling speed was 4 miles per hour (mph). Loading and unloading times were uniformly distributed between 10 and 14 minutes per batch (lot) moved. At the low speed setting, four-wheel hand trucks were used. The travelling speed was 0.8 mph, one fifth of the high setting value. Distribution of loading and unloading times was the same as that for fork lift trucks.

Table 5.27 gives the material handling speed settings for intra-cell part movement with batch production and conveyance. Parts were transferred among workstations within a cell in lots with batch production and conveyance. At the high speed setting, live roller conveyors with a speed of 6 mph were used. The times for loading and unloading were uniformly distributed between 0.8 and 1.2 minutes per batch (lot) moved. Two-wheel hand trucks were used at the low speed setting. Their travelling speed was 1.2 mph, one fifth of the high setting value. Loading and unloading times had a uniform distribution between 2.4 and 3.6 minutes per batch (lot) of parts moved.

Table 5.26 Material handling speed settings for inter-cell / department part movement

Material handling speed settings	Equipment type	Travelling speed	Loading & unloading time
High	Fork lift truck	4 mph, constant	Uniformly distributed with Upper limit: 14 min/lot Lower limit: 10 min/lot
Low	Four-wheel hand truck	0.8 mph, constant	Uniformly distributed with Upper limit: 14 min/lot Lower limit: 10 min/lot

For intra-cell part movement with single-unit production and conveyance, parts were transferred among workstations within a cell one piece by one piece. As shown in Table

5.28, the high setting was the same as that for batch production and conveyance. At the low speed setting, parts were handled manually by workers with a travelling speed of 1.2 mph. Times for loading and unloading were uniformly distributed between 14 and 22 seconds per part moved.

Table 5.27 Material handling speed settings for intra-cell part movement with batch production and conveyance

Material handling speed settings	Equipment type	Travelling speed	Loading & unloading time
High	Live roller conveyor	6 mph, constant	Uniformly distributed with Upper limit: 1.2 min/lot Lower limit: 0.8 min/lot
Low	Two-wheel hand truck	1.2 mph, constant	Uniformly distributed with Upper limit: 3.6 min/lot Lower limit: 2.4 min/lot

Table 5.28 Material handling speed settings for intra-cell part movement with single-unit production and conveyance

Material handling speed settings	Equipment type	Travelling speed	Loading & unloading time
High	Live roller conveyor	6 mph, constant	Uniformly distributed with Upper limit: 1.2 min/part Lower limit: 0.8 min/part
Low	Manual handling by workers	1.2 mph, constant	Uniformly distributed with Upper limit: 22 sec/part Lower limit: 14 sec/part

To take into account the adverse effects of backtracking part movement on material handling, it was assumed that intra-cell backtracking part movement speeds were always kept at the corresponding low settings. For example, in the case of intra-cell part movement with single-unit production and conveyance, backtracking parts were always handled manually by workers, even when live roller conveyors were being used.

Besides, as described in Subsection 5.4.3, the fact that different material handling methods may lead to, not only different material handling speeds, but also quite different travelling distances was also taken into account in this study. In a manufacturing cell where a live roller conveyor was used, parts always had to travel along the U-loop path from a workstation to another even though the two workstations are opposite to each others. However, in the case where parts were transported manually in a cell, workers were free to move in the area of the cell and hence always had the flexibility to follow the shortest path to travel around workstations without being limited to a fixed path. Consequently, the two different transportation methods would lead to different travelling distances.

Through the design of the experimental system, we had developed a manufacturing environment with the necessary features and parameters for our investigation. The hybrid push / pull Kanban system constituted the fundamental mechanism of the shop operation since the objective of our study was to investigate the performance of job shop manufacturing with Kanban-based production control. The resultant algorithms and parameters through the design stage were later implemented in the simulation model of the manufacturing shop. The actual performance measures used to evaluate the shop performance are addressed in Chapter 6.

CHAPTER 6

DESIGN OF THE FIRST SET OF EXPERIMENTS

Two groups of simulation experiments were performed in this study. In the first set of experiments, the influence of four factors: shop layout, production flow patterns, material handling speed and part family setup reduction factor (PFSRF) on the performance of job shop manufacturing with Kanbans was investigated.

In the first set of experiments, the coefficients of variation (the ratios of standard deviation to mean) of setup and processing times were held constant for all shop models. However, as reported by Philipoom *et al.* (1987), the variability of processing times had a substantial effect on the performance of a job shop with Kanban-based production control. Villeda *et al.* (1988) also addressed the influence of the variability of operation times on a Kanban-based system. Therefore, the second set of simulation experiments was designed to investigate the influence of the variability (expressed in coefficients of variation) of processing and setup times on the performance of a job shop environment with Kanban-based production control.

In the second set of experiments, the coefficients of variation of setup and processing times were introduced as a factor to investigate their influence on the shop performance. The material handling speed was treated as a background variable (See Section 9.4 for details) in this set of experiments and the information gained in the first set of experiments was utilised to determine the material handling speed settings. Other factors investigated were the same as for the first set of experiments. This chapter covers the design of the first set of experiments. The design of the second set of experiments is illustrated in Chapter 9.

Since this research project was a simulation experiment in nature, a Design of Experiment approach was essential to plan the way the experiment was conducted, and how the output of the experiment was analysed. The design of the experiment involved the selection of three elements: the independent variables and their levels to be investigated, the dependent variables to be measured, and the appropriate statistical analyses of the simulation output.

Note that the definition of independent and dependent variables is taken from Moen *et al.* (1991). A dependent variable is a variable observed or measured in an experiment (i.e. the outcome of an experiment). An independent variable is a variable that is deliberately varied or changed in a controlled manner in an experiment to observe its impact on the response variable. The three aspects for the design of the first set of experiments will be covered in the following sections.

6.1 Selection of the Independent Variables and Their Levels to be Investigated

In the first set of experiments, the three independent variables, Shop Layout, Part Family Setup Reduction Factor and Material Handling Speed represented the influential factors that may affect the performance of a Kanban-controlled job shop. The design of the levels for the three independent variables is illustrated below.

The Shop Layout (SL) variable incorporated not only various types of layouts, but also production flow patterns. The three basic layouts investigated were functional layout (FL), cellular layout with backtracking flow allowed and cellular layout with unidirectional flow. Each of the basic cellular layouts was further distinguished between the one with batch production and conveyance (BPC) and the one with single-unit production and conveyance (SUPC). Hence, as shown in Table 6.1, five levels of the SL variable, FL, CBB, CBU, CSB and CSU were investigated.

As discussed in Subsection 5.5.3, the Part Family Setup Reduction Factor (PFSRF) variable stands for the portion of full setup time incurred when a machine process consecutive jobs of the same part family. As summarised in Table 6.1, high, medium and low levels of this variable (representing small, medium and large setup time reduction achievable through cellular manufacturing, respectively) were examined.

Table 6.1 Summary of the independent variables for the first set of experiments

Independent variable	Levels	Descriptions		
Shop Layout (SL)	FL	Functional layout		
	CBB	Cellular layout with BPC and backtracking flow allowed		
	CBU	Cellular layout with BPC and unidirectional flow		
	CSB	Cellular layout with SUPC and backtracking flow allowed		
	CSU	Cellular layout with SUPC and unidirectional flow		
Part Family Setup Reduction Factor (PFSRF)	High	PFSRF = 0.7		
	Medium	PFSRF = 0.5		
	Low	PFSRF = 0.2		
Material handling speed (MHS)		**Material handling speed settings**		
		inter-cell / department	intra-cell with BPC	Intra-cell with SUPC
	LLL	low	low	low
	LLH	low	low	high
	LHH	low	high	high
	HLL	high	low	low
	HLH	high	low	high
	HHH	high	high	high

The Material Handling Speed (MHS) variable was designed to examine how the relative efficiency of inter-cell and intra-cell part transportation affects the performances of the shops with various layouts and production flow patterns. As shown in Table 6.1, the MHS variable had six levels. The three intra-cell material handling speed levels were investigated at both high and low inter-cell / department material handling speed settings.

Note that in a well-managed manufacturing shop, a single part should be able to be handled more efficiently than a batch of parts. In other words, it is not likely that the speed of moving parts in batches is faster than that of moving parts one piece by one piece. Therefore, the MHS levels at which the material handling speed setting was high for intra-cell part movement with BPC and low for intra-cell part movement with SUPC (i.e. LHL and HHL levels) were not investigated. The high and low settings for inter-cell and intra-cell material handling speeds have been illustrated in Subsection 5.5.4.

Thus, this set of experiments was based on the 5 × 3 × 6 full factorial design, with five, three and six levels for the SL, PFSRF and MHS independent variables, respectively.

6.2 Selection of the Dependent Variables to be Measured

As summarised in Table 6.2, three dependent variables were used for evaluating the shop performance, namely: average work-in-process inventory (AWIP), average flow time (AFT) and average setup to processing time ratio (ASPTR). AWIP and AFT were selected because they were considered two of the most important performance measures for JIT manufacturing. The effectiveness of applying JIT techniques is eventually reflected on the decrease of flow time. As wastes (defined in the broadest sense) are being eliminated, delays in production processes are reduced and therefore, parts are routed through production processes faster. In addition, existence of wastes in production processes is best identified visually by the inventory level. As wastes happen, parts are accumulated due to delays in production processes, and consequently, the inventory level goes up. Although ASPTR is not directly related to shop performance, it was selected particularly for evaluating the effectiveness of cellular manufacturing in setup time reduction (Refer to Section 2.1). Statistics on the results of the three dependent variables from the experiments were collected to investigate the shop performance at the different levels of the independent variables.

Table 6.2 Summary of the dependent variables for the first set of experiments

Dependent variable	Descriptions
Average work-in-process inventory (AWIP)	Total number of parts in the system, averaged over the observation time period.
Average flow time (AFT)	The amount of time spent by a part from entering the system until the completion of all operations, averaged over all completed parts during the observation time period.
Average setup to processing time ratio (ASPTR)	Ratio of total amount of time spent for setting up machines to total amount of time spent for processing parts, averaged over all machines in the observation time period.

To take into account the different lot sizes used for individual part types as well as different shop layouts, AWIP was expressed in total number of parts instead of total number of jobs and AFT, in hours per part instead of per job.

6.3 Selection of the Appropriate Statistical Analyses of the Simulation Output

Two methods of analysis of variance, the overall *F*-test and the planned comparison (Lindman 1992) were used for analysing the experiment results represented by the dependent variables.

6.3.1 Statistical output analyses by the *F*-test

The overall *F*-test was used to detect whether there was any differences in the shop performances attributed to the different levels of the Shop Layout variable. A One-way analysis of variance (ANOVA) was carried out for each of the three dependent variables at each of level of the PFSRF and MHS variables. Therefore in total 3×3×6 = 54 ANOVAs were performed to achieve the results of overall *F*-tests.

6.3.2 Statistical output analyses by the planned comparison

The overall *F*-tests by ANOVAs, however, were of limited use to this study because they did not tell where the differences came from if there were any. Therefore, Lindman's planned comparison was used to pinpoint the causes of differences by answering the following research questions, as put forward in Chapter 4 (Note that Research question 4 was answered by the second set of experiments.):

Research question 1: Do shop layout and part flow patterns have any influence on the performance of a Kanban-controlled job shop? This question is addressed through the following four sub-questions.

> Sub-question 1.1: For the cellular layout shops with batch production and conveyance (BPC), is there any difference in performance between the shop with backtracking flow allowed and the shop with unidirectional flow ?
>
> Sub-question 1.2: Similar to Sub-question 1.1, but for the cellular layout shops with single-unit production and conveyance (SUPC).
>
> Sub-question 1.3: Among the shops with cellular layouts, are those with BPC different from those with SUPC in their performance ?
>
> Sub-question 1.4: Is there any difference between functional layout and cellular layout in terms of shop performance ?

Research question 2: How does the extent of setup time reduction through cellular manufacturing affect the performances of the shops with the various layouts and production flow patterns ?

Research question 3: How does material handling speed affect the performances of the shops with the various layouts and production flow patterns ?

To apply planned comparison to answer the research questions, null hypotheses corresponding to the research questions were first formulated. For example, sub-question 1.1 is equivalent to investigating the truth of the statement: "For the cellular layout shops with BPC, the shop performance with backtracking flow allowed is the same as that with unidirectional flow". Since this statement has not yet been proved to be true or false, it is a 'null hypothesis'. If the null hypothesis cannot be rejected (i.e. is true), we may conclude that there is no difference between the shop performances (or on the contrary). The null hypothesis for sub-question 1, H_0(1a), can be expressed by the following equation:

$$H_0(1a): \mu_{CBB} = \mu_{CBU}, \tag{6.1}$$

where μ_x = the population mean of the dependent variable studied at level x of the Shop Layout independent variable, at each of the MHS and PFSRF levels. Similarly, the null hypothesis for sub-question 1.2, H_0(1b), can be written as:

$$H_0(1b): \mu_{CSB} = \mu_{CSU}, \tag{6.2}$$

Sub-question 1.3 was answered by testing the null hypothesis:

$$H_0(2): \mu_{CBB} + \mu_{CBU} = \mu_{CSB} + \mu_{CSU} \tag{6.3}$$

If H_0(2) was true (i.e. couldn't be rejected), no significant difference could be identified between the cellular layouts with batch production and conveyance (i.e. CBB and CBU) and those with single-unit production and conveyance (i.e. CSB and CSU). Hence, Sub-question 1.4 was answered by comparing the performance of the functional layout with overall average performance of all the cellular layouts and accordingly, the following null hypothesis was tested:

$$H_0(3): \mu_{FL} = 1/4(\mu_{CBB} + \mu_{CBU} + \mu_{CSB} + \mu_{CSU}). \tag{6.4}$$

If H_0(3) was true (i.e. couldn't be rejected), no significant difference could be identified between the cellular layouts and the functional layout.

However, if $H_0(2)$ was rejected, significant difference could be identified between the cellular layouts with batch production and conveyance and those with single-unit production and conveyance. In this case, to answer Sub-question 1.4, the functional layout was compared with the superior ones between the two types of cellular layouts. Therefore, the following null hypothesis was tested:

$$H_0(3): \mu_{FL} = 1/2(\mu_{CBB} + \mu_{CBU}) \qquad (6.5)$$

if the performance of the cellular layout shops with batch production and conveyance was found to be superior (i.e. $\mu_{CBB} + \mu_{CBU} < \mu_{CSB} + \mu_{CSU}$). However, on the contrary, if the cellular layout shops with single-unit production and conveyance performed better (i.e. $\mu_{CSB} + \mu_{CSU} < \mu_{CBB} + \mu_{CBU}$), $H_0(3)$ was then reduced to:

$$H_0(3): \mu_{FL} = 1/2(\mu_{CSB} + \mu_{CSU}). \qquad (6.6)$$

Research question 2 and 3 were answered by comparing the results of planned comparisons at different levels of the PFSRF and MHS variables, respectively.

To take into account the possible unequal variances for the dependent variables at different levels of the independent variables, the formulas of *Approximate F Test* (Lindman 1992: 54) were used to test the above proposed hypotheses. For a linear comparison

$$H_0(k): \sum_i c_{ik} \mu_i = 0$$

where c_{ik} are the constants that define the desired comparison and μ_i is the population mean of group i. For example, by simple rearrangement, equation (6.6) can be written as:

$$H_0(3): \mu_{FL} - 1/2\ \mu_{CSB} - 1/2\ \mu_{CSU} = 0$$

Therefore, following the above definition, $c_{FL,3} = 1$, $c_{CSB,3} = 1/2$ and $c_{CSU,3} = 1/2$. For a given comparison, C_k and D_k can be calculated as follows:

$$C_k = \sum_i c_{ik} \overline{X}_{i\cdot} \tag{6.7}$$

$$D_k = \sum_i c_{ik}^2 \hat{\sigma}_i^2 / n_i \tag{6.8}$$

where $\overline{X}_{i\cdot}$, $\hat{\sigma}_i^2$ and n_i are the sample mean, variance and size of group i, respectively. Then approximately,

$$C_k^2 / D_k \sim F_{(1, d_k)},$$

where $F_{(1, d_k)}$ is the F distribution with 1 degree of freedom in the numerator and d_k degrees of freedom in the denominator. d_k is approximately

$$d_k = D_k^2 \Big/ \left[\sum_i c_{ik}^4 \hat{\sigma}_i^4 \Big/ \left(n_i^3 - n_i^2 \right) \right] \tag{6.9}$$

Let $F_{\alpha(1, d_k)}$ be the value of F to reach the α level of significance and p be the probability that

$$p = P(C_k^2 / D_k \geq F_{\alpha(1, d_k)}).$$

The null hypothesis, $H_0(k)$, is rejected if and only if $p \leq \alpha$.

In summary, unequal variances result in lower degrees of freedom and thus loss of some power for the test. However, since a large sample size was adopted in this study, all hypotheses were tested with high degrees of freedom (as shown in Appendix 10 and 14), and thus high accuracy still could be achieved for the planned comparisons.

CHAPTER 7

DEVELOPMENT AND OPERATION OF THE SIMULATION MODEL FOR THE FIRST SET OF EXPERIMENTS

In Chapter 5, we had described the design of the experimental system. In order to make production runs so that the necessary statistics on the dependent variables for different system conditions (Refer to Chapter 6) can be collected, the designed experimental system must actually be implemented.

In this study, simulation modelling was employed for system implementation. As defined by Russell (1990: 1-1), a simulation of a system is the operation of a model that is a representation of the system. Therefore, to simulate the designed experimental system, a simulation model of the system was first developed in the form of a simulation program. Then, the simulation program, with input data corresponding to different system conditions, was executed and statistics on the dependent variables were collected for further analysis. The development and operation of the simulation model involved four parts: selection of the simulation language, development / coding of the simulation model, verification of the simulation model and running the simulation program. They will be illustrated individually below.

7.1 Selection of the Simulation Language

In order to select a suitable language for developing the simulation model, we must first understand the differences between a simulation program and a general-purpose program, such as a program coded in C, FORTRAN or BASIC language. The differences are mainly in three aspects:

(1) In a simulation program, concurrent execution of program modules is often involved. For example, in a manufacturing shop with more than one machine, all machines are running concurrently. Therefore, there must be a timing routine in the

background which controls the concurrent execution (in simulated time) of the routines for all machines. Similar examples are parts being processed simultaneously, forklift trucks travelling at the same time, etc.

(2) Queues are very often involved in a simulation program. For example, when a container of parts arrives at a workstation, it has to be put in a queue if all machines are busy at that time. Therefore, a mechanism for handling queues is required in a simulation program.

(3) Usually, collection of the statistics of variables is necessary in a simulation program. Some examples are average total number of parts in the system, average time spent for machine setup, etc. A simulation program must support collection of a variety of statistics on variables.

Although all the above differences can be coded by a general-purpose language as well, coding of these special functions is time consuming and the programmer needs knowledge of the methods to implement these functions. On the other hand, simulation languages support all these specific functions for simulation. A model builder needs not to know the underlying principles for implementing these functions. Therefore, development of a simulation model is more straightforward and effective with a simulation language.

Considering the requirements for a simulation program, we selected SIMSCRIPT II.5 general-purpose simulation language for developing the simulation model. Although plenty of advanced simulation software packages other than SIMSCRIPT II.5, such as Promodel, Arena, AweSim, Witness, Simprocess, etc. are available, we selected SIMSCRIPT II.5 for the following reasons:

1. It supports all the above mentioned special functions for a simulation program.
2. Most of the other simulation packages are module-oriented. Although this feature makes development of simulation models easier, particularly for those researchers

without programming background, some flexibility in model development is usually sacrificed.

3. On the other hand, the general-purpose nature of SIMSCRIPT II.5 similar to other high-level languages, such as BASIC and FORTRAN, supports the programming of complicated and fully customised logic and modelling elements, which are required for this study because of the complexity of the shop model.
4. The English-like structure of SIMSCRIPT II.5 enables development and coding of a simulation model at the same time. Model building is therefore made more efficient.

Detailed descriptions of the SIMSCRIPT II.5 simulation program developed for the shop model will be presented in the next section.

7.2 Development / Coding of the Simulation Model

A SIMSCRIPT II.5 program consists of three primary sections:

(1) A preamble that declares the modelling elements used in the program,
(2) A main program where execution of statements begins, and
(3) Routines called by the main program or other routines.

The preamble and main program will be illustrated in Subsections 7.2.1 and 7.2.2, respectively. The routines for the four stages of model development will be described in Subsections 7.2.3 through 7.2.6.

7.2.1 Description of the preamble

The preamble is the first section of any SIMSCRIPT II.5 program. It includes no executable statements. All modelling elements must be declared in the preamble. Four modelling elements, namely: processes, permanent entities, temporary entities and global variables were declared in the preamble of our simulation program. They are described as follows.

(a) Processes

In SIMSCRIPT II.5, a process is the primary dynamic modelling element, which represents an object and the sequence of actions it experiences throughout its life in the model. There may be one or more instances (or copies) of a process during a simulation run. The processes used in the shop model for this study are listed in Table 7.1.

Table 7.1 List of processes for the simulation model

Process name	Description
EXPERIMENT	Generates machines and initiates jobs into the system.
SIM.RUN.MASTER*	Collects and resets statistics in a simulation run.
MACHINE	Sets up machines and processes parts.
SHIP.FILD.CONTR	Moves the containers filled with processed parts from the preceding workstation to the succeeding workstation.
RETN.EMPTY.CONTR	Returns empty containers from the succeeding workstation to the preceding workstation.
SHIP.FILD.CLCON	Moves the containers filled with processed parts from the preceding cell to the succeeding cell.
RETN.EMPTY.CLCON	Returns empty containers to the preceding cell.
CMPLTD.CLCON	Moves containers filled with completed parts to the receiving department
CMPLTD.CONTR	Moves containers filled with processed parts to the cell outgoing storage area.

* SIMSCRIPT II.5 allows the use of periods in element names for easy identification.

For example, the MACHINE process represents the actions that a machine may carry out for processing parts or setting up the machine. Since there were twenty-eight machines in the simulated shop environment, an instance of the MACHINE process was created to represent each machine. Each process declared in the preamble was further described by a process routine. The process routine embodied the logic description of a process. For example, the logic in the MACHINE process tells what actions to perform when a container is emptied, when processing of a container of parts is completed, etc.

One unique feature of the process is the modelling of the passing of time in the logic of process routines. For example, in our shop model, the time for processing a part and the time period that an idle machine had to wait till the next container arrived were modelled in the MACHINE process. The functions of the processes used in the simulation program of this study will be further described in Subsections 7.2.3-6.

(b) Permanent entities

In SIMSCRIPT II.5, a permanent entity is used to represent a passive static data structure. Therefore, permanent entities are suitable for storing the data of system parameters and configuration. Table 7.2 summarises the permanent entities used in the shop model for this study.

Table 7.2 List of permanent entities for the simulation model

Permanent entity name	Description
MACH.ENTY	Defines, for each machine: - the machine ID, - the machine type, - the ID of the workstation where the machine is located, and - the ID of the cell where the machine is located.
JOB.TYPE	Defines the lot size for each part type.
JOB.TASK	Defines, for each part type: - the operation sequence, - the part family No., - the numbers of intra-cell Kanban / container sets, - the numbers of inter-cell Kanban / container sets, and - the intra-cell travelling distances

For example, as shown in Table 7.2, the MACH.ENTY permanent entity stored the configuration data for machines. Since these data were static (i.e. not to be manipulated) throughout a simulation run, they were, therefore, stored in a permanent entity.

(c) Temporary entities

Temporary entities are used to model passive (as opposed to processes) dynamic objects. They are passive because no action, logic or lapse of time is involved for temporary entities. A temporary entity is similar to a data item. However, the data items represented by temporary entities are dynamic. During the execution of the model, they may be short-lived (i.e. may be destroyed sometime) or their numbers of instances (i.e. copies) may vary. In addition, a temporary entity may own a queue or be put in a queue. Table 7.3 shows the temporary entities used for the shop model of this study.

For example, the temporary entity, PROD.ORDER was used to model the work order for an operation (processing a container of parts or setting up the machine) assigned to a specific machine. When an operation was assigned, an instance of PROD.ORDER was created. When the assigned operation was completed, the corresponding instance of PROD.ORDER was then destroyed. Since the number of jobs (i.e. containers of parts) being processed in the system varied from time to time, the number of the instances of PROD.ORDER also varied during the execution of the model. In addition, when a machine was busy, the instances of PROD.ORDER assigned to the machine had to be put in a queue. Therefore, because of the dynamic nature of the work order, it was best modelled by a temporary entity.

(d) Global variables

In SIMSCRIPT II.5, a variable is either global or local in scope. The variables declared in the preamble are global variables. They can be accessed by the main program and all the routines. Variables can be defined in routines as well. However, variables defined in a routine are only temporary for that specific routine. When the routine is called, those defined variables are created. When the routine is ended, the associated variables are destroyed. The global variables used for the shop model of this study are summarised in Table 7.4.

Table 7.3 List of temporary entities for the simulation model

Temporary entity name	Description
PROD.ORDER	A work order for an operation to be done on a specific machine.
MACH.OP	Specifies the ID of the machine assigned to process a specific work order.
TASK.OP	Specifies the ID of the workstation required for a specific operation.
CONTAINER	The container for intra-cell part movement. It is assigned a capacity and the ID of the workstation where it belongs. It may be attached with a intra-cell conveyance Kanban (i.e. WDRL.KBN).
WDRL.KBN	The conveyance Kanban for intra-cell part movement. It specifies the succeeding operation to be performed for a specific part type and the workstation to which parts should be transported.
CELL.CONTR	The container for inter-cell part movement. It is assigned a capacity and the ID of the cell where it belongs. It may be attached with a inter-cell conveyance Kanban (i.e. CELL.WD.KBN)
CELL.WD.KBN	The conveyance Kanban for inter-cell part movement. It specifies the succeeding operation to be performed for a specific part type and the cell to which parts should be transported.
JOB	The job order which specifies the part type and quantity (lot size) of a batch of parts to be produced.

The global variables declared in the preamble were of four modes: real, integer, array and random. The random variable is special for a simulation language. In our program, the JOB.MIX random variable was used to generate the part type for an arriving job from the probabilities given in Table 5.25 (Refer to Subsection 5.5.1). Please note that for brevity, those global variables used for program control and collection of statistics are not given in Table 7.4.

Table 7.4 List of global variables for the simulation model

Variable name	Mode	Description
START.UP.TIME	real	Initial transient period of a simulation run
SAMPLE.INTVL.TIME	real	Data-recording period for one observation
NON.SMPL.INTVL.TIME	real	Non-recording period between observations
MEAN.JOB.ARVL.TIME	real	Mean job inter-arrival time
FMLY.SETUP.FTR	real	Family setup reduction factor
MIN.DEPT.LD.TIME	real	Lower limit of the loading and unloading time for inter-cell / department part movement
MAX.DEPT.LD.TIME	real	Upper limit of the loading and unloading time for inter-cell / department part movement
DEPT.MOVE.SPEED	real	Inter-cell / department material handling speed
MIN.WKS.LD.TIME	real	Lower limit of the loading and unloading time for intra-cell part movement
MAX.WKS.LD.TIME	real	Upper limit of the loading and unloading time for intra-cell part movement
WKS.MOVE.SPEED	real	Intra-cell material handling speed
MIN.BKTRK,LD.TIME	real	Lower limit of the loading and unloading time for backtracking part movement
MAX.BKTRK.LD.TIME	real	Upper limit of the loading and unloading time for backtracking part movement
BKTRK.MOVE.SPEED	real	Material handling speed for backtracking
PROC.GAMMA.ALPHA	real	α value for the distribution of processing times
SETUP.GAMMA.ALPHA	real	α value for the distribution of setup times
JOB.SEL.RULE	text	Job selection rule
QUE.SEL.RULE	text	Queue selection rule
REPLICATION	integer	Number of replications for each simulation run
CL.DIST.MATRIX	array	Matrix of inter-cell distances
JOB.MIX	random	Probability of part types to be assigned to an arriving job

In this subsection, we have covered the modelling elements declared in the first section, the preamble, of the simulation program. In the next subsection, we will describe the second section, the main program, of the simulation program.

7.2.2 Description of the main program and related routines

The main program is the first executable section of a SIMSCRIPT II.5 program. The execution of the simulation program begins at the first statement of the main program. The functions of the main program for the shop model we developed are given in Figure 7.1.

```
1  MAIN:
2     CALL READ.INPUT.DATA routine
3     CALL CREATE.CONTR.WDKBN routine
4     CALL PRINT.INPUT.DATA routine
5     CALL PRINT.WS.DISTANCE routine
6     CALL PRINT.CONTR.WDKBN routine
7     ACTIVATE a SIM.RUN.MASTER process now
8     ACTIVATE an EXPERIMENT process now
9     start simulation
10 EXIT MAIN.
```

Figure 7.1 Description of the functions for the Main program

Note that in this subsection and the following subsections, we use a tool of structured software design, namely, Structured English (Sommerville 1996), to describe the functions of the main program and routines. The program-like language of Structured English is useful for communicating the actions and logic to be performed in a program to programmers and nonprogrammers alike. However, for some special actions related to simulation, we still used the original SIMSCRIPT II.5 commands (e.g. WAIT, ACTIVATE, SUSPEND, etc.). In addition, we will follow the SIMSCRIPT II.5 coding convention of using capital letters for commands, routine names, variables and model entities.

As shown in Figure 7.1, the main program has four functions: setting the system configuration (lines 2-3), printing the system parameters (lines 4-6), initialising processes (lines 7-8) and starting simulation (line 9).

The input data was read and Kanban / container sets were created by calling the routines at lines 2 and 3, respectively. For the purpose of verification, the input data, distance matrices and created Kanban / container sets were printed out at lines 4, 5 and 6, respectively. At line 7, a SIM.RUN.MASTER process was activated for the control of simulation replications. An EXPERIMENT process was activated (line 8) for initiating machines and job generation. The simulation run was then started at line 9. The functions of the SIM.RUN.MASTER and EXPERIMENT processes are further specified as follows.

The functions of the SIM.RUN.MASTER process routine are given in Figure 7.2. Note that lines started with “ " ” (e.g. line 2) are remarks and not executable. In each simulation run, the statistics on dependent variables were reset (line 4) after waiting for a initial transient time period (line 3). The REPEAT UNTIL loop (lines 6-13) performed the replications for the simulation run. For each replication, the statistics on dependent variables were collected and printed out (line 9) after waiting for a data-recording time period (line 8). Each data-recording period was followed by a non-recording period (line 11). The statistics on dependent variables were reset after each non-recording period (line 12).

```
1  Process SIM.RUN.MASTER:
2     ''Handling the initial transient period
3     WAIT for START.UP.TIME days
4     CALL RESET.STATICS routine
5     ''Performing the replications
6     REPEAT UNTIL all replications completed
7        ''Collecting and printing statistics
8        WAIT for SAMPLE.INTVL.TIME days
9        CALL PRINT.RESULTS routine
10       ''Resetting statistics during non-recording period
11       WAIT NON.SMPL.INTVL.TIME days
12       CALL RESET.STATISTICS routine
13    ENDREPEAT
14 EXIT SIM.RUN.MASTER.
```

Figure 7.2 Description of the functions for the SIM.RUN.MASTER process

Figure 7.3 specifies the functions of the EXPERIMENT process. The FOR loop (lines 3-5) created an instance of the MACHINE process for each of the machines specified by the MACH.ENTY permanent entity. The DO UNTIL loop between lines 7 and 10 was responsible for initiating new jobs (containers filled with parts to be processed) throughout the period of the simulation run. In each iteration, the JOB.GENERATOR routine was called (line 9) to initiate a new job into the system after the passing of an exponentially distributed job inter-arrival time (line 8).

```
1  Process EXPERIMENT:
2     ''Generating machine processes
3     FOR each machine specified by MACH.ENTY
4        ACTIVATE a MACHINE process for each machine
5     ENDFOR
6     ''Generating new jobs
7     DO UNTIL end of the simulation run
8        WAIT for a exponentially distributed time period
9        CALL JOB.GENERATOR routine to generate a new job
10    ENDDO
11 EXIT EXPERIMENT.
```

Figure 7.3 Description of the functions for the EXPERIMENT process

In this subsection, we have described the second section of the simulation program, namely, the main program. The MACHINE process is contained in the machine-level model and will be further described in Subsection 7.2.3. The JOB.GNERATOR routine is contained in the shop-level model and will be further described in Subsection 7.2.6.

The third primary section, the routines, of the simulation program was evolved gradually through four stages. At each stage, the simulation model was further expanded by adding more routines to the model developed at the previous stage, until the complete shop model was finalised.

At the first stage, routines for the functions of a machine (i.e. machine-level model) were coded. At the second stage, the machine-level model was upgraded to a workstation-level model by adding routines supporting part movement between workstations. The workstation-level model was further upgraded to the cell-level model at the third stage by adding routines supporting part movement between cells. Finally, at the fourth stage, routines for handling arriving and completed jobs were added and the complete shop-level model was achieved.

The functions of the routines supporting the models of the four development stages will be described individually in Subsections 7.2.3-6. Please note that because of the large number of routines developed for the simulation program, we are not intending to cover all routines in the following subsections. Instead, only those routines necessary for understanding the principle structure of the simulation program will be described in detail. A full listing of the source codes has been produced as a separate document.

7.2.3 Description of the machine-level model

At the stage of the machine-level model development, the MACHINE process routine, the CMPLTD.CONTR process routine and the QUE.MASTER routine were developed. Their functions will be described individually as follows.

(a) Description of the functions for the MACHINE process routine

The functions of the MACHINE process routine are given in Figure 7.4. The MACHINE process was the 'engine' of the shop model because it was the only active element that performed operations on parts and machine setups. Since machines exist throughout the period of a simulation run, the machine process routine was an iterative DO UNTIL loop between lines 2 and 32.

At the beginning of the DO UNTIL loop, the IF statement at line 3 checked whether there was any work order assigned to this machine. If no work order was assigned to this machine, then this MACHINE process was suspended (line 30). Note that SUSPEND is a special SIMSCRIPT II.5 command uniquely for the purpose of simulation control. Once the SUSPEND command is executed, the execution of the process routine will be halted until the process is reactivated again. Since the execution of the process routine has been halted at the statement containing the SUSPEND command, there is no way that the process routine can reactivate itself. In other words, a suspended process routine can only be reactivated by other routines.

```
Process MACHINE:
  DO UNTIL end of the simulation run
    IF a WORK.ORDER for this MACHINE found
      ''Processing a container of parts
      IF this WORK.ORDER being for processing a CONTAINER
        REMOVE conveyance KANBAN from this CONTAINER
        ''Returning the conveyance Kanban
        CALL CLR.KBN.POST routine to return this KANBAN
        REPEAT UNTIL this CONTAINER emptied
          REMOVE a part from this CONAINER
          PERFORM operation on this part
          PUT processed part in FILLED.CONTAINER
        ENDREPEAT
        ''Returning the empty container
        ACTIVATE a RETN.EMPTY.CONTR process to return
         this EMPTY.CONTAINER
        ''Handling the filled container
        ACTIVATE a CMPLTD.CONTR process to handle this
         FILLED.CONTAINER
        CALL QUE.MASTER routine to check for next job
      ''A work order for setting up the machine
      ELSE
        GET full setup time from gamma distribution
        GET part family setup reduction factor
        COMPUTE reduced setup time
        PERFORM setup for this MACHINE
      ENDIF
    ''No work order for the machine
    ELSE
      SUSPEND this MACHINE
    ENDIF
  ENDDO
EXIT MACHINE.
```

Figure 7.4 Description of the functions for the MACHINE process

In our simulation program, we implemented a mechanism for reactivating the MACHINE process routine by initiating work orders (modelled by PROD.ORDER temporary entities). Upon the issuing of a new work order to a specific machine, the corresponding MACHINE process routine was reactivated. Once the suspended MACHINE process routine was reactivated, the execution of the routine will continue from the statement next to the SUSPEND statement (i.e. line 31 in Figure 7.4) and the DO UNTIL loop would be repeated again starting from the IF statement at line 3. By using this mechanism of suspending and reactivating the MACHINE process routine, the idle state (i.e. waiting for parts to be processed) of a machine can be modelled.

As shown in Figure 7.4, if a work order for processing a container of parts was found for this machine (line 5), statements from line 6 to 20 would be executed. The conveyance Kanban attached to the assigned container was removed (line 6) and the CLR.KBN.POST routine was called at line 8 to return the Kanban to the preceding workstation. Then the REPEAT UNTIL loop (lines 9-13) was executed for processing parts until the assigned container was empty. All processed parts were stored in another filled container (line 12).

When the assigned container was emptied, a RETN.EMPTY.CONTR process was activated to return the empty container to the preceding workstation (line 15). Upon the completion of processing all parts, a CMPLTD.CONTR process was activated to move the filled container to the succeeding workstation (line 18-19). The QUE.MASTER routine was then called to check whether there was any container waiting to be processed by this machine (line 20). The CMPLTD.CONTR process routine and QUE.MASTER routine will be further described later.

If a work order for machine setup was found (line 22), the statements for machine setup (lines 23-26) were executed. After the completion of a work order, the DO UNTIL loop was then repeated again to search for another work order for the machine (line 3).

(b) Description of the functions for the CMPLTD.CONTR process routine

The CMPLTD.CONTR process routine was called by the MACHINE process routine to handle the container filled with processed parts. The functions of the CMPLTD.CONTR process routine are shown in Figure 7.5. The processing status of the parts in the container was checked to decide where to ship this filled container. If all necessary operations were completed for the parts in the container (line 3) (i.e. A job had been completed.), a CMPLTD.CLCON process would be activated to move this container to the shipping department (lines 4-5). The CMPLTD.CLCON was included in the shop-level model and will be described in Subsection 7.2.6.

```
1  Process CMPLTD.CONTR
2     ''All operations finished for the parts
3     IF all operations completed for the FILLED.CONTAINER
4        ACTIVATE a CMPLTD.CLCON process to handle this
5         FILLED.CONTAINER
6     ''A container requiring intra-cell movement
7     ELSE, IF this FILLED.CONTAINER to be shipped to
8      succeeding workstation in the cell
9        IF a conveyance KANBAN available for movement
10          ATTACH this KANBAN to this FILLED.CONTAINER
11          ACTIVATE a SHIP.FILD.CONTR process to ship this
12           FILLED.CONTAINER
13       ELSE
14          PUT this FILLED.CONTAINER in output buffer
15       ENDIF
16    ''A container requiring inter-cell movement
17    ELSE, IF this FILLED.CONTAINER to be shipped to
18     succeeding cell
19       IF a conveyance KANBAN available for movement
20          ATTACH this KANBAN to this FILLED.CONTAINER
21          ACTIVATE a SHIP.FILD.CLCON process to ship this
22           FILLED.CONTAINER
23       ELSE
24          PUT this FILLED.CONTAINER in cell outgoing storage
25       ENDIF
26    ENDIF
27 EXIT CMPLTD.CONTR
```

Figure 7.5 Description of the functions for the CMPLTD.CONTR process

If the filled container was to be moved to a succeeding workstation in the cell (lines 7-8), the statement at line 9 searched for a conveyance Kanban authorising the movement of this container. If an available conveyance Kanban was found, the Kanban was then attached to this filled container (line 10) and a SHIP.FILD.CONTR process was activated (lines 11-12) to move this container to the succeeding workstation designated by the Kanban. However, if no conveyance Kanban for authorising the movement of this container was found (line 13), this filled container would be queued in the output buffer of the workstation. The SHIP.FILD.CONTR process was included in the workstation-level model and will be described in Subsection 7.2.4.

If the filled container was to be moved to a succeeding workstation in another cell (lines 17-18), the statement at line 19 first checked if a corresponding conveyance Kanban was available for authorising the movement. If an available Kanban was found, the Kanban would be attached to this filled container (line 20) and a SHIP.FILD.CLCON process was activated (lines 21-22) to ship this filled container to the succeeding workstation designated by the Kanban. However, if no available conveyance Kanban for authorising this movement could be found (line 23), this filled container would be queued in the outgoing storage of the cell (24). Since the SHIP.FILD.CLCON process involved inter-cell movement, it was included in the cell-level model and will be described in Subsection 7.2.5.

(c) Description of the functions for the QUE.MASTER routine

The functions of the QUE.MASTER routine called by the MACHINE process routine are presented in Figure 7.6. The functions of the QUE.MASTER routine were to select a filled container which was waiting to be processed by a specific machine, and to issue work orders to the machine for processing the selected container.

As shown in Figure 7.6, the REPEAT FOR loop (lines 2-18) was executed to for each filled container waiting to be processed by the machine in the input buffer. Recall that for the Kanban system employed in this study, empty containers also served as production Kanbans (Refer to Subsection 5.5.2). In other words, the processing of a container of pats could only be initiated when there was a corresponding empty container available for storing the processed parts. Therefore, the IF statement at lines 5-6 checked for an available empty container for storing the processed parts.

```
1  Routine  QUE.MASTER:
2     REPEAT FOR each FILLED.CONTAINER in input buffer
3      requiring this MACHINE
4        ''Searching for the job with highest priority
5        IF an EMPTY.CONTAINER available for storing processed
6         parts from this FILLED.CONTAINER
7           COMPUTE queue priority for this FILLED.CONTAINER
8           COMPUTE job priority for this FILLED.CONTAINER
9           IF queue priority GREATER THAN previous one
10             SET this FILLED.CONTAINER as NEXT.CONTAINER
11          ELSE IF queue priority EQUAL previous one
12             IF job priority GREATER THAN previous one
13                SET this FILLED.CONTAINER as
14                 NEXT.CONTAINER
15             ENDIF
16          ENDIF
17       ENDIF
18    ENDREPEAT
19    IF a NEXT.CONTAINER found
20       PUT WORK.ORDER for setting up this MACHINE
21       PUT WORK.ORDER for processing this FINAL.CONTAINER on
22        this MACHINE
23       ASSIGN this FINAL.CONTAINER and this EMPTY.CONTAINER
24        to this MACHINE
25    ENDIF
26 EXIT QUE.MASTER.
```

Figure 7.6 Description of the functions for the QUE.MASTER routine

Recall that both the repetitive-lots queue selection rule and the shortest processing time (SPT) job selection rule were used in the shop environment for job scheduling (Refer to Subsection 5.5.3 (b)). Therefore, if an available empty container was found (lines 5-6) for the specific filled container in the input buffer, both the priority values for queue selection (line 7) and job selection (line 8) were calculated. If the queue selection priority value of the current filled container was higher than the previous one, the current filled container would be designated as the next container (the container to be processed next) (lines 9-10). Also, if the current filled container has a queue selection priority value equal to the previous one but a higher job selection priority value (line 11-12), the current filled container was also designated as the next container (lines 13-14).

If a next container could be selected (line 19), the work orders for setting up the machine (line 20) and processing parts (lines 21-22) would be initiated. Both the selected next container and the corresponding empty container were assigned to the machine (lines 23-24).

In the machine-level model, the interactions (movement of containers and Kanbans) among different instances of the MACHINE process were handled by five routines. Three of the five routines, namely: CLR.KBN.POST routine (line 8 in Figure 7.4), SHIP.FILD.CONTR process routine (line 11 in Figure 7.5) and RETN.EMPTY.CONTR process routine (line 15 in Figure 7.4) handled the interactions among workstations in a cell. Therefore, they were developed at the stage of workstation-level model development and will be described in detail in the next subsection.

Another routine, the SHIP.FILD.CLCON process routine handled the movement of filled containers between cells. Therefore, it was developed at the stage of cell-level model development and will be described in detail in Subsection 7.2.5. The last routine, CMPLTD.CLCON process routine, handled the movement of containers between cells and the shipping department. It was therefore developed at the stage of shop-level model development and will be described in detail in Subsection 7.2.6.

7.2.4 Description of the workstation-level model

At this stage of model development, three more routines were added to upgrade the machine-level model developed at the previous stage to the workstation-level model. The three routines added, namely: CLR.KBN.POST routine, SHIP.FILD.CONTR process routine and RETN.EMPTY.CONTR process routine supported the movement of containers (empty or filled) and conveyance Kanbans among workstations in a cell. They will be described individually below.

(a) Description of the functions for the CLR.KBN.POST routine

The functions of the CLR.KBN.POST routine are presented in Figure 7.7. This routine was responsible for returning the conveyance Kanban removed from a filled container to the preceding workstation.

```
1  Routine CLR.KBN.POST:
2      ''A Kanban for inter-cell part movement
3      IF this Kanban for inter-cell part movement
4         CALL RETN.CL.WDKBN routine for returning this KANBAN
5          to preceding cell
6      ''A Kanban for intra-cell part movement
7      ELSE
8         MOVE this KANBAN to preceding workstation
9         IF a FILLED.CONTAINER designated for this KANBAN found
10         in output buffer
11           ATTACH this KANBAN to this FILLED.CONTAINER
12           ACTIVATE a SHIP.FILD.CONTR process to move
13            this FILLED.CONTAINER to succeeding workstation
14        ELSE
15           ''No container waiting for the Kanban
16           PUT this KANBAN in Kanban queue
17        ENDIF
18     ENDIF
19 EXIT CLR.KBN.POST.
```

Figure 7.7 Description of the functions for the CLR.KBN.POST routine

As shown in Figure 7.7, If the conveyance Kanban was to be returned to a preceding workstation in another cell (line 3), the RETN.CL.WDKBN routine was called (lines 4-5) for returning this Kanban. Otherwise, this Kanban was returned to the preceding workstation in the cell (line 8). The functions of the RETN.CL.WDKBN routine will be described in Subsection 7.2.5.

Recall that for the Kanban system employed in the shop environment modelled, a conveyance Kanban was used to authorise the movement of a container filled with processed parts to the succeeding workstation (Refer to Subsection 5.5.2). Therefore, as shown in Figure 7.7, upon the arrival of the returned Kanban at a workstation, the filled containers queued in the output buffer were scanned (lines 9-10) to find one waiting for the authorisation of this Kanban for movement. If no filled container associated with this Kanban was found (line 15), the Kanban was then queued in the Kanban queue (line 16).

If a filled container requiring the returned Kanban was found, this Kanban would be attached to this filled container (line 11) and a SHIP.FILD.CONTR process was activated (lines 12-13) to move this authorised container to the succeeding workstation. The functions of the SHIP.FILD.CONTR process routine will be described next.

(b) Description of the functions for the SHIP.FILD.CONTR process routine

The SHIP.FILD.CONTR process was responsible for moving a container filled with parts to be processed to the succeeding workstation. The functions of the SHIP.FILD.CONTR process routine are presented in Figure 7.8. If the filled container was to be moved to a succeeding workstation in another cell (line 3), a SHIP.FILD.CLCON process was activated (lines 4-5) for moving this filled container; otherwise, the filled container was moved to the succeeding workstation in the cell (line 8). The functions of the SHIP.FILD.CLCON process routine will be further described in Subsection 7.2.5.

Upon the arrival of a filled container at the succeeding workstation, the IF statement at lines 9-10 checked whether there was any empty container available for storing the processed parts from the filled container (Recall that empty containers were also production Kanbans authorising the processing of parts). If no available empty container was found (line 25), the filled container would be queued in the input buffer of the workstation (line 26).

```
1  Process SHIP.FILD.CONTR:
2      ''A container for inter-cell part movement
3      IF this FILLED.CONTAINER to be moved to succeeding cell
4         ACTIVATE a SHIP.FILD.CLCON process to ship this
5          FILLED.CONTAINER
6      ''A container for intra-cell part movement
7      ELSE
8         MOVE this FILLED.CONTAINER to succeeding workstation
9         IF an EMPTY.CONTAINER available for storing processed
10         parts form this FILLED.CONTAINER
11           IF one or more MACHINE available for processing
12            this FILLED.CONTAINER
13              SELECT a MACHINE based on the dispatching rule
14              PUT WORK.ORDER for setting up this MACHINE
15              PUT WORK.ORDER for processing this
16               FILLED.CONTAINER on this MACHINE
17              ASSIGN this FILLED.CONTAINER and this
18               EMPTY.CONTAINER to this MACHINE
19              REACTIVATE this MACHINE
20           ''No machine is available.
21           ELSE
22              PUT this FILLED.CONTAINER in input buffer
23           ENDIF
24        ''No empty container is available now.
25        ELSE
26           PUT this FILLED.CONTAINER in input buffer
27        ENDIF
28     ENDIF
29 EXIT SHIP.FILD.CONTR.
```

Figure 7.8 Description of the functions for the SHIP.FILD.CONTR process

If an available associated empty container was found, the IF statement at lines 11-12 checked if there was any available machine for processing the filled container. If all machines were busy (line 21), the filled container would also be queued in the input buffer (line 22).

If one or more machines were available for processing the filled container, a machine would be selected based on the machine dispatching rule (line 13) (Refer to Subsection 5.5.3 (b)). Work orders for setting up the machine (line 14) and processing parts (lines

15-16) would then be issued. Both the filled container and the associated empty container were assigned to this selected machine (lines 17-18).

As described in Subsection 7.2.3, when a machine was idle, the corresponding instance of the MACHINE process was suspended. Therefore, after the necessary work orders were issued, the instance of the MACHINE process for the selected machine had to be reactivated (line 19). As shown in Figure 7.4, after the reactivation of a MACHINE process routine, the execution of the routine would be resumed from line 31. Therefore, the DO UNTIL loop would be repeated again from line 2 in the MACHINE process routine and the assigned work orders were processed as described in Subsection 7.2.3.

(c) Description of the functions for the RETN.EMPTY.CONTR process routine

The RETN.EMPTY.CONTR process handled the returning of empty containers from the succeeding workstation to the preceding workstation. The functions of the RETN.EMPTY.CONTR process routine are shown in Figure 7.9. If the empty container was to be returned to a proceeding workstation in another cell (line 3), a RETN.EMPTY.CLCON process was activated (lines 4-5) for returning this container.

Since an empty container for inter-cell part movement had been returned, a space in the input buffer was available for storing another container filled with parts to be processed from another cell. Therefore, the statement at line 7 checked the cell incoming storage (where filled containers from another cell were temporarily held) to find a filled container for the same part type as that for the returned empty container. If a matching filled container was found, a SHIP.FILD.CONTR process would be activated (lines 9-10) to move this filled container to this workstation.

If the empty container was to be returned to a preceding workstation in the cell (line 13), it would be moved to the preceding workstation (line 14). As illustrated in Subsection 5.5.2, an empty container also served as a production Kanban for authorising the processing of a specific filled container. Therefore, the statement at lines 15-16 checked whether this empty container was required for processing any filled container in the input buffer of this workstation. If this empty container was not required at that time (line 27), it would be queued in the container queue (line 28).

```
1  Process RETN.EMPTY.CONTR:
2     ''A container for inter-cell part movement
3     IF this EMPTY.CONTAINER being from preceding cell
4        ACTIVATE a RETN.EMPTY.CLCON process to return this
5         EMPTY.CONTAINER to preceding cell
6        ''Searching the incoming storage for a new container
7        IF the available input buffer space matching a
8         FILLED.CONTAINER waiting in cell incoming storage
9           ACTIVATE a SHIP.FILD.CONTR process to move this
10           FILLED.CONTAINER to this workstation
11       ENDIF
12    ''A container for intra-cell part movement
13    ELSE
14       MOVE this EMPTY.CONTAINER to preceding workstation
15       IF this EMPTY.CONTAINER required for processing a
16        FILLED.CONTAINER in input buffer
17          IF one or more MACHINE available for processing
18           this FILLED.CONTAINER
19             SELECT a MACHINE based on the dispatching rule
20             PUT WORK.ORDER for setting up this MACHINE
21             PUT WORK.ORDER for processing this
22              FILLED.CONTAINER on this MACHINE
23             ASSIGN this FILLED.CONTAINER and this
24              EMPTY.CONTAINER to this MACHINE
25             REACTIVATE this MACHINE
26          ''No machine is available.
27          ELSE
28             PUT this EMPTY.CONTAINER in container queue
29          ENDIF
30       ''The empty container is not required now.
31       ELSE
32          PUT this EMPTY.CONTAINER in container queue
33       ENDIF
34    ENDIF
35 EXIT RETN.EMPTY.CONTR.
```

Figure 7.9 Description of the functions for the RETN.EMPTY.CONTR process

If a filled container waiting for this empty container was found, the IF statement at lines 17-18 checked if there was any available machine for processing the filled container. If all machines were busy (line 27), the empty container would also be queued in the container queue (line 28).

However, if one or more machines were available for processing the filled container, a machine would be selected based on the machine dispatching rule (line 19) (Refer to Subsection 5.5.3 (b)). Work orders for setting up the machine (line 20) and processing parts (lines 21-22) would then be issued. Both the empty container and the associated filled container were assigned to this selected machine (lines 23-24). As described for the SHIP.FILD.CONTR process routine, the instance of the MACHINE process for the selected machine had to be reactivated (line 25) to resume the execution of the process routine.

At this stage of model development, the workstation-level model was evolved by adding three routines to the machine-level model developed at the first stage. In addition, three routines, namely: RETN.CL.WDKBN routine, SHIP.FILD.CLCON process routine and RETN.EMPTY.CLCON process routine, were called for handling the interactions among cells. They will be further described in the next section.

7.2.5 Description of the Cell-level model

The workstation-level model developed in the work described above was next upgraded to the cell-level model. Three routines, namely, RETN.CL.WDKBN routine, SHIP.FILD.CLCON process routine and RETN.EMPTY.CLCON process routine, were added to the simulation program. These routines supported the movement of Kanbans and containers (empty or filled) among cells in the shop. Their functions will be described in detail as follows.

(a) Description of the functions for the RETN.CL.WDKBN routine

The RETN.CL.WDKBN routine was called by the CLR.KBN.POST routine (See Subsection 7.2.4 (a)) to return a conveyance Kanban to a preceding workstation in another cell or to the receiving department (where job orders were issued). The functions of the RETN.CL.WDKBN routine are presented in Figure 7.10.

```
1  Routine RETN.CL.WDKBN
2     MOVE this KANBAN to preceding cell / receiving dept.
3     IF a FILLED.CONTAINER designated for this KANBAN found
4      in outgoing storage
5        ATTACH this KANBAN to this FILLED.CONTAINER
6        ACTIVATE a SHIP.FILD.CLCON process to move this
7         FILLED.CONTAINER to succeeding cell
8     ELSE
9        ''No container waiting for the Kanban
10       PUT this KANBAN in Kanban queue
11    ENDIF
12 EXIT RETN.CL.WDKBN
```

Figure 7.10 Description of the functions for the RETN.CL.WDKBN routine

When the Kanban was returned to the preceding workstation / receiving department (line 2), the statement at lines 3-4 checked the filled containers at the outgoing storage of the cell / receiving department to see whether any container could be authorised for movement by this Kanban. (Recall that a conveyance Kanban was used to authorise the movement of a filled container from a preceding workstation to the succeeding workstation). If no container was waiting for the authorisation by this Kanban (line 8), this returned Kanban will be queued in the Kanban queue (line 10).

On the other hand, if a filled container waiting authorisation by this Kanban was found, the Kanban would be attached to this filled container (line 5). A SHIP.FILD.CLCON process was then activated (lines 6-7) to move this filled container to the succeeding workstation.

(b) Description of the functions for the SHIP.FILD.CLCON process routine

The SHIP.FILD.CLCON process routine was called by three other routines: the CMPLTD.CONTR process routine (See Subsection 7.2.3 (b)), the SHIP.FILD.CONTR process routine (See Subsection 7.2.4 (b)) and the RETN.CL.WDKBN routine. The SHIP.FILD.CLCON process routine supported the movement of a container filled with parts to be processed to a succeeding workstation in another cell. Figure 7.11 shows the functions of this routine.

```
1  Process SHIP.FILD.CLCON
2     MOVE this FILLED.CONTAINER to succeeding cell
3     IF input buffer space available at succeeding workstation
4        ACTIVATE a SHIP.FILD.CONTR process to move this
5         FILLED.CONTAINER to succeeding workstation
6     ELSE
7        PUT this FILLED.CONTAINER in cell incoming storage
8     ENDIF
9  EXIT SHIP.FILD.CLCON
```

Figure 7.11 Description of the functions for the SHIP.FILD.CLCON process

Upon the arrival of the filled container at the cell, the statement at line 3 checked whether a space was available in the input buffer of the succeeding workstation. If the input buffer of the succeeding workstation was full, this filled container would be queued in the incoming storage of the cell (line 7). On the other hand, if a storage space was available in the input buffer of the succeeding workstation, a SHIP.FILD.CONTR process (Refer to Subsection 7.2.4 (b)) would be activated (lines 4-5) to move this filled container to the succeeding workstation.

(c) Description of the functions for the RETN.EMPTY.CLCON process routine

The RETN.EMPTY.CLCON process routine was called by the RETN.EMPTY.CONTR process routine (Refer to 7.2.4 (c)) to return an empty container to a preceding workstation in another cell. The functions of this routine are presented in Figure 7.12.

```
Process RETN.EMPTY.CLCON
   ''Container for storing raw material parts
   IF this EMPTY.CONTAINER being from the receiving dept.
      MOVE this EMPTY.CONTAINER to receiving dept.

      IF this EMPTY.CONTAINER required by a queued JOB
         FILL this EMPTY.CONTAINER with raw material parts
          required for starting this JOB

         IF a conveyance KANBAN available for authorising
          movement of this FILLED.CONTAINER
            ATTACH this KANBAN to this FILLED.CONTAINER
            ACTIVATE a SHIP.FILD.CLCON process to move this
             FILLED.CONTAINER to succeeding cell

         ELSE
            ''No conveyance Kanban available for shipment
            PUT this FILLED.CONTAINER in outgoing storage
         ENDIF

      ELSE
         ''The empty container not required now
         PUT this EMPTY.CONTAINER in container queue
      ENDIF

   ELSE
      ''Container for storing intermediate parts
      MOVE this EMPTY.CONTAINER to preceding cell

      IF this EMPTY.CONTAINER required for storing
       processed parts from a FILLED.CONTAINER in input
       buffer of preceding workstation

         IF one or more MACHINE available for processing
          this FILLED.CONTAINER
            SELECT a MACHINE based on the dispatching rule
            PUT WORK.ORDER for setting up this MACHINE
            PUT WORK.ORDER for processing this
             FILLED.CONTAINER on this MACHINE
            ASSIGN this FILLED.CONTAINER and this
             EMPTY.CONTAINER to this machine
            REACTIVATE this MACHINE

         ELSE
            ''No machine is available.
            PUT this EMPTY.CONTAINER in container queue
         ENDIF

      ELSE
         ''The empty container not required now
         PUT this EMPTY.CONTAINER in container queue
      ENDIF
   ENDIF
EXIT RETN.EMPTY.CLCON
```

Figure 7.12 Description of the functions for the RETN.EMPTY.CLCON process

The statement at lines 3 first checked whether this empty container was to be returned to the receiving department (i.e. a container for storing raw material parts) or a preceding cell (i.e. a container for storing intermediate parts).

If this empty container was for storing raw material parts, it would be moved to the receiving department (line 4). Since an empty container was also a production Kanban authorising the processing of parts, the statement at line 5 checked whether this empty container was required for initiating the processing of a queued job. If the container was not required for initiating a job at that time (line 17), it was then queued in the container queue (line 19).

If the empty container was required for initiating the processing of a queued job, the container would be filled with the raw material parts for producing the part type specified by this job (lines 6-7). Then the statement at lines 8-9 checked whether a conveyance Kanban was available for transporting this container filled with raw material parts to the succeeding workstation. If no conveyance Kanban was available (line 13), this filled container would be queued in the outgoing storage of the receiving department, where all job orders were received (line 15). However, if a conveyance Kanban was available, this Kanban would be attached to the filled container (line 10) and a SHIP.FILD.CLCON process would be activated for moving the container (lines 11-12).

On the other hand, if the empty container was for storing intermediate parts (line 21), it was then returned to the preceding workstation in another cell (line 23). The statement at lines 24-26 checked whether this empty container was required for authorising the processing of a filled container in the input buffer. If the empty container was not required at that time (line 40), it would be queued in the container queue (line 42).

However, if this returned empty container was required for storing the processed parts from a filled container in the input buffer, the statement at lines 27-28 checked whether there was any machine available for processing this filled container. If no machine was available (line 36), the empty container was then queued in the container queue (line 38). On the other hand, if one or more machines were available, a machine would be selected based on the machine dispatching rule (line 29) (Refer to Subsection 5.5.3 (b)).

After the machine was selected, work orders for setting up this machine (line 30) and for processing parts (lines 31-32) were issued. The empty container and the associated filled container were then assigned to the machine (lines 33-34). The instance of the MACHINE process for the selected machine was then reactivated and the issued work orders would be processed as described in Subsection 7.2.3.

In this subsection, we have described the three routines that supported the interactions among cells for the cell-level model. In the next subsection, we will describe the routines that were added to the cell-level model to achieve the final shop-level model.

7.2.6 Description of the Shop-level model

At this final stage of model development, the cell-level model was upgraded to achieve the final shop-level model for the designed shop environment. At the final stage, two more routines, namely, the JOB.GENERATOR routine and the CMPLTD.CLCON process routine were added for supporting the generation and termination of jobs. These two routines will be described in detail below.

(a) Description of the functions for the JOB.GENERATOR routine

The JOB.GENERATOR routine, which was called by the EXPERIMENT process routine (Refer to Subsection 7.2.2), generated new jobs and launched the containers with raw material parts for new jobs into the system. The functions of the JOB.GENERATOR routine are shown in Figure 7.13. At the beginning of the routine, a new job (i.e. an instance of the JOB temporary entity) was created (line 2). A part type was then generated for the new job (line 3) according to the probabilities specified in Table 5.25, and the lot size for the part type was assigned to the new job (line 4).

```
1  Routine JOB.GENERATOR
2     CREATE a NEW.JOB
3     GENERATE a part type for this NEW.JOB
4     GET the lot size for this NEW.JOB
5     IF an EMPTY.CONTAINER available at receiving dept. for
6      storing raw material parts for this NEW.JOB
7        FILL this EMPTY.CONTAINER with raw material parts
8         required for starting this NEW.JOB
9        IF a conveyance KANBAN available for authorising
10        movement of this FILLED.CONTAINER
11          ATTACH this KANBAN to this FILLED.CONTAINER
12          ACTIVATE a SHIP.FILD.CLCON process to move this
13           FILLED.CONTAINER to succeeding cell
14       ELSE
15          ''No conveyance Kanban available for shipment
16          PUT this FILLED.CONTAINER in outgoing storage
17       ENDIF
18    ELSE
19       ''No empty container available
20       PUT this NEW.JOB in job queue
21    ENDIF
22 EXIT JOB.GENERATOR
```

Figure 7.13 Description of the functions for the JOB.GENERATOR routine

The statement at lines 5-6 checked whether an empty container was available in the receiving department for storing the raw material parts for the new job. If no empty container was available for initiating the processing of the new job (line 18), the new job would be queued in the job queue (line 20).

On the other hand, if an empty container was available in the receiving department for initiating the new job, the empty container would be filled with the raw material parts for the part type specified by the new job (lines 7-8). Then the statement at line 9 checked whether a conveyance Kanban was available for authorising the movement of the filled container. If no conveyance was available (line 14), the filled container would be queued in the outgoing storage of the receiving department (line 16).

If an available conveyance Kanban was found, this Kanban would be attached to the filled container (line 11). A SHIP.FILD.CLCON process (Refer to Subsection 7.2.5 (b) was then activated to move this filled container to the succeeding cell (lines 12-13).

(b) Description of the functions for the CMPLTD.CLCON process routine

The CMPLTD.CLCON process routine, which was called by the CMPLTD.CONTR process routine (Refer to Subsection 7.2.3 (b)), handled a container storing the completed parts specified by a job. The functions of this routine are presented in Figure 7.14.

```
1  Process CMPLTD.CLCON
2     MOVE this COMPLETED.CONTAINER to shipping dept.
3     EMPTY this COMPLETED.CONTAINER
4     DESTROY the JOB fulfilled by this COMPLETED.CONTAINER
5     ACTIVATE a RETN.EMPTY.CLCON to return this
6      EMPTY.CONTAINER to preceding cell
7  EXIT CMPLTD.CLCON
```

Figure 7.14 Description of the functions for the CMPLTD.CLCON process

First, the container filled with completed parts was moved to the shipping department (line 2) and emptied (line 3). Then the instance of the JOB temporary entity corresponding to the completed parts was destroyed (i.e. The job was terminated). Finally, a RETN.EMPTY.CLCON process was activated to return the empty container to the preceding cell.

The overall view of the interactions among the routines described above is presented in Figure 7.15. Note that the two process routines (i.e. SIM.RUN.MASTER and EXPERIMENT) called by the main program are not included in the figure because they are not relevant to the modelling of the shop operations.

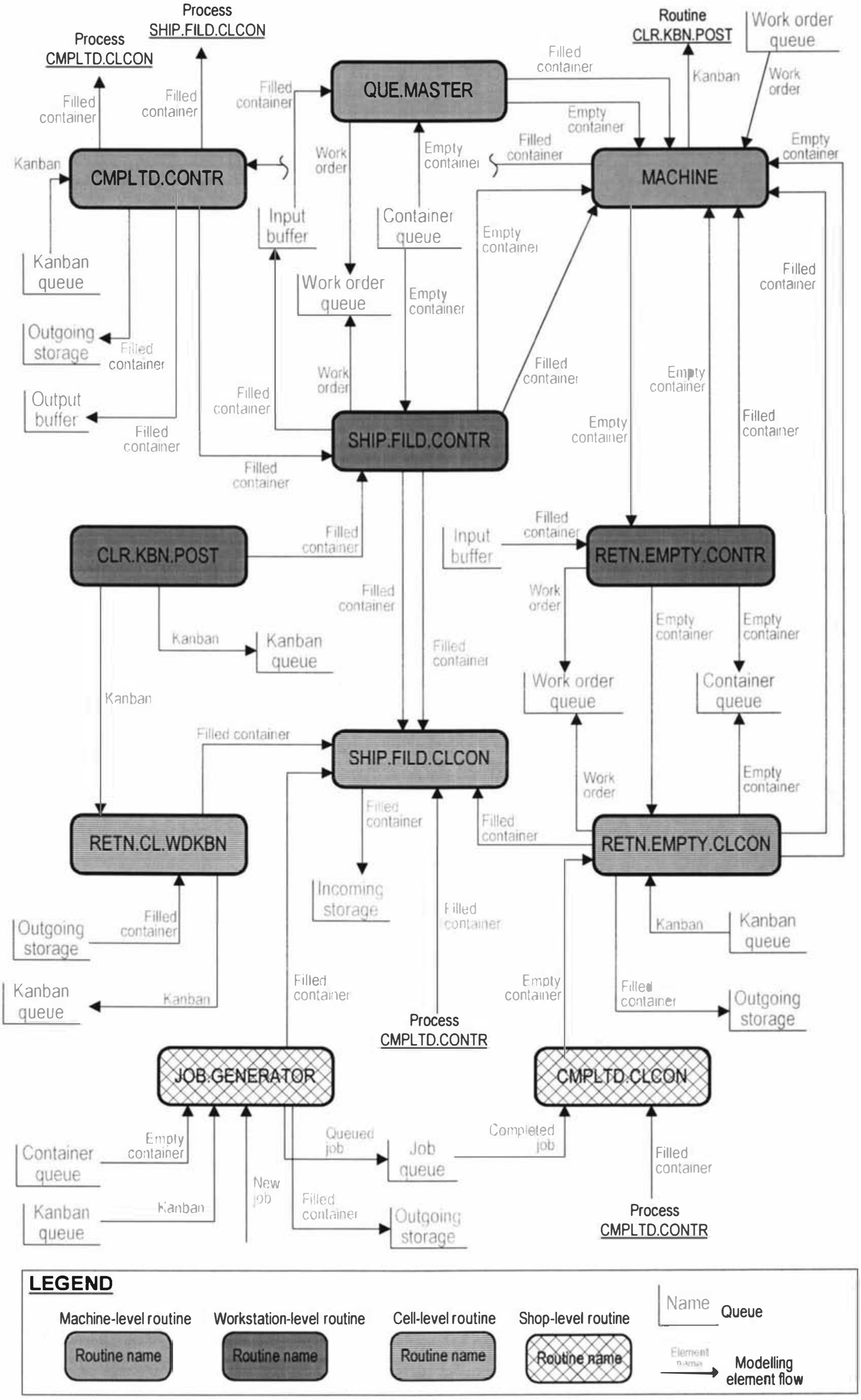


Figure 7.15 Interactions among the routines of the simulation program

As shown in Figure 7.15, the routines interact with each others through two ways: they interchange modelling elements (e.g. Kanbans, filled containers, etc.) with the routines they call, or they interact indirectly with each other through the manipulation of queues (e.g. the input buffer).

For example, the SHIP.FILD.CONTR process interacts directly with the MACHINE process by passing two modelling elements to it: the filled container and the empty container. On the other hand, the SHIP.FILD.CONTR process also interacts with the MACHINE process indirectly by introducing new ‘work orders’ to the work order queue. As described in 7.2.3 (a), work orders were used in the simulation program for conveying the information for processing a container of parts to a specific instance of the MACHINE process.

In this section, we have described the simulation program for the shop model. In order to make sure that the developed program operates as we expect, it had to be verified. The verification of the simulation program will be described in the next section.

7.3 Verification of the Simulation Model

After the simulation program was developed, all routines were successfully compiled and the execution file for the program was generated by the compiler. However, at this stage, the simulation program was not yet completed. We still had to verify that the logic and operations of the simulation program were executed as we expected. Verification was carried out immediately after each of the four model development stages. The following procedure was adopted to verify the simulation model:

(1) Statements for issuing event messages were inserted in the program codes where important actions took place (e.g. a container being shipped, a Kanban being returned, a job being completed, etc.).

(2) Statements for detecting errors were inserted in the program codes where errors may happen. For example, in the routine, CMPLTD.CLCON (Figure 7.14), statements were added to check whether the lot size of a container storing completed parts was consistent with that specified by the job.

(3) The program was run with a set of test data. All event and error messages were printed out. The size of the test data was smaller than the data for the shop environment being modelled, but sufficient for checking the actions and logic of the program.

(4) The event messages were walked through to find any incorrect actions and logic. All identified errors were then corrected.

In addition, Kanbans and containers played an important role in the control of inventory level and part movement. Therefore, after the completion of the shop-level model, the numbers of Kanbans and containers generated were printed out and verified to assure the routine for creating Kanbans and containers functioned correctly.

After going through the verification process, we were confident that the developed simulation model was a correct representation of the shop environment designed in Chapter 5. Once the simulation model was verified, it could be executed to carry out the experiments as designed in Chapter 6. In the next section, we will describe how to run the simulation program to correctly collect the statistics on the dependent variables.

7.4 Running the Simulation Program

The simulation program was executed in two phases: the preliminary runs and the production runs. Through preliminary runs we determined the initial transient period, the required numbers of conveyance Kanban-container sets and the simulation run length (replications). After these parameters were determined through the preliminary runs, production runs were performed to achieve the experiments designed in Chapter 6 and statistics on the dependent variables were collected for analysis. These tasks regarding preliminary and production simulation runs will be illustrated individually in the following subsections.

7.4.1 Determination of the initial transient period

In this study, a simulation run was started from an 'empty' condition (i.e. Initially all machines are idle and no job is in the system). Hence it could be expected that the simulated system would go through a initial transient period before the dependent variables reach a steady state. Therefore, the data gathered during the initial transient period would have to be discarded to avoid the collected statistics being biased.

The Welch's graphical procedure (Law and Kelton 1991, p. 545) was used to determine the initial transient period. The procedure involved the following steps:

(1) Seven replications with different random number seeds of the simulation run were made. Each replication was run for 130 periods, with each period being 120 simulated hours. Statistics on average work-in-process inventory, average flow time and average machine utilisation were collected for each period, leading to 130 observations in each replication.

(2) Let X_{ji} be the ith observation from the jth replication ($j = 1, 2, \ldots, n$; $i = 1, 2, \ldots, m$). For this study, $n = 7$ and $m = 130$. To reduce the variation of the original observations, the following averages were calculated:

$$\overline{X}_i = \sum_{j=1}^{n} X_{ji} / n.$$

The above averaged process has the same transient mean curve as the original process, but its plot has only (1/n)th the variance.

(3) To smooth out the high-frequency oscillations in $\overline{X}_1, \overline{X}_2, \ldots, \overline{X}_n$, (but leave the long-run trend), the moving average $\overline{X}_i(w)$ (where w is the 'window' and is a positive integer such that $w \le [m/2]$) were calculated as follows:

$$\overline{X}_i(w) = \begin{cases} \dfrac{\sum_{s=-w}^{w} \overline{X}_{i+s}}{2w+1} & \text{if } i = w+1, \ldots, m-w \\ \dfrac{\sum_{s=-(i-1)}^{i-1} \overline{X}_{i+s}}{2i-1} & \text{if } i = 1, \ldots, w \end{cases}$$

In this study, w was set to 30.

(4) $\overline{X}_i(w)$ for $i = 1, 2, \ldots, m\text{-}w$ was plotted and a value of $i = l$ was chosen so that $\overline{X}_{l+1}(w), \overline{X}_{l+2}(w), \ldots$ appeared to converge.

From the results of preliminary runs, we found that the cellular layout shop with single-unit production & conveyance and backtracking flow allowed (i.e. the CSB shop) had the longest average flow times. Therefore, the initial transient period was determined based on the moving averages of the dependent variables for the CSB shop since it took the longest time to reach a steady state. The resulting moving average plot of average work-in-process inventory for the CSB shop was shown in Figure 7.16. (The moving average plots for the three dependent variables are presented in Figures A6.1-3 of Appendix 6). The moving averages appeared to converge after the 48th period. Therefore, we decided to set the initial transient period, $l = 48$ periods = 5760 hours.

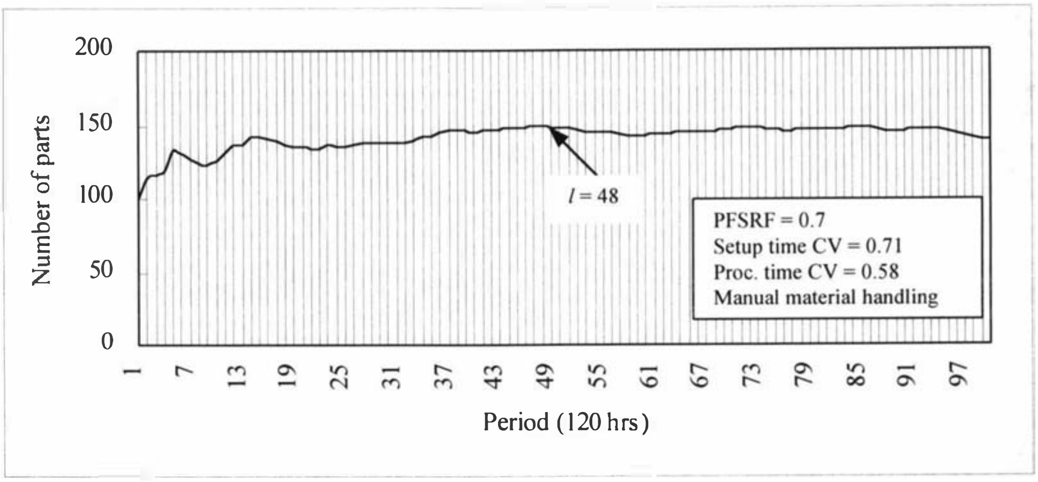


Figure 7.16 Moving average plot of average work-in-process inventory (Cellular layout with SUPC and backtracking flow allowed)

7.4.2 Determination of the numbers of conveyance Kanban-container sets

In a production system with Kanban-based production control, the numbers of conveyance Kanbans and containers (used as production Kanbans in this study) designated for each part type at each workstation are critical for the control of inventory-level and part movement.

The numbers of Kanbans and containers were set in pairs. A container for storing the parts for a specific part type at a workstation was assigned an associated conveyance Kanban for authorising the movement of this container. If the numbers of Kanban / container sets (for individual part types) were set too small, the production flow would be too tight (i.e. be blocked too often) because the numbers of Kanban-container sets were not enough for circulating parts smoothly. On the other hand, if the numbers of Kanban-container sets were too large, the production flow would be too loose because parts would be routed through machines faster at the cost of higher work-in-process inventory.

In a shop environment where production flow was too tight or too loose, the effects of independent variables on the responses of dependent variables can be biased. For example, if the production flow is too tight, a large setup time reduction may result in significantly less or no improvement in average flow time because of the blockage of the production flow. Consequently, in order to assess the shop performance correctly, reasonable numbers of Kanban-container sets need to be determined. In this study, the simulation approach presented by Philipoom *et al.* (1987) was used to determine the required numbers of Kanban-container sets through preliminary simulation runs.

The following steps were involved for determining the numbers of Kanban-container sets required for individual part types among the workstations in a cell:

(1) A simulation run was made for each workstation assuming that the production system was operated without backorder. In other words, when a filled container arrived at a workstation, there was always an available corresponding empty container for initiating the processing of the filled container. This assumption enabled all workstations to be 'decoupled' from each other.

(2) The production lead times of Kanban lots (batches) for each part type at a workstation were recorded for every 11th arrival so that the dependence among observations were reduced.

(3) 100 observations were collected in this manner for each part type at each workstation. These 100 lead time observations were ranked from smallest to largest and the 95th highest value was used as the estimated lead time value (denoted by LT_{95}).

(4) The following formula was used to determine the number of conveyance Kanban / container sets required for a specific part type at a workstation:

$$n = D \times LT_{95} \tag{7.1}$$

where n is the number of conveyance Kanban-container sets required for a part type at a workstation. D is the average demand of the part type in containers (lots) per day. LT_{95} is the estimated lead time value for the part type at the workstation in days.

(5) In addition to equation (7.1), the following constraint has to be satisfied for the cellular layout shops with single-unit production and conveyance (Yavuz and Satir 1995):

$$n \geq LS \tag{7.2}$$

where LS is the order lot size for a specific part type. For a cellular layout shop with single-unit production and conveyance (SUPC), the Kanban lot size for intra-cell part movement was one. Therefore, if the number of intra-cell Kanbans was set to be less than the order lot size, the workstation would starve for input material during the processing of a container (batch) of parts, and the system would be blocked.

As an example, Table 7.5 shows the numbers of intra-cell conveyance Kanbans for cell 1 of the cellular layout shop with batch production & conveyance (BPC) and unidirectional flow (i.e. the CBU shop). For example, for part type 6, the required number of Kanbans at workstation 3 (of machine type 10) was one. It means that one conveyance Kanban-container set was required for transporting the parts for part type 6 from workstation 2 to workstation 3. Similarly, one conveyance Kanban-container set was required for the part movement of part type 6 between workstation 3 and workstation 4.

Note that workstation 2 was the first workstation in cell 1 on the routing for part type 6. Therefore, the required number of Kanbans at workstation 2 indicates the available number of input buffer spaces for storing filled containers moved from the cell incoming storage.

Table 7.5 Numbers of intra-cell Kanbans for cell 1 of the CBU shop

Part Type	Demand (lots/day)	Number of Kanbans at Workstation No./Machine type				
		1/1	2/6	3/10	4/7	5/9
5	1.85	1	2	1	1	1
6	1.39		1	1	1	
11	0.95		1			
15	0.50	1			1	
16	0.62	1			1	

The required numbers of conveyance Kanban-container sets for inter-cell part movement were determined in the same manner by assuming there was no backorders among cells. The same procedure as described above was followed to determine the required numbers of conveyance Kanban-container sets for inter-cell part movement. In this case, LT_{95} is the estimated lead time value for a specific part type at a cell in days.

As an example, Table 7.6 shows the required numbers of inter-cell Kanbans for the cellular layout shops with unidirectional flow. For example, for part type 6, the required number of conveyance Kanban-container sets at cell 2 was two. In other words, two conveyance Kanban-container sets were required for transporting the parts of part type 6 from cell 1 to cell 2. Since cell 1 was the first cell on the routing for part type 6, the requirement of two Kanbans at cell 1 indicates two conveyance Kanban-container sets were required for transporting the parts for part type 6 from the receiving department to cell 1.

The required numbers of intra-cell and inter-cell conveyance Kanban-container sets for individual part types were given in Appendix 7. Since the shop configurations for the cellular layout shops with backtracking flow and those with unidirectional flow were different, a set of figures were obtained for each of the two basic shop layouts.

Table 7.6 Numbers of inter-cell Kanbans for the cellular layout shops with unidirectional flow

Part Type	Demand (lots/day)	Number of Inter-cell Kanbans at Cell No.				
		1	2	3	4	5
1	1.05		4			
2	0.57		2			1
3	1.13		5			
4	0.71		14			
5	1.85	5				
6	1.39	2	2			
7	0.88				1	2
8	1.37				4	4
9	2.17				3	3
10	0.60		3			2
11	0.95	2				
12	0.69			3		
13	0.71			1		
14	0.75			4		
15	0.50	1		2		
16	0.62	1		2		
17	0.57			2		
18	3.09			3		
19	0.22			1		

Note: The lead times based on single-unit production & conveyance were used for calculating the required numbers of Kanbans.

In addition, because of the additional constraint (equation (7.2)) for the cellular layout shop with SUPC, the required numbers of Kanbans were different for the cellular layout shops with SUPC and those with BPC. Therefore, for each of the basic cellular layouts (i.e. the cellular layout with backtracking flow and the cellular layout with unidirectional flow), the required numbers of Kanbans for SUPC and BPC were obtained individually.

7.4.3 Determination of the simulation run length (replications)

As illustrated in Subsection 7.4.1, in each simulation run, the system would go through a initial transient period before the dependent variables reach a steady state. At the end of the transient period, statistics on dependent variables were reset and independent observations of the statistics on the dependent variables could be collected. In this study, an observation was defined as the statistics (e.g. average) collected for a specific dependent variable during a period in the simulation run.

For a simulation model with stochastic characteristics, a simulation run has to be replicated (to collect more than one observations) to achieve the desired accuracy for the statistics on dependent variables. Although higher accuracy can be achieved through more replications, computing time also increases with increasing replications. Therefore, to perform simulation efficiently, it is important to decide the replications (or simulation run length) required for calculating statistics with the desired accuracy.

In this study, the blocking method (Emshoff and Sisson 1970: 199-200) was employed for collecting observations of the statistics on the dependent variables. However, we had modified this primitive method to reduce the degree of correlation among observations. Through several preliminary simulation runs, we decided to collect observations of the statistics on the dependent variables for every 1200-hour data-recording period. To assure the independence of observations (i.e. to reduce the auto-correlation), a 520-hour non-recording period was introduced between any two adjacent data-recording periods to ensure that jobs entering the system in the previous period were completed before the start of the next period. Statistics on dependent variables were reset at the beginning of each data-recording period.

By using the *method of batch means* presented by Law and Kelton (1991: 554-555), the sample mean and variance (as estimators for the population mean, μ and variance, δ^2, respectively) of a dependent variable in a simulation run were given as follows:

$$\overline{\overline{Y}}(n, k) = \sum_{j=1}^{n} \overline{Y}_j(k) / n \tag{7.1}$$

$$S^2(n) = \sum_{j=1}^{n} [\overline{Y}_j(k) - \overline{\overline{Y}}(n, k)]^2 / (n-1) \tag{7.2}$$

where

k = data-recording period = 1200 hours

n = total number of data-recording periods (replications) of the simulation run.

$\overline{\overline{Y}}(n, k)$ = sample mean of the dependent variable, Y for the simulation run with n data-recording periods of length k.

$\overline{Y}_j(k)$ = sample mean of the dependent variable, Y in the jth data-recording period.

$S^2(n)$ = sample variance of the dependent variable, Y for the simulation run

The estimate of the 100(1-α) percent confidence interval for the population mean, μ of the dependent variable, Y is given by

$$\overline{\overline{Y}}(n, k) \pm t_{n-1,\, 1-\alpha/2} \sqrt{\frac{S^2(n)}{n}} \tag{7.3}$$

where $t_{n-1,\, 1-\alpha/2}$ is the upper 1-α/2 critical point for the t distribution with n-1 degrees of freedom. Formula (7.3) shows that as the number of replications (i.e. n) increases, the error term (i.e. $t_{n-1,\, 1-\alpha/2} \sqrt{\frac{S^2(n)}{n}}$) for estimating the population mean decreases.

From the preliminary simulation runs, we found that with twenty-two replications (i.e. n = 22), errors equal to or smaller than 10% could be achieved for estimating the population means with a 95% confidence interval. Therefore, we decided that observations of the statistics for the three dependent variables were gathered for twenty-two data-recording periods (i.e. twenty-two replications) in a simulation run, leading to twenty-two independent observations.

7.4.4 Performing the production simulation runs

After the initial transient period, the required numbers of Kanbans and the number of replications had been decided, the simulation experiments were then carried out through production simulation runs. Each production simulation run was performed with a set of data representing a different combination of the levels for the independent variables. The levels of the independent variables to be investigated have been summarised in Table 6.1 of Section 6.1.

For example, as shown in Table 6.1, the shop configuration with the SL level = FL, the PFSRF level = 0.7 and the low inter-department material handling speed setting (i.e. with the MHS level = LLL, LLH or LHH) was simulated in one production simulation run. Therefore, in total 54 production simulation runs (six for the SL level = FL and twelve for each of the other four SL levels) were performed for the first set of experiments. Observations of the statistics on the three dependent variables were collected in each simulation production run as described in the last subsection. The results of the simulation experiments was then analysed by using the methods presented in Section 6.3.

In this chapter, we have illustrated the development and operation of the simulation model for the first set of experiments. The developed simulation model possessed all the required functions for the experimental system as presented in Chapter 5. Furthermore, we determined several essential parameters for running the simulation model, such as the initial transient period, the numbers of conveyance Kanban-container sets and the simulation run length (replications). In the next chapter, we will present the analyses and discussions of the simulation results for this set of experiments.

CHAPTER 8

ANALYSES AND DISCUSSIONS OF THE SIMULATION RESULTS FOR THE FIRST SET OF EXPERIMENTS

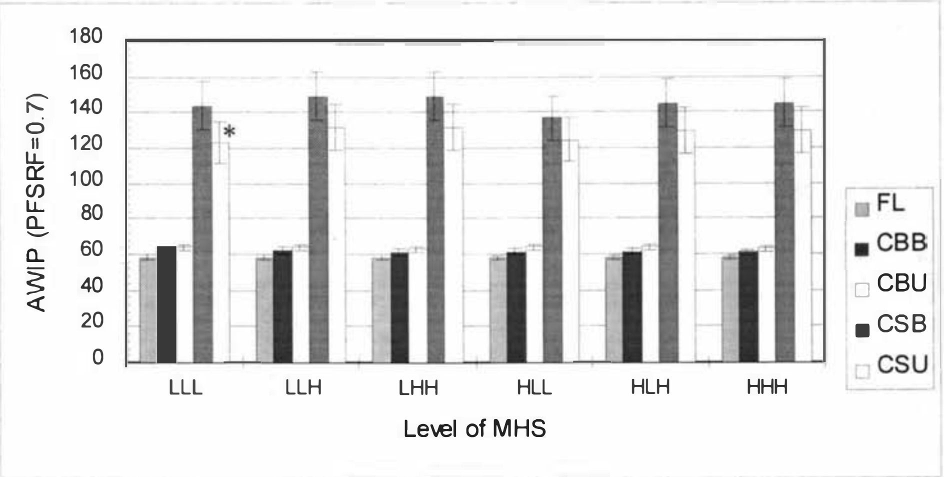
This chapter presents the results and discussions of the simulation output and statistical output analyses for the first set of experiments. As illustrated in Subsection 5.5.1, to have fair comparisons among the shops with different layouts and production flow patterns, the total numbers of parts produced for individual part types (i.e. the demands for individual part types) were the same for all shops investigated at each level of the Part Family Setup Reduction Factor (PFSRF). Therefore, to compare the different shops on the same basis, the results were also presented and discussed for each of the high, medium and low levels of the PFSRF variable separately. However, the influence of the Part Family Setup Reduction Factor still can be examined by comparing the results across the three PFSRF levels.

8.1 Simulation Results and Discussions for the High PFSRF Level

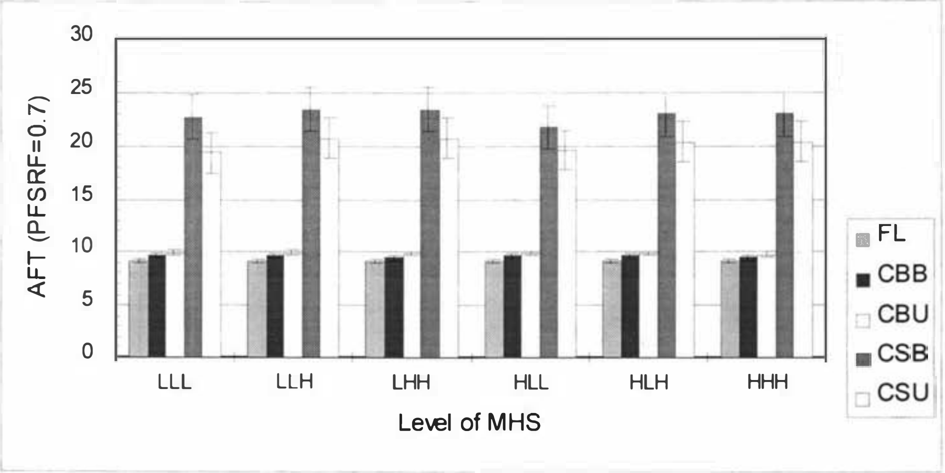
At each of the Part Family Setup Reduction Factor levels, the simulation output was analysed in two ways. First, the graphical method was used. The differences in the performances of individual shops were examined by presenting the simulation output in bar charts. Next, the hypotheses proposed in Section 6.3 were tested, and results and discussions were presented. By using the two analysis methods, the maximum information can be extracted from the simulation output.

8.1.1 Discussions of the simulation output presented in bar charts

The sample mean values on the three dependent variables, average work-in-process inventory (AWIP), average flow time (AFT) and average setup to processing time ratio (ASPTR) from the first set of experiments at the high PFSRF level are presented in Figure 8.1.



* The error lines indicate the 95% confidence intervals for μ.



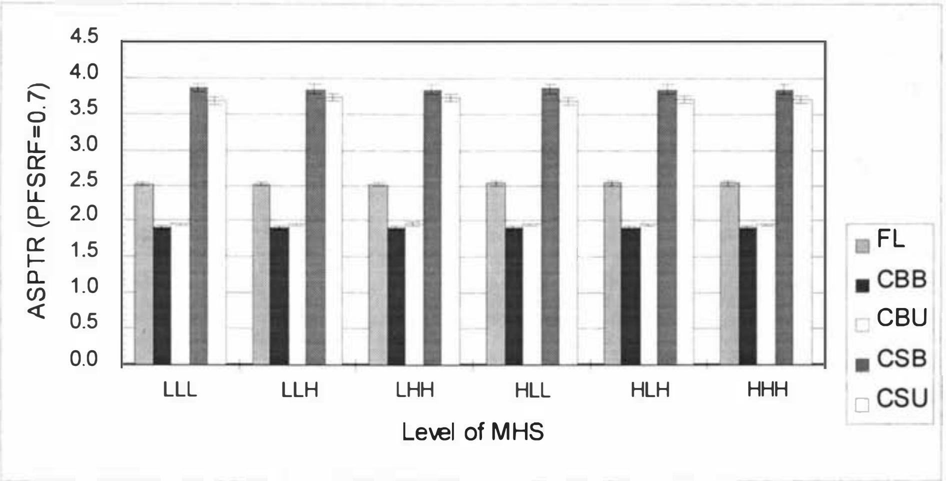


Figure 8.1 Simulation output summary of the first set of experiments at PFSRF level = High

For each dependent variable, the sample mean values in bar charts for the individual levels of the Shop Layout independent variable (i.e. FL, CBB, CBU, CSB and CSU) are presented for each level of the Material Handling Speed (MHS) independent variable. (See Section 6.1 for the definition of the independent variable levels). The error lines on the bar graphs represent the ranges of 95% confidence intervals for the population means of the dependent variables.

Apparently, at this level of the Part Family Setup Reduction Factor, the performances of the cellular layout shops with single-unit production and conveyance (SUPC) (i.e. CSB and CSU shops) were substantially inferior to those of other shops, even if the intra-cell material handling speed was fast (at the LLH, LHH, HLH and HHH levels of MHS). This outcome was contradictory to the long held view of several JIT proponents (Cheng and Podolsky 1993; Monden 1983; Schonberger 1986; Shingo 1989) that SUPC is essential for eliminating delay by lot conveyance and increasing production lead time. It seems that the argument does not always hold true in a job shop environment.

In a repetitive manufacturing environment, where job routings and setup times are more uniform, the benefits of single-unit production and conveyance can be achieved more easily because parts can be routed through workstations one piece by one piece smoothly without build-up of queues between operations. However, in a job shop environment, since routings of jobs are more variable, pieces of parts from different jobs may arrive at the input buffer of a workstation in the same period. Consequently, pieces of parts belonging to the same job may not be processed continuously by a workstation. In other words, delay times will be introduced between the operations of a part.

We will give an example here to explain the delay between the operations of a part. For the cellular layout with backtracking flow allowed, both part types 1 and 10 were processed by cell 2. The sequences of machine types required for processing part types 1 and 10 are 1-4-8-9 and 4-7-4-8, respectively. We assume that a batch (lot) of part type 1 is being processed by machine type 1. Now one piece of part type 1 is completed on machine type 1 and moved immediately to machine type 4 for another operation. At this time, a batch of part type 10 arrives and it is queued in front of machine type 4 since the operation on the piece of part type 1 is going on. If the operation on the piece of part type 1 on machine 4 is completed before the next piece of part type 1 comes, machine type 4 will now be setup for processing the batch of part type 10 since it is the first in the queue. Once machine type 4 starts processing the batch of part type 10, it will not be switched to processing other part types until the whole batch is completed. Therefore, if a piece of part type 1 arrives at machine type 4 when the batch of part type 10 is being processed, it has to wait until the completion of the batch of part type 10. As a result, a period of time delay (while waiting for the completion of the batch of part type 10) will be incurred between this piece and the previous piece of part type 1. Similarly the same situation may happen for machine type 8 since it is required by both part types 1 and 10.

This finding about the delay between operations for job shop manufacturing is consistent with that reported by Kelleher (1986), who claimed that to attain the benefits of single-unit production and conveyance, there is a need to keep the operations balanced (synchronised) to avoid queues between operations.

Less synchronised operations led to two major drawbacks. First because machine setups happened more often to switch the production between different part types (e.g. part types 1 and 10 in the above example), the time spent for setting up machines (or average setup to processing time ratio) became higher. Consequently, the benefit of setup time reduction brought about by cellular manufacturing was offset by the higher setup time. Second, the advantage of eliminating the delay caused by lot conveyance (See Section 1.2) by adopting single-unit production and conveyance was also offset by the delay between operations. Eventually, the potential of single-unit production and conveyance in reducing flow time might not be realised.

With the high PFSRF level, the effect of unsynchronisation between operations was more severe because parts had to spend longer times waiting for machine setups and thus pieces of parts from different jobs were more likely to be queued in front of workstations. Furthermore, because workstations / cells are closely linked to each other through Kanban signals in a Kanban-based system, any fluctuation in part of the system can be easily transmitted (and even amplified) to the entire system (Kimura and Terada 1981, Villeda *et al.* 1988). Therefore, the highly unsynchronised operations caused by single-unit production and conveyance rendered the Kanban-controlled job shop unstable and eventually led to its poor performance.

Figure 8.1 shows that the influence of material handling speed on the individual performances of the cellular layout shops with single-unit production and conveyance (i.e. CSB and CSU) were not significant. Though it seemed that average work-in-process inventory or average flow time was lower at some material handling speed levels for the two shops, we are not confident of these differences since there were always overlaps for their 95% confidence intervals of means at different MHS levels.

For the cellular layout shops with single-unit production and conveyance, the shop with unidirectional flow (i.e. the CSU shop) had lower average setup to processing time ratio than that with backtracking flow allowed (i.e. the CSB shop) at all the MHS levels. The unidirectional flow seemed to be effective in alleviating the adverse effect of unsynchronised operations. However, the differences in the AWIP and AFT performances of the CSB and CSU shops were not as significant as for their ASPTR because there were always overlaps among the 95% confidence intervals of their AWIP and AFT.

As shown in Figure 8.1, the cellular layout shops with batch production and conveyance (i.e. the CBB and CBU shops) had significantly lower average setup to processing time ratios than those of the functional layout (FL) shop. The superior performance of the CBB and CBU shops on ASPTR, however, did not result in better performance on average work-in-process inventory and average flow time. This finding will further discussed in the next subsection

No significant effect of material handling speed on the individual performances of the FL, CBB and CBU shops can be identified.

8.1.2 Discussions of the results of overall *F*-tests and planned comparisons

The bar charts given in Figure 8.1 were most useful for identifying the differences in the performances of individual shops over the different Material Handling Speed levels (e.g. We can easily see that the mean values on AWIP for the CSU shop are lower at the LLL and HLL levels of MHS). However, the use of bar charts in comparing the performances of different shops, particularly for the comparison between groups of shops (e.g. comparing the functional layout shop with all the cellular layout shops), was limited.

Overall *F*-tests and planned comparisons were more powerful for comparing the performances between different shops. The differences in the performances among different shops could be identified more precisely with a specific level of significance. In addition, planned comparisons were particularly useful for comparing groups of shops.

Table 8.1 shows the sample means, sample variances and 95% confidence intervals of population means for average work-in-process inventory at the high level of the Part Family Setup Reduction Factor. Apparently, the performances of the cellular layout shops with single-unit production and conveyance (i.e. CSB and CSU shops) were highly variable (i.e. with very large variances) and very inferior to those of other shops (The output summary of the all three dependent variables are given in Tables A8.1-3 of Appendix 8).

The *F* values calculated with such large differences in variances will be significantly biased although the *F*-test is robust to the assumption of equality of variances. Furthermore, although the *approximate F test* used for the planned comparisons is able to take into account unequal variances, many degrees of freedom will be lost and the power of tests will be much lower with greatly different variances. Hence, we decided that data for the cellular layout with single-unit production and conveyance (i.e. CSB and CSU) were not to be included in the overall *F*-test and planned comparisons.

Table 8.1 Simulation output summary on AWIP for the first set of experiments at the high PFSRF level

Dependent variable	MHS level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average work-in-process inventory (AWIP)	LLL	FL	22	58.38 ± 1.28	8.35
		CBB	22	61.98 ± 2.01	20.50
		CBU	22	63.92 ± 1.99	20.20
		CSB	22	143.84 ± 13.99	995.08
		CSU	22	123.50 ± 12.03	736.20
	LLH	FL	22	58.38 ± 1.28	8.35
		CBB	22	61.98 ± 2.01	20.50
		CBU	22	63.92 ± 1.99	20.20
		CSB	22	149.18 ± 14.97	1140.28
		CSU	22	132.28 ± 13.27	895.94
	LHH	FL	22	58.38 ± 1.28	8.35
		CBB	22	60.74 ± 2.11	22.54
		CBU	22	62.88 ± 1.77	15.99
		CSB	22	149.18 ± 14.97	1140.28
		CSU	22	132.28 ± 13.27	895.94
	HLL	FL	22	58.11 ± 1.36	9.39
		CBB	22	61.60 ± 2.10	22.33
		CBU	22	63.81 ± 1.77	15.98
		CSB	22	136.92 ± 10.14	523.04
		CSU	22	124.68 ± 12.54	799.44
	HLH	FL	22	58.11 ± 1.36	9.39
		CBB	22	61.60 ± 2.10	22.33
		CBU	22	63.81 ± 1.77	15.98
		CSB	22	145.09 ± 12.79	832.44
		CSU	22	129.72 ± 11.91	721.61
	HHH	FL	22	58.11 ± 1.36	9.39
		CBB	22	60.63 ± 1.96	19.49
		CBU	22	62.73 ± 1.89	18.24
		CSB	22	145.09 ± 12.79	832.44
		CSU	22	129.72 ± 11.91	721.61

Since the data for CSB and CSU shops were not included in the planned comparisons, the two null hypotheses:

$H_0(1b)$: $\mu_{CSB} = \mu_{CSU}$ and

$H_0(2)$: $\mu_{CBB} + \mu_{CBU} = \mu_{CSB} + \mu_{CSU}$

were not tested. $H_0(3)$ was then reduced to

$H_0(3)$: $\mu_{FL} = 1/2(\mu_{CBB} + \mu_{CBU})$.

Significant overall differences among the levels of Shop Layout were detected via the overall F-tests on all dependent variables for all MHS levels at a significance level of 0.002 or lower (See Table A9.1 of Appendix 9). Table 8.2 summarises the results of the planned comparisons (Refer to Table A10.1-3 of Appendix 10 for details). The results of the hypothesis tests are discussed individually as follows.

Table 8.2 Results of planned comparisons for the first set of experiments at the high PFSRF level

Dependent variable	MHS level	$H_0(1a)$	$H_0(3)$
AWIP	LLL	CBB=CBU	FL<(CBB+CBU)/2
	LLH	CBB=CBU	FL<(CBB+CBU)/2
	LHH	CBB=CBU	FL<(CBB+CBU)/2
	HLL	CBB=CBU	FL<(CBB+CBU)/2
	HLH	CBB=CBU	FL<(CBB+CBU)/2
	HHH	CBB=CBU	FL<(CBB+CBU)/2
AFT	LLL	CBB=CBU	FL<(CBB+CBU)/2
	LLH	CBB=CBU	FL<(CBB+CBU)/2
	LHH	CBB<CBU	FL<(CBB+CBU)/2
	HLL	CBB<CBU	FL<(CBB+CBU)/2
	HLH	CBB<CBU	FL<(CBB+CBU)/2
	HHH	CBB<CBU	FL<(CBB+CBU)/2
ASPTR	LLL	CBB=CBU	FL>(CBB+CBU)/2
	LLH	CBB=CBU	FL>(CBB+CBU)/2
	LHH	CBB<CBU	FL>(CBB+CBU)/2
	HLL	CBB<CBU	FL>(CBB+CBU)/2
	HLH	CBB<CBU	FL>(CBB+CBU)/2
	HHH	CBB<CBU	FL>(CBB+CBU)/2

Note: For all significant differences, $p \leq 0.05$.

(a) Comparison between the two cellular layout shops with batch production and conveyance [by testing $H_0(1a)$]

Between the cellular layout shops with batch production and conveyance (BPC), the shop with backtracking flow allowed (i.e. CBB shop) and the shop with unidirectional flow (i.e. CBU shop) performed equally in terms of average work-in-process inventory. But the CBB shop was superior to the CBU shop on the other two dependent variables when the intra-cell batch flow or inter-cell part movement speed was at the high setting. The findings show that more efficient intra-cell material handling did make the shop with backtracking flow allowed superior to the shop with unidirectional flow for the cellular layout with batch production and conveyance at the high PFSRF level.

On the other hand, since the CBU shop had been designed to achieve intra-cell unidirectional flow by creating inter-cell flows wherever necessary, it seems that more efficient inter-cell material handling should make the CBU shop perform better. However, with high PFSRF, even though parts were transported quickly from preceding cells to succeeding cells, they still had to spend a lot of time waiting for machine setups because of the higher setup times. Consequently, jobs were more likely to be congested at succeeding workstations with a high inter-cell material handling speed setting. This effect resulted in higher average setup to processing time ratio, which in turn led to higher average flow time.

(b) Comparison between the functional layout and the cellular layouts [by testing $H_0(3)$]

The comparison between the functional layout (i.e. FL) and the cellular layouts (i.e. CBB and CBU) through $H_0(3)$ shows that the shops with cellular layout consistently demonstrated lower average setup to processing time ratio than that of the shop with functional layout. This outcome is expected since the cellular layout was designed to capitalise on the similarities among the operational sequences of parts produced to achieve setup time reduction. However, despite their superior performance on ASPTR, the performance of the cellular layout shops on AWIP and AFT was inferior to that of the functional layout shop.

Flynn and Jacobs (1987) reported that though cellular manufacturing is effective in reducing setup times, a certain degree of inflexibility is also caused by dedicating machines in a cell to the production of a specific family of parts. In the functional layout, when a job arrives at a department with interchangeable machines of the same type, it can be processed on any machine that is available. However, in the cellular layout, a machine is only permitted to process parts of the family assigned to it. The consequence of the inflexibility of cellular layout is that machines tend to be less utilised (Morris and Tersine 1990) and build-up of queues is likely to happen. When the Part Family Setup Reduction Factor was high, the effect of inflexible use of machines was prominent for the cellular layout and led to poor queue-related performance, such as average work-in-process inventory. Eventually, the benefit of reduced setup times brought about by cellular manufacturing was more than offset by its poor AWIP performance at the high PFSRF level. Unavoidably, inferior performance on average work-in-process inventory, in turn, led to the inferior performance of average flow time.

The findings in this section show that functional layout should be more suitable for a job shop environment with Kanbans when the extent of setup time reduction achievable through cellular manufacturing is small (i.e. at the high level of the Part Family Setup Reduction Factor).

It is useful to note that the (statistically) significant differences identified by the planned comparisons seem not so important (in practice) on the bar charts in Figure 8.1. Those small differences could be identified statistically because the degrees of freedom for the planned comparisons were large enough.

Though statistical significance may not be scientifically important, it does provide important guidelines for industrial applications. For example, in Subsection 8.1.2, the results of planned comparisons show that the functional layout (FL) was superior to the cellular layouts (CBB and CBU) though the differences were not very important on the bar charts. Knowing this finding, engineers who are designing Kanban systems in job shop environments may want to conduct further experiments (with real or simulated systems), which incorporate the actual shop conditions and configurations, to assess the differences among these layouts.

In addition, it is not likely that the conditions in real manufacturing shops are as well controlled as those in simulated shop environments. If the similar experiments are performed in real shop environments, the dependent variables may be affected not only by the levels of the independent variables, but also by other uncontrolled factors. Therefore, differences that may not appear to be practically important in simulation experiments may turn out to be important in real shop environments. Besides, for a well managed shop where production goes smoothly, sometimes even small amounts of improvement are critical for remaining competitive in the market.

The results and analyses of the simulation output for the medium level of the Part Family Setup Reduction Factor will be discussed in the next section.

8.2 Simulation Results and Discussions for the Medium PFSRF Level

The discussions in this section are also in two parts. First, bar charts are used to examine the differences in the performances of individual shops. Next, the results from the overall *F*-tests and planned comparisons are presented and discussed.

8.2.1 Discussions of the simulation output presented in bar charts

Figure 8.2 shows the sample means and the 95% confidence intervals of population means for the dependent variables at the medium level of PFSRF. Again, material handling speed did not have any significant effect on the individual performances of the various layouts. However, one significant change at this level of the Part Family Setup Reduction Factor is that between the two cellular layout shops with single-unit production and conveyance (i.e. CSU and CSB shops), the CSU shop outperformed the CSB shop on all dependent variables. We are confident of the differences since there is no overlap between their 95% confidence intervals of population means.

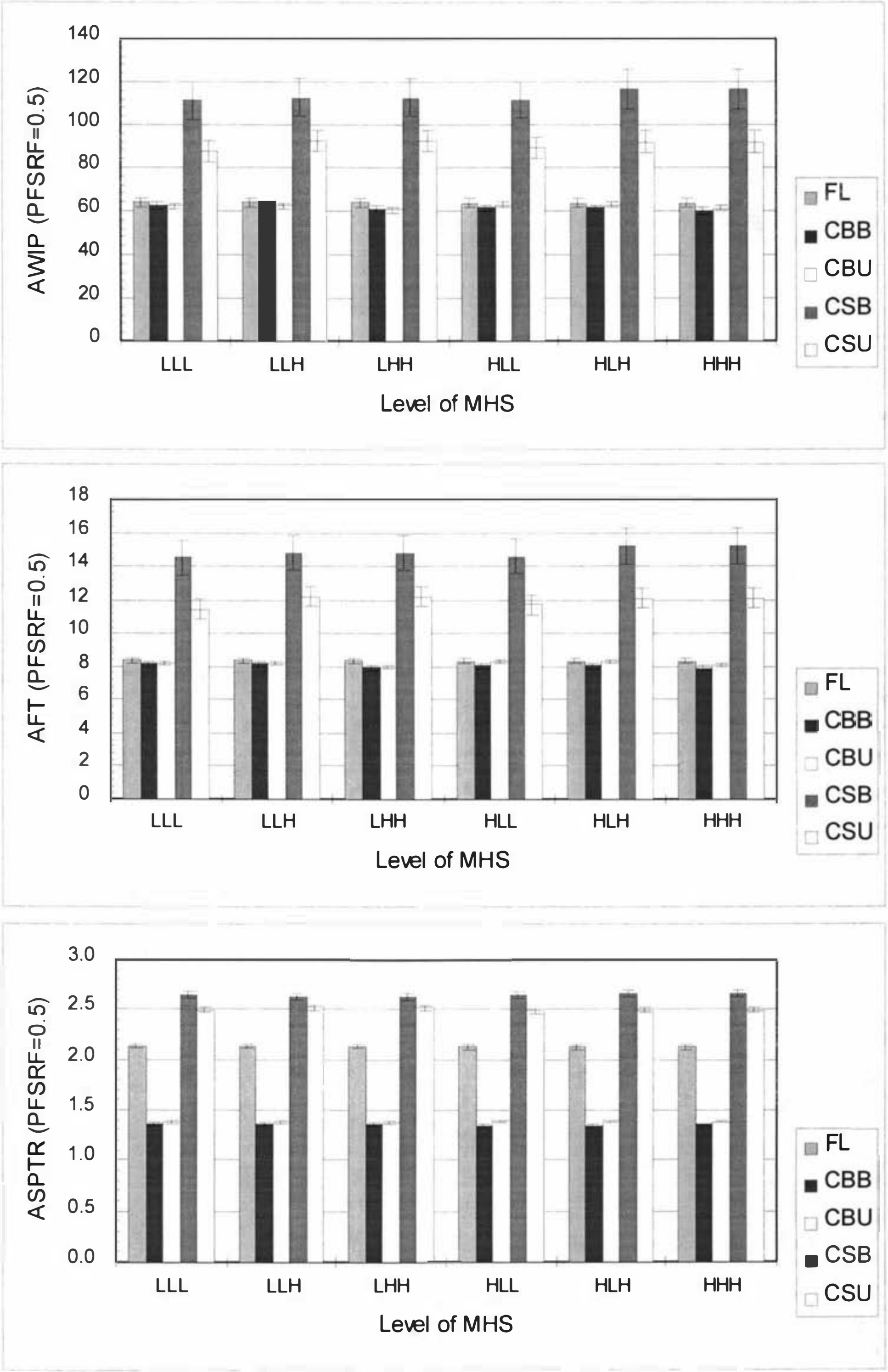


Figure 8.2 Simulation output summary of the first set of experiments at PFSRF level = Medium

This finding supports the discussion in the previous section and shows that the cellular layout shop with single-unit production and conveyance was more susceptible to the degree of synchronisation of production flow than other shops. When parts flowed in the same forward direction in a cell, production flows tended to be smoother and more synchronised than with backtracking flow allowed. Therefore, unidirectional flow was effective in alleviating the adverse effect of unsynchronised operations on the shop performance caused by single-unit production and conveyance.

8.2.2 Discussions of the results of overall *F*-tests and planned comparisons

Overall *F*-tests and planned comparisons were performed to identify the differences in shop performances caused by the different levels of the Shop Layout variable. Table 8.3 shows the sample means, sample variances and 95% confidence intervals of population means for average work-in-process inventory at the medium level of the Part Family Setup Reduction Factor. For the cellular layout shops with single-unit production and conveyance, the sample variances of the shop with unidirectional flow (i.e. the CSU shop) were relatively much smaller than at the high level of PFSRF, but the sample variances of the shop with backtracking flow allowed (i.e. the CSB shop) were still large. For the same reason as stated in Subsection 8.1.2, the data for the CSB shop were not included in the overall *F*-tests and planned comparisons to provide more power for the hypothesis tests (The output summary of the all three dependent variables are given in Tables A8.4-6 of Appendix 8).

Therefore, $H_0(1b)$ was not tested because the data for the CSB shop were not included. $H_0(2)$ was then reduced to:

$$H_0(2)\text{: } 1/2(\mu_{CBB} + \mu_{CBU}) = \mu_{CSU}.$$

If $H_0(2)$ was true, no difference could be identified among the performances of cellular layout shops, and $H_0(3)$ would be reduced to

$$H_0(3)\text{: } \mu_{FL} = 1/3(\mu_{CBB} + \mu_{CBU} + \mu_{CSU}).$$

Table 8.3 Simulation output summary on AWIP for the first set of experiments at the medium PFSRF level

Dependent variable	MHS level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average work-in-process inventory (AWIP)	LLL	FL	22	63.90 ± 1.97	19.69
		CBB	22	62.23 ± 1.56	12.42
		CBU	22	62.14 ± 1.31	8.76
		CSB	22	111.28 ± 8.07	315.80
		CSU	22	87.20 ± 4.30	94.12
	LLH	FL	22	63.90 ± 1.97	19.69
		CBB	22	62.23 ± 1.56	12.42
		CBU	22	62.14 ± 1.31	8.76
		CSB	22	112.17 ± 8.27	347.87
		CSU	22	92.46 ± 5.40	148.06
	LHH	FL	22	63.90 ± 1.97	19.69
		CBB	22	60.67 ± 1.68	14.33
		CBU	22	60.71 ± 1.40	9.93
		CSB	22	112.77 ± 8.27	347.87
		CSU	22	92.46 ± 5.40	148.06
	HLL	FL	22	63.62 ± 1.74	15.42
		CBB	22	61.30 ± 1.55	12.17
		CBU	22	62.81 ± 1.38	9.72
		CSB	22	111.53 ± 8.06	330.68
		CSU	22	88.98 ± 4.42	99.43
	HLH	FL	22	63.62 ± 1.74	15.42
		CBB	22	61.30 ± 1.55	12.17
		CBU	22	62.81 ± 1.38	9.72
		CSB	22	116.46 ± 9.91	499.11
		CSU	22	91.89 ± 5.72	166.57
	HHH	FL	22	63.62 ± 1.74	15.42
		CBB	22	60.20 ± 1.65	13.90
		CBU	22	61.22 ± 1.39	9.82
		CSB	22	116.46 ± 9.91	499.11
		CSU	22	91.89 ± 5.72	166.57

If $H_0(2)$ was rejected, the functional layout would be compared with the cellular layout(s) with superior performance. Therefore, $H_0(3)$ would be reduced to

$$H_0(3)\text{: } \mu_{FL} = 1/2(\mu_{CBB} + \mu_{CBU})$$

if the cellular layout shops with batch production and conveyance (i.e. the CBB and CBU shops) were found to be superior, or be reduced to

$$H_0(3)\text{: } \mu_{FL} = \mu_{CSU}$$

if the cellular layout shop with single-unit production and conveyance (i.e. the CSU shop only) was found to be superior.

The overall differences among the levels of the Shop Layout variable on all dependent variables were found to be significant by the overall *F*-tests for all MHS levels at significance levels lower than 0.001 (Refer to Table A9.2 of Appendix 9 for details). The results of planned comparisons are presented in Table 8.4 (Refer to Tables A10.4-6 of Appendix 10 for details). The results of the hypothesis tests are discussed individually below.

(a) Comparison between the two cellular layout shops with batch production and conveyance [by testing $H_0(1a)$]

The results of the comparison between the cellular layout shops with batch production and conveyance show almost the same patterns as for the high PFSRF level. The only differences between the results for the high and medium levels of PFSRF occurred for AFT at the LHH and HHH levels of MHS and for ASPTR at the LHH level of MHS. For the cellular layout shops with batch production and conveyance, the high intra-cell material handling speed slightly improved the relative performance of the shop with unidirectional flow (i.e. the CBU shop) and rendered its average flow time and average setup to processing time ratio similar to those of the shop with backtracking flow allowed (i.e. the CBB shop).

(b) Comparison between the cellular layouts with BPC and the cellular layout with SUPC [by testing $H_0(2)$]

The comparison between the cellular layouts with batch production and conveyance (BPC) and the cellular layout with single-unit production and conveyance (SUPC) shows that the cellular layout shops with BPC still outperformed the cellular layout shop with SUPC on all dependent variables. The medium level of the Part Family Setup Reduction Factor was still not sufficient to ease the disadvantage of unsynchronised operations caused by single-unit production and conveyance and to justify its use in a Kanban-controlled job shop.

Table 8.4 Results of planned comparisons for the first set of experiments at the medium PFSRF level

Dependent variable	MHS level	$H_0(1a)$	$H_0(2)$	$H_0(3)$
AWIP	LLL	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2=FL
	LLH	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2=FL
	LHH	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
	HLL	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2=FL
	HLH	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2=FL
	HHH	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
AFT	LLL	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
	LLH	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
	LHH	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
	HLL	CBB<CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
	HLH	CBB<CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
	HHH	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
ASPTR	LLL	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
	LLH	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
	LHH	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
	HLL	CBB<CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
	HLH	CBB<CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
	HHH	CBB<CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL

Note: For all significant differences, $p \leq 0.05$.

(c) Comparison between the functional layout and the cellular layouts [by testing $H_0(3)$]

Drastic changes were identified by comparing the functional layout with the cellular layouts. The cellular layout shops outperformed the functional layout shop on both average flow time and the average setup to processing time ratio. But for average work-in-process inventory, this was true only at LHH and HHH levels of the Material Handling Speed variable (i.e. with the high setting of intra-cell material handling speed).

Obviously, at the medium level of the Part Family Setup Reduction Factor, the potential of cellular manufacturing in setup time reduction was able to greatly overcome its disadvantage of inflexible use of machines and caused the performance of the cellular layout shops to be superior at most MHS levels. However, the queue-related performance of the cellular layout shop, such as average work-in-process inventory, was vulnerable to intra-cell material handling speed. With the low intra-cell material handling speed, the performance of the cellular layout shops on average work-in-process inventory was slightly degraded and similar to that of the functional layout shop.

In summary, with medium extent of setup time reduction achievable through cellular manufacturing (i.e. at the medium level of the PFSRF), the cellular layout with batch production and conveyance should be used for a job shop environment with Kanban-based production control. However, to achieve better shop performance, material handling equipment with higher speed should be adopted for intra-cell part movement. In addition, as long as the intra-cell material handling speed is high, the intra-cell production flow pattern (i.e. unidirectional flow or backtracking flow allowed) does not have significant effect on the shop performance. The results and analyses of the simulation output for the low level of the Part Family Setup Reduction Factor will be discussed in the next section.

8.3 Simulation Results and Discussions for the Low PFSRF Level

The same as for the high and medium levels of the Part Family Setup Reduction Factor (PFSRF), the discussions for the results and analyses of the simulation output are presented in two subsections. The bar charts of sample means with 95% confidence intervals for the population means on the dependent variables will be discussed first.

Then, the discussions of the results from overall *F*-tests and planned comparisons will be presented.

8.3.1 Discussion of the simulation output presented in bar charts

Figure 8.3 shows the sample means and the 95% confidence intervals of population means for the three dependent variables at the low Part Family Setup Reduction Factor level. Apparently, the performance of all cellular layout shops (i.e. CBB, CBU, CSB and CSU shops) were superior to that of the functional layout (FL) shop on all dependent variables for all levels of the Material Handling Speed (MHS). This difference is significant as there was no overlaps between the 95% confidence intervals of population means for the functional layout shop and the cellular layout shops.

As discussed in Subsection 8.1.2, the inflexibility caused by the dedication of machines in a cell to the processing of a part family led to the inferior performance on average work-in-process inventory for the cellular layout shops at the high PFSRF level. However, at the medium level of the Part Family Setup Reduction Factor, the performance of the cellular layout shops was much improved because the lower PFSRF level resulted in shorter machine setup times (or average setup to processing time ratio), which lessened the effect of inflexible use of machines for the cellular layouts.

Figure 8.3 shows that the low level of the Part Family Setup Reduction Factor resulted in a further decrease in the average setup to processing time ratio (ASPTR) for the cellular layouts. Because of the superior performance in ASPTR for the cellular layouts, the amount of parts waiting for available machines was smaller, and the effect of inflexible use of machines for the cellular layouts was much less than that at the high and medium PFSRF levels. Eventually, the performance of all the cellular layout shops in average work-in-process inventory (AWIP) was much improved, and superior AWIP performance in turn led to superior performance in average flow time.

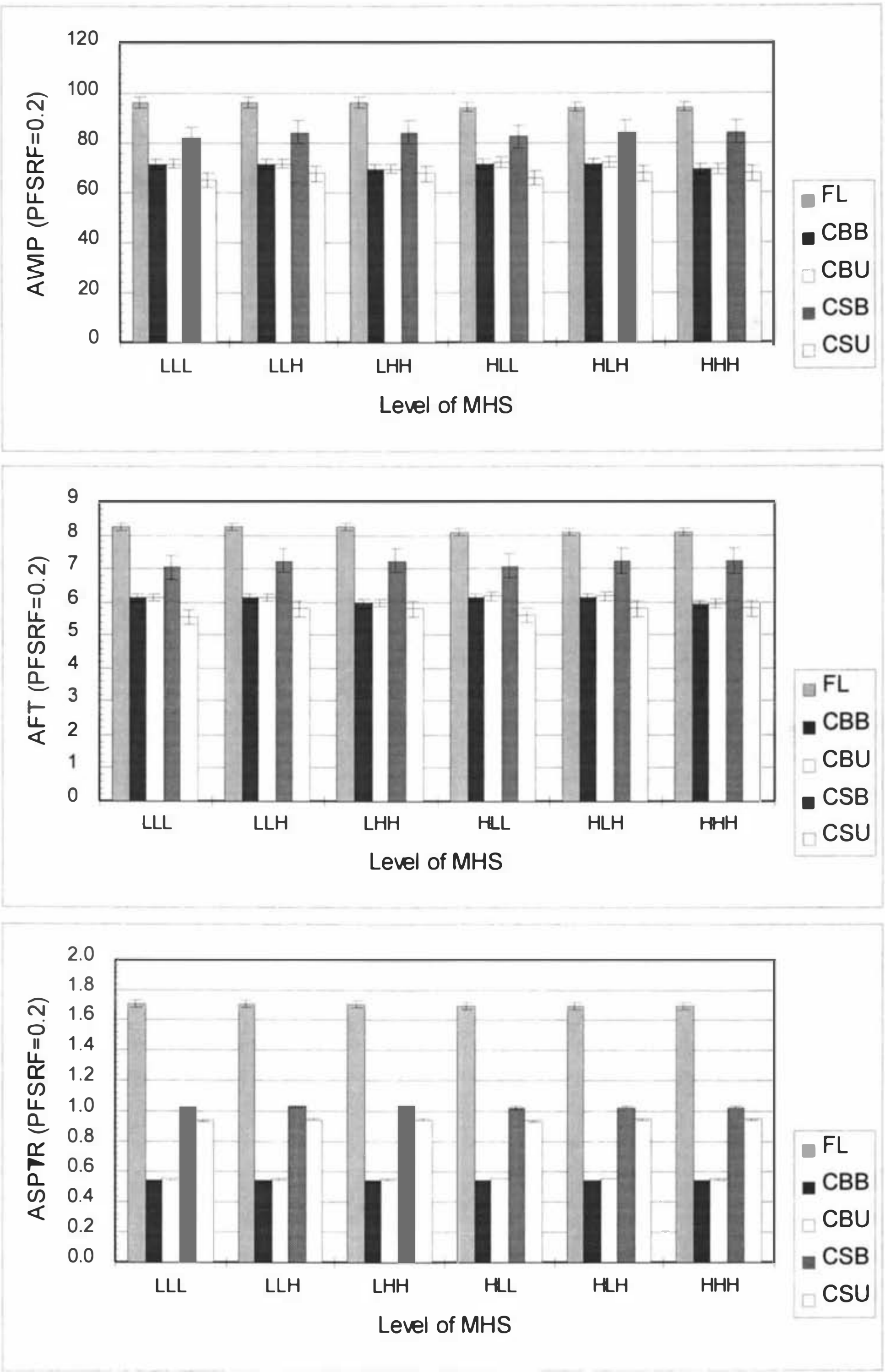


Figure 8.3 Simulation output summary of the first set of experiments at PFSRF level = Low

The more synchronised operations brought about by unidirectional flow were even more effective in realising the advantage of single-unit production and conveyance (SUPC) at the low level of PFSRF. As shown in Figure 8.3, for the cellular layout shops with SUPC, the shop with unidirectional flow (i.e. the CSU shop) outperformed the shop with backtracking flow allowed (i.e. the CSB shop) at all levels of the Material Handling Speed. Furthermore, the CSU shop also outperformed the cellular layout shops with batch production and conveyance (i.e. the CBB and CBU shops) when the intra-cell material handling speed was low (i.e. at the LLL and HLL levels of MHS). This was because the extent of decrease in AFT and AWIP brought by unidirectional flow was relatively more significant when the intra-cell material handling speed was low.

8.3.2 Discussions of the results of overall *F*-tests and planned comparisons

To identify the differences in the relative shop performances, overall *F*-tests and planned comparisons were performed. Table 8.5 summarises the simulation output on average work-in-process inventory at the low level of the Part Family Setup Reduction Factor. Since all the variances were in reasonable ranges, the data for all shops were included in the overall *F*-tests and planned comparisons (The output summary of the all three dependent variables are given in Tables A8.7-9 of Appendix 8). The original hypotheses as proposed in Subsection 6.3.2 were tested without any modification.

All *F*-tests on overall differences among the levels of the Shop Layout were significant at significance levels lower than 0.001 (Refer to Table A9.3 of Appendix 9 for details). The results of the planned comparisons by testing the proposed hypotheses will be discussed individually below (Refer to Tables A10.7-9 of Appendix 10 for details).

(a) Comparison between the two cellular layout shops with batch production and conveyance [by testing $H_0(1a)$]

Table 8.6 summarises the results of the planned comparisons among the cellular layouts. The results from testing the hypothesis $H_0(1a)$ show quite different patterns from those for the high and medium levels of PFSRF. As shown in Table 8.6, for the two shops with cellular layout and batch production and conveyance (i.e. the CBB and CBU shops), the shop with backtracking flow allowed (i.e. the CBB shop) exhibited lower average setup to processing time ratios at all levels of the Material Handling Speed.

Table 8.5 Simulation output summary on AWIP for the first set of experiments at the low PFSRF level

Dependent variable	MHS level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average work-in-process inventory (AWIP)	LLL	FL	22	96.44 ± 1.98	19.96
		CBB	22	71.48 ± 1.90	18.45
		CBU	22	71.77 ± 2.02	20.82
		CSB	22	82.16 ± 4.29	93.67
		CSU	22	64.99 ± 2.68	36.45
	LLH	FL	22	96.44 ± 1.98	19.96
		CBB	22	71.48 ± 1.90	18.45
		CBU	22	71.77 ± 2.02	20.82
		CSB	22	84.58 ± 4.48	102.01
		CSU	22	67.64 ± 3.34	56.80
	LHH	FL	22	96.44 ± 1.98	19.96
		CBB	22	69.52 ± 1.96	19.52
		CBU	22	69.62 ± 2.01	20.46
		CSB	22	84.58 ± 4.48	102.01
		CSU	22	67.64 ± 3.34	56.80
	HLL	FL	22	94.57 ± 1.84	17.27
		CBB	22	71.53 ± 1.86	17.67
		CBU	22	72.09 ± 2.15	23.55
		CSB	22	82.65 ± 4.69	111.69
		CSU	22	65.70 ± 3.08	48.38
	HLH	FL	22	94.57 ± 1.84	17.27
		CBB	22	71.53 ± 1.86	17.67
		CBU	22	72.09 ± 2.15	23.55
		CSB	22	84.42 ± 4.78	116.28
		CSU	22	67.63 ± 3.25	53.60
	HHH	FL	22	94.57 ± 1.84	17.27
		CBB	22	69.27 ± 1.75	15.57
		CBU	22	69.48 ± 2.06	21.52
		CSB	22	84.42 ± 4.78	116.28
		CSU	22	67.63 ± 3.25	53.60

However, at the low level of the Part Family Setup Reduction Factor, the disadvantage of less smooth and synchronised production flows brought about by intra-cell backtracking flow tended to be more significant than that at the high and medium levels of PFSRF. As a result, CBB and CBU shops performed equally on average work-in-process inventory and average flow time because CBB shop's superior performance on the average setup to processing time ratio was offset by the unfavourable effect of its backtracking flow.

Table 8.6 Results of planned comparisons among cellular layouts for the first set of experiments at the low PFSRF level

Dependent variable	MHS level	H_0(1a)	H_0(1b)	H_0(2)
AWIP	LLL	CBB=CBU	CSU<CSB	CBB+CBU=CSB+CSU
	LLH	CBB=CBU	CSU<CSB	CBB+CBU<CSB+CSU
	LHH	CBB=CBU	CSU<CSB	CBB+CBU<CSB+CSU
	HLL	CBB=CBU	CSU<CSB	CBB+CBU=CSB+CSU
	HLH	CBB=CBU	CSU<CSB	CBB+CBU<CSB+CSU
	HHH	CBB=CBU	CSU<CSB	CBB+CBU<CSB+CSU
AFT	LLL	CBB=CBU	CSU<CSB	CBB+CBU=CSB+CSU
	LLH	CBB=CBU	CSU<CSB	CBB+CBU<CSB+CSU
	LHH	CBB=CBU	CSU<CSB	CBB+CBU<CSB+CSU
	HLL	CBB=CBU	CSU<CSB	CBB+CBU=CSB+CSU
	HLH	CBB=CBU	CSU<CSB	CBB+CBU<CSB+CSU
	HHH	CBB=CBU	CSU<CSB	CBB+CBU<CSB+CSU
ASPTR	LLL	CBB<CBU	CSU<CSB	CBB+CBU<CSB+CSU
	LLH	CBB<CBU	CSU<CSB	CBB+CBU<CSB+CSU
	LHH	CBB<CBU	CSU<CSB	CBB+CBU<CSB+CSU
	HLL	CBB<CBU	CSU<CSB	CBB+CBU<CSB+CSU
	HLH	CBB<CBU	CSU<CSB	CBB+CBU<CSB+CSU
	HHH	CBB<CBU	CSU<CSB	CBB+CBU<CSB+CSU

Note: For all significant differences, $p \leq 0.05$.

(b) Comparison between the two cellular layout shops with single-unit production and conveyance [by testing $H_0(1b)$]

As shown in Table 8.6, the results of testing $H_0(1b)$ show that for the cellular layout shops with single-unit production and conveyance (i.e. the CSU and CSB shops), the shop with unidirectional flow (i.e. the CSU shop) always outperformed the shop with backtracking flow (i.e. the CSB shop). This result from testing $H_0(1b)$ coincides with the finding illustrated in Subsection 8.3.1 that the effectiveness of unidirectional flow in realising the advantage of single-unit production and conveyance became more prominent at the low level of PFSRF.

(c) Comparison between the cellular layouts with BPC and the cellular layouts with SUPC [by testing $H_0(2)$]

As indicated by the results of testing $H_0(2)$ in Table 8.6, among the shops with cellular layout, the shops with batch production and conveyance (BPC) (i.e. the CBB and CBU shops) outperformed the shops with single-unit production and conveyance (the CSB and CSU shops) on the average setup to processing time ratio for all levels of the Material Handling Speed. As discussed in Subsection 8.1.2, to realise the benefits of setup time reduction through cellular manufacturing, it is essential to overcome the poor performance in AWIP brought about by inflexible use of machines for the cellular layout. Since the average number of parts waiting for machine setups was smaller with a lower average setup to processing time ratio, the effect of inflexible use of machines was less significant for the cellular layout shops with BPC. Therefore, the cellular layout shops with BPC exhibited superior performance on average work-in-process inventory and in turn, average flow time at most of the Material Handling Speed levels.

However, as shown in Table 8.6, when the intra-cell material handling speed was low (i.e. at the LLL and HLL levels of the Material Handling Speed) the cellular layout shops with batch production and conveyance and the cellular layout shops with single-unit production and conveyance had similar performance on AWIP and AFT. As discussed in Subsection 8.3.1, this was because the extent of decrease in AFT and AWIP brought by unidirectional flow was relatively more significant when the intra-cell material handling speed was low.

(d) Comparison between the functional layout and the cellular layouts [by testing $H_0(3)$]

The results of the planned comparison between the cellular layouts and the functional layout are presented in Table 8.7. The cellular layout was found to be superior to the functional layout on all dependent variables. This finding coincided with that presented in Subsection 8.3.1 by examining Figure 8.3.

The shops with cellular layout were able to demonstrate superior performance because the disadvantage of dedicating the machines in a cell to the processing of a family of parts was less significant at the low level of the Part Family Setup Reduction Factor. Therefore, the potential of cellular manufacturing in achieving lower average work-in-process inventory and average flow time through larger extent of setup time reduction was fully exploited.

The findings in this section show that when the extent of setup time reduction achievable through cellular manufacturing is large (i.e. at the low level of the PFSRF), cellular layout should be adopted for a job shop environment with Kanban-based production control. Furthermore, the cellular layout with SUPC and unidirectional intra-cell production flow should be adopted when the intra-cell material handling speed is low; otherwise, the cellular layout with batch production and conveyance is more suitable.

The results and analyses of the simulation output for the first set of experiments have been discussed in this Chapter. The factors such as the shop layout, production flow patterns and the part family setup reduction factor were found to have substantial effects on both the individual and relative performances of the various shops investigated. The effect of material handling speed, however, was mainly on the relative performances among the different shops rather than on their individual performances.

Table 8.7 Results of planned comparisons between the cellular and functional layouts for the first set of experiments at the low PFSRF level

Dependent variable	MHS level	$H_0(3)$
AWIP	LLL	(CBB+CBU+CSB+CSU)/4<FL
	LLH	(CBB+CBU)/2<FL
	LHH	(CBB+CBU)/2<FL
	HLL	(CBB+CBU+CSB+CSU)/4<FL
	HLH	(CBB+CBU)/2<FL
	HHH	(CBB+CBU)/2<FL
AFT	LLL	(CBB+CBU+CSB+CSU)/4<FL
	LLH	(CBB+CBU)/2<FL
	LHH	(CBB+CBU)/2<FL
	HLL	(CBB+CBU+CSB+CSU)/4<FL
	HLH	(CBB+CBU)/2<FL
	HHH	(CBB+CBU)/2<FL
ASPTR	LLL	(CBB+CBU)/2<FL
	LLH	(CBB+CBU)/2<FL
	LHH	(CBB+CBU)/2<FL
	HLL	(CBB+CBU)/2<FL
	HLH	(CBB+CBU)/2<FL
	HHH	(CBB+CBU)/2<FL

Note: For all significant differences, $p \leq 0.05$.

Following the first set of experiments, a second set of experiments was performed to investigate the influence of the variability of processing and setup times on the performance of a Kanban-controlled job shop. The design of the second set of experiments will be illustrated in Chapter 9. The results and analyses of the simulation output for the second set of experiments will be discussed in Chapter 10.

CHAPTER 9

DESIGN AND EXECUTION OF THE SECOND SET OF EXPERIMENTS - FOR INVESTIGATING THE EFFECTS OF THE VARIABILITY OF SETUP AND PROCESSING TIMES

The effects of four influential factors: shop layout, production flow patterns, material handling speed and the part family setup reduction factor on the performance of a Kanban-controlled job shop have been investigated in the first set of experiments. The variability (or coefficients of variation) of setup and processing times was fixed throughout the experiments. By investigating the results from the first set of experiments we found that the synchronisation (balance) of operations had a significant effect on the performance of the cellular layout shop with single-unit production and conveyance (See Subsection 8.1.1). In addition, the influence of the variability of processing time on a Kanban-based system had been emphasised by both Philipoom *et al.* (1987) and Villeda *et al.* (1988).

Because operations tend to be less synchronised when setup and processing times are more variable, the effect of changing the coefficients of variation (CVs) of setup and processing times on the performance of a Kanban-controlled job shop may be important. To gain more understanding of this subject, the second set of experiments was thus carried out to examine the behaviour of the shop at different levels of the CVs for setup and processing times.

This chapter covers six parts, namely:

(1) design of the experimental system,
(2) selection of the independent variables and their levels to be investigated,
(3) selection of the dependent variables to be measured,
(4) settings of material handling speed,
(5) selection of the appropriate statistical analyses of the simulation output, and
(6) development and operation of the simulation model.

They will be illustrated individually in the following sections.

9.1 Design of the Experimental System

The experimental system design for the second set of experiments was the same as for the first set of experiments (See Chapter 5.), except that the coefficients of variation (or the shape parameter, α) of setup and processing times were no longer constant for the second set of experiments. The CV values of setup and processing times were varied in the second set of experiments to examine their influence on the shop performance. In the second set of experiments, the material handling speed was treated as a background variable instead of an independent variable. Details regarding the settings of the variables are given in the following sections.

9.2 Selection of the Independent Variables and Their Levels to be Investigated

In the second set of experiments, the influential factors which may affect the shop performance in a job shop environment with Kanban-based production control were represented by the three independent variables, Shop Layout (SL), the Part Family Setup Reduction Factor (PFSRF) and the Coefficient of Variation (CV).

The definitions of the SL and PFSRF variables were the same as for the first set of experiments (Please refer to Section 6.1). The CV variable is defined as

$$CV = \sigma / \mu \qquad (9.1)$$

where σ and μ are, respectively, the standard deviation and mean of the distribution (i.e. gamma distribution) for setup and processing times. For the gamma distribution with a shape parameter, α and a scale parameter, β, the CV can be expressed as

$$CV = \sigma / \mu = (\sqrt{\alpha}\,\beta) / (\alpha\beta) = \frac{1}{\sqrt{\alpha}} \qquad (9.2)$$

Thus the coefficient of variation for the gamma distribution can be set by simply changing the α value. In this set of experiments, both setup and processing time CVs had high, medium and low settings. The values of the three CV settings for setup and processing times are summarised in Table 9.1.

Table 9.1 Values for the setup and processing time CV settings

CV Setting	CV value for	
	Setup time	Processing time
High	1.06 (α = 0.89)	0.87 (α = 1.33)
Medium	0.71 (α = 2.00)	0.58 (α = 3.00)
Low	0.47 (α = 4.50)	0.38 (α = 6.75)

Note: α is the shape factor of the gamma distribution for the corresponding CV value.

The levels investigated for the three independent variables are summarised in Table 9.2. The levels for the Shop Layout and Part Family Setup Reduction Factor were the same as for the first set of experiments.

For the Coefficient of Variation, each of the three (high, medium and low) setup time CV settings was investigated with each of the three processing time CV settings. However, in a well managed job shop, the level of processing time variability is not likely to be higher than that of the setup time variability (Mahmoodi *et al.* 1990). Therefore, the CV levels at which processing time CV settings are higher than setup time CV settings (i.e. the MH, LH and LM levels of CV) were not investigated. In total, six levels of the Coefficient of Variation variable were investigated. Thus, the second set of experiments was based on the 5 × 3 × 6 full factorial design, with five, three and six levels for the SL, PFSRF and CV independent variables, respectively.

Table 9.2 Summary of the independent variables for the second set of experiments

Independent variable	Levels	Descriptions	
Shop Layout (SL)	FL	Functional layout	
	CBB	Cellular layout with BPC and backtrackin flow allowed	
	CBU	Cellular layout with BPC and unidirectiona flow	
	CSB	Cellular layout with SUPC an backtracking flow allowed	
	CSU	Cellular layout with SUPC an unidirectional flow	
Part Family Setup Reduction Factor (PFSRF)	High	PFSRF = 0.7	
	Medium	PFSRF = 0.5	
	Low	PFSRF = 0.2	
		CV settings for	
		Setup time	Processing time
Coefficient of Variation (CV)	HH	high	high
	HM	high	medium
	HL	high	low
	MM	medium	medium
	ML	medium	low
	LL	low	low

9.3 Selection of the Dependent Variables to be Measured

The same dependent variables as for the first set of experiments were used in this set of experiments as the measures of the shop performance (Please refer to Section 6.2). The three dependent variables were summarised in Table 9.3.

Table 9.3 Summary of the dependent variables for the second set of experiments

Dependent variable	Descriptions
Average work-in-process inventory (AWIP)	Total number of parts in the system, averaged over the observation time period.
Average flow time (AFT)	The amount of time spent by a part from entering the system until the completion of all operations, averaged over all completed parts during the observation time period.
Average setup to processing time ratio (ASPTR)	Ratio of total amount of time spent for setting up machines to total amount of time spent for processing parts, averaged over all machines in the observation time period.

9.4 Settings of the Material Handling Speed

In the second set of experiments, the material handling speed was treated as a background variable, which potentially could affect the dependent variables in the experiments but was not of interest as a independent variable. Since the dependent variables were affected by the background variables as well as the independent variables, the setting of the background variable was controlled in the experiments so that the effect of the independent variables was not distorted.

Therefore, in the second set of experiments, all material handling speeds except those for backtracking flow were set at their high settings, unless the results of the planned comparisons in the first set of experiments showed that low material handling speed settings led to better performance for some layouts. In this way, we could be sure that more efficient material handling facilities were used for all shops so that the performances of different shops could be compared on a equal basis, and the bias caused by different material handling speed settings was minimised.

For example, from Table 8.2, we knew that at the high PFSRF level, the CBU shop exhibited better performance on average flow time and average setup to processing time ratio when both inter-cell and intra-cell material handling speeds were at low settings. Therefore, the low settings of both inter-cell and intra-cell material handling speeds were used for the CBU shop when running the simulation. The settings of the material handling speeds for the various levels of the Shop Layout and Part Family Setup Reduction Factor independent variables are summarised in Table 9.4.

Table 9.4 Settings of Material handling speeds for the second set of experiments

PFSRF level	SL level				
	FL	CBB	CBU	CSB	CSU
0.7	high, —	high, high	low, low	high, high	high, high
0.5	high, —	high, low	low, high	high, high	high, high
0.2	high, —	high, high	high, high	high, low	high, low

Note: For each entry, the first setting is for inter-cell (department) material handling and the second, for intra-cell material handling.

The same design of the high and low settings for the material handling speed as for the first set of experiments was used in this set of experiments. Tables 9.5 gives the material handling speed settings for inter-cell / department part movement. Tables 9.6 and 9.7 show the material handling speed settings for intra-cell part movement with batch production and conveyance, and single-unit production and conveyance, respectively.

9.5 Selection of the Appropriate Statistical Analyses of the Simulation Output

Similar to the experimental design for the first set of experiments, the overall *F*-test and planned comparison were employed for analysing the results of the experiments.

Table 9.5 Material handling speed settings for inter-cell / department part movement

Material handling speed settings	Equipment type	Travelling speed	Loading & unloading time
High	Fork lift truck	4 mph, constant	Uniformly distributed with Upper limit: 14 min/lot Lower limit: 10 min/lot
Low	Four-wheel hand truck	0.8 mph, constant	Uniformly distributed with Upper limit: 14 min/lot Lower limit: 10 min/lot

Table 9.6 Material handling speed settings for intra-cell part movement with batch production and conveyance

Material handling speed settings	Equipment type	Travelling speed	Loading & unloading time
High	Live roller conveyor	6 mph, constant	Uniformly distributed with Upper limit: 1.2 min/lot Lower limit: 0.8 min/lot
Low	Two-wheel hand truck	1.2 mph, constant	Uniformly distributed with Upper limit: 3.6 min/lot Lower limit: 2.4 min/lot

Table 9.7 Material handling speed settings for intra-cell part movement with single-unit production and conveyance

Material handling speed settings	Equipment type	Travelling speed	Loading & unloading time
High	Live roller conveyor	6 mph, constant	Uniformly distributed with Upper limit: 1.2 min/part Lower limit: 0.8 min/part
Low	Manual handling by workers	1.2 mph, constant	Uniformly distributed with Upper limit: 22 sec/part Lower limit: 14 sec/part

9.5.1 Statistical output analyses by the *F*-test

The overall *F*-test was used to detect whether there was any differences in the shop performances attributed to the different levels of the Shop Layout variable. A One-way analysis of variance (ANOVA) was carried out for each of the three dependent variables at each of level of the PFSRF and CV variables. Therefore in total 3×3×6 = 54 ANOVAs were performed to achieve the results of the overall *F*-tests.

9.5.2 Statistical output analyses by the planned comparison

As illustrated in Subsection 6.3.2, because overall *F*-tests by ANOVAs did not tell where the differences came from if there was any, Lindman's planned comparison was used to pinpoint the causes of differences by answering the research questions put forward in Chapter 4. Research questions 1 and 2 were the same as those addressed by the first set of experiments (See Subsection 6.3.2). They are as follows:

Research question 1: Do shop layout and part flow patterns have any influence on the performance of a Kanban-controlled job shop? This question is addressed through the following four sub-questions.

> Sub-question 1.1: For the cellular layout shops with batch production and conveyance (BPC), is there any difference in performance between the shop with backtracking flow allowed and the shop with unidirectional flow ?
>
> Sub-question 1.2: Similar to Sub-question 1.1, but for the cellular layout shops with single-unit production and conveyance (SUPC).
>
> Sub-question 1.3: Among the shops with cellular layouts, are those with BPC different from those with SUPC in their performance ?
>
> Sub-question 1.4: Is there any difference between functional layout and cellular layout in terms of shop performance ?

Research question 2: How does the extent of setup time reduction through cellular manufacturing affect the performances of the shops with the various layouts and flow patterns ?

Research question 3 had been addressed by the first set of experiments. For the second set of experiments, we addressed another research question, namely,

Research question 4: To what extent do the coefficients of variation (CVs) of machine setup times and part processing times influence the performances of the shops with the various layouts and flow patterns ?

To answer Research question 1 (or Sub-questions 1.1 through 1.4), the same hypotheses expressed by equations (6.1) through (6.6) in Subsection 6.3.2 were tested for each dependent variable at each level of the Coefficient of Variation and Part Family Setup Reduction Factor independent variables. Research questions 2 and 4 were answered by comparing the results of planned comparisons across the different levels of the PFSRF and CV variables, respectively. The same formulas for the *Approximate F*-test as illustrated in Subsection 6.3.2 were used for testing the proposed hypotheses.

9.6 Development and Operation of the Simulation Model

The same simulation model coded in the SIMSRIPT II.5 simulation language as illustrated in Section 7.2 was used for the second set of experiments.

In order to observe whether the initial transient period used for the first set of experiments was sufficient for the higher CV values used in this set of experiments, preliminary simulation runs were performed for the CSB shop with the high level of PFSRF and HH level of CV (i.e. the worst case). The Welch's graphical procedure, as depicted in Subsection 7.4.1 was followed to study the initial transient periods. The moving average plot for average work-in-process inventory presented in Figure 9.1 shows that the initial transient period of 48 periods (5760 hours) used for the first set of experiments was sufficient for this set of experiments. The moving average plots for all the dependent variables are given in Appendix 11.

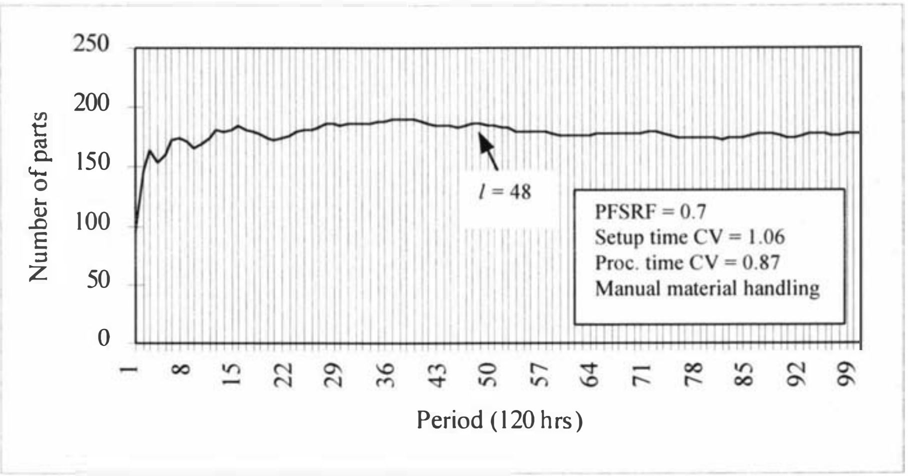


Figure 9.1 Moving average plot for average work-in-process inventory (Cellular layout with SUPC and backtracking flow allowed)

As described in Subsection 7.4.3, the revised blocking method was employed to obtain independent observations of the statistics on the dependent variables, and the method of batch means was utilised to obtain the estimations of sample variances, sample means and the confidence intervals of population means for the dependent variables. The same numbers of Kanbans and containers as determined in Subsection 7.4.2 were used for the second set of experiments.

CHAPTER 10

ANALYSES AND DISCUSSIONS OF THE SIMULATION RESULTS FOR THE SECOND SET OF EXPERIMENTS

The results and discussions of the simulation output and statistical output analyses for the second set of experiments are presented in this chapter. As explained at the beginning of Chapter 8, to compare the different shops on the same basis, the results were presented and discussed for each of the high, medium and low levels of the Part Family Setup Reduction Factor separately. The influence of the Part Family Setup Reduction Factor itself was examined by comparing the results across the three PFSRF levels.

10.1 Simulation Results and Discussions for the High PFSRF Level

As presented in Chapter 8, the simulation output was analysed in two ways for each of the part family setup reduction factor levels. First, the graphical method was used. The differences in the performances of individual shops were examined by presenting the simulation output in bar charts. Next, the hypotheses proposed in Section 9.5 were tested, and results and discussions were presented. By using the two analysis methods, the maximum amount of information could be extracted from the simulation output.

10.1.1 Discussions of the simulation output presented in bar charts

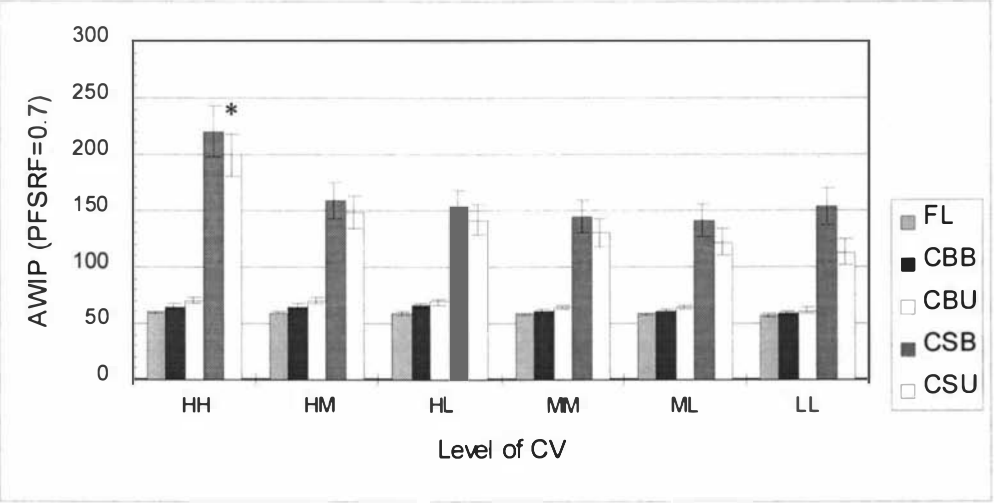
The sample mean values on the three dependent variables, average work-in-process inventory (AWIP), average flow time (AFT) and the average setup to processing time ratio (ASPTR) from the second set of experiments at the high PFSRF level are presented in Figure 10.1.

As shown in Figure 10.1, the performances of the cellular layout shops with single-unit production and conveyance (SUPC) (i.e. the CSB and CSU shops) were greatly inferior to those of other shops.

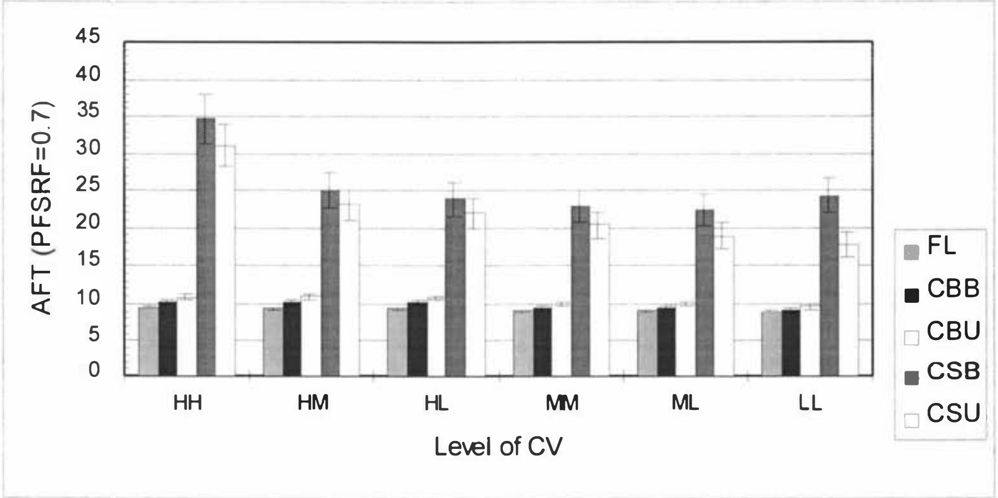
The influence of the Coefficient of Variation (CV) for processing times was dominant for the cellular layout shops with single-unit production and conveyance. When the CV level changed from HH to HM (Note the second letter indicates the processing time CV setting), the performances of the CSB and CSU shops on all dependent variables were greatly improved. These changes were significant since there was no overlap between the 95% confidence intervals. However, the influence of the processing time CV was lessened when the setup time CV setting was medium or low (i.e. at the MM, ML and LL levels of CV). The average work-in-process inventory and average flow time for the cellular layout shop with SUPC and unidirectional flow (i.e. the CSU shop) were further improved as the Coefficient of Variation reached the LL level.

The effect of the CV of setup times on the performances of the cellular layout shops with single-unit production and conveyance was not as important as that of processing times. For example, by comparing the bar graphs at the HL and ML levels of CV for the CSU shop, we found that the performances seemed to be improved at the ML level. However, we are not confident about these differences since there were overlaps between the corresponding 95% confidence intervals.

As explained in Subsection 8.1.1, the inferior performance of the cellular layout shops with single-unit production and conveyance at the high PFSRF level was mainly due to prominent effect of less synchronised operations caused by SUPC. Since operations tended to be more synchronised with a lower processing time CV, decreasing the processing time CV was therefore more effective in improving the performance of the cellular layout shops with single-unit production and conveyance. However, reducing the coefficient of variation of processing times was not sufficient to make the performances of the CSB and CSU shops superior to those of other shops (i.e. the FL, CBB and CBU shops).



* The error lines indicate the 95% confidence intervals for μ.



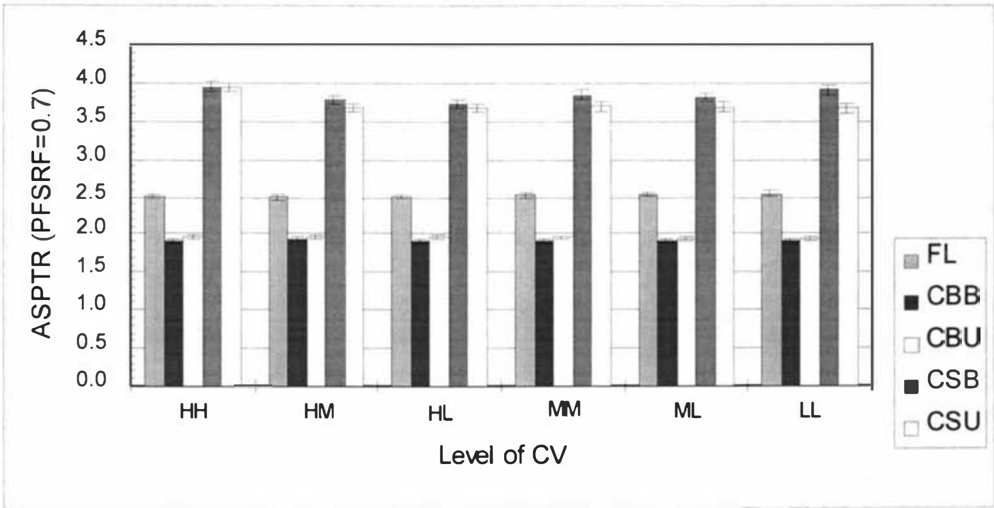


Figure 10.1 Simulation output summary of the second set of experiments at PFSRF level = High

It is interesting to note that when the Coefficient of Variation reached the LL level, the performance of the CSB shop tended to be worse. This finding indicates the importance of unidirectional flow for realising the advantage of reducing setup and/or processing time variability (or coefficient of variation).

In other words, the advantage of reducing setup and/or processing variability can only be realised when parts flow smoothly throughout the cell. In a cellular layout with backtracking flow allowed, although parts flow through a workstation smoothly with low variability in setup and processing times, congestion of part flow in the cell may still happen when they backtrack to another workstation. Eventually, the advantage brought about by the reduction in setup and/or processing time variability was offset by the adverse effect of backtracking flow. As we found in Figure 10.1, the effect of backtracking flow may even be amplified by reducing the CV of setup and/or processing times without reducing the setup times themselves (or the part family setup reduction factor).

Furthermore, for the two cellular layout shops with single-unit production and conveyance, the shop with unidirectional flow (i.e. the CSU shop) tended to outperform the shop with backtracking flow allowed (i.e. the CSB shop). Particularly, at the LL level of the Coefficient of Variation variable, the difference was significant since there was no overlap between their 95% confidence intervals for the dependent variables. Hence, we may conclude that at the high Part Family Setup Reduction Factor level, the more synchronised operations brought about by unidirectional flow was most effective in improving the performance of the cellular layout with single-unit production and conveyance when both setup and processing time CV settings were low. However, with the high PFSRF level, unidirectional intra-cell flow was not sufficient to make the performances of the cellular layout shops with single-unit production and conveyance superior to other shops.

The influence of the Coefficient of Variation on the performances of the remaining shops (i.e. FL, CBB and CBU shops) was dominated by the CV setting of the setup times. When the setup time CV changed from the high to medium setting (i.e. from HM to MM of the CV level), their performances on AWIP and AFT were significantly improved (i.e. no overlap among the individual 95% confidence intervals). Since setup times were longer at the high level of the Part Family Setup Reduction Factor, the performances of those shops were dominated by setup times. It was therefore reasonable that the effect of the setup time CV on their performances was more important.

10.1.2 Discussions of the results of overall *F*-tests and planned comparisons

As mentioned in Subsection 8.1.2, the bar charts given in Figure 10.1 were most useful for examining the differences in the performances of individual shops over the different Coefficient of Variation levels. However, the use of bar charts in comparing the performances of different shops, particularly for the comparison between groups of shops (e.g. comparing the functional layout shop with all the cellular layout shops), was limited.

Overall *F*-tests and planned comparisons were more powerful for comparing the performances between different shops than the bar charts. The differences in the performances among different shops could be identified more precisely with specific levels of significance. In addition, planned comparisons were particularly useful for comparing groups of shops.

Table 10.1 shows the sample means, sample variances and 95% confidence intervals of population means for the average work-in-process inventory at the high level of the Part Family Setup Reduction Factor. We can see that the performances of the cellular layout shops with single-unit production and conveyance (i.e. the CSB and CSU shops) were extremely variable (The output summary of the all three dependent variables are given in Tables A12.1-3 of Appendix 12). As explained in Subsection 8.1.2, to avoid the overall *F*-tests being biased by the large variances, and to increase the power of the *Approximate F* test for the planned comparisons, the data for the CSB and CSU were not included in the overall *F*-tests and planned comparisons.

Table 10.1 Simulation output summary on AWIP for the second set of experiments at the high PFSRF level

Dependent variable	CV level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average work-in-process inventory (AWIP)	HH	FL	22	60.08 ± 1.37	9.60
		CBB	22	65.06 ± 2.13	23.17
		CBU	22	70.03 ± 2.85	41.41
		CSB	22	219.88 ± 25.08	3199.01
		CSU	22	199.27 ± 21.63	2380.31
	HM	FL	22	59.63 ± 1.45	10.63
		CBB	22	64.92 ± 1.96	19.45
		CBU	22	70.33 ± 2.74	38.25
		CSB	22	159.37 ± 13.94	989.08
		CSU	22	147.66 ± 12.91	847.39
	HL	FL	22	59.43 ± 1.56	12.36
		CBB	22	65.66 ± 2.64	35.51
		CBU	22	68.86 ± 2.17	24.05
		CSB	22	153.11 ± 13.60	940.64
		CSU	22	141.37 ± 16.08	1315.51
	MM	FL	22	58.11 ± 1.36	9.39
		CBB	22	60.63 ± 1.96	19.49
		CBU	22	63.92 ± 1.99	20.20
		CSB	22	145.09 ± 12.79	832.44
		CSU	22	129.72 ± 11.91	721.61
	ML	FL	22	58.09 ± 1.35	9.22
		CBB	22	60.56 ± 1.91	18.46
		CBU	22	63.08 ± 1.76	15.82
		CSB	22	141.62 ± 14.89	1127.75
		CSU	22	121.53 ± 11.83	712.20
	LL	FL	22	57.22 ± 1.29	8.45
		CBB	22	58.28 ± 1.64	13.67
		CBU	22	61.53 ± 1.72	15.08
		CSB	22	153.59 ± 19.04	1843.50
		CSU	22	113.32 ± 10.47	557.69

Since the data for the CSB and CSU shops were not included in the planned comparisons, the two null hypotheses:

$H_0(1b)$: $\mu_{CSB} = \mu_{CSU}$ and

$H_0(2)$: $\mu_{CBB} + \mu_{CBU} = \mu_{CSB} + \mu_{CSU}$

were not tested. $H_0(3)$ was then reduced to

$H_0(3)$: $\mu_{FL} = 1/2(\mu_{CBB} + \mu_{CBU})$

The overall differences among the Shop Layout (SL) levels were found to be significant through the overall *F*-tests at all levels of the Coefficient of Variation variable, with significance levels lower than 0.001 (See Table A13.1 of Appendix 13 for details). The results of the hypothesis tests are discussed individually as follows.

(a) Comparison between the two cellular layout shops with batch production and conveyance [by testing $H_0(1a)$]

The results of the planned comparisons for the high Part Family Setup Reduction Factor level are presented in Table 10.2 (See Table A14.1-3 of Appendix 14 for details).

As indicated by the results of testing $H_0(1a)$, for the cellular layout shops with batch production and conveyance (BPC), the shop with backtracking flow allowed (i.e. the CBB shop) outperformed the shop with unidirectional flow (i.e. the CBU shop) on AWIP and AFT at all but the HL levels of CV. Some differences in average setup to processing time ratio between the CBB and CBU shops were also identified (at HH, HL and MM levels of the Coefficient of Variation). However, no specific pattern could be found to explain these differences. These differences in the performances between the two shops were likely to be attributed to the different material handling speed settings.

The above finding shows that as long as more efficient material handling facilities were employed, backtracking intra-cell flow was more advantageous for improving the performance (on AWIP and AFT) of the cellular layout with batch production and conveyance, at the high PFSRF level.

Recall that the cellular layout with backtracking flow allowed had been designed by keeping inter-cell part movement to a minimum (See Subsection 5.2.1 for details). When parts were transported (in batches) among cells more often (as for the cellular layout with unidirectional flow), parts had more chances to be queued in front of a workstation with other parts not only from other workstations in the cell, but also from other cells. On the other hand, for the cellular layout with backtracking flow allowed, most parts visited only one cell and therefore, the congestion of parts was lessened. Particularly, the advantage of backtracking flow was prominent with the high level of the Part Family Setup Reduction Factor since parts spent more time in waiting for machine setups. Consequently, backtracking flow was effective in reducing the waiting times, and leading to the superior performance of the CBB shop.

Table 10.2 Results of planned comparisons for the second set of experiments at the high PFSRF level

Dependent variable	CV level	$H_0(1a)$	$H_0(3)$
AWIP	HH	CBB<CBU	FL<(CBB+CBU)/2
	HM	CBB<CBU	FL<(CBB+CBU)/2
	HL	CBB=CBU	FL<(CBB+CBU)/2
	MM	CBB<CBU	FL<(CBB+CBU)/2
	ML	CBB<CBU	FL<(CBB+CBU)/2
	LL	CBB<CBU	FL<(CBB+CBU)/2
AFT	HH	CBB<CBU	FL<(CBB+CBU)/2
	HM	CBB<CBU	FL<(CBB+CBU)/2
	HL	CBB<CBU	FL<(CBB+CBU)/2
	MM	CBB<CBU	FL<(CBB+CBU)/2
	ML	CBB<CBU	FL<(CBB+CBU)/2
	LL	CBB<CBU	FL<(CBB+CBU)/2
ASPTR	HH	CBB<CBU	FL>(CBB+CBU)/2
	HM	CBB=CBU	FL>(CBB+CBU)/2
	HL	CBB<CBU	FL>(CBB+CBU)/2
	MM	CBB<CBU	FL>(CBB+CBU)/2
	ML	CBB=CBU	FL>(CBB+CBU)/2
	LL	CBB=CBU	FL>(CBB+CBU)/2

Note: For all significant differences, $p \leq 0.05$.

(b) Comparison between the functional layout and the cellular layouts [by testing $H_0(3)$]

The comparison between the functional layout (i.e. FL) and the cellular layouts (i.e. CBB and CBU) through $H_0(3)$ shows that the average setup to processing time ratios of the cellular layout shops were lower than those of the functional layout for all levels of the Coefficient of Variation variable. This outcome demonstrated that the higher potential of cellular manufacturing in capitalising on the similarities of operation sequences among different part types to achieve setup time reduction was not affected by the setup and processing time CV values. However, despite the superior performance of the cellular layout shops on ASPTR, the functional layout shop outperformed the cellular layout shops on AWIP and AFT for all CV levels.

As illustrated in Subsection 8.1.2, in a cellular layout, a machine was only permitted to process the family of parts assigned to it. Because of the inflexibility in the use of machines, machines tended to be less utilised and build-up of queues was more likely to happen. On the other hand, in the functional layout, when a job arrived at a department with interchangeable machines of the same type, it could be processed on any machine that was available. Consequently, inflexible use of machines rendered the performances of the cellular layout shops on the average work-in-process inventory and the average flow time inferior to those of the functional layout shop.

The findings in both this section and Section 8.1 show that functional layout should be more suitable for a job shop environment with Kanbans when the extent of setup time reduction achievable through cellular manufacturing is small (i.e. at the high level of the Part Family Setup Reduction Factor). The superior performance of the functional layout was found to be robust with respect to the levels of both material handling speed, and setup and processing time CVs.

Note that the (statistically) significant differences identified through the planned comparisons seem not so important (in practice) on the bar charts given in Figure 10.1. As explained in Subsection 8.1.2, the statistically significant differences do provide important guidelines for industrial applications. In addition, differences that may not appear to be practically important in a simulated shop environment may turn out to be important in a real shop environment.

The results and analyses of the simulation output for the medium level of the Part Family Setup Reduction Factor will be discussed in the next section.

10.2 Simulation Results and Discussions for the Medium PFSRF Level

As for the high PFSRF level, the discussions in this section is also divided into two parts. First, bar charts for the sample means and 95% confidence intervals of the three dependent variables are used to examine the differences in the shop performances caused by the different levels of the Coefficient of Variation variable. Then, the results from the overall *F*-test tests and planned comparisons are presented and discussed.

10.2.1 Discussions of the simulation output presented in bar charts

Figure 10.2 shows the sample means and the 95% confidence intervals of population means for the dependent variables at the medium level of the Part Family Setup Reduction Factor.

As found for the high PFSRF level, the influence of changing the Coefficient of Variation level was most important for the cellular layout shops with single-unit production and conveyance (i.e. the CSB and CSU shops). The effect of the changes in the CV level on the performances of the CSB and CSU shops was still dominated by the processing time CV setting (Note the second letter in the CV level represents the processing time CV setting). The effect of the Coefficient of Variation was most substantial as the processing time CV setting changed from high to medium when the setup time CV setting was high (i.e. when the CV level changed from HH to HM).

Furthermore, reducing the variability (or coefficients of variation) of setup and processing times was more effective in improving the performance of the CSU shop.

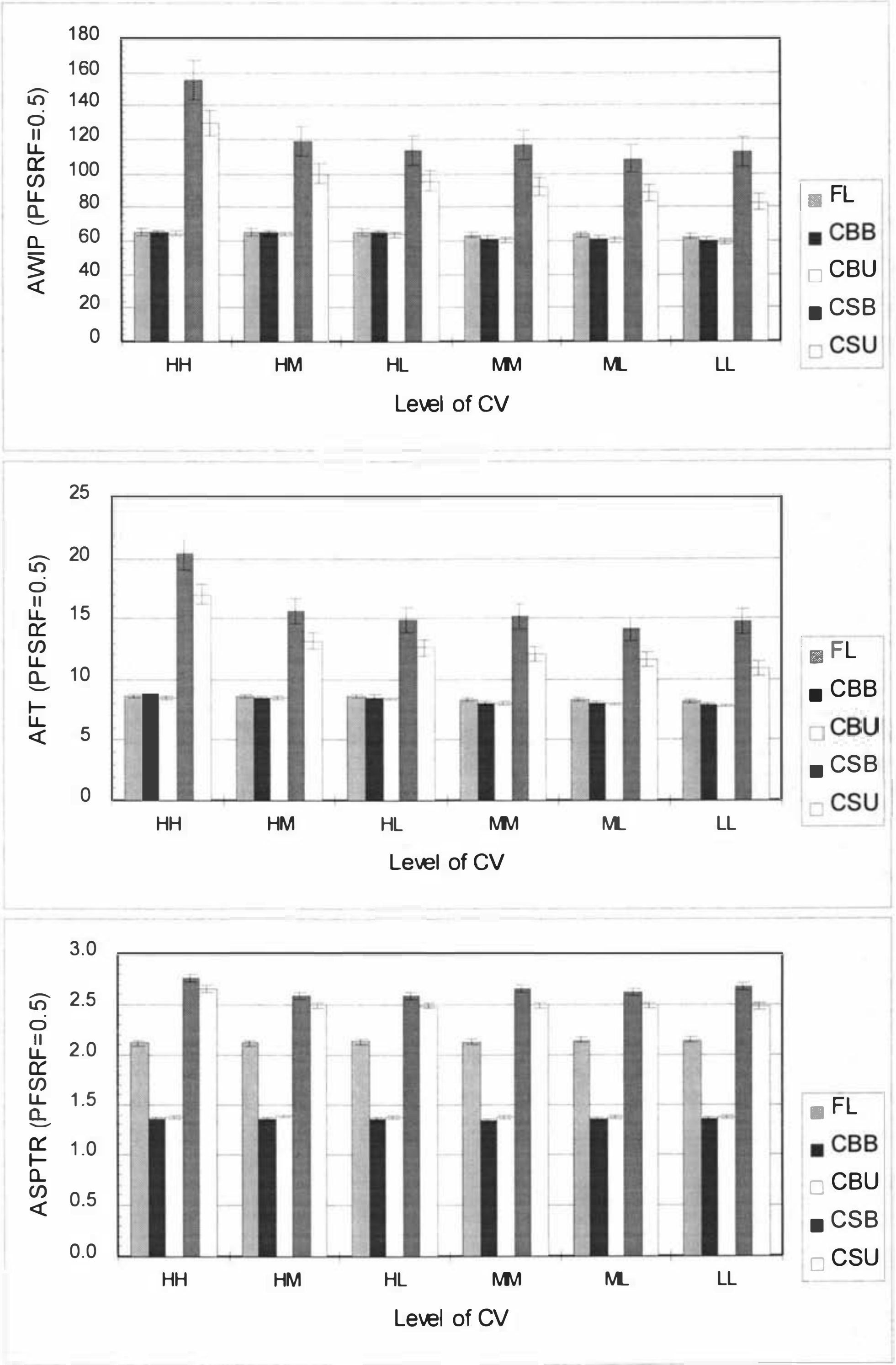


Figure 10.2 Simulation output summary of the second set of experiments at PFSRF level = Medium

As shown in Figure 10.2, when the CV level decreased from HM to LL, the AWIP and AFT performances of the CSU shop were continuously improved while there was no significant change in the performance of the CSB shop. As explained in Subsection 10.1.1, the advantage of reducing setup and processing time variability can only be realised when parts flow smoothly throughout cells for the cellular layout with single-unit production and conveyance. Therefore, unidirectional flow was essential for realising the benefit of reducing setup and processing time variability for the cellular layout with single-unit production and conveyance because production flow tended to be smoother with unidirectional flow.

The same as for the high PFSRF level, the performances of the cellular layout shops with single-unit production and conveyance (i.e. the CSB and CSU shops) were still inferior to those of other shops (i.e. the FL, CBB and CBU shops) on all the three dependent variables. The medium level of the Part Family Setup Reduction Factor was still not sufficient to entirely overcome the disadvantage of less synchronised operations caused by single-unit production and conveyance (Refer to Subsection 8.1.1).

However, some drastic changes in the performances of the cellular layout shops with single-unit production and conveyance were identified at this medium level of Part Family Setup Reduction Factor. As shown in Figure 10.2, between the cellular layout shops with single-unit production and conveyance, the shop with unidirectional flow (i.e. the CSU shop) outperformed the shop with backtracking flow allowed (i.e. the CSB shop) over all CV levels for all three dependent variables. The differences in the performances of the two shops were significant because there was no overlap between their 95% confidence intervals.

This finding about the effectiveness of unidirectional flow in improving the performance of the cellular layout with single-unit production and conveyance coincide with the outcome found in Subsection 8.2.1. When parts flowed in the same forward direction (i.e. with unidirectional flow) in a cell, production flows tended to be smoother and more synchronised than with backtracking flow allowed. Consequently, unidirectional flow was effective in alleviating the disadvantage of less synchronised operations brought about by single-unit production and conveyance (Please refer to Subsection 8.1.1). Since both the first and second sets of experiments resulted in the same finding, we are confident that the effectiveness of unidirectional flow in improving the performance of the cellular layout shop with single-unit production and conveyance was robust with respect to material handling speed and variability (i.e. the coefficient of variation) of setup and processing times.

For the cellular layout shops with batch production and conveyance (i.e. the CBB and CBU shops) and the functional layout (FL) shop, their performances were still dominated by the setting of the setup time coefficient of variation. The average work-in-process inventory and average flow time of the CBB and CBU shops were significantly improved (i.e. no overlap for the 95% confidence intervals) as the setup time CV setting decreased from high to medium (i.e. The CV level changed from HM to MM). However, for the functional layout shop, only the average flow time was improved when the setting of the setup time coefficient of variation changed from high to medium.

As depicted in Subsection 10.1.1, the effect of the setup time CV setting on the performances of the cellular layout shops with batch production and conveyance was more significant because the performances of these shops were still dominated by setup times at the medium PFSRF level.

10.2.2 Discussions of the results of overall *F*-tests and planned comparisons

Overall *F*-tests and planned comparisons were carried out to identify the differences in the shop performances caused by the different levels of the Shop Layout variable. In comparison with bar charts, Overall *F*-tests and planned comparisons were more powerful for comparing the performances between different shops. In addition, planned comparisons were particularly useful for comparing groups of shops.

Table 10.3 shows the sample means, sample variances and 95% confidence intervals of population means for the average work-in-process inventory at the medium level of the

Part Family Setup Reduction Factor (The output summary of all the three dependent variables are given in Tables A12.4-6 of Appendix 12). Obviously, the sample variances for the cellular layout shops with single-unit production and conveyance (i.e. the CSB and CSU shops) at the HH level of CV are substantially large. To avoid biasing the results of the overall *F*-tests and to increase the power of the *Approximate F* tests for the planned comparisons, the data for the CSB and CSU shops at the HH level of CV were excluded from the overall *F*-tests and the planned comparisons.

Table 10.3 Simulation output summary on AWIP for the second set of experiments at the medium PFSRF level

Dependent variable	CV level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average work-in-process inventory (AWIP)	HH	FL	22	65.51 ± 1.92	18.71
		CBB	22	65.04 ± 1.70	14.66
		CBU	22	64.57 ± 1.68	14.36
		CSB	22	155.62 ± 12.35	775.68
		CSU	22	129.57 ± 10.22	530.95
	HM	FL	22	65.55 ± 2.05	21.43
		CBB	22	64.93 ± 2.01	20.54
		CBU	22	64.27 ± 1.57	12.56
		CSB	22	119.06 ± 9.14	424.99
		CSU	22	99.94 ± 5.80	170.89
	HL	FL	22	65.54 ± 2.01	20.64
		CBB	22	65.14 ± 1.98	19.92
		CBU	22	63.93 ± 1.46	10.86
		CSB	22	113.21 ± 6.08	188.32
		CSU	22	95.73 ± 5.36	146.04
	MM	FL	22	63.62 ± 1.74	15.42
		CBB	22	61.30 ± 1.55	12.17
		CBU	22	60.71 ± 1.40	9.93
		CSB	22	116.46 ± 9.91	499.11
		CSU	22	91.89 ± 5.72	166.57
	ML	FL	22	63.82 ± 1.81	16.73
		CBB	22	61.47 ± 1.61	13.13
		CBU	22	60.62 ± 1.30	8.54
		CSB	22	108.31 ± 7.06	253.64
		CSU	22	88.51 ± 4.73	114.03
	LL	FL	22	62.59 ± 1.70	14.70
		CBB	22	60.17 ± 1.39	9.85
		CBU	22	59.22 ± 1.30	8.62
		CSB	22	112.83 ± 9.85	493.84
		CSU	22	82.57 ± 3.29	55.21

Since the data for the CSB and CSU shops at the HH level of the Coefficient of Variation were not included in the planned comparisons, the same hypotheses as proposed in Subsection 10.1.2 for the high PFSRF level were tested:

H_0(1a): $\mu_{CBB} = \mu_{CBU}$, and
H_0(3): $\mu_{FL} = 1/2(\mu_{CBB} + \mu_{CBU})$.

At other levels (the HM, HL, MM, ML and LL levels) of the Coefficient of Variation, because the sample variances for the CSU shop were in acceptable ranges, only the data for the CSB shop were excluded from the overall *F*-tests and planned comparisons.

Because the CSB shop was not included, H_0(1b) was not tested for the planned comparisons. H_0(2) was then reduced to:

H_0(2): $1/2(\mu_{CBB} + \mu_{CBU}) = \mu_{CSU}$.

If H_0(2) was true, no difference could be identified among the performances of cellular layout shops, and H_0(3) would be reduced to

H_0(3): $\mu_{FL} = 1/3(\mu_{CBB} + \mu_{CBU} + \mu_{CSU})$.

If H_0(2) was rejected, the functional layout would be compared with the cellular layout(s) with superior performance. Therefore, H_0(3) would be reduced to

H_0(3): $\mu_{FL} = 1/2(\mu_{CBB} + \mu_{CBU})$

if the cellular layout shops with batch production and conveyance (i.e. the CBB and CBU shops) were found to be superior, or be reduced to

H_0(3): $\mu_{FL} = \mu_{CSU}$

if the cellular layout shop with single-unit production and conveyance (i.e. the CSU shop only) was found to be superior.

Significant differences among the levels of the Shop Layout variable were identified by the overall *F*-tests at significance levels lower than 0.001(See Table A13.2 of Appendix 13.) for all but the HH levels of CV. (Note only three levels of SL were tested at the HH level of CV). The results of planned comparisons were given in Table 10.4 (See Tables A14.4-6 of Appendix 14 for details). The results of the hypothesis tests for the planned comparisons are discussed individually below.

(a) Comparison between the two cellular layout shops with batch production and conveyance [by testing $H_0(1a)$]

For the cellular layout shops with batch production and conveyance (i.e. the CBB and CBU shops), the CBB and CBU shops performed equally in terms of average work-in-process inventory (AWIP) and average flow time (AFT). Differences in the average setup to processing time ratios (ASPTR) between the two shops were detected via the planned comparisons at the HH, HL and MM levels of the Coefficient of Variation (CV). Since no particular pattern can be identified for the differences in ASPTR, it was likely that these differences were due to the differences in material handling speed settings at different SL levels.

As explained in Subsection 10.1.2, backtracking intra-cell flow was more advantageous for the cellular layout shops with batch production and conveyance at the high PFSRF level because it improved the congestion of parts brought about by inter-cell part movement. However, at this medium level of the Part Family Setup Reduction Factor, because of the lower setup times, the congestion of parts brought about by inter-cell part movement was lessened. Therefore, the adverse effects of backtracking flow, such as more jumbled production flow and less efficient material handling (Recall that the material handling speeds for backtracking flow were always at low settings.) became more critical at the medium PFSRF level.

Consequently, the disadvantage of backtracking flow rendered the performance of the CBB shop only similar to that of the CBU shop at the medium PFSRF level, although the CBB shop outperformed the CBU shop for most of the CV levels at the high PFSRF level.

Table 10.4 Results of planned comparisons for the second set of experiments at the medium PFSRF level

Dependent variable	CV level	$H_0(1a)$	$H_0(2)$	$H_0(3)$
AWIP	HH	CBB=CBU	N/A	(CBB+CBU)/2=FL
	HM	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2=FL
	HL	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2=FL
	MM	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
	ML	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
	LL	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
AFT	HH	CBB=CBU	N/A	(CBB+CBU)/2=FL
	HM	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2=FL
	HL	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2=FL
	MM	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
	ML	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
	LL	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
ASPTR	HH	CBB=CBU	N/A	(CBB+CBU)/2<FL
	HM	CBB<CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
	HL	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
	MM	CBB<CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
	ML	CBB<CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL
	LL	CBB=CBU	(CBB+CBU)/2<CSU	(CBB+CBU)/2<FL

Note: For all significant differences, $p \le 0.05$.

(b) Comparison between the cellular layouts with BPC and the cellular layout with SUPC [by testing $H_0(2)$]

The results of testing $H_0(2)$ presented in Table 10.4 show that the cellular layout shops with batch production and conveyance (BPC) (i.e. the CBB and CBU shops) outperformed the cellular layout shop with single-unit production and conveyance (SUPC) (i.e. the CSU shop) on all dependent variables at all levels of CV. The finding is consistent with that illustrated in Subsection 10.2.1 via examining Figure 10.2.

At the medium PFSRF level, the performances of the CSU shop were substantially improved by the more synchronised operations brought about by unidirectional flow. The extent of improvement, however, was not sufficient to entirely overcome the disadvantage of less synchronised operations caused by single-unit production and conveyance. Therefore, as for the high PFSRF level, the performance of the cellular layout shop with single-unit production and conveyance was still inferior to that of the cellular layout shop with batch production and conveyance.

(c) Comparison between the functional layout and the cellular layouts [by testing $H_0(3)$]

The results of testing $H_0(3)$ are presented in Table 10.4. The comparison between the cellular layouts and the functional layout shows that the cellular layout shops (i.e. the CBB and CBU shops) still consistently exhibited lower ASPTR than that of the functional layout, as for the high PFSRF level.

The differences in the performances between the cellular layout shops and the functional layout shop on average work-in-process inventory (AWIP) and average flow time (AFT) were dominated by the setup time CV setting (indicated by the first letter of the CV levels). As shown in Table 10.4, the CBB and CBU shops outperformed the FL shop on AWIP and AFT when the setup time CV setting was medium or low (i.e. at the MM, ML and LL levels of CV). However, they performed equally on AWIP and AFT at the high setting of the setup time CV (i.e. at the HH, HM and HL levels of CV).

The finding from the results of testing $H_0(3)$ supports the results shown in Figure 10.2. As discussed in Subsection 10.2.1, by examining Figure 10.2, we found that the performances of the CBB, CBU and FL shops were dominated by the setup time CV setting as well. However, the cellular layout shops tended to be more susceptible to the changes in the setup time CV because higher setup time CV values were likely to amplify the unfavourable effect of dedicating the machines in a cell to processing a family of parts.(Please refer to Subsection 8.1.2). Therefore, the high setup time CV setting somewhat offset the superior performance on ASPTR of the cellular layout shops, and rendered the AWIP and AFT performances of the cellular layout shops only similar to those of the functional layout shop.

From the first set of experiments (Please refer to Subsection 8.2.2), we found that at the medium level of PFSRF, the cellular layout with batch production and conveyance is more suitable for a job shop environment with Kanbans as long as faster material handling facilities are used for intra-cell part movement. From this set of experiments, however, we found that the conclusion in Subsection 8.2.2 only holds true when the extent of setup time variability is medium to low. In other words, if the variability of setup times is high, both layouts are equally suitable for a job shop environment with Kanbans.

In addition, as long as faster material handling facilities are adopted for intra-cell part movement, the intra-cell production flow pattern (i.e. unidirectional flow or backtracking flow allowed) does not affect the performance of the cellular layout shop with batch production and conveyance. This finding coincides with that in Subsection 8.2.2 for the first set of experiments.

10.3 Simulation Results and Discussions for the low PFSRF Level

Similar to the previous sections, the discussions of results and analyses of the simulation output for the low level of the Part Family Setup Reduction Factor are presented in two subsections. The bar charts of sample means with 95% confidence intervals for the population means on the dependent variables will be discussed first. Then the discussions of the results from overall *F*-tests and planned comparisons will be presented.

10.3.1 Discussion of the simulation output presented in bar charts

The simulation output at the low level of PFSRF is summarised in Figure 10.3. Several dramatic changes in the performances of the various shops are evident.

All cellular layout (i.e. CBB, CBU, CSB and CSU) shops showed much lower average setup to processing time ratios (ASPTR) than that of the functional layout (FL) shop at all levels of the Coefficient of Variation (CV). This indicates that the potential of cellular manufacturing in reducing setup times was most prominent at the low PRSRF level.

Similar to the results for the high and medium levels of PFSRF, the performance of the functional layout shop was still more affected by the setup time CV setting (indicated by the first letter of the CV level). As shown in Figure 10.3, the average work-in-process inventory (AWIP) and average flow time (AFT) of the FL shop were significantly improved (without any overlap between the 95% confidence intervals) when the setup time CV setting was medium or low (i.e. at the MM, ML and LL levels of CV).

For the cellular layout shops with single-unit production and conveyance (SUPC), the performance of the shop with unidirectional flow (i.e. the CSU shop) was affected by not only the processing time CV setting (as found for the high and medium PFSRF levels), but also the setup time CV setting. While the CV level changed from HH to LL, the performance of CSU shop on AWIP and AFT were improved continuously. More importantly, the same as for the medium level of PFSRF, the CSU shop again outperformed the CSB shop significantly without any overlap between their 95% confidence intervals. In addition, at the ML and LL levels of CV, the CSU shop even significantly outperformed the cellular layout shops with batch production and conveyance (i.e. the CBB and CBU shops) on AWIP and AFT.

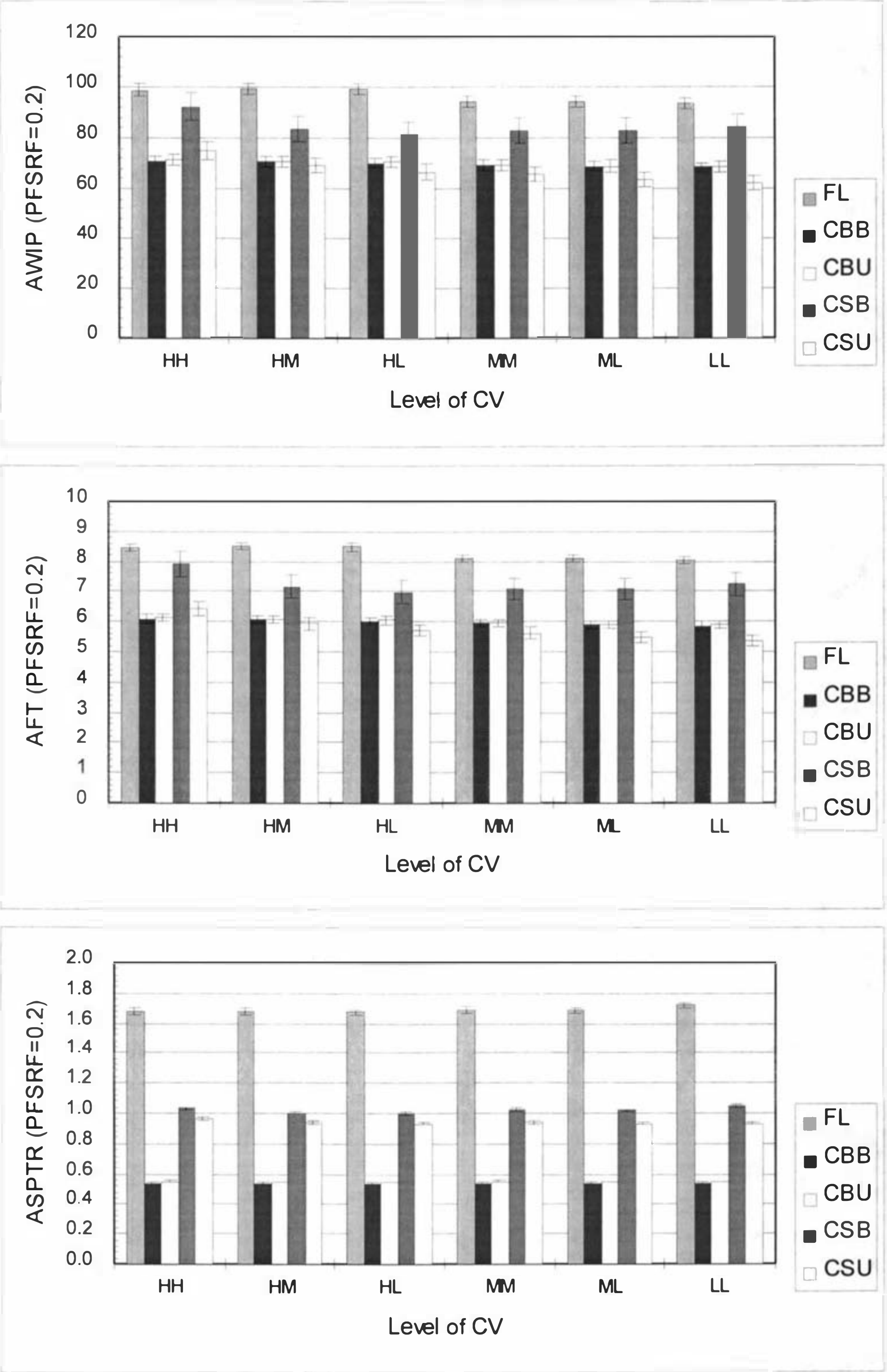


Figure 10.3 Simulation output summary of the second set of experiments at PFSRF level = Low

The importance of unidirectional flow for improving the performance of the cellular layout shop with single-unit production and conveyance (SUPC) had been identified and discussed in Subsections 10.1.1 and 10.2.1 for the high and medium levels of PFSRF, respectively. At the low level of PFSRF, the unfavourable effect of inflexible use of machines for the cellular layout and the disadvantage of less synchronised operations brought about by SUPC were substantially improved because of the lower setup times. Therefore the potential of unidirectional flow in realising the benefits of single-unit production and conveyance became more prominent at the low level of PFSRF.

From the first set of experiments, we also found that the CSU shop outperformed the CSB shop at all levels of the Material Handling Speed for the low level of the Part Family Setup Reduction Factor. Therefore, the results from the first and second sets of experiments both show that unidirectional flow should be adopted if single-unit production and conveyance is to be implemented in a job shop environment with Kanban-based production control. In addition, the effectiveness of unidirectional flow in realising the benefit of single-unit production and conveyance was found to be robust with respect to material handling speed and the variability (or coefficient of variation) of setup and processing times.

For the cellular layout shop with SUPC and backtracking flow allowed (i.e. the CSB shop), the effect of changing the CV level was still dominated by the processing time CV setting, as found for the high and medium levels of PFSRF. As shown in Figure 10.3, when the setup time CV setting was high and the processing time CV setting changed from high to medium (i.e. from HH to HM level of CV), the average work-in-process inventory and average flow time of the CSB shop decreased. However, we are not confident about the significance of this change since there were always overlaps among the individual 95% confidence intervals for AWIP and AFT at different CV levels.

For the functional layout (FL) shop, the effect of changing the CV levels was still dominated by the setup time CV setting (as found for the high and medium levels of

PFSRF). The average work-in-process inventory and average flow time of the functional layout shop were lower when the setup time CV setting was medium or low (i.e. at the MM, ML and LL levels of CV). This difference was significant since there was no overlap between the 95% confidence intervals for the high and the lower (i.e. medium and low) setup time CV settings.

As opposed to the findings for the high and medium levels of PFSRF, no significant effect of changing the CV levels on the cellular layout shops with batch production and conveyance (i.e. the CBB and CBU shops) could be identified because there were always overlaps among their individual 95% confidence intervals at the different CV levels.

10.3.2 Discussions of the results of overall *F*-tests and planned comparisons

To identify the differences in the relative shop performances, overall *F*-tests and planned comparisons were then performed. Table 10.5 summarises the simulation output on average work-in-process inventory (AWIP) at the low level of the Part Family Setup Reduction Factor (PFSRF). Since all the variances were in acceptable ranges, the data for all shops were included in the overall *F*-tests and planned comparisons (The output summary of the all three dependent variables are given in Tables A12.7-9 of Appendix 12). The original hypotheses for the planned comparisons proposed in Subsection 9.5.2 were tested without any modification.

Significant differences among the different levels of the Shop Layout variable were detected by the overall *F*-tests for all levels of CV with significance levels lower than 0.001 (See Table A13.3 of Appendix 13 for details). The results of the planned comparisons by testing the proposed hypotheses will be discussed individually below (See Tables A14.7-9 of Appendix 14 for details).

(a) Comparison between the cellular layout shops with batch production and conveyance [by testing $H_0(1a)$]

Table 10.5 Simulation output summary on AWIP for the second set of experiments at the low PFSRF level

Dependent variable	CV level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average work-in-process inventory (AWIP)	HH	FL	22	98.88 ± 2.56	33.43
		CBB	22	71.04 ± 1.77	15.86
		CBU	22	71.44 ± 2.31	27.07
		CSB	22	92.40 ± 6.66	225.82
		CSU	22	74.93 ± 3.81	73.86
	HM	FL	22	99.35 ± 2.84	41.11
		CBB	22	70.75 ± 1.93	19.03
		CBU	22	70.85 ± 2.23	25.35
		CSB	22	83.48 ± 4.49	102.75
		CSU	22	69.27 ± 2.89	42.49
	HL	FL	22	99.11 ± 2.37	28.50
		CBB	22	70.19 ± 2.01	20.64
		CBU	22	70.55 ± 2.39	29.16
		CSB	22	81.41 ± 4.40	98.35
		CSU	22	66.78 ± 2.80	39.81
	MM	FL	22	94.57 ± 1.84	17.27
		CBB	22	69.27 ± 1.75	15.57
		CBU	22	69.48 ± 2.06	21.52
		CSB	22	82.65 ± 4.69	111.69
		CSU	22	65.70 ± 3.08	48.38
	ML	FL	22	94.63 ± 1.71	14.92
		CBB	22	68.91 ± 1.95	19.30
		CBU	22	68.91 ± 2.05	21.34
		CSB	22	82.65 ± 4.99	126.59
		CSU	22	63.77 ± 2.60	34.47
	LL	FL	22	93.78 ± 1.83	17.12
		CBB	22	68.35 ± 1.89	18.11
		CBU	22	68.66 ± 2.17	23.99
		CSB	22	84.47 ± 5.10	132.09
		CSU	22	62.33 ± 2.61	34.72

The comparisons among the performances of the cellular layout shops are summarised in Table 10.6. The results of testing $H_0(1a)$ show that for the cellular layout shops with batch production and conveyance (i.e. the CBB and CBU shops), the shop with backtracking flow allowed (i.e. the CBB shop) outperformed the shop with unidirectional flow (i.e. the CBU shop) on ASPTR at all levels of the Coefficient of Variation.

The superior performance of the CBB shop on the average setup to processing time ratio supports the argument illustrated in Subsection 10.1.2. The reduced inter-cell part movement for the CBB shop led to its superior performance in the average setup to processing time ratio. This finding will be explained by using the following example.

Table 10.6 Results of planned comparisons among cellular layouts for the second set of experiments at the Low PFSRF level

Dependent variable	CV level	$H_0(1a)$	$H_0(1b)$	$H_0(2)$
AWIP	HH	CBB=CBU	CSU<CSB	CBB+CBU<CSB+CSU
	HM	CBB=CBU	CSU<CSB	CBB+CBU<CSB+CSU
	HL	CBB=CBU	CSU<CSB	CBB+CBU<CSB+CSU
	MM	CBB=CBU	CSU<CSB	CBB+CBU<CSB+CSU
	ML	CBB=CBU	CSU<CSB	CBB+CBU<CSB+CSU
	LL	CBB=CBU	CSU<CSB	CBB+CBU<CSB+CSU
AFT	HH	CBB=CBU	CSU<CSB	CBB+CBU<CSB+CSU
	HM	CBB=CBU	CSU<CSB	CBB+CBU<CSB+CSU
	HL	CBB=CBU	CSU<CSB	CBB+CBU<CSB+CSU
	MM	CBB=CBU	CSU<CSB	CBB+CBU<CSB+CSU
	ML	CBB=CBU	CSU<CSB	CBB+CBU<CSB+CSU
	LL	CBB=CBU	CSU<CSB	CBB+CBU<CSB+CSU
ASPTR	HH	CBB<CBU	CSU<CSB	CBB+CBU<CSB+CSU
	HM	CBB<CBU	CSU<CSB	CBB+CBU<CSB+CSU
	HL	CBB<CBU	CSU<CSB	CBB+CBU<CSB+CSU
	MM	CBB<CBU	CSU<CSB	CBB+CBU<CSB+CSU
	ML	CBB<CBU	CSU<CSB	CBB+CBU<CSB+CSU
	LL	CBB<CBU	CSU<CSB	CBB+CBU<CSB+CSU

Note: For all significant differences, $p \leq 0.05$.

As shown in Table 5.11 (in Subsection 5.2.1), for the cellular layout with backtracking flow allowed, part type 6 was processed in cell 3, which processed the part family consisting of five part types, namely: 5, 6, 15, 16, 18. On the other hand, As shown in Table 5.18 (in Subsection 5.2.2), for the cellular layout with unidirectional flow, part type 6 had to be processed in cell 1 first, and then transported to cell 2 for other operations. The part family processed by cell 1 consisted of part types 5, 6, 11, 15, 16 and the part family processed by cell 2 consisted of part types 1, 2, 3, 4, 6, 10. Therefore, for the cellular layout with backtracking flow allowed, part type 6 had chances to be queued with other four part types (i.e. part types 5, 15, 16, 18) at the workstations of cell 3. However, for the cellular layout with unidirectional flow, part type 6 might be queued with four other part types (i.e. part types 5, 11, 5,16) at the workstations of cell 1, and again, with five other part types (i.e. part types 1, 2, 3, 4, 10) at the workstations of cell 2.

Since more other part types were likely to be queued with part type 6 for the cellular layout with unidirectional flow, the probability of part type 6 being processed consecutively by a workstation tended to be lower (Recall that no setup time was incurred if parts of the same part type were processed consecutively by a workstation). Consequently, in the long run, the time spent for setting up machines (or the average setup to processing time ratio) tended to be longer for the cellular layout with unidirectional flow.

At the low PFSRF level, the ASPTR performance of the cellular layout shops tended to be less constrained by the Part Family Setup Reduction Factor. As a result, the effect of reduced inter-cell part movement brought about by intra-cell backtracking flow became more significant, and rendered the ASPTR of the CBB shop lower than that of the CBU shop.

However, at the low level of the Part Family Setup Reduction Factor, the adverse effects of backtracking flow, such as more jumbled production flow and less efficient material handling (Recall that the setting of the material handling speed for backtracking flow was always low.) also became more significant. Therefore, the advantage of reduced inter-cell part movement for the CBB shop was somewhat offset by the disadvantage of backtracking flow. Consequently, both the cellular layout shops with batch production and conveyance (i.e. the CBB and CBU shops) exhibited similar performances on the average work-in-process inventory and average flow time at all CV levels.

(b) Comparison between the two cellular layout shops with single-unit production and conveyance [by testing $H_0(1b)$]

The results of testing the hypothesis, $H_0(1b)$ show that for the cellular layout shops with single-unit production and conveyance (i.e. the CSB and CSU shops), the CSU shop demonstrated consistent superior performance on all dependent variables to that of the CSB shop. This finding coincides with that found in Subsection 10.3.1 by examining Figure 10.3.

At the low level of PFSRF, the unfavourable effect of inflexible use of machines for the cellular layout (Refer to Subsection 8.1.2 (b) for details.) and the disadvantage of less synchronised operations brought about by single-unit production and conveyance (Refer to Subsection 8.1.1 for details.) were substantially improved because of the lower setup times. Therefore, the potential of unidirectional flow in realising the benefit of single-unit production and conveyance became more prominent at the low level of PFSRF, and eventually led to the superior performance of the CSU shop.

(c) Comparison between the cellular layouts with BPC and the cellular layouts with SUPC [by testing $H_0(2)$]

The results of testing the hypothesis, $H_0(2)$ indicated that on the average, the cellular layout shops with batch production and conveyance (i.e. the CBB and CBU shops) always outperformed those with single-unit production and conveyance (i.e. the CSB and CSU shops).

However, as shown in Figure 10.3, the inferior performance of the cellular layout shops with single-unit production and conveyance was mainly due to the poor performance of the CBB shop (i.e. the shop with backtracking flow allowed). Actually, the performance of the CSU shop (i.e. the shop with unidirectional flow) itself was similar to that of the CBB and CBU shop. In addition, the CSU shop even significantly outperformed the CBB and CBU shops on AWIP and AFT at the ML and LL levels CV. It appears that the potential of unidirectional intra-cell production flow in achieving the benefit of single-unit production and conveyance was most effective with low processing time variability (or coefficient of variation) and medium to low setup time variability.

(d) Comparison between the functional layout and the cellular layouts [by testing $H_0(3)$]

As shown in Table 10.7, the results of testing $H_0(3)$ show that the cellular layout shops outperformed the functional layout shop on all dependent variables over all levels of the Coefficient of Variation. This result agrees with that obtained in Subsection 8.3.2 (d) for the first set of experiments. Therefore, we are confident that at the low PFSRF level, the superior performance of the cellular layouts was robust with respect to both material handling speed and the variability (or coefficient of variation) of setup and processing times.

As illustrated in Subsection 8.3.2 (d), the cellular layout shops were able to demonstrate superior performance because the disadvantage of dedicating the machines in a cell to the processing of a family of parts was less significant at the low level of the Part Family Setup Reduction Factor. Therefore, the potential of cellular manufacturing in achieving lower average work-in-process inventory and average flow time through larger extent of setup time reduction was fully exploited.

In this section, we found that cellular layout is more suitable for a job shop environment with Kanban-based production control when large extent of setup time reduction (i.e. with low level of PFSRF) is achievable by adopting cellular manufacturing. However, the production flow patterns to be adopted for the cellular layout depend on the extent of the variability (or the coefficients of variation) of setup and processing times. The cellular layout with single-unit production and conveyance is more suitable when the processing time variability is low and the setup time variability is medium to low. However, at other levels of the setup / processing time variability, batch production & conveyance and single-unit production & conveyance tend to be equally suitable for the cellular layout.

Table 10.7 Results of planned comparisons among the cellular and functional layouts for the second set of experiments at the Low PFSRF level

Dependent variable	CV level	$H_0(3)$
AWIP	HH	(CBB+CBU)/2<FL
	HM	(CBB+CBU)/2<FL
	HL	(CBB+CBU)/2<FL
	MM	(CBB+CBU)/2<FL
	ML	(CBB+CBU)/2<FL
	LL	(CBB+CBU)/2<FL
AFT	HH	(CBB+CBU)/2<FL
	HM	(CBB+CBU)/2<FL
	HL	(CBB+CBU)/2<FL
	MM	(CBB+CBU)/2<FL
	ML	(CBB+CBU)/2<FL
	LL	(CBB+CBU)/2<FL
ASPTR	HH	(CBB+CBU)/2<FL
	HM	(CBB+CBU)/2<FL
	HL	(CBB+CBU)/2<FL
	MM	(CBB+CBU)/2<FL
	ML	(CBB+CBU)/2<FL
	LL	(CBB+CBU)/2<FL

Note: For all significant differences, $p \leq 0.05$.

In addition, if batch production and conveyance is adopted for the cellular layout, the intra-cell flow pattern (i.e. unidirectional flow or backtracking flow allowed) does not cause any significant difference in the shop performance (in terms of average work-in-process inventory and average flow time). On the other hand, if single-unit production and conveyance is adopted for the cellular layout, unidirectional intra-cell production flow should be adopted to achieve better shop performance.

The results and analyses of the simulation output for the second set of experiments have been discussed in this chapter. The effect of changing the CV level on the performance of a Kanban-controlled job shop was investigated for the different levels of the Shop Layout and Part Family Setup Reduction Factor variables.

In general, the influence of the variability (of coefficients of variation) of setup and processing times on the performances of individual layouts was more important than on their relative performances. The performances of the cellular layout shops with batch production and conveyance and the functional layout shop were more likely to be affected by the variability of setup times. For the cellular layout shops with single-unit production and conveyance, the performance of the shop with backtracking flow allowed was more likely to be affected by the processing time variability, while both setup and processing time variability had significant influence on the performance of the shop with unidirectional flow.

Some similarities regarding the effect of the Part Family Setup Reduction Factor (or the extent of setup time reduction achievable through cellular manufacturing) were found in both the first and second sets of experiments. The results of both sets of experiments indicated that functional layout is more suitable for a Kanban-controlled job shop when only a small extent of setup time reduction (i.e. high PFSRF level) can be achieved through cellular manufacturing. On the other hand, if a large extent of setup time reduction (i.e. low PFSRF level) is achievable through cellular manufacturing, cellular layout should be adopted for a Kanban-controlled job shop. However, when medium extent of setup time reduction (i.e. medium level of PFSRF) is achievable through cellular manufacturing, both material handling speed and variability of setup and processing times will affect the choice of the shop layout adopted.

The findings regarding the effects of the four independent variables (i.e. Shop layout, Part Family Setup Reduction Factor, Material Handling Speed and Coefficient of Variation) from both the two sets of experiments will be concluded in Chapter 11.

CHAPTER 11

CONCLUSIONS

In comparison with other manufacturing environments, the production efficiency of job shop manufacturing tends to be lower because of its characteristics of low and irregular volume of demand, high product variety and complex product routings. As depicted in Section 1.2, several Just-in-Time (JIT) manufacturing techniques, such as cellular manufacturing, single-unit production and conveyance (SUPC), Kanban-based production control and efficient material handling, are very often suggested as effective tools for reforming job shop manufacturing. However, though there have been abundant reports on Kanban-based systems, far fewer efforts have been devoted to the study of the issues related to applying the Kanban-based production control in a job shop environment. Therefore, how and to what extent those suggested JIT techniques can affect the performance of job shop manufacturing was not well explored. As a result, inadequate understanding of how a job shop with Kanban-based production control behaves under different shop conditions and configurations has discouraged manufacturers from adopting not only the Kanban method but also other effective JIT techniques in job shop environments.

Through this study, we have successfully investigated the influence of several essential factors on the performance of job shop manufacturing with Kanban-based production control, and obtained more understanding of the behaviour of a typical Kanban-controlled job shop under various shop conditions and configurations. Several important findings revealed through this study will serve as useful guidelines for manufacturing firms intending to adopt those suggested JIT tools in job shop environments with Kanbans.

In this study, the following four essential influential factors affecting the performance of a Kanban-controlled job shop were identified:

- shop layout / production flow patterns (represented by Shop Layout or SL),

- material handling speed (MHS),
- variability of setup and processing times (represented by Coefficient of Variation or CV), and
- extent of setup time reduction achievable through cellular manufacturing (represented by Part Family Setup Reduction Factor or PFSRF).

To investigate the effects of these factors on the shop performance, two sets of simulation experiments with different levels of the above influential factors were carried out, and the effects of the influential factors were identified through statistical analyses of the simulation outputs. The effects of these influential factors will be individually concluded as follows.

11.1 Effect of Shop Layout and Production Flow Patterns

In the experimental design of this study, shop layout and production flow patterns were incorporated into the different levels of a single independent variable, Shop Layout (See Section 6.1). Three basic shop layouts were investigated, namely: the functional layout, the cellular layout with backtracking flow allowed and the cellular layout with unidirectional flow. Each of the two basic cellular layouts was further distinguished between the one with batch production and conveyance (BPC) and the one with single-unit production and conveyance (SUPC).

The effect of shop layout and production flow patterns can be considered in three aspects:

- differences between the cellular layout and the functional layout,
- differences between the cellular layouts with unidirectional flow and those with backtracking flow allowed, and
- difference between the cellular layouts with single-unit production and conveyance and those with batch production and conveyance.

Furthermore, the extent of setup time reduction achievable through cellular manufacturing was found to have substantial interactions with other influential factors. In other words, the extent of setup time reduction achievable through cellular manufacturing affected not only the dependent variables, but also the effects of other influential factors. Therefore, the effect of shop layout and production flow patterns will be summarised for each of the three aspects, at the different extents of setup time reduction achievable through cellular manufacturing (i.e. different levels of the Part Family Setup Reduction Factor) in the following subsections.

11.1.1 Comparison between the cellular layout and the functional layout

The comparison between the cellular and functional layouts is summarised in Table 11.1. The results show that cellular manufacturing was, as expected, capable of capitalising on the similarities among the operational sequences of parts to achieve setup time reduction and resulted in lower average setup to processing time ratios (ASPTR). However, the potential of cellular manufacturing in improving the average work-in-process inventory (AWIP) and average flow time (AFT) of the Kanban-controlled job shop was found to be substantially dependent on the extent of setup time reduction achievable through converting functional layout into cellular layout (i.e. the part family setup reduction factor).

Table 11.1 Summary of the comparison between the cellular and functional layouts

Setup time variability	Amount of setup time reduction achievable through cellular manufacturing		
	small	medium	large
high	F	=	C
low	F	C	C

Note: 1. The comparison is based on AWIP and AFT.
2. The entries are defined as follows:
'F': Functional layout is more suitable.
'C': Cellular layout is more suitable.
'=': Both layouts are suitable.

When the extent of setup time reduction achievable through cellular manufacturing was small (i.e. at the high PFSRF level), the inflexibility of dedicating machines to processing part families caused the performance of the cellular layout shops to be inferior to that of the functional layout shop (See Subsection 8.1.2 (b)). In addition, the flexibility brought about by interchangeable machines in functional departments and setup time reduction through the queue selection heuristic rendered the functional layout superior to the cellular layouts.

When medium extent of setup time reduction could be achieved through adopting cellular manufacturing (i.e. at the medium PFSRF level), the potential of cellular manufacturing in setup time reduction was able to greatly overcome its disadvantage of inflexible use of machines and made the performance of the cellular layout shops similar, or even superior at some occasions, to that of the functional layout shop. Provided more efficient material handling facilities were employed (Refer to Section 9.4.), a medium to low setup time variability is more likely to justify the adoption of cellular manufacturing in a Kanban-controlled job shop; otherwise, the performances for cellular and functional layouts are similar.

When a large setup time reduction was achievable though the adoption of cellular manufacturing (i.e. at the low PFSRF level), the cellular layout was always superior to the functional layout regardless of the levels of material handling speed and variability of setup and processing times. The performance of the cellular layout shops was superior because the unfavourable effect of dedicated use of machines for cellular manufacturing was less significant and the potential of cellular manufacturing in setup time reduction was fully exploited at this level of PFSRF.

This conclusion agrees with the conclusion made by Suresh (1992) that for a given lot size, setup reduction through converting a functional to a cellular system must be above a certain threshold value before a cellular manufacturing system would outperform a corresponding functional system. Agarwal *et al.* (1995) extended the study by Suresh (1992) and further confirmed that there exists a region of the combinations of mean setup to processing time ratios and setup time values where both the cellular manufacturing system and the functional system can outperform each other depending upon the level of setup time reduction and lot size values.

11.1.2 Comparison between the cellular layouts with unidirectional flow and those with backtracking flow allowed

For the cellular layout shops with batch production and conveyance, the relative performances between the shop with backtracking flow allowed (i.e. the CBB shop) and the shop with unidirectional flow (i.e. the CBU shop) was more susceptible to the material handling speed than to the variability of setup and processing times. The comparison between the CBB and CBU shops at the different material handling speed levels is summarised in Table 11.2.

Table 11.2 Summary of the comparison between the cellular layouts with batch production and conveyance

Material handling speed for		Amount of setup time reduction achievable through cellular manufacturing		
inter-cell	intra-cell	small	medium	large
high	high	B	=	=
high	low	B	B	=
low	high	B	=	=
low	low	=	=	=

Note: 1. The comparison is based on AWIP and AFT.
2. The entries are defined as follows:
'B': The layout with backtracking flow allowed is more suitable.
'=': Both layouts are suitable.

With a small setup time reduction achievable through cellular manufacturing (i.e. the high PFSRF), the high inter-cell or intra-cell material handling speed resulted in lower average flow time and average setup to processing time ratios for the CBB shop. The performances of the CBB and CBU shops on average work-in-process inventory were similar regardless of the material handling speed levels (Refer to Subsection 8.1.2 (a)).

However, when the extent of setup time reduction achievable through cellular manufacturing became larger, the influence of material handling speed tended to be less significant and the performances of the two cellular layout shops with batch production and conveyance tended to be similar in terms of average work-in-process inventory and average flow time (Refer to Subsections 8.2.2 (a) and 8.3.2 (a)).

When the extent of setup time reduction achievable through cellular manufacturing was small, the CBB shop outperformed the CBU shop for most levels of the variability of setup and processing times, provided more efficient material handling facilities were employed. This was due to the disadvantage of increased queue length brought about by the more intensive inter-cell part movement of the cellular layout with unidirectional flow (Refer to 10.1.2 (a)).

However, when the extent of setup time reduction through cellular manufacturing was increased to medium or large, the superior performance of the shop with backtracking flow allowed was somewhat offset by the more significant disadvantage of backtracking flow. As a result, the performances of the two cellular layout shops tended to be similar in terms of average work-in-process inventory and average flow time (Refer to Subsections 10.2.2 (a) and 10.3.2 (a)) .

Among the cellular layout shops with single-unit production and conveyance, the shop with unidirectional flow (i.e. the CSU shop) always demonstrated superior performance to that of the shop with backtracking flow allowed (i.e. the CSB shop) when a medium to large extent of setup time reduction was achievable through cellular manufacturing (i.e. at the medium and low levels of PFSRF). This finding suggests that unidirectional intra-cell production flow was essential for realising the benefit of adopting single-unit production and conveyance in a job shop environment with Kanban-based production control. Furthermore, since the same finding was derived from both the first and second sets of experiments, we are confident that the favourable effect of unidirectional flow was robust with respect to material handling speed and the variability of setup / processing times (Refer to Subsections 8.2.1, 8.3.1, 10.2.1 and 10.3.1).

It appeared that the adverse effects of less synchronised operations on shop performances caused by single-unit production and conveyance could be alleviated by the smoother and more synchronised production flow resulted from unidirectional intra-cell production flow. This finding agrees with the conclusion made by Kelleher (1986) that balanced (synchronised) operations were essential for achieving the benefit of single-unit production and conveyance in a job shop environment.

11.1.3 Comparison between the cellular layouts with SUPC and those with BPC

An important finding from this study, which is contradictory to the view point held by several JIT proponents, is that single-unit production and conveyance (SUPC) is not necessarily superior to batch production and conveyance (BPC) in a Kanban-controlled job shop environment. Our findings show that the cellular layout shops with batch production and conveyance were superior to those with single-unit production and conveyance on most occasions.

However, it is worth noting that the cellular layout shops with single-unit production and conveyance demonstrated much better performance when the extent of setup time reduction achievable through cellular manufacturing was large (i.e. at the low level of PFSRF), particularly for the shop with unidirectional flow (i.e. the CSU shop).

With a large setup time reduction achievable through cellular manufacturing, the CSU shop even outperformed the cellular layout shops with batch production and conveyance with low intra-cell material handling speed, or with low processing time variability and medium to low setup time variability (provided more efficient material handling facilities were employed) (Refer to Subsections 8.3.1 and 10.3.1).

The conclusion in this subsection suggest that in a job shop environment with Kanban-based production control, such shop conditions with large setup time reduction achievable through cellular manufacturing, unidirectional intra-cell production flow, low intra-cell material handling speed, low processing time variability and medium to low setup time variability are more likely to justify the adoption of single-unit production and conveyance.

11.2 Effect of Material Handling Speed

As illustrated in Chapter 8, the effect of material handling speed on the performances (in terms of average work-in-process inventory and average flow time) of individual shops with different layouts and production flow patterns was found to be not important. However, the relative performances among the different shops were affected by material handling speed, though the effect of material handling speed was not as substantial as that of other influential factors. Table 11.3 summarises the effect of material handling speed on the relative shop performance.

Table 11.3 Summary of the effects of material handling speed on the relative shop performance

Difference investigated	Amount of setup time reduction achievable through cellular manufacturing		
	small	medium	large
functional layout vs. cellular layout		A	
backtracking flow allowed vs. unidirectional flow	AR*	R	
batch production & conveyance vs. single-unit production &conveyance			A

* The entry for a specific difference investigated at a specific level of setup time reduction is defined as follows:
'AR': The effects of both intra- and inter-cell material handling speeds are important.
'A': The effect of intra-cell material handling speed is important.
'R': The effect of inter-cell material handling speed is important.
blank: The effect of material handling speed is not important.

Since material handling speed also had some interactions with the extent of setup time reduction achievable through cellular manufacturing, the effect of material handling speed will be summarised for the different extents of setup time reduction achievable through cellular manufacturing in the following subsections.

11.2.1 Conclusions for the high PFSRF level

With only a small setup time reduction achievable through cellular manufacturing (i.e. at the high PFSRF level), higher (inter-cell or intra-cell) material handling speed resulted in both lower average flow time and average setup to processing time ratios for the cellular layout shop with BPC and backtracking flow allowed (i.e. the CBB shop) than the cellular layout shop with BPC and unidirectional flow (i.e. the CBU shop) (Refer to Subsection 8.1.2 (a)).

However, as concluded in Subsection 11.1.1, at the high PFSRF level, because of the disadvantage of inflexible use of machines, the performance of the cellular layout shops was inferior to that of the functional layout shop regardless of the influence of material handling speed.

11.2.2 Conclusions for the medium PFSRF level

When a medium setup time reduction was achievable through cellular manufacturing (i.e. at the medium level of PFSRF), the influence of material handling speed on the relative performance of the cellular layout shops with batch production and conveyance was lessened. Only the higher inter-cell material handling speed resulted in lower average flow time and average setup to processing ratios of the CBB shop (Refer to Subsection 8.2.2 (a)).

In addition, at the medium level of PFSRF, the relative performance between the cellular layouts and the functional layout was somewhat affected by material handling speed. The cellular layout shops outperformed the functional layout shop, except that lower intra-cell material handling speed rendered the average work-in-process inventory of the cellular layout shops similar to that of the functional layout shop. Therefore, although cellular layout was found to be more suitable for a Kanban-controlled job shop at the medium PFSRF level, faster material handling facilities for intra-cell part movement should be employed to achieve better shop performance (Refer to Subsection 8.2.2 (c)).

11.2.3 Conclusions for the low PFSRF level

When a large setup time reduction could be achieved by adopting cellular manufacturing (i.e. at the low PFSRF level), material handling speed mainly affects the relative performance between the cellular layout shops with BPC and the cellular layout shops with SUPC. When the intra-cell material handling speed was low, the cellular layout with SUPC and unidirectional flow was found to be more suitable for a Kanban-controlled job shop; otherwise, the cellular layout with batch production and conveyance should be adopted.

In general, the effect of material handling did not substantially affect the decision on the shop layout and production flow patterns to be adopted for a Kanban-controlled job shop. To achieve better production performance in a job shop environment with Kanban-based production control, it is more important to select the correct shop layout and production flow patterns based on the extent of setup time reduction achievable through cellular manufacturing. Once the shop layout and production flow patterns are decided, proper material handling facilities can then be selected based the above conclusions to achieve better shop performance.

11.3 Effect for the Variability of Setup and Processing Times

As illustrated in Chapter 10, in contrast to the effect of material handling speed, the influence of the variability (or coefficients of variation) of setup and processing times was mainly on the individual performances of the different shops instead of their relative performances. The effect of setup / processing time variability on the individual shop performances is summarised in Table 11.4.

Similar to the findings for the other influential factors, the variability of setup and processing times was also found to have substantial interactions with the extent of setup time reduction achievable through cellular manufacturing (or the Part Family Setup

Reduction Factor). Therefore, the effects for the variability of setup and processing times will be concluded for each of the PFSRF level below.

Table 11.4 Summary of the effect of setup / processing time variability on the individual shop performances

Shop layout investigated	Amount of setup time reduction achievable through cellular manufacturing		
	small	medium	large
Functional layout	S*	S	S
Cellular layout with single-unit production & conveyance	P	SP	SP
Cellular layout with batch production & conveyance	S	S	

* The entry for a specific shop layout investigated at a specific level of setup time reduction is defined as follows:
'S': The effect of setup time variability is important.
'P': The effect of processing time variability is important.
'SP': The effects of both setup and processing time variability are important.
blank: The effect of setup and processing time variability is not important.

11.3.1 Conclusions for the high PFSRF level

When the extent of setup time reduction through cellular manufacturing was small (i.e. at the high PFSRF level), reduction in the processing time variability resulted in improvement in the performance of the cellular layout shops with single-unit production and conveyance. As discussed in Subsection 8.1.1, since the performance of the cellular layout shops with single-unit production and conveyance was dominated by the unfavourable effect of highly unsynchronised operations at the high level of PFSRF, it was reasonable that the lower processing time variability lessened the disadvantage of unsynchronised operations to some extent and led to improved shop performance. However, reduction in the variability of processing times was not sufficient to make the performance of the cellular layout shops with single-unit production and conveyance superior to that of the other shops (i.e. the cellular layout shops with batch production & conveyance and the functional layout shop).

On the other hand, for the remaining shops, the influence of setup time variability on their performances was more important. Because the performances of these shops were mainly confined by the longer setup times at the high level of PFSRF, the lower setup time variability was effective in reducing the unfavourable effect of longer setup times and leading to better shop performances (Refer to Subsection 8.1.1).

The effect of setup and processing time variability on the relative performance between the various shops was not significant at this level of PFSRF. In addition, as concluded in Subsection 11.1.1, at the high PFSRF level, because of the disadvantage of inflexible use of machines, the performance of the cellular layout shops were inferior to that of the functional layout shop regardless of the influence of setup and processing time variability.

11.3.2 Conclusions for the medium PFSRF level

If medium extent of setup time reduction could be achieved through adopting cellular manufacturing (i.e. at the medium level of PFSRF), the effect of the variability of setup and processing times was the same as that for the high PFSRF level, except that reducing setup time variability became more effective in improving the performance of the cellular layout shop with single-unit production & conveyance and unidirectional flow (i.e. the CSU shop) (Refer to Subsection 8.2.1). However, because of the disadvantage of less synchronised operations (Refer to Subsection 8.1.1), the performance of the cellular layout shops with single-unit production and conveyance was still inferior to that of other shops.

At the medium PFSRF level, the setup time variability had significant effect on the relative performance between the functional layout shop and the cellular layout shops. Provided more efficient material handling facilities were employed, the cellular layout shops (with batch production and conveyance) outperformed the functional layout shop (in terms of average work-in-process inventory and average flow time) with medium to low setup time variability. Otherwise, their performances on average work-in-process inventory and average flow time were similar (Refer to 10.2.2 (c)).

11.3.3 Conclusions for the low PFSRF level

When a large setup time reduction was achievable by adopting cellular manufacturing, reduction in the variability of both setup and processing times significantly improved the performance (in terms of average work-in-process inventory and average flow time) of the cellular layout shop with single-unit production & conveyance and unidirectional flow (i.e. the CSU shop). Furthermore, the CSU shop outperformed all other shops (in terms of average work-in-process inventory and average flow time) with low processing time variability and medium to low setup time variability (Refer to Subsection 10.3.1).

Similar to the findings for the high and medium levels of PFSRF, reduction in the setup time variability resulted in lower average work-in-process inventory and average flow time for the functional layout. However, in contrast to the findings for the high and medium PFSRF levels, the influence of setup and processing time variability on the performance of the cellular layout shops with batch production and conveyance was not significant (Refer to Subsection 10.3.1).

No significant effect of the setup and processing time variability on the relative performance of the various shops could be found. As concluded in Subsection 11.1.1, at the medium PFSRF level, the cellular layout shops outperformed the functional layout shop regardless of the influence of setup and processing time variability.

Similar to the conclusion for the effect of material handling speed in Section 11.2, the effect of setup and processing variability did not substantially affect the decision on the shop layout and production flow patterns to be adopted for a Kanban-controlled job shop. We found that the selection of shop layout and production flow patterns based on the extent of setup time reduction achievable through cellular manufacturing was essential for achieving better production performance in a job shop environment with Kanban-based production control. Once the shop layout and production flow patterns are decided, reduction of setup and / or processing time variability should then be considered to improve the shop performance by referring to the above conclusions.

11.4 Effect for the Extent of Setup Time Reduction Achievable through Cellular Manufacturing

Several proponents of JIT manufacturing (Monden 1983: 67, Kelleher 1986, Schonberger 1986: 9 and Cheng and Podolsky 1993) emphasised that converting the traditional functional layout into cellular layout was essential for reforming job shop manufacturing. However, through this study, we found that converting functional layout into cellular layout does not necessarily bring about improved shop performance in a job shop environment with Kanban-based production control.

Our finding agrees with that reported by Suresh (1992) and Agarwal (1995), who concluded that for a given lot size, setup time reduction through converting a functional layout to a cellular layout must be above a certain threshold before a cellular manufacturing system would outperform a corresponding functional system. In addition, we found that the extent of setup time reduction achievable through cellular manufacturing not only had a significant effect on the performance of a Kanban-controlled job shop, but also had significant interactions with other influential factors (as concluded in the previous sections for the individual influential factors).

The findings from our study show that cellular layout is more suitable for a Kanban-controlled job shop when a medium to large setup time reduction can be achieved by adopting cellular manufacturing, provided more efficient material handling facilities are adopted. Otherwise, functional layout should be adopted for a Kanban-controlled job shop if the extent of setup reduction achievable by adopting cellular manufacturing is small.

The extent of setup time reduction achievable through cellular manufacturing, shop layout and production flow patterns together were the most essential factors which influenced the production performance in a job shop environment with Kanban-based production control. We found that to successfully implement the Kanban mechanism in a job shop, it is essential to select the correct shop layout and production flow patterns (i.e. batch production & conveyance vs. single-unit production & conveyance, and unidirectional flow vs. backtracking flow allowed) according to what extent of setup time reduction can be achieved by adopting cellular manufacturing (as concluded in Section 11.1). In addition, when planning the shop layout, the cell formation and layout planning procedures (as illustrated in Sections 5.2-4) should be followed to properly position cells / departments on the available floor area.

Once the shop layout and production flow patterns are decided, attention should be given to the selection of appropriate material handling facilities (as concluded in Section 11.2) and the reduction of setup / processing time variability (as concluded in Section 11.3) to attain better shop performance.

From this research project, we realise that implementation of the Just-in-Time techniques in a job shop environment is not as simple as grouping machines into cells or putting Kanban cards in the shop. The benefits of those JIT related tools (e.g. Kanban-based production control, cellular manufacturing, single-unit production and conveyance) cannot be realised without taking into account the effects of those influential factors investigated in this study. We believe that the conclusions in this chapter as well as the content in other chapters will provide valuable information for manufacturing firms to successfully implement JIT techniques in job shop environments.

In the next chapter, we will give the managerial implications derived from the conclusions, and our recommendations for both industrial applications and future research work.

CHAPTER 12

MANAGERIAL IMPLICATIONS AND RECOMMENDATIONS

In this chapter, important managerial implications will be derived from the conclusions of this study. They will serve as practical guidelines for those manufacturers who wish to implement Just-in-Time manufacturing techniques in job shop environments. Then recommendations for industrial applications and future research work will be given.

12.1 Managerial Implications

From the conclusions of this study, we are able to arrive at the following managerial implications:

(1) The selection of an appropriate shop layout and production flow patterns based on the extent of setup time reduction achievable through cellular manufacturing should be given the first priority in the design and planning of the Kanban-based production control system in a job shop environment. In practice, the case studies by Gunasekaran and Lyu (1997) and Martin-Vega *et al.* (1989) emphasised the importance of layout planning in realising the benefits of Kanban-based systems as well.

In a job shop environment with Kanbans, the traditional functional layout is more appropriate if only small amount of setup time reduction can be achieved by adopting cellular manufacturing (Refer to Subsections 11.1.1, 8.1.2(b) and 10.1.2(b)). The use of cellular layout should only be considered when a medium to large setup time reduction is achievable by adopting cellular manufacturing (Refer to Subsections 11.1.1, 8.2.2(c), 8.3.2(d), 10.2.2(c) and 10.3.2(d)).

(2) The method of single-unit production and conveyance is more appropriate for repetitive manufacturing. In a job shop environment, where parts require quite different routings, the adoption of single-unit production and conveyance should

only be considered when setup time can be reduced significantly by adopting cellular manufacturing and where intra-cell material handling facilities with lower speed (e.g. workers) are used (Refer to Subsection 8.1.1).

Furthermore, if single-unit production and conveyance is to be implemented, unidirectional intra-cell production flow should be used, and the variability of both setup and processing times must be significantly reduced. (Refer to Subsections 11.1.2, 11.1.3, 8.3.1 and 10.3.1).

(3) As opposed to single-unit production and conveyance, the method of batch production and conveyance is more suitable for a job shop environment with Kanban-based production control when a small to medium setup time reduction is achievable through cellular manufacturing (Refer to Subsections 11.1.3, 8.1.1, 8.2.2(b), 10.1.1 and 10.2.2(b)). In addition, one important advantage of batch production and conveyance is that it is more robust with respect to the influence of the intra-cell production flow pattern (i.e. unidirectional flow vs. backtracking flow allowed) than single-unit production and conveyance. (Refer to Subsections 11.1.2, 8.1.2(a), 8.2.2(a), 10.1.2(a) and 10.2.2(a)).

(4) As concluded in Section 11.2, as long as the shop layout and production flow patterns are properly selected, and material handling facilities with reasonable speed are used, the effectiveness of employing faster material handling methods in increasing the performance of a Kanban-controlled job shop is limited. Therefore, to achieve the benefits of using Kanbans in a job shop environment, layout changes should always be given the higher priority than investment in faster (or more advanced) material handling facilities.

(5) As illustrated in Section 11.3 and Chapter 10, reducing the variability of setup / processing times is effective in achieving higher productivity in a job shop environment with Kanbans. The study by Philipoom *et al.* (1987) also highlighted the importance of reducing processing time variability in achieving better performance of a job shop with Kanbans. However, it should not be ignored that the

effectiveness of reducing setup / processing time variability varies for shops with different layouts and production flow patterns.

Reduction in the variability of both setup and processing times is effective in improving the performance of the cellular layout with single-unit production & conveyance and unidirectional flow (Note that the use of single-unit production and conveyance should only be considered when a large setup time reduction is achievable through cellular manufacturing). However, for the functional layout and the cellular layout with batch production & conveyance, reduction in the variability of setup times should be given the higher priority (The use of the cellular layout with single-unit production & conveyance and backtracking flow allowed is not recommended).

Reduction in the variability of setup/processing times can be achieved by implementing standard operations. The implementation of the standard operations involves preparing standard operating charts, training workers to follow standard operations and continuous improvement of operations (Shingo 1989: 141-148).

(6) The issue of improving the production performance of job shop manufacturing by adopting JIT techniques is particularly important for the manufacturing firms in New Zealand. Because of the relatively much smaller market in New Zealand than in other more industrialised countries, such as U.S., U.K. and Japan, manufacturers often have to adopt the job shop manufacturing approach. However, with the high manpower cost in New Zealand, it is essential for job shop manufacturers to improve their production performance if they want to remain competitive in the market.

Some typical New Zealand industries where the results of this study can be applied include: communication equipment where the variability of the demand is high, automation / control products (PLCs, Inverters, etc.), sheet metal products (equipment racks, cabinets, heat sinks, etc.), metal / machining products (tube fittings, connectors, etc.), and process instruments (pressure gauges, thermometers, flowmeters, valves, etc.).

12.2 Recommendations for Industrial Applications

Through this research project, we have gained invaluable knowledge of the requirements and approaches for realising the potential of Just-in-Time manufacturing in improving the production performance in a job shop environment. Based on our experience in conducting the simulation experiments and the results obtained from the study, we have the following recommendations deserving attention for industrial applications.

12.2.1 Vulnerability of the Kanban-based systems to disturbances

A Kanban-based production control system is more vulnerable to disturbances (e.g. less synchronised operations, variability in setup / processing times, etc.) than traditional systems without Kanbans. Any fluctuation in part of the system can be easily transmitted (and even amplified) to the entire system (Kimura and Terada 1981, Villeda *et al.* 1988).

More Kanban / container sets are needed to buffer production fluctuations if disturbances happen too often. Eventually, the advantages of using the Kanban for continuous improvement (e.g. reducing work-in-process inventory) will be lost with larger numbers of Kanbans and containers. Therefore, a crucial prerequisite for successful implementation of the Kanban method is that manufacturers should endeavour to bring the disturbances down to a minimum in any case (Monden 1983: 26-28, Cheng and Podolsky 1993: 85-88).

12.2.2 Incorporating the planning of cellular manufacturing in TQM activities

The findings of our study support the effectiveness of cellular manufacturing in improving the performance of job shop manufacturing with Kanban-based production control, provided the shop layout and production flow patterns are properly selected (Refer to Subsection 11.1.1, Sections 8.2-3 and Sections 10.2-3). However, we would like to emphasise, that implementing cellular manufacturing is not as simple as merely grouping machines into cells.

As pointed out by Vakharia and Selim (1994), the introduction of cellular manufacturing will affect the existing structure, personnel, methods, and procedures of a plant. Some issues, like stabilisation of end product demand, activity-based costing systems, changes in the structural configuration of the operations function, team atmosphere within each cell and support of top management will also need to be resolved. These issues are all the aspects addressed by Total Quality Management (TQM). We thus strongly suggest that the planning for cellular manufacturing be introduced as part of the company-wide TQM activities.

12.2.3 Using simulation and statistical methods correctly

When planning a Kanban-based system, it is important to evaluate the feasibility of system parameters and configurations. If the system is a new one, it is impossible to carry out such feasibility studies on a real system. Even where an existing system is available, the required interruptions and modifications to the existing system for performing such studies can be costly, if not impossible.

As shown in this study, simulation in conjunction with statistical methods is an effective, yet inexpensive decision support tool for evaluating the expected system performance at the planning and design stages. For example, in our study, each simulation run had to simulate about fourteen years (43,080 working hours) of the production activities to achieve the appropriate statistical reliability in the results. This job can never be accomplished on a real system, but it can be done by simulation in about three hours. Simulation is particularly useful when the system is too complicated to be studied by other modelling methods, such as the analytical method, the empirical method, etc.; or characterised by stochastic properties, which can be easily incorporated in a simulation model.

We would like to point out, however, improper use of simulation and statistical methods can lead to wrong decisions. For example, if the initial transient period of a simulation run is simply determined by assumption or even ignored, as had done in many simulation studies, the effect of initial transient may substantially bias the simulation results. Another example is that interpreting the simulation results based merely on the mean values of dependent variables (again, as had done in many simulation studies) without investigating their confidence intervals can lead to totally different conclusions.

To achieve correct simulation results and to interpret the simulation results correctly, the following issues deserve attention in performing a simulation experiment (Refer to Chapter 7 for details):

(1) A simulation model should be systematically verified after it is developed and coded to make sure the model functions as expected.

(2) If the purpose of a simulation study is to examine the system's steady-state behaviour, the statistics collected during the initial transient period must be discarded to avoid the simulation results being biased. The initial transient period of a simulation run should be determined through a valid procedure, such as the Welch's graphical procedure (Law and Kelton 1991, p. 545) instead of by assumption.

(3) As shown in Equation 7.3, the number of replications, n (i.e. the simulation run length) of a simulation run is directly related to how precisely the confidence interval of the population mean can be estimated. The larger the number of replications, the smaller is the error in estimating the population mean (i.e. The confidence interval is narrower). To achieve an acceptable confidence interval for the population mean, an appropriate number of replications should be decided by performing preliminary simulation runs before the commencement of a full simulation experiment. An experimenter will risk making wrong decisions based on simulation results with large errors if the number of replications of a simulation is not determined appropriately.

(4) To interpret the simulation results correctly, we suggest that the confidence intervals of population means or suitable hypothesis tests be used for comparing the sample means of different treatment groups. If the confidence intervals had not been shown on the bar graphs of Figures 8.1-3 and 10.1-3, the interpretation of the

simulation results would be substantially different. As shown in the discussions of Chapters 8 and 10, comparing two treatment groups solely by their sample means is only appropriate when there is no overlap between their confidence intervals for population means.

12.3 Recommendations for Future Research Work

This research project has made a significant advance in the area of applying Just-in-Time (JIT) manufacturing techniques in the job shop environment. The effects of several influential factors on the production performance in a job shop environment with Kanbans were investigated, and many important findings were revealed. However, for JIT manufacturing techniques to be widely accepted in job shop environments as they are for repetitive manufacturing, further understanding of how to apply these techniques effectively for job shop manufacturing is still needed. Therefore, we would like to suggest the following directions for future research work in this area.

12.3.1 Investigating the effects of setup times and the setup to processing time ratio

Agarwal *et al.* (1995) investigated the behaviour of a cellular layout (CL) shop and a functional layout (FL) shop as a function of two parameters: the mean setup time (T) to processing time (t) ratio (denoted by $R=T/t$) and the mean setup time.

They identified five distinct regions within the defined ranges of the two parameters where: (1) the CL and FL shops were both unstable, (2) the FL shop always outperformed the CL shop, (3) the CL shop always outperformed the FL shop (consisting of two regions) and (4) the CL and FL shops could outperform each other (a mixed region) depending on the amount of setup time reduction achievable by adopting cellular manufacturing (or the part family setup reduction factor), and lot size values.

In this study, the R and the T values were defined as constants lying in the 'mixed region' so that the influence of the part family setup reduction factor could be investigated. However, in consideration of the findings by Agarwal *et al.*, varying the *R* and *T* values may affect the production performance in a job shop environment with Kanban-based production control as well. In addition, the influence of material handling speed may be different with different *R* and *T* values.

Therefore, extending this study by investigating the influence of *R* and *T* values on the production performance of a Kanban-controlled job shop is a potential area for future research work.

12.3.2 Investigating the influence of setup time reduction by improving setup operations

As concluded in Section 11.4, the amount of setup time reduction achievable through cellular manufacturing (or the part family setup reduction factor) had a substantial effect on the performance of job shop manufacturing with Kanbans. However, in addition to setup time reduction achieved by adopting cellular manufacturing, substantial setup time reduction is also achievable by improving setup operations. Shingo (1985) suggested that an average of setup time reduction around 80 to 95 percent is achievable by improving setup operations, such as preparation of material, clamping and removing dies and tools, centring and determining dimensions of tooling, and trial processing and adjustment.

Therefore, another subject deserving further study is the examination of how and to what extent the amount of setup time reduction achieved by improving setup operations affect the production performance in a job shop environment with Kanban-based production control.

12.3.3 Assessing the importance of influential factors using fractional factorial design

As illustrated in Sections 6.1 and 9.2, the full factorial design was adopted for both the two sets of experiments for this study. The strength of the full factorial design is that complete information regarding the main and interaction effects of the factors investigated can be obtained. However, as the number of factors increases, the number of runs required by a full factorial design increases geometrically. For example, for our project, each set of experiments required 5 × 3 × 6 = 90 runs. If we add another factor with three levels, the number of runs required will increase to 5 × 3 × 6 × 3 = 270. In addition, as the number of factors increases, an increasing portion of the data for the full factorial design is used to estimate higher-order interactions. These interactions are often of little interest to the experimenter (Moen *et al.* 1991).

Therefore, if we use the full factorial design to investigate the effects of all the relevant factors (included in this study and recommended in previous subsections) for future research work, the size of experiments will become extremely large and interpretation of the interaction effects will be very complicated. In this case, fractional factorial designs are more suitable. Fractional factorial designs enable the estimation of important effects while keeping the size of experiments practical.

We suggest that a set of experiments with the fractional factorial design or screening experiments such as the Plackett Burman design are performed first to identify the importance of all the relevant factors with fewer levels. Based on the information gained from these experiments, factors with important main effects and / or interactions can be identified. Then, experiments with the full factorial design can be conducted to obtain detailed information on the effects and interactions of those important factors.

Since the emergence of the Just-in-Time manufacturing in late 1973 in Japan, JIT has been recognised globally as one of the most important tools for increasing the productivity of manufacturing plants. In general, JIT is not as easily applied to job shop manufacturing as to repetitive and continuous manufacturing. This study should stimulate the awareness of the problems as well as the benefits of using JIT manufacturing techniques in job shop environments.

More research effort is still needed to understand all the issues related to the implementation of JIT manufacturing techniques in job shop environments.

Understanding of the requirements for realising the benefits of JIT manufacturing techniques will eventually help job shop manufacturing firms to implement these techniques more correctly and more effectively.

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APPENDIX 1
FROM-TO CHARTS FOR THE VARIOUS SHOP LAYOUTS

Table A1.1 From-to chart for the cellular layout with unidirectional flow

unit: batches per year

From (Cell)	To (Cell)						
	In	1	2	3	4	5	Out
In*	--	1382	1057	1568	1149		
1		--	362	291			729
2			--			304	1264
3				--			1859
4					--	1149	
5			149			--	1304
Out*							--

Table A1.2 From-to chart for the cellular layout with backtracking flow allowed

unit: batches per year

From (Cell)	To (Cell)					
	In	1	2	3	4	Out
In	--	1115	1155	2179	764	
1		--				1115
2			--			1155
3				--	291	1888
4					--	1055
Out						--

Table A1.3 From-to chart for the functional layout

unit: batches per year

From (Dept.)	To (Dept.)													
	In	1	2	3	4	5	6	7	8	9	10	11	12	Out
In	--	2862		1060	269		2502					1207	96	
1		--	640		978		698	546						
2			--		640		515							
3				--		1060								
4					--			1492	2327					
5			515			--	545							
6					1393		--	1166			1222			479
7					539			--	1164	1011	1763	546	387	270
8								270	--	2952				269
9										--				3963
10								1222			--	546		1763
11								984			546	--	769	
12													--	1252
Out														--

APPENDIX 2
FLOW-OF-MATERIAL INTENSITIES FOR THE VARIOUS SHOP LAYOUTS

Table A2.1 Flow-of-material intensity for the cellular layout with unidirectional flow

Between Pair of Cells			Flow-of-Material Intensity (batches per year)	Importance of Relationship Rating
3	--	Out	1859	1*
In	--	3	1568	1
In	--	1	1382	2
5	--	Out	1304	2
2	--	Out	1264	2
In	--	4	1149	3
4	--	5	1149	3
In	--	2	1057	3
1	--	Out	729	4
2	--	5	453	Unimportant
1	--	2	362	Unimportant
1	--	3	291	Unimportant

* Note: An *importance of relationship* rating of '1' indicates that closeness between the pair of cells/departments is the most essential. The larger the number of rating is, the less important is the closeness.

Table A2.2 Flow-of-material intensity for the cellular layout with backtracking flow allowed

Between Pair of Cells	Flow-of-Material Intensity (batches per year)	Importance of Relationship Rating
In -- 3	2179	1
3 -- Out	1888	1
In -- 2	1155	3
2 -- Out	1155	3
In -- 1	1115	3
1 -- Out	1115	3
4 -- Out	1055	3
In -- 4	764	4
3 -- 4	291	Unimportant

Table A2.3 Flow-of-material intensity for the functional layout (continued on the next page)

Between Pair of Departments	Flow-of-Material Intensity (batches per year)	Importance of Relationship Rating
9 -- Out	3963	1
7 -- 10	2985	2
8 -- 9	2952	2
In -- 1	2862	2
In -- 6	2502	2
4 -- 8	2327	3
4 -- 7	2031	3
10 -- Out	1763	3
7 -- 11	1530	4
7 -- 8	1434	4
4 -- 6	1393	4
12 -- Out	1252	4
6 -- 10	1222	4
In -- 11	1207	4
6 -- 7	1166	4
10 -- 11	1092	4
In -- 3	1060	4
3 -- 5	1060	4
7 -- 9	1011	4
1 -- 4	978	4

Table A2.3 Flow-of-material intensity for the functional layout (continued)

Between Pair of Departments	Flow-of-Material Intensity (batches per year)	Importance of Relationship Rating
11 -- 12	769	Unimportant
1 -- 6	698	Unimportant
1 -- 2	640	Unimportant
2 -- 4	640	Unimportant
1 -- 7	546	Unimportant
5 -- 6	545	Unimportant
2 -- 5	515	Unimportant
2 -- 6	515	Unimportant
6 -- Out	479	Unimportant
7 -- 12	387	Unimportant
7 -- Out	270	Unimportant
In -- 4	269	Unimportant
8 -- Out	269	Unimportant
In -- 12	96	Unimportant

APPENDIX 3
FLOW RELATIONSHIP DIAGRAMS FOR THE VARIOUS SHOP LAYOUTS

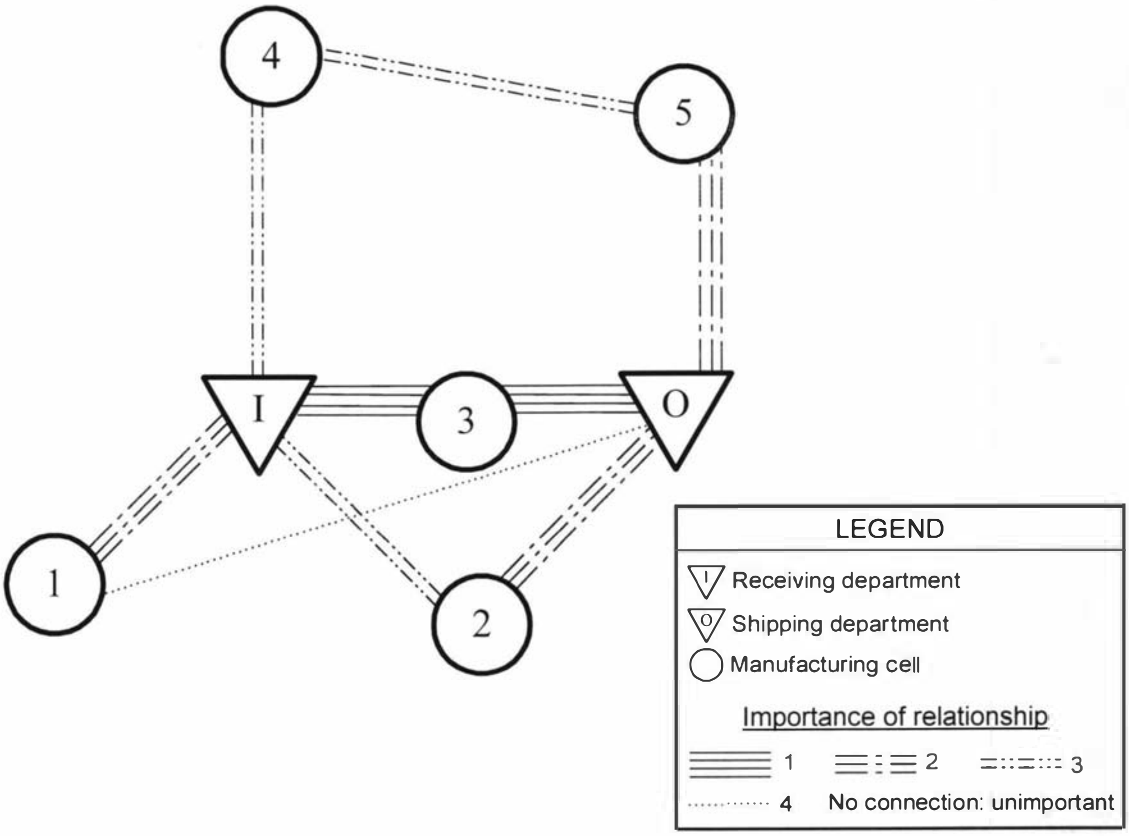

Figure A3.1 Flow relationship diagram for the cellular layout with unidirectional flow

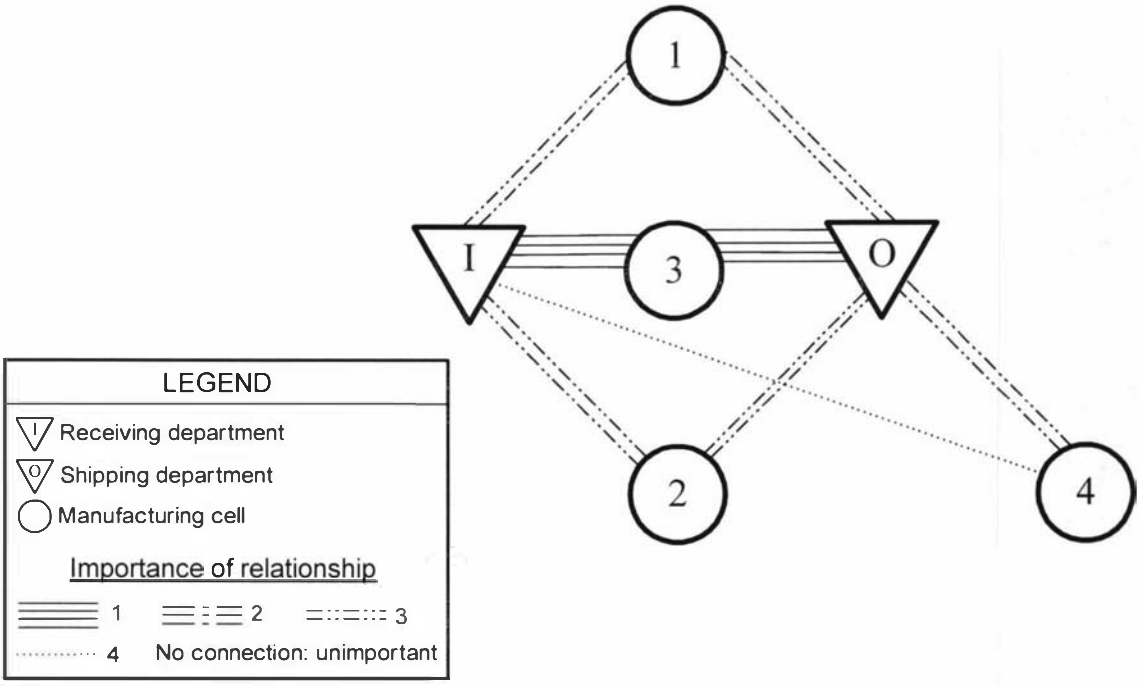

Figure A3.2 Flow relationship diagram for the cellular layout with backtracking flow allowed

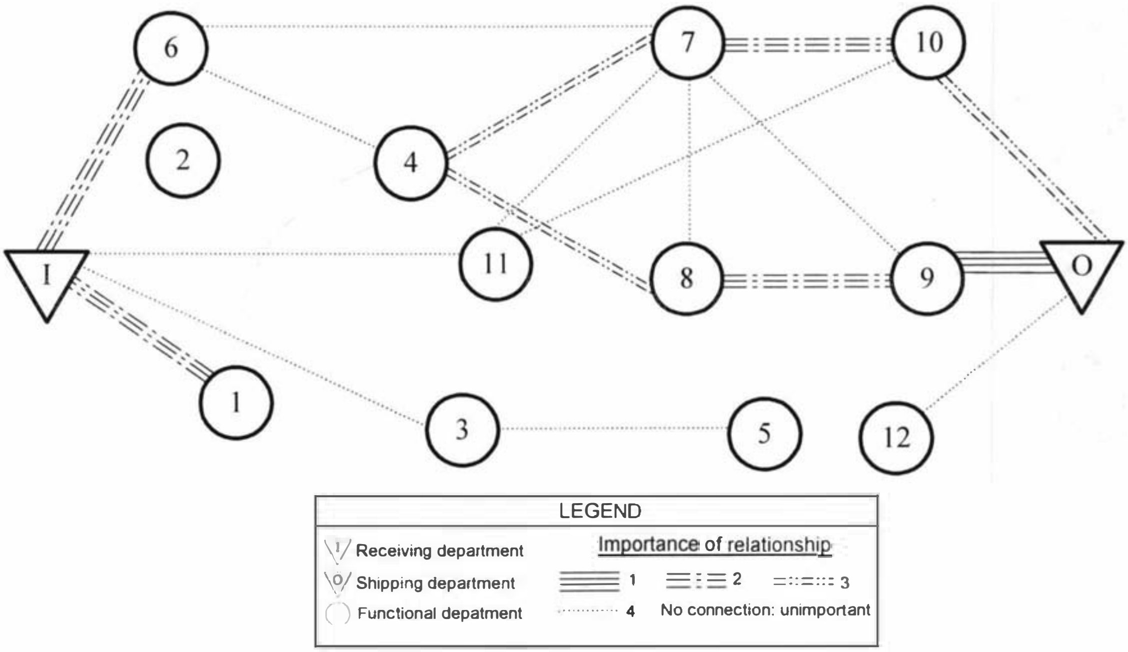

Figure A3.3 Flow relationship diagram for the functional layout

APPENDIX 4
SPACE RELATIONSHIP DIAGRAMS FOR THE VARIOUS SHOP LAYOUTS

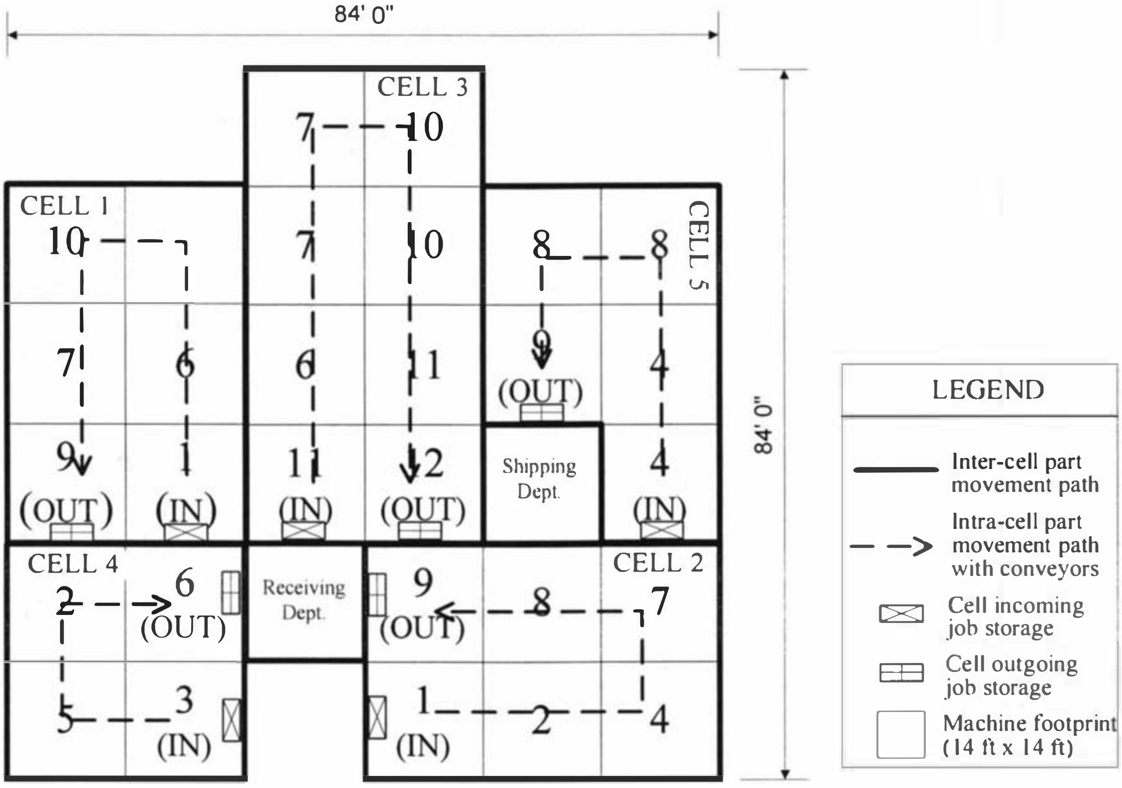

Figure A4.1 Space relationship diagram for the cellular layout with unidirectional flow

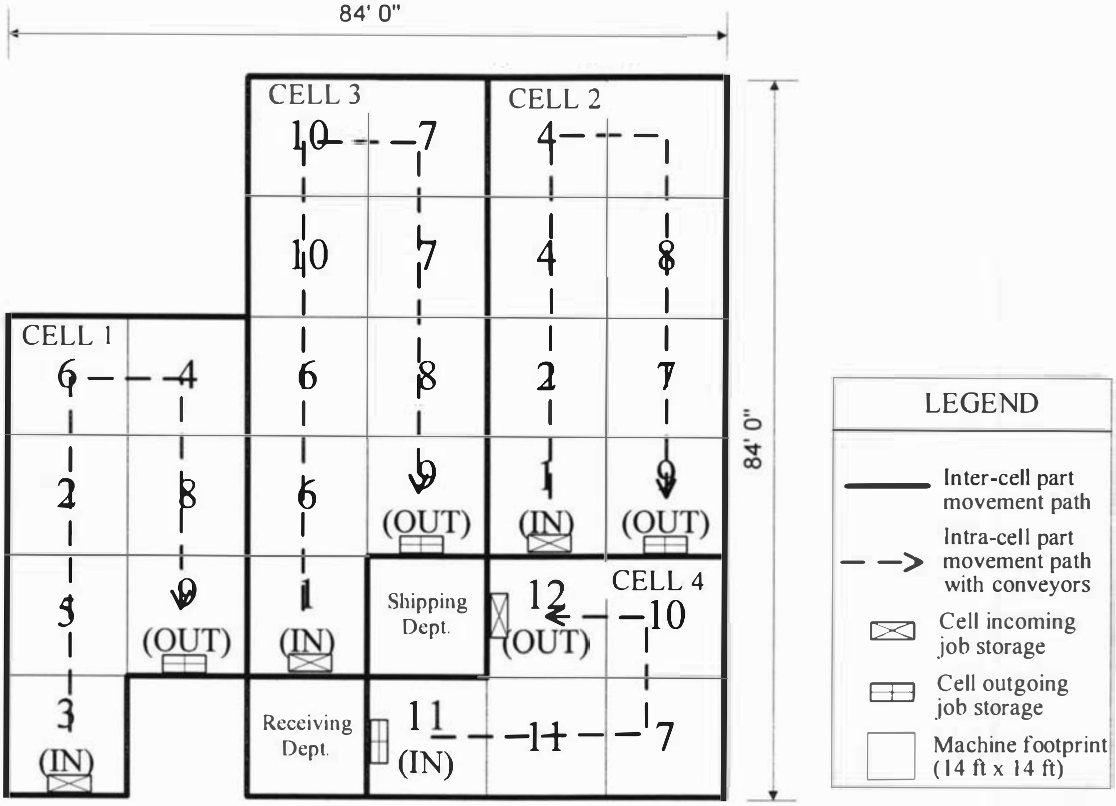

Figure A4.2 Space relatioship diagram for the cellular layout with backtracking flow allowed

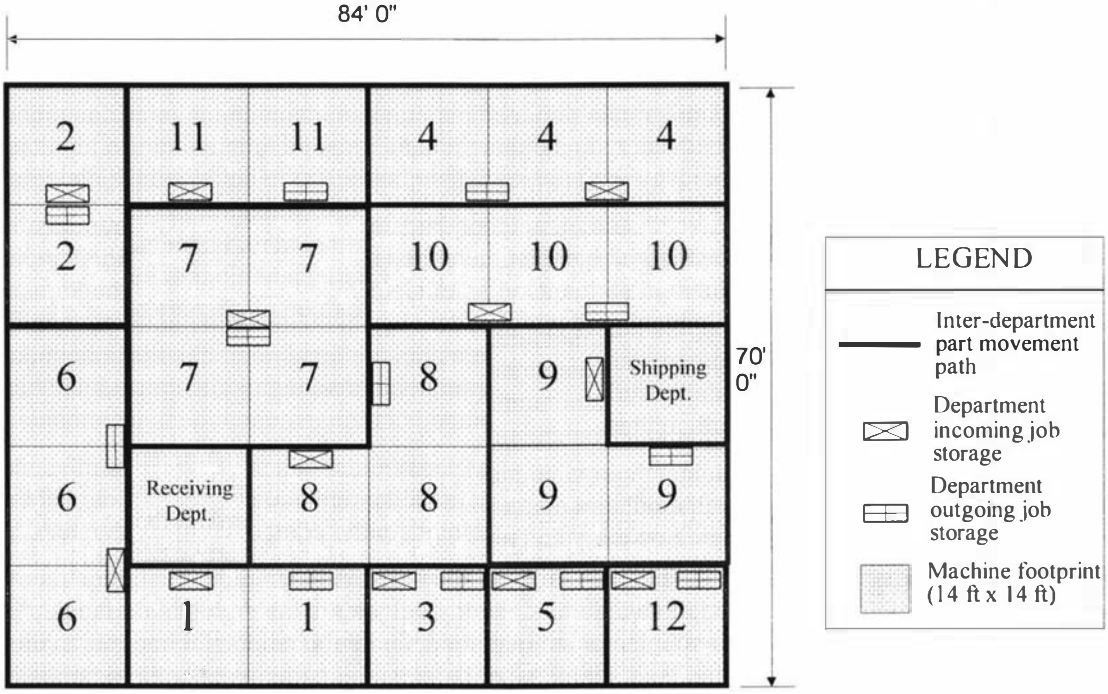

Figure A4.3 Space relationship diagram for the functional layout

APPENDIX 5

INTER-CELL / DEPARTMENT AND INTRA-CELL TRAVELLING DISTANCE MATRICES

Table A5.1 Intra-cell distance matrix for Cell 1 with unidirectional flow (material handling by a conveyor)

unit: feet

From Workstation No./ Machine type	To Workstation No./Machine Type						
	In	1/1	2/6	3/10	4/7	5/9	Out
In	--	7	21	49	63	77	84
1/1		--	14	42	56	70	77
2/6			--	28	42	56	63
3/10				--	14	28	35
4/7					--	14	21
5/9						--	7
Out							--

Table A5.2 Intra-cell distance matrix for Cell 2 with unidirectional flow (material handling by a conveyor)

unit: feet

From Workstation No./ Machine type	To Workstation No./Machine Type							
	In	6/1	7/2	8/4	9/7	10/8	11/9	Out
In	--	7	21	35	49	63	77	84
6/1		--	14	28	42	56	70	77
7/2			--	14	28	42	56	63
8/4				--	14	28	42	49
9/7					--	14	28	35
10/8						--	14	21
11/9							--	7
Out								--

Table A5.3 Intra-cell distance matrix for Cell 3 with unidirectional flow (material handling by a conveyor)

From Workstation No./ Machine type	To Workstation No./Machine Type							
	In	12/11	13/6	14/7	15/10	16/11	17/12	Out
In	--	7	21	42	56	77	91	98
12/11		--	14	35	49	70	84	91
13/6			--	21	35	56	70	77
14/7				--	14	35	49	56
15/10					--	21	35	42
16/11						--	14	21
17/12							--	7
Out								--

Table A5.4 Intra-cell distance matrix for Cell 4 with unidirectional flow (material handling by a conveyor)

unit: feet

From Workstation No./ Machine type	To Workstation No./Machine Type					
	In	18/3	19/5	20/2	21/6	Out
In	--	7	21	35	49	56
18/3		--	14	28	42	49
19/5			--	14	28	35
20/2				--	14	21
21/6					--	7
Out						--

Table A5.5 Intra-cell distance matrix for Cell 5 with unidirectional flow (material handling by a conveyor)

unit: feet

From Workstation No./ Machine type	To Workstation No./Machine Type				
	In	22/4	23/8	24/9	Out
In	--	14	42	63	70
22/4		--	28	49	56
23/8			--	21	28
24/9				--	7
Out					--

Table A5.6 Intra-cell distance matrix for Cell 1 with unidirectional flow (manual material handling)

unit: feet

From Workstation No./ Machine type	To Workstation No./Machine Type						
	In	1/1	2/6	3/10	4/7	5/9	Out
In	--	7	35	49	35	21	--
1/1		--	28	42	28	14	21
2/6			--	28	14	28	35
3/10				--	28	42	49
4/7					--	28	35
5/9						--	7
Out							--

Table A5.7 Intra-cell distance matrix for Cell 2 with unidirectional flow (manual material handling)

unit: feet

From Workstation No./ Machine type	To Workstation No./Machine Type							
	In	6/1	7/2	8/4	9/7	10/8	11/9	Out
In	--	7	35	49	49	35	21	--
6/1		--	28	42	42	28	14	21
7/2			--	28	28	14	28	35
8/4				--	14	28	42	49
9/7					--	28	42	49
10/8						--	28	35
11/9							--	7
Out								--

Table A5.8 Intra-cell distance matrix for Cell 3 with unidirectional flow (manual material handling)

unit: feet

From Workstation No./ Machine type	To Workstation No./Machine Type							
	In	12/11	13/6	14/7	15/10	16/11	17/12	Out
In	--	7	35	56	56	35	21	--
12/11	--	--	28	49	49	28	14	21
13/6	--	--	--	35	35	14	28	35
14/7	--	--	--	--	14	35	49	56
15/10	--	--	--	--	--	35	49	70
16/11	--	--	--	--	--	--	28	35
17/12	--	--	--	--	--	--	--	7
Out	--	--	--	--	--	--	--	--

Table A5.9 Intra-cell distance matrix for Cell 4 with unidirectional flow (manual material handling)

unit: feet

From Workstation No./ Machine type	To Workstation No./Machine Type					
	In	18/3	19/5	20/2	21/6	Out
In	--	7	35	35	21	--
18/3		--	28	28	14	21
19/5			--	14	28	35
20/2				--	28	35
21/6					--	7
Out						--

Table A5.10 Intra-cell distance matrix for Cell 5 with unidirectional flow (manual material handling)

unit: feet

From Workstation No./ Machine type	To Workstation No./Machine Type				
	In	22/4	23/8	24/9	Out
In	--	14	42	35	--
22/4		--	28	28	21
23/8			--	21	28
24/9				--	7
Out					--

Table A5.11 Intra-cell distance matrix for Cell 1 with backtracking flow allowed (material handling by a conveyor)

unit: feet

From Workstation No./ Machine type	To Workstation No./Machine Type								
	In	1/3	2/5	3/2	4/6	5/4	6/8	7/9	Out
In	--	7	21	35	49	63	77	91	--
1/3		--	14	28	42	56	70	84	91
2/5		28	--	14	28	42	56	70	77
3/2		42	28	--	14	28	42	56	63
4/6		56	42	28	--	14	28	42	49
5/4		56	42	28	14	--	14	28	35
6/8		42	28	14	28	28	--	14	21
7/9		28	14	28	42	42	28	--	7
Out									--

Table A5.12 Intra-cell distance matrix for Cell 2 with backtracking flow allowed (material handling by a conveyor)

unit: feet

From Workstation No./ Machine type	To Workstation No./Machine Type							
	In	8/1	9/2	10/4	11/8	12/7	13/9	Out
In	--	7	21	42	77	91	105	--
8/1	--	--	14	35	70	84	98	105
9/2	--	28	--	21	56	70	84	91
10/4	--	49	35	--	35	49	63	70
11/8	--	42	28	21	--	14	28	35
12/7	--	28	14	35	28	--	14	21
13/9	--	14	28	49	42	28	--	7
Out								--

Table A5.13 Intra-cell distance matrix for Cell 3 with backtracking flow allowed (material handling by a conveyor)

unit: feet

From Workstation No./ Machine type	To Workstation No./Machine Type							
	In	14/1	15/6	16/10	17/7	18/8	19/9	Out
In	--	7	28	56	70	91	105	--
14/1		--	21	49	63	84	98	105
15/6		35	--	28	42	63	77	84
16/10		63	42	--	14	35	49	56
17/7		63	42	14	--	21	35	42
18/8		42	21	35	35	--	14	21
19/9		28	21	49	49	28	--	7
Out								--

Table A5.14 Intra-cell distance matrix for Cell 4 with backtracking flow allowed (material handling by a conveyor)

unit: feet

From Workstation No./ Machine type	To Workstation No./Machine Type					
	In	20/11	21/7	22/10	23/12	Out
In	--	14	35	49	63	--
20/11		--	21	35	49	56
21/7		35	--	14	28	35
22/10		35	14	--	14	21
23/12		21	28	28	--	7
Out						--

Table A5.15 Intra-cell distance matrix for Cell 1 with backtracking flow allowed (manual material handling)

unit: feet

From Workstation No./ Machine type	To Workstation No./Machine Type								
	In	1/3	2/5	3/2	4/6	5/4	6/8	7/9	Out
In	--	7	35	49	63	63	49	35	--
1/3		--	28	42	56	56	42	28	21
2/5		28	--	28	42	42	28	14	21
3/2		42	28	--	28	28	14	28	35
4/6		56	42	28	--	14	28	42	49
5/4		56	42	28	14	--	28	42	49
6/8		42	28	14	28	28	--	28	35
7/9		28	14	28	42	42	28	--	7
Out									--

Table A5.16 Intra-cell distance matrix for Cell 2 with backtracking flow allowed (manual material handling)

unit: feet

From Workstation No./ Machine type	To Workstation No./Machine Type							
	In	8/1	9/2	10/4	11/8	12/7	13/9	Out
In	--	7	35	56	49	35	21	--
8/1		--	28	49	42	28	14	21
9/2		28	--	35	28	14	28	35
10/4		49	35	--	21	35	49	56
11/8		42	28	21	--	28	42	49
12/7		28	14	35	28	--	28	35
6/9		14	28	49	42	28	--	7
Out								--

Table A5.17 Intra-cell distance matrix for Cell 3 with backtracking flow allowed (manual material handling)

unit: feet

From Workstation No./ Machine type	To Workstation No./Machine Type							
	In	14/1	15/6	16/10	17/7	18/8	19/9	Out
In	--	7	42	70	70	49	35	--
14/1		--	35	63	63	42	28	21
15/6		35	--	42	42	21	21	28
16/10		63	42	--	14	35	49	56
17/7		63	42	14	--	35	49	56
18/8		42	21	35	35	--	28	35
19/9		28	21	49	49	28	--	7
Out								--

Table A5.18 Intra-cell distance matrix for Cell 4 with backtracking flow allowed (manual material handling)

unit: feet

From Workstation No./ Machine type	To Workstation No./Machine Type					
	In	20/11	21/7	22/10	23/12	Out
In	--	28	49	49	35	--
20/11		--	35	35	21	21
21/7		35	--	14	28	35
22/10		35	14	--	28	35
23/12		21	28	28	--	7
Out						--

Table A5.19 Inter-cell distance matrix for the cellular layout with unidirectional flow

unit: feet

From (Cell)	To (Cell)						
	In	1	2	3	4	5	Out
In	--	21	21	7	21	49	--
1		--	56	28	42	70	63
2		28	--	14	28	42	35
3		28	28	--	42	28	21
4		14	28	14	--	56	49
5		56	56	42	70	--	7
Out							--

Table A5.20 Inter-cell distance matrix for the cellular layout with backtracking flow allowed

unit: feet

From (Cell)	To (Cell)					
	In	1	2	3	4	Out
In	--	49	49	7	7	--
1		--	56	14	28	35
2		98	--	56	56	35
3		70	14	--	28	7
4		70	14	28	--	7
Out						--

Table A5.21 Inter-department distance matrix for the functional layout

unit: feet

From (Dept.)	To (Department)													
	In	1	2	3	4	5	6	7	8	9	10	11	12	Out
In	--	7	49	28	84	42	14	28	21	77	56	49	56	--
1	--	--	70	7	77	21	21	35	28	84	63	70	35	77
2	--	56	--	77	63	91	49	35	56	84	63	14	105	91
3	--	35	91	--	84	7	42	56	49	49	28	77	14	56
4	--	77	49	84	--	70	84	42	49	63	42	35	84	56
5	--	49	105	28	70	--	56	70	63	49	42	91	7	42
6	--	21	35	42	84	56	--	28	21	77	56	35	70	84
7	--	35	35	42	56	56	42	--	21	49	28	21	70	56
8	--	42	56	49	63	63	49	21	--	42	21	42	77	49
9	--	84	98	63	49	49	91	63	70	--	35	84	35	7
10	--	77	77	56	42	42	84	42	49	7	--	63	56	14
11	--	70	28	77	35	63	63	21	42	56	35	--	77	63
12	--	63	119	42	56	28	70	84	77	35	56	105	--	28
Out	--	--	--	--	--	--	--	--	--	--	--	--	--	--

APPENDIX 6
DEPENDENT VARIABLE MOVING AVERAGE PLOTS FOR THE FIRST SET OF EXPERIMENTS

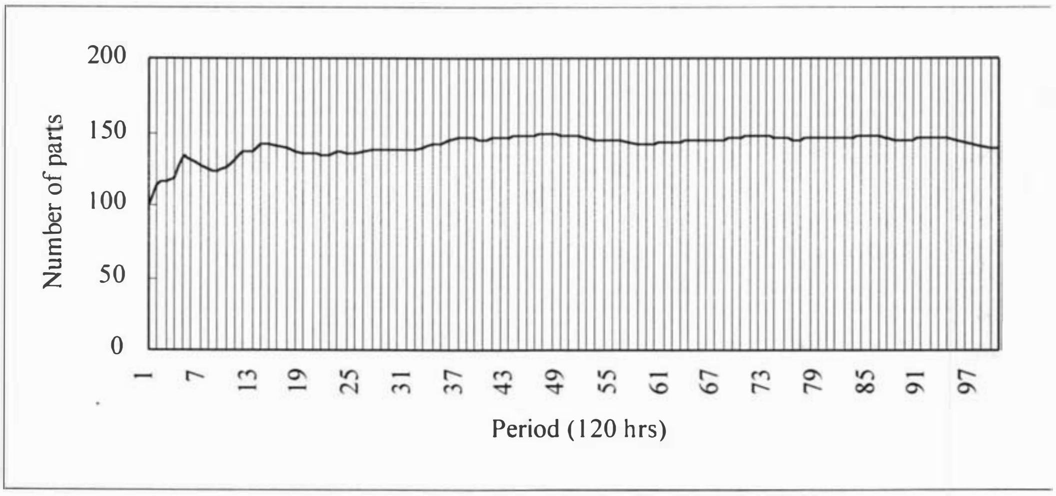

Figure A6.1 Moving average plot for average work-in-process inventory (Cellular layout with SUPC and backtracking flow allowed)

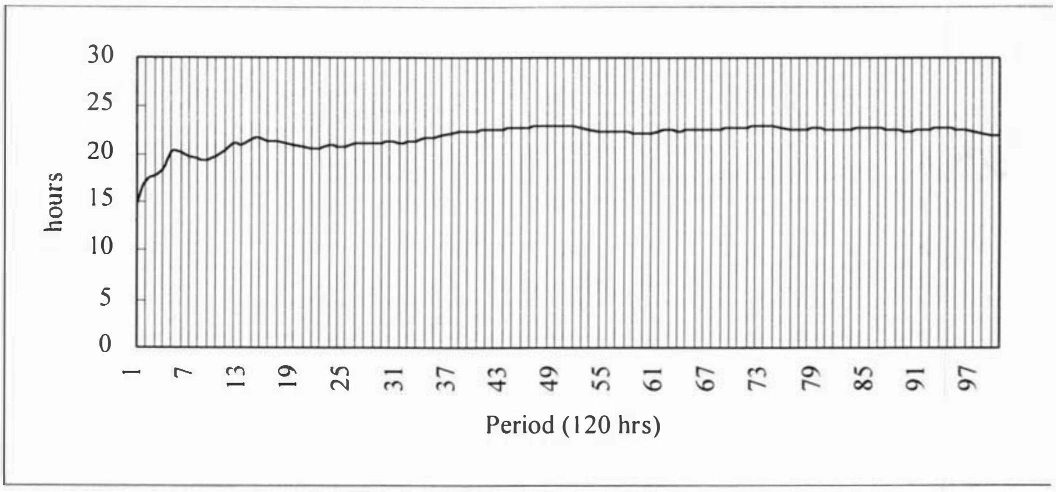

Figure A6.2 Moving average plot for average flow time (Cellular layout with SUPC and backtracking flow allowed)

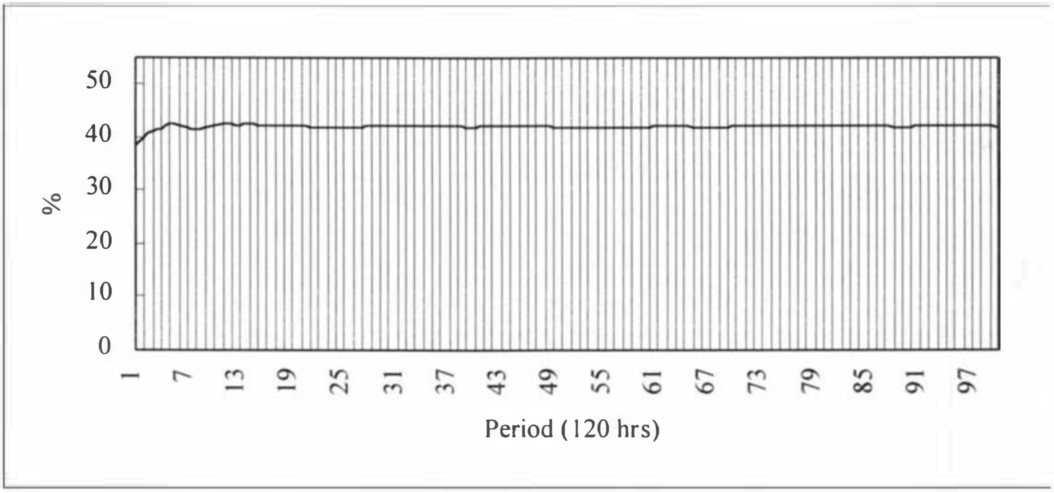

Figure A6.3 Moving average plot for average machine utilization (Cellular layout with SUPC and backtracking flow allowed)

APPENDIX 7
NUMBERS OF INTRA-CELL AND INTER-CELL CONVEYANCE KANBANS

Table A7.1 Numbers of intra-cell Kanbans for Cell 1 with unidirectional flow and SUPC*

Part Type	Demand (lots/day)	Number of Kanbans at Workstation No./Machine type				
		1/1	2/6	3/10	4/7	5/9
5	1.85	3	3	3	3	3
6(a)**	1.39		2	2	2	
11	0.95		4			
15(a)	0.50	5			5	
16(a)	0.62	4			4	

* single-unit production and conveyance

** The letter in ‘ ( ) ‘ indicates the sequence of the cells in which a specific part type was processed.

Table A7.2 Numbers of intra-cell Kanbans for Cell 2 with unidirectional flow and SUPC

Part Type	Demand (lots/day)	Number of Kanbans at Workstation No./Machine type					
		6/1	7/2	8/4	9/7	10/8	11/9
1	1.05	3		3		3	3
2(a)	0.57	5		5	5		
2(c)	0.57				5		
3	1.13	3	3	3	3	3	3
4	0.71	7		7	7		7
6(b)	1.39					2	2
10(a)	0.60			6	6		

Table A7.3 Numbers of intra-cell Kanbans for Cell 3 with unidirectional flow and SUPC

Part Type	Demand (lots/day)	Number of Kanbans at Workstation No./Machine type					
		12/11	13/6	14/7	15/10	16/11	17/12
12	0.69	16		16			16
13	0.71					10	10
14	0.75	19		19	19		
15(b)	0.50	5			5	5	5
16(b)	0.62	4			4	4	4
17	0.57	15		15			15
18	3.09		2	2	2		
19	0.22						14

Table A7.4 Numbers of intra-cell Kanbans for Cell 4 with unidirectional flow and SUPC

Part Type	Demand (lots/day)	Number of Kanbans at Workstation No./Machine type			
		18/3	19/5	20/2	21/6
7(a)	0.88				3
8(a)	1.37	3	3	3	3
9(a)	2.17	2	2		2

Table A7.5 Numbers of intra-cell Kanbans for Cell 5 with unidirectional flow and SUPC

Part Type	Demand (lots/day)	Number of Kanbans at Workstation No./Machine type		
		22/4	23/8	24/9
2(b)	0.57	5	5	
7(b)	0.88	3	3	3
8(b)	1.37	3	3	3
9(b)	2.17	2	2	2
10(b)	0.60	6	6	

Table A7.6 Numbers of intra-cell Kanbans for Cell 1 with unidirectional flow and BPC*

Part Type	Demand (lots/day)	Number of Kanbans at Workstation No./Machine type				
		1/1	2/6	3/10	4/7	5/9
5	1.85	1	2	1	1	1
6(a)	1.39		1	1	1	
11	0.95		1			
15(a)	0.50	1			1	
16(a)	0.62	1			1	

* batch production and conveyance

Table A7.7 Numbers of intra-cell Kanbans for Cell 2 with unidirectional flow and BPC

Part Type	Demand (lots/day)	Number of Kanbans at Workstation No./Machine type					
		6/1	7/2	8/4	9/7	10/8	11/9
1	1.05	1		1		1	1
2(a)	0.57	1		1	1		
2(c)	0.57				1		
3	1.13	1	1	1	1	1	1
4	0.71	1		1	1		1
6(b)	1.39					1	1
10(a)	0.60			1	1		

Table A7.8 Numbers of intra-cell Kanbans for Cell 3 with unidirectional flow and BPC

Part Type	Demand (lots/day)	Number of Kanbans at Workstation No./Machine type					
		12/11	13/6	14/7	15/10	16/11	17/12
12	0.69	2		1			2
13	0.71					1	1
14	0.75	2		1	1		
15(b)	0.50	1			1	1	1
16(b)	0.62	1			1	1	1
17	0.57	1		1			1
18	3.09		1	1	2		
19	0.22						1

Table A7.9 Numbers of intra-cell Kanbans for Cell 4 with unidirectional flow and BPC

Part Type	Demand (lots/day)	Number of Kanbans at Workstation No./Machine type			
		18/3	19/5	20/2	21/6
7(a)	0.88				1
8(a)	1.37	1	1	1	1
9(a)	2.17	1	1		2

Table A7.10 Numbers of intra-cell Kanbans for Cell 5 with unidirectional flow and BPC

Part Type	Demand (lots/day)	Number of Kanbans at Workstation No./Machine type		
		22/4	23/8	24/9
2(b)	0.57	1	1	
7(b)	0.88	1	1	1
8(b)	1.37	1	1	1
9(b)	2.17	1	1	2
10(b)	0.60	1	1	

Table A7.11 Numbers of intra-cell Kanbans for Cell 1 with backtracking flow allowed and SUPC

Part Type	Demand (lots/day)	Number of Kanbans at Workstation No./Machine type						
		1/3	2/5	3/2	4/6	5/4	6/8	7/9
7	0.88				3	3	3	3
8	1.37	3	3	3	3	3	3	3
9	1.08	4	4		4	4	4	4
11	0.95				4			

Table A7.12 Numbers of intra-cell Kanbans for Cell 2 with backtracking flow allowed and SUPC

Part Type	Demand (lot/day)	Number of Kanbans at Workstation No./Machine type					
		8/1	9/2	10/4	11/8	12/7	13/9
1	1.05	3		3	3		3
2	0.72	4		4	4	4	
3	1.13	3	3	3	3	3	3
4	0.83	6		6		6	6
10	0.71			5	5	5	

Table A7.13 Numbers of intra-cell Kanbans for Cell 3 with backtracking flow allowed and SUPC

Part Type	Demand (lots/day)	Number of Kanbans at Workstation No./Machine type					
		14/1	15/6	16/10	17/7	18/8	19/9
5	2.78	2	2	2	2		2
6	1.39		2	2	2	2	2
15(a)	0.50	5					
16(a)	0.62	4					
18	3.09		2	2	2		

Table A7.14 Numbers of intra-cell Kanbans for Cell 4 with backtracking flow allowed and SUPC

Part Type	Demand (lots/day)	Number of Kanbans at Workstation No./Machine type			
		20/11	21/7	22/10	23/12
12	0.69	16	16	16	
13	0.71	10		10	
14	0.75	19	19		19
15(b)	0.50	5	5	5	5
16(b)	0.62	4	4	4	4
17	0.57	15	15	15	
19	0.22			14	

Table A7.15 Numbers of intra-cell Kanbans for Cell 1 with backtracking flow allowed and BPC

Part Type	Demand (lots/day)	Number of Kanbans at Workstation No./Machine type						
		1/3	2/5	3/2	4/6	5/4	6/8	7/9
7	0.88				1	1	1	1
8	1.37	1	1	1	1	1	1	1
9	1.08	1	1		2	1	1	1
11	0.95				1			

Table A7.16 Numbers of intra-cell Kanbans for Cell 2 with backtracking flow allowed and BPC

Part Type	Demand (lots/day)	Number of Kanbans at Workstation No./Machine type					
		8/1	9/2	10/4	11/8	12/7	13/9
1	1.05	1		1	1		1
2	0.72	1		1	1	1	
3	1.13	1	1	1	1	1	1
4	0.83	1		1		1	1
10	0.71			1	1	1	

Table A7.17 Numbers of intra-cell Kanbans for Cell 3 with backtracking flow allowed and BPC

Part Type	Demand (lots/day)	Number of Kanbans at Workstation No./Machine type					
		14/1	15/6	16/10	17/7	18/8	19/9
5	2.78	2	2	2	2		2
6	1.39		1	1	1	1	1
15(a)	0.50	1					
16(a)	0.62	1					
18	3.09		2	2	2		

Table A7.18 Numbers of intra-cell Kanbans for Cell 4 with backtracking flow allowed and BPC

Part Type	Demand (lots/day)	Number of Kanbans at Workstation No./Machine type			
		20/11	21/7	22/10	23/12
12	0.69	1	2	2	
13	0.71	1		1	
14	0.75	1	2		1
15(b)	0.50	1	1	1	1
16(b)	0.62	1	1	1	1
17	0.57	1	1	1	
19	0.22			1	

Table A7.19 Numbers of inter-cell Kanbans for the cellular layout with unidirectional flow

Part Type	Demand (lots/day)	Number of Inter-cell Kanbans at Cell No.				
		1	2	3	4	5
1	1.05		4			
2	0.57		2			1
3	1.13		5			
4	0.71		14			
5	1.85	5				
6	1.39	2	2			
7	0.88				1	2
8	1.37				4	4
9	2.17				3	3
10	0.60		3			2
11	0.95	2				
12	0.69			3		
13	0.71			1		
14	0.75			4		
15	0.50	1		2		
16	0.62	1		2		
17	0.57			2		
18	3.09			3		
19	0.22			1		

Note: The lead times based on single-unit production & conveyance were used for calculating the required numbers of Kanbans.

Table A7.20 Numbers of inter-cell Kanbans for the cellular layout with backtracking flow allowed

Part Type	Demand (lots/day)	Number of Inter-cell Kanbans at Cell No.			
		1	2	3	4
1	1.05		2		
2	0.72		3		
3	1.13		3		
4	0.83		11		
5	2.78			5	
6	1.39			2	
7	0.88	2			
8	1.37	4			
9	1.08	24			
10	0.71		4		
11	0.95	9			
12	0.69				7
13	0.71				1
14	0.75				6
15	0.50			1	2
16	0.62			1	1
17	0.57				3
18	3.09			3	
19	0.22				1

Note: The lead times based on single-unit production & conveyance were used for calculating the required numbers of Kanbans.

Table A7.21 Numbers of inter-department Kanbans for the functional layout

Part Type	Number of Inter-department Kanbans at Department No.(i.e. Machine Type)											
	1	2	3	4	5	6	7	8	9	10	11	12
1	1			1				1	1			
2	1			1			1	1				
3	1	1		2			2	2	2			
4	1			2			1		1			
5	2					2	2		2	2		
6						1	1	2	2	1		
7				1		1		1	1			
8		1	2	2	2	1		1	1			
9			1	2	1	1		2	1			
10				1			1	1				
11						2						
12							1				1	2
13											1	2
14							2			2	2	
15	1						1			1	1	1
16	1						1			1	1	2
17							1				1	2
18						2	2			2		
19												1

APPENDIX 8
SUMMARY OF THE SIMULATION OUTPUT FOR THE FIRST SET OF EXPERIMENTS

Table A8.1 Simulation output summary on AWIP for the first set of experiments at the high PFSRF level

Dependent variable	MHS level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average work-in-process inventory (AWIP)	LLL	FL	22	58.38 ± 1.28	8.35
		CBB	22	61.98 ± 2.01	20.50
		CBU	22	63.92 ± 1.99	20.20
		CSB	22	143.84 ± 13.99	995.08
		CSU	22	123.50 ± 12.03	736.20
	LLH	FL	22	58.38 ± 1.28	8.35
		CBB	22	61.98 ± 2.01	20.50
		CBU	22	63.92 ± 1.99	20.20
		CSB	22	149.18 ± 14.97	1140.28
		CSU	22	132.28 ± 13.27	895.94
	LHH	FL	22	58.38 ± 1.28	8.35
		CBB	22	60.74 ± 2.11	22.54
		CBU	22	62.88 ± 1.77	15.99
		CSB	22	149.18 ± 14.97	1140.28
		CSU	22	132.28 ± 13.27	895.94
	HLL	FL	22	58.11 ± 1.36	9.39
		CBB	22	61.60 ± 2.10	22.33
		CBU	22	63.81 ± 1.77	15.98
		CSB	22	136.92 ± 10.14	523.04
		CSU	22	124.68 ± 12.54	799.44
	HLH	FL	22	58.11 ± 1.36	9.39
		CBB	22	61.60 ± 2.10	22.33
		CBU	22	63.81 ± 1.77	15.98
		CSB	22	145.09 ± 12.79	832.44
		CSU	22	129.72 ± 11.91	721.61
	HHH	FL	22	58.11 ± 1.36	9.39
		CBB	22	60.63 ± 1.96	19.49
		CBU	22	62.73 ± 1.89	18.24
		CSB	22	145.09 ± 12.79	832.44
		CSU	22	129.72 ± 11.91	721.61

Table A8.2 Simulation output summary on AFT for the first set of experiments at the high PFSRF level

Dependent variable	MHS level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average flow time (AFT)	LLL	FL	22	9.18 ± 0.13	0.0838
		CBB	22	9.69 ± 0.24	0.2883
		CBU	22	9.97 ± 0.21	0.2305
		CSB	22	22.70 ± 2.14	23.18
		CSU	22	19.32 ± 1.80	16.46
	LLH	FL	22	9.18 ± 0.13	0.0838
		CBB	22	9.69 ± 0.24	0.2883
		CBU	22	9.97 ± 0.21	0.2305
		CSB	22	23.41 ± 2.24	25.61
		CSU	22	20.74 ± 2.08	21.98
	LHH	FL	22	9.18 ± 0.13	0.0838
		CBB	22	9.94 ± 0.25	0.3227
		CBU	22	9.81 ± 0.18	0.1576
		CSB	22	23.41 ± 2.24	25.61
		CSU	22	20.74 ± 2.08	21.98
	HLL	FL	22	9.14 ± 0.13	0.0817
		CBB	22	9.62 ± 0.25	0.3109
		CBU	22	9.95 ± 0.18	0.1590
		CSB	22	21.71 ± 1.58	12.68
		CSU	22	19.57 ± 2.13	23.08
	HLH	FL	22	9.14 ± 0.13	0.0817
		CBB	22	9.62 ± 0.25	0.3109
		CBU	22	9.95 ± 0.18	0.1590
		CSB	22	22.92 ± 1.98	19.94
		CSU	22	20.37 ± 1.70	14.64
	HHH	FL	22	9.14 ± 0.13	0.0817
		CBB	22	9.47 ± 0.23	0.2602
		CBU	22	9.78 ± 0.20	0.2033
		CSB	22	22.92 ± 1.98	19.94
		CSU	22	20.37 ± 1.70	14.64

Table A8.3 Simulation output summary on ASPTR for the first set of experiments at the high PFSRF level

Dependent variable	MHS level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average setup to processing time ratio (ASPTR)	LLL	FL	22	2.52 ± 0.029	0.00430
		CBB	22	1.91 ± 0.028	0.00409
		CBU	22	1.95 ± 0.020	0.00195
		CSB	22	3.86 ± 0.072	0.02618
		CSU	22	3.68 ± 0.056	0.01593
	LLH	FL	22	2.52 ± 0.029	0.00430
		CBB	22	1.91 ± 0.028	0.00409
		CBU	22	1.95 ± 0.020	0.00195
		CSB	22	3.85 ± 0.063	0.02002
		CSU	22	3.74 ± 0.050	0.01259
	LHH	FL	22	2.52 ± 0.029	0.00430
		CBB	22	1.91 ± 0.028	0.00407
		CBU	22	1.95 ± 0.020	0.00214
		CSB	22	3.85 ± 0.063	0.02002
		CSU	22	3.74 ± 0.050	0.01259
	HLL	FL	22	2.53 ± 0.029	0.00435
		CBB	22	1.91 ± 0.026	0.00340
		CBU	22	1.95 ± 0.024	0.00293
		CSB	22	3.85 ± 0.071	0.02530
		CSU	22	3.69 ± 0.052	0.01383
	HLH	FL	22	2.53 ± 0.029	0.00435
		CBB	22	1.91 ± 0.026	0.00340
		CBU	22	1.95 ± 0.024	0.00293
		CSB	22	3.85 ± 0.041	0.00839
		CSU	22	3.70 ± 0.061	0.01883
	HHH	FL	22	2.55 ± 0.029	0.00435
		CBB	22	1.90 ± 0.022	0.00257
		CBU	22	1.95 ± 0.023	0.00273
		CSB	22	3.85 ± 0.041	0.00839
		CSU	22	3.70 ± 0.061	0.01883

Table A8.4 Simulation output summary on AWIP for the first set of experiments at the medium PFSRF level

Dependent variable	MHS level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average work-in-process inventory (AWIP)	LLL	FL	22	63.90 ± 1.97	19.69
		CBB	22	62.23 ± 1.56	12.42
		CBU	22	62.14 ± 1.31	8.76
		CSB	22	111.28 ± 8.07	315.80
		CSU	22	87.20 ± 4.30	94.12
	LLH	FL	22	63.90 ± 1.97	19.69
		CBB	22	62.23 ± 1.56	12.42
		CBU	22	62.14 ± 1.31	8.76
		CSB	22	112.17 ± 8.27	347.87
		CSU	22	92.46 ± 5.40	148.06
	LHH	FL	22	63.90 ± 1.97	19.69
		CBB	22	60.67 ± 1.68	14.33
		CBU	22	60.71 ± 1.40	9.93
		CSB	22	112.77 ± 8.27	347.87
		CSU	22	92.46 ± 5.40	148.06
	HLL	FL	22	63.62 ± 1.74	15.42
		CBB	22	61.30 ± 1.55	12.17
		CBU	22	62.81 ± 1.38	9.72
		CSB	22	111.53 ± 8.06	330.68
		CSU	22	88.98 ± 4.42	99.43
	HLH	FL	22	63.62 ± 1.74	15.42
		CBB	22	61.30 ± 1.55	12.17
		CBU	22	62.81 ± 1.38	9.72
		CSB	22	116.46 ± 9.91	499.11
		CSU	22	91.89 ± 5.72	166.57
	HHH	FL	22	63.62 ± 1.74	15.42
		CBB	22	60.20 ± 1.65	13.90
		CBU	22	61.22 ± 1.39	9.82
		CSB	22	116.46 ± 9.91	499.11
		CSU	22	91.89 ± 5.72	166.57

Table A8.5 Simulation output summary on AFT for the first set of experiments at the medium PFSRF level

Dependent variable	MHS level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average flow time (AFT)	LLL	FL	22	8.39 ± 0.16	0.1254
		CBB	22	8.17 ± 0.15	0.1145
		CBU	22	8.19 ± 0.11	0.0564
		CSB	22	14.50 ± 0.95	4.43
		CSU	22	11.46 ± 0.47	1.12
	LLH	FL	22	8.39 ± 0.16	0.1254
		CBB	22	8.17 ± 0.15	0.1145
		CBU	22	8.19 ± 0.11	0.0564
		CSB	22	14.80 ± 0.96	4.73
		CSU	22	12.19 ± 0.62	1.95
	LHH	FL	22	8.39 ± 0.16	0.1254
		CBB	22	7.96 ± 0.16	0.1296
		CBU	22	8.00 ± 0.11	0.0623
		CSB	22	14.80 ± 0.96	4.73
		CSU	22	12.19 ± 0.62	1.95
	HLL	FL	22	8.35 ± 0.13	0.0858
		CBB	22	8.05 ± 0.15	0.1174
		CBU	22	8.28 ± 0.11	0.0593
		CSB	22	14.57 ± 0.94	4.51
		CSU	22	11.70 ± 0.49	1.23
	HLH	FL	22	8.35 ± 0.13	0.0858
		CBB	22	8.05 ± 0.15	0.1174
		CBU	22	8.28 ± 0.11	0.0593
		CSB	22	15.17 ± 1.17	6.99
		CSU	22	12.10 ± 0.65	2.17
	HHH	FL	22	8.35 ± 0.13	0.0858
		CBB	22	7.90 ± 0.16	0.1235
		CBU	22	8.06 ± 0.11	0.0645
		CSB	22	15.17 ± 1.17	6.99
		CSU	22	12.10 ± 0.65	2.17

Table A8.6 Simulation output summary on ASPTR for the first set of experiments at the medium PFSRF level

Dependent variable	MHS level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average setup to processing time ratio (ASPTR)	LLL	FL	22	2.13 ± 0.024	0.00294
		CBB	22	1.36 ± 0.016	0.00123
		CBU	22	1.38 ± 0.013	0.00087
		CSB	22	2.65 ± 0.036	0.00631
		CSU	22	2.49 ± 0.027	0.00367
	LLH	FL	22	2.13 ± 0.024	0.00294
		CBB	22	1.36 ± 0.016	0.00123
		CBU	22	1.38 ± 0.013	0.00087
		CSB	22	2.63 ± 0.042	0.00912
		CSU	22	2.52 ± 0.027	0.00360
	LHH	FL	22	2.13 ± 0.024	0.00294
		CBB	22	1.36 ± 0.017	0.00144
		CBU	22	1.38 ± 0.015	0.00117
		CSB	22	2.63 ± 0.042	0.00912
		CSU	22	2.52 ± 0.027	0.00360
	HLL	FL	22	2.13 ± 0.020	0.00212
		CBB	22	1.35 ± 0.015	0.00117
		CBU	22	1.39 ± 0.015	0.00121
		CSB	22	2.65 ± 0.031	0.00479
		CSU	22	2.48 ± 0.029	0.00418
	HLH	FL	22	2.13 ± 0.020	0.00212
		CBB	22	1.35 ± 0.015	0.00117
		CBU	22	1.39 ± 0.015	0.00121
		CSB	22	2.66 ± 0.035	0.00633
		CSU	22	2.50 ± 0.031	0.00475
	HHH	FL	22	2.13 ± 0.020	0.00212
		CBB	22	1.35 ± 0.014	0.00096
		CBU	22	1.38 ± 0.009	0.00041
		CSB	22	2.66 ± 0.035	0.00633
		CSU	22	2.50 ± 0.031	0.00475

Table A8.7 Simulation output summary on AWIP for the first set of experiments at the low PFSRF level

Dependent variable	MHS level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average work-in-process inventory (AWIP)	LLL	FL	22	96.44 ± 1.98	19.96
		CBB	22	71.48 ± 1.90	18.45
		CBU	22	71.77 ± 2.02	20.82
		CSB	22	82.16 ± 4.29	93.67
		CSU	22	64.99 ± 2.68	36.45
	LLH	FL	22	96.44 ± 1.98	19.96
		CBB	22	71.48 ± 1.90	18.45
		CBU	22	71.77 ± 2.02	20.82
		CSB	22	84.58 ± 4.48	102.01
		CSU	22	67.64 ± 3.34	56.80
	LHH	FL	22	96.44 ± 1.98	19.96
		CBB	22	69.52 ± 1.96	19.52
		CBU	22	69.62 ± 2.01	20.46
		CSB	22	84.58 ± 4.48	102.01
		CSU	22	67.64 ± 3.34	56.80
	HLL	FL	22	94.57 ± 1.84	17.27
		CBB	22	71.53 ± 1.86	17.67
		CBU	22	72.09 ± 2.15	23.55
		CSB	22	82.65 ± 4.69	111.69
		CSU	22	65.70 ± 3.08	48.38
	HLH	FL	22	94.57 ± 1.84	17.27
		CBB	22	71.53 ± 1.86	17.67
		CBU	22	72.09 ± 2.15	23.55
		CSB	22	84.42 ± 4.78	116.28
		CSU	22	67.63 ± 3.25	53.60
	HHH	FL	22	94.57 ± 1.84	17.27
		CBB	22	69.27 ± 1.75	15.57
		CBU	22	69.48 ± 2.06	21.52
		CSB	22	84.42 ± 4.78	116.28
		CSU	22	67.63 ± 3.25	53.60

Table A8.8 Simulation output summary on AFT for the first set of experiments at the low PFSRF level

Dependent variable	MHS level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average flow time (AFT)	LLL	FL	22	8.26 ± 0.12	0.074
		CBB	22	6.13 ± 0.12	0.079
		CBU	22	6.15 ± 0.11	0.065
		CSB	22	7.04 ± 0.33	0.563
		CSU	22	5.57 ± 0.18	0.158
	LLH	FL	22	8.26 ± 0.12	0.074
		CBB	22	6.13 ± 0.12	0.079
		CBU	22	6.15 ± 0.11	0.065
		CSB	22	7.24 ± 0.35	0.632
		CSU	22	5.79 ± 0.23	0.271
	LHH	FL	22	8.26 ± 0.12	0.074
		CBB	22	5.96 ± 0.13	0.089
		CBU	22	5.96 ± 0.12	0.069
		CSB	22	7.24 ± 0.35	0.632
		CSU	22	5.79 ± 0.23	0.271
	HLL	FL	22	8.10 ± 0.11	0.061
		CBB	22	6.14 ± 0.12	0.077
		CBU	22	6.17 ± 0.12	0.079
		CSB	22	7.08 ± 0.36	0.659
		CSU	22	5.63 ± 0.21	0.225
	HLH	FL	22	8.10 ± 0.11	0.061
		CBB	22	6.14 ± 0.12	0.077
		CBU	22	6.17 ± 0.12	0.079
		CSB	22	7.23 ± 0.37	0.702
		CSU	22	5.79 ± 0.22	0.257
	HHH	FL	22	8.10 ± 0.11	0.061
		CBB	22	5.94 ± 0.11	0.065
		CBU	22	5.95 ± 0.12	0.071
		CSB	22	7.23 ± 0.37	0.702
		CSU	22	5.79 ± 0.22	0.257

Table A8.9 Simulation output summary on ASPTR for the first set of experiments at the low PFSRF level

Dependent variable	MHS level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average setup to processing time ratio (ASPTR)	LLL	FL	22	1.71 ± 0.018	0.00166
		CBB	22	0.54 ± 0.0048	0.00012
		CBU	22	0.55 ± 0.0038	0.00008
		CSB	22	1.02 ± 0.0092	0.00043
		CSU	22	0.94 ± 0.0068	0.00023
	LLH	FL	22	1.71 ± 0.018	0.00166
		CBB	22	0.54 ± 0.0048	0.00012
		CBU	22	0.55 ± 0.0038	0.00008
		CSB	22	1.03 ± 0.0081	0.00033
		CSU	22	0.95 ± 0.0075	0.00028
	LHH	FL	22	1.71 ± 0.018	0.00166
		CBB	22	0.54 ± 0.0038	0.00007
		CBU	22	0.55 ± 0.0053	0.00014
		CSB	22	1.03 ± 0.0081	0.00033
		CSU	22	0.95 ± 0.0075	0.00028
	HLL	FL	22	1.69 ± 0.025	0.0032
		CBB	22	0.54 ± 0.0053	0.00014
		CBU	22	0.55 ± 0.0045	0.00010
		CSB	22	1.02 ± 0.0092	0.00043
		CSU	22	0.94 ± 0.0060	0.00019
	HLH	FL	22	1.69 ± 0.025	0.0032
		CBB	22	0.54 ± 0.0053	0.00014
		CBU	22	0.55 ± 0.0045	0.00010
		CSB	22	1.03 ± 0.0080	0.00033
		CSU	22	0.95 ± 0.0063	0.00020
	HHH	FL	22	1.69 ± 0.025	0.0032
		CBB	22	0.54 ± 0.0045	0.00010
		CBU	22	0.55 ± 0.0041	0.00009
		CSB	22	1.03 ± 0.0080	0.00033
		CSU	22	0.95 ± 0.0063	0.00020

APPENDIX 9
SUMMARY OF OVERALL *F*-TEST RESULTS FOR THE FIRST SET OF EXPERIMENTS

Table A9.1 Overall *F*-test results of the first set of experiments at the high PFSRF level

Dependent Variable	MHS Level	Mean Value					*F*	*p*
		FL	CBB	CBU	CSB	CSU		
AWIP	LLL	58.38	61.98	63.92	-	-	10.62	< 0.001
	LLH	58.38	61.98	63.92	-	-	10.62	< 0.001
	LHH	58.38	60.74	62.88	-	-	7.11	0.002
	HLL	58.11	61.60	63.81	-	-	11.45	< 0.001
	HLH	58.11	61.60	63.81	-	-	11.45	< 0.001
	HHH	58.11	60.63	62.73	-	-	7.50	0.001
AFT	LLL	9.18	9.69	9.97	-	-	17.34	< 0.001
	LLH	9.18	9.69	9.97	-	-	17.34	< 0.001
	LHH	9.18	9.49	9.81	-	-	11.56	< 0.001
	HLL	9.14	9.62	9.95	-	-	19.85	< 0.001
	HLH	9.14	9.62	9.95	-	-	19.85	< 0.001
	HHH	9.14	9.47	9.78	-	-	12.51	< 0.001
ASPTR	LLL	2.52	1.91	1.95	-	-	748.3	< 0.001
	LLH	2.52	1.91	1.95	-	-	748.3	< 0.001
	LHH	2.52	1.91	1.95	-	-	739.1	< 0.001
	HLL	2.53	1.91	1.95	-	-	750.7	< 0.001
	HLH	2.53	1.91	1.95	-	-	750.7	< 0.001
	HHH	2.53	1.90	1.95	-	-	835.8	< 0.001

Table A9.2 Overall *F*-test results of the first set of experiments at the medium PFSRF level

Dependent Variable	MHS Level	Mean Value						
		FL	CBB	CBU	CSB	CSU	*F*	*p*
AWIP	LLL	63.90	62.23	62.14	-	87.20	97.78	< 0.001
	LLH	63.90	62.23	62.14	-	92.46	103.0	< 0.001
	LHH	63.90	60.67	60.71	-	92.46	109.0	< 0.001
	HLL	63.62	61.30	62.81	-	88.98	112.7	< 0.001
	HLH	63.62	61.30	62.81	-	91.89	93.07	< 0.001
	HHH	63.62	60.20	61.22	-	91.89	98.48	< 0.001
AFT	LLL	8.39	8.17	8.19	-	11.46	160.7	< 0.001
	LLH	8.39	8.17	8.19	-	12.19	152.3	< 0.001
	LHH	8.39	7.96	8.00	-	12.19	162.3	< 0.001
	HLL	8.35	8.05	8.28	-	11.70	178.9	< 0.001
	HLH	8.35	8.05	8.28	-	12.10	136.1	< 0.001
	HHH	8.35	7.90	8.06	-	12.10	144.6	< 0.001
ASPTR	LLL	2.13	1.36	1.38	-	2.49	3220	< 0.001
	LLH	2.13	1.36	1.38	-	2.52	3372	< 0.001
	LHH	2.13	1.36	1.38	-	2.52	3189	< 0.001
	HLL	2.13	1.35	1.39	-	2.48	3186	< 0.001
	HLH	2.13	1.35	1.39	-	2.50	3042	< 0.001
	HHH	2.13	1.35	1.38	-	2.50	3417	< 0.001

Table A9.3 Overall *F*-test results of the first set of experiments at the low PFSRF level

Dependent Variable	MHS Level	Mean Value						
		FL	CBB	CBU	CSB	CSU	*F*	*p*
AWIP	LLL	96.44	71.48	71.77	82.16	64.99	88.04	< 0.001
	LLH	96.44	71.48	71.77	84.58	67.64	72.08	< 0.001
	LHH	96.44	69.52	69.62	84.58	67.64	79.47	< 0.001
	HLL	94.57	71.53	72.09	82.65	65.70	65.67	< 0.001
	HLH	94.57	71.53	72.09	84.42	67.63	60.22	< 0.001
	HHH	94.57	69.27	69.48	84.42	67.63	69.63	< 0.001
AFT	LLL	8.26	6.13	6.15	7.04	5.57	129.6	< 0.001
	LLH	8.26	6.13	6.15	7.24	5.79	102.1	< 0.001
	LHH	8.26	5.96	5.96	7.24	5.79	111.5	< 0.001
	HLL	8.10	6.14	6.17	7.08	5.63	95.13	< 0.001
	HLH	8.10	6.14	6.17	7.23	5.79	85.04	< 0.001
	HHH	8.10	5.94	5.95	7.23	5.79	98.30	< 0.001
ASPTR	LLL	1.71	0.54	0.55	1.02	0.94	9882	< 0.001
	LLH	1.71	0.54	0.55	1.03	0.95	10081	< 0.001
	LHH	1.71	0.54	0.55	1.03	0.95	9999	< 0.001
	HLL	1.69	0.54	0.55	1.02	0.94	5990	< 0.001
	HLH	1.69	0.54	0.55	1.03	0.95	6124	< 0.001
	HHH	1.69	0.54	0.55	1.03	0.95	6237	< 0.001

APPENDIX 10
RESULTS OF PLANNED COMPARISONS FOR THE FIRST SET OF EXPERIMENTS

Table A10.1 Results of planned comparisons for AWIP at the high PFSRF level

Dependent Variable	MHS Level	Hypotheses Tested	*df**	*F*	*p*
AWIP	LLL	$H_0(1a)$	42	2.04	0.16
		$H_0(3)$	59	24.76	< 0.001
	LLH	$H_0(1a)$	42	2.04	0.16
		$H_0(3)$	59	24.76	< 0.001
	LHH	$H_0(1a)$	41	2.61	0.11
		$H_0(3)$	58	14.34	< 0.001
	HLL	$H_0(1a)$	41	2.81	0.10
		$H_0(3)$	56	24.55	< 0.001
	HLH	$H_0(1a)$	41	2.81	0.10
		$H_0(3)$	56	24.55	< 0.001
	HHH	$H_0(1a)$	42	2.56	0.12
		$H_0(3)$	56	14.92	< 0.001

* *df* = degrees of freedom

Table A10.2 Results of planned comparisons for AFT at the high PFSRF level

Dependent Variable	MHS Level	Hypotheses Tested	*df*	*F*	*p*
AFT	LLL	$H_0(1a)$	41	3.42	0.072
		$H_0(3)$	62	42.72	< 0.001
	LLH	$H_0(1a)$	41	3.42	0.072
		$H_0(3)$	62	42.72	< 0.001
	LHH	$H_0(1a)$	38	4.72	0.036
		$H_0(3)$	58	23.65	< 0.001
	HLL	$H_0(1a)$	38	4.99	0.032
		$H_0(3)$	58	46.15	< 0.001
	HLH	$H_0(1a)$	38	4.99	0.032
		$H_0(3)$	58	46.15	< 0.001
	HHH	$H_0(1a)$	41	4.66	0.037
		$H_0(3)$	61	26.32	< 0.001

Table A10.3 Results of planned comparisons for ASPTR at the high PFSRF level

Dependent Variable	MHS Level	Hypotheses Tested	*df*	*F*	*p*
ASPTR	LLL	$H_0(1a)$	37	3.79	0.059
		$H_0(3)$	36	1328	< 0.001
	LLH	$H_0(1a)$	37	3.79	0.059
		$H_0(3)$	36	1328	< 0.001
	LHH	$H_0(1a)$	38	6.89	0.012
		$H_0(3)$	36	1321	< 0.001
	HLL	$H_0(1a)$	42	6.35	0.016
		$H_0(3)$	37	1346	< 0.001
	HLH	$H_0(1a)$	42	6.35	0.016
		$H_0(3)$	37	1346	< 0.001
	HHH	$H_0(1a)$	42	7.10	0.011
		$H_0(3)$	34	1416	< 0.001

Table A10.4 Results of planned comparisons for AWIP at the medium PFSRF level

Dependent Variable	MHS Level	Hypotheses Tested	*df*	*F*	*p*
AWIP	LLL	$H_0(1a)$	41	0.0078	n.s.
		$H_0(2)$	23	138.4	< 0.001
		$H_0(3)$	33	2.59	0.12
	LLH	$H_0(1a)$	41	0.0078	n.s.
		$H_0(2)$	23	131.4	< 0.001
		$H_0(3)$	33	2.59	0.12
	LHH	$H_0(1a)$	41	0.0011	n.s.
		$H_0(2)$	23	144.1	< 0.001
		$H_0(3)$	34	8.82	0.005
	HLL	$H_0(1a)$	41	2.29	0.14
		$H_0(2)$	23	151.9	< 0.001
		$H_0(3)$	36	2.57	0.12
	HLH	$H_0(1a)$	41	2.29	0.14
		$H_0(2)$	22	113.8	< 0.001
		$H_0(3)$	36	2.57	0.12
	HHH	$H_0(1a)$	41	0.97	n.s.
		$H_0(2)$	23	124.0	< 0.001
		$H_0(3)$	37	8.76	0.005

*n.s. = not statistically significant

Table A10.5 Results of planned comparisons for AFT at the medium PFSRF level

Dependent Variable	MHS Level	Hypotheses Tested	df	F	p
AFT	LLL	H_0(1a)	38	0.038	n.s.
		H_0(2)	23	203.3	< 0.001
		H_0(3)	35	5.50	0.025
	LLH	H_0(1a)	38	0.038	n.s.
		H_0(2)	22	177.2	< 0.001
		H_0(3)	35	5.50	0.025
	LHH	H_0(1a)	37	0.14	n.s.
		H_0(2)	22	194.9	< 0.001
		H_0(3)	37	20.9	< 0.001
	HLL	H_0(1a)	38	6.38	0.016
		H_0(2)	23	215.9	< 0.001
		H_0(3)	42	5.74	0.021
	HLH	H_0(1a)	38	6.38	0.016
		H_0(2)	22	153.6	< 0.001
		H_0(3)	42	5.74	0.021
	HHH	H_0(1a)	38	3.06	0.088
		H_0(2)	22	167.8	< 0.001
		H_0(3)	43	22.02	< 0.001

*n.s. = not statistically significant

Table A10.6 Results of planned comparisons for ASPTR at the medium PFSRF level

Dependent Variable	MHS Level	Hypotheses Tested	df	F	p
ASPTR	LLL	H_0(1a)	41	2.80	0.10
		H_0(2)	27	6615	< 0.001
		H_0(3)	29	3727	< 0.001
	LLH	H_0(1a)	41	2.80	0.10
		H_0(2)	27	7065	< 0.001
		H_0(3)	29	3727	< 0.001
	LHH	H_0(1a)	42	3.08	0.087
		H_0(2)	29	6860	< 0.001
		H_0(3)	31	3600	< 0.001
	HLL	H_0(1a)	42	14.76	< 0.001
		H_0(2)	27	5730	< 0.001
		H_0(3)	33	4679	< 0.001
	HLH	H_0(1a)	42	14.76	< 0.001
		H_0(2)	26	5238	< 0.001
		H_0(3)	33	4679	< 0.001
	HHH	H_0(1a)	36	13.55	< 0.001
		H_0(2)	24	5502	< 0.001
		H_0(3)	28	5164	< 0.001

Table A10.7 Results of planned comparisons for AWIP at the low PFSRF level

Dependent Variable	MHS Level	Hypotheses Tested	*df*	*F*	*p*
AWIP	LLL	$H_0(1a)$	42	0.049	n.s.
		$H_0(1b)$	35	49.88	< 0.001
		$H_0(2)$	55	1.97	0.17
		$H_0(3)$	44	409.4	< 0.001
	LLH	$H_0(1a)$	42	0.05	n.s.
		$H_0(1b)$	39	39.78	< 0.001
		$H_0(2)$	57	8.93	0.004
		$H_0(3)$	42	455.0	< 0.001
	LHH	$H_0(1a)$	42	0.005	n.s.
		$H_0(1b)$	39	39.78	< 0.001
		$H_0(2)$	58	18.94	< 0.001
		$H_0(3)$	42	530.4	< 0.001
	HLL	$H_0(1a)$	41	0.17	n.s.
		$H_0(1b)$	36	39.52	< 0.001
		$H_0(2)$	54	2.45	0.12
		$H_0(3)$	52	343.1	< 0.001
	HLH	$H_0(1a)$	41	0.17	n.s.
		$H_0(1b)$	37	36.51	< 0.001
		$H_0(2)$	54	7.40	0.009
		$H_0(3)$	45	413.2	< 0.001
	HHH	$H_0(1a)$	41	0.028	n.s.
		$H_0(1b)$	37	36.51	< 0.001
		$H_0(2)$	53	18.79	< 0.001
		$H_0(3)$	43	526.0	< 0.001

*n.s. = not statistically significant

Table A10.8 Results of planned comparisons for AFT at the low PFSRF level

Dependent Variable	MHS Level	Hypotheses Tested	*df*	*F*	*p*
AFT	LLL	$H_0(1a)$	42	0.046	n.s.
		$H_0(1b)$	32	66.28	< 0.001
		$H_0(2)$	45	2.77	0.10
		$H_0(3)$	50	709.4	< 0.001
	LLH	$H_0(1a)$	42	0.046	n.s.
		$H_0(1b)$	36	50.97	< 0.001
		$H_0(2)$	48	12.08	0.001
		$H_0(3)$	41	894.8	< 0.001
	LHH	$H_0(1a)$	41	0.0003	n.s.
		$H_0(1b)$	36	50.97	< 0.001
		$H_0(2)$	49	25.53	< 0.001
		$H_0(3)$	43	1017	< 0.001
	HLL	$H_0(1a)$	42	0.20	n.s.
		$H_0(1b)$	34	52.51	< 0.001
		$H_0(2)$	46	3.25	0.078
		$H_0(3)$	59	591.9	< 0.001
	HLH	$H_0(1a)$	42	0.20	n.s.
		$H_0(1b)$	35	47.04	< 0.001
		$H_0(2)$	46	9.96	0.003
		$H_0(3)$	47	826.6	< 0.001
	HHH	$H_0(1a)$	42	0.012	n.s.
		$H_0(1b)$	35	47.04	< 0.001
		$H_0(2)$	44	25.59	< 0.001
		$H_0(3)$	44	1067	< 0.001

*n.s. = not statistically significant

Table A10.9 Results of planned comparisons for ASPTR at the low PFSRF level

Dependent Variable	MHS Level	Hypotheses Tested	d*f*	*F*	*p*
ASPTR	LLL	$H_0(1a)$	40	10.32	0.003
		$H_0(1b)$	39	229.8	< 0.001
		$H_0(2)$	60	19275	< 0.001
		$H_0(3)$	22	17340	< 0.001
	LLH	$H_0(1a)$	40	10.32	0.003
		$H_0(1b)$	42	255.1	< 0.001
		$H_0(2)$	65	21344	< 0.001
		$H_0(3)$	22	17340	< 0.001
	LHH	$H_0(1a)$	38	14.25	< 0.001
		$H_0(1b)$	42	255.1	< 0.001
		$H_0(2)$	67	20816	< 0.001
		$H_0(3)$	22	17292	< 0.001
	HLL	$H_0(1a)$	41	10.76	0.002
		$H_0(1b)$	36	240.1	< 0.001
		$H_0(2)$	62	19226	< 0.001
		$H_0(3)$	22	8892	< 0.001
	HLH	$H_0(1a)$	41	10.76	0.002
		$H_0(1b)$	40	243.3	< 0.001
		$H_0(2)$	70	22090	< 0.001
		$H_0(3)$	22	8892	< 0.001
	HHH	$H_0(1a)$	42	17.46	< 0.001
		$H_0(1b)$	40	243.3	< 0.001
		$H_0(2)$	65	23992	< 0.001
		$H_0(3)$	22	8968	< 0.001

APPENDIX 11
DEPENDENT VARIABLE MOVING AVERAGE PLOTS FOR THE SECOND SET OF EXPERIMENTS

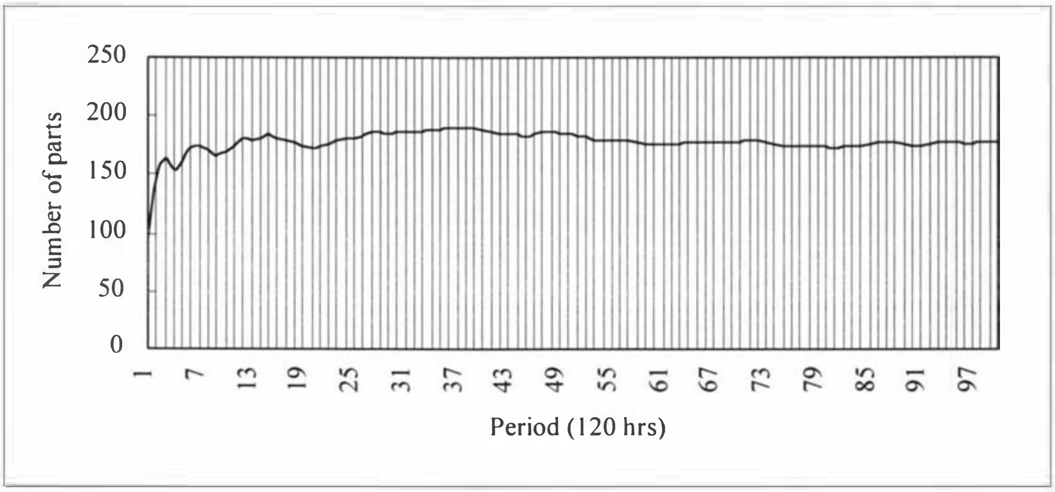

Figure A11.1 Moving average plot for average work-in-process inventory (Cellular layout with SUPC and backtracking flow allowed)

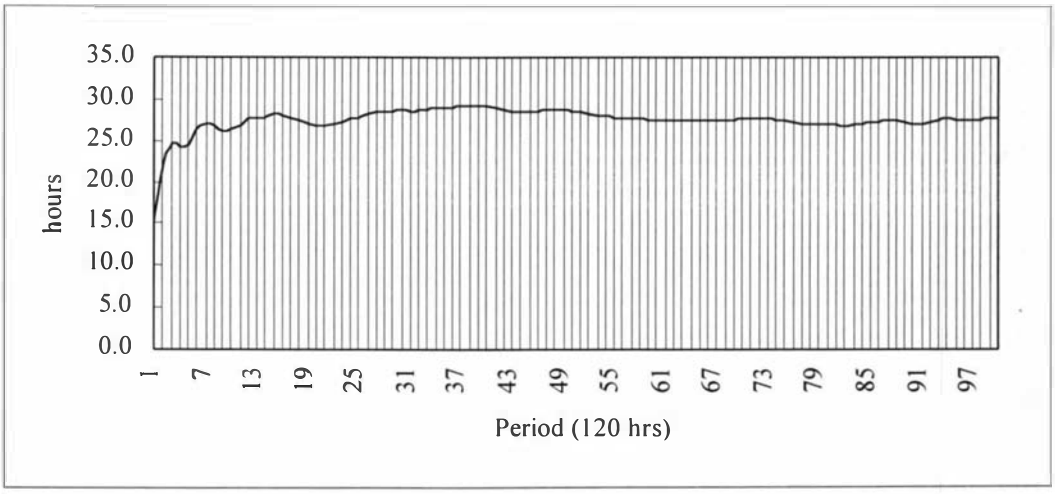

Figure A11.2 Moving average plot for average flow time (Cellular layout with SUPC and backtracking flow allowed)

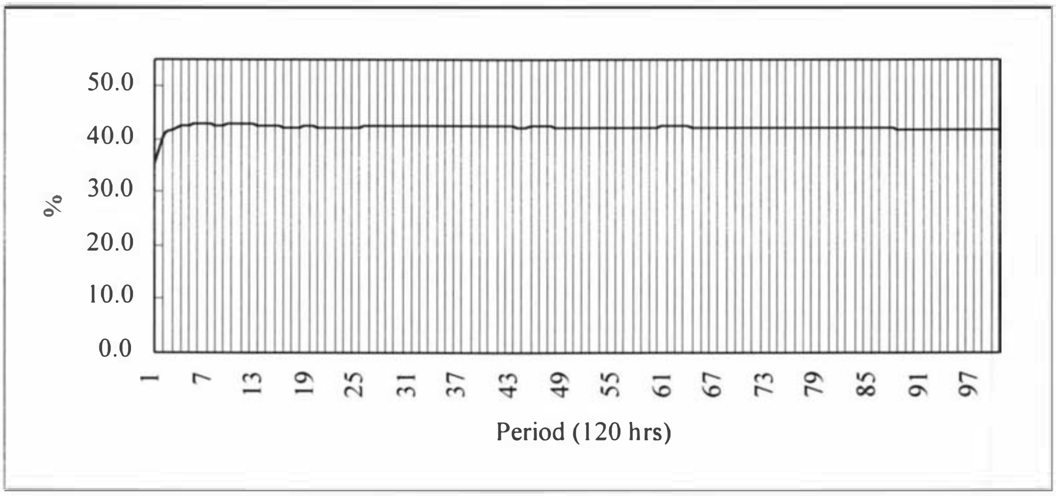

Figure A11.3 Moving average plot for average machine utilisation (Cellular layout with SUPC and backtracking flow allowed)

APPENDIX 12

SUMMARY OF THE SIMULATION OUTPUT FOR THE SECOND SET OF EXPERIMENTS

Table A12.1 Simulation output summary on AWIP for the second set of experiments at the high PFSRF level

Dependent variable	CV level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average work-in-process inventory (AWIP)	HH	FL	22	60.08 ± 1.37	9.60
		CBB	22	65.06 ± 2.13	23.17
		CBU	22	70.03 ± 2.85	41.41
		CSB	22	219.88 ± 25.08	3199.01
		CSU	22	199.27 ± 21.63	2380.31
	HM	FL	22	59.63 ± 1.45	10.63
		CBB	22	64.92 ± 1.96	19.45
		CBU	22	70.33 ± 2.74	38.25
		CSB	22	159.37 ± 13.94	989.08
		CSU	22	147.66 ± 12.91	847.39
	HL	FL	22	59.43 ± 1.56	12.36
		CBB	22	65.66 ± 2.64	35.51
		CBU	22	68.86 ± 2.17	24.05
		CSB	22	153.11 ± 13.60	940.64
		CSU	22	141.37 ± 16.08	1315.51
	MM	FL	22	58.11 ± 1.36	9.39
		CBB	22	60.63 ± 1.96	19.49
		CBU	22	63.92 ± 1.99	20.20
		CSB	22	145.09 ± 12.79	832.44
		CSU	22	129.72 ± 11.91	721.61
	ML	FL	22	58.09 ± 1.35	9.22
		CBB	22	60.56 ± 1.91	18.46
		CBU	22	63.08 ± 1.76	15.82
		CSB	22	141.62 ± 14.89	1127.75
		CSU	22	121.53 ± 11.83	712.20
	LL	FL	22	57.22 ± 1.29	8.45
		CBB	22	58.28 ± 1.64	13.67
		CBU	22	61.53 ± 1.72	15.08
		CSB	22	153.59 ± 19.04	1843.50
		CSU	22	113.32 ± 10.47	557.69

Table A12.2 Simulation output summary on AFT for the second set of experiments at the high PFSRF level

Dependent variable	CV level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average flow time (AFT)	HH	FL	22	9.46 ± 0.17	0.1468
		CBB	22	10.17 ± 0.25	0.3199
		CBU	22	10.90 ± 0.32	0.5104
		CSB	22	34.72 ± 3.74	71.34
		CSU	22	31.06 ± 3.16	50.66
	HM	FL	22	9.38 ± 0.14	0.0994
		CBB	22	10.15 ± 0.23	0.2683
		CBU	22	10.96 ± 0.30	0.4721
		CSB	22	24.97 ± 2.00	20.42
		CSU	22	23.05 ± 1.89	18.13
	HL	FL	22	9.35 ± 0.16	0.1285
		CBB	22	10.26 ± 0.33	0.5394
		CBU	22	10.73 ± 0.25	0.3183
		CSB	22	23.91 ± 2.00	20.36
		CSU	22	22.03 ± 2.21	24.92
	MM	FL	22	9.14 ± 0.13	0.0817
		CBB	22	9.47 ± 0.23	0.2602
		CBU	22	9.97 ± 0.21	0.2305
		CSB	22	22.92 ± 1.98	19.94
		CSU	22	20.37 ± 1.70	14.64
	ML	FL	22	9.14 ± 0.13	0.0868
		CBB	22	9.46 ± 0.22	0.2479
		CBU	22	9.95 ± 0.19	0.1853
		CSB	22	22.30 ± 2.31	27.05
		CSU	22	18.96 ± 1.68	14.44
	LL	FL	22	9.01 ± 0.12	0.0789
		CBB	22	9.11 ± 0.19	0.1826
		CBU	22	9.60 ± 0.19	0.1863
		CSB	22	24.38 ± 3.08	48.23
		CSU	22	17.75 ± 1.46	10.84

Table A12.3 Simulation output summary on ASPTR for the second set of experiments at the high PFSRF level

Dependent variable	CV level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average setup to processing time ratio (ASPTR)	HH	FL	22	2.52 ± 0.03	0.00593
		CBB	22	1.91 ± 0.03	0.00331
		CBU	22	1.97 ± 0.03	0.00439
		CSB	22	3.95 ± 0.06	0.01817
		CSU	22	3.94 ± 0.08	0.02987
	HM	FL	22	2.50 ± 0.03	0.00559
		CBB	22	1.93 ± 0.03	0.00333
		CBU	22	1.96 ± 0.02	0.00299
		CSB	22	3.79 ± 0.06	0.01918
		CSU	22	3.68 ± 0.04	0.00808
	HL	FL	22	2.51 ± 0.03	0.00457
		CBB	22	1.91 ± 0.03	0.00377
		CBU	22	1.95 ± 0.02	0.00190
		CSB	22	3.74 ± 0.06	0.02012
		CSU	22	3.68 ± 0.06	0.02105
	MM	FL	22	2.53 ± 0.03	0.00435
		CBB	22	1.90 ± 0.02	0.00257
		CBU	22	1.95 ± 0.02	0.00195
		CSB	22	3.85 ± 0.04	0.00839
		CSU	22	3.70 ± 0.06	0.01883
	ML	FL	22	2.54 ± 0.03	0.00506
		CBB	22	1.91 ± 0.02	0.00219
		CBU	22	1.94 ± 0.02	0.00280
		CSB	22	3.82 ± 0.07	0.02160
		CSU	22	3.69 ± 0.07	0.02234
	LL	FL	22	2.55 ± 0.02	0.00293
		CBB	22	1.91 ± 0.02	0.00278
		CBU	22	1.94 ± 0.03	0.00393
		CSB	22	3.91 ± 0.06	0.01759
		CSU	22	3.67 ± 0.05	0.01207

Table A12.4 Simulation output summary on AWIP for the second set of experiments at the medium PFSRF level

Dependent variable	CV level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average work-in-process inventory (AWIP)	HH	FL	22	65.51 ± 1.92	18.71
		CBB	22	65.04 ± 1.70	14.66
		CBU	22	64.57 ± 1.68	14.36
		CSB	22	155.62 ± 12.35	775.68
		CSU	22	129.57 ± 10.22	530.95
	HM	FL	22	65.55 ± 2.05	21.43
		CBB	22	64.93 ± 2.01	20.54
		CBU	22	64.27 ± 1.57	12.56
		CSB	22	119.06 ± 9.14	424.99
		CSU	22	99.94 ± 5.80	170.89
	HL	FL	22	65.54 ± 2.01	20.64
		CBB	22	65.14 ± 1.98	19.92
		CBU	22	63.93 ± 1.46	10.86
		CSB	22	113.21 ± 6.08	188.32
		CSU	22	95.73 ± 5.36	146.04
	MM	FL	22	63.62 ± 1.74	15.42
		CBB	22	61.30 ± 1.55	12.17
		CBU	22	60.71 ± 1.40	9.93
		CSB	22	116.46 ± 9.91	499.11
		CSU	22	91.89 ± 5.72	166.57
	ML	FL	22	63.82 ± 1.81	16.73
		CBB	22	61.47 ± 1.61	13.13
		CBU	22	60.62 ± 1.30	8.54
		CSB	22	108.31 ± 7.06	253.64
		CSU	22	88.51 ± 4.73	114.03
	LL	FL	22	62.59 ± 1.70	14.70
		CBB	22	60.17 ± 1.39	9.85
		CBU	22	59.22 ± 1.30	8.62
		CSB	22	112.83 ± 9.85	493.84
		CSU	22	82.57 ± 3.29	55.21

Table A12.5 Simulation output summary on AFT for the second set of experiments at the medium PFSRF level

Dependent variable	CV level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average flow time (AFT)	HH	FL	22	8.60 ± 0.16	0.1363
		CBB	22	8.54 ± 0.16	0.1301
		CBU	22	8.50 ± 0.15	0.1161
		CSB	22	20.38 ± 1.49	11.26
		CSU	22	17.04 ± 1.24	7.76
	HM	FL	22	8.60 ± 0.17	0.1515
		CBB	22	8.52 ± 0.20	0.2072
		CBU	22	8.47 ± 0.13	0.0883
		CSB	22	15.56 ± 1.07	5.85
		CSU	22	13.14 ± 0.65	2.15
	HL	FL	22	8.60 ± 0.17	0.1437
		CBB	22	8.55 ± 0.20	0.2013
		CBU	22	8.43 ± 0.13	0.0871
		CSB	22	14.87 ± 0.70	2.47
		CSU	22	12.60 ± 0.60	1.83
	MM	FL	22	8.35 ± 0.13	0.0858
		CBB	22	8.05 ± 0.15	0.1174
		CBU	22	8.00 ± 0.11	0.0623
		CSB	22	15.17 ± 1.17	6.99
		CSU	22	12.10 ± 0.65	2.17
	ML	FL	22	8.38 ± 0.14	0.1053
		CBB	22	8.07 ± 0.15	0.1190
		CBU	22	7.99 ± 0.10	0.0495
		CSB	22	14.11 ± 0.82	3.43
		CSU	22	11.64 ± 0.52	1.36
	LL	FL	22	8.21± 0.14	0.0956
		CBB	22	7.90 ± 0.12	0.0728
		CBU	22	7.80 ± 0.10	0.0518
		CSB	22	14.74 ± 1.18	7.07
		CSU	22	10.88 ± 0.33	0.56

Table A12.6 Simulation output summary on ASPTR for the second set of experiments at the medium PFSRF level

Dependent variable	CV level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average setup to processing time ratio (ASPTR)	HH	FL	22	2.12 ± 0.03	0.00346
		CBB	22	1.37 ± 0.01	0.00082
		CBU	22	1.38 ± 0.01	0.00112
		CSB	22	2.77 ± 0.04	0.00727
		CSU	22	2.66 ± 0.03	0.00533
	HM	FL	22	2.12 ± 0.04	0.00645
		CBB	22	1.36 ± 0.02	0.00142
		CBU	22	1.38 ± 0.01	0.00100
		CSB	22	2.59 ± 0.04	0.00651
		CSU	22	2.49 ± 0.04	0.00655
	HL	FL	22	2.14 ± 0.03	0.00335
		CBB	22	1.35 ± 0.01	0.00107
		CBU	22	1.37 ± 0.01	0.00081
		CSB	22	2.58 ± 0.04	0.00745
		CSU	22	2.49 ± 0.03	0.00565
	MM	FL	22	2.13 ± 0.02	0.00212
		CBB	22	1.35 ± 0.02	0.00117
		CBU	22	1.38 ± 0.02	0.00117
		CSB	22	2.66 ± 0.04	0.00633
		CSU	22	2.50 ± 0.03	0.00475
	ML	FL	22	2.15 ± 0.03	0.00322
		CBB	22	1.35 ± 0.02	0.00117
		CBU	22	1.37 ± 0.01	0.00091
		CSB	22	2.63 ± 0.04	0.00860
		CSU	22	2.50 ± 0.02	0.00277
	LL	FL	22	2.14 ± 0.03	0.00393
		CBB	22	1.36 ± 0.01	0.00108
		CBU	22	1.37 ± 0.01	0.00113
		CSB	22	2.68 ± 0.03	0.00569
		CSU	22	2.48 ± 0.02	0.00262

Table A12.7 Simulation output summary on AWIP for the second set of experiments at the low PFSRF level

Dependent variable	CV level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average work-in-process inventory (AWIP)	HH	FL	22	98.88 ± 2.56	33.43
		CBB	22	71.04 ± 1.77	15.86
		CBU	22	71.44 ± 2.31	27.07
		CSB	22	92.40 ± 6.66	225.82
		CSU	22	74.93 ± 3.81	73.86
	HM	FL	22	99.35 ± 2.84	41.11
		CBB	22	70.75 ± 1.93	19.03
		CBU	22	70.85 ± 2.23	25.35
		CSB	22	83.48 ± 4.49	102.75
		CSU	22	69.27 ± 2.89	42.49
	HL	FL	22	99.11 ± 2.37	28.50
		CBB	22	70.19 ± 2.01	20.64
		CBU	22	70.55 ± 2.39	29.16
		CSB	22	81.41 ± 4.40	98.35
		CSU	22	66.78 ± 2.80	39.81
	MM	FL	22	94.57 ± 1.84	17.27
		CBB	22	69.27 ± 1.75	15.57
		CBU	22	69.48 ± 2.06	21.52
		CSB	22	82.65 ± 4.69	111.69
		CSU	22	65.70 ± 3.08	48.38
	ML	FL	22	94.63 ± 1.71	14.92
		CBB	22	68.91 ± 1.95	19.30
		CBU	22	68.91 ± 2.05	21.34
		CSB	22	82.65 ± 4.99	126.59
		CSU	22	63.77 ± 2.60	34.47
	LL	FL	22	93.78 ± 1.83	17.12
		CBB	22	68.35 ± 1.89	18.11
		CBU	22	68.66 ± 2.17	23.99
		CSB	22	84.47 ± 5.10	132.09
		CSU	22	62.33 ± 2.61	34.72

Table A12.8 Simulation output summary on AFT for the second set of experiments at the low PFSRF level

Dependent variable	CV level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average flow time (AFT)	HH	FL	22	8.46 ± 0.16	0.1358
		CBB	22	6.09 ± 0.12	0.0705
		CBU	22	6.12 ± 0.14	0.0958
		CSB	22	7.91 ± 0.52	1.3776
		CSU	22	6.41 ± 0.27	0.3674
	HM	FL	22	8.50 ± 0.18	0.1565
		CBB	22	6.07 ± 0.13	0.0888
		CBU	22	6.07 ± 0.13	0.0898
		CSB	22	7.17 ± 0.35	0.6283
		CSU	22	5.94 ± 0.20	0.1950
	HL	FL	22	8.48 ± 0.14	0.1040
		CBB	22	6.02 ± 0.13	0.0905
		CBU	22	6.04 ± 0.15	0.1137
		CSB	22	6.98 ± 0.34	0.5724
		CSU	22	5.72 ± 0.19	0.1894
	MM	FL	22	8.10 ± 0.11	0.0611
		CBB	22	5.94 ± 0.11	0.0652
		CBU	22	5.95 ± 0.12	0.0711
		CSB	22	7.08 ± 0.36	0.6589
		CSU	22	5.63 ± 0.21	0.2248
	ML	FL	22	8.11 ± 0.09	0.0414
		CBB	22	5.91 ± 0.13	0.0843
		CBU	22	5.90 ± 0.12	0.0719
		CSB	22	7.08 ± 0.39	0.7641
		CSU	22	5.46 ± 0.17	0.1481
	LL	FL	22	8.03 ± 0.10	0.0506
		CBB	22	5.86 ± 0.12	0.0784
		CBU	22	5.88 ± 0.13	0.0835
		CSB	22	7.24 ± 0.39	0.7905
		CSU	22	5.34 ± 0.17	0.1530

Table A12.9 Simulation output summary on ASPTR for the second set of experiments at the low PFSRF level

Dependent variable	CV level	SL level	Sample size	95% confidence interval for μ	Sample variance
Average setup to processing time ratio (ASPTR)	HH	FL	22	1.68 ± 0.03	0.00352
		CBB	22	0.54 ± 0.01	0.000146
		CBU	22	0.55 ± 0.01	0.000214
		CSB	22	1.03 ± 0.01	0.000387
		CSU	22	0.96 ± 0.01	0.000523
	HM	FL	22	1.68 ± 0.02	0.00193
		CBB	22	0.54 ± 0.01	0.000166
		CBU	22	0.55 ± 0.00	0.000092
		CSB	22	1.00 ± 0.01	0.000377
		CSU	22	0.94 ± 0.01	0.000422
	HL	FL	22	1.67 ± 0.02	0.00121
		CBB	22	0.54 ± 0.01	0.000206
		CBU	22	0.55 ± 0.01	0.000174
		CSB	22	1.00 ± 0.01	0.000542
		CSU	22	0.93 ± 0.01	0.000308
	MM	FL	22	1.69 ± 0.03	0.00320
		CBB	22	0.54 ± 0.00	0.000104
		CBU	22	0.55 ± 0.00	0.000086
		CSB	22	1.02 ± 0.01	0.000435
		CSU	22	0.94 ± 0.01	0.000185
	ML	FL	22	1.68 ± 0.02	0.00291
		CBB	22	0.54 ± 0.00	0.000120
		CBU	22	0.55 ± 0.00	0.000079
		CSB	22	1.02 ± 0.01	0.000395
		CSU	22	0.93 ± 0.01	0.000241
	LL	FL	22	1.72 ± 0.02	0.00250
		CBB	22	0.54 ± 0.00	0.000094
		CBU	22	0.55 ± 0.00	0.000069
		CSB	22	1.05 ± 0.01	0.000349
		CSU	22	0.93 ± 0.01	0.000319

APPENDIX 13
SUMMARY OF OVERALL *F*-TEST RESULTS FOR THE SECOND SET OF EXPERIMENTS

Table A13.1 Overall *F*-test results of the second set of experiments at the high PFSRF level

Dependent Variable	CV Level	Mean Value					*F*	*p*
		FL	CBB	CBU	CSB	CSU		
AWIP	HH	60.08	65.06	70.03	-	-	22.04	< 0.001
	HM	59.63	64.92	70.33	-	-	27.67	< 0.001
	HL	59.43	65.66	68.86	-	-	21.11	< 0.001
	MM	58.11	60.63	63.92	-	-	11.43	< 0.001
	ML	58.09	60.56	63.80	-	-	12.44	< 0.001
	LL	57.22	58.28	61.53	-	-	8.93	< 0.001
AFT	HH	9.46	10.17	10.90	-	-	35.40	< 0.001
	HM	9.38	10.15	10.96	-	-	49.15	< 0.001
	HL	9.35	10.26	10.73	-	-	33.31	< 0.001
	MM	9.14	9.47	9.97	-	-	20.02	< 0.001
	ML	9.14	9.46	9.95	-	-	21.27	< 0.001
	LL	9.01	9.11	9.60	-	-	14.59	< 0.001
ASPTR	HH	2.52	1.91	1.97	-	-	547.00	< 0.001
	HM	2.50	1.93	1.96	-	-	575.08	< 0.001
	HL	2.51	1.91	1.95	-	-	706.37	< 0.001
	MM	2.53	1.90	1.95	-	-	909.45	< 0.001
	ML	2.54	1.91	1.94	-	-	834.74	< 0.001
	LL	2.55	1.91	1.94	-	-	895.10	< 0.001

Table A13.2 Overall *F*-test results of the second set of experiments at the medium PFSRF level

Dependent Variable	CV Level	Mean Value					*F*	*p*
		FL	CBB	CBU	CSB	CSU		
AWIP	HH	65.51	65.04	64.57	-	-	0.31	n.s.*
	HM	65.55	64.93	64.27	-	99.94	119.80	< 0.001
	HL	65.54	65.14	63.93	-	95.73	106.30	< 0.001
	MM	63.62	61.30	60.71	-	91.89	97.76	< 0.001
	ML	63.82	61.47	60.62	-	88.51	102.69	< 0.001
	LL	62.59	60.17	59.22	-	82.57	121.50	< 0.001
AFT	HH	8.60	8.54	8.50	-	-	0.39	n.s.
	HM	8.60	8.52	8.47	-	13.14	179.74	< 0.001
	HL	8.60	8.55	8.43	-	12.60	161.55	< 0.001
	MM	8.35	8.05	8.00	-	12.10	142.79	< 0.001
	ML	8.38	8.07	7.99	-	11.64	165.99	< 0.001
	LL	8.21	7.90	7.80	-	10.88	242.10	< 0.001
ASPTR	HH	2.12	1.37	1.38	-	-	2281.6	< 0.001
	HM	2.12	1.36	1.38	-	2.49	1805.4	< 0.001
	HL	2.14	1.35	1.37	-	2.49	2601.1	< 0.001
	MM	2.13	1.35	1.38	-	2.50	3088.6	< 0.001
	ML	2.15	1.35	1.37	-	2.50	3554.3	< 0.001
	LL	2.14	1.36	1.37	-	2.48	3222.1	< 0.001

* n.s. = not statistically significant

Table A13.3 Overall *F*-test results of the second set of experiments at the low PFSRF level

Dependent Variable	CV Level	Mean Value					*F*	*p*
		FL	CBB	CBU	CSB	CSU		
AWIP	HH	98.88	71.04	71.44	92.40	74.93	49.31	< 0.001
	HM	99.35	70.75	70.85	83.48	69.27	79.00	< 0.001
	HL	99.11	70.19	70.55	81.41	66.78	88.80	< 0.001
	MM	94.57	69.27	69.48	82.65	65.70	74.70	< 0.001
	ML	94.63	68.91	68.91	82.65	63.77	81.43	< 0.001
	LL	93.78	68.35	68.66	84.47	62.33	83.46	< 0.001
AFT	HH	8.46	6.09	6.12	7.91	6.41	65.84	< 0.001
	HM	8.50	6.07	6.07	7.17	5.94	114.74	< 0.001
	HL	8.48	6.02	6.04	6.98	5.72	131.18	< 0.001
	MM	8.10	5.94	5.95	7.08	5.63	108.12	< 0.001
	ML	8.11	5.91	5.90	7.08	5.46	116.49	< 0.001
	LL	8.03	5.86	5.88	7.24	5.34	119.18	< 0.001
ASPTR	HH	1.68	0.54	0.55	1.03	0.96	4992.8	< 0.001
	HM	1.68	0.54	0.55	1.00	0.94	7959.6	< 0.001
	HL	1.67	0.54	0.55	1.00	0.93	9628.7	< 0.001
	MM	1.69	0.54	0.55	1.02	0.94	6097.9	< 0.001
	ML	1.69	0.54	0.55	1.02	0.93	6424.9	< 0.001
	LL	1.72	0.54	0.55	1.05	0.94	7712.9	< 0.001

Appendix 14

Results of Planned Comparisons for the Second Set of Experiments

Table A14.1 Results of planned comparisons for AWIP at the high PFSRF level

Dependent Variable	CV Level	Hypotheses Tested	*df**	*F*	*p*
AWIP	HH	$H_0(1a)$	39	8.44	0.006
		$H_0(3)$	60	47.62	< 0.001
	HM	$H_0(1a)$	38	11.15	0.002
		$H_0(3)$	58	56.19	< 0.001
	HL	$H_0(1a)$	41	3.78	0.059
		$H_0(3)$	58	49.51	< 0.001
	MM	$H_0(1a)$	42	6.00	0.019
		$H_0(3)$	57	19.80	< 0.001
	ML	$H_0(1a)$	42	6.73	0.013
		$H_0(3)$	55	20.69	< 0.001
	LL	$H_0(1a)$	42	8.06	0.007
		$H_0(3)$	53	10.13	0.002

* *df* = degrees of freedom

Table A14.2 Results of planned comparisons for AFT at the high PFSRF level

Dependent Variable	CV Level	Hypotheses Tested	*df*	*F*	*p*
AFT	HH	$H_0(1a)$	40	14.37	< 0.001
		$H_0(3)$	60	72.34	< 0.001
	HM	$H_0(1a)$	39	19.74	< 0.001
		$H_0(3)$	60	106.6	< 0.001
	HL	$H_0(1a)$	39	5.68	0.022
		$H_0(3)$	60	9.23	< 0.001
	MM	$H_0(1a)$	42	11.13	0.002
		$H_0(3)$	62	36.04	< 0.001
	ML	$H_0(1a)$	41	12.15	0.001
		$H_0(3)$	59	36.47	< 0.001
	LL	$H_0(1a)$	42	14.06	< 0.001
		$H_0(3)$	59	15.46	< 0.001

Table A14.3 Results of planned comparisons for ASPTR at the high PFSRF level

Dependent Variable	CV Level	Hypotheses Tested	df	F	p
ASPTR	HH	$H_0(1a)$	41	9.37	0.004
		$H_0(3)$	35	942.4	< 0.001
	HM	$H_0(1a)$	42	3.63	0.063
		$H_0(3)$	33	952.6	< 0.001
	HL	$H_0(1a)$	38	5.66	0.022
		$H_0(3)$	34	1204	< 0.001
	MM	$H_0(1a)$	41	8.33	0.006
		$H_0(3)$	32	1467	< 0.001
	ML	$H_0(1a)$	41	3.06	0.088
		$H_0(3)$	32	1328	< 0.001
	LL	$H_0(1a)$	41	3.71	0.061
		$H_0(3)$	44	1869	< 0.001

Table A14.4 Results of planned comparisons for AWIP at the medium PFSRF level

Dependent Variable	CV Level	Hypotheses Tested	df	F	p
AWIP	HH	$H_0(1a)$	42	0.17	n.s.*
		$H_0(3)$	38	0.42	n.s.
	HM	$H_0(1a)$	40	0.29	n.s.
		$H_0(2)$	23	153.3	< 0.001
		$H_0(3)$	37	0.66	n.s.
	HL	$H_0(1a)$	39	1.05	0.31
		$H_0(2)$	23	139.2	< 0.001
		$H_0(3)$	37	0.79	n.s.
	MM	$H_0(1a)$	42	0.36	n.s.
		$H_0(2)$	22	121.9	< 0.001
		$H_0(3)$	36	7.20	0.011
	ML	$H_0(1a)$	40	0.74	n.s.
		$H_0(2)$	23	138.9	< 0.001
		$H_0(3)$	35	7.65	0.01
	LL	$H_0(1a)$	42	1.08	0.30
		$H_0(2)$	25	192.4	< 0.001
		$H_0(3)$	35	9.53	0.004

*n.s. = not statistically significant

Table A14.5 Results of planned comparisons for AFT at the medium PFSRF level

Dependent Variable	CV Level	Hypotheses Tested	*df*	*F*	*p*
AFT	HH	H_0(1a)	42	0.13	n.s.
		H_0(3)	40	0.63	n.s.
	HM	H_0(1a)	36	0.21	n.s.
		H_0(2)	22	213.0	< 0.001
		H_0(3)	41	1.09	0.30
	HL	H_0(1a)	36	1.17	0.29
		H_0(2)	23	195.5	< 0.001
		H_0(3)	41	1.29	0.26
	MM	H_0(1a)	38	0.34	n.s.
		H_0(2)	22	164.7	< 0.001
		H_0(3)	42	17.63	< 0.001
	ML	H_0(1a)	36	0.81	n.s.
		H_0(2)	22	204.6	< 0.001
		H_0(3)	38	18.15	< 0.001
	LL	H_0(1a)	41	1.75	0.19
		H_0(2)	23	341.9	< 0.001
		H_0(3)	35	22.63	< 0.001

Table A14.6 Results of planned comparisons for ASPTR at the medium PFSRF level

Dependent Variable	CV Level	Hypotheses Tested	*df*	*F*	*p*
ASPTR	HH	H_0(1a)	41	2.40	0.13
		H_0(3)	27	3121	< 0.001
	HM	H_0(1a)	41	7.48	0.009
		H_0(2)	25	3883	< 0.001
		H_0(3)	25	1762	< 0.001
	HL	H_0(1a)	41	3.30	0.08
		H_0(2)	25	4556	< 0.001
		H_0(3)	27	3462	< 0.001
	MM	H_0(1a)	42	7.96	0.007
		H_0(2)	26	5300	< 0.001
		H_0(3)	33	4765	< 0.001
	ML	H_0(1a)	41	4.82	0.033
		H_0(2)	29	8570	< 0.001
		H_0(3)	28	3605	< 0.001
	LL	H_0(1a)	42	2.24	0.14
		H_0(2)	30	8720	< 0.001
		H_0(3)	27	2991	< 0.001

Table A14.7 Results of planned comparisons for AWIP at the low PFSRF level

Dependent Variable	CV Level	Hypotheses Tested	*df*	*F*	*p*
AWIP	HH	$H_0(1a)$	39	0.08	n.s.
		$H_0(1b)$	33	22.41	< 0.001
		$H_0(2)$	43	39.64	< 0.001
		$H_0(3)$	35	380.6	< 0.001
	HM	$H_0(1a)$	41	0.004	n.s.
		$H_0(1b)$	36	30.58	< 0.001
		$H_0(2)$	56	3.80	< 0.001
		$H_0(3)$	33	18.53	< 0.001
	HL	$H_0(1a)$	41	0.06	n.s.
		$H_0(1b)$	36	34.09	< 0.001
		$H_0(2)$	59	6.49	0.014
		$H_0(3)$	39	443.8	< 0.001
	MM	$H_0(1a)$	41	0.03	n.s.
		$H_0(1b)$	36	39.52	< 0.001
		$H_0(2)$	53	10.29	0.002
		$H_0(3)$	43	526.0	< 0.001
	ML	$H_0(1a)$	42	0.00001	n.s.
		$H_0(1b)$	32	48.71	< 0.001
		$H_0(2)$	47	8.06	0.007
		$H_0(3)$	48	580.5	< 0.001
	LL	$H_0(1a)$	41	0.05	n.s.
		$H_0(1b)$	31	64.67	< 0.001
		$H_0(2)$	47	10.09	0.003
		$H_0(3)$	46	508.4	< 0.001

Table A14.8 Results of planned comparisons for AFT at the low PFSRF level

Dependent Variable	CV Level	Hypotheses Tested	df	F	p
AFT	HH	$H_0(1a)$	41	0.092	n.s.
		$H_0(1b)$	31	28.09	< 0.001
		$H_0(2)$	37	51.07	< 0.001
		$H_0(3)$	34	688.5	< 0.001
	HM	$H_0(1a)$	42	0.0006	n.s.
		$H_0(1b)$	33	40.31	< 0.001
		$H_0(2)$	47	20.45	< 0.001
		$H_0(3)$	33	647.85	< 0.001
	HL	$H_0(1a)$	41	0.058	n.s.
		$H_0(1b)$	34	45.61	< 0.001
		$H_0(2)$	51	9.22	0.004
		$H_0(3)$	42	854.3	< 0.001
	MM	$H_0(1a)$	42	0.012	n.s.
		$H_0(1b)$	34	52.51	< 0.001
		$H_0(2)$	44	14.15	< 0.001
		$H_0(3)$	44	1067	< 0.001
	ML	$H_0(1a)$	42	0.007	n.s.
		$H_0(1b)$	29	63.22	< 0.001
		$H_0(2)$	39	10.81	0.002
		$H_0(3)$	55	1322	< 0.001
	LL	$H_0(1a)$	42	0.045	n.s.
		$H_0(1b)$	29	83.85	< 0.001
		$H_0(2)$	39	13.89	< 0.001
		$H_0(3)$	52	1124	< 0.001

Table A14.9 Results of planned comparisons for ASPTR at the low PFSRF level

Dependent Variable	CV Level	Hypotheses Tested	*df*	*F*	*p*
ASPTR	HH	$H_0(1a)$	41	4.09	0.05
		$H_0(1b)$	41	116.9	< 0.001
		$H_0(2)$	69	14131	< 0.001
		$H_0(3)$	22	7869	< 0.001
	HM	$H_0(1a)$	39	6.35	0.016
		$H_0(1b)$	42	106.8	< 0.001
		$H_0(2)$	66	15300	< 0.001
		$H_0(3)$	22	14228	< 0.001
	HL	$H_0(1a)$	42	6.32	0.016
		$H_0(1b)$	39	112.4	< 0.001
		$H_0(2)$	69	12777	< 0.001
		$H_0(3)$	24	21464	< 0.001
	MM	$H_0(1a)$	42	17.46	< 0.001
		$H_0(1b)$	36	240.1	< 0.001
		$H_0(2)$	57	20731	< 0.001
		$H_0(3)$	22	8968	< 0.001
	ML	$H_0(1a)$	40	12.06	0.001
		$H_0(1b)$	40	274.6	< 0.001
		$H_0(2)$	62	19707	< 0.001
		$H_0(3)$	22	9673	< 0.001
	LL	$H_0(1a)$	41	12.23	0.001
		$H_0(1b)$	42	414.8	< 0.001
		$H_0(2)$	61	21019	< 0.001
		$H_0(3)$	22	12014	< 0.001

APPENDIX 15

LIST OF PUBLICATIONS

1. A paper entitled "Information Flow Model for JIT Shopfloor Control Systems" has been extended from Section 5.2 of this thesis and presented to World Manufacturing Congress (WMC 97) in November 1997 at Auckland, New Zealand.

2. A modified version of the content of Chapters 1-8 of this thesis constituted a paper entitled " A Simulation Study of the Factors Influencing the Performance of a Kanban-controlled Job Shop", which was presented to the 5th Annual New Zealand Engineering and Technology Postgraduate Conference at Palmerston North, New Zealand in November 1998.

3. The content of the first set of experiments of this thesis also provided material for a paper on "Investigating the Factors Influencing the Shop Performance in a Job Shop Environment with Kanban-based Production Control", which was submitted to *International Journal of Production Research* and is being reviewed.

4. A paper entitled "A Simulation Study of Applying JIT Techniques for Job Shop Manufacturing" has been condensed from chapters 9-11 of this thesis, and presented to the IASTED International Conference on Applied Modelling and Simulation, 1-3 September, 1999, Cairns, Australia.