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A SIMULATION ANALYSIS OF A MIXED-MODEL JUST-IN-TIME PRODUCTION SYSTEM

A Dissertation
Presented for the
Doctor of Philosophy
The University of Mississippi

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Dr. Frank Weibe, Major Professor

We have read this dissertation
and recommend its acceptance

Accepted for the Council

Dean of The Graduate School

DEDICATION

This dissertation is dedicated to my wife and my brother

Asmaa Jamal Muhanna

and

Moayed Hasan Ashqar

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ABSTRACT

Just-in-time production system has attracted the attention of American managers as well as researchers. Many studies have been conducted to evaluate the performance of JIT in different settings. In this research, a simulation analysis of a mixed-model just-in-time production system will be conducted. The purpose is to find the effect of different numbers of Kanbans, different container sizes, different processing time distributions and different setup times on the performance of the mixed-model JIT production system. Cellular manufacturing will be introduced. SLAM will be used as the simulation language. Finally, in this study attempts are made to show how mixed-models of different configurations can be simulated under different conditions. Simulation results show the relative performance of a mixed-model production system. Computational problems and related findings are also reported.

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CHAPTER 1

INTRODUCTION

Historical Background

During the 1970's many Japanese manufacturers switched to using just-in-time systems and in the 1980's many American firms began embracing JIT techniques. JIT received widespread attention during the oil crisis in 1973; while most Japanese companies lost money, Toyota showed a huge profit using their JIT with Kanban.

Burck (1982) pointed out that Toyota in 1980 turned over their inventory every 4 days and reduced their break-even point to 64% of sales. It was determined that Japan's cost advantage for a comparable car was $1700 during that time. The cost difference over U.S firms was attributed mainly to adversarial labor relations, excessive inventories, lagging productivity, and inferior quality performance. When Harley Davidson began using JIT concepts, their break-even point was lowered by 32 %, defects were reduced by 24 %, in-process inventory decreased from $23 million to just over $8.5 million, and the proportion of stockouts declined significantly (Schwind, 1984).

Aggarawl and Aggarawl (1985) have reported that Japanese businesses that have used the Kanban method for more than five years have increased productivity by 30% and have reduced in-process inventory by 60%. In the U.S.

lowered inventories since they introduced the Kanban approach. It is also reported that Westinghouse eliminated 95% of stockouts and reduced its in-process inventory by 45% (Industry Week, 1982). Krajewski, King, Ritzman and Wong (1987) simulated the use of Kanban and obtained a reduction of 80% in the levels of in-process inventory while meeting more delivery dates. Indeed, Inman and Mehra (1990) reported that their computer search of the literature showed over 700 articles on JIT, published during the previous 5 years. The authors of these articles have shown that the implementation of JIT leads to inventory reduction, shorter lead time, better use of resources, and reduces manufacturing costs and increases profit margins.

JIT was first adopted in repetitive manufacturing systems. Today, it is spreading to other industries such as small manufacturing firms (Celley, Clegg, Smith, and Vonderembse 1987; Inman and Mehra 1992). Also, JIT is common in transportation and electronics industries (crawford, Blackstone, & coy, 1988). Mehra and Inman (1992) outline the benefits of JIT as:

- Less work in process
- Quality improvement
- Higher productivity
- Higher equipment efficiency
- Higher worker morale, motivation and efficiency

Attributes of JIT

Basis of JIT

JIT is based on the concept of producing exactly the required quantity and type of products at exactly the required time for each subsequent stage of production. The result is a synchronized production environment where each stage exactly feeds the next. JIT systems employ a pull process in which the final stage of production dictates the flow and timing of preceding processes. In a JIT environment, end-products are assembled just in time for delivery, and subassemblies are built just in time for final assembly. Final assembly drives, or "pulls" the production of all parts in the feeder shops (Goeflin, Luss, Rosenwein, & Wah, 1989).

Elements of JIT

There are several elements which, when combined, create a JIT system. These include the smoothing of production, job standardization, specific process designs and an ordering and delivering system called Kanban (Monden, 1981). Among these elements Kanban appears to be the core of the JIT system (Ebrahimpour & Fathi, 1985).

Philosophy of JIT

The just-in-time philosophy is comprised of three management thrusts: JIT production management, total quality management (TQM), and preventive maintenance. Under the JIT philosophy, waste is first discovered as the firm reduces inventory and forces its productive system to maintain prior output levels with fewer resources at its disposal. With waste identified, a series of management methods and techniques can be applied to eliminate the problem. Voss and Robinson (1987) stated that "JIT may be viewed as a production methodology which aims to improve overall productivity through the elimination of waste, which leads to improved quality".

Factors Contributing to the Success for Japanese JIT Systems

The success of Japanese JIT systems has been attributed to several factors, including Japanese government cooperation with and support for industry (Vogel, 1978), the Japanese management style (Cole, 1980; Hayes, 1981; Juran, 1979; Pascale, 1977 and Wheelwright, 1981), and the cultural and social characteristics of the Japanese labor force (Marshal, 1977). The Japanese spend a great deal of time getting everyone involved in the decision making process. Although much time is spent obtaining a consensus, once it is reached the plan is implemented more rapidly since every one is committed to the plan. The Japanese also place strong emphasis on keeping the lines of communications open within the company (Cole, 1980).

Most large Japanese companies employ their workers for lifetime. This tradition allows employees to see a link between their success and the company's success. Japanese consider vendors as co-workers and are treated as an extension of the factory. The companies tend to have long term relationships with their vendors.

Requirements for JIT

1. Flexibility. The JIT system requires flexibility in the production processes such that small runs of products can be produced economically. Economical small production runs are achieved by reducing the equipment setup time, which is the fixed cost component associated with each production run. With the advent of flexible manufacturing systems (FM) this requirement has become a reality (Galenic & Goldhar, 1984). The current industrial revolution is adapting to FM and integrating these systems into completely computer-integrated manufacturing (CIM) systems. The result is a highly flexible operation with very short setup times (Galenic & Goldhar, 1984; Merchant, 1983).

2. Kanbans. Kanban pronounced (Kahn-bahn), is the Japanese word for card. Kanbans are considered the nerves of a JIT pull-system (Wang & Wang, 1990). Kanbans provide information about what and how much to produce from one station to another. Kanban cards serve as a communication vehicle for JIT production.

There are two types of Kanbans-withdrawal and production that have been used in the industry. Withdrawal Kanbans are used when parts are to be moved between the output and input buffer areas while production Kanbans are used when production is to take place (Monden, 1983).

Kanbans control the stage-to-stage authorization of container production.

JIT with Kanban is based on the premise that significant savings can be achieved by reducing inventory levels to an absolute minimum (i.e., one unit, if possible). This premise is true only if setup costs are also reduced so that total inventory costs are minimized at near unit levels, which the Japanese have been able to do. Kanbans are not necessarily required for JIT or pull systems to operate. In essence, Kanbans are just a physical realization of the control information required for material pull to be accomplished. It is quite feasible, in fact, to use computer control, instead of Kanbans, to provide the pull control structure (Lu, 1985; Monden, 1983).

3. <u>Small Setup Times</u>. The Japanese try to reduce setup times to less than ten minutes in order to produce small lot sizes rather than large ones.

4. <u>Frozen Demand Schedule</u>. In JIT systems, the Master Production Schedules must be frozen for about one to three months (Huang et al., 1983) in order not to cause the lines to get out of balance. An unbalanced line can cause production to backup and reduces further the variability in work load at work stations. Toyota has found that its JIT system can handle demand fluctuations of up to 10 % by adjusting the length of the workday. Workers stay until the work is done.

5. Work Force Attributes. The worker in Japan is highly trained and has a strong, positive philosophical view of his/her job. This tends to result in very little variability in job-processing times. In addition, the Japanese worker doesnot tend to "call it a day" until a job is finished (Huang et al., 1983). Japanese workers tend to be cross-trained, highly skilled, and very disciplined, which, when combined with a high degree of job automation, results in relatively standardized machine processing and setup times with little variation (Huang et al., 1983).

6. Quality Control. In JIT systems the ultimate goal is to achieve zero defects by adopting total quality control. At many of these factories defects are measured in parts per million. Another aspect of quality control is preventive maintenance, which helps in reducing the number of defects and the amount of machine downtime. Quality control is the responsibility of the worker on the production line; companies with JIT systems generally have small quality control staffs. They also generally do not have rework lines to fix the defective parts which in many U.S. factories take up from 15 % to 40 % of total machine capacity in the plant (Shronberger, 1982).

Results from a study by Voss and Robinson (1987) examining the application of JIT manufacturing techniques in the United Kingdom show that zero defects programs generated the most significant benefits by British JIT users.

Flexible Manufacturing System (FMS)

In the U.S., an estimated 75% of all machined parts are produced in lots of less than 200 work pieces, and that between 50% and 75% of the U.S. expenditures on manufactured parts are items with an annual demand of less than 100,000 units (Look, 1975). The percentage is continuing to increase as customers have more specific requests resulting in even smaller lots (Guple, 1989).

A flexible manufacturing system, or FMS, is broadly defined by the United States National Bureau of Standards as an arrangement of machines (usually numerical control machining centers with tool changers) interconnected by a transport system. The transporter carries work to the machines on pallets or other interface units so that work machine registration is accurate, rapid and automatic. A central computer controls both machines and transport system. Also, FMS could be defined as a group of machines and related equipment brought together to completely process a group or family of parts (Meredith, 1989).

Flexible manufacturing systems sometimes process several different work pieces at any one time (Nagarur, 1992). However, computer integration (scheduling, monitoring operations, handling material control, and taking appropriate actions in case of sudden changes in the system) and flexibility of the system (ability of the system to quickly adjust to any changes in relevant factors like machine failures) are very important to a flexible manufacturing systems (Nagarur, 1992).

Researchers and practioners alike have found designing, planning, scheduling and controlling of FMS more complex than in conventional systems. This complexity rises from the perceived need to exploit the production scope flexibility of the FMS to its fullest potential (Lo, 1992). FMS consists of a set of highly automated machines which are arranged in a cellular manner (Das, 1993). According to, Natendran & Kochikar, (1992) and Buzacott and Mandelbaum (1986) explain flexibility as the ability to respond speedily and effectively to environmental changes such as demand variation, changes in product specifications and changes in input quality, as well as to dynamic situations arising within the system such as breakdowns and blocking of machines. Flexibility enables producers to handle variations in input and output conditions, the reduction in response times achieved via dynamic scheduling, and the ability to tolerate technological changes (Natendran & Kochikar, 1992). It is difficult to define and quantify flexibility, and to date there is no standard procedure or objective way of expressing flexibility (Nagarur, 1992). However, Swamidass and Newell (1987) found that the competitive value of manufacturing flexibility lies in its ability to neutralize the effects of demand uncertainty.

Benefits of FMS

Chen and Atul (1994) outlined the benefits of FMS as:

1. Improved market performance: A more adequate and rapid response to market demand for product diversity, product innovation, customer responsiveness and aggregate volume, lower sales prices, shorter delivery times, higher delivery reliability, improved product quality.

2. Reduced cost of operation: Reduced direct labor or even unmanned operation, reduced indirect labor, overhead costs and floor space, shorter processing, setup and manufacturing lead times, reduced batch sizes and work-in-progress.

3. Improved operation management: Linking of production control and automated manufacture, fewer human errors, increased scheduling flexibility, just-in-time manufacture, improved and consistent quality and productivity.

Types of Flexibility

Browne (1984) defined seven types of flexibilities:

1. process flexibility: the ability to produce a given set of part types by using different materials, in several ways.

2. product flexibility: the ability to change over to produce a new (set of) products very economically and quickly.

3. Routing flexibility: the ability to vary machine visitation sequence and to continue producing the given set

of part types. This ability exists when there are several routes or when each operation can be performed on more than one machine.

4. Volume flexibility: the ability to operate an FMS profitably at different production volumes.

5. Expansion flexibility: the capability of building a system and expanding it as needed easily and modularly.

6. Operation flexibility: the ability to interchange the ordering of several operations for each part type.

7. Production flexibility: the ability to quickly and economically vary the part spectrum for any product that an FMS can produce.

Pull System vs Push System

Multistage production processes can be classified into two types (Kimura & Terada, 1981): push systems or pull systems.

Push systems

A forecast of demand which includes allowances for lead times is determined for each stage. The push process is controlled through inventory levels set at each stage in the system. To protect against an incorrect forecast, in-process inventory levels are often inflated to include safety stocks that can result in unnecessarily high carrying costs. Buffer inventories or, as they are sometimes called, safety stocks serve to cushion the effects of unpredictable events. The inventory over and above the average demand requirement is considered to be buffer stock held to meet any demand in excess of the average. The higher the level of inventory, the better the customer service, i.e., the fewer the stockouts and backorders. A stockout exists when a customer's order for an item cannot be filled because the inventory of that item has run out. If there is a stockout, the firm will usually backorder the materials immediately, rather than wait until the next regular ordering period (Meredith, 1992).

Pull systems

In a pull system the succeeding stage demands and withdraws in process units from the preceding stage only according to the rate and time at which the succeeding stage needs the items. In a Pull system, the production orders are calculated on the basis of actual demand (Tahashi, Hiraki & Soshiroda, 1993). The basic objectives of a pull system are to: (a) minimize in-process inventory, (b) minimize fluctuations of in-process inventory in order to simplify inventory controls, (c) prevent amplified transmission of demand fluctuations from stage to stage, (d) raise the level of shop control through decentralization, and (e) reduce defects (Kimura & Terada, 1981).

The efficiency of the pull system is often measured in terms of the number of containers of goods produced and stored at each stage -- the more inventory, the lower the efficiency. When demand for a preceding stage's output is generated by the succeeding stage, the preceding stage's unit of inventory is transferred to the succeeding stage where it is processed. The removal of inventory at the preceding stage authorizes the manufacture of an additional unit to replace the one just taken (Huang et al., 1983). The production Kanban subsequently replaces the withdrawal Kanban. The withdrawal Kanban is sent back to the preceding stage where it authorizes the production of another container which is now required at the succeeding stage. This creates a continuous cycle of container movement between the stages. In other words, the production Kanban acts as an intra-process control apparatus and the withdrawal Kanban serves as the inter-process control apparatus (Huang et al., 1983).

Pull-Push Integration

Many researchers tried to integrate both systems in order to utilize their advantages (Kimura & Terada 1981; Sarker & Fitzsimmon 1989; Tabe & Tanaka, 1980; Takahashi, Muramatsu & Ishii, 1987; Olhager & Ostlund, 1990; Hodgson & Wang, 1991). There are two strategies for the integration, i.e., vertical integration and horizontal integration. Vertical integration implies that the system consists of two levels, the upper level consisting of a push-type and the lower level consisting of a pull-type. Horizontal integration implies that all the stages are not ordered by either of the production ordering systems, but that some stages are ordered by a push-type and other stages are ordered by a pull-type production system.

Finally, Takahash et al. (1993) found that pull-push integration is effective in decreasing the amplifications at preceding stages. Also Ming-Wei and Shi-Lian (1992) concluded that in an inventory manufacturing environment there is always a need to combine material requirement planning (MRP II) with JIT. Besides, they believe that a hybrid system has to be selected based on the conditions of the enterprise.

Types of Production Shops

Groover (1980) suggested two schemes to classify production shops: by the production volume and by the layout of the plant. Two types of shops under the production volume scheme are briefly summarized.

Flow-shop

Flow-shop refers to the production of an item which requires a long sequence of operations. Flow-shops are heavily automated with special-purpose equipment. The characteristics of this process design are relatively fixed inputs, operations throughput times and outputs. A flow-shop is used to achieve a smooth and rapid flow of large volumes of products through a system. The flow-shop is made possible by highly standardized products or services that require highly standardized processing operations. Product layouts achieve a high degree of both labor and equipment utilization and that tends to offset the high equipment costs usually associated with this type of layout. Because items move quickly from operation to operation, investment in work-in-process (WIP) is often minimal. However, operations are so closely tied to each other so that the entire system has a high vulnerability to being shut down due to either mechanical failure or high absenteeism. Preventive maintenance periodic inspection and replacement of worn parts or those with high failure rates is used to reduce the probability of breakdowns during operations (Stevenson, 1996; Meredith, 1992).

Job-Shop

Browne and Davies (1981) defined job-shop production as follows: "Job-shop production is defined as the manufacture of a product in small batches or lots by a series of operations. The production system must be flexible and uses general purposes equipment in order to accommodate varying customer requirements and fluctuations in demand. Job-shop production is a situation which falls between pure jobbing production and mass production. Yet the quantity required is insufficient to justify mass production. Because of the large variety of jobs involved, the job-shop operation is inherently complex."

By definition, a job-shop is likely to employ general purpose equipment which can provide common fundamental operations for any variation of a given product type. Therefore, manufacturers in a job-shop environment may experience numerous engineering changes and material substitutions during the manufacturing process due to the variety of customer requirements and relatively small production lot size. This type of production system produces orders to meet specific customer's requests, which are often on-time orders. A job-shop must have general purpose production equipment and highly skilled workers because of the variety of products it manufactures. In a job-shop each output, or small batch of outputs, is processed differently. Therefore, the flow of work through the facility tends to be of an intermittent nature. The general characteristics of this form are a grouping of staff and equipment according to function; a large variety of inputs; a considerable amount of transport of either staff or materials; and large variations in system flow times (the time it takes for a complete "job", a billable set of tasks, to be processed) (Meredith, 1992).

Differences between job-shop manufacturing and flow-shop manufacturing

Job-Shop. * Machines are organized around a manufacturing or engineering group of similar machines or labor skills, which is considered as a workcenter.

* Required volume of master production scheduling (MPS)

is not uniform and continuous.

* Work order and purchasing order are generated through MRP logic and algorithms ("push" system).

* Lead time and order policy are very important.

* Both stock and work-in-process are to be considered.

* Planning horizon and planning period are long.

* Shop order with certain batch size goes from one work center to another. Shop floor control covers all the operations. Operation priority is very important.

Flow-Shop. * Machines are organized according to the kinds of parts which have to be produced. Various production lines are set up to machine certain kinds of parts.

* MPS is uniform and continuous.

* Work order and purchasing order are generated through JIT logic and algorithms ("pull" system).

* Lead time is not very important, the theoretical batch size is 1.

* Theoretically no stock, only work-in-process to be considered.

* Planning horizon and planning period are short.

* Parts to be produced flow through the production line. Shop floor control functions only at checkpoints (or stock points). Operation priority is not important.

Cellular Manufacturing (CM)

Cellular manufacturing is the application of Group

Technology (GT) principles to manufacturing. Specifically, parts that require similar processing are placed into part families. Simultaneous with the part family determination, the equipment is grouped into machine cells, with each machine cell dedicated to the production of a particular part family (Shafer & Meredith, 1992).

Benefits of CM include reduction in the work-in-process inventory, reduced lead times, simplified shop floor control, and possibly, job enrichment (Shafer et al., 1992).

However, according to Flynn (1984) cellular layout had superior performance in terms of average move distance and average setup. Whereas, the functional layout has superior performance on all queue related variables.

CM possesses the following two fundamental characteristics: (a) Machining parts are classified into different families, and (b) machines are arranged into cells according to the manufacturing requirements of a particular family (Huang & Houck, 1985).

Group Technology (GT)

Group technology was broadly defined by Shunk (1987) as a disciplined approach that is utilized to increase the effectiveness of managing parts, processes, equipment, tools, people, or even customer needs. GT is a manufacturing philosophy in which the machines are grouped into "cells" and the parts and assemblies produced are divided into "families" in such away that each cell completes all the items it makes without back-flow or cross-flow between cells (Radharamanan, 1994).

GT can reduce tooling and fixture expenses, material handling costs, production planning and control efforts, need for floor space, lead time, and WIP. Also it can improve quality, increase worker satisfaction, reduce design effort, and provide easier and more accurate cost estimates.

Research Questions and Objectives

Research questions

Is the mixed-model, JIT production system affected by using different numbers of kanbans?

Is the mixed-model, JIT production system affected by using different sizes of containers?

Is the mixed-model, JIT production system affected by using different distributions of processing time?

Is the mixed-model, JIT production system affected by using different setup times?

Is the mixed-model, JIT production system affected by the joint influence of any combination of two or all the variables used in this study?

Research Objective

The proposed study will simulate the operation of a mixed-model, just-in-time production system. The purposes are:

1. To explore the effects of factors such as number of Kanbans, container size, different distributions of processing time and different setup times on the performance of a mixed-model JIT production system. Exploring such effects can determine the extent to which a production manager can implement JIT within the existing production environment, the results that can be expected, and the problems that might arise. Also, the study may help the managers formulate their policies in regard to different aspects of production policies.

2. This study will stress the role of cellular manufacturing systems in meeting a dynamic environment.

3. Mixed-model systems are not typically incorporated in academic research studies.

4. To build a simulation model that can be used by other researchers.

5. To extend in several important ways previous research that has been conducted.

This dissertation differs from other studies in the field in that the focus is on using a multistage, multiproduct model with cellular manufacturing system. Previous studies havenot used cellular manufacturing systems. Model structures used in simulating production systems can be categorized into two major groups: multiline, multistage ; and singleline, multistage models (Chu & Shih, 1992). Chu et al. (1992) found that most of the models used were relatively small in scale, but this study will use a large scale model. The largest model was done by Sarker and Fitzimmons (1989), a nine-stage model. Therefore, findings of previous studies may need to be verified, as small-scale models do not reflect actual production environments (Chu et al., 1992). Also, most studies consider one or two finished products (Gupta & Gupta, 1989; O'Callaghan, 1986; Olhager, 1983). This study will consider four finished products in an effort to bring the environment closer to the real situation. Finally, little attempt has been made to expand the research process to include multiline, multiproduct, multistage (and more flexible) systems, in an environment where processing time is a variable. Container capacity and its relationship to the number of kanbans has not been properly investigated in such environments (Abdou & Dutta, 1993). Simulation offers a promising approach for these complex systems (Abdou et al., 1993). This is what this study intends to achieve.

Chapter 2

Literature Review

Introduction

The literature on JIT contains conceptual and empirical studies, simulations, mathematical models, and case studies. Numerous literature reviews of JIT systems have been conducted (Billington, McClain & Thomas, Sarker 1984; Bollinger, 1981; Buzacott & Yao, 1986; Panwalker & Iskander, 1977; Villeda, Dudek, Smith, 1988; Person, 1989). Through an extensive literature search, Golhar and Stamn (1991) identified 860 just-in-time (JIT) articles published in professional journals since 1970. When they excluded the articles published in nonrefereed journals, 211 research papers were selected for further analysis. Two general review articles have integrated the reported research in the field (Im & Lee, 1989; Sohal et al., 1988). The first article on JIT implementation in manufacturing appeared in the 1970s (Sugimori et al., 1989).

Although not much work has been done towards the quantification or analytical investigation of the just-in-time production system, a few studies have explored the effect of factors such as variable processing times, variable master scheduling, and imbalance between production stages (Huang et al., 1983; Monden, 1981; a,b,c, 1983). However, none of these studies concentrated on examining these factors in-depth except Sakakibara, Barbara and

Schroeder (1993) who proposed a theory and described the development of a reliable and valid instrument for measuring the critical dimensions of JIT practice. They derived 16 critical dimensions of JIT practice from the descriptive, prescriptive, and empirical literature, and from a series of plant visits. They described summated scales, corresponding to the 16 critical dimensions of JIT practice. Most conceptual studies consider only a few variables associated with the basic tenets of JIT philosophy. Lack of standard terminology for critical variables coupled with a narrow research focus limits the generalizability of the findings. The usefulness of empirical studies on JIT implementation is also limited because of their small sample size (Golhar & Stamn, 1991). The literature review in this study will include all relevant studies in both optimization and simulation.

Optimization Models

Optimization models were used to examine different problem areas related to the flow-shop. These models examined the effects of variable demand, bottlenecks, machine breakdowns and variable processing times. Formulating Kanban-controlled lines as Markov chains has been a popular strategy to find the optimal number of Kanbans. In these models, researchers usually assume processing times to be exponential and give the state of the system by the number of full containers between each pair of stations. Since lines processing a single part type are unlikely to exhibit the variability of the exponential distribution, Markov models should be used only to give an estimate of worst-case performance. Although optimization models were used, these models do not adequately reflect the dynamics of an operating JIT manufacturing system which must respond to issues such as the increase in part commonality. These studies are reviewed in more detail below.

Multistage models

Kimura and Terada (1981) developed a model of a multistage serial production process producing a single item with unlimited productive capacity. Container capacity was assumed to be one. The objective of their model was to determine the optimal number of circulating Kanbans and thus the level of inventory carried at each stage of production. They found that in the case where the size of the order unit is small compared with the production quantity level, production will not be amplified in the preceding stage. Higher lead time caused a larger level of amplification in production fluctuations.

Bitran and Chang (1987) extended the work of Kimura and Terada by examining a multistage production system using JIT. The objective was to determine the number of Kanbans. They used a deterministic model and tried to solve the following problems: (a) container-for-container, which dealt with the optimization of the number of kanbans where exactly one full container of an item was required to produce one full container of a subsequent item, (b) one container-for-multiple containers, which optimized the number of kanbans where exactly one full container was required to produce an integrated number of full containers of a subsequent item, and (c) multiple container-for-one container, which optimized the number of kanbans where an integral number of full containers were required to produce exactly one full container of a subsequent item. Bitran and Chang do not provide test results of these models, but they suggest that the model could be extended to include direct treatments of independent external demand, uncertainties in demand and machine reliability.

Moeeni and Chang (1990) and Li and Co (1991) have simplified Bitran and Chang's model by assuming that production capacities are unlimited. Their argument is that stations should have the capacity to satisfy the demands represented by the production Kanbans detached in each period. The assumption of infinite capacities not only removes the capacity constraints but also eliminates the need to keep track of the number of the units in partially filled containers. Moeeni et al. (1990) solved the infinite capacity problem by using a heuristic that applies when each stage has the same inventory holding cost. Sample problems showed that the performance of the heuristic was satisfactory and improved with decreasing finished-goods demand variability.

Li and Co (1991) developed bounds for an efficient Kanban assignment and applied them to solve a dynamic programming problem.

Jordan (1988) modeled the two-line, two-stage system as a queuing network using a Markov chain with a finite inventory and random processing times at each stage. Four different distributions were used. Each had a mean processing of 48 minutes. To calculate the expected daily production or the average inventory level for a given number of Kanbans, a backward iteration was applied to the Markov chain state space. Expected production per day increased to a limit of 10.0 units as the number of Kanbans increased. Average production was always higher for the narrow normal distribution than for the wide normal, since variation in service times increased the probability of the queue becoming empty. Jordan found that iterative methods are useful when the problem is small and when the approximation of service distributions by another distribution with the same mean and variance is valid for steady-state results such as average production rate or average inventory level. Finally, Jordan used his model to check the simulation results obtained by Huang, Rees, and Taylor (1983) for two-card systems. Based on a comparison of average production rates, Jordan concluded that the simulation methodology of

Huang et al. (1983) suffered from procedural problems. However, Berkley (1990) contrasted Jordan's findings and suggested that the Jordan model should not be applied to the problem of setting kanban numbers on manual JIT lines.

Berkley (1992) addressed the application of the two-card kanban system to flow shops. He showed by presenting many examples how the approximation method can be used to determine the required number of kanbans, the required withdrawal cycle time, or both. The optimal material-handling frequency and number of kanbans must be determined by minimizing the sum of transportation and inventory costs. When the material-handling operation between all pairs of stations occurs simultaneously, the flow shops have been decomposed into individual stations modeled as imbedded Markov chains. The analyses of individual stations are then aggregated to produce an approximation of the entire flow shop. This approximation provides an efficient and accurate means of simultaneously evaluating alternative numbers of kanbans and withdrawal cycle times.

Bard & Colany (1991) developed a mathematical model to assist line managers in determining an optimal kanban policy at each work station in a general assembly shop. They presented an example based on the assembly of printed wire boards (PWB) at the Texas Instrument (TI) plant in Austin, Texas. The basic operations involve the attachment of electronic components and accessory parts to unpopulated

PWBs. This is carried out by either inserting leads through holes previously drilled in the boards, or by mounting components directly on the surface. The facility is composed of five major sections: the warehouse; the JIT kanban staging area; the component preparation area; through-hole insertion area; and surface mount area. Brad and Golany developed a mixed integer linear program to extend Bitran and Chang's model and to allow for material shortages, the production of multiple parts at each stage, nonzero processing and setup times, and blocking by part type. They transformed the mixed integer linear program into a nonlinear nonconvex program and solved it using a cutting plane algorithm. They showed that the resulting solutions have total setup, holding, and shortage costs of approximately half those obtained using the Toyota equation (1).

Kim (1985) tried to determine the maximum stock level for each stocking point so that the probability of a stockout was no greater than a preselected target value. His major contribution was the introduction of a periodic pull system (PPS) as an alternative to the Kanban control of JIT production.

Sipper and Shapira (1989) used a partial differential method to analyze the behavior of a very simple two stage serial production line. The objective was to minimize the total cost associated with late deliveries under two competing policies. Under the first policy, the production system was governed by a work in process (WIP) policy in which inventory was held in anticipation of expected shortages. Under the second policy, the production system was governed by JIT in which a late penalty per unit time was imposed when shortages occurred. They developed a decision rule which revealed the conditions under which WIP and JIT policies were attractive. In other words, the decision rule stated that when work-in-process cost was equal to average shortage cost, the firm should be indifferent between WIP and JIT policies. When the ratio between the two was either less than or greater than one half, a JIT or WIP policy, respectively, dominated.

Wang and Wang (1990, 1991) modeled two-card systems with serial, split, and merge configurations as continuous-time Markov chains. They assumed order points to be one so that the systems could be run with only one withdrawal Kanban between each pair of stations. They evaluated Markov chains for alternative numbers of production Kanbans to find the solution minimizing total inventory holding and shortage cost. Kim (1985) modeled the input and output buffer inventories of fixed-withdrawal-cycle systems as discrete-time Markov chains. He then set the number of production and withdrawal Kanbans to achieve a desired probability of stocking out.

The usefulness of both the Wang and Wang (1990, 1991) and Kim (1985) methods is limited by the assumption of station independence. Wang and Wang assumed that the production and demand processes of all stations were independent. Kim assumed that production capacities were infinite so that the steady-state input and output buffer inventory distributions of each station depended only on the finished-goods demand distribution of the last station. This means that when a line experiences frequent station blocking or starving-symptoms of station interdependence these models will not give accurate results. Deleersnyder, Hodgson, Muller, and O'Grady (1989) modeled a line with blocking by total queue size as a discrete-time Markov chain to study the effects of Kanban numbers, machine reliability, and processing-time and finished-goods demand variability. They showed that the number of Kanbans did not have a strong effect on finished-goods demand backlog until inventory levels reached a lower limit.

The dimensionality problem associated with Markov chains limits the Jordan and Deleersnyder, Hodgson, Muller, and O,Grady models to lines having a relatively small number of stations. So and Pinault (1988) overcame this problem by decomposing lines into individual M/M/1 queues with bulk service. They assumed each station to have both input and output buffers and limited the total number of full containers permitted by a single card type. They combined their analyses of the individual stations using a heuristic procedure to approximate the entire line. So and Pinault reported that, because stations were assumed to have an infinite supply of raw material, their approximation is valid only when Kanban numbers are large enough to prevent station starvation.

Mitra and Mitrani (1990) termed the blocking mechanism used by So and Pinault "minimal blocking" and proposed an alternative decomposition approximation. This blocking mechanism is minimal in the sense that the input and output queues are limited by a single constraint while the two-card system places (Kanban) constraints on both maximum input and output queues. Mitra and Mitrani assumed that processing times, raw material interarrival, and finished-part demand interarrival times were exponential so the stations could be modeled by a continuous-time Markov chain. Numerical examples showed that the largest errors occurred for the longer lines with few Kanbans and frequent station blocking and starving.

Mascolo, Frein, Dalley, and David (1991) gave petri net representations for the So and Pinault (1988), Mitra and Mitrani (1990), and Kimura and Terada (1981) Kanban models. They obtained numerical results for individual Kanban-controlled stations having multiple stages using an approximate product from solutions. Results showed that the approximations were most accurate when stations were not saturated by demands and had large processing-time variances and numbers of Kanbans. They did not consider multiple station lines because the blocking caused by finite Kanban numbers generates solutions that do not have product form.

Berkley (1992) developed a decomposition approximation using imbedded Markov chains for two-card systems with periodic material handling and Erlang processing times. I give several examples to show how the approximation could be used to find the required number of Kanbans, the required withdrawal cycle time, or both.

Single-Stage Model

Graham (1992) developed a steady-state Markovian model for calculating the number of kanbans required to control single-stage processes feeding assembly lines. A Markovian model of an alternative just-in-time system, in which the off-line process is triggered by the passage of vehicle bodies past a point prior to the assembly area, showed that the use of a trigger system leads to lower inventory levels and greater pressure for improvement than a kanban system.

Requirements-Driven Systems

Requirements-driven systems combine the advantages of material requirements planning (MRP) and Kanban systems. The basic idea is to control the card counts in the Kanban system on the basis of the requirements generated by an MRP system. This method is suitable for dynamic batch-manufacturing shops in which part types and product mixes change significantly from period to period.

Groenevelt and Karmarkar (1988) and Karmarkar (1986a, 1986c) described a dynamic Kanban system in which they used MRP to calculate the gross requirements for each part. They then offset these requirements for production lead time and used them to determine the number of Kanbans authorized in each period. Groenevelt and Karmarkar observed that the requirements-driven system obtains the advantages of MRP through the use of detailed information about future demands as well as the incentives provided by the Kanban system to reduce production lead times. The disadvantages of this system is that it assumes production lead times are known to the MRP system. If lead times change substantially over the planning horizon, the number of Kanbans may not be correct.

Ding and Yuen (1991) studied hybrid systems in which some stations are controlled by MRP while others are controlled by Kanban. To account for parts made at the Kanban-controlled stations, they proposed that an order be released in the MRP system whenever gross requirements accumulate to a part's container or Kanban size. A simulation study showed their system's performance to be similar to Groenevelt and Karmarkar's (1988) dynamic Kanban system.

Deleersnyder, Hodgson, King, O'Grady, and Savva (1992) compared hybrid MRP/Kanban, pure MRP, and pure Kanban systems. In the hybrid system, station production is limited not only by the constraints in the pure Kanban system (number of empty finished-goods containers, number of full component containers, and station capacity), but also by a schedule-determined quota. They found that the hybrid system requires less inventory than the pure Kanban system but more inventory than the pure MRP system to achieve a desired finished-goods service level.

Simulation Studies

The JIT simulation studies fall into four distinct categories, these are: demand variability, priority scheduling rules, process time variability and part commonality. These simulation studies considered a number of factors, including balanced and unbalanced workstations, number of Kanbans, container size, demand variability, scheduling rules, part commonality and process time variability. Balanced and unbalanced workstations, number of kanbans, container size and process time variability have received the most attention. The major simulation studies are discussed below.

Multistage flow-shop studies

Flow-shop problems have received much of the empirical attention because JIT was first implemented in flow-shops. A review of the relevant studies follows.

Huang et al. (1983) modeled a multiline, multistage JIT manufacturing system. They tried to observe the effects of variable processing times, stage bottlenecks and variable demand rates on the performance of a JIT system with Kanban. Performance was measured by the amount and cost of overtime and the number of Kanbans required to meet a production schedule. They found that increases in process variability were associated with increases in the amount and cost of overtime.

Huang et al. (1983) emphasized the impact of various processing-time distributions on system performance (in terms of inventories, Kanban requirements, overtime requirements, cost analysis for Kanban, etc.), variability in the demand rate, and the effect of variable processing times. Variability in the demand rate resulted in increased overtime, implying that for JIT system, the master production schedule must be nearly frozen over the short term for JIT to be successful. The interaction between demand variability and process variability was also significant. Furthermore, they recommended that firms which operate under varying processing times and high fluctuations in demand not to adopt a JIT system with Kanbans without a transitional period. Moreover, they wanted firms to standardize machine processing times, reduce setups and train workers for cross utilization in the transition period. Finally, they demonstrated that the number of Kanbans could be adjusted to provide additional buffer stock to help alleviate the problems of process and demand variability.

Berkley (1990) used Markov-numerical analysis to compare the performance of Jordan's and Huang et al.'s method of production control. Simulation analysis is then used to determine the effects of finite withdrawal cycle times. Results show that, for equal number of kanbans, Huang et al.'s two-card method of production control provides substantially greater expected production rates than Jordan's method. Further, expected production rates of JIT lines were shown to be highly dependant on withdrawal cycle times. These results suggest that the Jordan model should not be applied to the problem of setting kanban numbers on manual JIT lines.

Monden (1984) commented on the conclusions drawn by Huang et al. (1983). He stated that the Kanban system should be able to adapt to daily changes in demand with plus 10% deviations from the monthly Master Production Schedule (MPS). Large seasonal fluctuations in demand can be accommodated by setting up the monthly MPS appropriately.

Ebrahimpour and Fathi (1985) developed a simulation model to study a single-cell Kanban system under the cyclical demand pattern.

O'Callaghan (1986) formulated a multistage simulation model of a Kanban system. He concentrated on studying the behavior of the system in adapting to changes in management policies and environmentally induced uncertainties. He assumed a close proximity between the subsequent stages and therefore used only a production Kanban to study the model.

Villeda, Dudeck and Smith (1988) in a study similar to Huang et al. (1983) concluded that the "high-medium-low" mean operation times method showed a consistent improvement in the output rate of the JIT production system with Kanban. They examined a JIT production system with variable operation times. A system with three subassembly lines feeding one final assembly station was considered. They studied the reduction of variability effects by unbalancing the subassembly line through assignment of work content at each station. They found that the output rates of the unbalanced stations were always superior to the output rates of the perfectly balanced configurations. The extent of improvement over the output rate of the balanced system increased directly with the variability of operation times in final assembly and the subassembly stations, and inversely with the interstate buffer capacity allowed in the system. In addition they found that all cases with balanced work centers had almost the same percentage of utilization. The work centers of the unbalanced configurations showed a consistent high-medium-low pattern of utilization. Their major finding was that process time variability at the final assembly stage tends to be transmitted and amplified to the entire JIT system.

In contrast to Villeda et al.'s (1988) study, Sarker and Harris (1988) used a two-line, six operation process to determine the effects of five different processing time variations on the performance of the system as compared to the system in balance for the base case. All operation times were distributed normally with a mean of six minutes and a standard deviation of one. The queues for each stage were preloaded with one unit of work in process; container size was fixed at one unit. Performance was measured by the average queue waiting time at each station, average utilization at each station, average cycle time and average production rate in units per day (throughput). Sarker and Harris (1988) concluded that imbalance in the JIT (regardless of the specific case type) caused one of the following conditions: unequal utilization of stations, fluctuating throughput, increase in work-in-process, and selective blockage and starvation on the line. Most significantly, Sarker and Harris found that when the ratio of processing time between two stations was 1.0 plus or minus 10% balanced station utilization occurred and throughput was stabilized at a relatively high level.

Gupta and Gupta (1989) studied a two-line, three-stage production system using dual Kanbans. They found that increased variability in processing times leads to a decrease in the production rate and to an increase in shortages. In addition, high variability in processing times increased the amount of overtime required to meet the production schedule. These results match the results obtained by Huang et al. (1983). They found also that increasing the size of containers and decreasing the number of Kanbans leads to higher levels of WIP inventory. Furthermore, increasing the number of production Kanbans when other parameters remained constant, didnot increase the production rate. When production rates were increased with the addition of more Kanbans, WIP increased. The additional inventory acted as a cushion for variable processing times. This implied that a trade-off exists between overtime and inventory holding costs when process time variability cannot be reduced.

Philipoom, Rees, Taylor and Huang (1987) developed a procedure to dynamically adjust the number of Kanbans in order to examine the effect of process variability. They modeled a shop consisting of six workcenters producing two finished products under conditions of process variability. They found that the number of Kanbans could be successfully adjusted to achieve a minimum cost trade-off between the holding cost of excess WIP and the shortage cost of insufficient WIP. Moreover, they used the same shop to identify the factors which influence the number of Kanbans in a JIT system. They concluded that the following factors influence the number of Kanbans required at a workcenter: (a) throughput velocity (the rate at which items flow through a workcenter machine), (b) the coefficient of variation in processing times (the degree of variability of processing times), (c) machine utilization (the availability of slack time on a machine), and (d) the autocorrelation of processing times (the degree to which successive processing times on a specific machine are related to each other). They also found that the probability of a backorder varied inversely with the throughput velocity and directly with the coefficient of variation.

Khaudhary and Whinston (1990) presented a control methodology for flow shops that is decentralized and adaptive in nature and has low data handling and computational requirements. The methodology is based on stochastic automatic methods for modeling learning behavior. It is proposed that such a methodology can be used with kanban type control techniques to make flow shop systems more flexible and adaptive. The system is inherently adaptive to changing job input patterns into the flow line, providing such a system with a much needed measure of flexibility.

Magazine and Silver (1978) concluded that the effects of blocking (where a station holds a completed unit because of lack of space to deposit it for the next station) and starving (where the station is idle because of inadequate supply of units from the previous station) is greatest for those stations closest to the blocked or starved station. The effects on other stations diminished as the station got further away. The first and last stations of an assembly line affected stations in one direction only; the beginning station was subject by blocking and the end station to starving. The middle stations affected stations in both blocking and starving. Hence, these middle stations were more critical and should be allocated less work.

Sarker and Fitzsimmons (1989) conducted a simulation study to investigate the effects of variance of operation times and interstage buffers on the performance of a pull system and compared the results to a push system. They found that the variability in processing times and the inability to allocate the tasks equally to different stages created a problem of imbalance in such a production line. The output rate of a pull system is more sensitive to high variability times (Cv) than that of a push system. Also, they observed that a pull system is always better at minimal WIP, but is less efficient than a push system, especially at higher coefficients of variation. They found that the utilization of resources (with no buffer in between the stages) in the push system was very high even at higher coefficients of variation of processing times at different stages. The average line efficiency decreased almost linearly as the coefficient of variation increased. Importantly, the efficiency in a pull system was lower than that of a push system. As the coefficient of variation of a stage's operation time increased, the difference in efficiencies became more pronounced. The utilization of all production facilities along the line remained almost constant for a lower coefficient of variation of the processing time. The utilization of a stage's facilities in a pull system was significantly lower than in a push system both with and without breakdowns of machines. The efficiency of a pull system increased by a significant amount with a uniform buffer size of one unit throughout the production line. Barker, Powell and Pyke (1990) concluded that the model of a push system used by Sarker et al. (1989) as their base case is actually a serial line with large buffers, whereas, the pull system is actually a serial line with small buffers. The differences they attribute to pull tactics versus push tactics are really due to differences in the size of buffers. In a serial line with finite buffers, it is not meaningful to distinguish between push tactics and pull tactics. Thus the research question examined by Saker and Fitzsmmons is ill-conceived, and, therefore their results are flawed.

El-Rayah (1979a, 1979b) concluded that push production lines with small interstage buffers reacted in the same way to imbalance regardless of the service time distribution. The following performance measures were used:

1. production rate,
2. daily output rate,
3. overtime required to meet daily demand,
4. in-production activity inventory in the final

assembly stage,

5. post-production activity inventory in the final assembly stage,

6. level of work in progress,

7. workcenter utilization , and

8. waiting time at the final assembly station due to lack of parts.

The probability of both blocking and starving at any station was increased by smaller interstage queuing capacities, higher variability in operation times, and a large number of stations in the line. El-Rayeh found that unbalanced configurations had higher production rates than balanced ones.

H. Wang and H. P. Wang (1990) discussed the role of kanbans in a JIT production system in the context of maintaining a minimum level of in-process inventory. A model determines the optimum number of kanbans for three production settings, one is applicable to JIT machining shops, while the other two are suitable for JIT assembly shops. The thrust of the model is to demonstrate how partial advantages of the JIT production can be obtained for a shop, even when full implementation of the JIT philosophy is not possible. JIT is a multifaceted manufacturing concept involving productivity, quality, production planning and production control. With certain planning and control efforts, the kanban component can be implemented to reduce inventory cost.

Meral and Ekrip (1991) simulated a simple production line producing a single product where the processing times at workstations are variable and demand arrivals are deterministic. The study doesnot confirm the bowl phenomenon in terms of the production rate. When the only measure of performance is the production rate, balanced strategies are always superior to the bowl-phenomenon-based strategies in pull production lines with normal processing times.

Golhar and Chaturvedi (1991) simulated a nine workstation, sequential production line to examine the effects of stochastic demand, processing time and the number of Kanbans on system performance. They found that the system performs best with four Kanbans, while keeping variances of the performance measures at a minimum.

Ramnarayanan and Gillenwater (1991) simulated a multi-line multistage stochastic just-in-time production system to investigate the effects of number of Kanbans, container size, setup time and delivery frequency on the system's performance.

* Fewer Kanbans in the system resulted in improved performance with respect to the inventory measure and lower mean WIP inventory levels in the system.

* Smaller container sizes enabled higher performance with respect to both inventory measures and scheduling measures.

* Shorter setups had the same effect.

* A more frequent delivery strategy led to deteriorating performance with respect to scheduling measures, resulting in larger mean cycle times and higher mean shortage levels.

Muralidhar, Scott, and Wilson (1992) conducted a simulation study to determine if the selection of the distribution used to describe processing times in JIT simulations will affect the simulation results. They used three distributions, namely, the truncated normal, the gamma, and the long-normal distributions. The results conclusively indicate that, for the range of processing time characteristics considered, performance is insensitive to the type of distribution selected. Also, for a system with a given product structure and system characteristics similar to those described in the study, the performance of the system is a function of CV. Finally, decision-makers considering the implementation of pull production processes can simulate alternative design considerations as long as an accurate estimate of the level of CV is available.

Abdou and Dutta (1993) simulated a multistage, multi-product manufacturing system. They tried to determine the number of circulating Kanbans and the corresponding container capacity. Also, they investigated the relationship between overall cost and response time as related to the material handler for different combinations of container capacity and number of Kanbans in the system.

Single Stage Flow-Shop Problems

Deleersnyder et al. (1989) considered a single stage item manufacturing process with production and inventory constraints. Their N-stage serial model takes into account the random nature of demand and machine failures. They investigated tradeoffs between shortages and inventory for several levels of demand variability, machine unreliability, and Kanbans. Reducing the number of Kanbans in a loop resulted in a decrease in inventory levels at that stage. Also, because of starvation effects it resulted in a decrease in all downstream inventory levels (and a simultaneous increase in the backlog levels).

MultiStage Job-Shop Studies

Gravel and Price (1988) adapted the Kanban method to a job shop environment and tested three different rules for assigning lots to machines: (a) operation weighted critical ratio, (b) shortest processing time (SPT), and (c) the operation weighted critical path. The job-shop consisted of nine machines, seven finished products and approximately fifty-two operations required per finished product. They found that JIT can be successfully implemented in a relatively small industry, even if current operations are conducted as a job-shop versus a flow-shop.

Davis and Stubitz (1987) used a digital simulation written in SIMAN to model an actual job shop characterized by unbalanced production times between work centers and high demand variability. The job shop was characterized as having a variety of possible routings. Their study included the modeling of transportation between workcenters by using actual distances in the shop and three transport vehicles. They found that the use of Kanban and a pull system could be beneficial even in a nontypical JIT environment by reducing the shop floor required by the firm's MRP system.

Krajewski, King, Ritzman, and Wong (1987) assessed the robustness of the Kanban system when applied to manufacturing environments likely to be encountered in the U.S and compared the Kanban environment with both MRP and ROP environments. They attempted to identify the factors that have the biggest impact on performance regardless of the type of system in use. The results revealed that the Kanban system when implemented in certain environmental settings did perform better than the traditional systems used in the U.S. They found that reducing setup times and lot sizes were the most effective ways to cut inventory levels and improve customer service. Moreover, the degree of product standardization and product structure were found to be high impact factors, whereas inventory record inaccuracy, equipment failures and vender reliability were less crucial.

Rees, Huang, and Taylor (1989) compared Kanban to traditional MRP control and explored how Kanban could be adapted to a typical American job shop. They used a hypothetical production operation that included multiple workcenters, machines and product structures for both serial and assembly operations. The Kanban system was implemented in an a sample shop with shortened cycle times and reduced setup times and cost. Significant savings were obtained when compared to the shop without the reduced setup times and cost. Also, they found that when setup and cycle times were shortened in an MRP shop, costs were reduced. MRP was found to be capable of handling lumpy demand better than the Kanban system even in the presence of stochastic processing times. The primary conclusion of the study was that if companies cannot successfully introduce Group Technology (GT), then staying with an MRP system while working to improve lead times, setup times and shortening the time buckets may be a more cost effective approach than a conversion to JIT with kanban.

Scheduling Rules

There are many studies that consider the effects of scheduling rules. Lee (1987) investigated the effects of scheduling rules, job mix, demand levels, container size, number of Kanbans and pull frequency (for a constant demand level) on JIT performance. Lee and Seah (1988) considered an eight-station flow line with a two-card constant order quantity and a nonconstant withdrawal cycle method of Kanban control. The effects of two parameters were investigated: the nature of processing time distributions, and setup times (and batch quantity). Berkley (1988) compared the performance of FCFS, SPT, and SPT/LATE on Kanbans-controlled lines with different and (nonzero) conveyance periods.

Summary

This chapter presented previous research in JIT production systems with emphasis on mathematical programming and simulation studies. Mathematical programming studies considered many factors such as number of Kanbans and some sequencing heuristics. Simulation studies considered a number of factors such as balanced and unbalanced workstations, number of Kanbans, container size, demand variability, scheduling rules and process time variability. Of these factors, balanced and unbalanced workstations, number of Kanbans and process time variability have received the most attention. However, each study used a different model with different assumptions, experimental factors, and measures of performance. It is very difficult to compare and verify individual results. Below is a summary of some major conclusions that are consistent across previous studies.

* Several factors, such as setup time, lot size, and variability in processing time and demand rate, have been found to be crucial to the success of JIT implementations (Huang et al., 1983; Kimura & Tereda 1981; Krajewski et al., 1987).

* Bottleneck problems cannot be solved by increasing

the number of kanbans (inventory levels), (Changchit & Kung 1988; Huang et al., 1983; Lu et al., 1989). Two approaches have been used to solve this problem: (a) increase transferability of skilled worker, and (b) use automated machinery at the bottleneck station.

* Some studies (Gupta & Gupta, 1989; Huang et al., 1983) showed that an increase in variability of processing times leads to a decrease in production rate and increase in shortages. Management must consider the tradeoff between increasing inventories and using overtime in order to meet the required demand.

* Higher production rate can only be realized when the number of buffers (number of kanbans) is optimal (Gupta & Gupta, 1989; Huang et al., 1983; Lu et al., 1989; Schroer et al., 1984, 1985).

* A pull system with a certain degree of variability in the final assembly stage will transmit and amplify the effect of variability to the entire system (Huang et al., 1983; Kimura & Terada 1981; Villeda et al., 1988).

* Schroer et al. (1984, 1985) showed that there is no major difference in utilization between systems with one kanban card or two kanban cards if the time between parts arrival is the same.

* Several studies showed that, if processing time was increased due to machine breakdown, the use of buffers will increase the line efficiency of a pull-type system (Gupta &

Gupta, 1989; Krajewski et al., 1987; Sarker & Fitzimmons, 1989).

* Balanced and smoothed operations at each stage are essential for successful JIT implementation (Changchit & Kung, 1988; Gupta & Gupta, 1988; Huang et al., 1983; Krajewski et al., 1987; Sarker & Harris, 1988). In addition, if the variation in processing time is significant, the output rates with unbalanced stations are always superior to those with perfectly balanced design (Villeda et al., 1988).

* Sarker and Fitzimmons (1989) showed that high variation in processing time at individual stations will lower the production rate of a pull system much faster than a push system.

* Abdou and Dutta (1993) concluded that few attempts has been made to expand the process to include multiline, multiproduct, multistage (and more flexible) systems in an environment where processing time is variable. In particular, the container capacity and its relationship to the number of kanbans hasnot been properly investigated in such environments.

Chapter 3

Research Design

Introduction

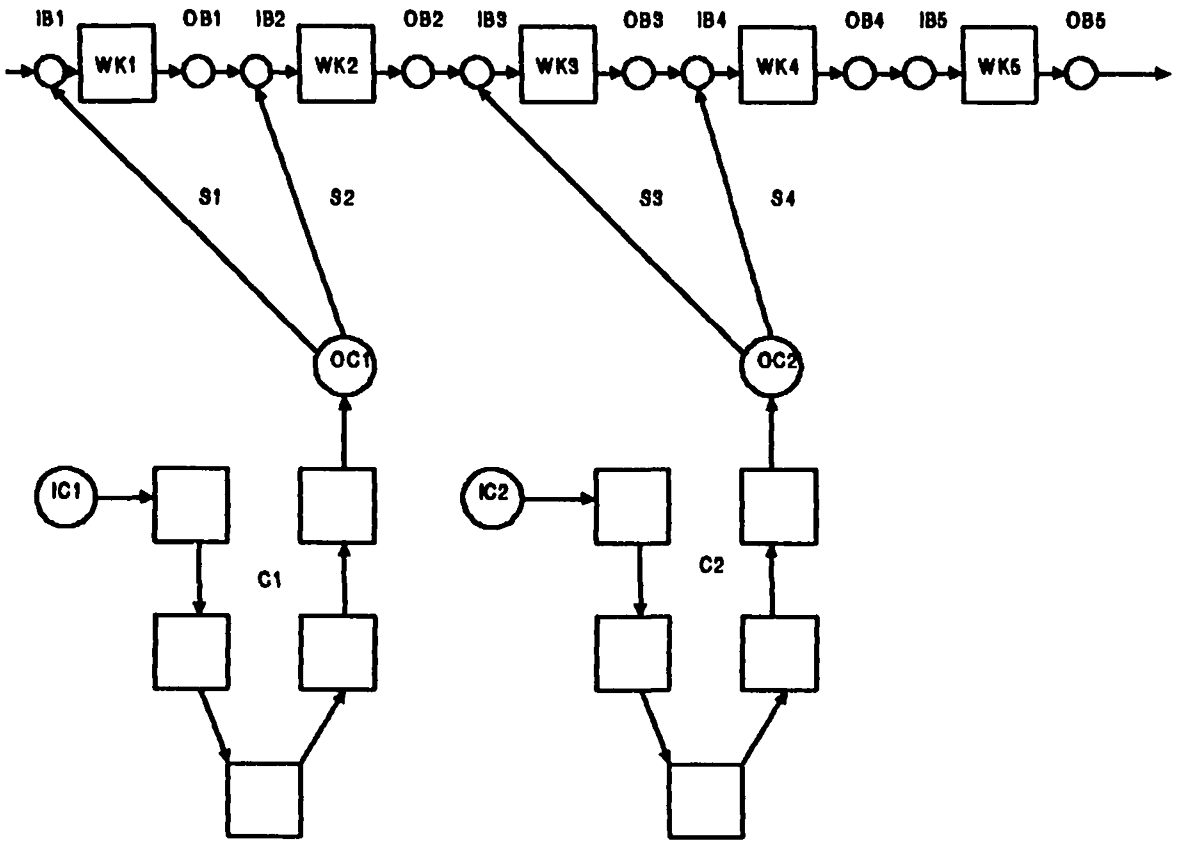
A simulation approach will be used to examine the effects of number of Kanbans, container size, different distributions of processing time and different setup times on a mixed-model just-in-time production system performances. Simulation has been used extensively in the modeling of production systems and will be used in this research to capture the dynamics of system operation. Simulation Language for Alternative Modeling (SLAM II) (Pritsker, 1986) will be used as a simulation language.

Simulation has been widely used as a vehicle to study issues related to JIT. Some of these issues are: to identify and study the internal and external factors that affect the success of JIT implementations; to determine the number of Kanbans (inventory level) required at each work station; to investigate the effect of demand and processing time variations (Changchit & Terrell, 1988; Ramnarayanan & Gillenwater, 1991; Golhar & Chaturvedi, 1991; Abdou & Dutta, 1993); to evaluate the relative performance of JIT production with other types of production systems such as MRP (Jonsson & Olhager, 1983; Krajewski et al., 1987), order point systems (Ritzman et al., 1984), and push-type systems (Kimura & Terada, 1981; Lu et al., 1989; Sarker & Fitzimmons, 1989); to identify factors detrimental to the success of JIT implementations (Ebrahimpour & Fathi, 1984; Gupta & Gupta, 1989; Huang et al., 1983; Krajewski et al., 1987; Philipoom et al., 1989; Sarker & Harris, 1988); to explore the benefits and risks associated with implementing a fully functional full manufacturing strategy, to perform sensitivity analysis (Mejabi & Wasserman, 1992).

The remainder of this chapter is organized as follows. First, the problem is described in detail. Then, the experimental factors, performance measures, and research hypotheses are discussed.

Problem Description

The experimental model and the product structure used throughout this investigation are depicted respectively in Figure 1 and Figures 2a and 2b. Figure 1 represents a single-line, five stage production which withdraw subassemblies from two manufacturing cells (C1,C2). This configuration was chosen based on the observation that American manufacturing facilities usually represent a mixed-model which provides the flexibility to produce a wide range of end products in small lots, enabling the producer to hold small inventories of finished products but still provide short customer delivery time. Under JIT, the objective is to have a constant usage rate for each component going into final assembly to facilitate the use of Kanban (Vollman, Berry, & Whybark, 1992). Unlike traditional single-model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WK1
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IC1
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C1
C2

Figure (1)

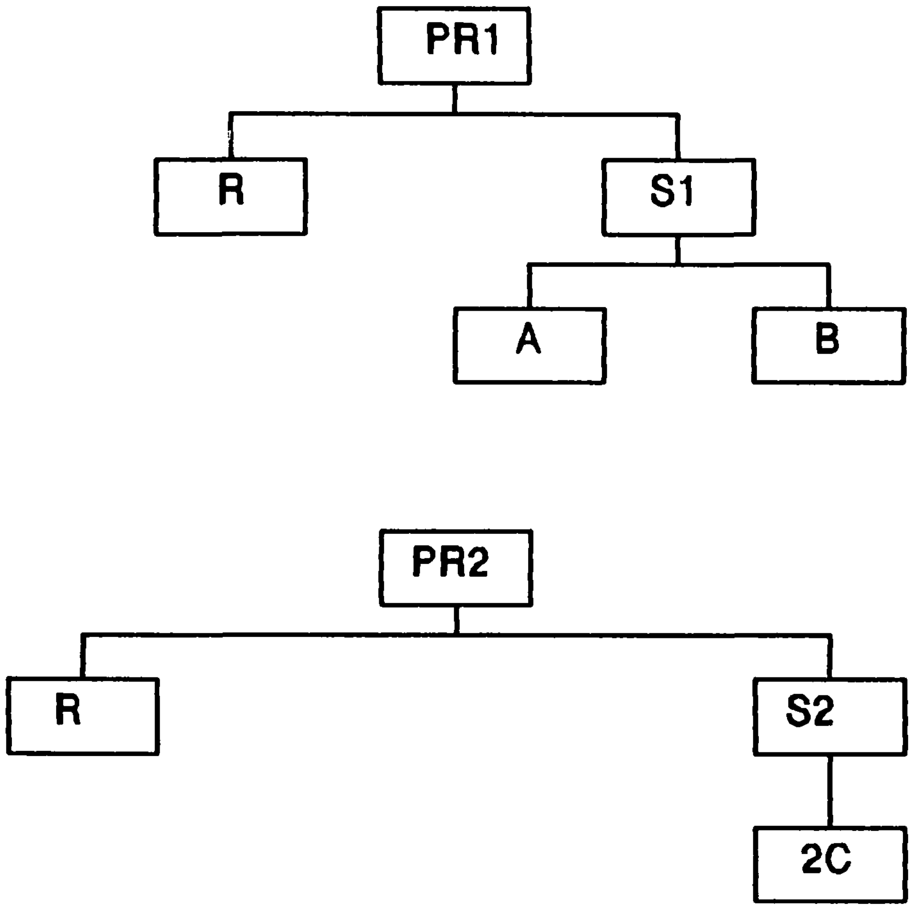


Figure (2a)

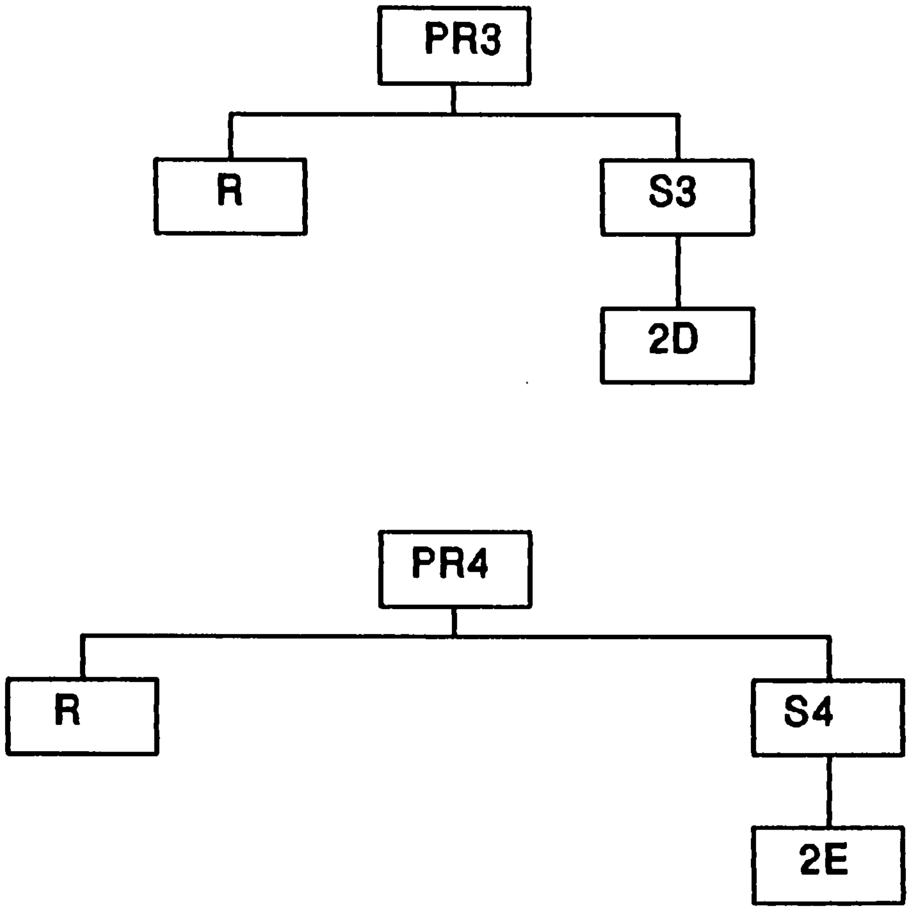


Figure (2b)

assembly lines which produce a standard item in high volume, many JIT systems assemble a variety of end items in small lot production. These systems have been called "mixed-model" assembly lines (Miltenburg & Sinnamon, 1989; Miltenburg, 1989; Sumichrast & Russel, 1990). JIT systems only work when there is a constant rate of usage for all parts (Miltenburg, 1989). Therefore, products are sequenced in very small lots to minimize the variation in the usage of each part. The manufacturing cells, in turn, draw components from two input buffers (IC1, IC2). Five machines are located in each cell. However, each cell is equally capable of producing all types of components. As components are completed, they are moved from the cells to the store locations (IB1, IB2, IB3, IB4). Previous studies have not reported the use of a cellular layout. The layout of machines within the cells follows a U-form design with one entrance and one exit. The design reflects the importance of reduced travel distance between machines, increased flexibility of worker movement between machines, and reduced physical space to hold inventory (Monden, 1983). With this type of layout, transport time for parts and Kanban moving within and between cells is small in relation to waiting and processing time and, therefore, will not be modeled.

Four end products labeled (PR1,PR2,PR3,PR4) are produced. The end products are composed of subassemblies and components. Many JIT studies used similar product structure (e.g., Karajewski et al., 1987; Philipoom et al., 1987; Ramnaraynan, 1991). Figures 2a and 2b shows the components of each product.

C1 combines a unit of A and a unit of B to make one unit of S1. WK1 combine the base or R with one unit of S1 to make one unit of PR1 which needs to be processed by all other work stations on the production line.

C1 combines 2 units of C to make one unit of S2. WK2 combines S2 with R to make one unit of PR2.

C2 combines two units of D to make one unit of S3. WK3 combines R with S3 to make one unit of PR3.

C2 combines two units of E to make one unit of S4. WK4 combines R with two units of S4 to make one unit of PR4. The production line or assembly line is composed of five workcenters (WK1,...,WK5). The last workcenter assembles the end products. Each stage has an input buffer (IB1, IB2, IB3, IB4, IB5) and an output buffer (OB1, OB2, OB3, OB4, OB5) as shown in Figure 2.

The main line production system is a pull system in which the Kanban equals one. When the succeeding station demands an item from the preceding station, the single item at the preceding station's inventory is transferred to the succeeding station for subsequent processing. The removal of one unit of inventory from the preceding station immediately triggers the production of an additional unit at that station to replace the item just taken. As a result, each station on the line produces just in time whenever the succeeding station has demand for it. This feedback information is passed to the first station on the line via the Kanban in a backward direction opposite to the direction items flow.

A two card Kanban system is used. One Kanban is called a production Kanban (P) and the other is called a withdrawal Kanban (W). However, full explanation of the mechanism of the kanban process is found in the following chapter.

Methodology

Advantages and disadvantages of simulation

A simulation approach will be used. Advantages and disadvantages of simulation will be discussed below (Law & Keton, 1982):

Advantages

* Most complex, real-world systems with stochastic elements cannot be accurately described by a mathematical model which can be evaluated analytically.

* Simulation allows one to estimate the performance of an existing system under a projected set of operating conditions.

* Alternative proposed system designs (or alternative operating policies for a single system) can be compared via simulation to see which best meets a specified requirement.

* In a simulation we can maintain much better control

over experimental conditions than would generally be possible when experimenting with the system itself.

* Simulation allows us to study a system with a long time frame.

Disadvantages

* Simulation models are often expensive and time-consuming to develop.

* On each run a stochastic simulation model produces only estimates of a model's true characteristics for a particular set of input parameters. For this reason, simulation models are generally not as good at optimization as they are at comparing a fixed number of specified alternative system designs.

* The large volume of numbers produced by a simulation study often creates a tendency to place greater confidence in a study's results than is justified.

Characteristics and Assumptions of the Model

A simulation model of the above system subject to the following characteristics and assumptions will be developed:

* Two manufacturing cells each with five machines to produce subassemblies. The daily demand of subassemblies and the corresponding daily requirements for raw material are obtained through Material Requirement Planning (MRP).

* There are five workstaions each with one machine.

* Two card Kanban are used, a production and a withdrawal Kanban.

* The JIT production system is a multiproduct (or mixed-model).

* The amount of defective units which leads to yield uncertainty in production systems is very low in pull production systems. Therefore, it will be neglected.

* It is assumed that there is a continuous and infinite supply of raw material at the first station on the line and for the manufacturing cells.

* Demand for production is created at the last station of the line. It is assumed to be fixed at 80, 60, 50, 40 units for products PR1, PR2, PR3, PR4 respectively.

* The incorporation of machine maintenance in this study is a realistic assumption for measuring the performance of the system. The maintenance time is constant with a mean of 15 minutes. The machine maintenance is a usual phenomenon in JIT production systems. When the time for maintenance occurs which is in the middle of the day, the processing at that station is stopped immediately and the machines are scheduled for maintenance sequentially. Once the maintenance is completed, the preempted job is restarted at that station. Finally, in a pull production system, preventive maintenance causes idle time in preceding workstations due to lack of production orders, while causing starvation in succeeding workstations.

* Each simulation experiment was conducted subject to the following parameters. The duration of an individual

simulation run was the length of time (in minutes) required to meet the demand requirement of a single day. A normal day is 480 minutes, but overtime might be needed. An experiment consists of 125 days (i.e., six months).

* The type of nodes required for the system are described below:

- Queue: to hold or keep a file of the finished or unfinished product at a station.

- Select or assemble: to combine or match the input material (WIP) and Kanban together such that they may be carried to the following station for processing.

- Goon: to branch the flow of an entity or to feedback the Kanban to the preceding station for the supply of WIP from that station.

- Batch: to combine entities until a specified threshold level is reached and then releases a single entity referred to as a batched entity.

- Resources: to model machines at each work station and at each cellular manufacturing cell.

Factors and Factor Levels

Number of Kanbans

Most studies in this area were conducted with the Kanban levels set between 1 and 12 (e.g., Gupta & Gupta, 1989; Sugimori, 1981; Ramnarayanan & Gillenwater, 1991). The objective of a JIT system is to reach a Kanban level of one.

This level of WIP inventory may provide low inventory levels but it might also result in low service levels. However, determination of the number of kanbans at each workstation that guarantees the desired system performance of a large production line has remained an unexplored issue in the literature. In this study, we will examine the impact on system performance by using Kanban levels of 1, 2, 6 and 8. These levels are based on previous research and on results obtained that systems with normal distribution of processing time perform better with low levels of kanbans, whereas systems with exponential distributions perform better with higher level of kanbans.

Container sizes

Most studies in this area were conducted with container sizes of 3 to 20 units (e.g., Kimura & Terada, 1981; Ramnarayanan & Gillenwater, 1991). In this study, we will use four different level of container sizes 5, 10, 15, and 20. Container size is expressed in terms of assembly units.

Processing Time

Many studies in the area of production lines have made the assumption of exponential processing times at work stations (Meral et al., 1991; Saker et al., 1989; Changchit & Terrell, 1988; Huang et al., 1983). According to Saker et al. (1989), this was mainly for one or more of the following reasons: "(a) appropriateness of the distribution compared to the real life data, (b) mathematical ease of handling, and (c) the literature is heavily dominated by this distribution" (p. 1720).

Exponential distributions will be used in this study. On the other hand, in pull production systems variability in processing times is low (Meral et al., 1991). Therefore, normal distribution of processing time will be used. Consistent with Huang et al. (1983) and Gupta et al. (1989), two normal distributions will used; one with a small standard deviation (equalling one-tenth of the mean) and one with a large standard deviation (equalling one-fourth of the mean).

There is no study which provides justification for or explains why and how a particular random variable was chosen (Chu et al., 1992).

Setup Time

Short setups have been described as both a goal and a requirement for JIT systems to operate (Hay, 1988; Lu, 1985; & Monden, 1983). Many researchers used 3% and 20% for setup time relative to processing time (Krajewski et al., 1987; Lee, 1987; Philipoom et al., 1987; & Rees et al., 1987). However, in U.S. manufacturing environments, setup ranges from a 1:1 to 25:1 ratio of unit processing time (Krajewski et al., 1987). Mirza and Malstrom (1994) found that in JIT environments significant reductions in setups costs may be achieved, but it is not always possible to drive these costs to zero or near zero values.

In this study, 4 levels of setup times will be used. Ratios of setup time to unit processing time were as follows: 2%, 5%, 15% and 25% .

Performance Measures

Chu and Shih (1992) classified three measures that were used in evaluating the performance of production systems: overall, inventory related and due-date related measures. However, three criteria, utilization of facility, output (production) rate and work-in-process (WIP), have been used more frequently than other measures. Performance will be evaluated with respect to the following detailed process measures:

Work-in-process inventory (WIP)

This is one of the measures used to gauge the effectivenesss of the system; it is the total inventory in the production cell at any instant. WIP comprises the sum of the storage levels, level of WIP currently undergoing transformation at the production line and i_{th} stage and the level of production storage of the production line and i_{th} stage.

In some Kanban systems management may wish to test the impact of its policies on inventories at each stage of the system through (a) a decrease in the number of Kanbans, (b) a decrease in the size of the containers, and (c) an increase in the size of containers but a decrease in the number of Kanbans. The number of Kanbans establishes both the maximum inventory allowed and the slack or flexibility to place more production orders due to an increase in demand. Sometimes, the system may have enough production capacity to meet the increase in demand, and it may be bounded by inventory policy due to fewer Kanbans being allowed in the system. This, in turn, may constrain the production rate of each stage.

Another way of reducing the inventory is to reduce the size of the containers while maintaining the number of Kanbans and the production capacity. Schonberger (1982) and many others have suggested that the essence of a Kanban system is to place more orders of small sizes more frequently rather than orders of large sizes at relatively lower frequencies.

The JIT system is expected to produce to meet demand. Past due demand is not allowed; overtime is used as necessary to meet the production schedule.

Overtime

A day is 480 minutes. If more than 480 minutes are required to meet the daily demand. Overtime is recorded. The data for overtime in Appendix 2 is accumulative for the six months.

Capacity utilization

Muralidhar et al. (1992) defined capacity utilization as the actual utilized production compared to the maximum potential production capacity. This measure is used to determine the effectiveness of the system by including the idle time in each stage. It measures the proportion of the time that a service facility is busy.

Average utilization of cellular machine one

It is the average for the five machines in that cell.

Average utilization of cellular machine two

It is the average for the five machines in that cell.

Level of shortage

This is used to determine the number of units short in meeting the demand of a particular day. This measure provides some indication of the overtime required on a daily basis.

Mean inventory holding time per unit item at the last station

It is a measure of performance that can be traded off with the mean backorder time per unit demand. The mean holding time per unit at the last workstation decreases as the degree of imbalance on the line increases. However, at higher levels of capacity utilization, mean inventory holding time per unit is very low.

Statistical tools

The statistical analysis of the outputs from a simulation is similar to the statistical analysis of the data obtained from an actual system. According to Pritsker (1986), there are two types of questions that relate to the output of simulation models:

"1. What is the inherent variability associated with the simulation model?

2. What can be inferred about the performance of the real system from the use of the simulation model?" (p. 724).

MANOVA will be the main statistical tool used to test for main effects and interaction effects.

Research Hypotheses

The research will respond to the following hypotheses:

Ho: There is no difference in JIT system performance due to the different number of Kanbans used, where K = 1, 2, 6, 8.

Ho: There is no difference in JIT system performance due to the different container sizes (CC), where cc = 5, 10, 15, 20.

Ho: There is no difference in JIT system performance due to the interaction effect of different number of Kanbans and container sizes.

Ho: There is no difference in JIT system performance due to the different processing time distributions (P), where p is exponentially distributed and normally distributed with low and high standard deviation.

Ho: There is no difference in JIT system performance due to the interaction between number of Kanbans, different container sizes and different distributions of processing time.

Ho: There is no difference in JIT system performance due to the different setup times.

Ho: There is no difference in JIT performance due to the interaction of the number of Kanbans, different Container Sizes, different distributions of processing time, and different setup times.

Discussion

The number of Kanbans establishes both the maximum inventory allowed and the flexibility to place more production orders due to an increase in demand. Sometimes the system may have enough production capacity to meet the increase in demand, and it may be bounded by inventory policy due to fewer Kanbans allowed in the system. This in turn, may constrain the production rate of each stage. By reducing the number of Kanbans, the WIP inventory at each stage declines.

Another way of reducing the inventory is reducing the size of the containers while maintaining the number of Kanbans and the production capacity. Production rate at each stage is not limited by the capacity but rather by the lack of inventory. This prevents the system from meeting the demand and results in an increased shortage.

Shonberger (1982a) and many others have suggested that the essence of a Kanban system is to place more orders of smaller sizes more frequently rather than orders of large sizes at relatively lower frequencies. The impact of increasing the size of Kanban containers, while reducing the number of Kanbans in such a way that the maximum inventory allowed in the system remains constant, increases substantially WIP inventories at each stage of the system.

In general, the following results are expected.

* Reducing the number of Kanbans has the followings:

Decrease WIP

Decrease mean utilization levels

* Reducing container size.

Decrease WIP inventory levels

Decrease the mean shortage levels

Increase mean utilization levels

* Exponential processing time.

Increase WIP

Decrease shortage levels

Decrease mean utilization levels

Imbalance between stages

* Normal processing time.

Decrease WIP

Increase utilization levels

* Low setup.

Decrease WIP

Increase mean utilization levels

In addition, there will be other interaction effects.

Chapter 4

Simulation Model and Experiment design

The simulation model incorporated in this study is shown in Appendix 1a and b. The remainder of this chapter is organized as follows. First, there is a description of the simulation experiment. Then, the starting conditions are discussed. Finally, related issues to simulation such as validation, verification and run length are addressed.

Main Experiment

Stage five

When an entity, one unit is worth of demand, is created at the CREATE node CRI with the first demand occurring at time TF, the entity will immediately join the queue at node QD after being batched (containerized) at BATCH node BAT6. SELECT node S52 assembles the units from nodes OB5 and QD and routes a unit to GOON node G54, where two entities are released. One entity exits the system stage and represents a processed unit. The second entity represents the production Kanban and is routed to node PK5 to initiate the processing at this stage of the input unit at node IB5. When a unit is in node IB5 and the production Kanban at node PK5, they are assembled at node W5 and an entity is routed to node G51. From node G51 an entity is routed to the preceding stage representing the withdrawal Kanban.

The second entity represents the unit to be processed by machine 5, the production activity of this stage. Upon completion of service, the entity is placed in node OB5 to await the next demand for the stage, which occurs when the next entity arrives at node QD.

When a demand is created as a pull at the end of the line, the whole production line is triggered to produce the WIP products at all the stages simultaneously as if the line was working for a long time and a steady state condition has been achieved.

Once the system starts the production, it will not be stopped unless the lot (which is usually controlled by the terminate node) is completed or the time of production schedule (simulation run length) is over.

The initial capacity of the queue node is 1 (meaning that "one" Kanban has already arrived or is available). The number in the queues in each stage determines the number of kanbans in each stage.

Stage four

SELECT node S42 assembles the units from node OB4 and node WK4. Two entities emanate from node G43. One entity is routed to the following stage, stage 5 which represents a WIP and is placed at node IB5. The second entity represents the production Kanban and is routed to node GK4, where two entities emanate from node GK4. One entity is routed to node PK4B which represents a production kanban for product (PR4). In this case, only 40 kanbans will be released to allow the processing of 40 units demanded for product (PR4). The second entity is routed to node PK4A which represents a production kanban for the component R needed for the other products. SELECT node W4 assembles the units from nodes PK4B and IB4B which represents the processed raw material from the other stages, and node IBS4, which represents the subassembly from cellular manufacturing C2. One entity is routed to node G41. SELECT node S41B assembles the units from nodes PK4A and IB4A, One entity is routed to node G41. Two entities emanate from node G41. One entity is routed to the preceding stage to node WK3 representing a withdrawal Kanban. The second entity represents the entity to be processed by machine 4, the production activity of the stage. After processing the unit, it is batched or containerized by BATCH node BAT4 and, when the container is full it is placed at node OB4.

Stage three

SELECT node S32 assembles the units from node OB3 and node WK3. Two entities emanate from node G33. One entity is routed to the following stage, stage 4 which represents a WIP and is placed at node IB4. The second entity represents the production Kanban and is routed to node GK3, where two entities emanate from node GK3. One entity is routed to node PK3B which represents a production kanban for product (PR3). In this case, only 50 kanbans will be released to allow the processing of 50 units demanded for product (PR3). The second entity is routed to node PK3A which represents a production kanban for the component R needed for the other products, too. SELECT node W3 assembles the units from nodes PK3B and IB3B, which represents the processed raw material from the other stages, and node IBS3, which represents the subassembly from cellular manufacturing C2. One entity is routed to node G31. SELECT node S31B assembles the units from nodes PK3A and IB3A, One entity is routed to node G31. Two entities emanate from node G31. One entity is routed to the preceding stage to node WK2 representing a withdrawal Kanban. The second entity represents the entity to be processed by machine 3, this production activity of the stage. After processing the unit, it is batched or containerized by BATCH node BAT3 and, when the container is full it is placed at node OB3.

Stage two

SELECT node S22 assembles the units from node OB2 and node WK2. Two entities emanate from node G23. One entity is routed to the following stage, stage 3 which represents a WIP and is placed at node IB3. The second entity represents the production Kanban and is routed to node GK2, where two entities emanate from node GK2. One entity is routed to node PK2B which represents a production kanban for product (PR2). In this case, only 60 kanbans will be released to allow the processing of 60 units demanded for product (PR2). The second entity is routed to node PK2A which represents a production kanban for the component R needed for the other products. SELECT node W2 assembles the units from nodes PK2B and IB2B which represents the processed raw material from the other stages, and node IBS4 which represents the subassembly from cellular manufacturing C1. One entity is routed to node G21. SELECT node S21B assembles the units from nodes PK2A and IB2A One entity is routed to node G21. Two entities emanate from node G21. One entity is routed to the preceding stage to node WK1 representing a withdrawal Kanban. The second entity represents the entity to be processed by machine 2, the production activity of this stage. After processing the unit, it is batched or containerized by BATCH node BAT2 and, when the container is full it is placed at node OB2.

<u>Stage one</u>

SELECT node S12 assembles the units from node OB1 and node WK1. Two entities emanate from node G13. One entity is routed to the following stage, stage 2 which represents a WIP and is placed at node IB2. The second entity represents the production Kanban and is routed to node GK1, where two entities emanate from node GK1. One entity is routed to node PK1B which represents a production kanban for product (PR1). In this case, only 80 kanbans will be released to allow the processing of 80 units demanded for product (PR1). The second entity is routed to node PK1A which represents a production kanban for the component R needed for the other products. SELECT node W1 assembles the units from nodes PK1B and IB1B which represents an entity created by CREATE node CRM2 (R) which will immediately join the queue at nodes IB1A and IB1B, the processed raw material from the other stages, and node IBS1 which represents the subassembly from cellular manufacturing C1. One entity is routed to node G11. SELECT node S11B assembles the units from nodes PK1A and IB1A. One entity is routed to node G11. One entity emanates from node G11. That entity represents the entity to be processed by machine 1, the production activity of this stage. After processing the unit, it is batched or containerized by BATCH node BAT1 and, when the container is full, it is placed at node OB1.

Cellular Manufacturing System

In the push system, the raw materials are fed through the first stage and subsequently pass through the following stages in the same order as they are fed to the first stage. The first stage draws the work piece from an interstage storage, and after passing through all the stages in a fixed sequence, the subassembly is deposited in a storage corresponding to the type of product which used that subassembly. It was assumed that there are no stockouts of raw materials.

Starting Conditions

The JIT system in this research is a terminating system because it satisfies the following conditions. Initial conditions are well defined and the ending time of the simulation is determined by the nature of the problem under study (Banks & Carson, 1984). However, a terminating system is characterized by a distinct starting time under well specified initial conditions and a distinct stopping time, or alternatively, a distinct stopping event (Banbes & Carson, 1984). The terminating modeling approach has been used in JIT research (Huang et al., 1983; Rees et al., 1989). They used a terminating simulation which used one production day as an independent observation. In their JIT studies, the system produced to exactly meet demand under various levels of demand variability, using discrete, single unit lot production and conveyance. Also, the starting conditions were well defined. At the start of each production day, one full container of each part type was available so that part pulls could be made immediately. For the purpose of this research, the starting time of the terminating simulation is the beginning of a work day with an initial condition: the system contains one full standard container for each part required by the system so that production begins immediately upon the issuance of the first demand pull. Other studies have also used starting conditions similar to this (e.g., Huang et al., 1983; Sarker et al., 1988; Dudek et al., 1988).

Run Length

There is a tradeoff between run length and number of replications of the simulation (Pritsker, 1993). In this study, I intended to use a few long runs. That would produce a better estimate of the steady state mean because the initial bias is introduced fewer times and less data is truncated. However, the duration of the simulation would be specified by specifying the time at which the simulation is to end. Also, the duration of simulation would be specified by specifying the number of entities which are to be entered into the model. The simulation executes when all the entities that entered into the system are completely processed.

Multiple simulation runs of a single scenario are required to introduce true randomness to a model and develop distribution of plausible results (Dietz, 1992).

Validation

Validation is the process of determining that the simulation is a reasonable representation of the system (Pritsker et al., 1993). Trial runs were performed and the models were extensively checked using the SLAM II discrete event Trace option. This process verified that Kanbans were operating correctly, demand pulls for the right parts were performed and performance measures were collected and calculated accurately. The structure and operation of the system is compared to the structure and operation of the model; each individual component is examined.

Validation and verification are the most important stages in simulation studies. Chu et al. (1992), Krajewski et al.(1987) were the only ones to discuss validation and verification. Others tend to ignore this issue (Chu et al., 1992).

Verification

Verification is the process of determining that a simulation run is executing as intended (Pritsker et al., 1993). That process was accomplished by manually checking that each model element is described correctly and that modeling elements are interfaced as specified and by reviewing data inputs and outputs and insuring that no significant discrepancies exist between expected and observed model performance. Verification was also done by watching the running of a model as each status change occurs and following the logical flow described in the model by using the Trace statement.

Chapter 5

RESULTS

Mixed model performance data are summarized and detailed analyses are presented in this chapter. Table 5a summarizes the MANOVA results obtained for all dependent variables. The F's associated with Wilks were used to illustrate (aptitude by method):

Set up F = .558 P < .945
Process F = 640.92 P = .00
Kanban F = 96.08 P = .00
Container F = 279.90 P = .00

The MANOVA results indicated that most of main effects were significant as shown in table 5a. Also, the regression analysis showed the same results for the main effects. Very few of the two-way interactions were significant, whereas none of the three ways and four ways interaction were significant.

Setup time was not significant which could be a breakthrough i.e. many manufacturers who tried to embrace JIT were not able to do so because of being unable to shorten setup time. Reducing setup time is precondition to embrace JIT. However, we are dealing with a mixed model JIT production system and that result could be pertaining only to this type of configuration and/or setup time up to 25% of processing time is not significant. Finally, more investigation is needed before making a final conclusion about setup time with different setup times as well as different configurations.

The abbreviations below are used for the performance measures in this study.

WIP : Mean Work-In-Process

OT : Mean Overtime

SH : Mean shortage in units to meet daily demand

UT.AL : Mean Utilization of Assembly Line. It is the average of the five machines in the five workstations.

UT.CM1 : Mean utilization of the five sequential machines in the first cellular center

UT.CM2 : Mean utilization of the second cellular manufacturing center

Await : Average waiting time for the container in the last workstation of the assembly line

The results of the main effects and two-way interactions are included in Appendices 2 and 3.
Graphs and tables will be used to analyze the results. Main effects will be discussed thoroughly, whereas some of two way interactions though not significant will be analyzed to give better understandings of the main effects as well as to give some insights about the performance of the mixed model production system.

Table 5a

Summary of MANOVA Results

	S	P	K	C	P & S	K & S	K & P	C & S	C & P	C & K	K & P & S	C & P & S	C & K & S	C & K & P	K & P & S & C
OT	*		*		*	*	*	*	*	*	*	*	*	*	*
SH	*				*	*	*	*	*	*	*	*	*	*	*
UT.AL			*		*	*	*	*	*	*	*	*	*	*	*
UT.CM1	*				*	*	*	*	*	*	*	*	*	*	*
UT.CM2	*				*	*	*	*		*	*	*	*	*	*
AWAIT	*				*	*	*	*			*	*	*	*	*
WIP	*				*	*	*	*	*	*	*	*	*	*	*

Where (*) indicate that the interaction is not significant.

Work-In-Process (WIP)

MANOVA results for the WIP (Table 5b) indicated that most of the main effects were significant. None of the two-way and three-way interactions as well as the four-way interactions were significant.

Main effects

As the number of K's increases, WIP increases. This result is consistent with the intent of JIT and with all previous studies in this field. Monden (1983) and Wang et al. (1990) suggested that the essence of a Kanban system

Table 5b

Analysis of Variance

Work-In-Process Inventory By C K P S

Source of Variation	Sum of Squares	DF	Mean Squares	F	Sig of F
Main Effects					
Within+Residual	15847.89	180	88.04		
Contain	19674.40	3	6558.13	74.49	.000
Kanban	549442.82	3	183147.61	2080.19	.000
Process	10260.74	2	5130.37	58.27	.000
Setup	94.07	3	31.36	.36	.785
Two-Way Interactions					
Within+Residual	584541.97	146	4003.71		
C & K	918.47	9	102.05	.03	1.000
C * P	8120.65	6	1353.44	.34	.916
C * S	379.13	9	42.13	.01	1.000
K * P	943.61	6	157.27	.04	1.000
K * S	253.55	9	28.17	.01	1.000
P * S	162.53	6	27.09	.01	1.000
Three-Way Interactions					
Within+Residual	592153.82	110	5383.22		
C * K * P	791.09	18	43.95	.01	1.000
C * P * S	770.29	18	42.79	.01	1.000
C * K * S	996.81	27	36.92	.01	1.000
K * P * S	607.91	18	33.77	.01	1.000
Four-Way Interactions					
Within+Residual	593416.06	137	4331.50		
C * K * P * S	1903.85	54	35.26	.01	1.000

Where:

WIP = Mean work-in-process
K = # of Kanbans
C = Container size
P = Processing time
S = Setup time

was to place more orders of smaller sizes more frequently rather than orders of larger sizes at relatively low frequencies. As this is done, WIP goes down.

The WIP at one stage is dependent on how quickly the WIP is passed through the succeeding stages. However, it is often believed that the push system can cause an increase in the total WIP without an increase in the output.

WIP decreased as the size of the container size increased from 5 to 10 units as seen in graph 5-1. This result is inconsistent with the results of previous research, JIT theory and queuing theory. Larger container size means more WIP in the system. The reason behind this could be that the model in this experiment is a mixed model and different results are expected, or a batch of five is not significant or unbatching is better for small sizes. With container size of ten or more, WIP increased. This result is consistent with JIT theory, queuing theory and the results of previous research.

WIP maintained the same direction with processing time normally distributed with either high and low standard deviations. However, with exponential distribution, WIP decreased. Sarker et al. (1984) also revealed that in a pull system the output decreases and the total WIP increases as the coefficient of variation of a stage processing time increases. Therefore, the above result is inconsistent with the results of previous research. The reason behind this is that different results are expected for the mixed model production system.

Two-Way Interactions

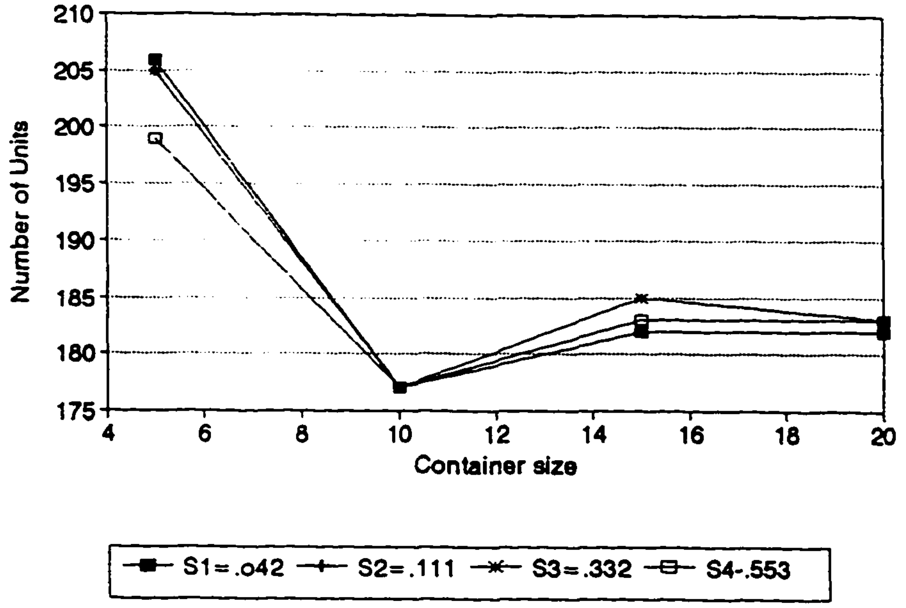
Container size and Setup time. As graph (5-1) shows, WIP decreases as the size of container increases from 5 to 10 units and WIP goes down from 206 to 177 units. Increasing the size of container to 15 and 20 resulted in increasing WIP slightly. Increasing the size of the container means more units in the system, large queues and therefore more WIP.

Kanban and Setup time. WIP decreases substantially as the number of Kanbans decreases as shown by graph (5-2). Also, the graph shows some interaction between setup time and number of K's. In general, more K's mean more units in the system or more WIP.

Setup time and Processing time. Normally distributed processing times with low and high variation have little or no impact, WIP going down from 194 to 190 units. On the other hand, an exponential processing time distribution decreases WIP substantially, WIP going down from 194 to 175 units. This result is inconsistent with the results of previous research that indicated as the level of variation increases, WIP should increase not decrease. The reason behind this is that could be different results are expected when dealing with a mixed model production system.

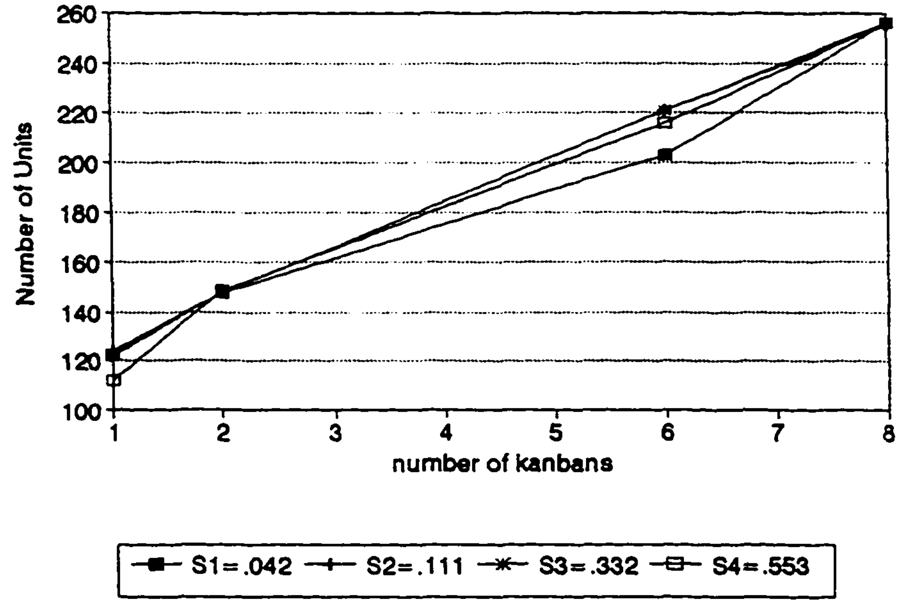
As predicted, a longer setup resulted in a longer container & setup time graph 5-1

Work-In-Process



Kanban & Setup time grap 5-2

Work-In-Process

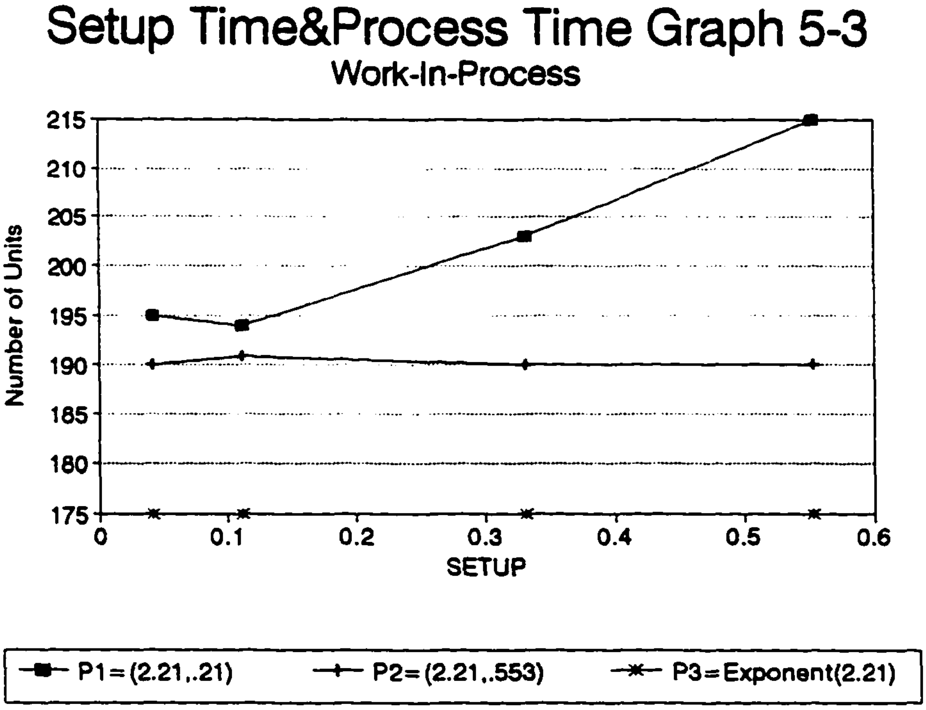


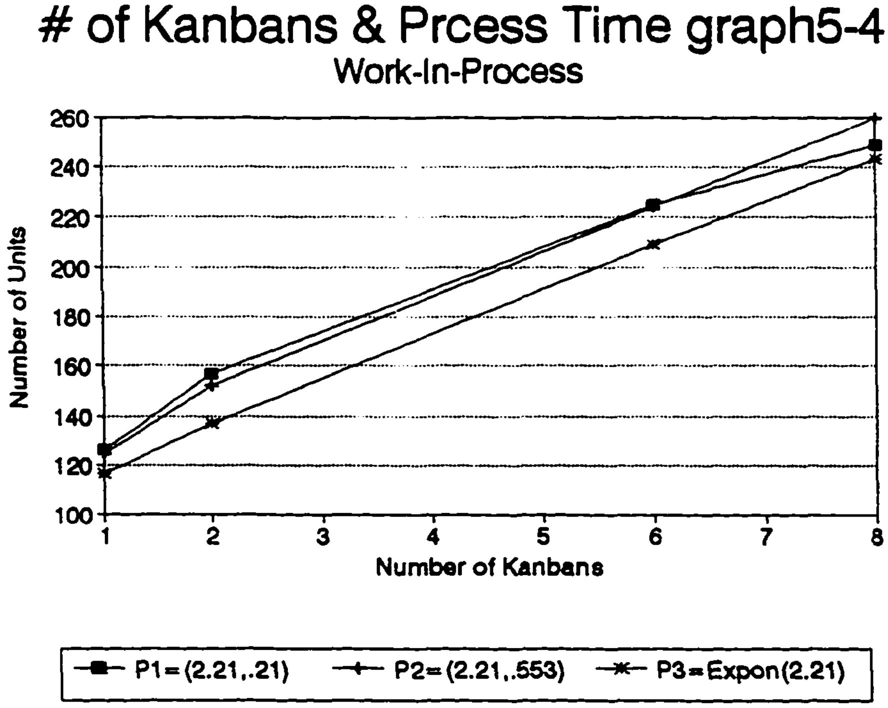
waiting time and therefore larger WIP, e.g., with setup time of .335 minutes, WIP increases to 203 units, but with setup time of .553 WIP increases to 215 units as shown by graph (5-3). Also, when setups are large, units stay in the system for a longer period of time thus increasing the value of WIP inventory. Besides, there is some interaction between normal processing time distributions and setup times as shown by graph (5-3).

Kanbans and Processing time. As graph (5-4) shows, decreasing the number of K's decreases WIP substantially regardless of processing time variation. However, decreasing the number of K's with exponential distribution resulted in decreasing WIP at a rate more than with normal processing time distributions.

Kanban and Container. As graph (5-5) and table 3a in Appendix 2 show, decreasing the number of K's while decreasing the size of C decreased WIP substantially. Larger batch sizes add batch time related delays to the already long queuing times. Batch related delays could be due to waiting for a container to be filled and due to larger queues at the processing centers.

At lower container sizes, K's could be increased without incurring large increases in WIP inventory levels. Consistent with the results of Gupta and Gupta (1989), the strategy of increasing container sizes while reducing the number of k's resulted in large WIP inventory levels. Also,

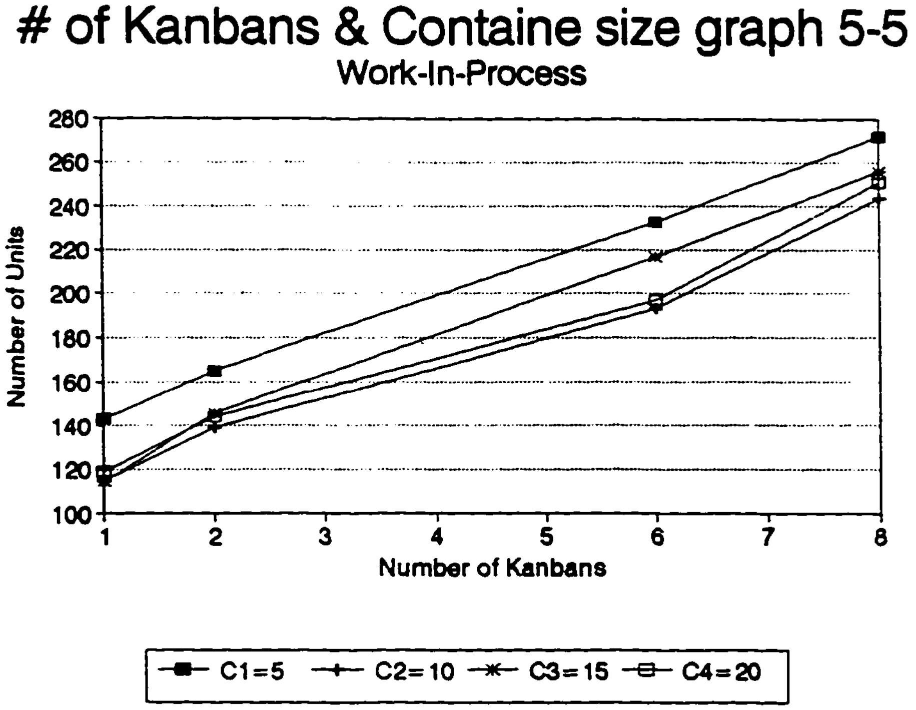

Setup Time&Process Time Graph 5-3
Work-In-Process
Number of Units
215
210
205
200
195
190
185
180
175
0
0.1
0.2
0.3
0.4
0.5
0.6
SETUP
P1=(2.21,.21)
P2=(2.21,.553)
P3=Exponent(2.21)


# of Kanbans & Prcess Time graph5-4
Work-In-Process
Number of Units
260
240
220
200
180
160
140
120
100
1
2
3
4
5
6
7
8
Number of Kanbans
P1=(2.21,.21)
P2=(2.21,.553)
P3=Expon(2.21)

the graph shows some interaction between number of kanbans and container size.

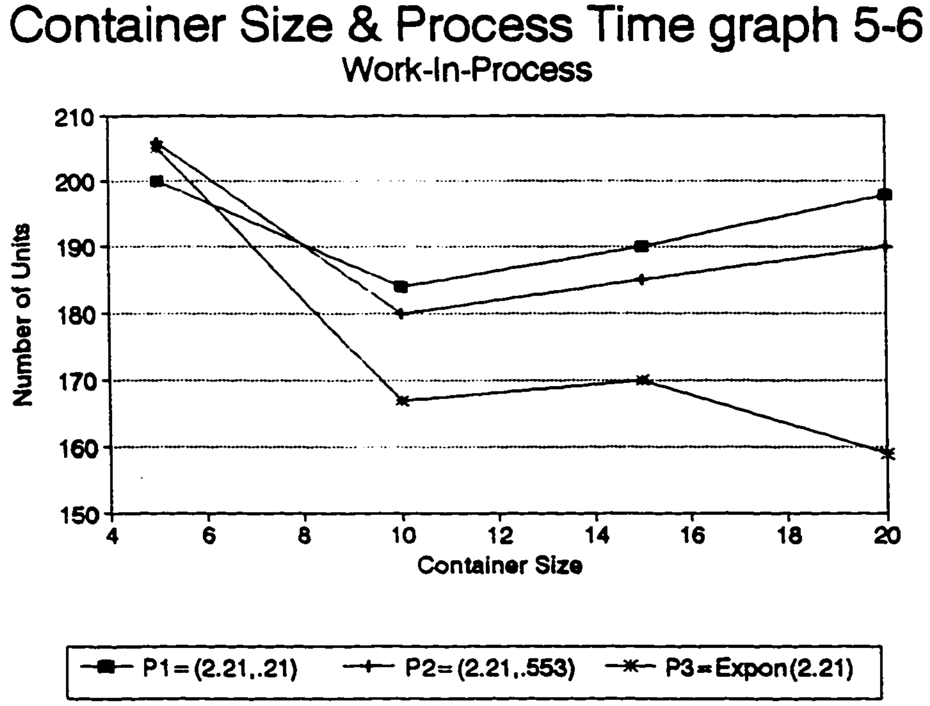
Container size and Processing time. Graph (5-6) and table 3a in Appendix 2, show that, when container size was increased from 5 to 10 with processing times having low and high coefficient of variation, WIP decreased. However, increasing the container size coupled with exponential distribution processing time decreases WIP more than with a normal distribution processing time. This result is inconsistent with the results of previous research as previously discussed. But, increasing the container size more than 10 coupled with normal processing time resulted in increasing WIP. This result is consistent with results of previous research as previously discussed. However, increasing the container size from 10 to 15 coupled with exponential time resulted in increasing WIP. But, increasing the container size from 15 to 20 coupled with exponential time distribution resulted in decreasing WIP. Again as previously discussed, this result is inconsistent with previous research.

In conclusion, the number of K's should be minimized. The reason for this is that a K between two adjacent stations represents the maximum inventory level, and therefore should be kept to a minimum. A number of researchers like Schonberger (1982), Rees et al. (1987), Mayazaki et al. (1988) and Abdou et al. (1993) supported the



# of Kanbans & Containe size graph 5-5

Work-In-Process



Container Size & Process Time graph 5-6

Work-In-Process

aforesaid conclusion. Specifically, these studies pointed out that the fewer the number of Kanbans, the better, because of the sensitivity of inventory costs to this value. The number of such containers released at one time, i.e., the number of Kanbans and the rate of release, could be controlled to provide a minimum value of total cost of operating the system. Thus, the essence of a Kanban system is to place more orders of a small size. However, the relationship between inventory and K's is more complex for a multiproduct, multistage system than for a single product system.

Overtime (OT)

MANOVA results for OT (table 5c) indicate that half of the main effects were significant. None of the interactions were significant.

Main effects

Generally speaking, increasing the number of K's resulted in reducing overtime. Increasing container size resulted in increasing OT substantially. Table 3b in Appendix 2 shows that OT increased to around 22,000 minutes with container size 5 and to 36,000 with container size 10 to 45,000 with container size 15 and, finally, to 60,000 with container size 20.

Table 5C

Analysis of Variance

Overtime by C K P S

Source of Variation	Sum of Squares	DF	Mean Squares	F	Sig of F
Main Effects					
Within+Residual	6972621020	180	38736783		
C	13415153201	3	4.472E+09	115.44	.000
K	82625146.68	3	27541716	.71	.547
P	27283687599	2	1.634E+10	352.17	.000
S	8344613.74	3	2781537.9	.07	.975
Two-Way Interactions					
Within+Residual	44727046332	146	306349632		
C * K	200120496.2	9	22235611	.07	1.000
C * P	1720791770	6	286798628	.94	.471
C * S	304639686.2	9	33848854	.11	.999
K * P	135157779.8	6	22526297	.07	.998
K * S	375568122.1	9	41729791	.14	.999
P * S	299107394.5	6	49851232	.16	.986
Three-Way Interactions					
Within+Residual	45418207463	110	412892795		
C * K * P	626670398.9	18	34815022	.08	1.000
C * K * S	742622968.3	27	27504554	.07	1.000
C * P * S	525413574.8	18	29189643	.07	1.000
K * P * S	449517175.8	18	24973176	.06	1.000
Four-Way Interactions					
Within+Residual	46169419927	137	337003065		
C * K * P * S	1593011653	54	29500216	.09	1.000

Where:

OT = Over time
K = # of Kanbans
C = Container size
P = Processing time
S = Setup time

Processing time, normally distributed with a high standard deviation, resulted in an increase of OT compared with normal processing time with a low standard deviation. However, an exponential processing time distribution resulted in a high increase in OT compared to a normal distribution processing time. When the size of container was doubled from 5 to 10 units, OT increased by 4000-5000 minutes, but when the container size increased from 10 to 15 units, OT increased by the same amount. However, increasing the size of container from 15 to 20, resulted in increasing OT by 10,000 minutes. In conclusion, variable processing times also result in large fluctuations in daily overtime. With the normal distribution, the amount of overtime required will fluctuate almost twice as much as the amount of the processing time variation. In other words, overtime variability is amplified by the variability in processing times in the JIT system.

Two-Way Interactions

Container and Setup. Setup had no significant influence on overtime (OT), but increasing container size resulted in increasing OT substantially as shown in graph (5-7). Also, the graph shows some interaction between container size and setup time.

Processing time and Setup time. Increasing setup from 2% of the processing time to 5% increased OT by 1400 minutes but increasing (S) more than 5% had no impact on OT.

Exponential distribution of processing time had a major impact on OT as shown by graph (5-8). Also, the graph shows some interaction between processing time and setup time.

Kanban and Processing time. Increasing the number of K's with normal processing time distribution resulted in decreasing OT, but increasing K's with exponential time distribution resulted in increasing OT substantially as shown in graph (5-9).

Container and Processing time. Increasing the size of the container (C) with processing time normally distributed with low and high standard deviations resulted in increasing OT but the substantial increase of OT occurred when the size of container increased along with an exponential distribution of processing time as shown by graph (5-10). Increasing the size of container from 10 to 15 increased OT by 38,000 minutes, whereas increasing container size from 15 to 20 increased OT by 12,000 minutes. Also, the graph shows some interaction between container size and processing time.

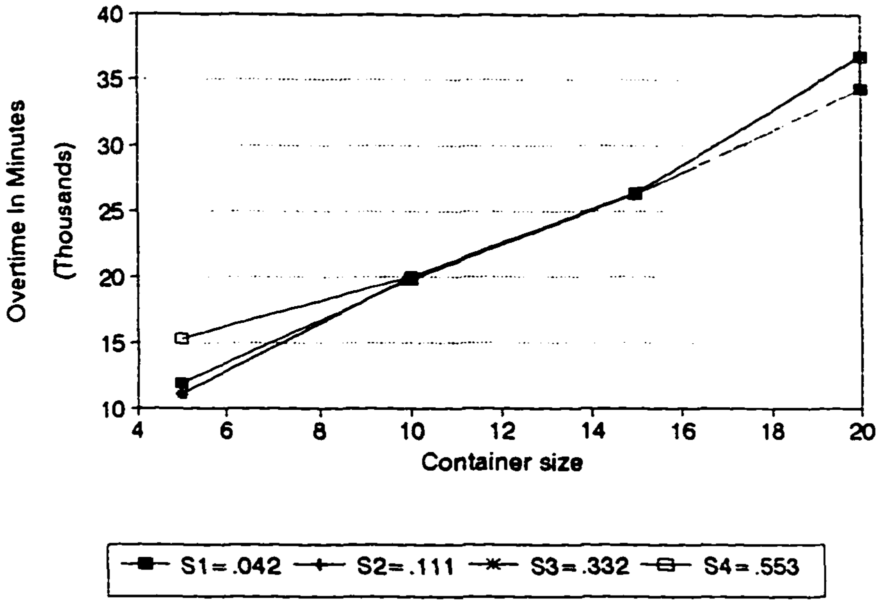
Average Utilization of Assembly Line (AL)

Utilization data was collected for both the cellular manufacturing systems as well as the assembly line. The purpose was to see if there was a difference between the cellular manufacturing cells and the assembly line.

MANOVA results for average utilization of an assembly line as shown in table 5d indicated that main effects of the

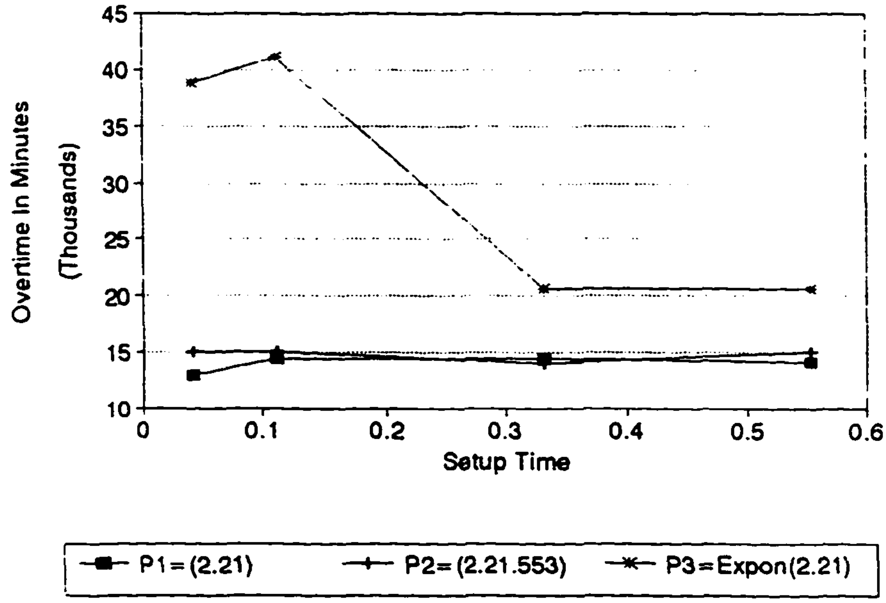
Container Size & Setup Time graph5-7

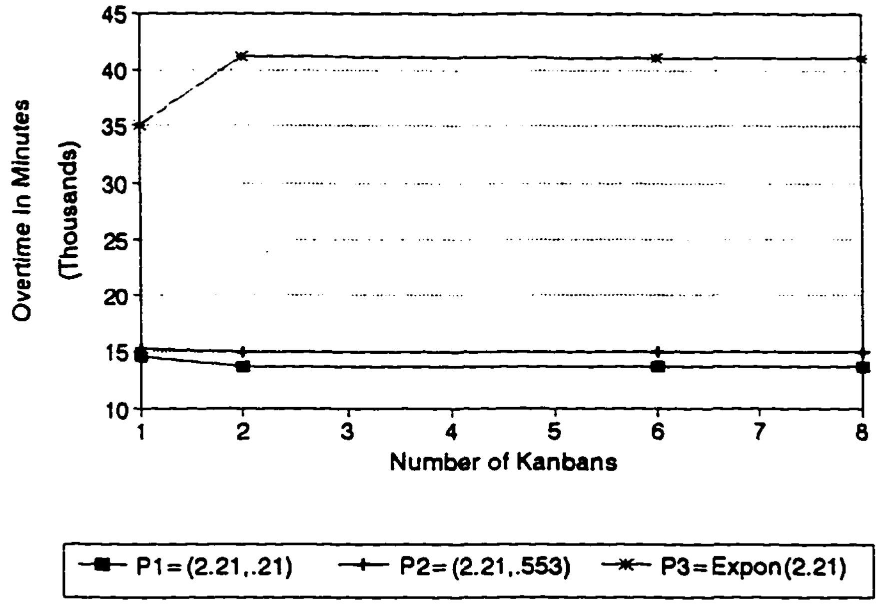
Overtime



Setup Time & Process Time graph5-8

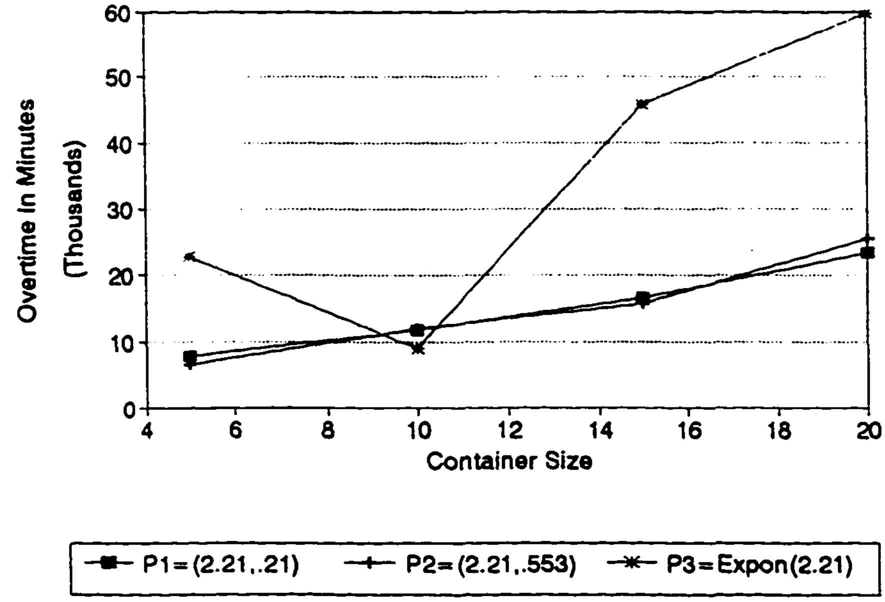
Overtime





# of Kanbans & Process Time graph5-9

Overtime



Container Size&Process Time graph 5-10

Overtime

container size as well as process time were significant, but the effect of kanban and setup were not significant. Also, none of the effects of interactions were significant.

Main Effects

Decreasing the number of k's has no impact on the average utilization of the assembly line. Increasing the size of container from 5 to 10 resulted in decreasing (AL) from .90 to .84, and increasing (C) from 10 to 15 lowered (AL) from .84 to .77 and finally increasing (C) from 15 to 20 resulted in lowering (AL) to .67. Simply, decreasing the size of the container resulted in increasing (AL). Mean utilization decreased as container size increased. That decrease could be attributed to the large reduction in setup time per unit when large container sizes were used. Usually, utilization increases as setup time increases, but, if the assembly line is fully utilized, reducing the number of Kanbans will result in the same service at lower cost, due to lower WIP levels in the flow-shop.

Utilization was lower at preceding workstations than at the succeeding stages. This result is consistent with the result of several researchers (e.g., Ramnarayanan, 1991; Kimura & Terada, 1981; Sarkar & Fitzsimmons, 1989).

Process times following the normal distribution perform better than those represented by an exponential distribution.

Table 5d

Analysis of Variance

Average Utilization of Assembly Line by C K P S

Source of Variation	Sum of Squares	DF	Mean Squares	F	Sig of F
Main Effects					
Within+Residual	.02	180	.00		
C	1.43	3	.48	3673.01	.000
K	.00	3	.00	.27	.845
P	8.55	2	4.28	32907.16	.000
S	.00	3	.00	1.63	.184
Two-Way Interactions					
Within+Residual	9.99	146	.07		
C * K	.00	9	.00	.00	1.000
C * P	.02	6	.00	.04	1.000
C * S	.00	9	.00	.00	1.000
K * P	.00	6	.00	.00	1.000
K * S	.00	9	.00	.00	1.000
P * S	.00	6	.00	.00	1.000
Three-Way Interactions					
Within+Residual	10.00	110	.09		
C * K * P	.00	18	.00	.00	1.000
C * K * S	.00	27	.00	.00	1.000
C * P * S	.00	18	.00	.00	1.000
K * P * S	.00	18	.00	.00	1.000
Four-Way Interactions					
Within+Residual	10.01	137	.07		
C * K * P * S	.00	54	.00	.00	1.000

Where:

AL = Average Utilization of the Assembly Line
K = # of Kanbans
C = Container size
P = Processing time
S = Setup time

Container size and setup have no impact on (AL), but, as stated earlier, decreasing the size of container resulted in increasing (AL) substantially as shown in graph (5-11).

Increasing the variation in the processing time distribution resulted in lowering (AL) by 7%, whereas exponential distribution time resulted in lowering substantially (AL) by 48%. Finally, setup time has no impact on (AL).

Two-Way Interactions

Container and Setup time. Container size and setup had no impact on (AL). As stated earlier, decreasing the size of container resulted in increasing (AL) substantially as shown in graph (5-11). Also, the graph shows some interaction between container size and setup time.

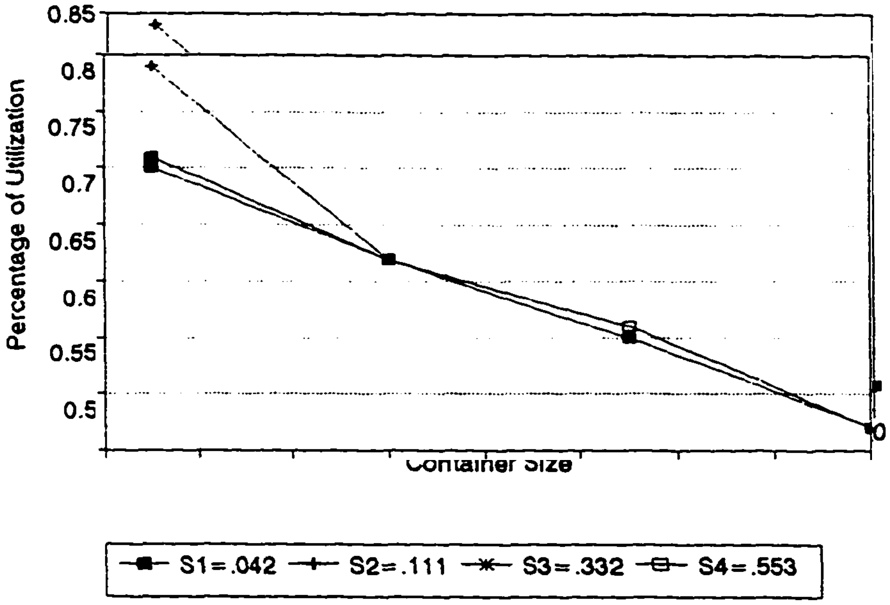
Processing time and Setup time. Setup (S) along with processing time (P) had no impact on (AL), but different processing time distributions had a significant impact on (AL) as shown in graph (5-12). In general, as the coefficient of variation increases (AL) decreases.

Kanban and Container size. Kanban (K) and Container (C) had little impact on (AL), but different sizes of containers had an impact on (AL) as shown in graph (5-13).

Container and Process. As the size of container decreases along with low variation in processing time, resulted in improving (AL). However, small container size with exponential processing time distribution resulted in

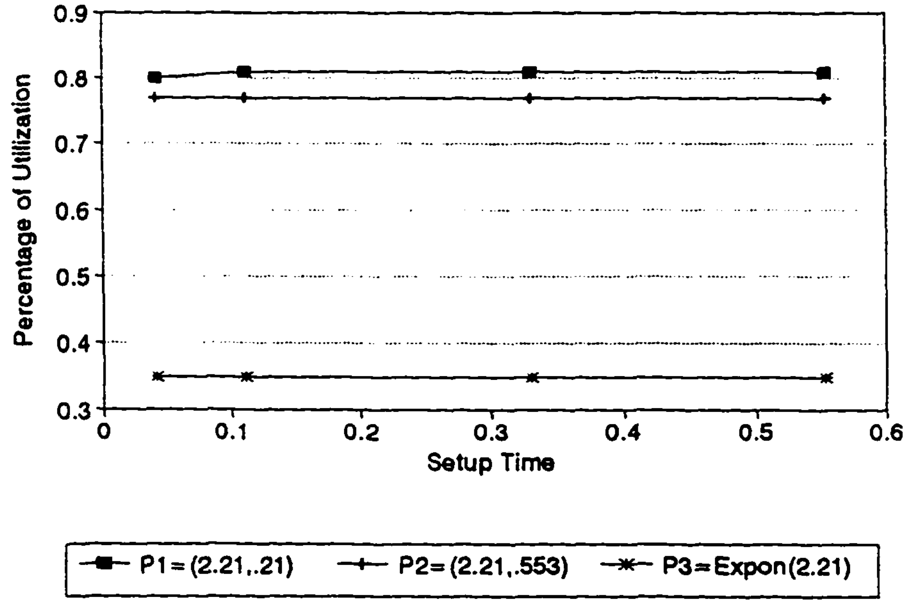
Container Size&Setup Time graph 5-11

Average Utilization of Assembly Line



Process Time&Setup Time graph 5-12

Average Utilization of Assembly Line



better result compared to large container sizes and exponential distribution as shown in graph (5-14).

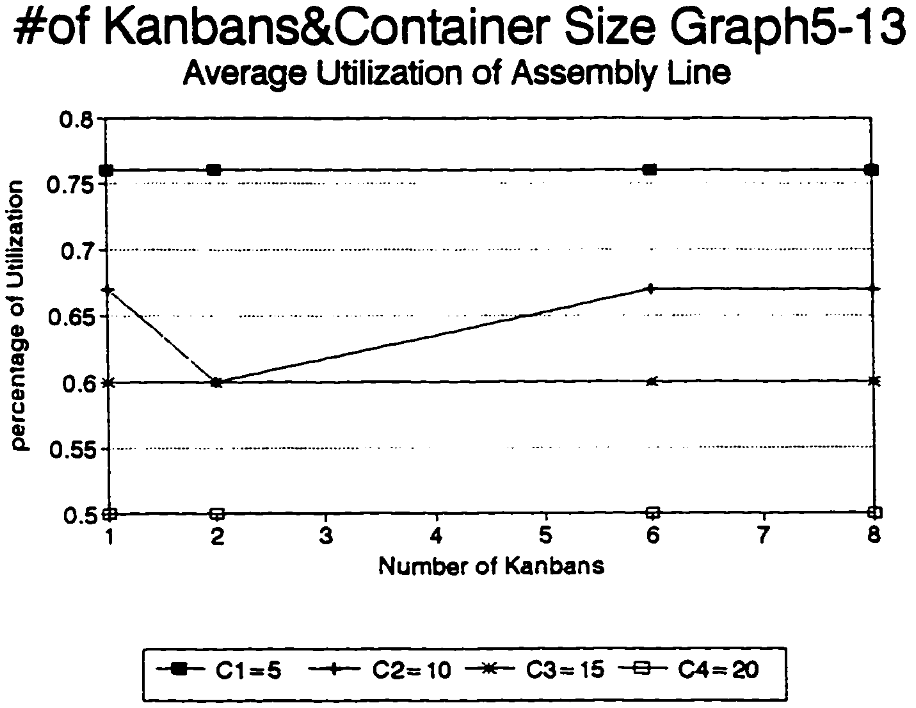
Average Utilization of Cellular Manufacturing One (AU1)

MANOVA results for average utilization indicated that three out of four main effects were significant. The interactions were not significant as shown in table d.

Main Effects

For a given number of Kanbans, station utilization was almost stable. That insensitivity to the number of K's could be attributed to the low demand loading of 140/230 = 61% considered in this experiment. Because of its higher production capacity, the system was able to cope with the variability in demand or even processing time. This shows that one or more Kanbans can be distributed without any impact on station utilization.

Setup times had no impact on utilization of cellular manufacturing one. However, the best results were obtained with setup time as 5% of the processing time, a normal processing time distribution with a low standard deviation, and two K's. Processing time distribution with a low standard deviation yielded a better result compared with normal distribution with a high standard deviation. For an exponential time distribution, average station utilization decreased with increasing number of K's and container size equal to five, but with other different container sizes and


#of Kanbans&Container Size Graph5-13
Average Utilization of Assembly Line
percentage of Utilization
0.8
0.75
0.7
0.65
0.6
0.55
0.5
1
2
3
4
5
6
7
8
Number of Kanbans
C1=5
C2=10
C3=15
C4=20

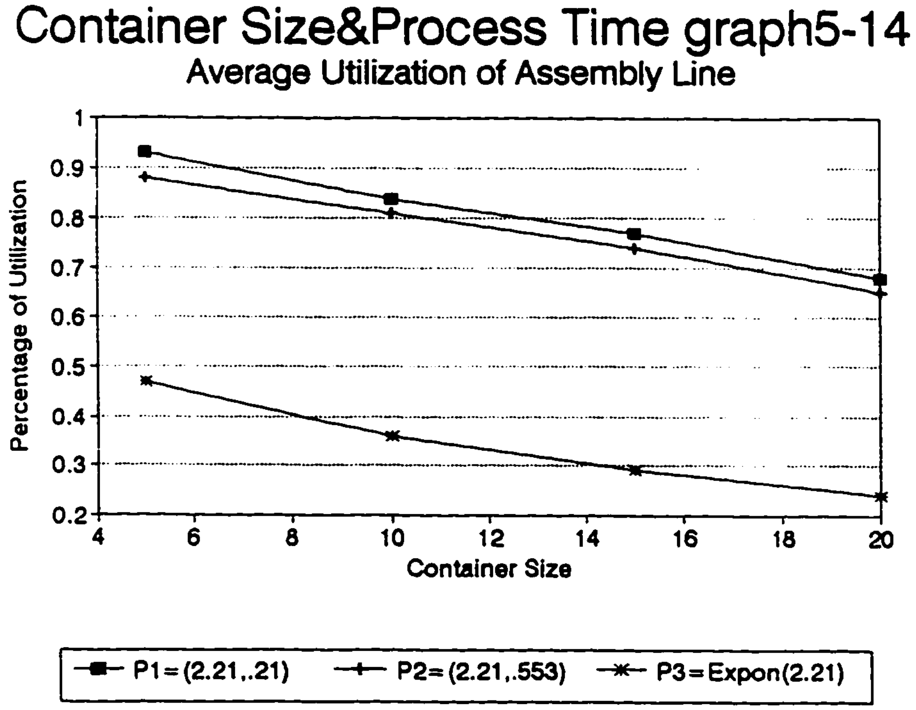

Container Size&Process Time graph5-14
Average Utilization of Assembly Line
Percentage of Utilization
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
4
6
8
10
12
14
16
18
20
Container Size
P1=(2.21,.21)
P2=(2.21,.553)
P3=Expon(2.21)

Table 5e

Analysis of Variance

Average Utilization of Cellular Manufacturing One By C K P S

Source of Variation	Sum of Squares	DF	Mean Squares	F	Sig of F
Main Effects					
Within+Residual	.04	180	.00		
C	.04	3	.01	67.22	.000
K	.00	3	.00	6.50	.000
P	1.95	2	.98	4807.28	.000
S	.00	3	.00	.19	.903
Two-Way Interactions					
Within+Residual	2.01	146	.01		
C * K	.00	9	.00	.02	1.000
C * P	.02	6	.00	.21	.974
C * S	.00	9	.00	.03	1.000
K * P	.00	6	.00	.01	1.000
K * S	.00	9	.00	.00	1.000
P * S	.00	6	.00	.01	1.000
Three-Way Interactions					
Within+Residual	2.03	110	.02		
C * K * P	.00	18	.00	.01	1.000
C * K * S	.00	27	.00	.00	1.000
C * P * S	.00	18	.00	.01	1.000
K * P * S	.00	18	.00	.00	1.000
Four-Way Interactions					
Within+Residual	2.03	137	.01		
C * K * P * S	.00	54	.00	.00	1.000

Where:

AU1 = Average Utilization for Cellular Manufacturing One
K = # of Kanbans
C = Container size
P = Processing time
S = Setup time

different number of K's it remained almost constant. Thus, for an exponential time distribution, one Kanban and small container size would be enough to obtain maximum station utilization if the demand load increased.

Increasing the container size from five to ten gave better results and from ten to fifteen gave even better results but average station utilization remained almost the same for container size of twenty. Thus, increasing the container size would yield better results.

Two-Way Interactions

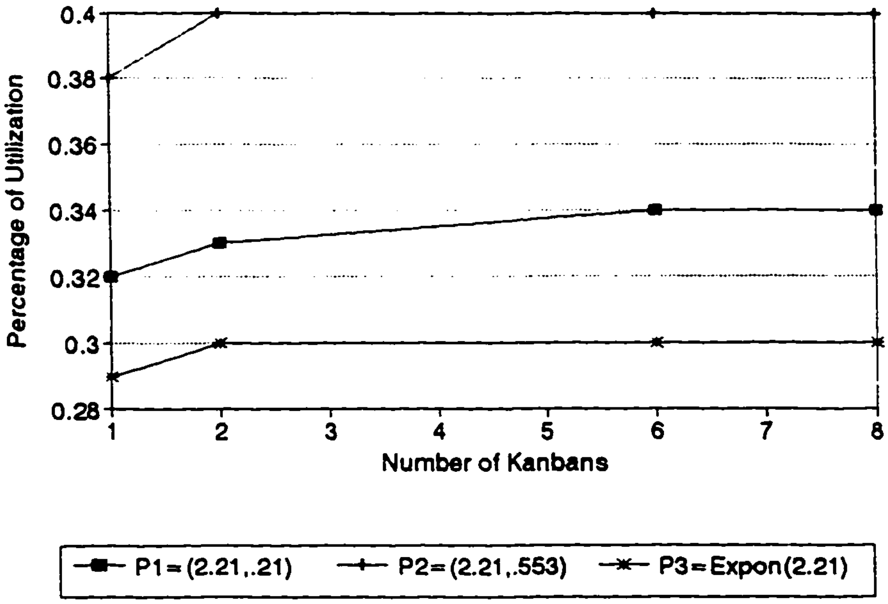
Container size and Setup time. Container size and setup time had little impact on average station utilization. Two or more K's accompanied with larger than 5-unit container sizes yielded the best results as shown in graph (5-15).

Processing time and Setup time. Different distributions of normal processing time with different setup times had little impact on station utilization. However, different setup time distributions with exponential time distribution yielded a lower utilization of the work station as shown in graph (5-16).

Kanbans and Processing time. As expected, different K's with different distributions of normal processing times resulted in a constant average station utilization of .73, but different K's with an exponential time distribution resulted in a lower but constant average utilization of cellular manufacturing one as shown in graph (5-17).

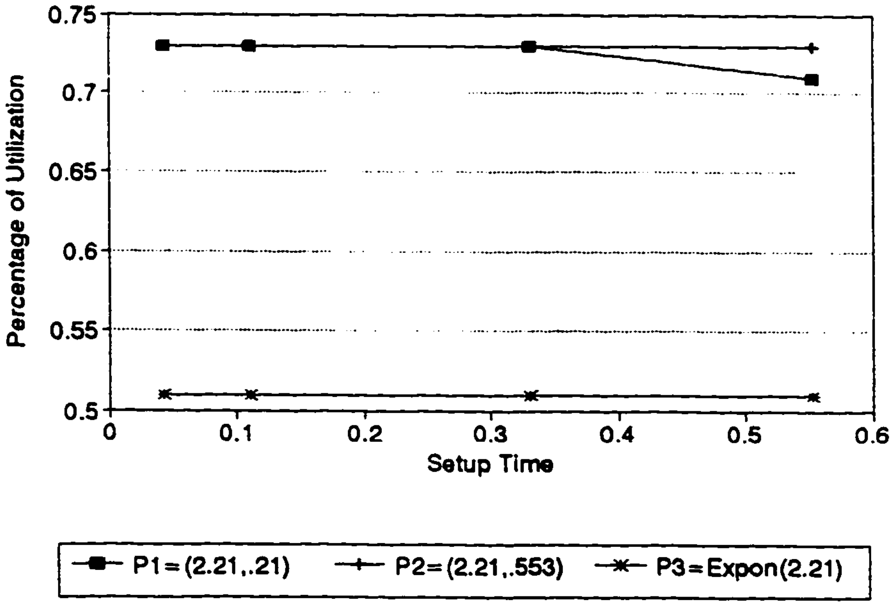
# of Kanbans&Process Time graph5-15

Average Utilization of Cellular One



Setup Time&Process Time graph5-16

Average Utilization of Cellular One



Container size and Processing time. Larger container size with different normal processing time distributions gave better results in terms of average station utilization compared with an exponential time distribution. Thus, larger size of containers with normal processing time distribution will yield good results as shown in graph (5-18).

Average Utilization of Cellular Manufacturing Two (AU2)

Generally speaking, the average rate of utilization is very low in the second manufacturing cell. The minimum is .28, the maximum is .43, and the average is .37. This compares with cellular manufacturing one in which the minimum is .47, the maximum is .77 and the average is .66. This can be attributed to the low demand load assigned to the cell which is 90 units out of 230 units of the total output.

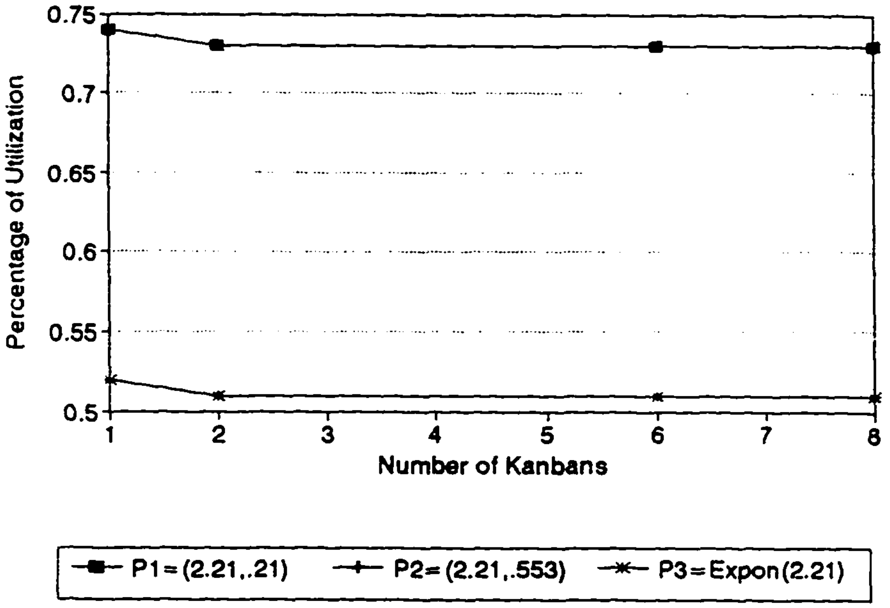
MANOVA results in table 5e indicate that most of the main effects are significant. None of the two-way and three-way as well as four-way interactions are significant.

Main Effects

Kanbans. Increasing the number of K's from 1 to 2 improved average utilization for cellular manufacturing two, but increasing K's by more than two had no impact on the average utilization. This insensitivity could be attributed to the low demand loading of 90/230 = .39 considered in the experiment.

# of Kanbans&Process Time graph5-17

Average Utilization of Cellular One



Container Size&Process Time graph5-18

Average Utilization of Cellular One

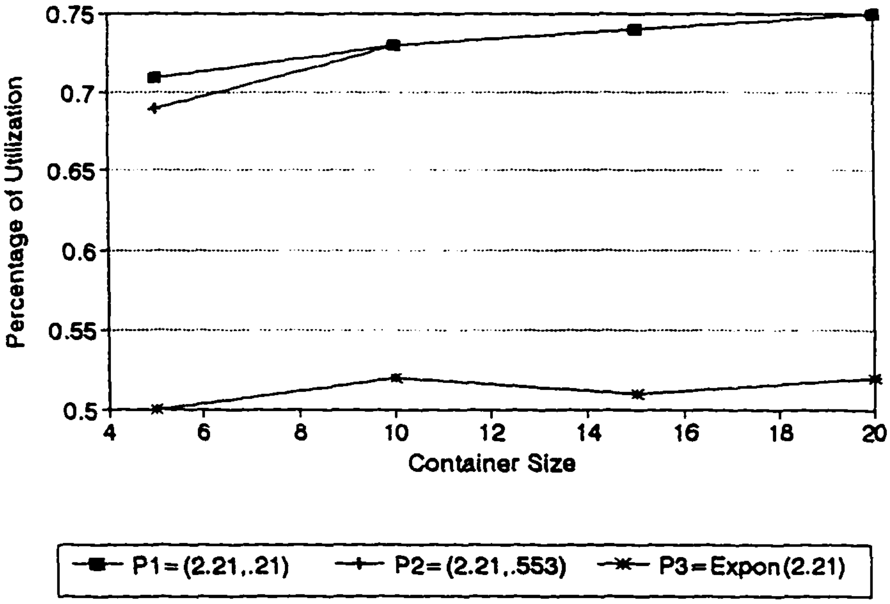


Table 5f

Analysis of Variance

Average Utilization of Cellular Manufacturing Two By C K P S

Source of Variation	Sum of Squares	DF	Mean Squares	F	Sig of F
Main Effects					
Within+Residual	.25	180	.00		
C	.08	3	.03	19.92	.000
K	.01	3	.00	2.92	.036
P	.32	2	.16	112.14	.000
S	.01	3	.00	2.34	.075
Two-Way Interactions					
Within+Residual	.56	146	.00		
C * K	.00	9	.00	.11	.999
C * P	.05	6	.01	1.98	.072
C * S	.04	9	.00	1.17	.319
K * P	.00	6	.00	.16	.987
K * S	.01	9	.00	.15	.998
P * S	.02	6	.00	.98	.443
Three-Way Interactions					
Within+Residual	.57	110	.01		
C * K * P	.01	18	.00	.09	1.000
C * K * S	.01	27	.00	.10	1.000
C * P * S	.08	18	.00	.82	.676
K * P * S	.01	18	.00	.11	1.000
Four-Way Interactions					
Within+Residual	.65	137	.00		
C * K * P * S	.03	54	.00	.10	1.000

Where:

AU2 = Average Utilization for Cellular Manufacturing Two
K = # of Kanbans
C = Container size
P = Processing time
S = Setup time

Increasing the size of the container from 5 to 10 to 15 resulted in increasing average utilization, but increasing the size of the container by more than 15 resulted in decreasing average utilization. Average utilization was the lowest when the container size equaled five.

Normally distributed processing time with a low standard deviation yielded better results than normally distributed processing time with a high standard variation. However, an exponential distribution resulted in the lowest average of utilization in cellular manufacturing two. Thus, as variation in the processing time increased, average utilization decreased.

Two-Way Interactions

Container size and Setup time. Increasing the container size up to 15 resulted in increasing average utilization but when the container size increased more than 15, average utilization started to decrease. Setup time had no impact whatsoever on average utilization as shown in graph (5-19). Also, the graph shows some interaction between container size and setup time.

Kanban and Setup time. As the number of K's increased with the first setup time, which made 2% of the processing time, average utilization improved, but different K's with different setups resulted in decreasing average utilization as shown in graph (5-20).

Processing time and Setup time. Increasing setup (S) more than 2% of processing time along with a normally distributed processing time with low standard deviation resulted in lowering average utilization. Normally distributed processing time with high standard deviation and an exponential distribution with different setups resulted in a constant average utilization as shown in graph (5-21).

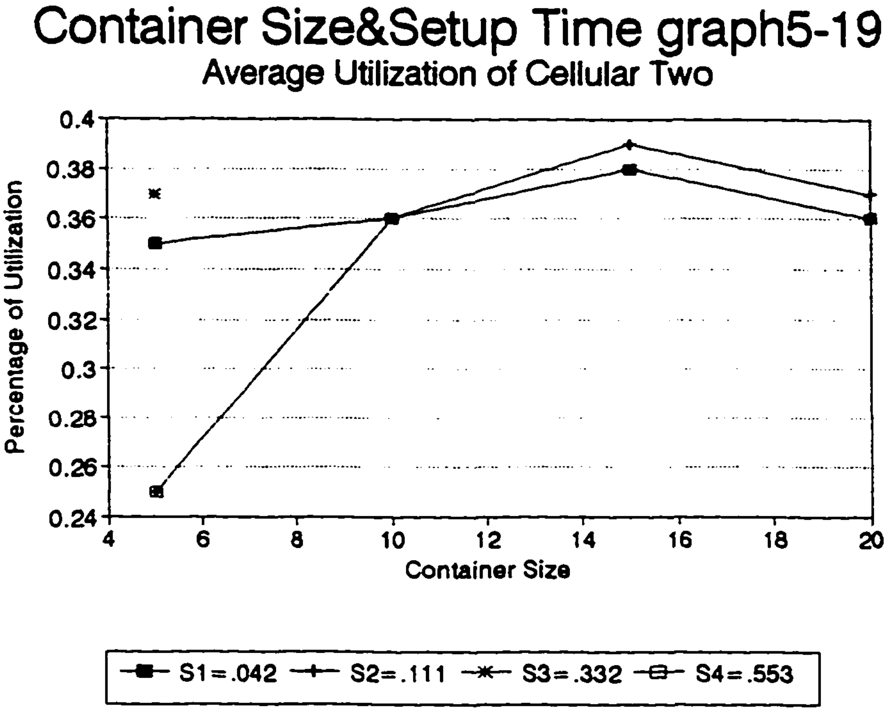
Kanban and Container. Increasing the number of K's while increasing the size of container up to 15 resulted in improving average utilization, but increasing the number of K's with container size equal to 20 resulted in decreasing average utilization as shown in graph (5-22).

Shortage

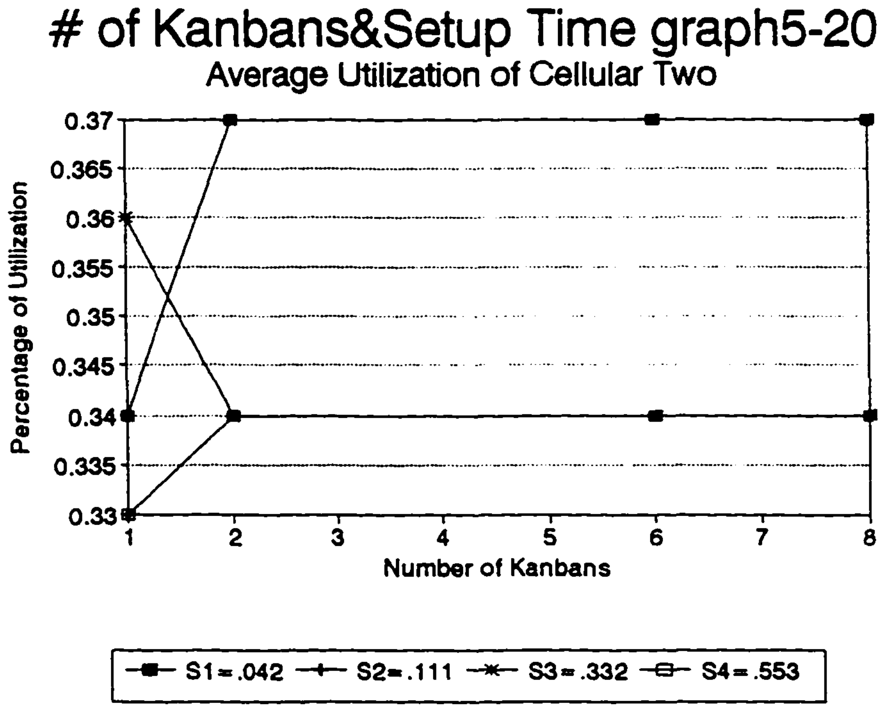
MANOVA results for shortage (SH) indicated that three out of four main effects were significant. None of the-two way and three-way interactions as well as four-way interactions were significant as shown in table 5g.

Main effects

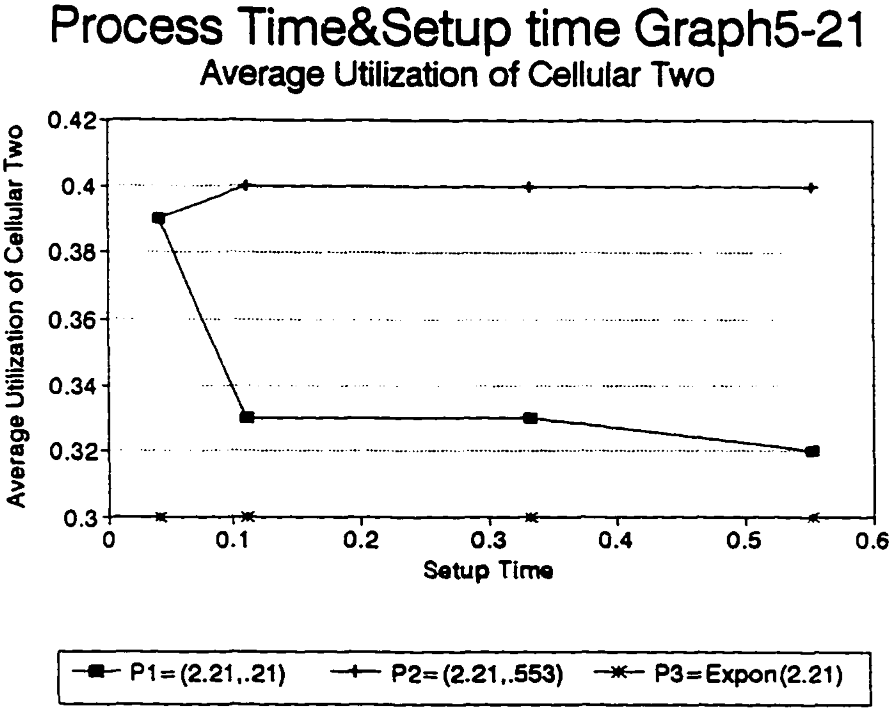
Decreasing the number of K's had no impact on the level of shortage. However, increasing the size of container by more than 10, resulted in some shortages. The level of the shortage was not big. Only 5 units, or 2.17% of the total demand, were requested when the container size equaled 15 and 10 units and 4.33% when the container size equaled 20 as shown by graph (5-23). That trend continues with different normal processing time distributions. With an exponential


Container Size&Setup Time graph5-19

Average Utilization of Cellular Two

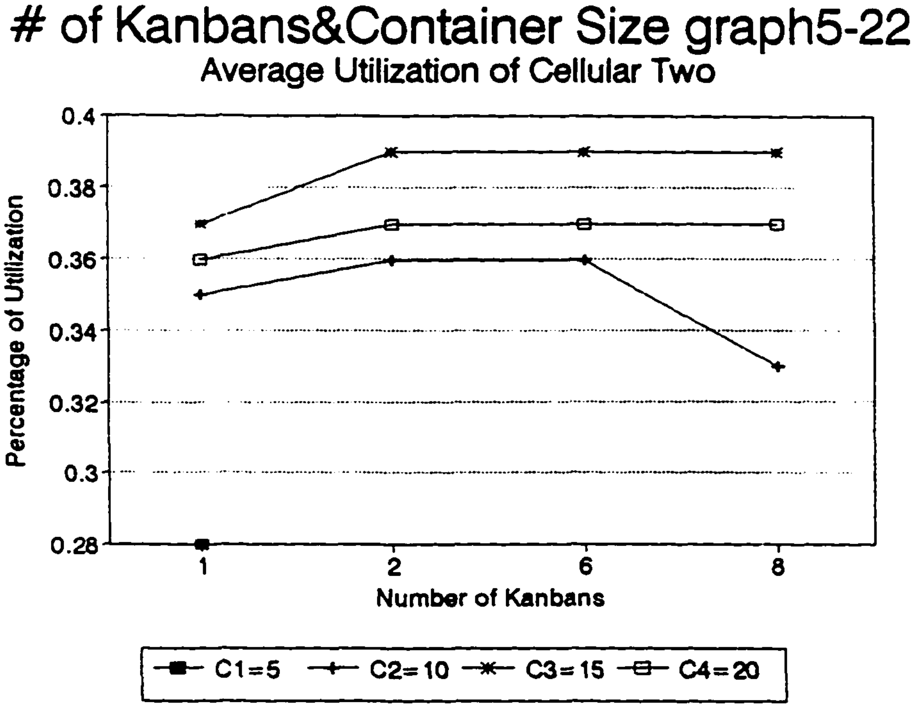

# of Kanbans&Setup Time graph5-20

Average Utilization of Cellular Two



Process Time&Setup time Graph5-21

Average Utilization of Cellular Two



# of Kanbans&Container Size graph5-22

Average Utilization of Cellular Two

Table 5g

Analysis of Variance

Shortage by C K P S

Source of Variation	Sum of Squares	DF	Mean Squares	F	Sig of F
Main Effects					
Within+Residual	81.25	180	.45		
C	3156.25	3	1052.08	2330.77	.000
K	6.25	3	2.08	4.62	.004
P	4.17	2	2.08	4.62	.011
S	.00	3	.00	.00	1.000
Two-Way Interactions					
Within+Residual	3204.17	146	21.95		
C * K	18.75	9	2.08	.09	1.000
C * P	12.50	6	2.08	.09	.997
C * S	.00	9	.00	.00	1.000
K * P	12.50	6	2.08	.09	.997
K * S	.00	9	.00	.00	1.000
P * S	.00	6	.00	.00	1.000
Three-Way Interactions					
Within+Residual	3210.42	110	29.19		
C * K * P	37.50	18	2.08	.07	1.000
C * K * S	.00	27	.00	.00	1.000
C * P * S	.00	18	.00	.00	1.000
K * P * S	.00	18	.00	.00	1.000
Four-Way Interactions					
Within+Residual	3247.92	137	23.71		
C * K * P * S	.00	54	.00	.00	1.000

Where:

SH = Shortage
K = # of Kanbans
C = Container size
P = Processing time
S = Setup time

time distribution there was a shortage of another 5 units when K equals one and the container size equals five. None of the two-way or three-way or four-way interactions had any type of influence on level of shortage.

Average Waiting Time for the Last Station

MANOVA results for average waiting time for the last work station (AW) in table (5h) indicated that three out of four main effects were significant. Two out of six two-way interactions were significant, too. But none of three-way or four-way interactions were significant.

Main Effects

The main purpose of using average waiting time for the last station was to gain insight into the dynamic nature of a JIT using kanbans and to provide a basis for more detailed future research.

As the number of Kanbans increased, average waiting time increased. The reason behind that could be that increased Kanban levels allowed more units to be processed in the assembly line, resulting in large queues at the final assembly stage. For example, reducing the number of K's from 6 to 2 resulted in reducing (AW) from 60 minutes to 20 minutes and reducing the number of K's from 2 to 1 resulted in reducing (AW) from 20 to 9 minutes. On the other hand if the assembly line was not utilized fully, increasing the number of Kanbans would result in fewer shortages.

Table 5h

Analysis of Variance

Average Waiting Time for the Last Workstation By C K P S

Source of Variation	Sum of Squares	DF	Mean Squares	F	Sig of F
Main Effects					
Within+Residual	804589.39	180	4469.94		
C	1139750.19	3	379916.73	84.99	.000
K	1289976.16	3	429992.05	96.20	.000
P	437270.65	2	218635.32	48.91	.000
S	29.39	3	9.80	.00	1.000
Two-Way Interactions					
Within+Residual	2945057.27	146	20171.63		
C * K	316580.19	9	35175.58	1.74	.084
C * P	273636.51	6	45606.08	2.26	.041
C * S	148.83	9	16.54	.00	1.000
K * P	136057.87	6	22676.31	1.12	.351
K * S	88.63	9	9.85	.00	1.000
P * S	46.48	6	7.75	.00	1.000
Three-Way Interactions					
Within+Residual	3594123.38	110	32673.85		
C * K * P	76922.77	18	4273.49	.13	1.000
C * K * S	251.97	27	9.33	.00	1.000
C * P * S	197.11	18	10.95	.00	1.000
K * P * S	120.55	18	6.70	.00	1.000
Four-Way Interactions					
Within+Residual	3671077.29	137	26796.18		
C * K * P * S	538.49	54	9.97	.00	1.000

Where:

AW = Average Waiting Time for the last Station
K = # of Kanbans
C = Container size
P = Processing time
S = Setup time

Smaller container sizes cause smaller batch time in the final assembly stage, resulting in less waiting time. When setup times are lower, components pass through the assembly line rapidly, resulting in longer waiting line for the final assembly. Thus, one Kanban has better results in terms of average waiting time for the last station. One possible explanation for this is that increased Kanban levels enabled more units to be processed in the assembly line, resulting in longer waiting lines at the final assembly stage.

As the container size decreased, the average waiting time (AW) decreased substantially. For example, decreasing the size of container from 20 to 15 resulted in decreasing AW from 55 to 35 minutes, and decreasing the size of the container from 15 to 10 to 5 resulted in decreasing (AW) from 35 to 21 to 9 minutes, respectively. Thus, the smallest container size yielded better results.

Normally distributed processing time with either a low or high standard deviation has a substantial impact on average waiting time as shown in table f in Appendix 2. However, an exponential processing time distribution has a substantial but worse impact on (AW) than normally distributed processing time. Thus, normally distributed processing time is better and recommended.

Two-Way Interactions

Container size and setup time. Setup time has no impact on AW. Container size, on the other hand, has a major impact. Decreasing the size of container from 20 to 15 to 10 to 5 resulted in reducing AW from 249 to 168 to 95 to 47 minutes respectively, as shown in graph (5-24).

Processing time and Setup time. As mentioned before, both normally distributed processing time with low and high standard deviation had the same influence. An exponential distribution had a worse impact when compared with normal processing time. For example, average waiting was 106.5 minutes with normal processing time distribution and was 209 minutes with exponential time distribution as shown in graph (5-25).

Kanban and Processing time. Increasing the number of K's from 1 to 2 to 6 to 8 with normal processing time distribution resulted in increasing (AW) from 30 to 62 to 150 to 185 minutes as shown in graph (5-26). Increasing the number of K's from 1 to 2 to 6 to 8 resulted in increasing (AW) from 63 to 120 to 292 to 354 minutes. Thus, one Kanban with normal processing time would be the best combination.

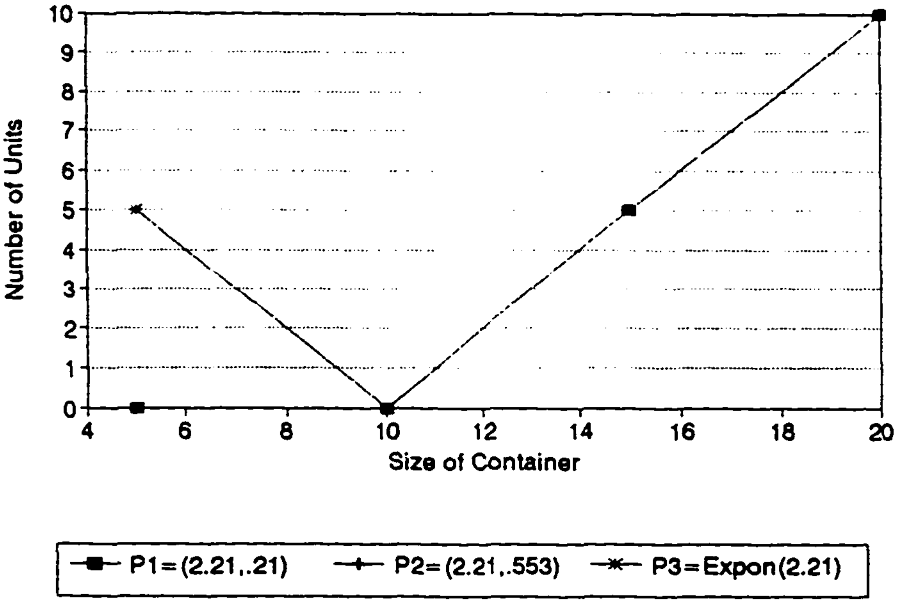
Kanban and Container. Decreasing the number of K's while decreasing the size of container had a substantial impact on (AW) as shown in graph (5-27).

Container size and Processing time

Decreasing the container size with normal processing time resulted in better results than with exponential time distributions as shown in graph (5-28).

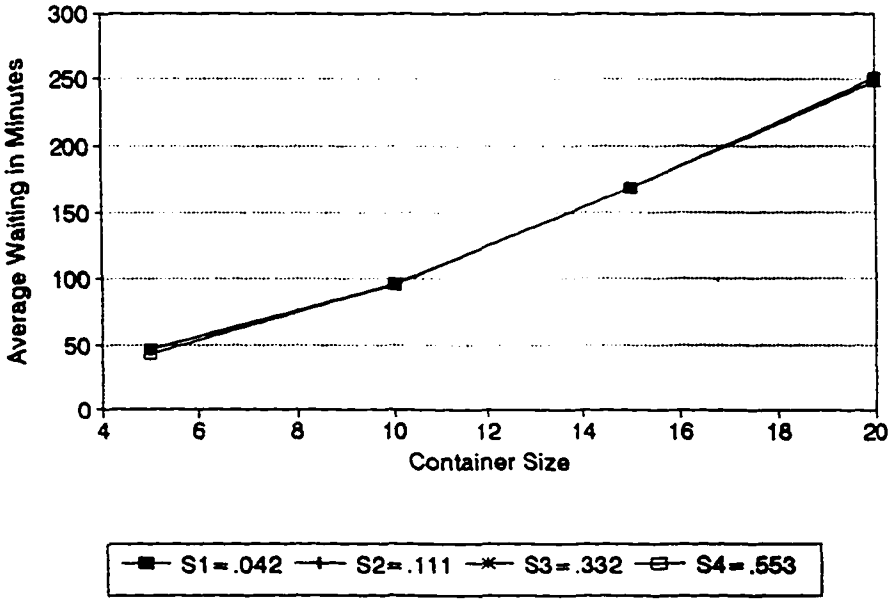
Container Size&Process Time graph5-23

Shortage



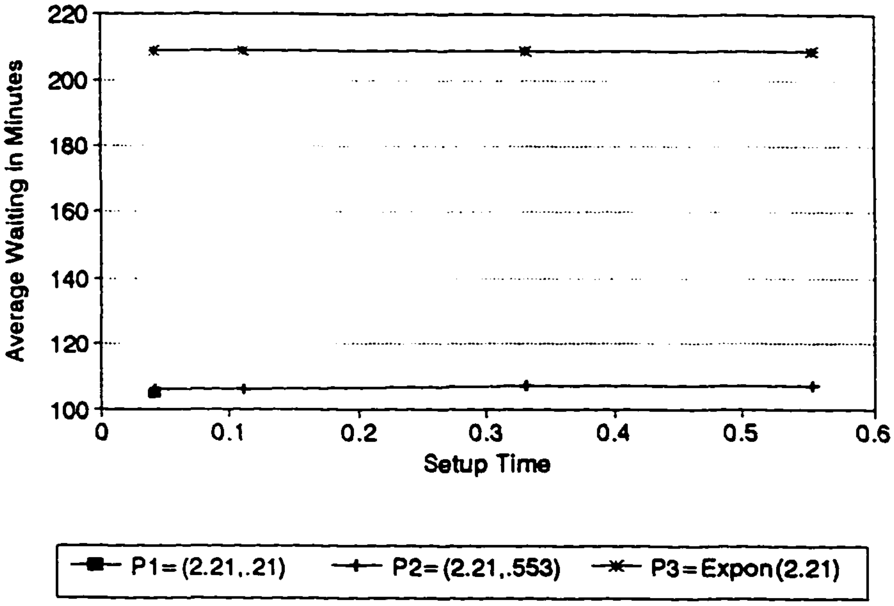
Container Size&Setup Time graph 5-24

Average Waiting for the last Station



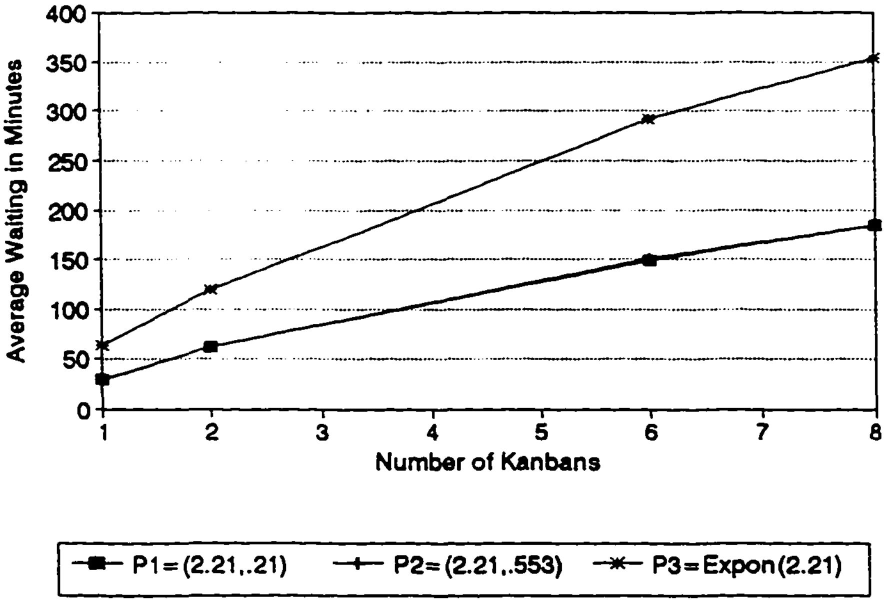
Setup time&Process Time graph5-25

Average Waiting for the Last Station



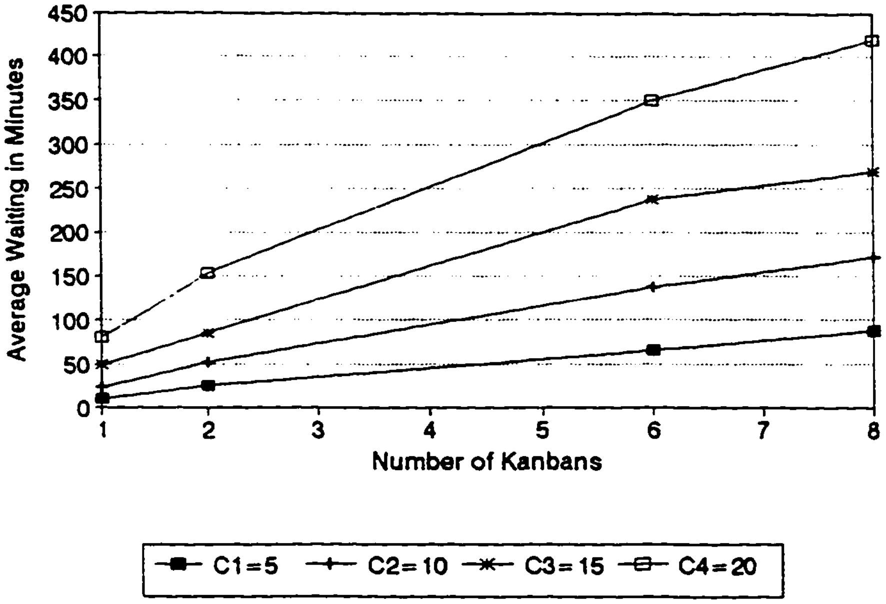
# of Kanbans&Process Time graph5-26

Average Waiting for the Last Station



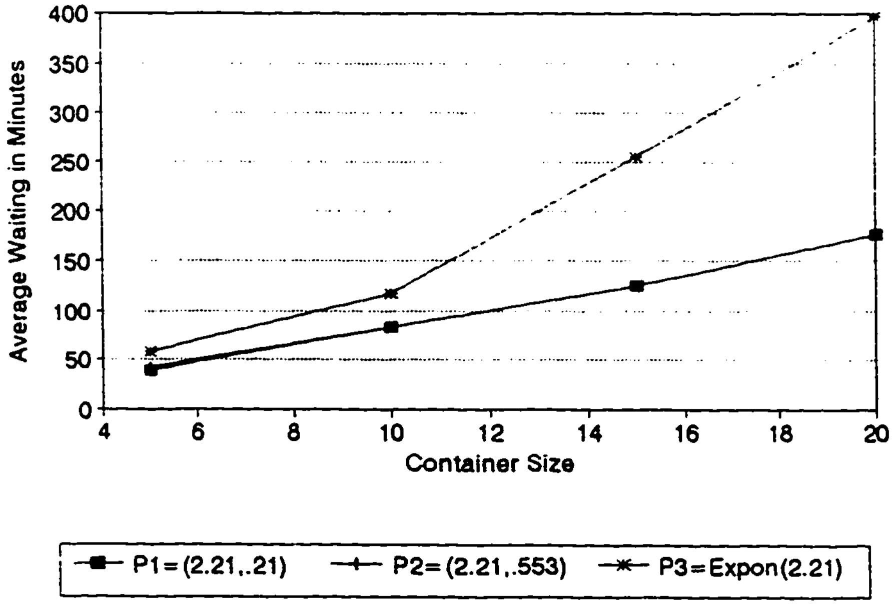
of Kanbans&Container Size graph5-27

Average Waiting for the last station



Container Size&Process Time graph5-28

Average Waiting for the Last Station



Chapter 6

Conclusion and Recommendation

This chapter summarizes the variables used in this study, the performance measures, the main results of the research, draws some general conclusions and suggests directions for future research. The variables used in this study are:

Variables	Levels
1. Number of Kanbans	1,2,6,8
2. Different container sizes	5,10,15,20
3. Different processing time distributions	(2.21,.21) (2.21,.553) Exponential (2.21)
4. Different setup times	(.042,.004) (.111,.011) (.332,.033) (.553,.055)

The performance measures used are:

1. Mean work-in-process-inventory.
2. Mean overtime
3. Average utilization assembly line
4. Average utilization cellular manufacturing one
5. Average utilization cellular manufacturing two
6. Average shortage
7. Average waiting time for the last station.

Summary of the Results

1. With respect to the first research question, it is clear that the number of kanbans affects the performance of mixed-model JIT systems like the one studied. The study showed that decreasing Kanban levels resulted in:

- Lowering WIP inventory levels,
- Increasing overtime,
- No impact on the average utilization of the assembly line,
- No impact on average utilization of cellular manufacturing one,
- Lowering average utilization of cellular manufacturing cell two,
- No impact on shortage,
- Decreasing average waiting time.

2. With respect to the second research question, it is clear that different container sizes affect the performance of mixed-model JIT systems like the one studied. Reducing container size resulted in:

- Increasing work-in-process,
- Decreasing overtime,
- Increasing average utilization of the assembly line,
- Lowering average utilization of cellular manufacturing one,
- Lowering average utilization of cellular

manufacturing two,

* Reducing shortage levels,
* Decreasing average waiting time.

3. With respect to the third research question, it is clear that different processing time distributions affect the performance of mixed-model JIT systems like the one studied. However, processing time (in the case of normal distribution with low standard deviation) resulted in:

* WIP remained constant,
* Overtime decreased,
* Average utilization of the assembly line decreased by a low percentage,
* Average utilization of the cellular manufacturing one improved,
* Average utilization of the cellular manufacturing two improved,
* No impact on shortage,
* Average waiting time increased.

4. Processing time (normal distribution with high standard deviation) resulted in:

* Work-in-process remaining constant,
* Increasing overtime,
* Lowering average utilization of the assembly line,
* Lowering average utilization of cellular manufacturing one,

- No impact on shortage,
- Increasing average waiting time.

5. Processing time (exponential distribution) resulted in:

- Increasing WIP,
- High increase in overtime,
- Decreasing average utilization of the assembly line substantially,
- Lowering average utilization of cellular manufacturing one,
- Lowering average utilization of cellular manufacturing two,
- Increasing the level of shortage,
- Increasing average waiting time substantially.

Generally speaking, decreasing the number of Kanbans in the system resulted in lowering work-in-process in the system and lowering mean waiting time for the last station. On the other hand, it resulted in deteriorating average utilization per assembly line of cellular manufacturing number one and two. Reducing container size resulted in decreasing overtime, improving utilization of the assembly line, decreasing average waiting time as well as reducing average shortage. On the other hand, it resulted in increasing work-in-process and lowering average utilization of cellular manufacturing one and two.

Normal processing time distributions resulted in improving average utilization of manufacturing cell one and two, keeping work-in-process constant and reducing overtime. On the other hand, they lowered average utilization of the assembly line and increased average waiting time.

Processing time with an exponential distribution had an inverse effect in all performance results. That could be attributed to the fact that exponential processing time assumptions usually donot hold because the variability in processing times in a pull system is low. This result is supported by Meral et al. (1991).

Finally, setup times with a normal distribution and ratios up to 25% of the processing times did not have much influence on the performance measures of the system.

Implications

If the workers are unable to reduce the variability in processing times, overtime will be increased. Thus, the manager is confronted with a tradeoff between overtime cost and in-process inventory costs, since increasing the number of Kanbans reduces overtime (Huang et al., 1983).

For a system with similar characteristics to those described in this study, the performance of the system is a function of number of Kanbans, container size and processing time distributions.

A basic structure and a simulation methodology to model a just-in-time and a mixed model production system are developed in this study to use these models to analyze different sets of conditions. Also, these models can be used to provide information to the production manager as to how the system should be modeled to achieve better performance or other improved results.

The state-of-the-art simulation adopted in this paper for modeling the JIT and the mixed model production system may not solve all problems, but it can give some guidance to the analyst on how to approach a simulation model for a JIT and mixed model production system.

The examples covered in this study provide tools for more different types of production systems. This may provide information to the production manager as to how the system should be modeled to achieve better performance or other improved results.

The prior knowledge of performance of a mixed-model with different coefficients of variation for processing times may provide a reference to the designer or the industrial engineer for the design of buffers or the incorporation of more Kanbans in the system to improve the efficiency of the line.

As the coefficient of variation increases, production rate of a pull system decreases. In other words, the manager should be aware that a high variation of processing times lowers the production system, this result is supported by Sarker et al. (1989).

Limitations

1. There is no consideration of machine breakdown or defective items.

2. Total work content is assumed to consist of a number of identical unit operations.

3. There is no actual data: The situation faced by the line designers in practice is different from the situation described in this research.

4. The number of runs are only 125 due to the capacity of SLAM II software.

5. No schedule rule has been used in this research.

6. Raw materials are assumed to be available when needed and no machine breakdown or defective products are modeled. These are idealistic assumptions, even for the most efficient JIT system.

7. Each day was considered an independent run and the statistics program cleared the system after each run.

Future Research

1. A mathematical model for the optimum allocation of buffers in front of different stages along the line can be developed as well as analytical models involving multiple item and multiple line flows.

2. Scheduling rules: application of a schedule heuristic as well as algorithm to see the effect of this factor on the performance of the mixed model.

3. Relaxing the restrictive assumption of identical unit operations to design more realistic lines.

4. The application of different Kanban levels at different stages.

5. Comparison of the conventional JIT production systems to alternative JIT systems such as a periodic pull system, where the manual information processing time of a Kanban method is replaced by on-line computerized processing. Also, a comparison to the special type of Kanban introduced by Philipoom et al. (1990), in which a signal Kanban for work stations with relatively high setup times and developed mathematical programming models may enable to determine the optional lot size used in conjunction with the signal Kanban.

6. Empirical studies are needed to: (a) determine the condition in which mixed models operate, (b) to determine which measure should be used to evaluate JIT performance, and (c) to develop a common terminology of performance measures.

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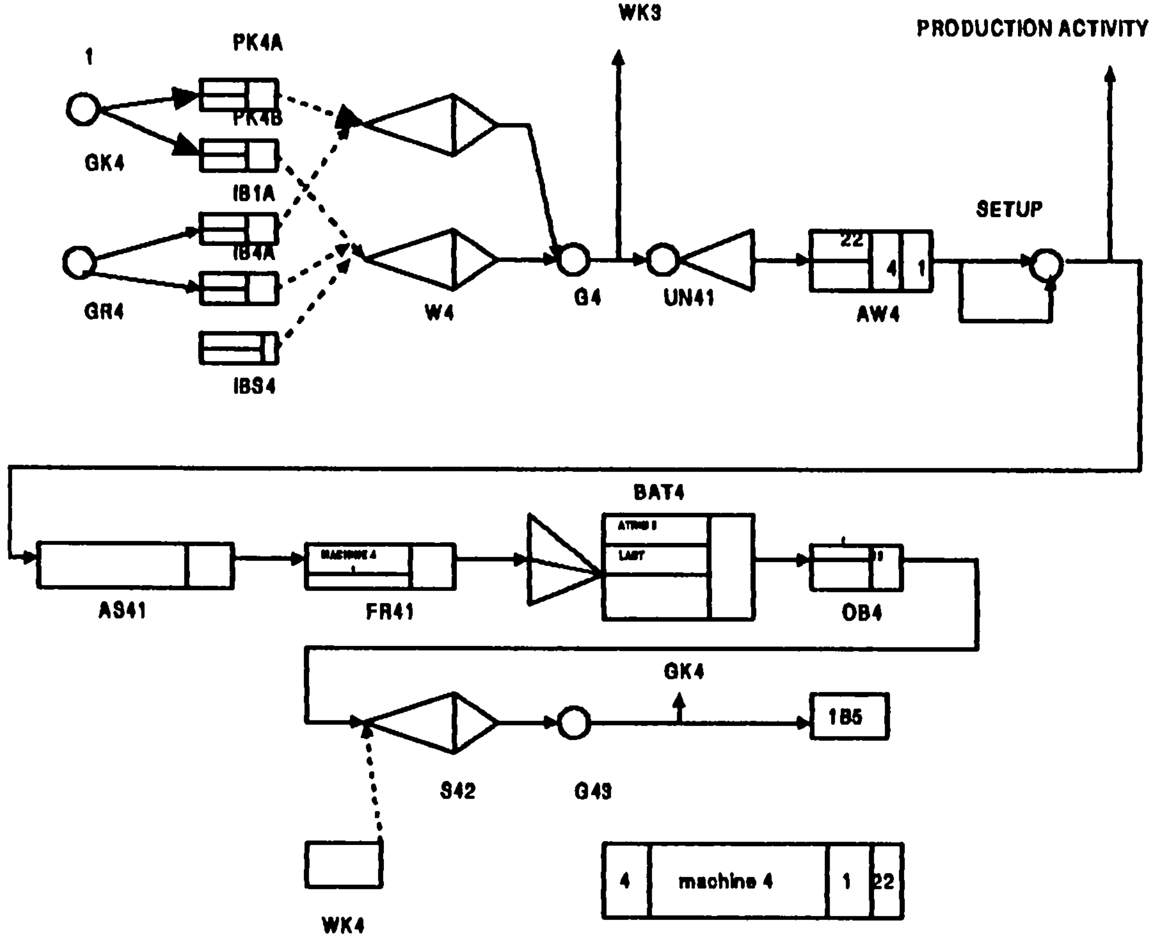
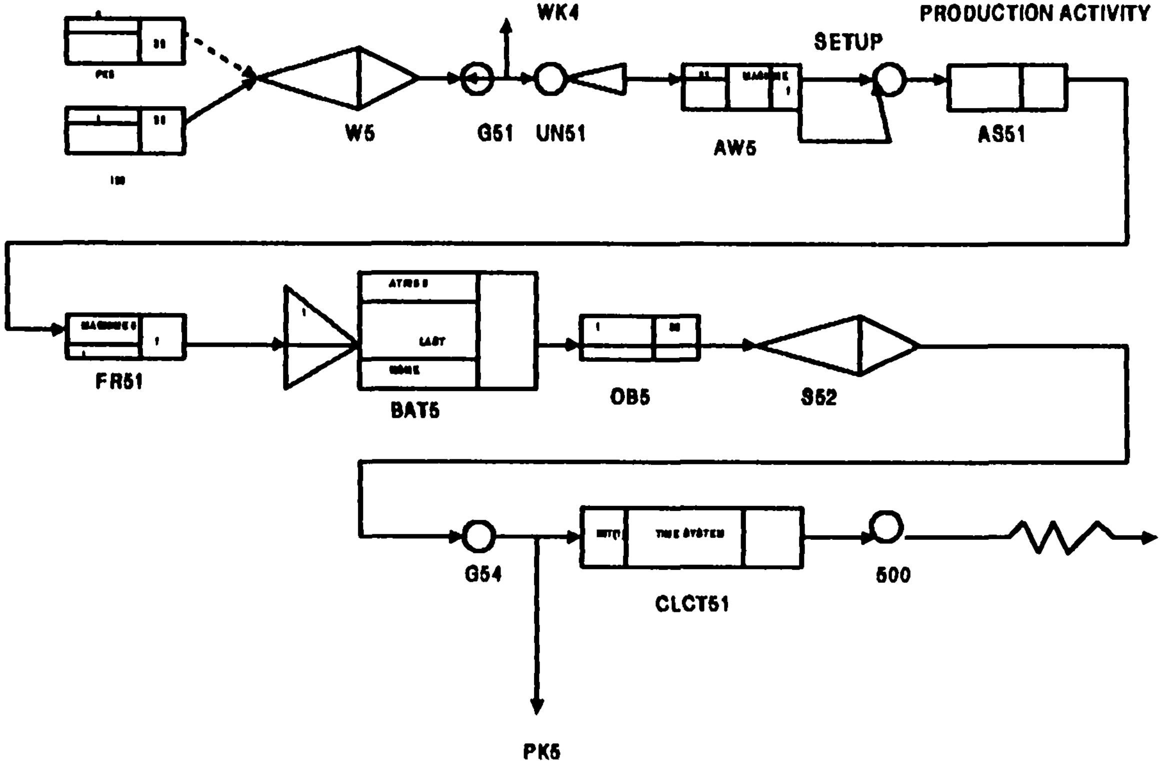
APPENDICES 1a-1d
SIMULATION Model

Appendix (1a)

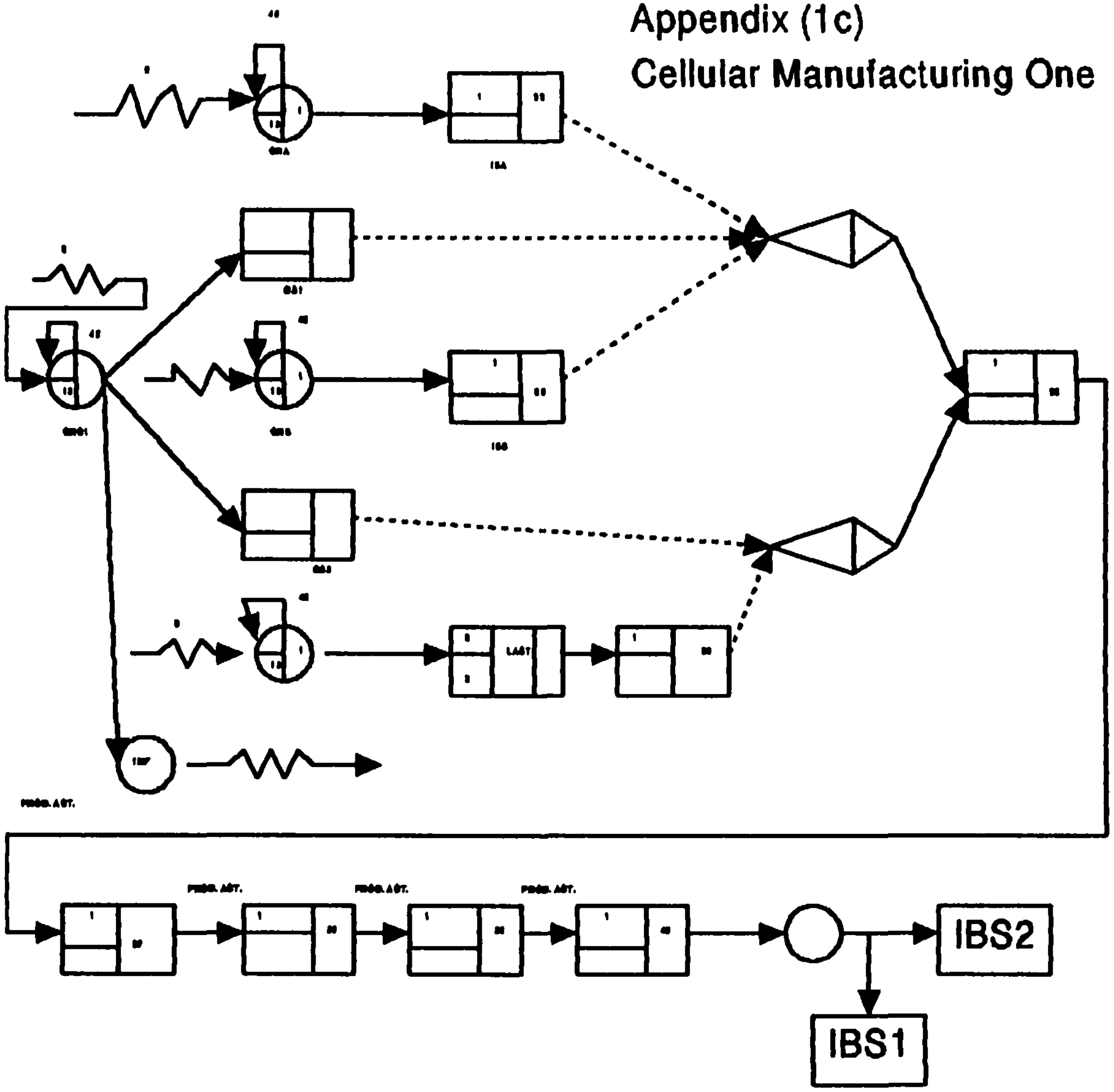
Stage (4)



APPENDIX (1b)
STAGE (5)



Appendix (1c)
Cellular Manufacturing One



APPENDIX (1d)

```
GEN,,EXPERIMENT 12,2/7/1997,100,Y,N,Y/Y,Y,Y/100,132;
LIMITS,58,3,500;
INITIALIZE,,100000,N,N,N;

   REDEFINITION IS IGNORED.

   REDEFINITION IS IGNORED.
NETWORK;
;FILE TEMP16
;FILE TEMP16
      RESOURCE/1,MACHINE1,4;
      RESOURCE/2,MACHINE2,10;
      RESOURCE/3,MACHINE3,16;
      RESOURCE/4,MACHINE4,22;
      RESOURCE/5,MACHINE5,27;
;
;STAGE ONE
;
GK1   GOON,1;
      ACTIVITY,,XX(1).NE.1,PK1A;
      ACTIVITY,,XX(1).EQ.1,PK1B;
PK1A  QUEUE(51),,,,S11B ;
S11B  SELECT,ASM/HIGH(1),,,PK1A,IB1A;
      ACTIVITY(1);
G11   GOON,1;
      ACTIVITY;
UN11  UNBATCH,3;
      ACTIVITY;
AW1   AWAIT(4),MACHINE1;
      ACTIVITY/1,XX(12),XX(1).NE.ATRIB(2),;SETUP1;
      ACTIVITY/2,,XX(1).EQ.ATRIB(2);
G12   GOON;
      ACTIVITY/3,XX(17),,;PRODUCTION1;
AS11  ASSIGN,XX(1)=ATRIB(2);
      ACTIVITY;
FR11  FREE,MACHINE1;
      ACTIVITY;
BAT1  BATCH,1,ATRIB(3);
      ACTIVITY;
OB1   QUEUE(5),1,,,S12  ;
S12   SELECT,ASM/HIGH(1),,,OB1 ,WK1 ;
      ACTIVITY(1);
G13   GOON;
      ACTIVITY/4,,,GK1;PRODUCTION KANBAN;
      ACTIVITY/5,,,GR2;
PK1B  QUEUE(1),,,,W1   ;
W1    SELECT,ASM/HIGH(1),,,PK1B,IB1B,IBS1;
      ACTIVITY(1),,,G11;
;
```

```
;SETUP
;
;PRODUCTION
;
CRM2  CREATE,40,,,12;
      ACTIVITY;
GR1   GOON,1;
      ACTIVITY,,XX(1).NE.1;
      ACTIVITY,,XX(1).EQ.1,IB1B;
IB1A  QUEUE(52),1,,,S11B ;
IB1B  QUEUE(2),1,,,W1    ;
;
IBS1  QUEUE(3),1,,,W1    ;
;
;SRAGE TWO
;
;SETUP
;
;PRODUCTION
;
GK2   GOON,1;
      ACTIVITY,,XX(1).NE.2,PK2A;
      ACTIVITY,,XX(1).EQ.2,PK2B;
PK2A  QUEUE(53),,,,ZAAC ;
ZAAC  SELECT,ASM/HIGH(1),,,PK2A,IB2A;
      ACTIVITY(1);
G21   GOON,2;
      ACTIVITY/8,,,WK1;WITHADRAWAL KANBAN;
      ACTIVITY,,,UN21;
WK1   QUEUE(6),,,,S12  ;
UN21  UNBATCH,3;
      ACTIVITY;
AW2   AWAIT(10),MACHINE2;
      ACTIVITY/9,XX(12),XX(1).NE.ATRIB(2),;SETUP2;
      ACTIVITY/10,,XX(1).EQ.ATRIB(2);
G22   GOON;
      ACTIVITY/11,XX(16),,;PRODUCTION2;
AS21  ASSIGN,XX(1)=ATRIB(2);
      ACTIVITY;
FR1   FREE,MACHINE2;
      ACTIVITY;
BAT2  BATCH,1,ATRIB(3);
      ACTIVITY;
OB2   QUEUE(11),1,,,S22  ;
S22   SELECT,ASM/HIGH(1),,,OB2 ,WK2 ;
      ACTIVITY(1);
G23   GOON;
      ACTIVITY/12,,,GK2;PRODUCTION KANBAN;
      ACTIVITY/13,,,GR3;
PK2B  QUEUE(7),,,,W2   ;
W2    SELECT,ASM/HIGH(1),,,PK2B,IB2B,IBS2;
```

```
      ACTIVITY(1),,,G21;
;
GR2   GOON,1;
      ACTIVITY,,XX(1).NE.2,IB2A;
      ACTIVITY,,XX(1).EQ.2,IB2B;
IB2A  QUEUE(54),1,,,ZAAC ;
IB2B  QUEUE(8),1,,,W2    ;
;
IBS2  QUEUE(9),1,,,W2    ;
;
CRA   CREATE,40,,,12,1;
      ACTIVITY;
IBA   QUEUE(33),1,,,ZAAD ;
ZAAD  SELECT,ASM/HIGH(1),,,IBA ,QS1 ,IBB ;
      ACTIVITY(1)/53,XX(18),,;PRODUCTION 1C1;
ZAAF  QUEUE(36),1,,;
      ACTIVITY(1)/55,XX(19),,;PRODUCTION 2C1;
      QUEUE(37),1,,;
      ACTIVITY(1)/56,XX(20),,;PRODUCTION 3C1;
      QUEUE(38),1,,;
      ACTIVITY(1)/57,XX(21),,;PRODUCTION 4C1;
      QUEUE(39),1,,;
      ACTIVITY(1)/58,XX(22),,;PRODUCTION 5C1;
OC1   QUEUE(40),1,,;
      ACTIVITY(1);
      GOON,2;
      ACTIVITY,,,IBS1;
      ACTIVITY,,,IBS2;
;
;STAGE THREE
;
CRB   CREATE,40,,,12,1;
      ACTIVITY;
IBB   QUEUE(34),1,,,ZAAD ;
;
;PRODUCTION
;
;SETUP
;
CRC1  CREATE,40,,,12,1;
      ACTIVITY,,XX(1).LE.1;
      ACTIVITY,,XX(1).EQ.2,QS2;
      ACTIVITY,,XX(1).GT.2,ZAAG;
QS1   QUEUE(31),,,,ZAAD ;
QS2   QUEUE(32),,,,ZAAE ;
ZAAE  SELECT,ASM/HIGH(1),,,QS2 ,IBC ;
      ACTIVITY(1)/54,XX(18),,ZAAF;PRODUCTTION 1C1;
ZAAG  TERMINATE;
;
GK3   GOON,1;
      ACTIVITY,,XX(1).NE.3,PK3A;
```

```
         ACTIVITY,,XX(1).EQ.3,PK3B;
PK3A     QUEUE(55),,,,ZAAH ;
ZAAH     SELECT,ASM/HIGH(1),,,PK3A,IB3A;
         ACTIVITY(1);
G31      GOON,2;
         ACTIVITY/16,,,WK2;WITHADRAWAL KANBAN;
         ACTIVITY,,,UN31;
WK2      QUEUE(12),,,,S22  ;
UN31     UNBATCH,3;
         ACTIVITY;
AW3      AWAIT(16),MACHINE3;
         ACTIVITY/17,XX(12),XX(1).NE.ATRIB(2),;SETUP3;
         ACTIVITY/18,,XX(1).EQ.ATRIB(2);
G32      GOON;
         ACTIVITY/19,XX(15),,;PRODUCTION3;
AS31     ASSIGN,XX(1)=ATRIB(2);
         ACTIVITY;
FR31     FREE,MACHINE3;
         ACTIVITY;
BAT3     BATCH,1,ATRIB(3);
         ACTIVITY;
OB3      QUEUE(17),1,,,S32  ;
S32      SELECT,ASM/HIGH(1),,,OB3 ,WK3 ;
         ACTIVITY(1);
G33      GOON;
         ACTIVITY/20,,,GK3;PRODUCTION KANBAN;
         ACTIVITY/21,,,GR4;
PK3B     QUEUE(13),,,,W3   ;
W3       SELECT,ASM/HIGH(1),,,PK3B,IB3B,IBS3;
         ACTIVITY(1),,,G31;
;
GR3      GOON,1;
         ACTIVITY,,XX(1).NE.3,IB3A;
         ACTIVITY,,XX(1).EQ.3,IB3B;
IB3A     QUEUE(56),1,,,ZAAH ;
IB3B     QUEUE(14),1,,,W3   ;
;
IBS3     QUEUE(15),1,,,W3   ;
;
CRC      CREATE,40,,,12,1;
         ACTIVITY;
         ACCUMULATE,2,2;
         ACTIVITY;
IBC      QUEUE(35),1,,,ZAAE ;
;
;STAGE FOUR
;
CRD      CREATE,40,,,12,1;
         ACTIVITY;
         ACCUMULATE,2,2;
         ACTIVITY,XX(12);
```

```
IBD     QUEUE(43),1,,,ZAAI ;
ZAAI    SELECT,ASM/HIGH(1),,,IBD ,QS3 ;
        ACTIVITY(1)/65,XX(23),,;PRODUCTION 1C2;
ZAAL    QUEUE(45),1,,;
        ACTIVITY(1)/68,XX(24),,;PRODUCTION 2C2;
        QUEUE(46),1,,;
        ACTIVITY(1)/69,XX(25),,;PRODUCTION 3C2;
        QUEUE(47),1,,;
        ACTIVITY(1)/70,XX(26),,;PRODUCTION 4C2;
        QUEUE(48),1,,;
        ACTIVITY(1)/71,XX(27),,;PRODUCTION 5C2;
        QUEUE(49),1,,;
        ACTIVITY(1);
        GOON,2;
        ACTIVITY,,,IBS3;
        ACTIVITY,,,IBS4;
;
GK4     GOON,1;
        ACTIVITY,,XX(1).NE.4,PK4A;
        ACTIVITY,,XX(1).EQ.4,PK4B;
PK4A    QUEUE(57),,,,ZAAJ ;
ZAAJ    SELECT,ASM/HIGH(1),,,PK4A,IB4A;
        ACTIVITY(1);
G41     GOON,2;
        ACTIVITY/24,,,WK3;WITHADRAWAL KANBAN;
        ACTIVITY,,,UN41;
WK3     QUEUE(18),,,,S32   ;
UN41    UNBATCH,3;
        ACTIVITY;
AW4     AWAIT(22),MACHINE4,,1;
        ACTIVITY/25,XX(12),XX(1).NE.ATRIB(2),;SETUP4;
        ACTIVITY/26,,XX(1).EQ.ATRIB(2);
G6      GOON;
        ACTIVITY/27,XX(14),,;PRODUCTION4;
AS41    ASSIGN,XX(1)=ATRIB(2);
        ACTIVITY;
FR41    FREE,MACHINE4;
        ACTIVITY;
BAT4    BATCH,1,ATRIB(3);
        ACTIVITY;
OB4     QUEUE(23),1,,,S42   ;
S42     SELECT,ASM/HIGH(1),,,OB4 ,WK4 ;
        ACTIVITY(1);
G43     GOON;
        ACTIVITY/28,,,GK4;PRODUCTION KANBAN;
        ACTIVITY/29,,,IB5;
PK4B    QUEUE(19),,,,W4    ;
W4      SELECT,ASM/HIGH(1),,,PK4B,IB4B,IBS4;
        ACTIVITY(1),,,G41;
;
;SETUP
```

```
;
;PRODUCTION
;
GR4     GOON,1;
        ACTIVITY,,XX(1).NE.4,IB4A;
        ACTIVITY,,XX(1).EQ.4,IB4B;
IB4A    QUEUE(58),1,,,ZAAJ ;
IB4B    QUEUE(20),1,,,W4    ;
;
CRC2    CREATE,40,,,12,1;
        ACTIVITY,,XX(1).EQ.3;
        ACTIVITY,,XX(1).EQ.4,QS4;
        ACTIVITY,,XX(1).GT.4,ZAAM;
QS3     QUEUE(41),,,,ZAAI ;
QS4     QUEUE(42),,,,ZAAK ;
ZAAK    SELECT,ASM/HIGH(1),,,QS4 ,IBE ;
        ACTIVITY(1)/66,XX(23),,ZAAL;PRODUCTION 1C2;
ZAAM    TERMINATE;
;
IBS4    QUEUE(21),1,,,W4    ;
;
;the updated one
;
CRE     CREATE,40,,,12,1;
        ACTIVITY;
        ACCUMULATE,2,2;
        ACTIVITY;
IBE     QUEUE(44),1,,,ZAAK ;
;
;stage five
;
PK5     QUEUE(25),,,,W5    ;
W5      SELECT,ASM/HIGH(1),,,PK5 ,IB5 ;
        ACTIVITY(1);
G51     GOON,2;
        ACTIVITY/32,,,WK4;WITHDRAWAL KANBAN;
        ACTIVITY,,,UN51;
WK4     QUEUE(24),,,,S42   ;
UN51    UNBATCH,3;
        ACTIVITY;
AW5     AWAIT(27),MACHINE5,,1;
        ACTIVITY/33,XX(12),XX(1).NE.ATRIB(2),;SETUP5;
        ACTIVITY/34,,XX(1).EQ.ATRIB(2);
        GOON;
        ACTIVITY/35,XX(13),,;PRODUCTION5;
AS51    ASSIGN,XX(1)=ATRIB(2);
        ACTIVITY;
FR51    FREE,MACHINE5;
        ACTIVITY;
BAT5    BATCH,1,ATRIB(3);
        ACTIVITY;
```

```
OB5    QUEUE(28),1,,,S52  ;
S52    SELECT,ASM/HIGH(1),,,OB5 ,QD  ;
       ACTIVITY(1);
G54    GOON;
       ACTIVITY/36,,,PK5;PRODUCTION KANBAN;
       ACTIVITY/37,,,CLC5;
CLC51  COLCT,INT(1),TIME IN SYSTEM;
       ACTIVITY/38;
       TERMINATE,500;
;
;SETUP
;
;PRODUCTION
;
IB5    QUEUE(26),1,,,W5   ;
;
;XX(1)=PART TYPE OF LAST ENTITY MACHINED
;
;ATRIB(2)=PART TYPE
;
CR1    CREATE,2.1,,1,230;
       ACTIVITY/40;
       ASSIGN,XX(12)=RNORM(.042,.0042),XX(13)=RNORM(2.1,.21),XX(14)=RNORM(2.
       .21),XX(15)=RNORM(2.1,.21),XX(16)=RNORM(2.1,.21),XX(17)=RNORM(2.1,.21
       18)=RNORM(40,4),XX(19)=RNORM(40,4),XX(20)=RNORM(40,4);
       ACTIVITY/41;
       ASSIGN,XX(21)=RNORM(40,4),XX(22)=RNORM(40,4),XX(23)=RNORM(40,4),XX(24
       RNORM(40,4),XX(25)=RNORM(40,4),XX(26)=RNORM(40,4),XX(27)=RNORM(40,4);
       ACTIVITY;
ZAAB   ASSIGN,XX(8)=NNACT(19)+NNQ(16)+NNQ(17)+NNQ(14)+NNQ(15)+NNQ(56),XX(9)=
       NNACT(27)+NNQ(22)+NNQ(23)+NNQ(20)+NNQ(21)+NNQ(58),XX(7)=NNACT(11)+NNQ
       NNQ(11)+NNQ(8)+NNQ(9)+NNQ(54),1;
       ACTIVITY;
ZAAO   ASSIGN,XX(30)=NNQ(33)+NNQ(34)+NNQ(35)+NNQ(36)+NNQ(37)+NNQ(38)+NNQ(39)
       40),XX(31)=NNACT(57)+NNACT(58)+NNACT(56)+NNACT(55)+NNACT(54)+NNACT(5
       ACTIVITY;
       ASSIGN,XX(10)=NNACT(35)+NNQ(27)+NNQ(28)+NNQ(26),XX(32)=NNQ(43)+NNQ(44
       NNQ(45)+NNQ(46)+NNQ(47)+NNQ(48)+NNQ(49),XX(33)=NNACT(66)+NNACT(67)+NN
       68)+NNACT(69)+NNACT(70)+NNACT(71);
       ACTIVITY;
AS2    ASSIGN,XX(2)=XX(2)+1,ATRIB(3)=20,XX(6)=NNQ(4)+NNQ(5)+NNACT(3)+NNQ(2)+
       3)+NNQ(52),XX(11)=XX(6)+XX(7)+XX(8)+XX(9)+XX(10)+XX(30)+XX(31)+XX(32
       33),ATRIB(2)=XX(1),1;
       ACTIVITY/42,,XX(2).GE.191.AND.XX(2).LE.231;
       ACTIVITY/43,,XX(2).GE.141.AND.XX(2).LT.191,P3;
       ACTIVITY/44,,XX(2).GE.81.AND.XX(2).LT.141,P2;
       ACTIVITY/45,,XX(2).LE.80,P1;
P4     ASSIGN,ATRIB(2)=4;
       ACTIVITY/46;
BAT6   BATCH,1,ATRIB(3);
       ACTIVITY/50;
QD     QUEUE(29),,,,S52  ;
P3     ASSIGN,ATRIB(2)=3;
       ACTIVITY/47,,,BAT6;
```

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P2      ASSIGN,ATRIB(2)=2;
        ACTIVITY/48,,,BAT6;
P1      ASSIGN,ATRIB(2)=1;
        ACTIVITY/49,,,BAT6;
;
;preventive maintenance
;
        CREATE,480,240,,1;
        ACTIVITY;
        ALTER,MACHINE1,-1;
        ACTIVITY,15;
        ALTER,MACHINE1,+1;
        ACTIVITY;
        GOON;
        ACTIVITY;
        ALTER,MACHINE2,-1;
        ACTIVITY,15;
        ALTER,MACHINE2,+1;
        ACTIVITY;
        GOON;
        ACTIVITY;
        ALTER,MACHINE3,-1;
        ACTIVITY,15;
        ALTER,MACHINE3,+1;
        ACTIVITY;
        GOON;
        ACTIVITY;
        ALTER,MACHINE4,-1;
        ACTIVITY,15;
        ALTER,MACHINE4,+1;
        ACTIVITY;
        GOON;
        ACTIVITY;
        ALTER,MACHINE5,-1;
        ACTIVITY,15;
        ALTER,MACHINE5,+1;
        ACTIVITY;
        TERMINATE;
        END;
TIMST,XX(6),WIP1;
TIMST,XX(7),WIP2;
TIMST,XX(8),WP3;
TIMST,XX(9),WP4;
TIMST,XX(10),WP5;
TIMST,XX(30),WPC1;
TIMST,XX(31),WPC1;
TIMST,XX(32),WPC2;
TIMST,XX(33),WPC2;
TIMST,XX(11),WPT;
FIN;
```

APPENDICES 2a-2g
RESULTS of the Main Effects

Appendix 2a
Work-in-Process-Inventory

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.042,.004)

Kanbans	Containers 5	10	15	20
1	142.131	118.050	114.427	131.766
2	167.230	145.975	154.373	159.338
6	242.260	217.976	226.373	231.338
8	278.260	253.976	262.375	267.368

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.111,.011)

Kanbans	Containers 5	10	15	20
1	138.454	119.440	115.213	132.180
2	162.453	146.191	154.586	159.701
6	237.693	218.192	226.586	231.701
8	273.692	254.192	262.586	267.699

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.332,.032)

Kanbans	Containers 5	10	15	20
1	138.698	119.119	115.712	131.449
2	162.732	146.896	155.395	160.723
6	238.317	218.900	227.395	232.723
8	274.317	254.900	263.396	268.722

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.553,.055)

Kanbans	Containers 5	10	15	20
1	138.896	118.615	116.255	129.038
2	163.028	147.639	156.339	161.710
6	167.638	219.645	228.339	235.710
8	274.987	255.645	264.339	269.710

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.044,.004)

Kanbans	Containers 5	10	15	20
1	142.475	116.024	115.777	123.838
2	165.051	141.373	149.112	151.944
6	239.594	213.480	217.111	223.944
8	275.595	247.480	257.111	257.945

Appendix 2a contd.
Work-in-Process-Inventory

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.111,.011)

Kanbans	Containers 5	10	15	20
1	142.469	116.013	115.942	123.503
2	167.014	141.502	149.336	152.104
6	239.701	213.625	217.336	224.104
8	275.701	247.625	257.339	258.103

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.332,.033)

Kanbans	Containers 5	10	15	20
1	142.565	116.092	115.978	123.383
2	165.236	142.040	149.968	153.037
6	240.121	214.173	217.968	225.037
8	276.122	248.173	257.967	259.036

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.553,.055)

Kanbans	Containers 5	10	15	20
1	142.731	116.242	116.216	123.457
2	165.539	142.493	150.469	153.625
6	240.532	214.661	218.469	225.625
8	276.533	248.661	258.468	254.624

Processing time = EXPON(2.1)
Setup time = EXPON(.042)

Kanbans	Containers 5	10	15	20
1	147.611	110.626	109.700	101.448
2	166.523	128.431	132.508	118.895
6	238.534	200.318	206.422	190.902
8	268.534	230.318	236.422	226.902

Processing time = EXPON(2.21)
Setup time = EXPON(.105)

Kanbans	Containers 5	10	15	20
1	147.738	110.702	109.761	101.328
2	166.568	128.435	132.478	118.915
6	238.457	200.322	206.396	190.922
8	268.458	230.322	236.396	226.922

Appendix 2a Contd.
Work-in-process inventory

Processing time = EXPON(2.21)
Setup time = EXPON(.315)

Kanbans	Containers 5	10	15	20
1	147.734	110.412	109.642	101.547
2	166.551	128.225	132.447	119.028
6	238.365	200.200	206.443	191.031
3	268.336	230.200	276.443	227.031

Processing time = EXPON(2.21)
Setup time = EXPON(.525)

Kanbans	Containers 5	10	15	20
1	147.865	110.333	109.610	101.658
2	166.565	128.269	132.585	119.150
6	238.330	200.232	206.581	191.158
8	268.330	230.232	236.581	227.158

Appendix 2b
Overtime in minute
Per-6 months

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.042,.004)

	Containers 5	10	15	20
Kanbans				
1	6499.836	10327.953	15028.359	25144.172
2	6487.523	11890.844	16726.695	10225.703
6	6487.523	11890.844	16726.695	10225.703
8	6487.523	11890.844	16726.695	25265.102

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.111,.011)

	Containers 5	10	15	20
Kanbans				
1	4512.711	11881.719	16777.516	25265.102
2	3786.258	11887.797	16716.539	25265.102
6	3786.258	11887.797	16716.539	25265.102
8	3786.258	11887.797	16716.539	25265.102

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.332,.032)

	Containers 5	10	15	20
Kanbans				
1	4627.066	11864.852	16726.883	25265.102
2	3880.836	11891.227	16727.367	25265.102
6	3880.836	11891.227	16727.367	25265.102
8	3880.836	11891.227	16727.367	25265.102

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.553,.055)

	Containers 5	10	15	20
Kanbans				
1	4712.840	11869.625	16726.555	25265.102
2	3968.348	11887.219	16739.938	25265.102
6	53194.113	11887.219	16739.938	25265.102
8	3968.348	11887.219	16739.938	25265.102

Overtime in minute Appenix 2b contd.
Per-6 months contd

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.044,.004)

Kanbans	Containers 5	10	15	20
1	6767.664	11823.953	16687.688	25566.180
2	6483.180	11866.617	16654.500	25302.727
6	6492.805	11866.617	16654.500	25302.727
8	6492.805	11866.617	16654.500	25302.727

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.111,.011)

Kanbans	Containers 5	10	15	20
1	6786.555	11827.828	16719.422	25556.180
2	6492.641	11869.250	16659.609	25302.727
6	6496.266	11869.250	16659.609	25302.727
8	6496.266	11869.250	16659.609	25302.727

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.332,.033)

Kanbans	Containers 5	10	15	20
1	6812.891	11809.320	16757.312	25589.141
2	6486.078	18873.086	16643.867	25347.102
6	6490.680	18873.086	16643.867	25347.102
8	6490.680	18873.086	16643.867	25347.102

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.553,.055)

Kanbans	Containers 5	10	15	20
1	6874.344	11835.320	16752.688	25554.055
2	6493.242	11871.055	16638.297	25265.102
6	6482.688	11871.055	16638.297	25265.102
8	6482.688	11871.055	16638.297	25265.102

Overtime in minute Appendix 2b contd.
Per- 6 months contd

Processing time = EXPON(2.21)
Setup time = EXPON(.042)

Kanbans	Containers 5	10	15	20
1	21881.797	36053.031	45743.955	59866.718
2	23089.930	35986.008	45818.448	59866.718
6	22891.070	35984.664	45818.448	59866.718
8	22891.070	35984.664	45818.448	59866.718

Processing time = EXPON(2.21)
Setup time = EXPON(.105)

Kanbans	Containers 5	10	15	20
1	22020.383	35960.094	45743.599	59847.1875
2	23190.633	35962.711	45743.599	59847.1875
6	22785.672	35948.445	45743.599	59847.1875
8	22785.672	35948.445	45743.599	59847.1875

Processing time = EXPON(2.21)
Setup time = EXPON(.315)

Kanbans	Containers 5	10	15	20
1	22333.789	36387.406	45879.815	59732.774
2	23087.117	36220.227	45879.815	59782.774
6	22714.258	36200.133	45879.815	59782.774
8	22714.258	36200.133	45879.815	59782.774

Processing time = EXPON(2.21)
Setup time = EXPON(.525)

Kanbans	Containers 5	10	15	20
1	22418.242	36491.672	45921.074	59832.051
2	23072.633	36276.031	45921.074	59832.051
6	22701.078	36255.938	45921.074	59832.051
8	22701.078	36255.938	45921.074	59832.051

Appendix 2c
Average Utilization Assembly Line

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.042,.004)

Containers	5	10	15	20
Kanbans				
1	.904	.856	.782	.680
2	.90	.84	.77	.674
6	.90	.84	.77	.674
8	.90	.84	.77	.672

Processing time =RNORM(2.21,.21)
Setup time =RNORM(.111,.011)

Containers	5	10	15	20
Kanbans				
1	.93	.84	.77	.676
2	.94	.84	.77	.674
6	.94	.84	.77	.672
8	.94	.84	.77	.674

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.332,.032)

Containers	5	10	15	20
Kanbans				
1	.93	.84	.77	.68
2	.94	.84	.77	.68
6	.94	.84	.77	.68
8	.94	.84	.77	.68

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.553,.055)

Containers	5	10	15	20
Kanbans				
1	.932	.84	.77	.68
2	.94	.84	.77	.68
6	.91	.84	.77	.68
8	.94	.84	.77	.68

Processing time = RNORM(2.21.553)
Setup time = RNORM(.042.004))

Containers	5	10	15	20
Kanbans				
1	.875	.81	.742	.65
2	.872	.81	.74	.65
6	.872	.81	.74	.65
8	.872	.81	.74	.65

Average Utilization Assembly Line Appendix 2c contd

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.111,.011)

Kanbans	Containers 5	10	15	20
1	.874	.81	.742	.65
2	.902	.81	.74	.65
6	.872	.81	.74	.65
8	.872	.81	.74	.65

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.332,.033)

Kanbans	Containers 5	10	15	20
1	.876	.814	.742	.65
2	.878	.81	.742	.65
6	.878	.81	.742	.65
8	.878	.81	.742	.65

Procwssing time = RNORM(2.21,.553)
Setup time = RNORM(.553,.055)

Kanbans	Containers 5	10	15	20
1	.878	.814	.744	.65
2	.88	.812	.746	.65
6	.88	.812	.746	.65
8	.88	.812	.746	.65

Processing time = EXPON(2.21)
Setup time = EXPON(.042)

Kanbans	Containers 5	10	15	20
1	.468	.36	.296	.238
2	.462	.36	.29	.238
6	.462	.36	.29	.238
8	.462	.36	.29	.238

Processing time = EXPON(2.21)
Setup time = EXPON(.105)

Kanbans	Containers 5	10	15	20
1	.47	.362	.296	.238
2	.462	.36	.29	.238
6	.466	.36	.29	.238
8	.466	.36	.29	.238

Average Utilization Assembly Line contd Appendix 2c contd

Processing time = EXPON(2.21)
setup time = EXPON(.315)

Kanbans \ Containers	5	10	15	20
1	.47	.362	.288	.24
2	.464	.36	.294	.24
6	.468	.36	.294	.24
8	.468	.36	.294	.24

Processing time = EXPON(2.21)
Setup time = EXPON(.525)

Kanbans \ Containers	5	10	15	20
1	.472	.362	.298	.248
2	.464	.362	.296	.24
6	.47	.362	.294	.24
8	.47	.362	.296	.24

Appendix 2d
Average utilization
Cellular manufacturing one

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.042,004)

	Containers 5	10	15	20
Kanbana				
1	.688	.738	.7708	.7506
2	.6822	.7182	.7418	.7488
6	.6822	.7182	.7418	.7488
8	.6862	.7182	.7418	.7488

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.111,.011)

	Containers 5	10	15	20
Kanbans				
1	.7364	.7494	.7094	.7212
2	.7536	.7494	.7094	.7212
6	.7112	.7502	.7362	.7494
8	.7112	.7502	.7362	.7494

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.332,.032)

	Containers 5	10	15	20
Kanbans				
1	.711	.7252	.758	.7494
2	.7102	.7182	.7362	.7494
6	.7102	.7182	.7362	.494
8	.7098	.7182	.7362	.7494

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.553,.055)

	Containers 5	10	15	20
Kanbans				
1	.7114	.7262	.763	.7494
2	.71	.7182	.7398	.7494
6	.6824	.7182	.7398	.7494
8	.71	.7182	.7398	.7494

Average utilization Appendix 2d contd.
Cellular manufacturing one

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.044,.004)

Kanbans	Containers 5	10	15	20
1	.6942	.737	.756	.7502
2	.6832	.721	.7334	.7494
6	.682	.7202	.7334	.7494
8	.682	.7202	.7334	.7494

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.111,.011)

Kanbans	Containers 5	10	15	20
1	.6952	.7374	.7572	.7502
2	.682	.7212	.7344	.7502
6	.6826	.7212	.7344	.7502
8	.6826	.7212	.7344	.7502

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.332,.033)

Kanbans	Containers 5	10	15	20
1	.6952	.7368	.7568	.7502
2	.6842	.7212	.7328	.7502
6	.6832	.7212	.7328	.7502
8	.6832	.7212	.7328	.7502

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.553,.055)

Kanbans	Containers 5	10	15	20
1	.6952	.7352	.7588	.7502
2	.6836	.7212	.7328	.7502
6	.6824	.7212	.7382	.7502
8	.6824	.7212	.7382	.7502

Processing time = EXPON(2.21)
Setup time = EXPON(.042)

Kanbans	Containers 5	10	15	20
1	.5302	.5272	.513	.5194
2	.4998	.5222	.5106	.519
6	.4964	.5208	.5106	.519
8	.4964	.5208	.5106	.519

Average utilization Appendix 2d contd.
Cellular manufacturing one

Processing time = EXPON(2.21)
Setup time = EXPON(.105)

	Containers 5	10	15	20
Kanbans				
1	.5296	.5282	.513	.5194
2	.5	.523	.5106	.519
6	.4984	.5224	.4724	.519
8	.498	.522	.4724	.519

Processing time = EXPON(2.21)
Setup time = EXPON(.315)

	Containers 5	10	15	20
Kanbans				
1	.5266	.5262	.5136	.5198
2	.5	.5222	.5106	.519
6	.5	.522	.51	.519
8	.5	.522	.51	.519

Processing time = EXPON(2.21)
Setup time = EXPON(.525)

	Containers 5	10	15	20
Kanbans				
1	.5276	.526	.5136	.5198
2	.5012	.5212	.5106	.519
6	.5006	.5212	.51	.519
8	.5006	.5212	.51	.519

Appendid 2e
Average Utilization
Cellular Manufacturing Two

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.042,.004)

Containers	5	10	15	20
Kanbans				
1	.3654	.347	.3348	.3143
2	.3716	.397	.423	.407
6	.3713	.397	.423	.407
8	.3716	.397	.423	.407

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.111,.011)

Containers	5	10	15	20
Kanbans				
1	.08	.394	.4004	.4076
2	.081	.3972	.4234	.4072
6	.081	.397	.423	.407
8	.081	.397	.423	.407

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.332,.032)

Containers	5	10	15	20
Kanbans				
1	.80	.3906	.4012	.4076
2	.081	.3974	.4232	.4076
6	.081	.397	.4232	.4076
8	.08	.397	.4232	.4076

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.553,.055)

Containers	5	10	15	20
Kanbans				
1	.0798	.3786	.3964	.4076
2	.0808	.397	.4192	.4076
6	.08	.397	.4192	.4076
8	.0806	.397	.4192	.4076

Average Utilization Appendix 2e contd
Cellular Manufacturing two contd

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.044,.004)

Kanbans	Containers 5	10	15	20
1	.3552	.379	.3920	.4138
2	.3712	.3952	.4272	.4066
6	.3722	.3952	.4272	.4066
8	.372	.395	.4112	.4066

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.111,.011)

Kanbans	Containers 5	10	15	20
1	.354	.379	.402	.4026
2	.371	.3938	.4262	.4078
6	.3714	.3938	.4262	.4078
8	.3714	.3938	.4262	.4078

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.332,.033)

Kanbans	Containers 5	10	15	20
1	.3534	.3798	.4024	.402
2	.3698	.3946	.4276	.4064
6	.371	.3946	.4276	.4064
8	.371	.3946	.4276	.4064

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.553,.055)

Kanbans	Containers 5	10	15	20
1	.353	.3808	.3996	.4028
2	.3704	.38	.4226	.4076
6	.372	.38	.4226	.4076
8	.372	.38	.4226	.4076

Average Utilization Appendix 2e contd
Cellular Manufacturing two

Processing time = EXPON(2.21)
Setup time = EXPON(.042)

Kanbans	Containers 5	10	15	20
1	.279	.2856	.3222	.2944
2	.3046	.2942	.3106	.2956
6	.3094	.2958	.31	.2956
8	.3094	.2958	.31	.2956

Processing time = EXPON(2.21)
Setup time = EXPON(.105)

Kanbans	Containers 5	10	15	20
1	.2786	.2854	.32226	.2952
2	.3042	.2926	.3254	.2956
6	.3082	.2926	.325	.2956
8	.3082	.2926	.325	.2956

Processing time = EXPON(2.21)
Setup time = EXPON(.315)

Kanbans	Containers 5	10	15	20
1	.2812	.2862	.3206	.2852
2	.3044	.2908	.3254	.2956
6	.3078	.2918	.325	.2956
8	.3078	.2918	.325	.2956

Processing time = EXPON(2.21)
Setup time = EXPON(.525)

Kanbans	Containers 5	10	15	20
1	.279	.27661	.3206	.2938
2	.3044	.291	.3258	.2956
6	.3068	.2918	.325	.2956
8	.2896	.2918	.325	.2956

Appendix 2f
Shortage

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.042,.004)

Containers	5	10	15	20
Kanbans				
1	0	0	5	10
2	0	0	5	10
6	0	0	5	10
8	0	0	5	10

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.111,.011)

Containers	5	10	15	20
Kanbans				
1	0	0	5	10
2	0	0	5	10
6	0	0	5	10
8	0	0	5	10

Prossing time = RNORM(2.21,.21)
Setup time = RNORM(.332,.032)

Containers	5	10	15	20
Kanbans				
1	0	0	5	10
2	0	0	5	10
6	0	0	5	10
8	0	0	5	10

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.553,.055)

Containers	5	10	15	20
Kanbans				
1	0	0	5	10
2	0	0	5	10
6	0	0	5	10
8	0	0	5	10

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.044,.004)

Containers	5	10	15	20
Kanbans				
1	0	0	5	10
2	0	0	5	10
6	0	0	5	10
8	0	0	5	10

Appendix 2f contd

Shortage

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.111,.011)

Kanbans \ Containers	5	10	15	20
1	0	0	5	10
2	0	0	5	10
6	0	0	5	10
8	0	0	5	10

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.332,.033)

Kanbans \ Containers	5	10	15	20
1	0	0	5	10
2	0	0	5	10
6	0	0	5	10
8	0	0	5	10

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.553,.055)

Kanbans \ Containers	5	10	15	20
1	0	0	5	10
2	0	0	5	10
6	0	0	5	10
8	0	0	5	10

Processing time = EXPON(2.21)
Setup time = EXPON(.042)

Kanbans \ Containers	5	10	15	20
1	0	0	5	10
2	0	0	5	10
6	0	0	5	10
8	0	0	5	10

Processing time = EXPON(2.21)
Setup time = EXPON(.105)

Kanbans \ Containers	5	10	15	20
1	0	0	5	10
2	0	0	5	10
6	0	0	5	10
8	0	0	5	10

Shortage Appendix 2f contd

Processing time = EXPON(2.21)
Setup time = EXPON(.315)

Kanbans \ Containers	5	10	15	20
1	0	0	5	10
2	0	0	5	10
6	0	0	5	10
8	0	0	5	10

Processing time = EXPON(2.21)
Setup time = EXPON(.525)

Kanbans \ Containers	5	10	15	20
1	0	0	5	10
2	0	0	5	10
6	0	0	5	10
8	0	0	5	10

Average waiting time for Appendix 2g.
The last station

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.042,.004)

	Containers 5	10	15	20
Kanbans				
1	8.766	21.117	35.577	55.362
2	21.119	46.316	72.529	103.037
6	60.678	119.782	176.143	236.380
8	77.907	149.406	214.435	299.776

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.111,.011)

	Containers 5	10	15	20
Kanbans				
1	8.615	21.529	36.696	56.492
2	20.489	46.316	72.529	109.534
6	58.831	119.782	176143	251.283
8	75.536	149.400	214.435	299.776

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.332,.032)

	Containers 5	10	15	20
Kanbans				
1	7.920	21.835	36.791	55.328
2	19.717	46.316	72.529	109.534
6	58.849	119.782	176.143	251.283
8	75.559	149.406	214.435	299.776

Processing time = RNORM(2.21,.21)
Setup time = RNORM(.553,.055)

	Containers 5	10	15	20
Kanbans				
1	8.874	21.366	36.829	56.138
2	20.488	46.316	72.529	109.534
6	22.4	119.782	176.143	251.283
8	75.561	149.406	214.435	299.776

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.044,.004)

	Containers 5	10	15	20
Kanbans				
1	7.618	19.840	34.900	53.284
2	20.504	46.316	72.529	109.534
6	60.680	119.782	176.143	251.283
8	77.911	149.406	214.435	299.776

Average waiting time for Appendix 2g contd
The last station

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.111,.011)

Kanbans	Containers 5	10	15	20
1	7.517	20.698	34.846	51.847
2	21.226	46.316	71.888	109.534
6	60.680	119.782	174.585	251.283
8	77.911	149.406	212.539	299.776

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.332,.033)

Kanbans	Containers 5	10	15	20
1	7.841	19.381	33.937	51.884
2	20.401	46.316	71.888	109.534
6	60.680	119.782	174.585	251.283
8	77.911	149.406	212.539	299.776

Processing time = RNORM(2.21,.553)
Setup time = RNORM(.553,.055)

Kanbans	Containers 5	10	15	20
1	6.499	18.082	34.991	54.176
2	20.372	46.316	71.888	109.534
6	60.680	119.782	174.585	251.283
8	77.911	149.406	212.539	299.776

Processing time = EXPON(2.21)
Setup time = EXPON(.042)

Kanbans	Containers 5	10	15	20
1	14.641	30.161	77.580	130.445
2	29.483	54.855	148.468	240.822
6	81.645	172.184	360.565	552.474
8	104.828	214.767	438.949	659.092

Processing time = EXPON(2.21)
Setup time = EXPON(.105)

Kanbans	Containers 5	10	15	20
1	14.640	30.154	77.580	130.445
2	30.827	66.578	148.468	240.822
6	85.367	172.184	360.565	552.474
8	109.607	214.767	438.949	659.092

Average waiting time for Appendix 2g contd
The last station contd

Processing time = EXPON(2.21)
Setup time = EXPON(.315)

	Containers 5	10	15	20
Kanbans				
1	14.611	30.090	77.580	130.445
2	30.827	66.578	148.468	240.822
6	85.267	172.184	360.565	552.474
8	109.607	214.767	438.949	659.092

Processing time = EXPON(2.21)
Setup time = EXPON(.525)

	Containers 5	10	15	20
Kanbans				
1	14.651	30.018	77.580	130.445
2	29.483	66.578	148.468	240.822
6	81.645	172.184	360.565	552.474
8	104.828	214.767	438.949	659.092

Appendix 3a-3f
Results of the Two-way Interactions

Appendix 3a

Contaier & Setup time

Work-In-Process

	S1	S2	S3	S4
Cotainers				
5	206	205	205	199
10	177	177	177	177
15	182	182	185	183
20	182	182	183	183

Overtime

	S1	S2	S3	S4
Containers				
5	11912	11077	11116	15256
10	19786	19900	19998	20021
15	26270	26383	26426	26441
20	34316	36826	36818	36787

Average utilization assembly line

	S1	S2	S3	S4
Containers				
5	.75	.76	.76	.76
10	.67	.67	.67	.67
15	.60	.60	.60	.61
20	.52	.52	.52	.52

Average utilization cellular manufacturing one

	S1	S2	S3	S4
Containers				
5	.62	.64	.64	.63
10	.66	.67	.66	.66
15	.67	.68	.66	.67
20	.67	.67	.67	.67

Average utilization cellular manufacturing two

	S1	S2	S3	S4
Containers				
5	.35	.35	.35	.35
10	.36	.36	.36	.36
15	.38	.39	.39	.38
20	.36	.37	.37	.37

Appendix 3a contd.
Container and setup time

Shortage

Containers	S1	S2	S3	S4
5	0	0	5	10
10	0	0	5	10
15	0	0	5	10
20	0	0	5	10

Average holding time for the last station

Containers	S1	S2	S3	S4
5	47	46	47	43
10	95	96	96	96
15	168	168	168	168
20	249	251	251	251

Appendix 3b
Kanban and Setup time

Work in process

	S1	S2	S3	S4
Kanban				
1	122.4	123.66	123.17	112.34
2	148.167	147.99	148.167	148.5
6	202.333	220.81	220.81	215.99
8	255.6	255.166	256.11	255.89

Overtime

	S1	S2	S3	S4
Kanban				
1	22198.9	23575.46	23652.5	23687.98
2	22538.44	14859.16	23589.916	23602.79
6	22522.75	23525.98	23589.916	27671.41
8	22249	23525.98	23589.916	23568.25

Average utilization assembly line

	S1	S2	S3	S4
Kanban				
1	.64	.64	.64	.64
2	.63	.64	.64	.64
6	.63	.64	.64	.64
8	.63	.64	.64	.64

Average utilization cellular manufacturing one

	S1	S2	S3	S4
Kanban				
1	.665	.662	.664	.665
2	.653	.66	.655	.655
6	.652	.66	.655	.655
8	.652	.66	.655	.655

Average utilization cellular manufacturing two

	S1	S2	S3	S4
Kanban				
1	.34	.33	.333	.331
2	.37	.344	.344	.342
6	.37	.344	.344	.342
8	.37	.344	.344	.342

Appendix 3b contd.
Kanban and Setup time

Shortage

Kanban	S1	S2	S3	S4
1	3.75	3.75	3.75	3.75
2	3.75	3.75	3.75	3.75
6	3.75	3.75	3.75	3.75
8	3.75	3.75	3.75	3.75

Average holding time for the last station

Kanban	S1	S2	S3	S4
1	41	40	41	40
2	81	82	81	81
6	197	198	198	197
8	242	242	242	242

Appendix 3c
Process time and setup time

Work in process

Setup time	P1	P2	P3
S1	195.125	190	175.44
S2	193.9	191	175
S3	203	190.31	175
S4	215	190	175

Overtime

Setup time	P1	P2	P3
S1	13002	15111	38849
S2	14462	15116	41060
S3	14486	14015	20585
S4	14134	15111	20610

Average utilization assembly line

Setup time	P1	P2	P3
S1	.80	.77	.35
S2	.81	.77	.35
S3	.81	.77	.35
S4	.81	.77	.35

Average utilization cellular manufacturing one

Setup time	P1	P2	P3
S1	.727	.725	.514
S2	.734	.725	.514
S3	.730	.725	.514
S4	.725	.725	.514

Average utilization cellular manufacturing two

Setup time	P1	P2	P3
S1	.385	.393	.30
S2	.326	.396	.303
S3	.325	.396	.302
S4	.324	.393	.302

Appendix3c contd.
Process time and setup time

Shortage

Setup time	P1	P2	P3
S1	3.75	3.75	3.75
S2	3.75	3.75	3.75
S3	3.75	3.75	3.75
S4	3.75	3.75	3.75

Average holding time for the last station

Setup time	P1	P2	P3
S1	106	106	209
S2	107	106	209
S3	107	107	209
S4	105	107	209

Appendix 3d
Kanban and processing time

Work in Process

Kanban	P1	P2	P3
1	126.215	124.558	177.358
2	156.519	152.490	136.612
6	225.049	224.093	209.038
8	248.717	260.096	243.224

Overtime

Kanban	P1	P2	P3
1	14530.31	15232.38	35022.53
2	13662.75	14935.63	41226.69
6	13662.75	14935.63	41039.19
8	13662.75	14935.63	41039.19

Average utilization assenbly line

Kanban	P1	P2	P3
1	.805	.77	.342
2	.804	.771	.34
6	.804	.771	.34
8	.804	.77	.34

Average utilization cellular manufacturing one

Kanban	P1	P2	P3
1	.735	.735	.522
2	.7285	.732	.513
6	.728	.73	.51
8	.728	.73	.51

Average utilization cellular manufacturing two

Kanban	P1	P2	P3
1	.324	.384	.294
2	.345	.4	.304
6	.34	.4	.304
8	.34	.4	.304

Appendix 3d contd.
Kanban and Process time

Shortage

Kanban	P1	P2	P3
1	3.75	3.75	3.75
2	3.75	3.75	3.75
6	3.75	3.75	3.75
8	3.75	3.75	3.75

Average holding time for the last station

Kanban	P1	P2	P3
1	30	29	63
2	62	62	120
6	149	151	292
8	185	185	354

Appendix e
Container and Processing time

Work in process

Container	P1	P2	P3
5	200	206	205
10	184	180	167
15	190	185	170
20	198	190	159

Overtime

Container	P1	P2	P3
5	7748	6570	22705
10	11,789	11859	29,078
15	16,625	15732	45847
20	23,378	25370	59831

Average utilization assembly line

Container	P1	P2	P3
5	.93	.88	.47
10	.84	.81	.36
15	.77	.74	.29
20	.68	.65	.24

Average utilization cellular manufacturing one

Container	P1	P2	P3
5	.71	.71	.50
10	.73	.73	.52
15	.74	.74	.52
20	.75	.75	.52

Appendix 3e contd

Average utilization cellular manufacturing two

Container	P1	P2	P3
5	.39	.37	.30
10	.393	.39	.29
15	.413	.42	.30
20	.352	.41	.30

Shortage

Container	P1	P2	P3
5	0	0	5
10	0	0	0
15	5	5	5
20	10	10	10

Average holding time for the last station

Container	P1	P2	P3
5	39	42	58
10	84	84	118
15	125	125	256
20	178	178	396

Appendix f
Kanban and Container

Work in process

Kanban	5	10	15	20
1	143.281	115.139	113.686	118.682
2	165.374	138.956	145.799	144.015
6	233.295	192.794	217.118	196.875
8	272.171	244.310	255.785	251.352

Overtime

Kanban	5	10	15	20
1	11354.009	19844.817	26288.769	36877.814
2	11376.55	19956.841	26405.842	35130.58
6	15366.83	19951.75	26410.25	35546.917
8	9060.75	17236.75	26410.25	35346.917

Average utilization assembly line

Kanban	5	10	15	20
1	.757	.673	.603	.523
2	.759	.67	.602	.522
6	.755	.67	.602	.522
8	.757	.670	.6015	.522

Average utilization cellular manufacturing one

Kanban	5	10	15	20
1	.645	.666	.631	.611
2	.6325	.656	.659	.67
6	.624	.656	.658	.673
8	.628	.656	.658	.673

Average utilization cellular manufacturing two

Kanban	5	10	15	20
1	.262	.347	.367	.361
2	.276	.36	.39	.37
6	.271	.36	.39	.37
8	.277	.327	.389	.37

Appendix f contd.
Kanban and Container

Shortage

Kanban	5	10	15	20
1	5	0	5	10
2	0	0	5	10
6	0	0	5	10
8	0	0	5	10

Average holding time for the last station

Kanban	5	10	15	20
1	10	23	50	80
2	24	52	85	153
6	65	137	237	350
8	87	171	270	420