DESIGN AND ANALYSIS OF JUST-IN-TIME PRODUCTION SYSTEMS

A THESIS
SUBMITTED TO THE DEPARTMENT OF INDUSTRIAL ENGINEERING
AND THE INSTITUTE OF ENGINEERING AND SCIENCES
OF BILKENT UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

By
Ceyda Oğuz
October, 1988

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

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

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ABSTRACT

DESIGN AND ANALYSIS OF JUST-IN-TIME PRODUCTION SYSTEMS

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M.S. in Industrial Engineering
Supervisor: Asst. Prof. Cemal Dinçer
October, 1988

Just-in-Time (JIT) production systems have initially appeared in the Japanese manufacturing environment due to the scarcity of their critical resources. The main aim in JIT production systems is to eliminate waste. To achieve this objective, setup times, lead times, in-process inventories, and defective production must all be minimized. In the design process of a JIT production system, several factors such as lot size, number of kanbans, unit load size, and buffer capacities must be taken into account. In this study, a mathematical model is developed for a single-item, single-line, multi-stage, and multi-period JIT production system. The original model is nonlinear in both objective function and constraints. To reduce the computational difficulties, the nonlinear model is then approximated by a linear model. Next, a simulation model is developed to incorporate the stochastic nature of the demand. A sensitivity analysis is performed on unit load size and on buffer capacity under different demand patterns to examine their effects on the behavior of the model. The results show that those unit load size values exceeding 10 percent of the maximum demand in the planning horizon have no effect on the model.

Keywords: Just-in-Time Production Systems, Kanban Systems, Pull Systems, Unit Load Size.

ÖZET

TAM-ZAMANINDA ÜRETİM SİSTEMLERİNİN TASARIMI VE ANALİZİ

Ceyda Oğuz
Endüstri Mühendisliği Bölümü Yüksek Lisans
Tez Yöneticisi: Y. Doç. Cemal Dinçer
Ekim, 1988

Tam-Zamanında üretim sistemleri ilk olarak kritik kaynakların kısıtlı olduğu Japon üretim sistemlerinde belirmiştir. Tam-Zamanında üretim sistemlerinde, ana amaç tüm kaynakların her türlü boşa harcanımını azaltmaktır. Bu amaca ulaşabilmek için makina hazırlama zamanları, önsüreler, ara envanterler ve hatalı üretim enazlanmalıdır. Tam-Zamanında üretim sistemlerinin tasarımında öbek büyüklüğü, kanban sayısı, birim yük büyüklüğü ve ara stok kapasiteleri incelenmelidir. Bu çalışmada, tek ürünlü, tek hatlı, çok aşamalı ve çok dönemli Tam-Zamanında üretim sistemleri için bir matematiksel model geliştirilmiştir. Bu modelde hem amaç fonksiyonu hem de kısıtlar doğrusal değildir. Hesaplama zorluklarını azaltmak için bu model doğrusal bir modele indirgenmiştir. Daha sonra talebin stokastik olduğu durumu göz önüne alarak bir benzetim modeli geliştirilmiştir. Son olarak değişik talep yapıları altında birim yük büyüklüğü ve ara stok kapasitelerinin modelin davranışı üzerine etkilerini görmek için, duyarlılık analizleri yapılmıştır. Sonuçlar planlama ufkundaki en büyük talebin yüzde 10'unu aşan birim yük büyüklüğü değerlerinin model üzerine bir etkisi olmadığını göstermiştir.

Anahtar kelimeler : Tam-Zamanında Üretim Sistemleri, Kanban Sistemleri, Çekme Sistemleri, Birim Yük Büyüklüğü.

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1. INTRODUCTION

Production-inventory systems are concerned with the effective management of the total flow of goods which embraces the raw materials, purchased parts, semifinished goods, tools and other materials that are an integral part of the production process. The management of the flow of goods includes the planning, coordination and control of the procurement of goods, the production of raw materials, purchased parts, and semifinished goods, the process as to bring them into finished products and the delivery of finished products to satisfy the customer demand.

The effective management of the total flow of goods means the delivery of the finished products in appropriate quantities, to the required place, at the desired time and quality, and at a reasonable cost. This forms the ultimate goal of a production-inventory system. In achieving this ultimate goal of the production-inventory system three important criteria are throughput, inventory and operating expenses [12]. Throughout the time, many philosophies evolved against these criteria regarding different production-inventory systems. To name, Re-order Point (ROP), Material Requirements Planning (MRP), and Just-in-Time (JIT) are a few.

Production-inventory systems can be grouped as **push** and **pull** systems. The two systems can be analyzed and compared with each other from two aspects: information processing potential and shop floor control features.

Push systems highly depend on the computer capabilities for the information processing due to the complex and huge data processed. Regarding this property, push systems become expensive compared to pull systems.

On the shop floor, the production is realized by the forecast demand in push systems. Production takes place according to a schedule. Furthermore, the items are sent to the next stage as soon as their production is completed in a stage.

Long setup time is the main characteristic of the push systems in which production efficiency is measured by the in-process inventories accumulated between production stages as buffers. Due to long setup times, production runs are long and therefore, the system ends up with long lead times. Besides, vendor lead times are long. But long lead times affect the accuracy of forecast adversely. Since forecast regulates the production in push systems, the accuracy of demand forecast affects the decisions to a great extent.

Due to the possible input of the inaccurate and/or incorrect data to the system, shop floor can deviate from the plans and system may be nervous. In order to compensate for the nervousness of the system, some safety stocks are needed.

Safety stocks are also held in order to prevent the production system from stopping due to machine breakdowns, poor quality products, and late material deliveries, in short to handle uncertainties of the system. This causes high level of inventories and makes it difficult to change product lines. So they affect flexibility of the production line together with unnecessarily high carrying costs. Large safety stocks cause the production to start earlier than necessary and results with increased lead times together with early consumption of resources and priority distortions [15].

In summary, push systems are superior to other systems if manufacturing is complex, items are common to most end items, and there exists dependent demand.

Material Requirements Planning (MRP) is the concept that reflects the characteristics of push systems. MRP has been started to replace the order-point-based production during the 1960's. Main reasons for wide use of MRP were the vast varieties and types of products that have been arisen and the increasing power of computers together with their low costs in those days [12]. Throughout the years, it is well established with its use by different companies while trying to find the most successful MRP implementation. Experience shows that the master production schedule is the most critical part in MRP, since MRP is a planning process in which the demands of the dependent items are calculated from the items whose demands are independent and master production schedule is the statement of the future demand for independent items [28].

Schonberger [38] states that MRP is a lot-oriented inventory system which has a medium tight degree of inventory control. The role of the computer is essential and it finds common applications in environments such as job-lot manufacturing with large product variety and highly competitive market.

MRP starts with a master production schedule for end items. Then by using master production schedule, Bill-of-Material and Inventory Status Records, it determines the net requirements by time-phasing. After offseting lead times, it generates planned orders. Then, those are pushed to the shop floor. The parts are pushed from raw materials to finished products according to the detailed schedule. So, the push system is a schedule-based system. When periods are short and lot for lot mechanism is used MRP approaches to Just-in-Time philosophy which characterizes pull systems.

The execution of MRP at the shop floor is not powerful due to the unreliable and unstable production processes and invalid schedules. The remedy for these problems is to create allowances for scrap. But, this solution results with the unnecessary inventories, increased lead times, and consumption of scarce resources. Furthermore, MRP ignores the aggregation in capacity and grouping and/or sequencing of products in the Bill-of-Material [29].

In MRP, the basic logic is to schedule lots by exploding, time-phasing, and sizing the requirements. As an extension of this logic, as the lot sizes increase, the throughput time and lead time of that lot will increase resulting with an increase of the throughput of all lots if setup time for that lot is significant. So, in order to achieve a smooth flow and maintain the total throughput, non-productive setup time must be reduced to a minimum.

Reduction of lot size may not be sensible in many job-shop or make-to-order environments, but it makes sense in most repetitive/ flowshop environments. MRP may lose its applicability in repetitive environments in scheduling individual lots since decreasing lot size means an increase in the number of lots. On the other hand, if demand is stable, best benefits can be obtained by adjusting the time slots in an MRP environment. The learning effect will result in best estimates for lead times and hence better lot sizing procedures. The more complex the product structure of the products to be scheduled, the more applicable MRP is.

In MRP, demand management step is required and master production schedule must be linked to a Capacity Requirements Planning (CRP) routine to synchronize the operations to the load placed on manufacturing. Capacity profiles not only take care of the product mix but also account for time-phasing. However, MRP only puts emphasis on the planning aspect. But a control on the actual performance with the planned one is also necessary. The material and capacity availability and feasibility has to be checked.

Manufacturing Resource Planning (MRP II) is developed in order to eliminate this handicap of MRP by connecting material requirements to capacity requirements and financial planning.

Pull systems have been arisen because of the complexity of the push systems. This system has attracted much attention from manufacturers because it permits to simplify the system instead of designing production control tools for a complex production system. Pull systems concentrate especially on the production environment because the simpler it is, the easier it can be controled.

On the shop floor, the production takes place according to orders which are initiated by the users of the parts not by some central planning source. In other words, the production is controled by the succeeding stage. A stage does not receive a schedule or a dispatch list as in the push systems. Another point in the shop floor activities is the movement of produced parts. In pull systems, units wait at the stage in which they are produced until they are required.

Pull systems have been designed to minimize the level and fluctuations of in-process inventory in order to simplify inventory controls, to prevent amplified transmission of demand fluctuations from one stage to the other, and to raise the level of shop control through decentralization [32].

Pull system is the mechanism of **Just-in-Time (JIT)** philosophy. JIT philosophy as defined by Monden [24] is "to produce the necessary units in the necessary quantity to the right location in the right quality at the necessary time". That is, in a manufacturing system, each stage produces "just-in-time" to meet the demand needed by succeeding stages, which is ultimately controled by the final product demand. The efficiency of the pull system is often measured in terms of the number of containers of goods produced and stored at each stage. In the ideal pull system, in-process inventory at each stage is one unit.

The main objective of the JIT production system is to eliminate all sources of waste. Waste is defined as anything that does not add value to the product [10]. Consequently, inventory and scrap in production are considered as major waste items. This objective leads to the concept of stockless production with an ideal case of having a lot size of one unit. But this may not be realistic because of the existing setup times. So, in order to achieve the objective of JIT production system, the requirement is to have minimum setup times together with minimum lead times which brings smaller lot sizes. These all affect the production decisions such as the amount produced and inventory levels.

After this aim is attained, the system will have minimum buffer stocks between stages and at each stage total setup times will reduce to a minimum. Having minimum buffer stocks forces the system for the defect free production to have a continuous production. Such a system also must have minimum breakdown in machines. Consequently, there will be a reliable production. When production rate changes, the containers are added and removed. Safety stock is included but in general it is limited to 10 percent of the daily demand [24].

Other benefits of the JIT system are minimum inventory investment, shorter production lead times, and faster reaction to demand changes. A smooth flow in production is achieved by synchronizing the stations and also changing the product mix after fulfilling the above goals of JIT production system. But this requires flexible machines and multifunctional workers. By this way the loads can be leveled easily. As a result JIT production system requires technological adjustments and organizational changes.

If scheduling and execution are demand driven then this is a pull system. But if throughput times are long in manufacturing or vendor lead times are long then at some stages push system is required in the manufacturing process in order to maintain responsiveness to customer demand. Push scheduling and execution may also be necessary to insure the best allocation and utilization of critical resources.

JIT production systems using pull system as its mechanism start with the design of a detailed assembly schedule for end products. The critical point for the effectiveness of JIT production system is the mix of products in detailed assembly schedule. A continuous flow of production can be achieved only when the correct mix of products is obtained. Once this schedule is determined, it is frozen for a period. Then period to period variations in this schedule are allowed to occur only gradually. This results with repetitive and smooth production loads due to small lots in mixed-model assembly.

For the capacity aspect, the final assembly sequence is the key issue in JIT production systems. This sequence has to be rarely changed in order to have a repetitive and smooth production, but product mix may change. Since there will be less variation in the sequence, this stable sequence results with high capacity utilization. Consequently a rigid system is the output of a JIT production system. But as explained above, in order to achieve this rigid system, the flexibility of the system by flexible working hours and multifunctional workers is a must. Flexible labor results with high degree of job security. Multifunctional workers can help to any worker who has problem when the system is halted. Also they replace other workers in case of absenteeism.

Once the detailed assembly schedule is established, the shop floor activities are performed completely on a manual basis using **Kanban System** which is the information processing system of the JIT philosophy. When parts are needed at assembly, they are withdrawn from the preceding stage. Then that stage begins its production in order to replenish the withdrawn amount to be ready for next order from the assembly. It also withdraws parts for its production from its preceding stage and this procedure repeats itself in the entire production system down to the raw materials. The parts are pulled through the production process by actual events. If production stops at an assembly work station, no parts are consumed and no parts are manufactured. In such a system each stage is closely linked to its succeeding and preceding stages. Whenever one of the stages stops for any reason, all system will come to a halt.

Shop floor control in the short term in JIT production system is the most crucial point. So, since in short term capacity is fixed, a JIT approach can easily be used. But in medium term, since a flexible capacity is required, to balance loads and to generate orders for non-repetitive work MRP can be used.

JIT philosophy can be used as a productivity improvement system as well as a material flow and production control system as explained above. The main point is to recognize and resolve the bottleneck operation in the system in improving productivity.

Whenever the system is in balance, some of the inventories are withdrawn until a bottleneck operation is encountered. A balanced system is defined as to have no shortage and overtime in the system in the context of JIT philosophy. A bottleneck operation is the one that cannot produce the required amount for its succeeding stage or having large amounts of overtime. In order to have a balanced system again, this problem has to be solved. If it is due to manpower, extra workers are cross trained to support the workforce. If the problem is caused by a machine, the capacity increase options are sought. This brings either setup time reduction or preventive maintenance improvements. The problem can arise because of the lack of quality. In this case quality improvements take place. To buy additional equipments is the last remedy to eliminate the bottleneck from the system.

When the system is in the steady state condition after solving the initial problems, more inventories are again removed to find another bottleneck operation and the above procedure is then repeated. The Japanese have followed this procedure for many years. It has resulted with high quality, flexible workforce, small setup times, and excellent preventive maintenance. Furthermore, the removal of inventories not only decreases the in-process inventories, but also reduces the lead times. As a consequence, the safety stocks are decreased. All these affect the finished product and the lead times for finished products shorten due to the small safety stocks which results an increase in the accuracy of the demand forecast. Those are not the goals of the JIT production system but the output of continually debottlenecking the manufacturing plants.

The idea in JIT production systems is to visualize the production process as a series of stations on an assembly line which requires synchronized stations and results with the minimization of buffer inventories together with the considerable reduction of lead times.

Also due to the idea of JIT production system, it requires a stable repetitive environment. JIT production system differs from MRP system mainly in two aspects:

- Implementing the priority system.
- Dealing with capacity.

The priority in MRP is determined by a central planning system. In JIT production systems, the priority is determined by each production stage in a decentralized way. In JIT production system there is no capacity planning. If master production schedule results in overloaded capacity, adjustments have to be made during production. In MRP capacity requirements are projected through the planning horizon.

In this study, a single-item, single-line, multi-stage, and multi-period JIT production system is analyzed. After developing a model for such a system in the broadest sense, the model is approximated to ease the computational difficulties. We perform a sensitivity analysis on some parameters of the model to see their effects on the behavior of the model.

In the following chapter, the JIT production systems are explained in detail and literature on JIT production systems is reviewed. In Chapter 3, the developed model, together with its approximated version, is given. Solution procedures for the approximated model including the design of the analysis and problem generation are covered in Chapter 4. In Chapter 5, the solutions of the above procedures are analyzed and the results are summarized. Conclusions together with suggestions for further research on JIT production systems are presented in Chapter 6.

2. JUST-IN-TIME PRODUCTION SYSTEMS

Just-in-Time philosophy is evolved from the Japanese manufacturing environment. The environment that applied JIT philosophy is called JIT production system which is alternatively named as Zero Inventories, Material As Needed (MAN),continuous flow manufacturing (by IBM), stockless production or repetitive manufacturing system (by HP), and Toyota system.

2.1 History of Just-in-Time

After World War II, Japanese were suffering from deficiency of all kind of resources. They had very small land and scarce natural resources. Due to the war, money and manpower were also considerably insufficient. In order to enter into the world market and to compete with American and Western companies, they had to learn to use their scarce resources with the lowest cost possible. So they developed the concept of elimination of waste by seeing everything that is not used as a waste. According to them, the major waste was the inventories which are held to keep the production system operating. The defective parts and machine breakdowns are the obstacles in this way which interrupt the production process.

JIT production system was developed in Toyota motor company by the former vice-president T. Ohno. The JIT philosophy is emerged by taking and revising the basic ideas of American manufacturing system and shaping them in Japanese environment.

It is the supermarket idea of America that affects T.Ohno and initiates the concept of JIT production system. In a supermarket, there is no in-between stages. It is the last stage for products and customers are directly confronted with all problems as poor quality, shortages, and perishables. Also there is a vast variety of products. The replenishment of products are triggered by the empty shelves. The ideal is some optional space available for large inventories (warehousing) and adaptable for quick stock turnover and easy stock replacement [21]. Taking this idea as the starting point T.Ohno has developed the Toyota production system, and hence JIT philosophy.

There is a yearly production plan which shows the aggregate plans for that year in Toyota. From this plan, a two-step monthly production plan is generated. In the first step, as Monden [26] described, types and quantities of cars are suggested two months before, and then in the second step the detailed plan is determined one month before the particular month in question. The daily production schedule is the output of this monthly production plan. This plan is critical because the smoothed production is the result of this schedule. The next step, due to Monden [26], is "to organize this daily schedule into an ordinal schedule. This ordinal schedule shows the time priority order to assemble the various kinds of cars". This averages the quantity to be produced per day. Ordinal schedule is based on the cycle time which is defined by Monden [26] as "the time needed to produce one unit of a specific kind of car". This cycle time must be derived using the number of units of demand. To find the optimal ordinal schedule is somewhat difficult and it is attained in Toyota by a heuristic computer program [26].

This ordinal schedule is the input of the starting point on the final assembly and all other stages are only given the rough monthly estimates from which they extract the daily output quantities needed and the necessary cycle times, and they are supported by their succeeding stages which are initiated by the ordinal schedule.

After the oil shock in 1971, the importance of JIT philosophy was understood by other Japanese companies and it began to be applied throughout the country. After 1980, some American companies also began to implement JIT production system in their environments.

2.2 Requirements of Just-in-Time

Objective of the Japanese production systems can be summarized in two items:

- Better quality.
- High inventory turnover which means lower investment.

The requirements of JIT production systems consist of the following:

- A stable repetitive environment.
- Flexible machines and multifunctional workers in order to obtain a smooth flow by synchronizing the stations and changing the product mix.
- Technology adjusting and organization changes.
- Flexible working hours.
- Right mix of products in the assembly schedule.
- Considerable amount of shop floor teamwork in decision making to ensure its success.
- Low setup times and costs and hence, reduction in lot sizes and lead times.

2.3 Assumptions and Elements of Just-in-Time

Main assumption of the system is that no production initiates without a production kanban.

Other assumptions related with production environment are as follows:

- Daily production schedules must be virtually identical.

- Actual daily production must closely approximate the schedule.
- Only smaller, repetitively manufactured parts should be controled by Kanban system.
- Parts should be produced and moved in standard quantities in the smallest containers possible.

Having these characteristics, repetitive manufacturing is ideal for a JIT system. JIT does not work well in a highly engineered, one-at-a-time environment either. But, the applicability of JIT to the repetitive manufacturing is mostly due to having a stable plant load. So, if this aspect can be established in other manufacturing environments, JIT can be successful in those environments as in repetitive manufacturing. Finch et. al. give many examples in which JIT is successfully applied in job shop and batch environment [11]. They also identify several aspects of the JIT system that are applicable to small manufacturers.

Small manufacturing systems also want to enjoy the benefits provided by JIT implementation. Among the elements of the JIT production system, uniform work load is the hardest to implement in small manufacturing systems. The major obstacles for the implementation are the uncontrollable demand patterns and vendor relations, and the lack of negotiating power. But as stated in [11], in small manufacturing systems, each element of JIT system has to be implemented one at a time trying to get benefits from that element rather than trying to implement all elements of JIT production system. Although production runs are short under JIT, there must be some repetition in product manufacturing.

In order to achieve the objectives mentioned above Japanese developed and used two concepts: elimination of waste and respect for people. The basic elements of waste elimination concept can be summarized as below:

1. **Minimized setup time**: In order to decrease inventories, production must be continuous with small lot sizes. This results with the increase in the number of lots produced. Production with small lot sizes can be achieved by reducing setup time. The quantity is set to a very small amount and setup time is tried to be reduced. In Japan, workers do

their own setups and have developed ways to shorten the time needed for a setup [27] and [24].

2. **Uniform plant loading:** To have a continuous production, load of plant must be uniform. To attain this goal output rate must be frozen which requires a monthly stable master production schedule and plant-wide standard quality. For uniform plant loading it is important to have a mix of products that meet the variations in demand.

3. **Jidoka - quality at the source:** To achieve plantwide standard quality, quality problems must be uncovered wherever and whenever seen. So, if any problem is observed by any worker, he has to halt the production line to eliminate the problem. If required, other workers must also be involved in the problem handling process.

4. **Group technology:** To achieve the continuous flow of production, the classical layout must be changed and group technology concepts must be implemented. Group technology is the arrangement of equipment of different types in one area to facilitate the existing manufacturing process [6]. In such a layout, cross-trained workers can operate all of the equipments in the cell. Since group technology results in product-oriented layouts, not only low- and moderate- volume production but also high-volume production can benefit from group technology, and hence, from JIT production [40]. Due to its grouping aspect, lead times are reduced significantly and utilization of work centers are increased in group technology.

5. **JIT production:** In Japanese manufacturing environment, the JIT production system which means to produce necessary units in the necessary quantities at the necessary time is appropriate. JIT production system tries to minimize inventory investment, to shorten production lead time, to react faster to demand changes, and to uncover any quality problems. JIT production system has to produce the right quantity each day. So if production falls behind the schedule, overtime has to be done at the same day. Also with JIT production, stockouts will be reduced resulting with a better service level to customers. In JIT production system, quality means that piece is correct when received and preventive maintenance is required to have machines available when

needed.

6. **Kanban production control system:** Kanban system is the information processing system of JIT production system which yields strong shop floor release and control. Kanban acts as a material flow and production control system for a plant and in some cases, for its vendors and provides a method of improving productivity. This is a paperless and manual system which uses dedicated containers and recycling traveling cards. The authority to produce or supply comes from downstream operations. While workcenters and vendors plan their work based on schedules, they execute based on kanbans which are completely manual.

7. **Focused factory networks:** In such a system, the factories are in the form of specialized small plants instead of highly vertically integrated large manufacturing facilities. A focused factory should not exceed 300 people and should produce one product line or a similar group of products [6]. The benefit of this concept is due to its power to increase production efficiencies and a narrow set of goals.

On the other hand, respect for people concept includes the following elements:

1. **Lifetime employment:** Decision responsibility is assigned collectively to the workers. Workers are sure that organization has a memory and know that their extra efforts will be repaid later. Also, job rotation is important because short run labor needs can be filled internally without having to fire or hire people as such needs come and go.

2. **Company unions:** Under this concept unions are not based on industry and workers are not identified according to their skills and kind of works they are employed for. They are supposed to work for the company for whom they are working through their lives. The developed promotion system also encourages the idea of company unions. As a result of the idea, the union and the company share the same objective which is to develop the company. This results with a cooperative relationship rather than a conflicting situation between workers and company.

3. **Attitude toward workers:** Japanese attach importance to employee training and education in developing their new manufacturing system. They give opportunity to workers to display their maximum capabilities. They have ways to incorporate the knowledge and creativity of the employees to their work. Since the workers know the problems better, they have to be listened and their advices must be taken. The workers have to be trained not only for their jobs but also for the whole process. Cross training is an important aspect in respect for people concept since it allows for the rotation of workers to reduce boredom and fatigue as well as allows workers to cover for an absent worker better.

4. **Automation / robotics:** This requires high investment and involvement of workers in automation. If they find their jobs dull, they go out of their way to figure out how to eliminate those jobs.

5. **Bottom-round management:** In arriving at a consensus, they involve all interested parties. So not only the managers, but also the workers can participate in the problem solving processes, discussions, and decision making. When a decision has to be made, everyone who will be affected by this decision is involved in making it. Here the important point is not the goodness of decision but rather how committed and informed people are. Another important aspect is that the responsibilities are shared by a group or team of employees for a set of tasks. The workers should be convinced that the teamwork is better than individual approach since different minds produce many solutions to the problem and best one can be chosen among them.

6. **Subcontractor networks:** In JIT philosophy, vendors are accepted as another work center of the factory. This means that vendor companies must locate nearby the factories and they also have to apply JIT philosophy to their companies in order to supply raw materials, parts and components to the factory just in time with small lots and hence in a frequent manner.

7. **Quality circles:** A quality circle is a group of volunteer employees who meet on a scheduled basis to discuss their functions and the problems they are encountering. These employees try to devise solutions to those problems and propose those solutions to management.

Weiss, in [46], says that "Japanese workers are not significantly less absent, are not less likely to quit, and do not work harder than American workers". The success of Japanese is in having more engineers per worker,selective hiring, benefits from steep wage profiles, substantial pay differences, and unique capital structure [46].

Everdell [10] determines the following elements as the non-cultural elements of the Japanese approach in JIT:

1. Avoid interrupted work flow.
    - Decrease setup time.
    - Control quality at the source.
    - Eliminate machine breakdown.
2. Eliminate material handling and stocking.
    - Rearrange equipment according to product flow (Group Technology or Flexible Manufacturing Cells).
    - Reduce space between operations (minimize material handling).
    - Eliminate stocking points and deliver to next operation (reduce levels in Bill-of-Material, extend routings).
3. Synchronize manufacturing.
    - Cross train operators (flexible manning).
    - Match machine speeds to master production schedule (uniform plant loading).
    - Schedule only what is needed.
    - Eliminate queues and banks (zero lead time).
    - Work with vendors to embrace JIT and deliver more frequently (cooperative purchasing).
4. Switch to pull scheduling.
    - Produce only what is consumed (kanban or equivalent).

2.4 Operational Issues

To accomplish the JIT production system some steps must be taken. First of all, flow process must be designed with respect to plant layout, preventive maintenance and setup times. Plant layout has to be designed so that the work is being balanced with minimum in-process inventory. Setup times have to be reduced in order to reduce lot sizes and lead times. Second step in JIT production system is to establish **Total Quality Control (TQC)** . Its aim is to pull only good products through the system. Because if the quality is not high, there is no way to have required number of parts at the necessary time. TQC reduces defective production, consequently, there is no reason for keeping high in-process inventories. Under TQC concept, the responsibility for quality is given to the production workers instead of quality inspectors from quality department. In all processes instead of random sampling all parts are inspected. In addition, the workers who produce the defective parts are obliged for rework. Together with the responsibility, the workers also have the authority to stop or slow down the production if they encounter a quality problem, if they cannot keep up with the production, or if they found a safety hazard. The two elements of JIT production system also helps TQC. First, small lot production permits easy detection of defective parts. Second, operating less than full capacity helps in achieving both quality and production goals by allowing to slow down or to stop production for quality problems and to rework the defective parts.

To consummate JIT production system, schedule must be stabilized, JIT requires a level schedule over a fairly long time horizon. Stabilizing the master schedule is the key to stabilize all other production processes and vendor requirements. In achieving the stabilized schedule, poor quality, machine failures and unanticipated bottlenecks have to be overcome by excess labor and machine not by safety stocks or early deliveries. In general, master schedule is planned 1 to 3 months at the monthly and the daily level. The outcome of this is the uniform load. Uniform load can be viewed from two points: average total production of a product per day, and average quantity of each variety of product within the greater total.

Cooperation with vendors in JIT production system is also essential and it is realized by providing a long-term picture of demand to these vendors.

Also, vendors should use JIT system themselves and their locations must be nearby. The tendency is to have one reliable vendor.

The critical problem areas in production must be uncovered even if it creates a work stoppage. Although this approach is costly in short term, it results with major improvements and savings in the long run. Reducing inventory whenever and wherever possible is one of the important steps in realizing JIT production system.

According to the JIT philosophy, buffers of inventory hide problems and the problems are never solved because either problems are not always obvious or the presence of inventory seems to make the problems less serious. So the problems have to be solved as they are identified rather than adding back to the inventory. The following is a good analogy to this fact: "The cartoon is a simple illustration of a fisherman sitting in a small boat in the middle of a lake. In the first frame, the water level in the lake (meant to represent inventory) is high concealing rocks (potential problems) on the lake's bottom; in the second, the water level has dropped, revealing the rocks and allowing the fisherman to more safely steer his course"[45].

Inventory is the measure of how well progress has been made in reducing the cost of manufacture. Obviously, zero waste and zero inventory are not attainable in the near term, but if those goals are tried to be attained, as Everdell states [10], there can be productivity gains of 40 % and inventory reductions greater than 50 % as typical one-to-three year pay backs.

While operating in JIT production system the product design must be improved to achieve standard product configuration and fewer standard parts. The initial savings of JIT is in indirect labor since it begins with rearranging, synchronizing, and balancing operations not directly with automation and robotics. Only after those are completed successfully, automation and hence, reduction in direct labor can take place. It should be stated here that automation becomes easier when JIT philosophy is applied but automation is not the ultimate goal of JIT philosophy. Its major point is to optimize and to transform the environment rather than concentrating on the system, automation or computerization.

The results of JIT are summarized by Everdell [10] as follows:

- indirect factory labor: sharply reduced,
- scrap and rework: sharply reduced,
- lead times move from months to weeks to days,
- space is freed-up: up to 2/3 reduction,
- inventory drops: better than 50 %,
- forecasting is easier: shorter lead times,
- distribution inventory reduced: less safety stock required; more frequent shipments,
- shop floor control virtually eliminated.

By using their new production system Japanese succeed to double the rate of inventory turnover and improve the quality an order of magnitude. As sometimes claimed this is not related with Japanese culture. The companies which are built in America and use JIT production system increase production, increase quality, reduce repairs, decrease warranty costs, and decrease indirect labor [11]. However, it is important to note that Japanese select product areas that they can become dominant and they do not dilute their effort to a wide spectrum.

The basic concept of economic lot size is again used in JIT approach. The lot size is decreased by driving down the setup costs and consequently minimizing the total cost. Research in the areas of improved methods and equipment, automation, and Group Technology approaches lead to reduced setup costs [27].

2.5 The Concept of Kanban

One of the major elements of JIT philosophy and the pull mechanism is the Kanban system. This system is the information processing and hence, shop floor control system of JIT philosophy. While kanbans are being used to pull the parts, they are also used to visualize and control in-process inventories.

Demand for parts triggers a replenishment and parts are supplied only as usage dictates. Similar withdrawals and replenishments occur all up and down the line from finished-goods inventory to vendors, all controled by kanbans. In fact, if supervisors decide the system is too loose because inventories are building up, they may decide to withdraw some kanbans, thereby tightening the system. Conversely, if the system seems too tight, additional kanbans may be introduced to bring the system into balance.

The detailed assembly schedule is known by the final assembly department for at least one week or two in advance. Also the lead times for withdrawing parts and subassemblies from previous stage are known. When final assembly needs some parts for its production then it issues a kanban withdrawal for those parts one lead time prior to that need. This is same time-phasing of MRP, but in a Kanban system it is decentralized to the department level.

A kanban is a taglike card which includes information related with the product and sent to the preceding stage from the subsequent stage. Production activity is regulated by kanbans. They are used to fulfill the requirements and initiate production. There are many kinds of kanbans. These kanban types are emergency kanban, subcontract kanban, special kanban, signal kanban, material kanban, production kanban, withdrawal kanban and kanban in combination. Those are described in detail in [25] and [20]. But the most widely used ones are the production kanban and the withdrawal kanban.

A withdrawal kanban specifies the kind and quantity of product which the subsequent process should withdraw from the preceding process, while a production kanban specifies the kind and the quantity of product which the preceding process must produce [19].

The buffer inventories held between stages are kept very low by management in JIT production systems. When a stage requires some parts for its production, a production kanban is released to the relevant stage. The production and withdrawals take places on a First-Come-First-Served (FCFS) basis in almost all cases. If there happens to be any conflicts, those are handled by management and supervisory intervention on the shop floor.

An important factor in JIT production system is that kanban ordering is triggered by actual usage not by planned orders so the errors due to the planning (i. e. , demand forecasting) are eliminated completely.

Kanban states the part number, card number, part description, container number, where part is produced (pick up), where part is used (drop off), type of the card, and container capacity [6]. Before the activities performed on the shop floor are described, the following definitions are needed.

In the JIT production system, each production station has a buffer ahead of it and the production station together with its buffer forms a stage in the system. Each production station sends its production to its buffer at the end of each period. Also, each production station can retrieve goods only from the buffer of preceding stage.

In a manufacturing system that has N stages, if the first stage refers to the stage that produce the final product (possibly the assembly stage) and the N-th stage refers to the first production stage that withdraws raw materials, then the (i-1)st stage will be the succeeding stage, whereas the (i+1)st stage will be the preceding stage according to the i-th stage.

An important characteristic of JIT production system is that it works with full or empty containers instead of units. The production amount is sent to the buffer only if the container is filled up. Also a production stage can retrieve from buffer of the previous stage only if there are some full containers. **Unit load size (ULS)** is the amount carried in a container. ULS can be equal to at most the capacity of the container. When the ULS is set for a stage, then the container cannot move from one stage to the other stage without filled up to its ULS.

The ULS can differ from stage to stage and it is an important design variable in the JIT production systems.

The general process in a JIT production system can be summarized as follows: The system consists of N stages as defined above. Each stage can have different ULS, buffer capacity and production capacity. The production can only be initiated if a demand occurs. The demand is external for the first stage (i.e., assembly stage) and internal for all other stages. Internal demand for a stage means the production amount of the succeeding stage in JIT production system.

Kanbans are attached to each container whether it is full or empty. A stage brings a full container from the buffer of its preceding stage to start its production. And then, this stage returns an empty container to the buffer of the preceding stage after attaching a production kanban to this container. This attached kanban is a production order for the preceding stage. When a stage retrieve a full container from the previous buffer it detaches the kanban from it and attaches this kanban to an empty container that it brings to the buffer. When the preceding stage takes the empty container together with the kanban, it has to start its production. So it goes to the previous buffer (according to this stage) and takes a full container by detaching its kanban and attaching it to the empty container that it brings. This procedure repeats itself throughout the production line until it reaches the raw material buffer.

As it can be seen each succeeding stage initiates the production of the previous stage with its production activity. In this system each production stage begins its production as soon as it retrieves the required material from the previous buffer and never stops until it completes its production.

According to the strategy explained above, whenever a container is filled by a production stage it is sent to its buffer. So, containers either move one-by-one to the buffer as soon as they are filled by their production stages or move to the succeeding production stages from those buffers as soon as demand arises.

There are some rules for using kanbans in order to realize JIT production and those are stated by Monden [25] as follows:

1. The subsequent process should withdraw the necessary products from the preceding process in the necessary quantities at the necessary point in time.

2. The preceding process should produce its products in the quantities withdrawn by the subsequent process.

3. Defective products should never be conveyed to the subsequent process.

4. The number of kanbans should be minimized.

5. The Kanban system should be used to adapt to only small fluctuations in demand.

There are two kinds of Kanban systems used. One of them is the single-card kanban which is used more widely than the second type, namely dual-card kanban. In the former one, only withdrawal kanban is used and production is scheduled instead of pulled with production kanban. The latter one is the aforementioned regular Kanban system. In Toyota's environment, this serves as a shop floor/ vendor release and control system [11].

Single-card kanban is less effective but easier to associate part requirements with end-product schedules. Since dual-card kanban provides greater control on the production, it is more appropriate for job shop environments in which several different parts are produced in one work center. For manufacturing environments in which only a few parts are produced in a work center, the control provided by single-card kanban can be adequate.

2.6 Problems in JIT Production Systems

If production rate changes from period to period, the number of kanbans should be changed accordingly. This requires a change in the in-process inventory levels. If in-process inventory goes up, the work center must produce enough containers in excess of demand to meet the added needs. If in-process inventory goes down, production must be postponed until excess in-process inventory is consumed. Those changes disrupt the smooth flow of product, thus demand must be fixed to have a continuous product flow.

Furthermore, if queue time or unit production time is long, the amount of in-process inventory may be quite excessive. Those are related to the manufacturing process as processing time and setup time, and have to be reduced to an acceptable minimum level. Otherwise, there will be unreasonable investment in inventory.

Thus, for a successful and applicable JIT production system, the requirements are stable schedules, reduced setup times, and improved process reliability.

JIT production system aims at minimum buffer inventory between stages in order to achieve its goals. But whenever a disruption in the system arises the entire system can easily come to a halt due to little slack between stages.

But this problem is considered as an opportunity to find the sources of the other problems of the system and correct them as not to recur.

Decentralized decision making in production may be a problem in many companies since organization of Western companies are characterized with centralized decision making. So, a large investment is required to train the personnel. One potential source of disruptions in a JIT production system is quality problems. These kind of problems must be investigated and solved at their sources in order to eliminate recurrences. Main problems of the JIT production system are considerable amount of time, effort, and money required by pre-JIT preparations. And the willingness to commit these things to correct problems at the source is essential for the success of the system.

2.7 Previous Work on JIT Production Systems

There has been quite a number of work concerning JIT production systems. Much of these work has focused on the conceptual side of JIT production systems. On the other hand, the research on the analytical part of JIT production systems is sparse.

The literature on the conceptual level for JIT production systems can be examined in two parts. First class of studies deal with the JIT philosophy including the elements of JIT production systems, the requirements and prerequisites together with the benefits and limitations for JIT production systems. Second part of the studies concentrate on the comparison of JIT production systems with other production-inventory systems such as ROP, MRP, or OPT [10], [13], [14], [15], [21], [28], [36], [38], [39].

JIT concept is described in a number of articles [2], [11], [12], [15], [21], [23], [25], [26], [27], [36], [42], [43], [44], [47], [48]. Particularly, in [21], [22], [25], [26], [27], [39], Toyota production system is demonstrated. Furthermore, [24] is one of the remarkable work done upon JIT production system which explains the Toyota production system implemented in Japan. While [14], [15], [21], [39], [43] and [44] discusses the pull mechanism, [21], [22], [24], [25], [36], [38], [39] and [47] describes the kanban concept in detail. Apart from those, the elements of JIT production systems are given in [6], [11], [23], [26],

[43] and [44]. The benefits of JIT production systems are reported in [11], [12], [36] and [44]. Limitations of JIT production systems are recited in [2], [9], [11], [13], [28], [39], [43], [44], and [47]. Among the requirements of JIT production system, shortening of setup time is discussed in [27]. In addition, production smoothing in JIT production systems is described in [23], [26] and [27]. Quality Control concept in JIT production systems is explained in [37] with the tools used in Total Quality Control (TQC). The control of quantity and quality in JIT production systems is discussed conceptually in [6]. Another paper that explains TQC concept is [9] in which the ways that JIT and TQC can help in solving the problems in developing countries are described.

The cultural aspects of Japanese together with their management style are reported in [1], [17], [30], and [46].

The layout aspects of JIT production system involving the use and effect of Group Technology and Cellular Manufacturing in JIT production systems are described in [40]. The impact of JIT production systems on building design, plant layout and material handling system is presented in [43]. The influence of JIT production system on warehousing is argued in [2].

The implementation of JIT production system in German companies together with its limitations of the integration of JIT production system with the existing production planning and control systems is discussed in [47]. In [11], the feasibility of the implementation of JIT production system in small manufacturing settings is argued. JIT implementations in several American companies, the steps taken by them, the concepts used in these companies are described in [41].

On the analytical side, the previous models in the literature mostly focused on simulation rather than the mathematical aspects of the JIT system.

One of the first work to develop mathematical models for Kanban system is due to Kimura and Tereda [19]. They provided several basic system equations for the Kanban system in a multi-stage serial production setting to show how the fluctuation of final demand influences the fluctuation of production and inventory volumes at upstream stages. In their theoretical analysis, they particularly assumed small container size and unlimited production capacity.

They showed that when the ULS is relatively small and there is no restriction on production capacity, the production fluctuation in the succeeding stages is transmitted to the preceding stages in a form which is identical with that of the original pattern with a time lag only. They also showed that when the production series of the final stages are independent, the inventory fluctuation at each stage is amplified in comparison with the fluctuation of final stage. According to their formulations, the fluctuations become smaller when there is a restriction on production capacity at the expense of increased backlog and production delay. In the case of large ULS, the formulations become difficult to analyze theoretically. Thus, they analyzed this case by simulation techniques. The analysis resulted that larger the ULS, larger the production and inventory fluctuations.

Recently, Bitran and Chang [4] provided a mathematical programming formulation for the Kanban system in a deterministic multi-stage assembly production environment. They transformed the formulated nonlinear integer problem into an integer linear model. Their model determines both the number of kanbans circulating in the system, and the inventory level at each stage. They have not made any assumptions about the size of the container and the model allows finite production capacity. They also investigated solution procedures for the resulting model that will make it usable in practice.

One of the most notable work on this subject is due to Trevino [44]. He explicitly developed design procedures for JIT production system. In his paper, the characteristics, requirements, some applications and pulling procedure of the JIT production system are briefly described. He also identified the fundamental design decisions of JIT manufacturing systems and discussed some design issues and analysis techniques. In this design procedure, the key element is the probability of stockout at the final assembly stage, which is constrained to a specific maximum value. Design alternatives such as assembly capacities, lot sizes, ULS and number of kanbans, which satisfy this constraint are identified through stochastic analyses and then evaluated with regard to total cost to select the preferred alternative.

Conway et. al. [5] considered the production lines with buffers between stations. After investigating their behavior, they determined the distribution and quantity of in-process inventory that accumulates.

Huang et. al. [16] simulated the JIT production system for a multi-line, multi-stage production system to determine its adaptability to an American production environment that includes variable processing times, variable master production scheduling, and imbalances between production stages. First they incorporated variable processing times to see their effects on system performance. Next, they determined the impact of bottlenecks at different stages and any interaction between bottleneck and the number of kanbans allowed. At last, they considered the combined effect of variable processing times and demand rates.

Rees et. al. [34] presented a methodology for dynamically adjusting the number of kanbans in a JIT shop by using simulation. The production environment is unstable due to the variability in processing times and demand. In this study, first the methodology is presented and then a hypothetical shop is simulated. Results are discussed based on three examples from the simulation.

Later Philipoom et. al. [32] investigated the factors influencing the number of kanbans while implementing a JIT manufacturing system in an American manufacturing environment. The factors that are identified include the throughput velocity, the coefficient of variation in processing times, the utilization of machines, and autocorrelation of processing times. They analyzed the effects of these factors and presented a methodology for determining the number of kanbans in a dynamic production environment by a simulation approach.

In their most recent work, Davis and Stubitz [7] considered a case study in order to develop a kanban system for the control of the production system. They applied simulation and optimization techniques and came out with the conclusion that the conceptual basis for the kanban approach was applicable to manufacturing systems which are not pure flow shops with balanced production times at each station. The optimization considers the minimization of the flow time of an order and the maximization of the processor utilizations which are conflicting. The optimization proposed belongs to the class of multiple stochastic criteria optimization over a discrete decision space. The functional approximation techniques of the response surface approach is adopted to detail the nature of compromise required among the objectives.

Stochastic optimization does not generate a unique criterion value for each functional evaluation. Therefore, simulation was chosen to establish the criterion value at each assignment of decision variables in the search algorithms.

3. MODELING OF THE SYSTEM

The philosophy of JIT manufacturing is to operate a simple and efficient manufacturing system capable of optimizing the use of manufacturing resources such as capital, equipment, and labor. This results in the development of a production system that can meet the quality and delivery demands of a customer at the lowest manufacturing price.

To achieve the above goal of the best use of resources when they are needed, a new design methodology of JIT production systems is proposed. The problem under consideration differs from those suggested by previous researchers in having no batch processing for kanbans. In previous studies, production kanbans have been assumed to be collected in a stack at the buffer during the period and at the beginning of next period all of the production kanbans have been sent to the production stage in order to trigger the production. In this study, it is assumed that whenever a production kanban is detached at buffer, it is sent to the production stage to start the production if that stage is already waiting for a production order. In batch processing case, if a stage is waiting for a production order it has to wait for possibly a batch of kanbans. Also, after a batch of kanbans arrive at that stage, the batch should be completed in that period. If it cannot be completed, then overtime has to be used although resources were idle in the previous period. So, instead of waiting for a batch, all kanbans move as soon as they are detached. This prevents having waiting time for kanbans for the production stage henceforth eliminating unnecessary idle time for the production stage.

A mathematical model is developed to incorporate the preceding characteristics into the design of the JIT production system. The model definition is given in Section 3.1 . In its full generality the model is highly nonlinear and

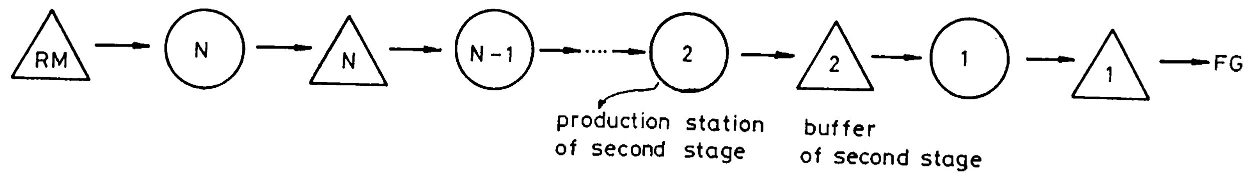

Figure 3.1: A multi-stage, single-line JIT production system

computationally prohibitive for solving realistic size problems. Some modifications are proposed and approximations on the nonlinear model to ease aforementioned computational difficulties are presented in Section 3.2 .

3.1 Model Definition

A model is developed for a multi-stage, multi-period, single-line, and single-item production system. The system has N production stations with a succeeding buffer station. Each production station together with its buffer is called a stage. The system is shown schematically in Figure 3.1 . Each stage has its own processing time, production capacity, buffer capacity, manufacturing lead time, variable production cost, inventory holding cost, backlog cost, container cost, and annual fixed machine cost. Furthermore, demand for the final product is realized for each time period.

Given the above data, the model determines, in terms of containers, unit load size (ULS), amount of production, production capacity, inventory level, amount of backlog, and capacity of buffer while minimizing the total cost of the system subject to several functional constraints.

The assumptions made for the system are stated below:

- no batch processing on kanbans,
- buffer capacity is limited with only maximum demand,

- no partially filled container can move between stations (only empty or full containers move through the system).

The definitions related with the model are given below:

Definitions:

Indices:

n : stage of production (n=1,...,N)
t : time period (t=1,...,T)

Parameters:

H^n : inventory holding cost at stage n per unit per period ($/unit-period)
S^n : cost of a backlog at a stage per unit per period ($/unit-period)
K^n : cost of containers including storage and space cost at stage n ($/container)
CC^n : container capacity at stage n (unit/container)
p : pulling rate (container/period)
D_t : demand of final product in period t (unit)
L^n : production lead time at stage n
U_t^n : unit variable production cost at stage n at time period t ($/unit-period)
AFC^n : annual fixed machine cost rate for stage n ($/period)
a^n : variable processing time for stage n (time unit/unit)

Decision Variables:

O_t^n : net accumulated number of empty containers at stage n in time period t, i. e. , production order quantity

P_t^n : production amount of stage n in time period t (number of full containers)

M^n : unit load size at stage n

C^n : production capacity of stage n

W_t^n : number of units of item remaining in a partially filled container at stage n in time period t

I_t^n : number of full containers in buffer at stage n in time period t (amount of inventory carried)

B_t^n : number of empty containers in buffer at stage n in time period t (amount of backlog)

X^n : number of containers in buffer at stage n

Original Model:

$$\begin{aligned} Min \quad TC = & \sum_{n,t} U_t^n(P_t^n M^n + W_t^n) + \sum_{n,t} H^n M^n I_t^n + \\ & \sum_{n,t} S^n M^n B_t^n + \sum_{n,t} AFC^n a^n M^n P_t^n + \sum_{n} K^n X^n \end{aligned}$$

s.t.

$$M^n \geq 1 \qquad \forall n \tag{1}$$

$$M^n \leq CC^n \qquad \forall n \tag{2}$$

$$P_t^n = min(O_t^n, C^n, I_{t-1}^{n+1} + P_{t-L^{n+1}}^{n+1}) \qquad \forall t, n = 1, ..., N-1 \tag{3}$$

$$P_t^N = min(O_t^N, C^N, I_{t-1}^{N+1}) \qquad \forall t \tag{4}$$

$$I_t^1 = I_{t-1}^1 + P_{t-L^1}^1 - \frac{D_t}{M^1} \qquad \forall t \geq L^1 + 1 \tag{5}$$

$$I_t^n = I_{t-1}^n + P_{t-L^n}^n - P_t^{n-1} \qquad \forall t \geq L^n + 1, n = 2, ..., N \tag{6}$$

$$W_1^1 = M^1 O_1^1 - D_1 \tag{7}$$

$$W_t^1 = W_{t-1}^1 + M^1 O_t^1 - D_t \qquad t = 2, ..., T \tag{8}$$

$$W_t^n = W_{t-1}^n + M^n O_t^n - M^{n-1} P_t^{n-1} \qquad \forall t, n = 2, ..., N \tag{9}$$

$$O_1^1 = \left[\frac{D_1}{M^1}\right]_+ \tag{10}$$

$$O_t^1 = O_{t-1}^1 - P_{t-1}^1 + \left[\frac{D_t - W_{t-1}^1}{M^1}\right]_+ \qquad t = 2, ..., T \tag{11}$$

$$O_1^n = \left[\frac{P_1^{n-1} M^{n-1}}{M^n}\right]_+ \qquad n = 2, ..., N \tag{12}$$

$$O_t^n = O_{t-1}^n - P_{t-1}^n + \left[\frac{P_t^{n-1} M^{n-1} - W_{t-1}^n}{M^n}\right]_+ \qquad t = 2, ..., T, \quad n = 2, ..., N \tag{13}$$

$$I_0^n = X^n \qquad \forall n \tag{14}$$

$$I_t^n = max(0, P_t^n - O_t^n) \qquad \forall t, n \tag{15}$$

$$B_t^n = max(0, O_t^n - P_t^n) \qquad \forall t, n \tag{16}$$

$$X^n \leq \frac{max(D_t : t = 1, ..., T)}{M^n} \qquad \forall n \tag{17}$$

$$X^n \geq \frac{min(D_t : t = 1, ..., T)}{M^n} \qquad \forall n \tag{18}$$

$$X^n \geq P_t^n \qquad \forall t, n \tag{19}$$

$$W_t^n \leq M^n - 1 \qquad \forall t, n \tag{20}$$

$$C^n \geq p \qquad \forall n \tag{21}$$

$$C^n \leq 1/a^n M^n \qquad \forall n \tag{22}$$

$$O_t^n, W_t^n \geq 0 \qquad \forall t, n \tag{23}$$

The objective of the above model is to find the design variables that minimize the total cost. The total cost of the system includes (1) the variable production cost (2) the inventory carrying cost (3) the cost of backlog (4) the storage cost of the containers and (5) the fixed machine cost.

The upper and lower bounds for the unit load size are defined by the constraints (1) and (2). ULS is the amount carried in the container. By definition, it must be at least one unit. Besides, ULS cannot exceed the container capacity. So, ULS of a stage must lie in between the container capacity of that stage and the least possible quantity.

The production amounts at each stage in each time period are dictated by the constraint sets (3) and (4). There are mainly three restrictions on the production quantity. The first one is due to the capacity restriction. In a stage, the production quantity must not exceed the available production capacity of that stage. Second, the production quantity must not be greater than the production order quantity. Producing more than the production order quantity causes unnecessary inventory which contradicts the main objective of the JIT philosophy. The production quantity of the preceding stage in this period together with the in-process inventory of the preceding stage from the previous period determines the maximum quantity that the production must not exceed. The preceding stage for the N-th stage is the stage that supplies raw materials to the line. So the restriction for N-th stage is only put by the raw materials inventory which is denoted by I_{t-1}^{N+1}. If this constraint is not satisfied, then the stage cannot find enough in-process inventory at the preceding stage to start its production. Thereby, the production will stop on the line at that stage. Likewise, due to the stoppage of production, this stage cannot supply in-process inventory to its succeeding stage. This structure repeats itself up to the first stage of the line. Consequently, the production will stop starting from the stage at which that constraint is not satisfied up to the first stage. As it can be seen, this constraint reflects the basic idea of pull mechanism. Since each of the above restrictions puts an upper bound on the production quantity, the minimum quantity among these three constraints determines the required production quantity.

The constraint sets (5) and (6) are simply the inventory balance equations. These constraints adjust the inventory level of a stage considering the production and the in-process inventory available from the previous time period together with the demand of that stage. In these constraints, for the first stage since demand is external, the customer demand is considered. For other stages, production quantity of the succeeding stage generates the demand for that stage. Furthermore, the production lead time is taken into account for the production of that stage. Henceforth, while balancing the inventory, the production occurred during the lead time instead of the production of that period is taken into account.

The constraint sets (7), (8) and (9) state the number of items remaining in a partially filled container (W_t^n). At a stage, the containers move to the buffer from production station only if they are filled up to their ULS. At the end of the period, there may be a container which is not filled up to its ULS yet. Such containers are called partially filled containers. These equations, in fact, keep the balance of items remaining in partially filled containers. In the balance, the production order quantity and the demand for that stage are considered together with the items remaining in the partially filled containers at that stage from the previous period. Since W_t^n cannot be greater than ULS, these constraints always force the production order quantity of that stage to approach the demand for that stage. Together with next set of constraints, production quantity is obliged to become equal to production order quantity.

Constraint sets (10), (11), (12) and (13) find out the production order quantity at each stage and in each time period. Indeed, these constraints are the balance equations for the production order quantity. These constraints take care of the production order quantity of that stage from previous period in addition to the demand for that stage. Demand is the external demand if that stage is the first stage in the production line, otherwise it is the internal demand, that is the production quantity of the succeeding stage. From these quantities, the production quantity of that stage in previous period is subtracted. Among the abovementioned quantities, the first and the third one are used to determine the inventories held (if their difference is positive) or the amount backlogged (if their difference is negative).

Constraint set (14) simply sets the initial inventory for each stage to the buffer capacity of that stage.

As constraint set (15) determine the inventory levels for each stage, constraint set (16) defines the amount of backlog. As indicated above, the difference between the production quantity and the production order quantity determines either the inventory held (if the difference is positive) or the amount backlogged (if the difference is negative). Since only one of them will be positive in the solution, the other one will be set to zero.

Constraint set (17) defines the upper bound whereas constraint sets (18) and (19) define the lower bounds for number of containers in buffer. The upper bound of the buffer capacity for each stage is set by the maximum demand in the time horizon. This follows from the fact that the production quantity of the first stage is dictated by the external demand and this activates the production activities of the preceding stages. So, the production quantity and hence the inventory held at any stage in any period can never exceed the maximum demand. Following the same logic, buffer capacity at each stage must be greater than the minimum demand in the time horizon. This forms one of the upper bounds for the buffer capacity. The other bound set by saying that the buffer capacity must be greater than the production quantity of that stage for any time period. In this way, there will be no chance for the produced units to find the buffer filled and to wait for a place in the buffer. In fact these constraints limit for the case where within a period total turnover can be more than empty buffers in the beginning.

The upper bound for units of items remaining in a partially filled container is specified by constraint set (20). W_t^n is basically used to determine that container which is not filled yet. In other words, the number of units in that container is less than its ULS. If just the opposite is true, then that container has to move to the buffer. To conclude, the upper bound for units of items remaining in a partially filled container must be equal to the ULS less one, considering the production as an integral value.

Constraint sets (21) and (22) are used to achieve the production requirements at each stage. If production capacity is not greater than the pulling rate for a stage, then there is always a chance for the disruption of the production due to the insufficient capacity.

The last constraint sets define the nonnegativity of production order quantity and the number of items remaining in a partially filled container.

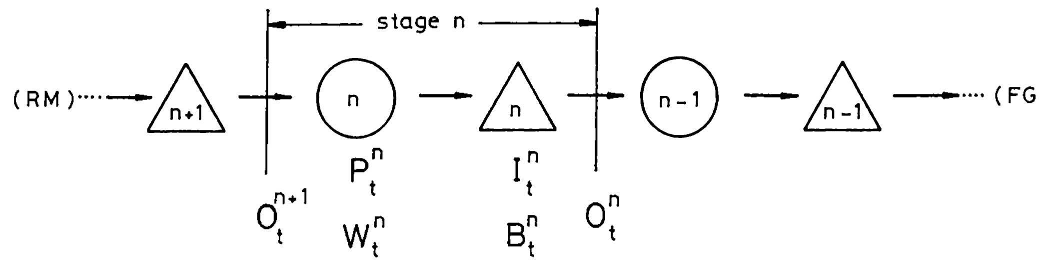

Figure 3.2: The interrelation of successive stages in JIT production system

The terms $[x]_+$ in constraint sets (5) and (10)-(13) indicate that these terms must be the smallest integer greater than or equal to the term x. This is required because the constraints are based on containers but the numerator of the term x is in terms of units. When units are converted to containers by dividing them to ULS values, the resulting number of containers must be an integral value. In Figure 3.2, the decision variables are shown on a hypothetical assembly line.

3.2 Model Modification and Approximations

The model constructed for a JIT production system in the preceding section is nonlinear in both objective function and constraints. But it is computationally restrictive to solve the model which has nonlinearities in both constraints and objective function. By taking one of the design variables, namely the unit load size, which causes nonlinearities, as a parameter, we can transform the nonlinear model into a linear one. The linear model is simpler and computationally superior. A sensitivity analysis is then performed to see whether the model is sensitive to unit load size or not.

Another difficulty in solving this model is the integer variables. In real life, the variables will have integer values. But in solving the model they are relaxed to have an approximate linear model which can be solved with ease.

When constraints (10)-(13) are reexpressed to solve the problem by the

LP packages, it causes an increase in the number of integer variables and in the number of constraints. In these constraints, the terms $[x]_+$ are required to get integer values in order to have meaningful solution. Integrality requirement brings $N \times T$ extra constraints and $N \times T$ additional variables which increase the size of the model. Accordingly, in order to remedy computational difficulties, we first relax these constraints and perform a perturbation analysis on the integral variables by maintaining the feasibility of the solution. Then, the results are compared to see whether they are significantly different or not. These are explained in Section 5.1.

Another necessity for approximating the original model is the limits of the commercial package programs on the number of constraints and variables. In its full generality, the original model will have $N \times (11T + 6)$ functional constraints together with $N \times (5T + 2)$ variables. When the values of N and T are large, commercial packages such as LINDO will not be capable of solving the model. Hence, the model must be modified in order to handle reasonably large problems.

After approximation, the resulting model becomes as below:

Modified Model:

i) Objective function is to minimize the total cost

$$Min \;\; TC = \sum_{n,t}(U_t^n + AFC^n a^n)M^n P_t^n + \sum_{n,t} U_t^n W_t^n + \sum_{n,t} H^n M^n I_t^n + \sum_{n,t} S^n M^n B_t^n + \sum_{n} K^n X^n$$

ii) Constraints

(1) Maximum possible production quantity

a) Total production must not exceed capacity (in terms of units)

$$M^n P_t^n + W_t^n - M^n C^n \leq 0 \qquad \forall t, \forall n \qquad (24)$$

b) Total production must not exceed the total in-process inventory of the preceding stage (in terms of units)

$$M^n P_1^n + W_1^n - M^{n+1} P_{1-L^{n+1}}^{n+1} \leq M^{n+1} I_0^{n+1}$$

$$n = 1, \ldots, N-1 \qquad (25)$$

$$M^n P_t^n + W_t^n - M^{n+1} I_{t-1}^{n+1} + M^{n+1} B_{t-1}^{n+1} - M^{n+1} P_{t-1-L^{n+1}}^{n+1} \leq 0$$

$$t = 2, \ldots, T, n = 1, \ldots, N-1 (26)$$

$$M^N P_1^N + W_1^N \leq X^{N+1} \qquad (27)$$

$$M^N P_t^N + W_t^N \leq I_{t-1}^{N+1} \qquad t = 2, \ldots, T \qquad (28)$$

c) Production must not exceed the empty buffer amount (buffer size - inventory on-hand) (in terms of containers)

$$P_1^n - X^n \leq -I_0^n \qquad \forall n \qquad (29)$$

$$P_t^n - X^n + I_{t-1}^n \leq 0 \qquad t = 2, \ldots, T, \forall n \qquad (30)$$

(2) Balance equations for the number of units of items remaining in a partially filled container

$$W_1^1 = M^1 O_1^1 - D_1 \qquad (31)$$

$$W_t^1 = W_{t-1}^1 + M^1 O_t^1 - D_t \qquad t = 2, \ldots, T \qquad (32)$$

$$W_t^n = W_{t-1}^n + M^n O_t^n - M^{n-1} P_t^{n-1} \qquad \forall t, n = 2, \ldots, N \quad (33)$$

(3) **Net inventory balance equations** (in terms of units)

$$M^1B_1^1 - M^1I_1^1 + M^1P_{1-L^1}^1 = D_1 - M^1I_0^1 \quad (34)$$

$$M^1B_t^1 - M^1B_{t-1}^1 - M^1I_t^1 + M^1I_{t-1}^1 + M^1P_{t-L^1}^1 = D_t$$

$$t = L^1 + 1, \ldots, T \quad (35)$$

$$M^nB_1^n - M^nI_1^n + M^nP_{1-L^n}^n - M^{n-1}P_1^{n-1} - W_1^{n-1} = -M^nI_0^n$$

$$n = 2, \ldots, N \quad (36)$$

$$M^nB_t^n - M^nB_{t-1}^n - M^nI_t^n + M^nI_{t-1}^n$$

$$+M^nP_{t-L^n}^n - M^{n-1}P_t^{n-1} - W_t^{n-1} = 0$$

$$t = L^n + 1, \ldots, T, n = 2, \ldots, N \quad (37)$$

(4) **Production order quantity balance equations** (in terms of units) (production order quantity = demand (or total production quantity of the succeeding stage) + backorder from previous time period - on-hand inventory from previous time period - units produced in a partially filled container in previous time period)

$$M^1O_1^1 = D_1 - M^1I_0^1 \quad (38)$$

$$M^1O_t^1 - M^1B_{t-1}^1 + M^1I_{t-1}^1 + W_{t-1}^1 = D_t$$

$$t = 2, \ldots, T \quad (39)$$

$$M^nO_1^n - M^{n-1}P_1^{n-1} - W_1^{n-1} = -M^nI_0^n$$

$$n = 2, \ldots, N \quad (40)$$

$$M^nO_t^n - M^nB_{t-1}^n + M^nI_{t-1}^n - M^{n-1}P_t^{n-1} + W_{t-1}^n - W_t^{n-1} = 0$$

$$t = 2, \ldots, T, n = 2, \ldots, N \quad (41)$$

(5) Bounds for buffer

$$X^n \leq \frac{max(D_t : t = 1, ..., T)}{M^n} \qquad \forall n \tag{42}$$

$$X^n \geq \frac{min(D_t : t = 1, ..., T)}{M^n} \qquad \forall n \tag{43}$$

(6) Upper bound for number of units remaining in a partially filled container

$$W_t^n \leq M^n - 1 \qquad \forall t, n \tag{44}$$

(7) Lower and upper bounds for capacity

$$C^n \geq p \qquad \forall n \tag{45}$$

$$C^n \leq \frac{1}{a^n M^n} \qquad \forall n \tag{46}$$

(8) Nonnegativity constraints

$$O_t^n, W_t^n \geq 0 \qquad \forall t, n \tag{47}$$

In the solution of the model, when we take ULS as a parameter as opposed to a variable, the third and fourth constraint sets drop and this reduces the number of constraints to $N \times (11T + 4)$. In addition,by parameterization of ULS, constraint sets (17), (18), (20) and (21) can be implicitly considered as upper bounds on the number of containers. Consequently, the model will have $N \times (9T + 1)$ explicit constraints. By giving the value of initial inventory for each stage as a parameter, the constraint set of (15) is also eliminated and the number of constraints reduces to $9N \times T$.

By considering net inventory balance $2N \times T$ constraints are saved and the model is end up with $7N \times T$ effective constraints.

4. PROPOSED SOLUTION PROCEDURES

In this study, two different approaches are used to solve the model developed in the preceding chapter. In the first approach, the deterministic case of the model is analyzed. Besides, a sensitivity analysis on some important parameters of the model is performed by using the capabilities of the LP packages.

Then by applying simulation techniques, a stochastic version of the model is analyzed. Under both deterministic and stochastic environments, the behavior of the model under different demand variations is observed while unit load size changes.

Moreover, the buffer capacity which is taken as a variable in deterministic case is considered as a parameter in simulation model. This causes an increase in the number of problems but it permits us to see the effect of buffer capacity changes.

4.1 Solution Strategies for the Deterministic Case

Suggested strategy for this case basically relies on optimization and statistical techniques. In order to solve the proposed model a mathematical module is developed. This mathematical module includes a data generator which provides the necessary data to the model. The output of this data generator is the input to the matrix generator which is the second part of the mathematical module. This part prepares the input of the third part, that is the mathematical package, in the necessary format with the given data of the data generator. Then the mathematical package solves the given model and its output is sent to a graphical analysis package. This mathematical module permits the examination of a large number of alternative data sets, especially for the sensitivity analyses. The relationship of the input, output and the programs used in the mathematical module is given in Figure 4.1.

The model is solved by **Hyper LINDO**, a commercial LP package. Then, a sensitivity analysis is performed on some parameters again using this LP package. Sensitivity analysis of the parameters forms one of the basic parts of the study. Because if the model is sensitive to the parameter then it will affect the optimum solution of the model. So, this parameter must be estimated accurately.

The sensitivity of the parameters are analyzed by testing them on the generated problems (empirical analysis). In this section, first the design of analysis and then the method of generating the problems are explained for the proposed solution procedures.

4.1.1 Design of the Analysis

In this model, there are twelve parameters that may affect the behavior of the model. These are:

1. Final product demand,
2. Production lead time,
3. Unit load size,
4. Variable processing time,
5. Pulling rate,
6. Container capacity,
7. Inventory holding cost,
8. Backlog cost,
9. Container cost,

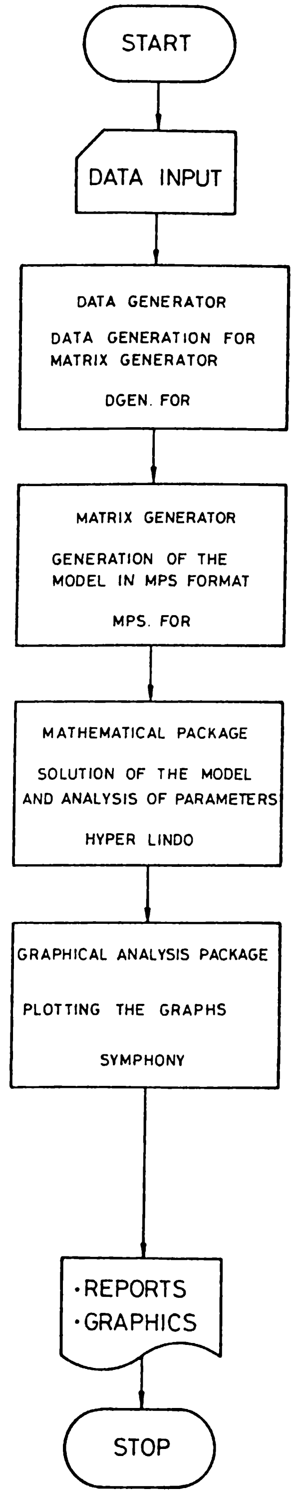

Figure 4.1: The Relationship Between Input, Programs and Output

10. Unit variable production cost,

11. Annual fixed machine cost.

Among those, items 1, 2, 4, and 5 must be consistent with each other. Furthermore, items 7, 8, and 10 must also be respectively consistent.

The major factors are expected to be final product demand, container capacity, and unit load size due to the peculiarity of JIT production system. As stated before, the production of each stage is controled ultimately by the final product demand. Also the efficiency of the pull system is often measured in terms of the number of containers of goods produced and stored at each stage which means the production amount at each stage and buffer size between stages. These two items are directly affected by container capacity and unit load sizes.

In addition to these, the number of stages and the number of time periods used in the model affect its solution time. JIT system usually requires a short time horizon as opposed to conventional production systems. So the number of time periods are smaller. The time buckets used in for the master production schedule are usually one month. This time bucket can even be reduced to one day. The time horizon is taken as three in the problems assuming that this is a 3-shift production system per day.

Different combinations of the above factors represent different problem structures. For a given structure, the model has to be solved and each of them is called a **problem**. But in order to eliminate the combined effect of the parameters, only one of the parameters has to be changed in each problem. Hence, it will be possible to see the effect of this parameter on the behavior of the model.

There are two ways for changing the value of parameters. One of them is to generate an explicit problem for each parameter as mentioned previously. The other one is to use the parametric analysis of Hyper LINDO.

For each of the parameters

- inventory holding cost

- backlog cost
- container and storage cost
- unit variable production cost
- annual fixed machine cost

a different problem which gives different cost patterns is generated. Different problems are also generated by selecting an appropriate cost pattern for the following parameters:

- final product demand
- production lead time
- unit load size
- container capacity

4.1.2 Problem Generation

In order to incorporate randomness of the data and to eliminate effect of biased data, twenty statistically independent runs are generated and then their average is taken as the result of each problem. In addition, to prevent the same pattern for each parameter, in each run the seed of the random generator is randomly set. But when looking at different problems, the seed of the parameter under consideration must be the same to ensure the same pattern for that parameter while the other parameters change their value.

In JIT philosophy, one seeks to have small inventories with small lot sizes in production. These are the main elements that affect the manufacturing lead time. Thereby, if this objective is attained then the manufacturing lead time will shorten. Manufacturing lead time is the sum of transportation lead time and the production lead time at a stage. Waiting and moving time form the transportation lead time and this is the major part of the manufacturing lead time. In JIT production system, the processing times become short due to the automation of the system. Since production lead time is affected by the size of the lot size together with the processing time, small processing times together with small lot sizes result in small production lead times. When transportation lead times are nearly zero and production lead time is small, the manufacturing lead time will essentially become negligible. Consequently, the production lead time is taken as zero for each stage to lessen the computational difficulty in solving the model.

Sensitivity analyses on demand and ULS are carried to see the effects of these parameters on the response of the model. ULS is, in general, the 10 percent of the demand of a given period. Although, 10 percent of the maximum of the demand considered in the analysis is 5, in order to observe the extended effect of ULS on the model, its value is taken as 10.

In these analyses, first a range for unit variable production cost is randomly generated. Then, taking this range as a basis, all other costs, inventory carrying cost, backlog cost, and container cost, are generated according to the relationships between these cost items. Since no actual data can be obtained, the previous empirical studies [20] are considered to determine these cost patterns and to generate the range for unit variable production cost.

The unit variable production cost is uniformly generated in the interval of 100 and 500. Inventory carrying cost is taken as 15 to 30 percent of unit variable production cost. Johnson and Montgomery [18] give the inventory carrying cost as $I = ic + w$ where i is the cost of carrying $1 of inventory per unit of time, c is the $ value of a unit and w is the storage cost per unit of average inventory per unit time. The factor i is called the inventory carrying cost rate and is typically in the range of 0.15 and 0.30. It is also stated that w is omitted in most cases. Only 0.15, 0.20, and 0.30 of unit variable production cost are considered in the analyses to simplify computations. Then, backlog cost is set to 2 to 5 times of inventory carrying cost. In this study only the 2, 4, and 5 times of inventory carrying cost are analyzed. In total, nine different cost patterns are investigated.

Container cost is taken as 50 percent of unit variable production cost times ULS regarding the data in [20]. Furthermore annual fixed machine cost is generated from the range of (200-800) again taking the data in [20] as a reference. The cost structure is given in Table 4.1. The pulling rate is also taken from [20].

unit variable production cost	inventory carrying cost	backlog cost	annual fixed machine cost	container cost
100-500	15-75	30-150	200-800	50-250
		60-300		
		75-375		
	20-100	40-200		
		80-400		
		100-500		
	30-150	60-300		
		120-600		
		150-750		

Table 4.1: Different cost structures for the sensitivity analysis of the costs

After analyzing the results, it is observed that none of the costs significantly affects the behavior of the model and hence, the model is not sensitive to them. The following data, i. e. , one of the patterns given above, is considered as the base data for the model:

unit variable production cost	inventory carrying cost	backlog cost	annual fixed machine cost	container cost
100-500	20-100	80-400	200-800	50-250

Furthermore, the variable processing time is seen to be sensitive to the capacity of the stages. The upper bounds of the production capacity of the stages are determined by the variable processing time and ULS values of the stages. As ULS values are being changed, the upper bound of the capacity changes too.

For the final product demand, three cases are considered in the analysis of the model:

- high demand variability (HV)
- medium demand variability (MV)
- low demand variability (LV)

The following data shows the range and the variance of demand generated for this study. The average demand of all cases is 30 units:

type of demand	range	variance
HV	10-50	133.3
MV	20-40	33.3
LV	25-35	8.3

There exist 10×3^n different data patterns to be examined where n denotes the number of stages in the system. Since as n increases the number of problems also increases, n is set to a reasonably small value to make the analysis of the wide range of parameter values possible. For that reason, it is taken as three to observe the gross effect of the production system. The first stage is the final assembly step in the production line that reflects the interaction of the external demand with the system. The third stage is to expose the effect of raw material delivery on the system. Finally, the second stage in the model stands for a particular intermediate stage in the production line which signifies the relations between the other two stages. Therefore, the results can easily be extended to a system with $n > 3$ by adding extra intermediate stages. In this study, the ULS value for each stage is first set to one. Then, the behavior of the model is investigated by changing the value of ULS for only one stage and holding the others constant.

4.2 Simulation of the System

The computational difficulty of linear programming approach depends on the number of stages, the number of time periods, and the number of parameters to be analyzed. In order to ease this difficulty, the number of stages and the number of time periods have been taken as small as possible in that approach. But, by allowing only three time periods, as it is the case in LP approach, it may not give the true behavior of the system. The behavior of the system has to be observed for the time horizon of the master production schedule. For example, if master production schedule is prepared for one month then the shop floor activities have to be planned for each shift or even for each hour. Therefore, the number of time periods that has to be considered can be as large as 600.

Since it is not computationally feasible to attack the problems of this size with the LP approach, simulation has become a natural tool. But due to its prescriptive nature, there is not any optimization in the simulation study. It shows only the relationship between various components of the system and predicts the performance of the system under different operating policies. In short, it evaluates the model numerically over a time period.

In the simulation study, a data generator inputs the required data into the system. The system is then simulated by a FORTRAN based simulator. A short explanation for the programs is given in Appendix B.

4.2.1 Design of the Analysis

The same cost structure used in LP approach is utilized in simulation to permit to see the differences between the solutions of the linear programming and simulation.

The number of stages is again taken as three, but, the number of time periods is increased to 600 in order to examine the behavior of the system in the long run.

Furthermore, as it can be seen from the output of LP solution, the buffer capacity is set proportional to the production amount and the model behaves as if it is uncapacitated. Therefore, in order to see the effect of buffer capacity on the system, it is taken as a parameter in the simulation.

4.2.2 Problem Generation

All the data are generated in the same way as in previous approach with the exception of production lead time. In simulation, production lead time is taken different from zero. It is allowed to change in a range which is a function of processing times. The upper and lower bounds of the range of production lead time is taken as the 10 times of the upper and lower bounds of variable processing times. Three cases are considered for the buffer capacity. In the first case, the buffer capacity is less than the mean demand. So it is generated from a uniform distribution of (10,30). In the second case, the buffer capacity is equal to the mean demand, that is 30 for all cases. In the final case, the buffer capacity is greater than the mean demand value.

In this study, by taking three stages, three levels of demand, and three levels of buffer, together with ten ULS values, 252 different problem structures are simulated. Each of these structures is called a **problem**. These problems are generated according to a random initial seed and this is called a **run**. Since it is not plausible to rely on the results of a single run, the average of ten different runs is analyzed in the simulation.

5. RESULTS OF THE STUDY

In this study, as mentioned previously, the inherent randomness of the model is incorporated by solving each problem with a different seed. To arrive at meaningful conclusions, average values of different runs for each problem were analyzed and based on these analyses some useful results were derived.

In this chapter, the results of the analyses together with their interpretations are presented. In the following sections, first the results of the LP approach are discussed. After giving the results of the simulation study, two different solution procedures are compared with each other. At the end of each section, the results are summarized graphically for the parameters under consideration.

5.1 Linear Programming Approach

When the results of the LP package are analyzed, it is seen that there is no inventory held at any period. In addition, backlog occurs at most in one period. Typical result is: produce the ordered amount without holding any inventory between stages and do not backlog. A typical result of one of the problem instances is provided at Appendix A.

In the solutions, the buffer capacity is set to the production amount of each period. The model suggests to change the number of containers traveling in the system at each time period as the production amount changes, instead of holding empty containers.

The constraint that brings an upper bound on the buffer capacities is the maximum demand of the time horizon. Since this is not a tight constraint on the buffer capacity, the model behaves as if it is uncapacitated for the buffer. Similarly, there is not any tight constraint on the production capacity. Consequently, the only restriction on the production quantity is the production order quantity.

When the total cost curve is plotted, it is seen that the cost function is concave. For the uncapacitated lot sizing problem with a concave objective function, the solution lies on one of the extreme points defined by the linear constraints [18]. The solution must be such that $P_t^n I_{t-1}^n = 0$. The results of the model supports this statement with not carrying any inventory at any time period. Consequently, $P_t^n I_{t-1}^n = 0$ holds for every t and every n. But this is an expected result since there is not any cost in the objective function related to capacity.

The objective function value, i. e. the total cost function, is examined to see the effect of demand variability while ULS changes. Here, each stage is taken one at a time, that is while changing the ULS of one stage, the ULS values of other stages are set to one. This is basically done to prevent the interaction effect of the other stages. The results of the study are summarized in Figure 5.1 to Figure 5.6. It is seen that the slope of the function is very steep as ULS changes from one to two. Then as ULS increases the curve becomes flatter. This trend is the same in all stages for all demand types. From the graphs we see that, the lowest total cost is achieved when ULS is one. This is the ideal case for a JIT production system.

When the behavior of the total cost is analyzed, it is seen that the total cost function is almost flat for ULS values exceeding five, i. e. , the 10 percent of the maximum demand. Hence, as it is claimed in actual manufacturing systems [24], the cost function is insensitive to ULS values exceeding 10 percent of the demand.

It has also been observed that some variables take non-integer values. But, these variables are naturally restricted to have integer values. After rounding the values of non-integer variables to integer values, due to some constraints, particularly due to equality constraints, infeasibilities might arise. Therefore, we perturbed the solution to obtain integer values while keeping the feasibility. Henceforth, the new feasible integer values are obtained and cost figures are recalculated. The analysis of the solutions shows that when all

variables	solutions obtained from LP package	values after rounding to integer
P_1^1	13.5	14
P_2^1	16.5	17
P_3^1	13	13
P_1^2	27	28
P_2^2	33	34
P_3^2	26	26
P_1^3	27	28
P_2^3	33	34
P_3^3	26	26
X^1	17	17
X^2	33	34
X^3	33	34
C^1	16.5	17
C^2	33	34
C^3	33	34
total cost	56285	57617

Table 5.1: An example for cost analysis between non-integer values and their rounded values

variables are perturbed to integer values total cost changes only at most 4 percent of the relaxed LP solution in each direction. An example of the effect of rounding the non-integer solutions on the total cost is given in the Table 5.1.

The above analyses are based on a reasonable number of stages and time periods together with a set of logical parameters. Considering this fact, the results of the analysis cannot be strongly generalized. They essentially help us to see how the model behaves under a specific scenario.

5.2 Simulation Approach

The results of the simulation give an idea about the long run behavior of the system. Again, the analysis of the solution is based on the average values of different runs for each problem.

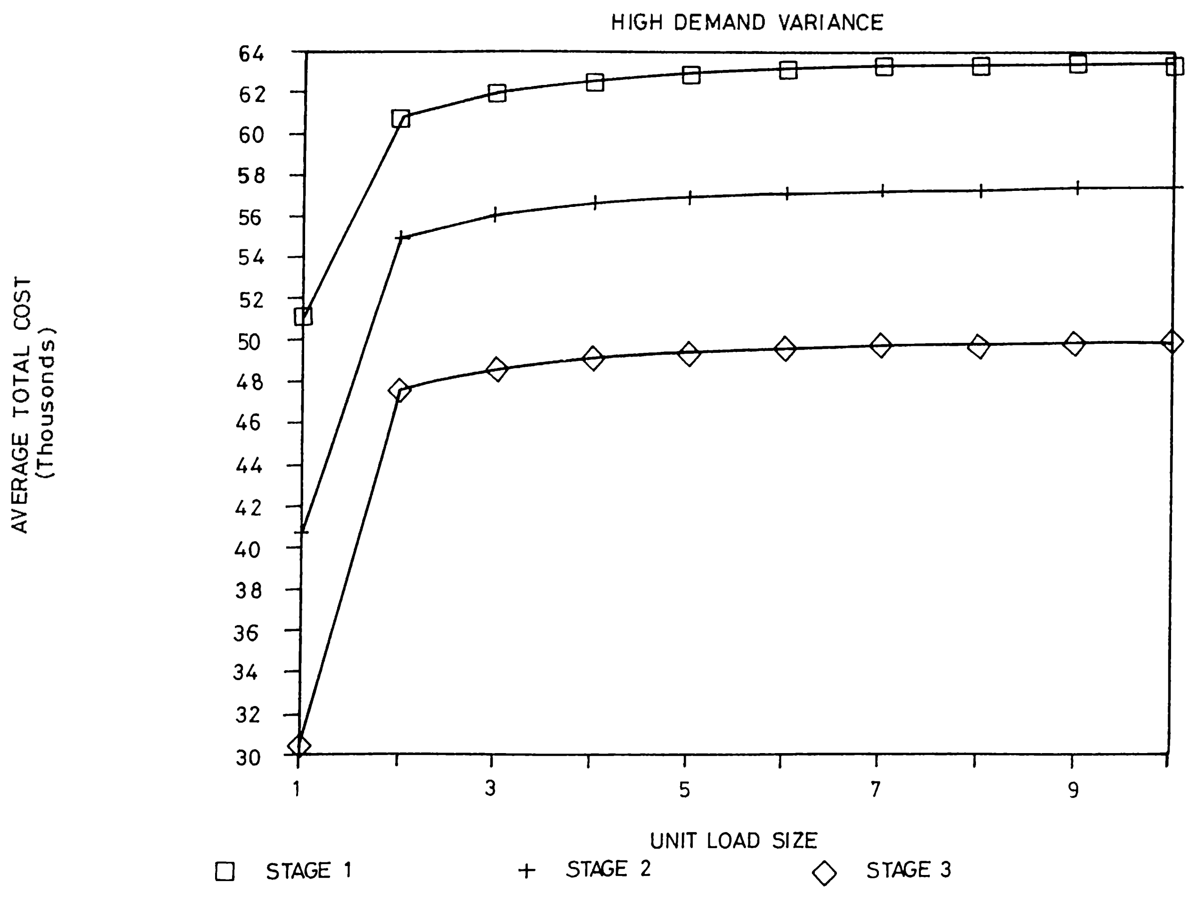

Figure 5.1: Total cost versus ULS for high demand variability

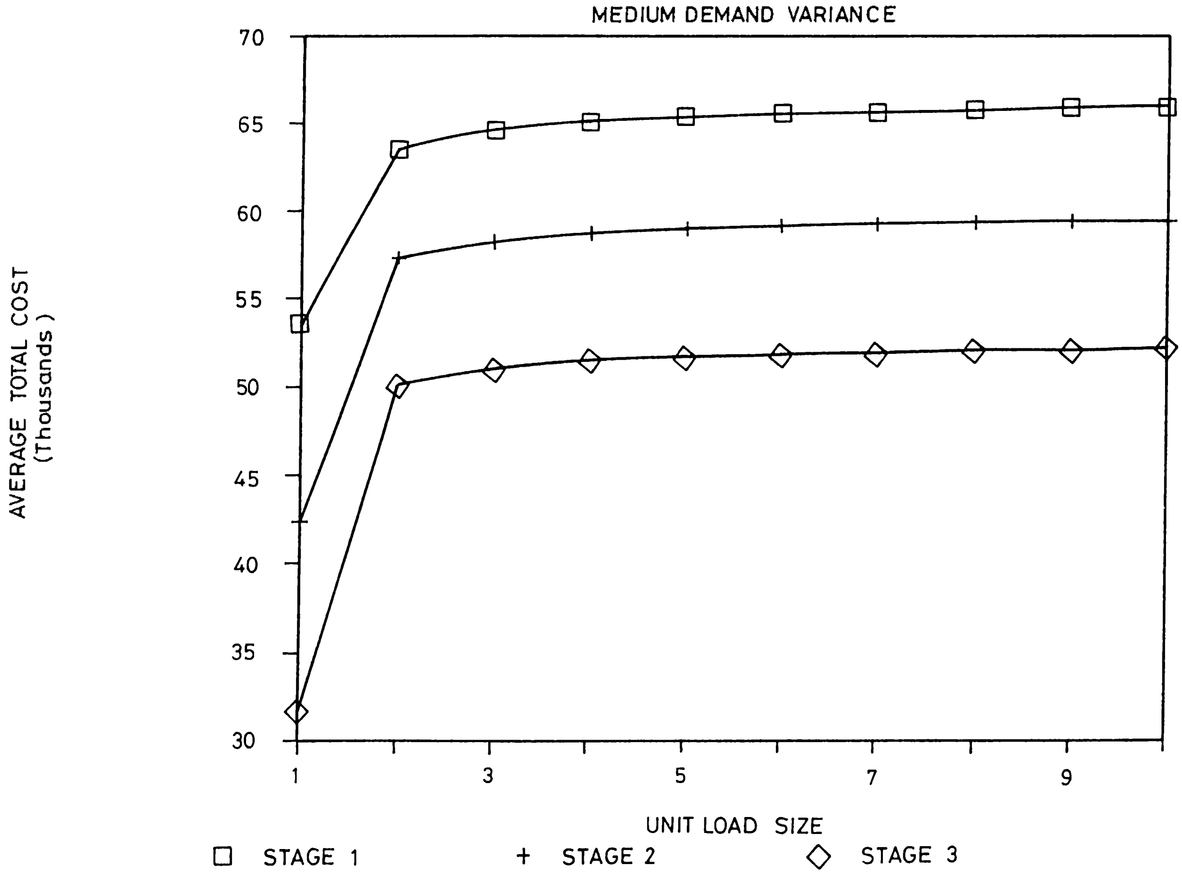

Figure 5.2: Total cost versus ULS for medium demand variability

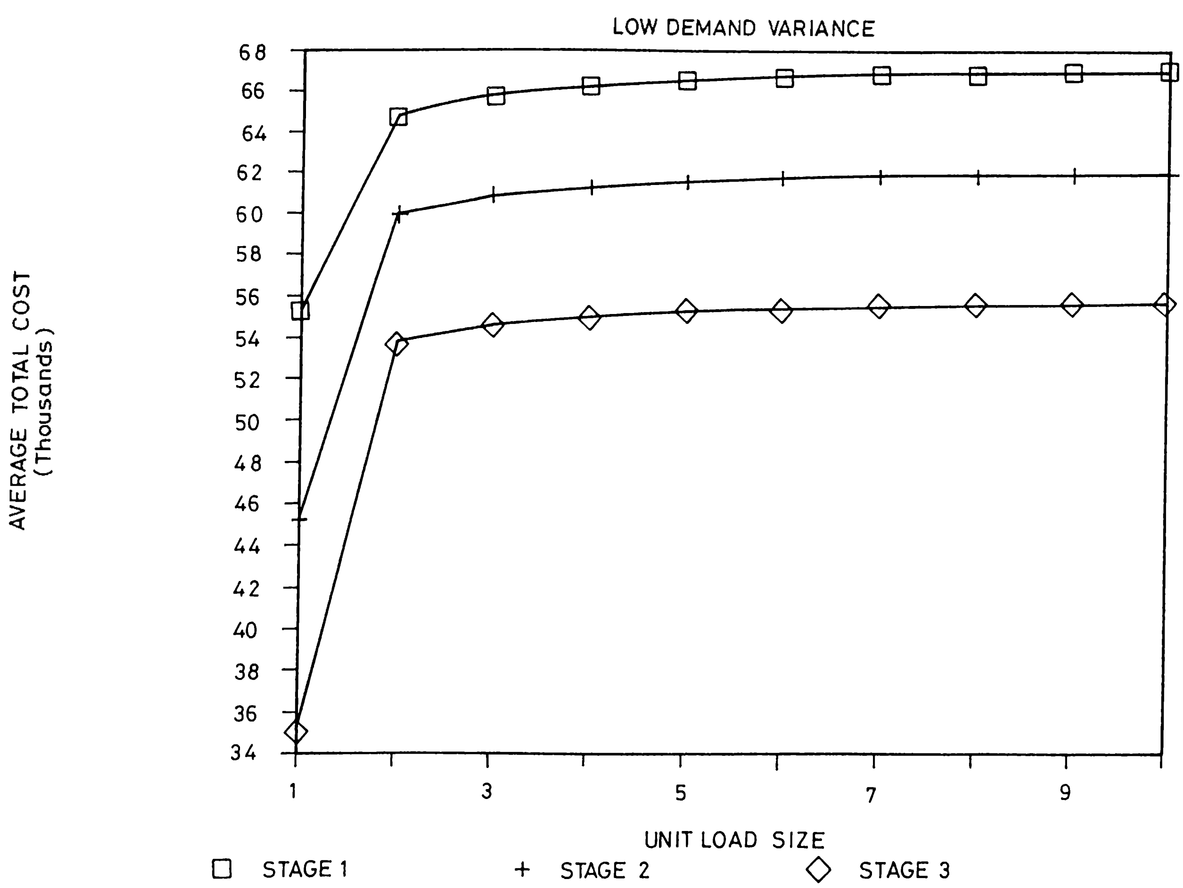

Figure 5.3: Total cost versus ULS for low demand variability

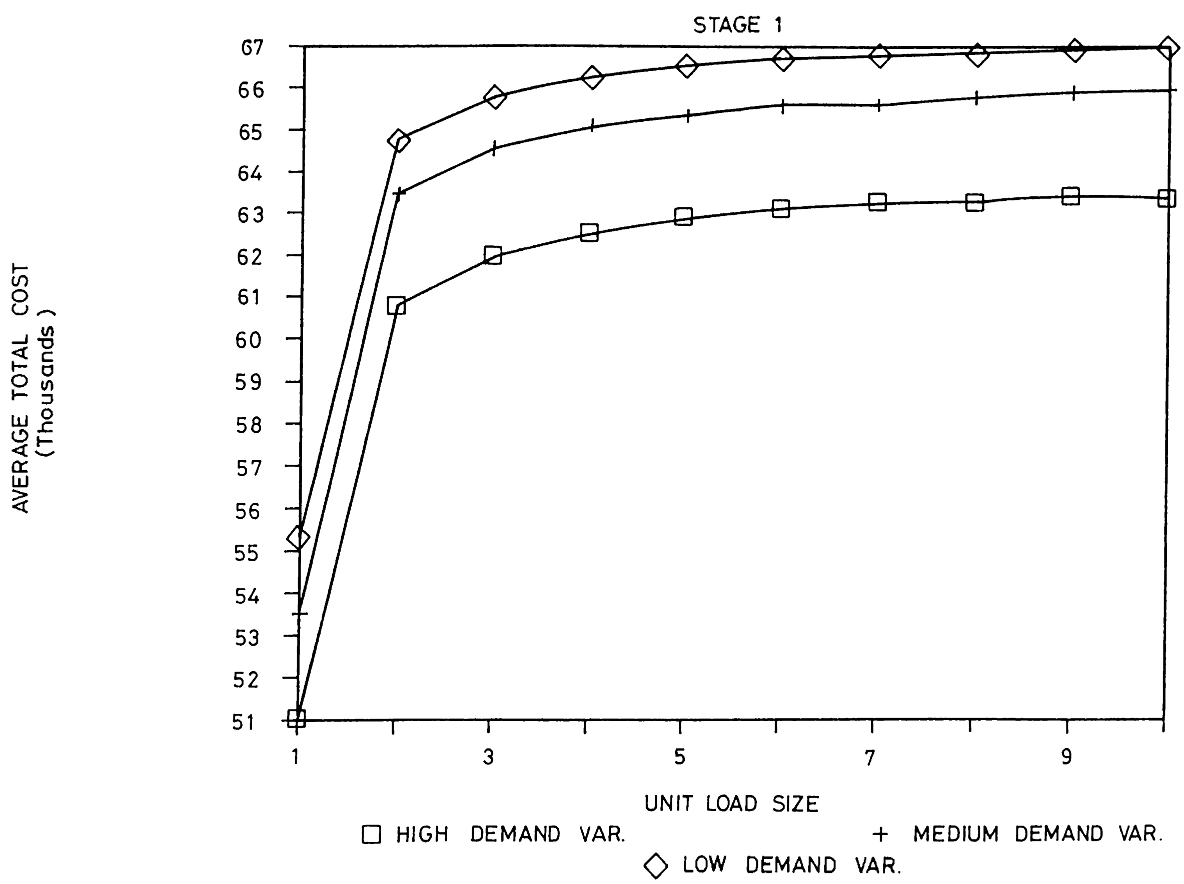

Figure 5.4: Total cost versus ULS for stage 1

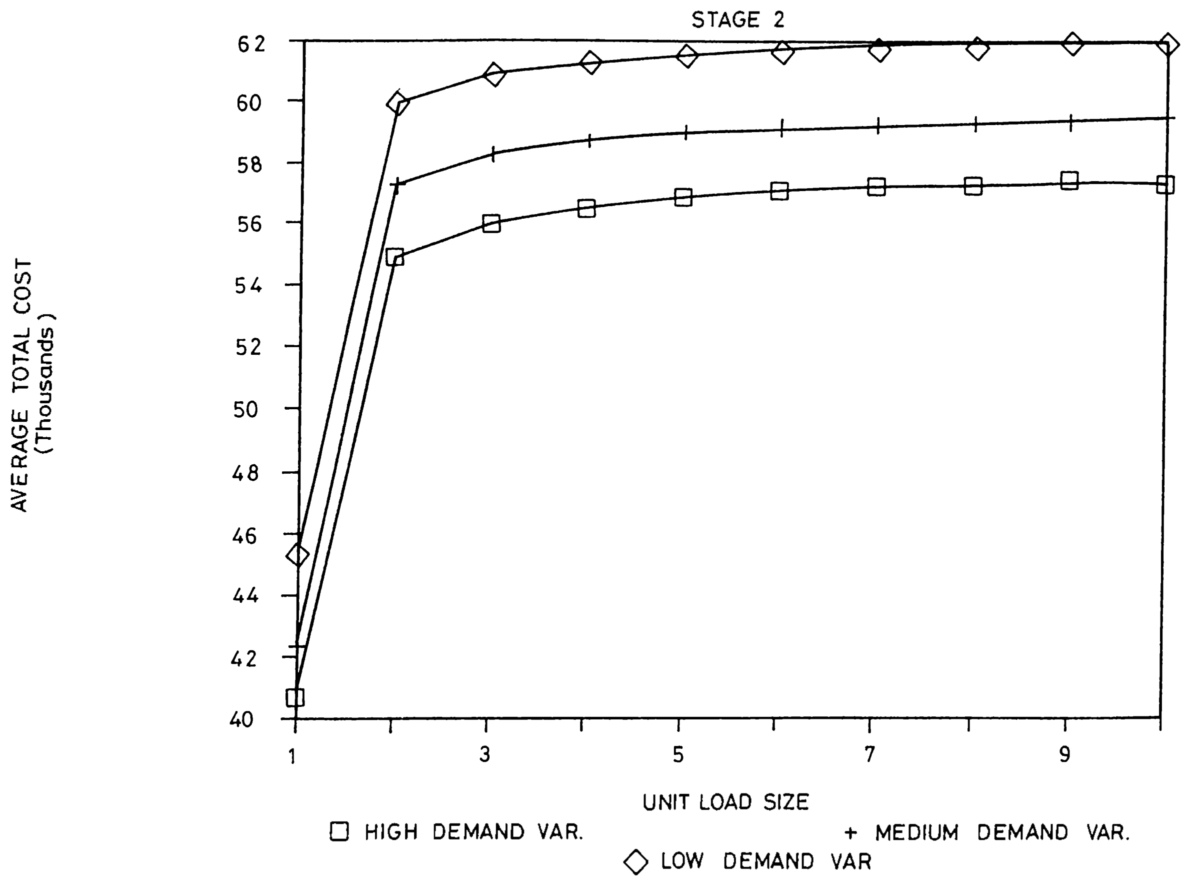

Figure 5.5: Total cost versus ULS for stage 2

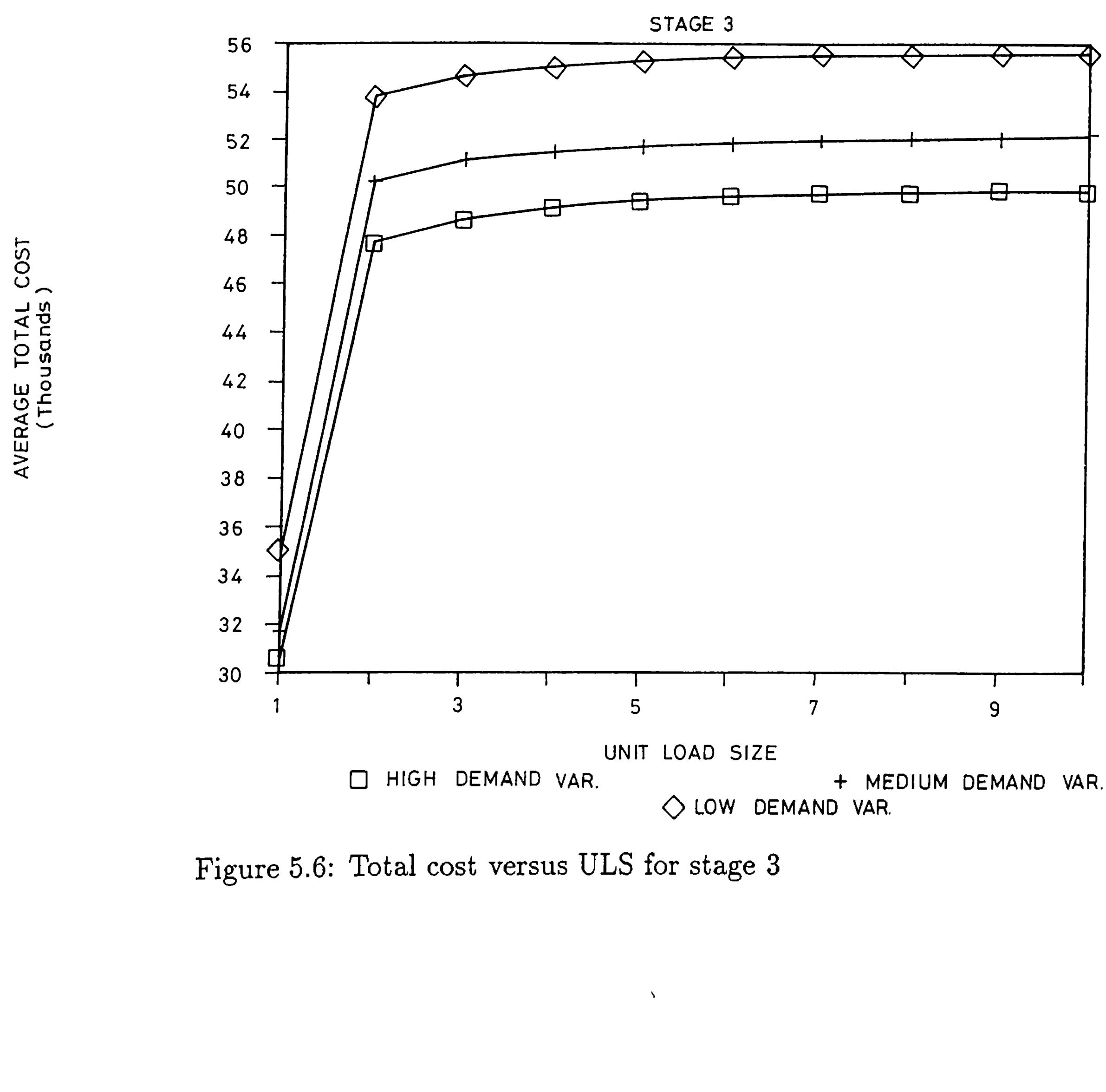

Figure 5.6: Total cost versus ULS for stage 3

The same sort of analysis is carried for the simulation as in the LP approach. Once again, ULS changes are analyzed for different demand variations for each stage. During the analysis, while changing the ULS value of one stage, the ULS values of the other stages are held constant. The purpose of this approach is to see the effect of ULS changes at one stage.

In the model, one of the constraints on the production quantity at a stage is the buffer capacity of that particular stage. As an extension, the buffer capacity is taken as a parameter to see its effect on the system. The results show that as buffer capacity increases, the cost function becomes concave. When buffer capacity is tight relative to the demand, hence production amount, the cost function becomes convex and one unit of ULS is no longer the optimum solution.

The results of the simulation support the LP solutions with respect to the buffer capacity. As buffer capacity increases, it behaves as an uncapacitated system and cost function changes to a concave function from a convex one for the first stage. In other stages, total cost decreases as ULS increases. This change in the behavior of the cost function is due to the number of time periods considered. In LP case, only three time periods are considered. This can represent the transient state of the system. But in simulation, the number of time periods is taken as 600 to see the behavior of the system in the long run. This means the results of the simulation reflects the steady state response of the system. The impact of the first stage is augmented in the long run as expected. In the short run, each stage resembles to each other. But in the long run due to the combined effects in time, the preceding stages behave differently from the initial stage.

In order to support the above claim, the simulation is performed for three period case and it is seen that the simulation results are the same as the LP results. It is seen that the behavior of three stages is almost the same with each other. Although there are some slight differences for the last two stages, these can be attributed to the side effects of other changes made in the simulation. The general result is that the cost function is always concave for all stages.

The slope of the cost function becomes flatter as ULS value increases. This means that there is no significant changes in the cost function after

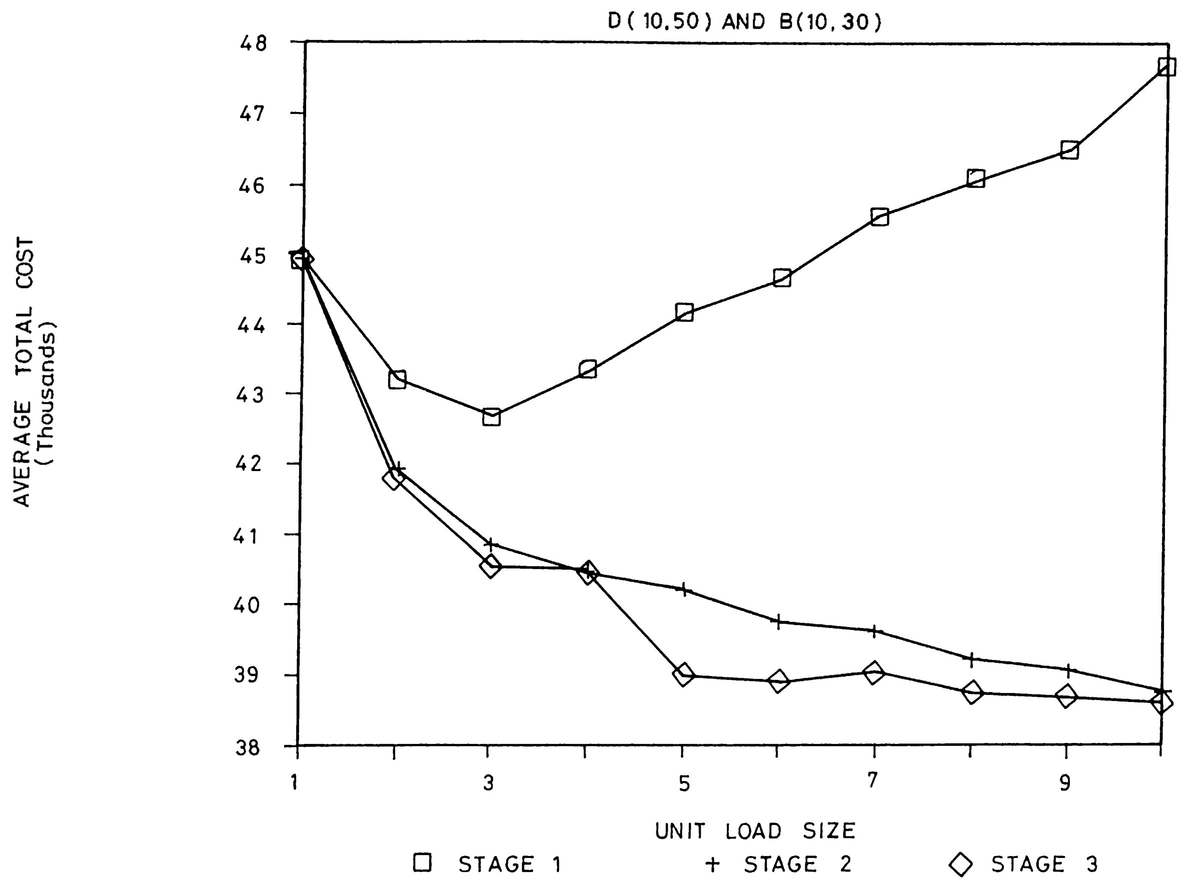

Figure 5.7: Total cost versus ULS for high demand variability and buffer capacity less than mean demand

some value of ULS. It is observed that as in the linear programming case, the model is insensitive to ULS values after the 10 percent of the maximum demand. Furthermore, the variations in the cost function decreases for stages closer to the raw material stage. This suggests that the pull system absorbs the fluctuations of the demand and other parameters and it prevents the transfer of these variations to the upper stages.

The results are given in the graphs of Figure 5.7 to Figure 5.12.

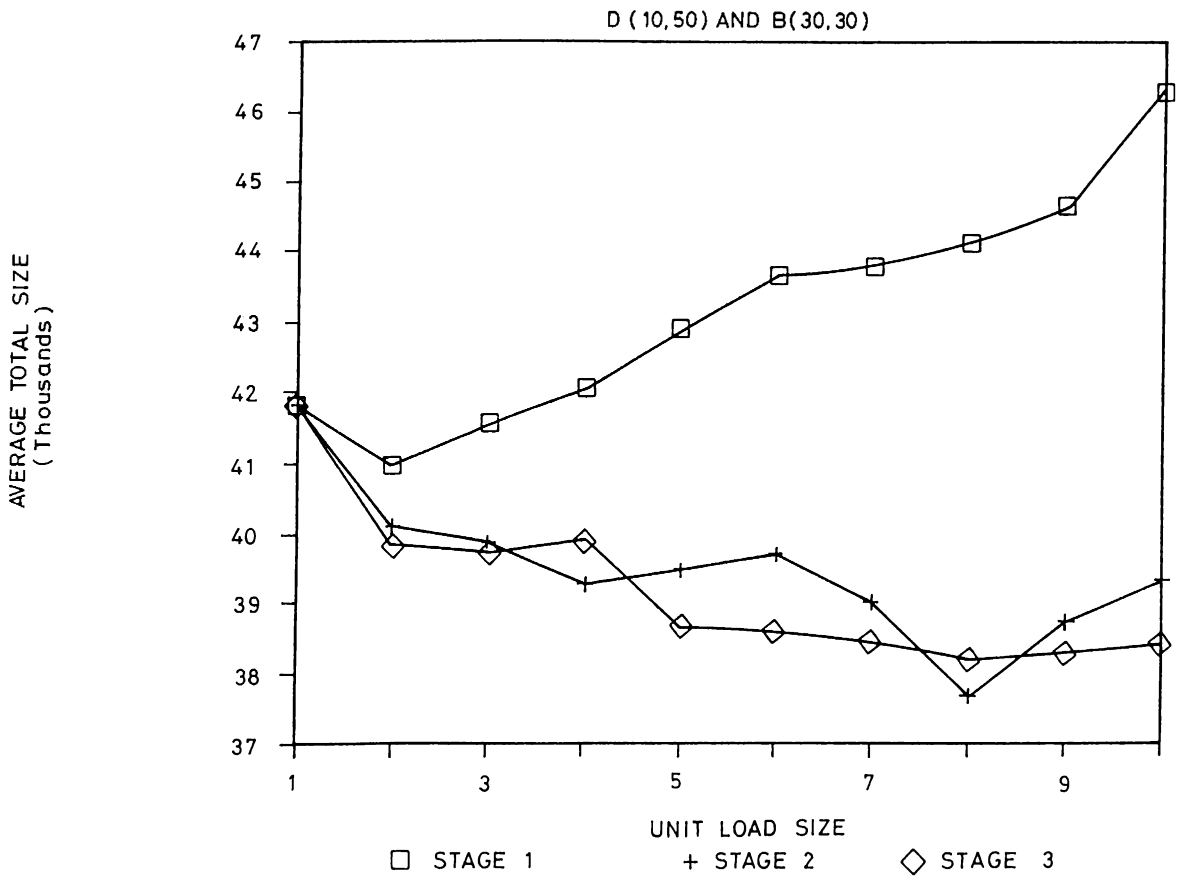

Figure 5.8: Total cost versus ULS for high demand variability and buffer capacity at mean demand

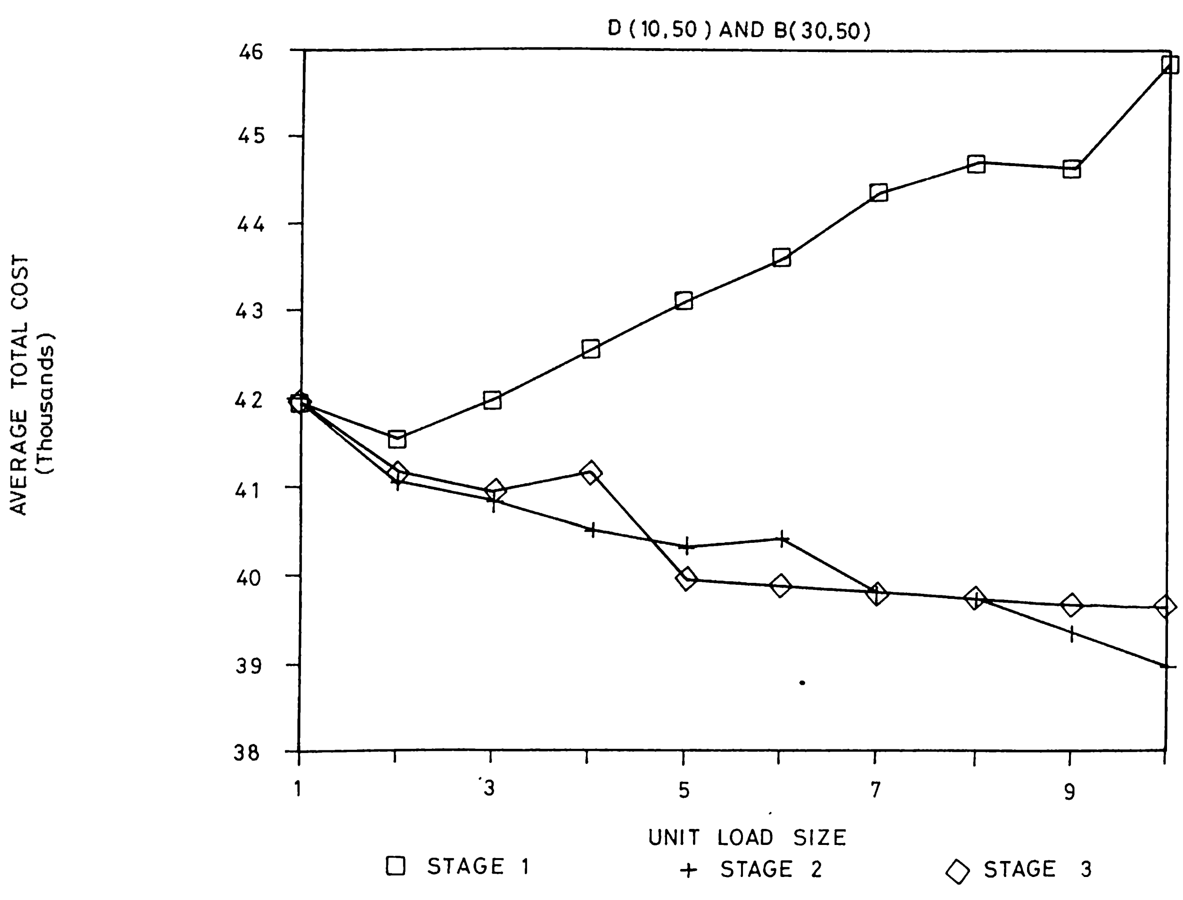

Figure 5.9: Total cost versus ULS for high demand variability and buffer capacity greater than mean demand

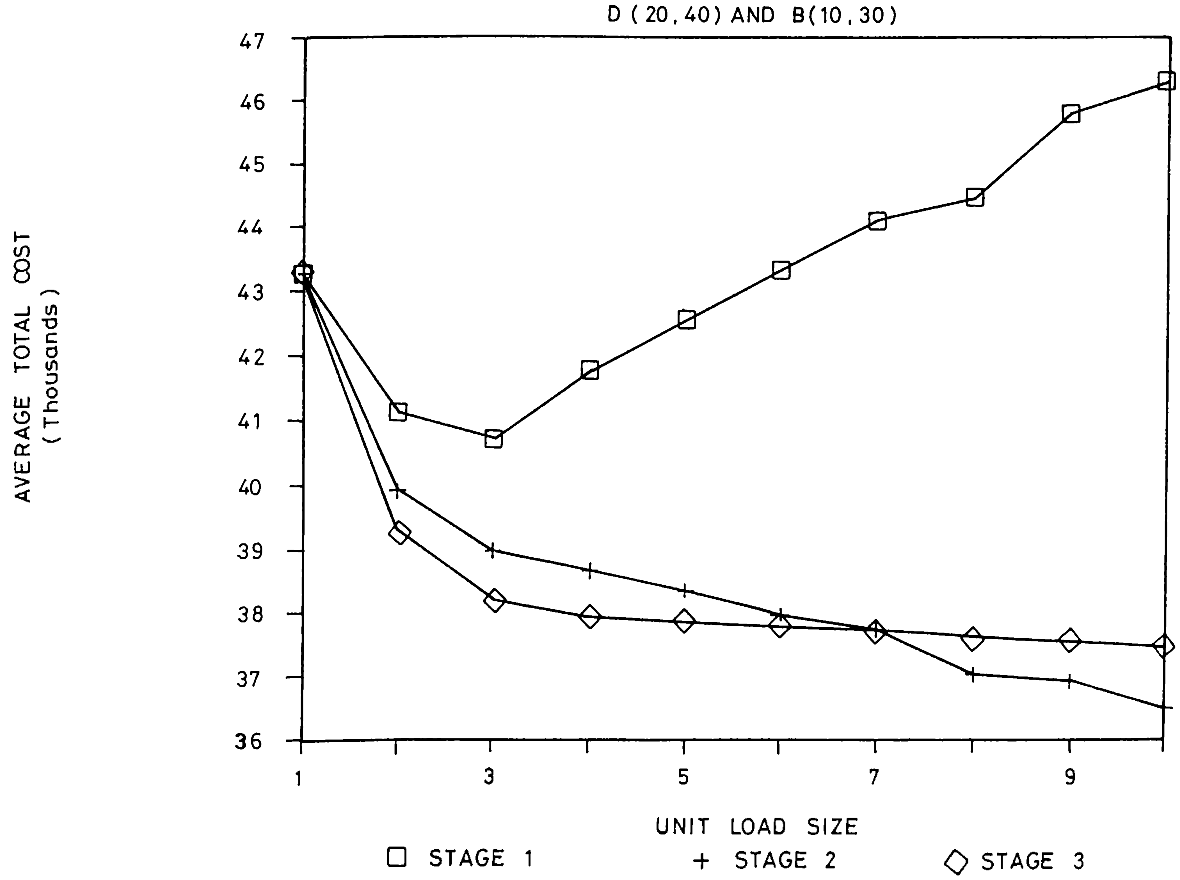

Figure 5.10: Total cost versus ULS for medium demand variability and buffer capacity less than mean demand

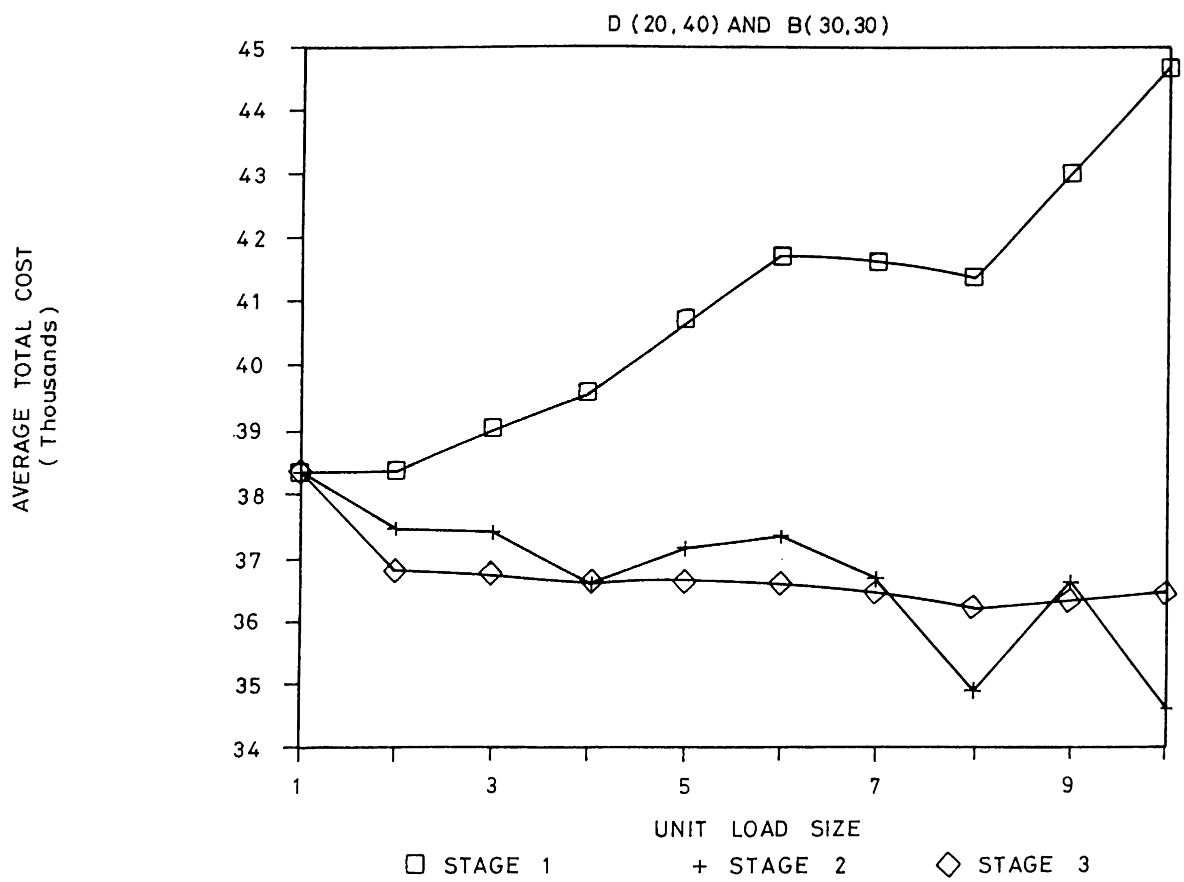

Figure 5.11: Total cost versus ULS for medium demand variability and buffer capacity at mean demand

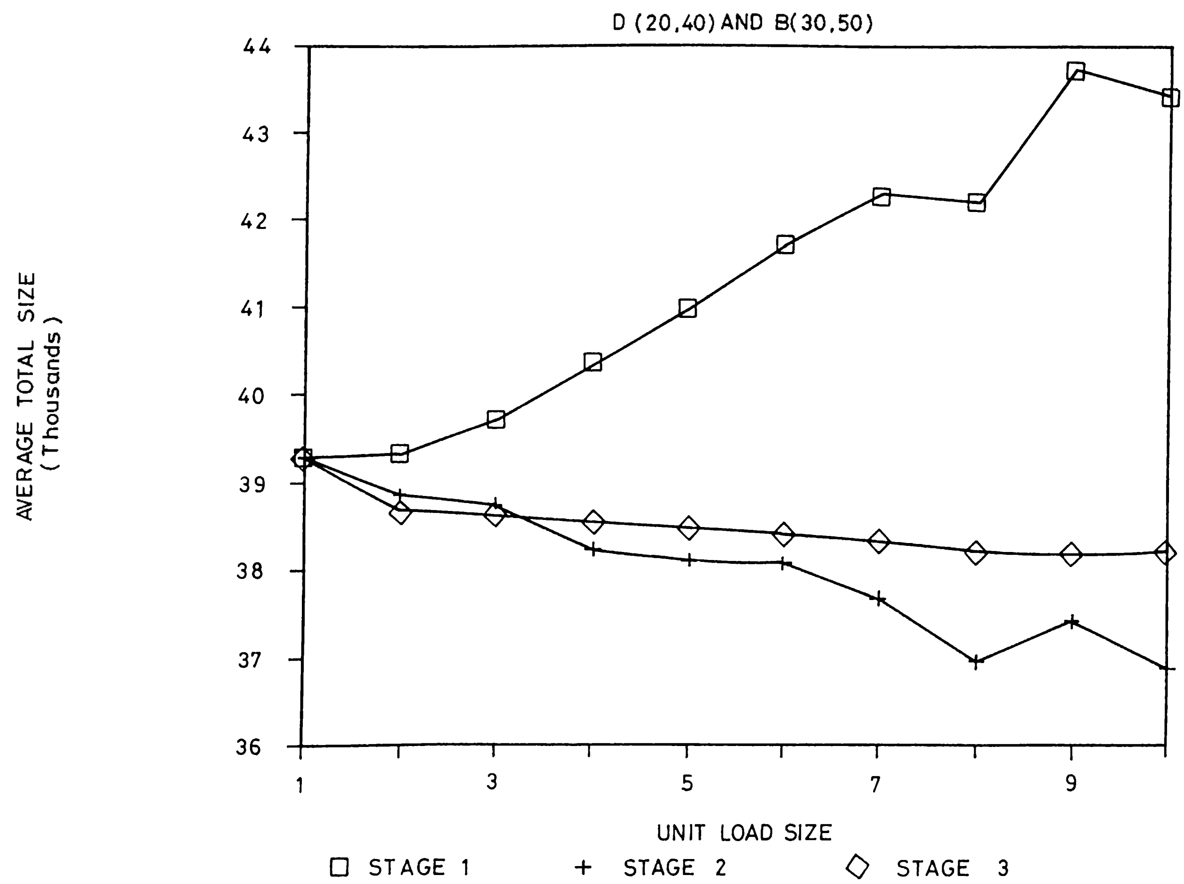

Figure 5.12: Total cost versus ULS for medium demand variability and buffer capacity greater than mean demand

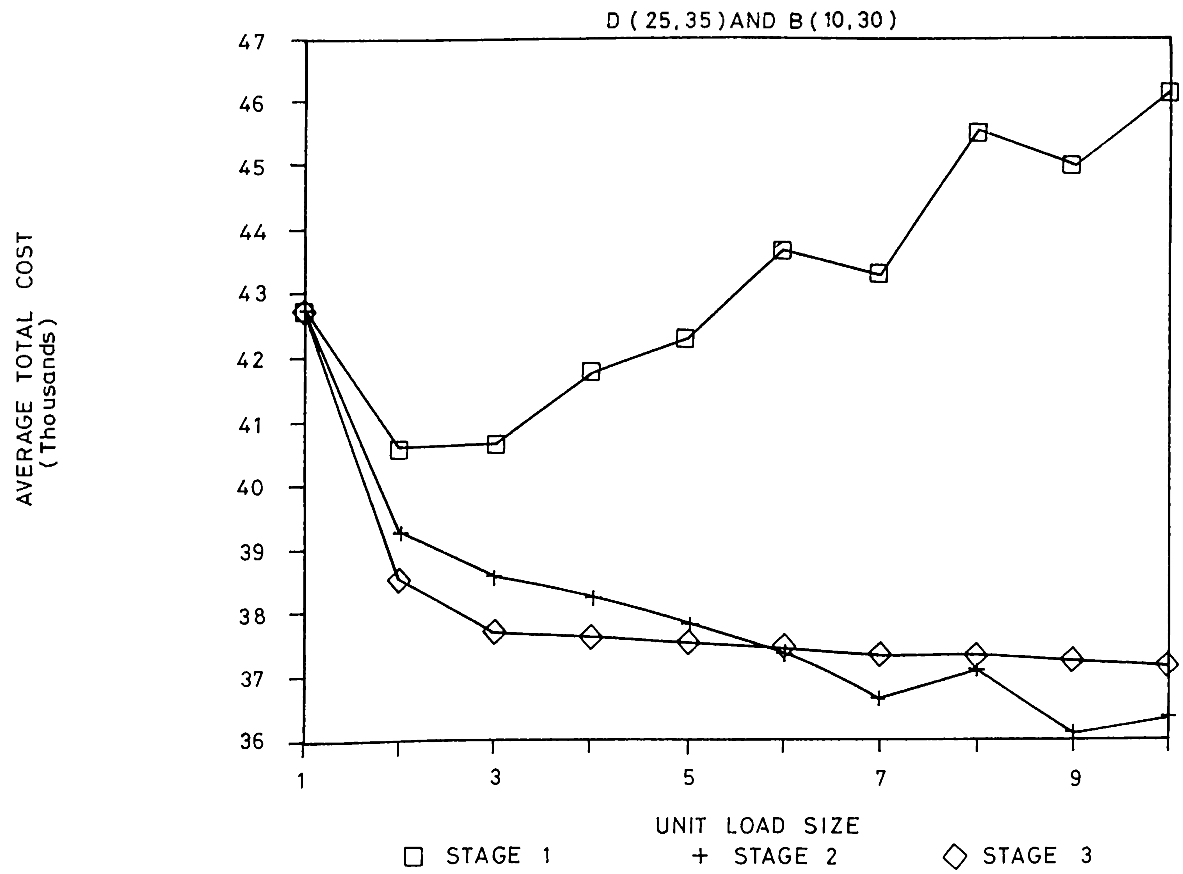

Figure 5.13: Total cost versus ULS for low demand variability and buffer capacity less than mean demand

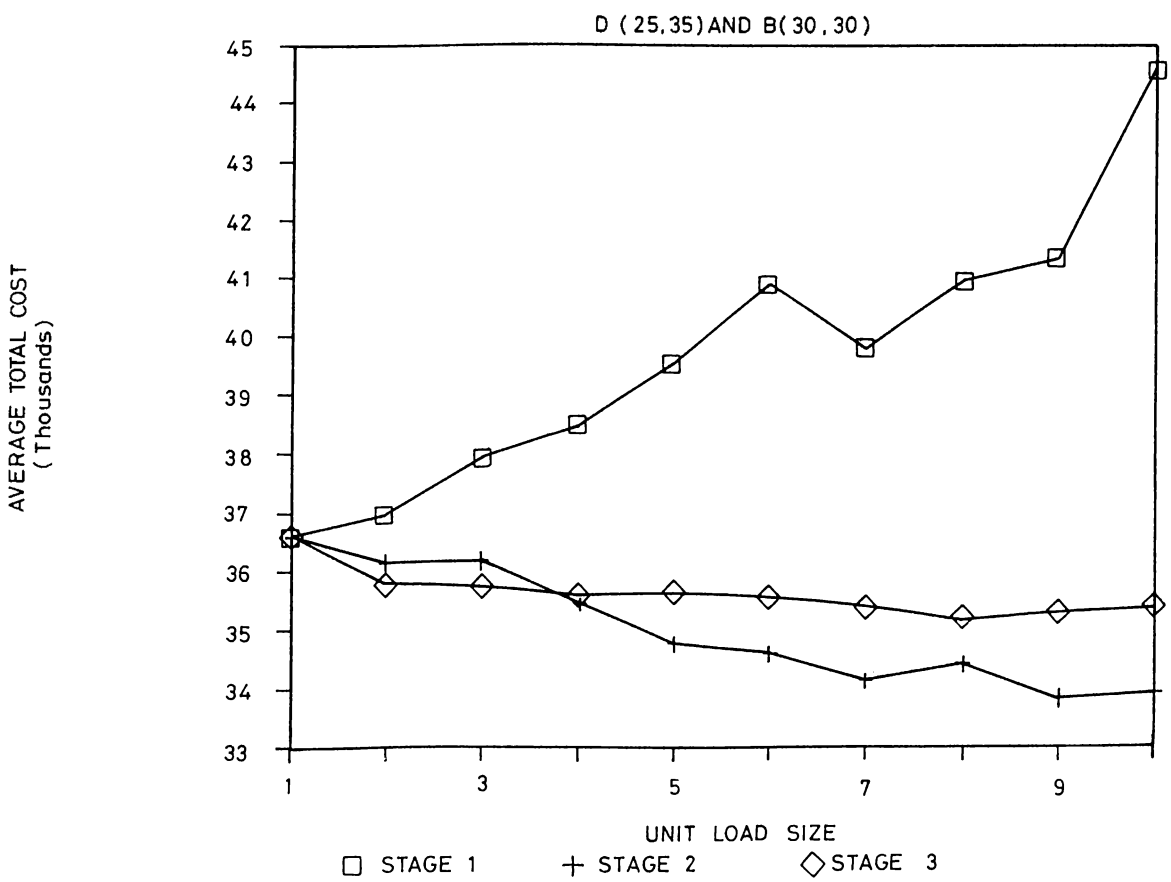

Figure 5.14: Total cost versus ULS for low demand variability and buffer capacity at mean demand

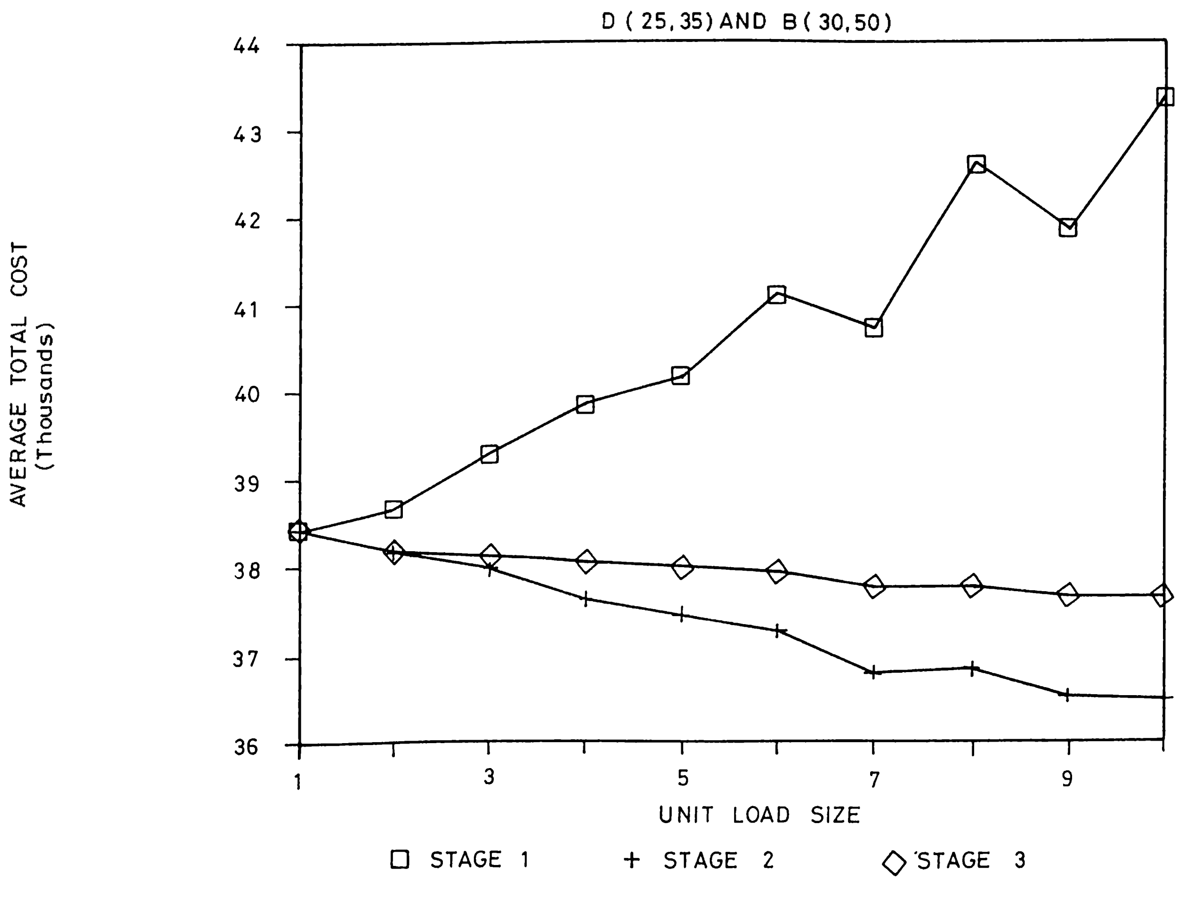

Figure 5.15: Total cost versus ULS for low demand variability and buffer capacity greater than mean demand

5.3 Comparison of the Results of Two Approaches

Analyzing and comparing the results of two approaches lead to the following conclusions:

1. ULS values exceeding the 10 percent of the maximum demand in the planning horizon has no effect on the behavior of the system in both the transient and the steady state.

2. Although the ideal case, i. e. , one unit of ULS is achieved in the transient state, the optimum ULS value is greater than that in the steady state. Since time buckets are short in a JIT production system, the transient behavior is important. Furthermore, it becomes more significant if demand is not stable..

3. The impact of the succeeding stages on preceding stages can be felt in the steady state. In this case, the stages behave differently and as we proceed through the raw materials stage the optimum ULS value increases. In the transient state, each stage shows similar behavior by not reflecting the impact of the succeeding stages.

4. Buffer capacity has an important effect on the response of the model. If the buffer capacity is high, then the system acts as if it is uncapacitated and the optimum ULS is achieved at one unit. But as buffer capacity decreases, the optimum ULS value increases. However, this increase as stated above never exceeds the 10 percent of the maximum demand. As there is no explicit cost related to capacity, the change in the capacity as ULS values change is expected.

6. CONCLUSION AND SUGGESTIONS FOR FURTHER RESEARCH

By designing an efficient JIT production system as suggested in this study, direct and indirect cost savings can be realized. These savings will mostly be due to improvements in production efficiency which implies using fewer materials and less labor and reducing overhead to achieve the same output.

Under JIT manufacturing system production control changes from pushing product through the production process to allowing manufacturing to pull its production needs (kanban system). The pull system results in a reduction in workload for production control and an increase in responsibility for the production function. The JIT philosophy is to simplify every phase of manufacturing and thereby prevent the waste. The actual mechanism that reduces inventory is the pull production system. The pull system works by preventing the build-up of inventory and allowing problem resolution.

In this study, a mathematical model for JIT production systems is developed and analyzed under several assumptions. The system considered is supposed to have a single item together with deterministic processing times and balanced production lines to make computational tractability possible. But the actual processing times are stochastic in most of the manufacturing environments. Also, if the system is a multi-item production system, then there will be the problem of determining the right mix of products.

In addition, multi-line production systems, both dedicated and shared type, are prevalent in majority of manufacturing settings as opposed to a single-line system considered here. The shared production lines bring the concept of mixed modeling for multi-product case. The application of mixed-models to shared lines becomes possible when setup times are reduced such that there is no delay in changing to a different model. From this point of view, the mixed model lines are similar to Flexible Manufacturing System cells. There is not any paper to date that we are aware of dealing with the mixed-model problem analytically in JIT production system. And that sort of work will be rewarding.

When the line is well-balanced, that is the cycle time is determined based on the slowest moving product or based on the lowest throughput rate, the problem is to determine the sequence and ratio of the parts to be introduced to the line as long as the schedules of the succeeding lines remain the same. So, re-scheduling and re-balancing is a problem in mixed-model lines due to the changes that occur in the final assembly mix.

Another problem in JIT production systems is line balancing. In most line balancing techniques, processing times are assumed to be constant but this does not generally hold in manufacturing environments. This problem becomes more complex in mixed-model lines if the processing times are stochastic. Because in mixed model lines standardization of operations and equal allocation of operations to work stations are difficult tasks. This results in accumulating in-process inventories in JIT environments. So, buffering is another issue that arises in the context of line balancing. The decision to be made is the placement and the size of the buffers in-between the stages.

Due to the variable processing times and limitations on buffer capacities, blocking and starving of stages can occur in line balancing. This problem can be handled by seeing the system as a queueing network or an analysis can be carried through a simulation model of the JIT system. In such an analysis, different distributions for the processing times, with different coefficients of variations can be tested as to their effects on the system performance. In a mixed model line, not only the variable processing times but also the different processing times among different products affect the buffer capacities. Hence, in addition to buffer sizing, scheduling rules for each station should also be considered. Furthermore, if setup cost is incurred on the production line, due to multiple products, lotsizing should be simultaneously taken into account with buffer sizing.

In multi-line systems, if the lines are shared, scheduling and sequencing problem arises. The main philosophy of JIT is to produce parts just in time, neither before nor after the required time. So both early and late completion are undesirable conditions. Cost of lateness can be defined explicitly whereas the cost associated with earliness can be defined indirectly. If a job is finished early there will be a capital tied up in the job, so an opportunity cost is incurred. Furthermore, early completion decreases the utilization and the efficiency of production.

A realistic objective would be to achieve minimum possible earliness. The scheduling and sequencing in a JIT mixed-model line turn out to be an n-job m-machine flow shop scheduling problem with the objective of minimizing the total earlinesses of jobs throughout the line. At this point the determination of due dates arises as an important concept. They provide the coordination and synchronization of all flow lines in the plant. Late due dates may cause backlogs whereas early due dates may cause extra in-process inventories to accumulate. Another problem in production systems may be to determine which products/stages to use JIT concept and for which of them to implement the MRP concept. This results with the so called hybrid systems.

The solution procedures for the abovementioned problems can be developed either by mathematical programming or simulation or queueing network approach. Up to now, most of the work done on these problems rely on simulation techniques. There are few research on queueing network, especially using phase type distribution for the processing times, for JIT production systems [3], [8].

Since resulting network is difficult to handle, in queueing networks, single-stage or two-stage system can be efficiently analyzed. Then determining a control mechanism between a set of two-stage or single- stage systems, the system can be generalized. Hence, an approximate solution can be found.

In [3], it has been shown that stochastic kanban-controled lines and tandem queues are equivalent. This means that they have identical average throughput and aggregate in-process inventories. Therefore, a kanban-controled system can be formulated as a continuous time Markov chain with discrete state space. So, this can be used to develop some methodologies to approximate average throughput and in-process inventories of a kanban-controled system.

APPENDIX A

This appendix presents the typical result of one of the problem instances: Low demand variation with unit load size of the first stage being equal to two.

These results show that there is not any amount carried in inventory. In addition, there is no backlogging. As it can be seen from the below table, the solution indicates to produce exactly the same amount as production orders at each stage at each period. Naturally, there will be no inventory carried and no backlog.

Furthermore, the buffer capacity is set to the production amount of each period. Similarly, production capacity is set to the maximum production amount at each stage during the planning horizon.

variable	value	reduced cost
X^1	17.00	-82.5726
X^2	33.00	-447.6212
X^3	33.00	-252.4527
C^1	16.50	0.0
C^2	33.00	0.0
C^3	33.00	0.0
P_1^1	13.5	0.0
P_2^1	16.5	0.0
P_3^1	13.0	0.0
P_1^2	27.0	0.0
P_2^2	33.0	0.0
P_3^2	26.0	0.0
P_1^3	27.0	0.0
P_2^3	33.0	0.0
P_3^3	26.0	0.0
O_1^1	13.5	0.0
O_2^1	16.5	0.0
O_3^1	13.0	0.0
O_1^2	27.0	0.0
O_2^2	33.0	0.0
O_3^2	26.0	0.0
O_1^3	27.0	0.0
O_2^3	33.0	0.0
O_3^3	26.0	0.0
objective function	64087.67	–

APPENDIX B

In this appendix, the computer programs that are used to analyze the system are briefly explained.

The programs used in the mathematical module developed for the deterministic analysis are DGEN.FOR and MPS.FOR. The first program, DGEN.FOR, is used to generate the required data of the model from the initial data explained in Chapter 4. DGEN.FOR generates the data in the input format of the next program, MPS.FOR. MPS.FOR generates the required input of the package program, Hyper LINDO, in the MPS format.

In the simulation, next-event time advance mechanism is used. Although, this is a periodic review case and fixed- increment time advance mechanism may be more appropriate, former one is preferred in order to be more flexible. Hence if it is decided to evaluate the system continuously (i. e. , as each event occurs in real life), the model can easily be modified for that case.

In the simulation there are three types of events exist:

1. Demand arrival (distributed U(1,1))
2. End of simulation (total time that simulation will run)
3. Evaluation of the system (occurs at the end of each period, so it is incremented by 1. Also it is same with demand arrival times because of periodic review approach)

The main event that specifies the time points when the system has been evaluated is the first event. Consequently, the demand occurrence time is generated from $U(1,1)$ distribution. So, in fact, the first and third activities occur at the same time and can be considered as one activity. But since in continuous review this will not be the case, this approach is used in the simulation.

The production activity is not considered as an event because it is not important to look at the system at points when production begins or ends. The essential point is to look at the system at the times of demand arrival and see how much inventory is accumulated. This accumulated inventory implicitly show the amount of production from the previous time point up to the current time point.

The production quantity (that is actually produced amount) is determined from the minimum of the values of buffer capacity, production capacity of that stage and the inventory on-hand of the preceding stage.

At the end of the simulation, the mean and variance of the total cost is analyzed under different policies. Then, according to the results obtained the best (or next best) policy is chosen.

In this study, total cost includes the production cost, inventory holding cost, backlog cost and container cost. Production cost consists of the processing cost together with the fixed machine cost.

Simulation program for the system explained above is coded in FORTRAN. The following are the list of subroutines used in the program.
INIT : initialization routine
TIMING : timing routine
DEMAND : event routine which processes type 1 events
REPORT : event routine which processes type 2 events (report generator)
EVALU : event routine which processes type 3 events
UPDT : subroutine to update areas under inventory functions when inventory level changes and when simulation ends (not an event routine)
UPDATE : subroutine to update the time since last event which changed the inventory level
PRODN : subroutine that evaluates production activities for each stage
UNIFRM(Z,A,B) : function which generates a continuous random variable uniformly distributed on the interval [A,B] where A and B are real-valued and A must be less than B, Z is the seed

DRAND(Z) : function which generates a random number between 0 and 1

The complete list of all programs can be obtained from:

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