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System dynamics modelling and analysis of just-in-time manufacturing systems.

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University of Windsor

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SYSTEM DYNAMICS MODELLING AND ANALYSIS
OF
JUST-IN-TIME MANUFACTURING SYSTEMS

by

Jagjit Kaur Brar

A Thesis
submitted to the
Faculty of Graduate Studies and Research
through the Department of
Industrial Engineering in Partial Fulfillment
of the requirements for the Degree
of Master of Applied Science at
the University of Windsor

Windsor, Ontario, Canada

1991

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ABSTRACT

Just-in-time systems have received considerable attention in the modern manufacturing environment due to some basic concepts of waste reduction and quality improvements. The pull nature of this system has been compared extensively to conventional push systems. Another type of system, long pull, combines both push and pull concepts. The objective of this research is to model and provide a comprehensive analysis of push, pull and long pull systems. The role of these systems on work-in-process inventories and throughput is investigated through simulation runs for the models developed using the simulation package DYNAMO (PC version). Also, some key observations related to the allocation, span of control and the associated levels of work-in-process inventories of the long pull have been given. Further, application of the models have been extended to analyze a local spark plug assembly plant. Problems encountered by the plant have been identified and accordingly, various policies were developed.

DEDICATION

To my parents

For their support, respect and ambition

For giving so much and making dreams a reality
through honesty, hard work and determination

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NOMENCLATURE

Notations used throughout this thesis have been listed in alphabetical order. The notations not included in the list are either explained at appropriate places, or are self explanatory.

NOTATIONS

bi	Work-in-process inventory levels at the intermediate buffer stages
$\overline{B}$	Average buffer content
C.I.	Confidence interval
CV	Coefficient of variation
DCR	Delivery completion rate of plated shells
DSPRi	Desired production rate of workstation i
FPS	Finished product storage location area
KLi	Level of units in a container at workstation i
KSIZE	Container size
LS	Lost sales
LT	Lead time for raw shells manufacturing
MEANi	Mean production rate of workstation i
OINTERVAL	Interval of time between orders for shells sent for plating
PLSi	Production storage location area of workstation i
PRCORR	Production rate correction factor
PRi	Production rate of workstation i
REJECTi	Rejected parts rate at workstation i
REJLEVi	Level of rejected parts at workstation i
RSPR	Raw shell production rate
SDi	Standard deviation of workstation i

SFP	Shells for plating inventory
SFPOO	Number of shells for plating on order
SFPOR	Shells sent for plating order rate
SFPUSE	Shells for production used
SP	Shells plated inventory
SPSTK	Shells plated safety stock level
STARTi	Starting day for workstation i
T	Throughput
TPRi	Transfer to production storage location area at workstation i
TSFPOO	Total number of shells sent for plating on order
TSP	Total number of shells plated

CHAPTER 1

INTRODUCTION

Just-in-time production systems have generated a great deal of interest in the modern manufacturing environment. Just-in-time (JIT) philosophy, first introduced by the Toyota Motor Co. over 25 years ago, has received much interest in its basic underlying concept of providing "only the necessary products, at the necessary time, in the necessary quantity" (Sugimori et al. 1977). Based on this concept these systems are potentially able to overcome the two major problems of protracted lead times and accumulation of excessive work-in-process inventories and throughput maximization. The advent of just-in-time production systems focused attention on serial production lines. Efficiency and throughput considerations replaced job shop layouts to flow shop orientation.

1.1 Role of work-in-process in serial production systems

One aspect of waste in many production systems is the accumulation of work-in-process (WIP) inventories. This buildup of inventories leads to several waste aspects: under-utilization of capital investment in inventories, use of excess floor space on the shop floor, use of labour for producing extra inventory and the risk of carrying items which may become obsolete in the future. However, in serial production systems buffers (work-in-process) located between adjacent work stations are often necessary when there is a lack of synchronization in the flow of production, e.g. variable processing times , bottleneck workstations, unreliable stations, breakdown of machinery, etc.. Work-in-process inventories act as decoupling agents between workstations, thereby providing independence of operations. The position and quantity of WIP plays an important role in smoothing the production flow: Material flows from one station to the next when it has completed the production process at that station. The production flow is hindered when either *blocking* or *starving* of workstations occurs. *Blocking* of a station occurs when the operation is complete and a subsequent station's buffer is full. *Starving* occurs when a station is ready to process a part but the preceding buffer is empty. The role of WIP inventories was studied on serial production systems using various strategies such as push, pull and long pull. A description of the strategies used is given in the following sections.

1.2 Push systems

An example of a three stage push system is represented by Figure 1. In a push system information is transmitted in the same direction as the part: jobs entering the system are queued at the first process and scheduled for further processes until the job leaves the system. The jobs leave the system in the same order that they are fed into the first process. In the case of a push system with infinite buffers there is no *blocking* of parts since there is no restriction placed on the buffer size. If the push system contains finite buffers (level of work-in-process in the buffer is limited) then blocking of parts may occur. The push system with infinite buffers (level of work-in-process in the buffers is not limited) does not react to changes in demand and the throughput is dictated by the production processes.

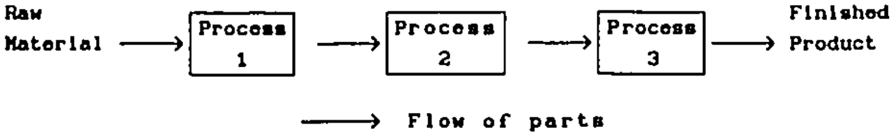

Figure 1: Push system

1.3 Kanban controlled pull systems

The transmittal of information distinguishes a pull system from a push system. In a pull system, parts move in the same direction as the push system, but the information concerning the processing of the part is given by the subsequent process.

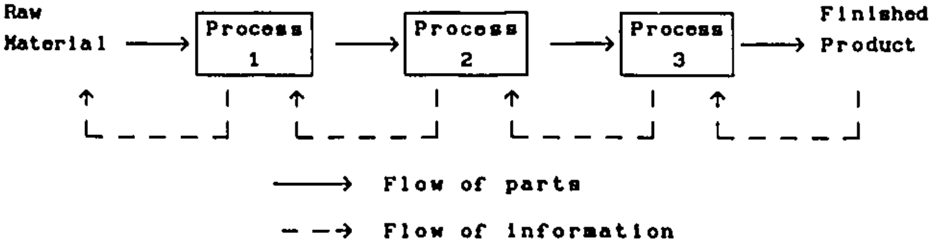

Figure 2: Pull system

In Figure 2 the part moves from process 1 to process 2 and finishes at prccess 3 but the transmittal of information starts at process 3 (i.e. the finished product). Process 3 requires process 2 to be finished which in turn requires process 1 to be complete. Process 3 is started if there is a demand present and the corresponding buffer for process 3 is depleted. When the buffer reaches a predetermined level called the trigger level this sends an information flow to process 2 to replenish the inventory depleted at process 3 until the trigger level is reached. Similarly, there are trigger levels for processes 1 and 2 and these processes will react in the same manner as described for process 3. These links between processes constitute feedback loops. A feedback loop consists of two or more linkages connected in such a manner that at any position within the loop the arrows can be followed to return to the original position.

Kanban in a pull system is a card attached to standard containers which issues the production and withdrawals of parts between workstations. It is usually viewed as an information system that controls production. There are two types of kanban cards: withdrawal kanbans and production kanbans. A withdrawal kanban specifies the quantity to be withdrawn by the subsequent process. Whereas a production kanban specifies the quantity of product to be produced by the preceding process. If workstations in a plant are located close to each other then the transportation of containers is minimal and can be neglected. Therefore withdrawal kanbans can be neglected.

1.4 Long pull systems

In the long pull systems the instant that one unit is finished at the end of the pull, one unit is allowed to enter the system. In this system the individual buffers are not limited but the total number of units in the span of the long pull is limited. This system is triggered in the same way that a pull triggers production from the preceding process. However, the control of the long pull encompasses more than just one workstation. In Figure 3 the span of the pull is located from process 3 and creates a pull on process 1 when the trigger level at process 3 is activated. Once process 1 is started the unit produced is pushed through the subsequent processes (2 and 3) in a similar manner as that of push system. A trigger may be active but process 1 may not produce an additional part if the maximum inventory allowed within the span of the pull is reached.

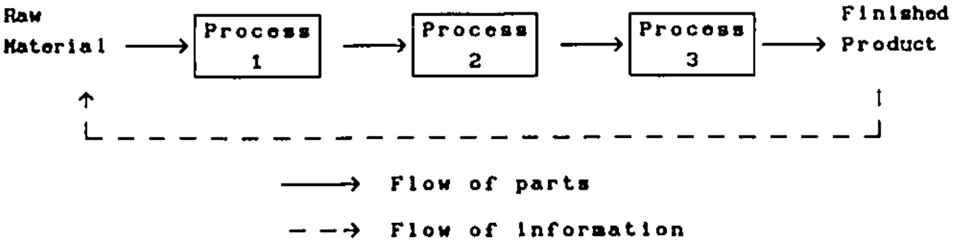

Figure 3: Long pull system

1.5 System dynamics modelling approach

The various systems mentioned were developed into simulation models using the concepts from system dynamics. The term dynamic addresses problems which involve quantities which change over time. System dynamics provides the following elements for effective planning and policy design:

i) An emphasis on understanding the system behaviour and designing policies to improve the behaviour.

ii) The use of a computer model to aid in the various interactions of policies and to test these policies under various exogenous factors.

Accordingly the thesis is organized as follows. In chapter 2 a comprehensive review of the existing literature were done. Motivation and objectiver of the existing research was also included in chapter 2. In chapter 3 a comprehensive analysis of the push, pull and long pull systems were done using system dynamics and various experiments were conducted to analyze the impact of WIP levels on throughput. In chapter 4 these concepts were applied to a local spark plug company and various policies were analyzed and conclusions were provided in chapter 5.

CHAPTER 2

LITERATURE REVIEW

Modeling, analysis and comparative studies have emerged quite recently on push and pull type systems. A thorough review of pull systems was presented by Sohal et al. (1983) and extensive descriptions and applicability of these systems were given by: Schonberger (1983), Bartezzaghi and Turco (1989), Chapman (1989) and Uzsoy and Martin-Vega (1990). Comparative studies of push and pull systems include: Sipper and Shapira (1989), Toni et al. (1987), Kimura and Terada (1981), Rees et al. (1989), Sarker and Fitzsimmons (1989), Baker et al. (1990) and Lambrecht and Segaert (1990). Specific applications to industry and implementational steps of these systems have also been given: Im and Lee (1988), Westbrook (1987), Crawford et al. (1988), and Fallon and Browne (1987).

2.1 Mathematical Models

A mathematical programming model for the kanban system in a deterministic multi-stage production environment was developed by Bitran and Chang (1987). The purpose of this model was to assist managers in determining the number of circulating kanbans, and consequently, the level of inventory at each stage. The model was made applicable to general manufacturing situations by making the assumption of relative container size between stages and allowing limited production capacity. The initial model which was nonlinear in nature was transformed to an integer linear model and was shown to give the same results as the nonlinear model. The mixed integer model was further transformed to a linear programming model and the error due to the linearization strategy was shown to approach zero asymptotically.

Miyazaki et al. (1988) considered the operational planning of the kanban and gave formulae to determine the total number of kanbans in terms of daily demand, lead time, safety stock level, economic lot size, container capacity, etc. The order interval was treated as a decision variable and as a result, the optimal order interval for the fixed interval withdrawal kanban and the supplier kanban, respectively, was determined so as to minimize the sum of the inventory cost and the withdrawal cost. This algorithm also determined the optimal number of kanbans required for the optimal order interval.

Mitra and Mitrani (1990) constructed a stochastic model for the analysis of a kanban discipline for cell coordination in production lines. In this study the authors developed a scheme for analyzing the performance of the kanban system and found that the kanban system performs better than the conventional manufacturing system in terms of throughput and inventory.

Philipoom et al. (1990) used a mathematical programming approach to determine the optimal lot sizes when using signal kanbans. This paper described the signal kanban as a special type of kanban used at workcentres which have relatively high setup times. This approach was offered as an alternative to firms that wish to use the JIT technique but are unable to reduce setup times at all workstations. This paper argues that although the use of buffer inventory lots is inconsistent with the JIT concept, it is an operational compromise that enables a company that does not totally meet the requirements for JIT implementation. Through the use of a simulation model it was concluded that the classical multi-product EOQ model will not always work in a JIT environment. Consequently, two integer mathematical programming models (one to minimize inventory and the other to minimize cost) were developed to determine the signal kanban lot sizes and to eliminate backorders.

2.2 System Dynamics Models

Ebrahimpour and Fathi (1984) studied the effect of kanban use on the level of work-in-process inventories. Through simulation runs inventory behaviour was compared using cyclical demand, steady growth, and the gradual reduction of cards when demand was stable. From this study they concluded that the reduction of cards does not decrease work-in-process inventory and in the case of cyclical demand environment, the work-in-process may increase due to delays inherent in the production line structure.

O'Calahan (1986) provided a thorough explanation of the kanban system and the conditions for its implementation. A system dynamics model for a three stage transfer line was developed and the system was subjected to shocks such as small changes in demand and running the system on "automatic mode" (little or no intervention from management). The shocks were simulated using different levels of kanban in the system.

The model was also used to test larger shocks when management was allowed to change the production capacity. .

Gupta and Gupta (1989a, 1989b) used the concept of system dynamics to model a JIT-kanban system and studied the behaviour of the system under various exogenous factors. In the development of the single cell model the objective of the study was to determine the relationship of the number of kanbans and the size of the containers to the production efficiency using various scenarios. The results of the study gave findings which were counter-intuitive: larger lot sizes are preferred to smaller ones. Rather than making a general statement, the authors proposed further model verification. The same authors also provided a system dynamics model for a two-line three stage production system.

2.3 Scheduling/Sequencing Models

Pourbabai (1986) suggested a model for scheduling a set of jobs with prespecified due dates and availability times in a flexible batch manufacturing system. Work stations were designed based on Group technology where there exists at least one work station with a set of compatible machines capable of processing all the necessary stages of each job. Instead of keeping track of the processing times for all the necessary stages of operation of each job at each compatible work station, an estimate of the total required processing time of each unit of each job at each compatible work station was given from a comprehensive simulation study. The objective of this model was to minimize the maximum tardiness such that the production of each job equals its demand in a mixed binary linear programming model.

Lee and Seah (1987) used the Simon simulation language to model the JIT system with kanbans. Measures of performance included: number of jobs completed, process utilization, set/run time ratio, mean and variance of queue time, mean and variance of job tardiness and work-in-progress level. Various scheduling rules were used: first-come-first-served (FCFS), shortest process time/lateness (SPT/LATE) and highest pull frequency/lateness (HPF/LATE). The results of the process times study was given for negative exponential distribution, constant process times, and normal distribution with a coefficient of variation of 0.2 and 0.4. Major conclusions drawn from this study were: the process times on the various machines need not be balanced if an appropriate scheduling rule is selected; better performance for process times following a normal distribution pattern than for a negative exponential distribution; the process utilization remains low for even for an overloaded pull system; reduction of set-up times with constant batch size results in better tardiness performance; and smaller container sizes improve the distribution of jobs within the system and give an overall improvement in the results.

Miltenburg and Sinnamon (1989) provided a theoretical basis for developing schedules for converting a mixed model multi-level production system into a JIT system. Scheduling algorithms and heuristics were developed for this problem. For products with similar part requirements with approximately the same number and mix of subassemblies, components and raw materials, only the final stage needs to be considered (Miltenburg 1989). In this paper products with significantly different subassemblies, components and raw material requirements were considered. Weights were used to determine the relative importance of the variability at each level of production. Miltenburg et al. considered keeping a constant rate of usage of all parts in the system but has not jointly considered other goals, such as levelling the load at each station on the final assembly line, not exceeding equipment capacities and reducing unnecessary set-up times. The final assembly line which developed in this paper is only appropriate for companies which have very small set-up times.

Egbelu and Wang (1989) focused on firms that can only receive raw material shipments in large quantities. Two methods of order shipment approaches were considered in this paper and consequently, two different models were developed for each case: the first model was for firms that are allowed to ship and deliver each order to its customer as soon as the order is completed in the shop; the second model was for firms required to ship all the orders at the same time. Mathematical models were developed to minimize the total inventory costs for the two cases of order shipment and delivery schedules were developed by using the technique of branching and fathoming to yield an optimal sequence.

Groeflin et al. (1989) developed a mathematical model and an algorithm for the final-assembly sequencing (FAS) problem for a mix of end products. Since each product imposes different requirements on the feeder shop, in terms of parts production, the feeder shops are driven by the sequence of the final assembly. The model suggested linking the FAS problem to smoothing the work-in-process levels of parts in feeder shops. The model given was formulated using a lexicographic minimax objective function instead of a single performance measure (e.g.: minimizing the sum of deviations of demand from the average usage) since it explicitly and dynamically gives priority to the part with the largest variability. The basis of the algorithm developed was an efficient interchange heuristic that attempts to interchange the order of assembly of a pair of end products. An interchange procedure was repeatedly applied to an initial feasible solution (which satisfies both release and due date constraints) until no further interchanges give an improvement in the objective function.

2.4 Simulation Studies

Philipoom et al. (1987) identified the factors that will influence the number of kanbans required at a workcentre for implementing a JIT system in an American production environment. The factors identified were: throughput velocity (i.e. rate at which items flow through a workcentre machine), coefficient of variation in processing time, machine utilization, and autocorrelation of processing times (the degree to which successive processing times on a specific machine are related to each other). To identify these factors a single workcentre using a single kanban during one time period was used to produce only one product on one machine. Given this simple scenario the factors that were likely to create a backorder at the workcentre were determined and as a result, the number of kanbans required. The second part of this paper described the simulation approach for determining workcentre lead times in order that the number of kanbans required at a workcentre to prevent backorders could be determined. The simulation approach was based on the assumption that workcentres could be decoupled (since no backorders were allowed) and modelled separately as queuing systems in order to determine the lead times.

Sarker and Harris (1988) studied the effects of imbalanced stage operation times (due to variability in processing times or the inability to equally allocate the tasks to different operators) on a JIT production system. Different effects of this imbalance were analyzed: variation of operation times at different parts of the production line, see-saw effect of operation times in intermediate stages and the bowl phenomenon on utilization of operators. From this analysis, some suggestions were made to managers for controlling a JIT production system with imbalance.

2.5 Motivation for proposed research

A review of the literature concerning push and pull systems was discussed in the previous section. Some of the literature found in simulation modelling gave counter intuitive results. Analysis of the long pull system such as, impact of work-in-process inventories on throughput, location of the long pull, span of control of each long pull and the corresponding amount of work-in-process inventory is required. Also, little has been done to study the feedback mechanism of push, pull and long pull systems. A comprehensive analysis of work-in-process inventories and their corresponding levels is required for these systems. This indicates the need to describe and model push, pull and long pull systems and make a comparative analysis of these systems.

2.6 Objectives of proposed research

The major objectives of the research are to:

1. Provide a description of push, pull and long pull systems.
2. Develop simulation models using a system dynamics for push, pull and long pull systems.
3. Perform simulation runs identifying the characteristics of these systems and make a comparative analysis.
4. Develop a simulation model of a local spark plug assembly plant to identify problems faced in the operations of the assembly system and give various policies to test the performance of the current system.

CHAPTER 3

SYSTEM DYNAMICS MODELS OF SERIAL PRODUCTION LINES

A few simulation models using the principles of system dynamics were developed for serial production lines using different strategies such as

- (i) Push with infinite buffers
- (ii) Push with finite buffers
- (iii) Pull
- (iv) Long pull

which were described earlier. The causal relationships of each system flow diagram were coded into simulation programs using the language DYNAMO (PC version). The behaviour of these systems was then studied under the stimulus of various exogenous factors.

3.1 Structure of the production system used for simulation experiments

The simulation models developed were constructed based on a single product four workstation serial production line (Figure 4). It is assumed there is always a supply of parts ready to be processed at the first workstation.

3.2 System configurations

The system flow diagrams for the various systems depicting the detailed interrelationships of the model are given. The flow diagram consists of rates and levels to illustrate the physical flow and information network of parts and materials in the system at any point in time

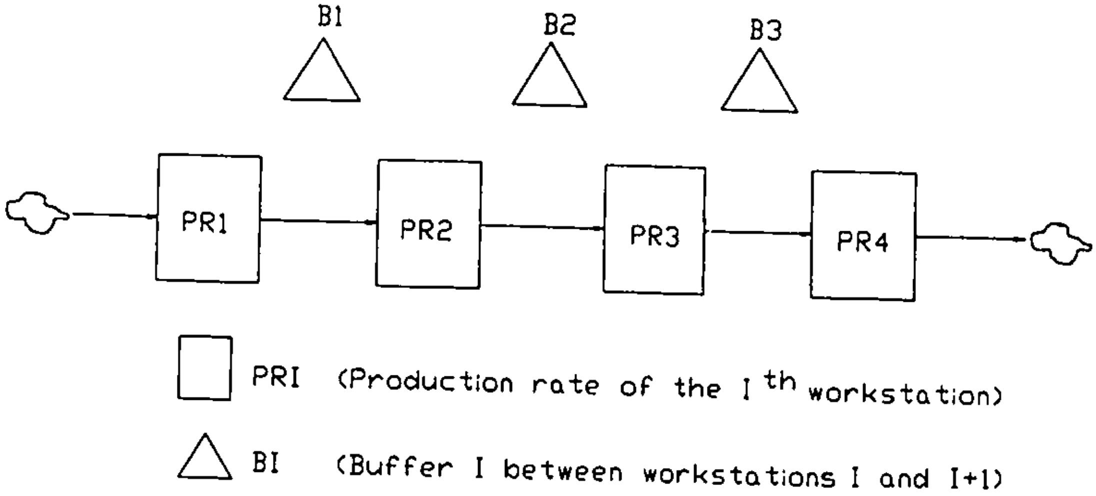

Figure 4: Four workstation serial production line

(solid lines represent the physical flow and dashed lines indicate the information flow). A detailed description of the system dynamics methodology is provided in Appendix-A1.

3.2.1 Push system with infinite buffers

The flow diagram for this system is shown in Figure 5. Storage areas in between two workstations are assumed to be unlimited and the work-in-process levels can accumulate without any restrictions. The only restriction in this system is when a station is *starved* (i.e. the station has to wait for material from the preceding station).

The system is examined by starting at the first workstation and progressing towards the final stage. This is consistent with the push nature of the system. Each unit of a part is processed at the first workstation and travels to subsequent stations when the station is available for processing the part. As shown in the flow diagram workstation one is given a production rate (PR1) and material is drawn from an infinite source so that it will never be starved.

This production rate controls the flow of finished items from the production process to the container which holds the lot produced at that station. The production rate of a workstation is derived from the desired production rate (DPR) and production variability (PV). The variability is included to model variations in production caused by minor adjustments of machinery due to rework or breakdowns, or inexperienced workers. The first workstation is designated a production rate (PR1) and is set to equal the desired production rate (DPR1) as the material is assumed to be drawn from an infinite source.

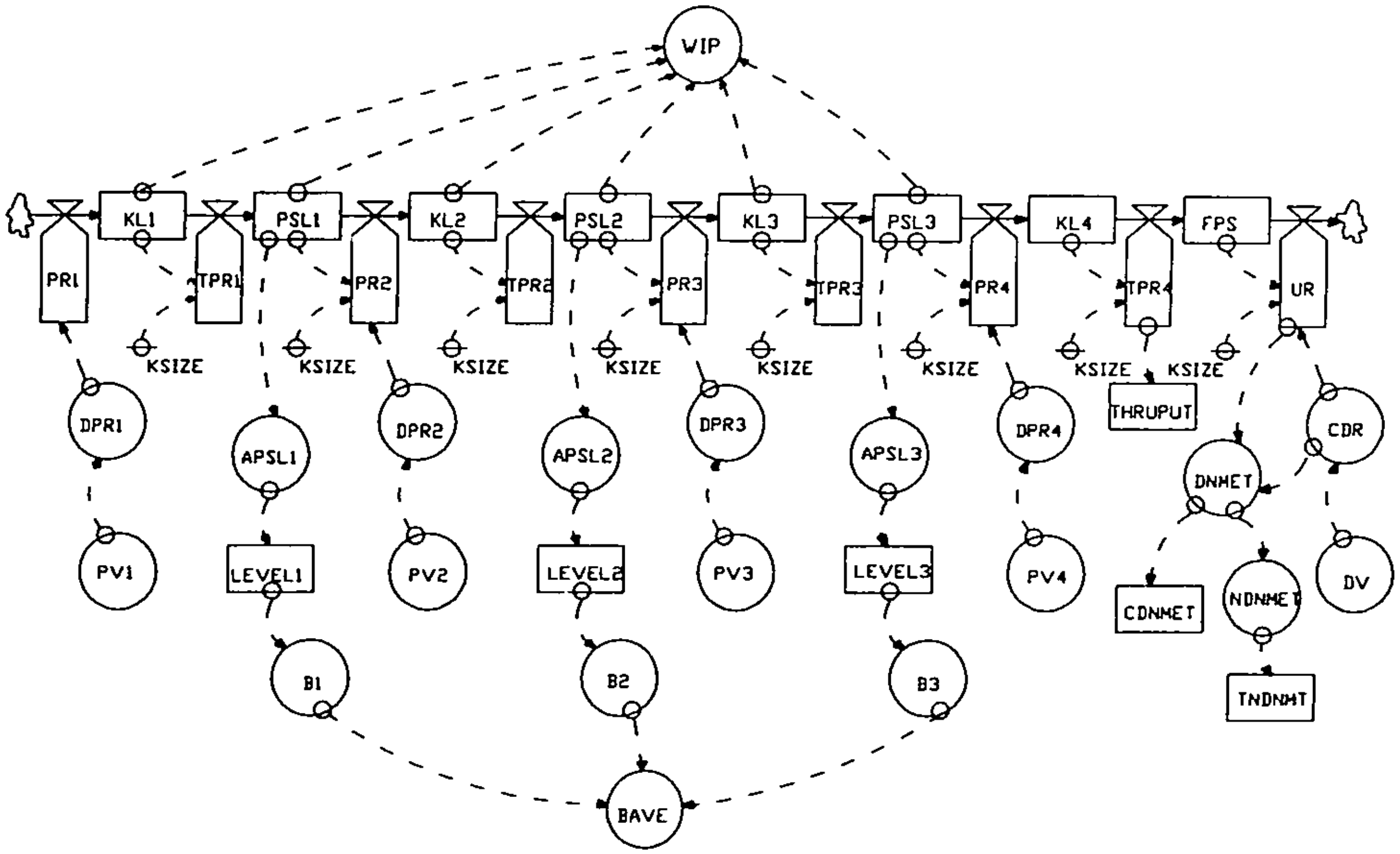

Figure 5: Flow diagram of push with infinite buffers

As the part completes its processing on any workstation it is transferred to a container (KL) at that station. Upon reaching a specified container limit (KSIZE) (i.e. the lot size) the container is transferred to the production storage area location (PSL) of that workstation. The production storage area at each stage is the inventory of materials to supply a production process at a subsequent stage. The production storage area of workstation one is designated as (PSL1). In a push system the units which are held in the storage area of a station are pushed to the next station when the next station is ready to process more units. Each workstation in a push system is ready to process units when they are available in the preceding station's production storage areas. In a similar manner, the parts are processed at and pushed onto the later workstations. The finished product storage is designated as (FPS). In the example considered the storage area of the fourth workstation is the finished product storage. The FPS of the last station will accumulate finished products unless it is depleted. The next rate located after the FPS area is the usage rate (UR). This rate is influenced by the current demand rate (CDR) which is influenced by an auxiliary variable (demand variability (DV)) to add uncertainty in demand and the amount of parts in FPS. The usage rate of the system is the minimum of the CDR and FPS.

To monitor the changes in the system additional auxiliary variables and levels are included. The accumulated level of each production storage area (APSL) is monitored so that average buffer size between workstations can be determined. Also, the level of work-in-process (WIP) which consists of the sum of the production storage areas and container levels of all stations between the first and second last stations of a line is used to find the amount of work-in-process in the system at any point of time. Another auxiliary variable for finding the throughput (THRUPUT) of the line is also included. The throughput of a line is the number of parts that have been processed by the system and the time required for processing all these parts.

3.2.2 Push system with finite buffers

A push system which has finite buffers limits the size of the buffers located between the workstations. Figure 6 represents the flow diagram of a push system with finite buffers. Each production storage area is limited to a given maximum level. If the storage area of a station is full the corresponding station will stop producing any more units and is said to be *blocked*. The first work station in this system draws from an infinite source so it will never be *starved* but the production rate (PR1) will have to check if PSL1 has space (i.e. the maximum buffer size has not been reached). The finite buffers in the line make the work proceed from a station to the downstream buffer whenever space is available, and from there to the downstream station when it becomes free. For the other workstations (in this example workstations two, three and four) there are two conditions to check before the processing of a part can occur on a workstation: the i^{th} workstation must check if there is enough inventory in the preceding station (i-1) to supply the production rate at station i and also check if there is enough buffer space in the subsequent station (i+1) for the units processed at station i. As shown in Figure 6 this is indicated by additional information flows from the storage area of each workstation (PSL's) to the workstation (PR's).

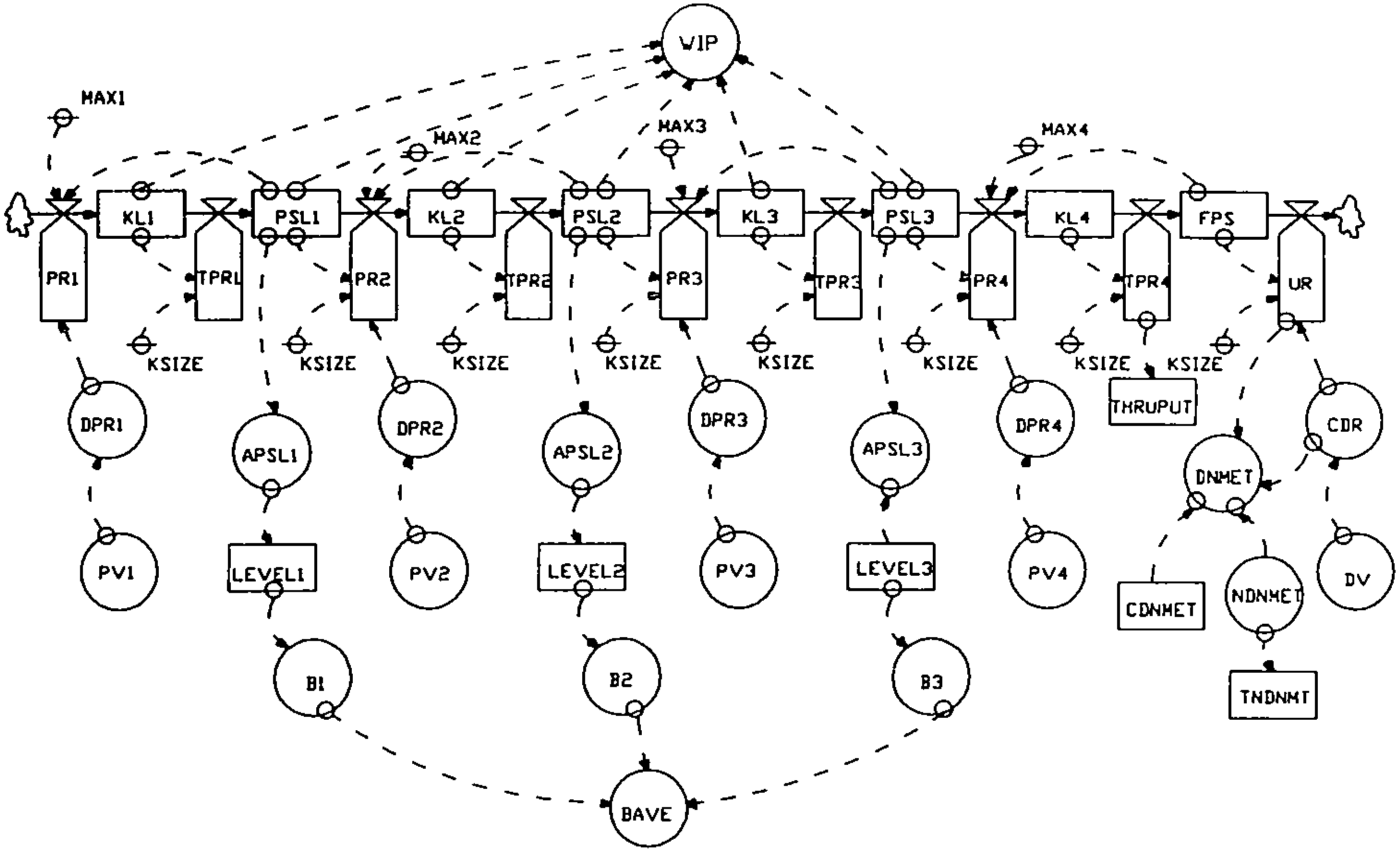

Figure 6: Flow diagram of push with finite buffers

3.2.3 Kanban controlled pull system

The system diagram for the pull system can be seen in Figure 7. In this system work is drawn along the line by downstream consumption. When an item moves out of a workstation, the usage triggers the production of the next item from the previous workstation. In keeping with the pull nature of the system the flow diagram description will start at the end of the serial production line. The usage rate is activated if there is a demand for a product. This rate draws from the finished product storage area (FPS). If the current demand rate depletes the inventory of the FPS area to a certain level, the trigger mechanism (which is a kanban level) for this storage level is activated and this in turn activates the production process at workstation four. The production rate (PR4) will continue to replenish the material consumed from the FPS area provided there is material in the previous buffer (PSL3) and until the trigger level is reached at FPS in which case it will stop production. The production storage location is supplied by a flow of intermediate goods dictated by the production transfer rates (TPR's). These transfer rates are for the purpose of executing the effect of transferring the kanban container (KL) from the production process to the storage location at the instant the container reaches full capacity (KSIZE). When PR4 is active it has to draw from a supply of material from the preceding storage area (PSL3). This will deplete material from PSL3 until the trigger mechanism for PR3 is activated. PR3 continues producing until the trigger level at PSL3 is reached. Similarly, this transfer of information will continue on to workstations two and one and start the production of parts at either workstation when their respective triggers are activated and continue until the material drawn at each station is replenished.

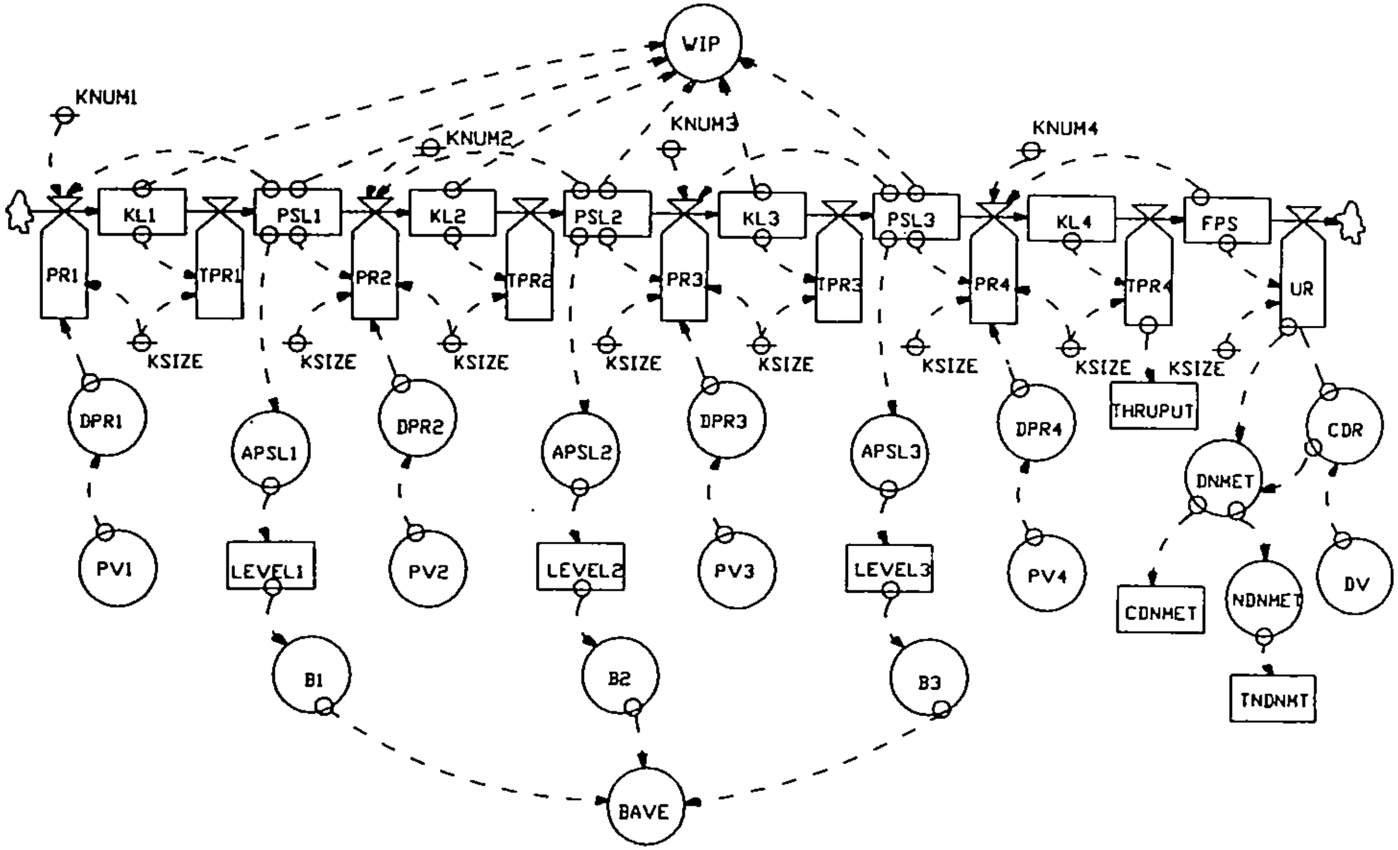

Figure 7: Flow diagram of pull system

3.2.4 Long Pull Strategy

The system flow diagram for the long pull is given in Figure 8. The long pull as seen in the system diagram starts from workstation four and spans workstations one, two and three to create a pull effect at workstation one. In this system a unit is allowed to enter the system from the moment one unit has finished production at the last stage (PR4) of the production process. The individual buffers in the system are not restricted but there is a limit on the total number of buffers allowed in the system at any point of time. In a manner similar to the pull system described in the previous section the pull here is started at workstation four when the trigger at FPS is activated by the consumption of material by the usage rate (UR) which is in effect when there is a demand for a product. In contrast to the pull strategy the trigger level does not activate the production process at the stage immediately preceding it but instead creates a pull at the first workstation. The production rate at workstation one (PR1) is active only if there is a pull and the maximum size of allowable inventory in the span of the pull is not exceeded. The maximum allowable inventory consists of the levels in the containers and the buffer sizes of the workstations within the span of the pull. The production process (PR1) at workstation one requires information about the level of the maximum allowable inventory (MAXINV), the level of WIP in the span of the pull and the level of production storage area at the end of the pull (FPS). This can be seen as information flows in the given flow diagram. Once a unit is produced at PR1 the unit is then pushed on to workstations two, three and four in a manner similar to that given for the push system with infinite buffers. For example, if a pull is created from workstation four and produces one unit at workstation one, the unit

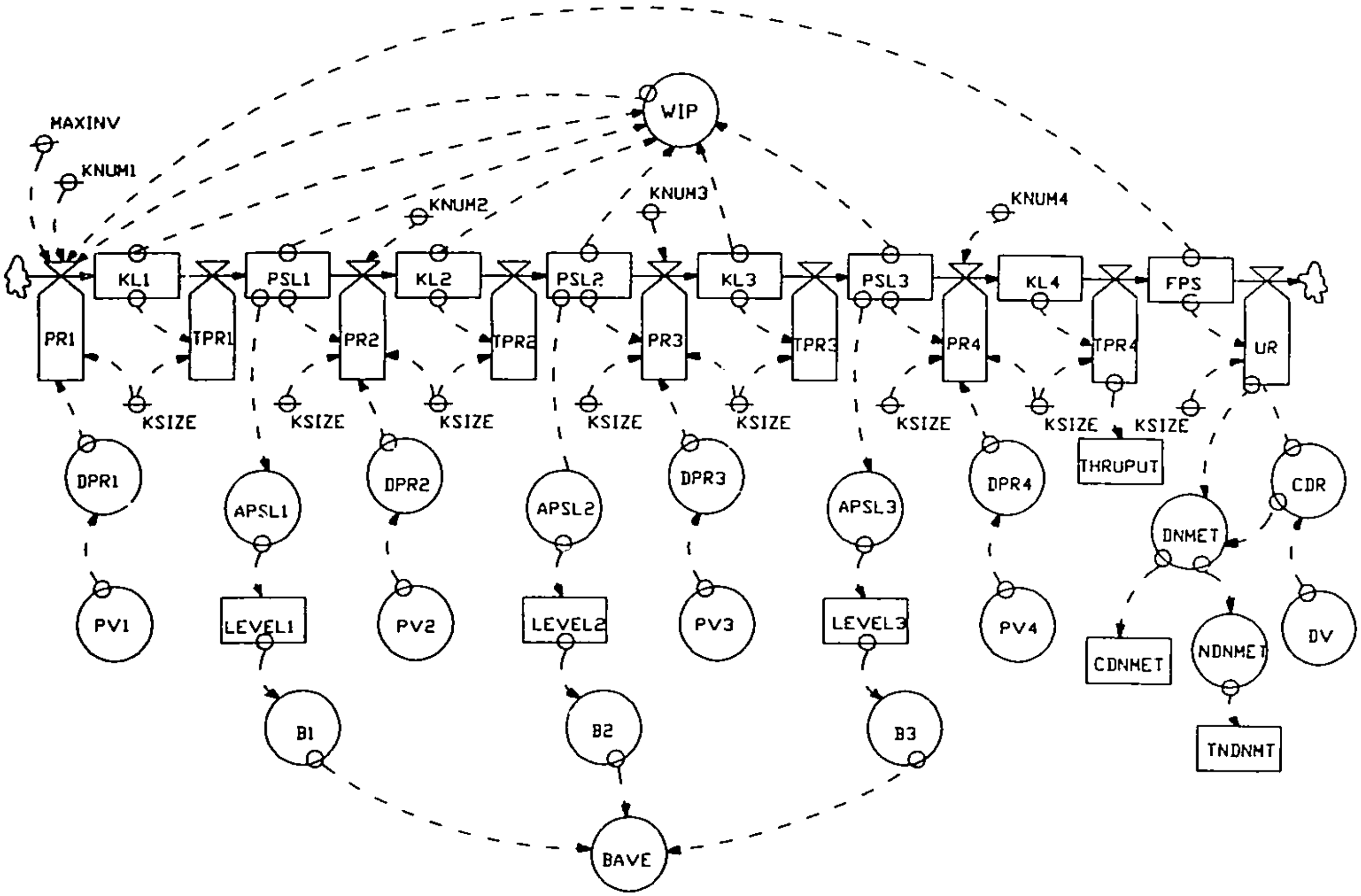

Figure 8: Flow diagram of long pull system

completed at workstation one will be pushed to the subsequent workstations until the production process is completed (FPS). Provided that the maximum inventory is not exceeded, the long pull will remain active until the trigger level at workstation four is reached.

Program listings of all the various strategies are given in Appendix A.2.

3.3 Analysis and discussions of simulation runs conducted

Upon completion of the simulation models different experiments were conducted to test the system behaviours under various operational conditions. Various performance parameters such as the throughput, average buffer contents, etc. were tested for all the systems. Most of the simulation runs were tested using ten different random number seeds. A statistical analysis was performed by first constructing 95% confidence intervals (C.I.) (Chatfield 1983) for these runs. Then Duncan's multiple range test (Hines and Montgomery 1980) was applied to these runs to see if there were significant differences at the 5 percent level between all pairs of means. The experiments were conducted to give a comprehensive analysis of the research issues related to serial production lines.

3.3.1 Analysis of push systems

Simulation Run 1: Effect of changes in lot size on WIP

System parameters:

(i) 3 workstations

(ii) Production rates for all stations are assumed to be normally distributed with a mean of 10 and a standard deviation of 0.25

(iii) Length of the run = 21

Runs conducted:

a) Container size (KSIZE) = 1

b) KSIZE = 3

c) KSIZE = 5

The results of thess experiments are shown in Figures 9 to 11. These results show that as the lot size increases WIP also increases. Also the variability in the production storage areas (PSL's) increases as KSIZE increases. This indicates that smaller lot sizes are preferable.

Simulation Run 2: Effect of changes in lot size on throughput

System parameters:

(i) 4 workstations

(ii) Production rates for all stations are assumed to be normally distributed with a mean of 10.

(iii) Length of the run = 105

The results are given in Table 1

Table 1: Effect of changes in lot size on throughput

Cases	KSIZE	Throughput (95% C.I.)			
		CV = 0.025	CV = 0.100	CV = 0.500	CV = 1.000
Case A	1	1042.90±0.23	1040.00±0.59	1024.60±3.36	1004.10±6.78
Case B	3	1035.30±0.68	1033.20±1.11	1017.90±3.66	998.70±6.90
Case C	5	1030.00±0.00	1026.00±1.51	1010.50±3.53	992.50±6.14

Duncan's multiple range test was performed and the results indicate that there are significant differences at a 5 percent level between all pairs of means for the throughput.

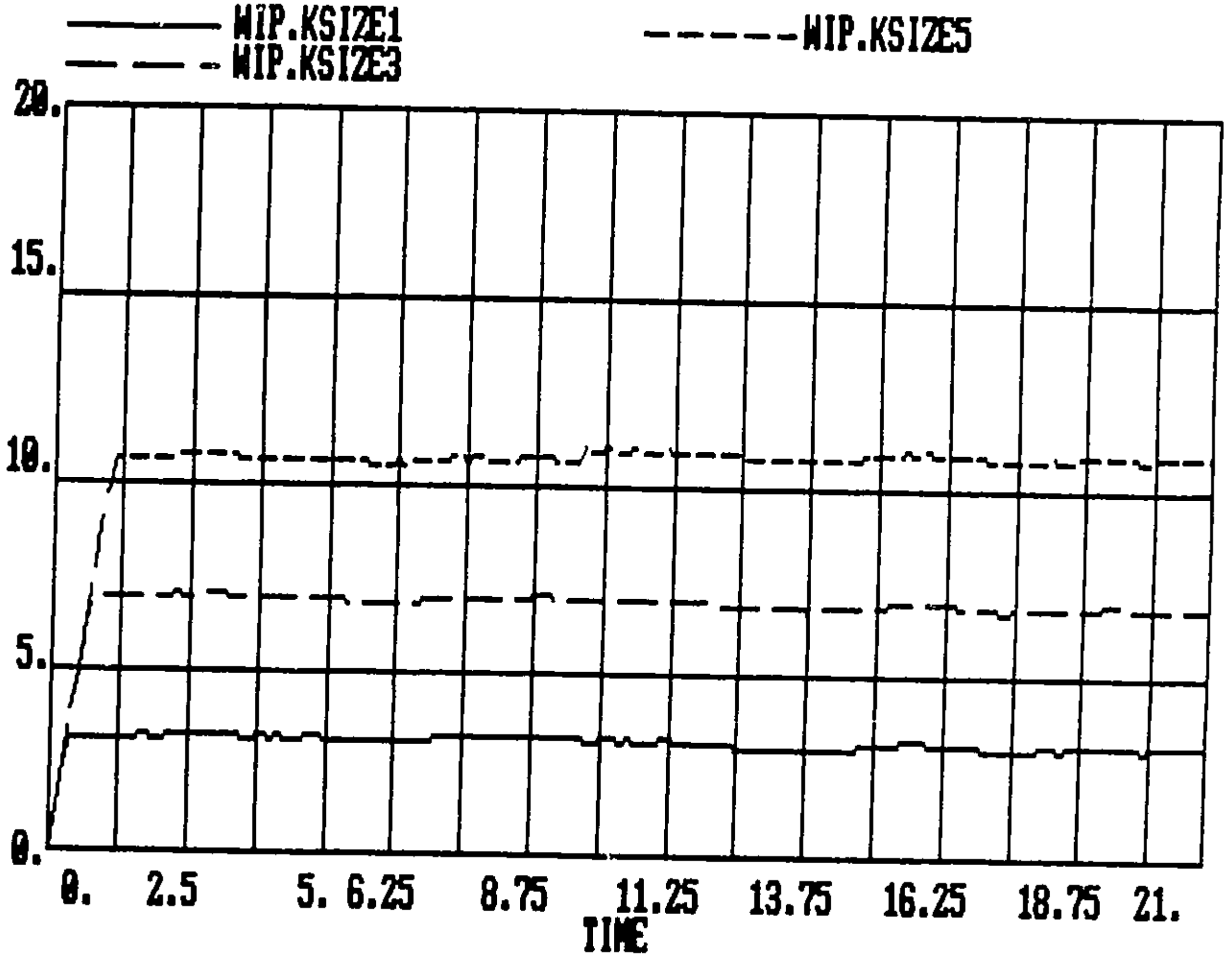

Figure 9: Effect of lot size on WIP

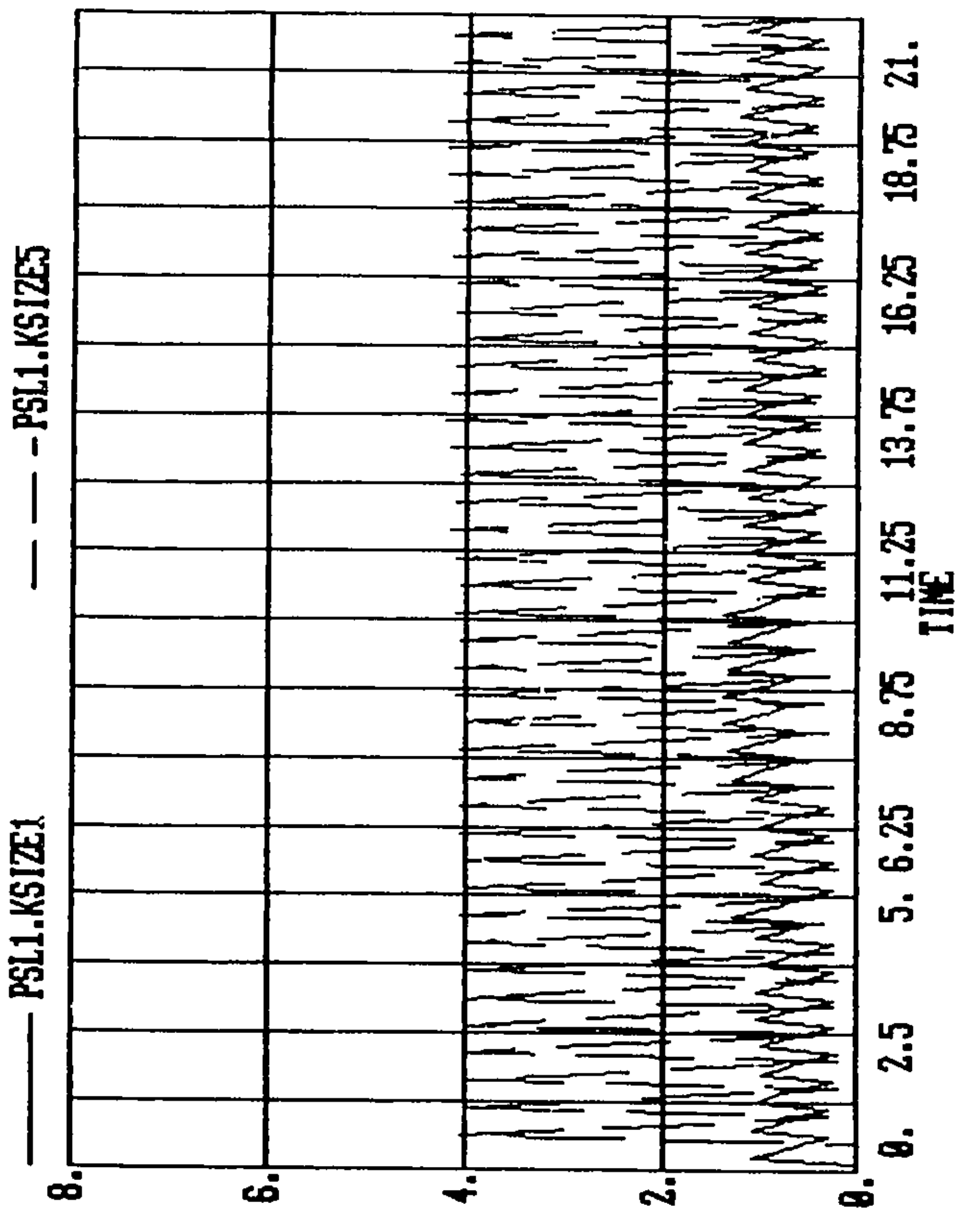

Figure 10: Effect of lot size on PSL1

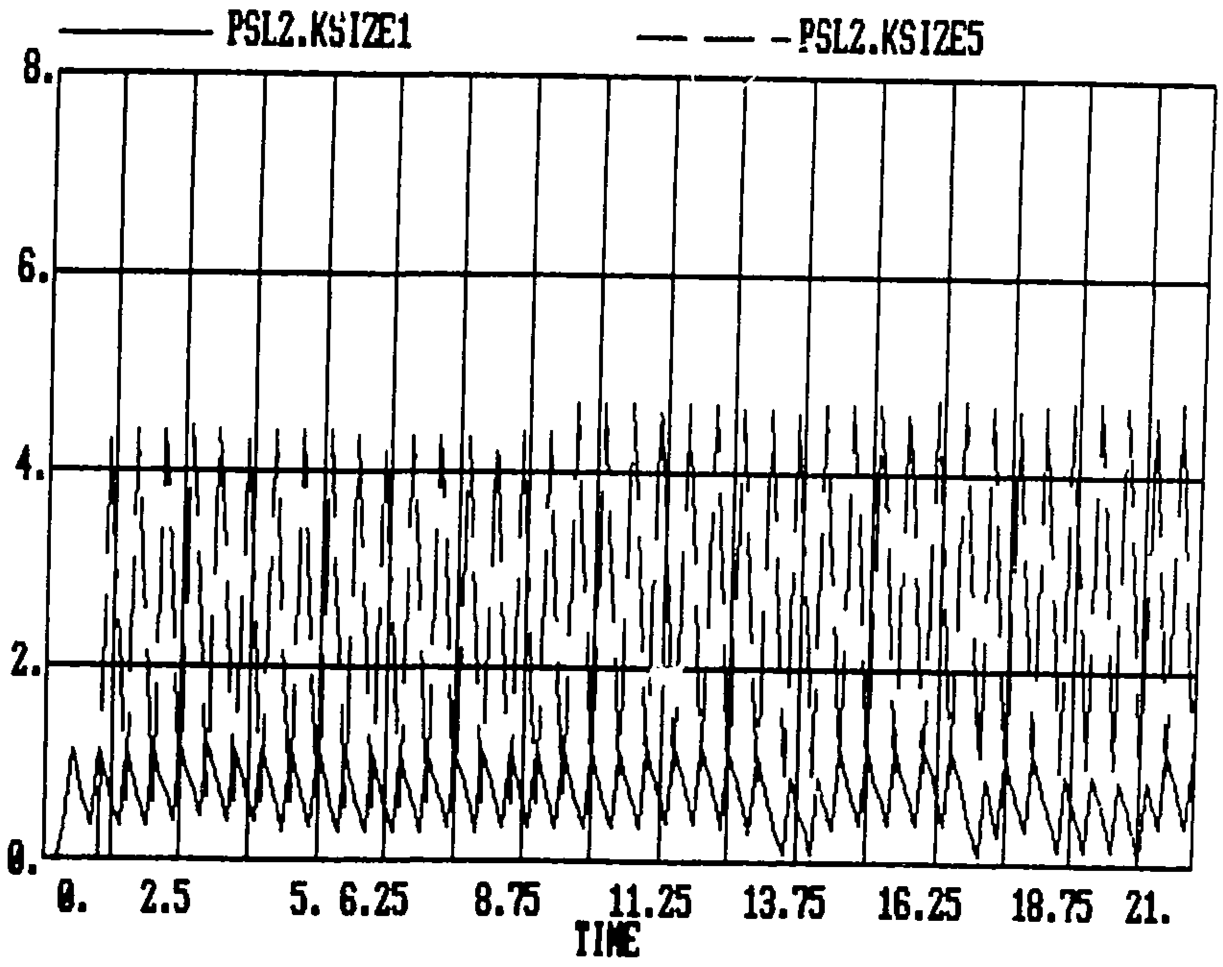

Figure 11: Effect of lot size on PSL2

From Table 1 it can be seen that as the lot size increases, the throughput decreases due to the waiting time for lots to be completed at one station before proceeding to the subsequent stations.

Simulation Run 3: Effect of increased variability of production rates

In this experiment the throughput of the line and the average buffer content were examined using different coeffients of variations (CV). The results are given in Table 2.

System Parameters:

(i) 4 workstations

(ii) The production rates of all workstations are normally distributed with a mean of 20.

(iii) Length of the run = 42

Table 2: Effect of increased variability of production rates

Cases	CV	b1 95% C.I.	b2 95% C.I.	b3 95% C.I.	Throughput 95% C.I.
Case A	0	1.43±0.00	1.43±0.00	1.43±0.00	831.00±0.00
Case B	0.1	2.70±0.53	2.29±0.49	2.15±0.23	826.80±1.06
Case C	0.3	5.62±1.57	4.25±1.70	3.79±0.71	817.00±3.02
Case D	0.5	8.21±2.76	6.26±2.65	5.63±1.15	808.70±4.71
Case E	1	15.30±5.36	10.91±5.57	9.43±2.25	783.4±9.76

Duncan's multiple range test was performed and the results indicate that there are significant differences at a 5 percent level between all pairs of means except for the following cases:

b1 - cases (A and B), (B and C) and (C and D)

b2 - cases (A, B, and C), and (C and D)

b3 - cases (A and B)

throughput - cases (A and B)

From these results it can be seen that the average buffer content increases as the coefficient of variation increases while the throughput decreases.

Simulation Run 4: Impact of bottleneck workstations:

System Parameters:

(i) 4 workstations

(ii) Production rates for all stations are given in Table 3 and are normally distributed with a standard deviation of 0.25

(iii) Length of run = 21

Table 3: Impact of bottleneck workstations

Cases	PR1	PR2	PR3	PR4	b1 95% C.I.	b2 95% C.I.	b3 95% C.I.	Throughput 95% C.I.
Case A	20	20	20	10	1.43 ±0.06	1.39 ±0.11	102.14 ±0.15	205.70 ±0.35
Case B	20	20	10	20	1.43 ±0.06	103.33 ±0.11	0.72 ±0.01	205.40 ±0.37
Case C	20	10	20	20	104.68 ±0.08	0.73 ±0.01	0.72 ±0.01	205.00 ±0.00
Case D	10	20	20	20	0.73 ±0.01	0.73 ±0.00	0.72 ±0.00	204.10 ±0.23

Duncan's multiple range test was performed for the throughput and the results indicate that there are significant differences at a 5 percent level between all pairs of means except for cases (A and B).

In an unbalanced line it is essential that the bottleneck does not suffer from starving as the throughput is dependant on the bottleneck workstation. In the case of a push system with infinite buffers the bottleneck pulls the buffer content towards itself and there is no starving as the WIP in the input buffer is allowed to buildup before the bottleneck station. This result is verified and is shown in Table 3. In Case D there is no accumulation of WIP before Workstation 1 since PR1 is assumed never to be starved of material.

Simulation Run 5: Effect of increased variability in case of a bottleneck workstation

System Parameters:

(i) 4 workstations

(ii) Production rates for the workstations 1, 2 and 3 are normally distributed with a mean of 20 while the bottleneck station 4 has a mean of 10.

(iii) Length of run = 105

Table 4: Effect of increased variability in case of a bottleneck workstation

Cases	CV	b1 95% C.I.	b2 95% C.I.	b3 95% C.I.	Throughput 95% C.I.
Case A	0	1.44±0.00	1.43±0.00	522.23±0.00	1046.00±0.00
Case B	0.1	3.30±0.64	2.98±0.61	518.20±0.86	1045.80±1.00
Case C	0.3	7.32±1.82	6.25±2.03	510.00±2.87	1046.20±2.99
Case D	0.5	13.45±6.00	9.28±3.24	502.16±4.97	1046.10±4.88
Case E	1	20.96±6.16	17.67±6.65	482.61±9.39	1045.60±9.54

Duncan's multiple range test was performed and the results indicate that there are significant differences at a 5 percent level between all pairs of means except for the following cases:

b1 - cases (A and B) and (B and C)

b2 - cases (A and B), (B and C) and (C and D)

b3 - cases (A and B)

Throughput - none are significantly different

The accumulation of inventory before the bottleneck is consistent with the results obtained in the previous experiment. As the coefficient of variation of all the workstations increases the inventory before the bottleneck decreases while the other buffers (b1 and b2) and the throughput remains the same.

Simulation Run 6: Placement of workstations with variable processing times

System Parameters:

(i) 3 workstations

(ii) Production rates for the workstations are normally distributed with a mean of 10. The variable workstations have a standard deviation of 2.

(iii) Length of run = 21

(iv) Case A: PR1 and PR2 are variable workstations ; PR3 is constant
Case B: PR1 and PR3 are variable workstations ; PR2 is constant
Case C: PR2 and PR3 are variable workstations ; PR1 is constant

Figure 12 shows the variation of WIP for Cases A, B, and C. The variation in WIP level is least for Case B. This result indicates that placing variable workstations at the first and last workstations gives better line performance.

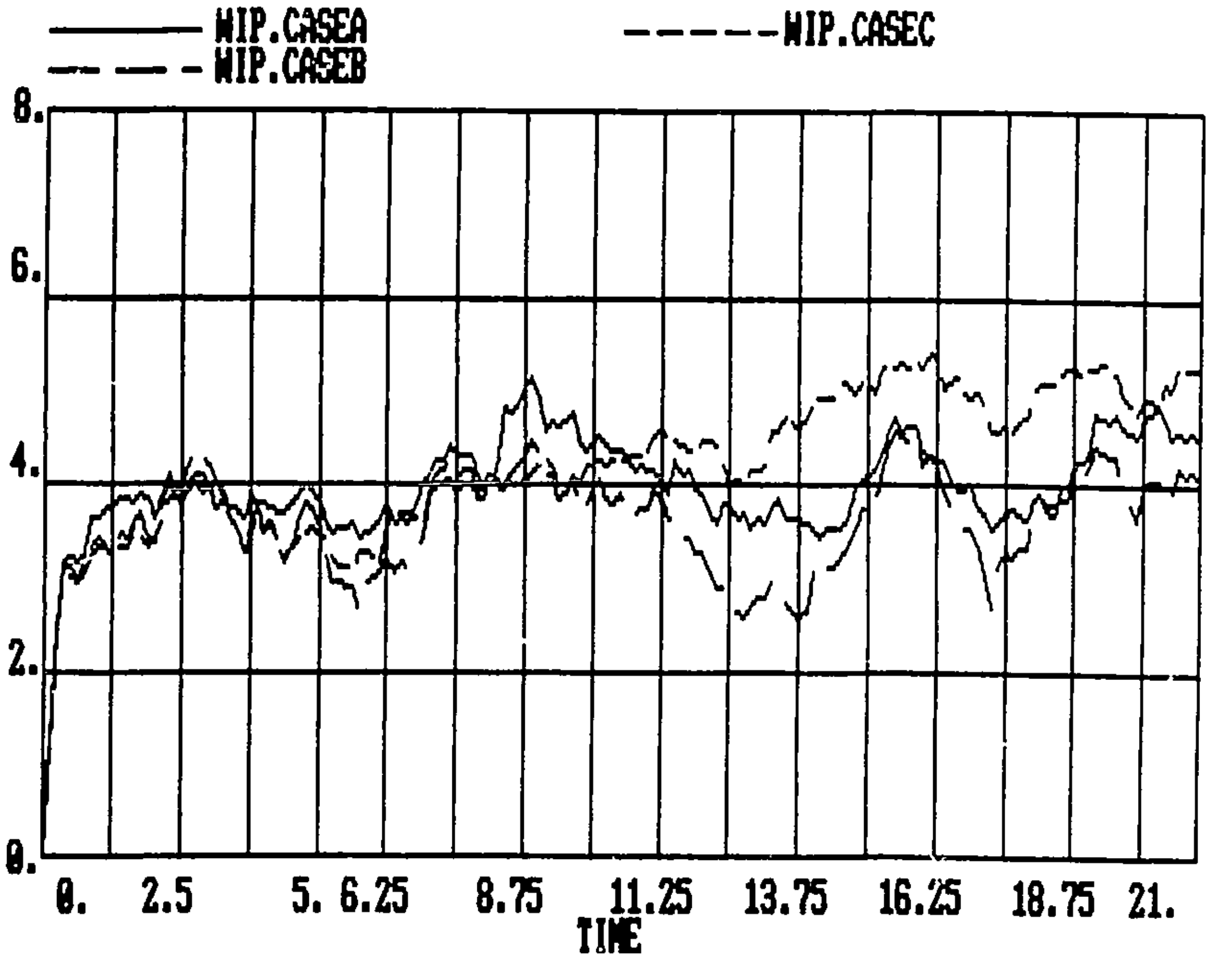

Figure 12: Effect of placement of workstation with variable processing time and WIP

Simulation Run 7: Placement of buffers in a balanced production line

System Parameters:

(i) 4 workstations

(ii) Production rates for the workstations are normally distributed with a mean of 10 and a standard deviation of 2.

(iii) Length of run = 105

(iv) Total number of buffer spaces available = 9

Table 5: Placement of buffers in a balanced production line

Cases	b1	b2	b3	Throughput 95% C. I.
Case A	3	3	3	1022.90±1.37
Case B	2	4	3	884.40±2.03
Case C	5	2	2	826.10±2.27
Case D	2	2	5	824.70±3.02
Case E	3	4	2	888.40±1.88
Case F	3	2	4	886.80±2.28
Case G	2	3	4	884.40±2.03

Duncan's multiple range test was performed for the throughput and the results indicate that there are significant differences at a 5 percent level between all pairs of means except for the following cases:

cases (C and D), (B, F and G) and (E and F)

As seen clearly in Table 5 the allocation of equal buffers (Case A) maximized throughput. For buffers which are close to equal allocation (Cases B, E, F and G) the throughput is less but for buffers which differ more in size (Cases C and D) the least throughput is attained.

Simulation Run 8: Placement of extra buffer slots

In experiment 7 it was shown that the equal allocation of buffers maximizes throughput. Using an equal allocation of buffers this experiment will test where additional buffers should be placed. Cases A, B and C are for the placement of one additional buffer while cases D, E, F, G, H and I are for the placement of two additional buffers.

System Parameters:

(i) 4 workstations

(ii) Production rates for the workstations are normally distributed with a mean of 20 and a standard deviation of 2

(iii) Length of run = 105

(iv) Total number of buffer spaces available = 9

Table 6: Placement of extra buffer slots

Cases	b1	b2	b3	Throughput 95% C.I.
Case A	4	3	3	1612.50±6.65
Case B	3	4	3	1684.30±4.72
Case C	3	3	4	1611.60±4.55
Case D	5	3	3	1612.50±6.65
Case E	3	5	3	1703.20±5.64
Case F	3	3	5	1611.60±4.55
Case G	4	4	3	1741.20±6.48
Case H	4	3	4	1730.50±6.23
Case I	3	4	4	1731.00±5.01

Duncan's multiple range test was performed for the throughput and the results indicate that there are significant differences at a 5 percent level between all pairs of means except for the following cases:

for one extra buffer slot - cases (A and C)

for two extra buffer slots - cases (D and F) and (H and I)

For the placement of one additional buffer slot it can be seen from Table 6 that Case B which has a center weighted spread is the best buffer allocation for maximizing throughput. If there are two additional buffer slots which must be added to the same buffer then a center weighted spread (Case E) is again the best allocation for maximizing throughput. If this restriction is removed then the buffers should be allocated as equally as possible.

Simulation Run 9: Reversibility in serial lines

In this experiment we test the effect of two serial lines that are mirror images of each other.

System parameters:

(i) 4 workstation

(ii) Production rates of all the workstations are assumed to be normally distributed with a mean of 10. The standard deviation of each workstation is listed in the table given below.

(ii) Length of the run = 105

Table 7: **Reversibility in serial lines**

Cases	SD1	SD2	SD3	SD4	b1 95% C. I.	b2 95% C. I.	b3 95% C. I.	Throughput 95% C. I.
Case A	3	0	0	0	3.09±1.10	0.90±0.27	0.88±0.24	1039.20±2.05
Case B	0	0	0	3	0.78±0.00	0.78±0.00	3.43±0.81	1041.80±1.54
Case C	3	3	0	0	3.78±0.90	2.11±0.54	0.77±0.00	1036.50±2.22
Case D	0	0	3	3	0.78±0.00	3.30±1.09	3.46±0.57	1038.10±2.62
Case E	3	3	3	0	3.78±0.90	3.22±0.96	1.83±0.24	1032.80±1.99
Case F	0	3	3	3	3.31±1.40	3.46±0.85	3.13±0.73	1034.10±2.27

Duncan's multiple range test was performed for the throughput and the results indicate that there are no significant differences at a 5 percent level between all pairs of means when making the following comparisons: (Case A with Case B), (Case C with Case D) and (Case E with Case F).

The results indicate that two serial production lines that are mirror images of each other have the same production capacity and have a similar trend of buffer allocation. This proves the following statement provided by Yamazaki and Sakasgawa (1975):

> Any serial line has a dual line which is identical except that the direction of material flow is reversed - the first workstation in the primal line is the last in dual line, etc. The production capacities of a line and its dual line are identical.

3.3.2 Analysis of pull system

Simulation Run 1: Nature of the pull system

System Parameters:

(1) 3 workstations

(ii) Production rates for the workstations are normally distributed with a mean of 10 and a standard deviation of 0.25

(iii) Demand rate is normally distributed with a mean of 5 and a standard deviation of 0.25

(iv) Length of run = 21

(v) KSIZE = 5 for each workstation

(vi) KNUM = 2 for each workstation

From Figures 13 to 15. the goal seeking nature of the pull system is demonstrated by the fluctuations in production rates caused by the system reacting to the changes in demand, i.e. production occurs only when there is a demand for that product.

Simulation Run 2: Variation in WIP inventory

System parameters:

(i) 3 workstations

(ii) Production rates for the workstations are normally distributed with a mean of 10 and a standard deviation of 0.25

(iii) Demand rate is normally distributed with a mean of 5 and a standard deviation of 0.25

(iv) Length of run = 21

Various cases of the WIP inventory were analyzed and are shown :

Table 8: Variation in WIP inventory (Cases analyzed)

Cases	KSIZE	KNUM
Case A	4	7
Case B	7	4
Case C	8	3
Case D	3	8

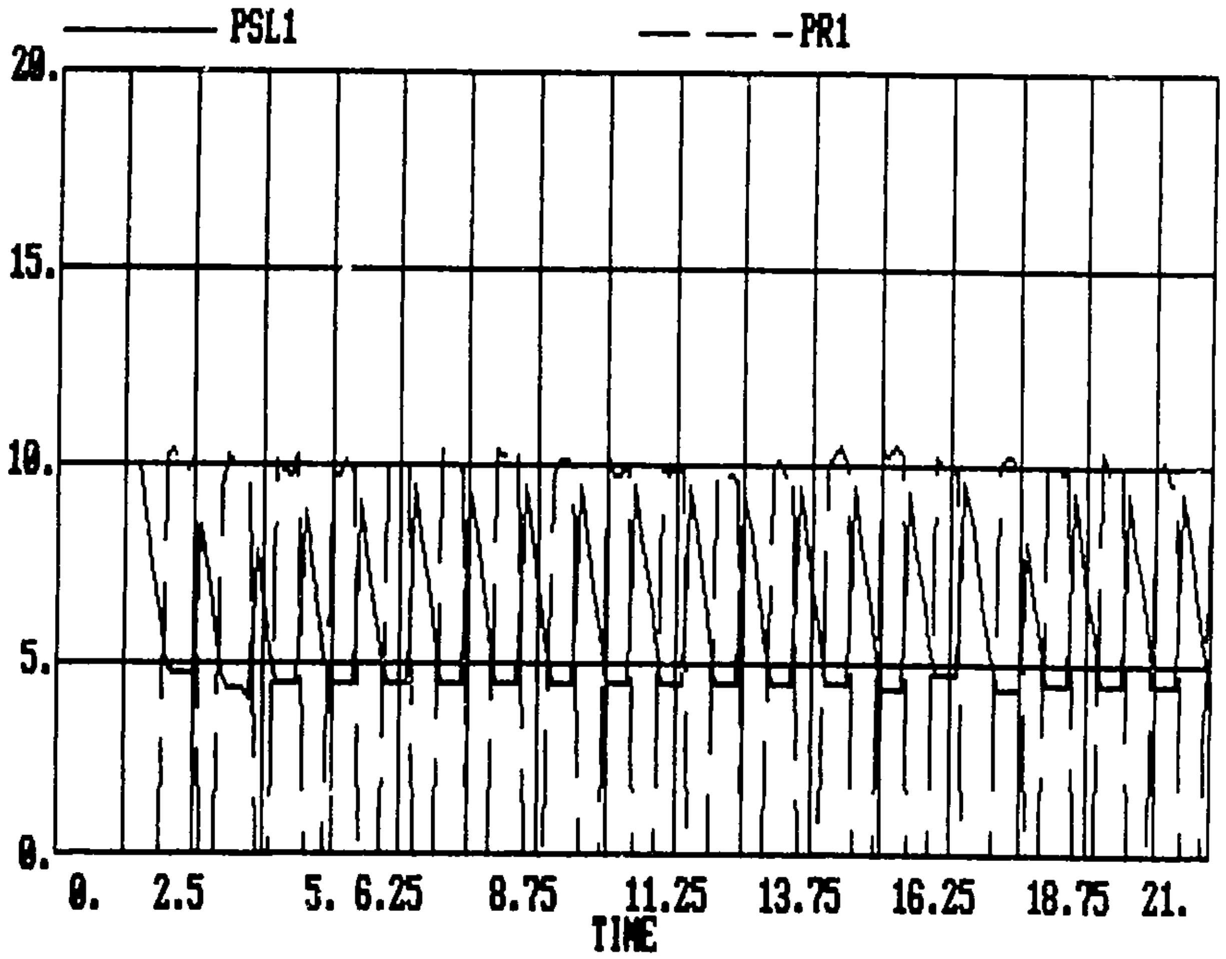

Figure 13: Nature of pull system - workstation 1

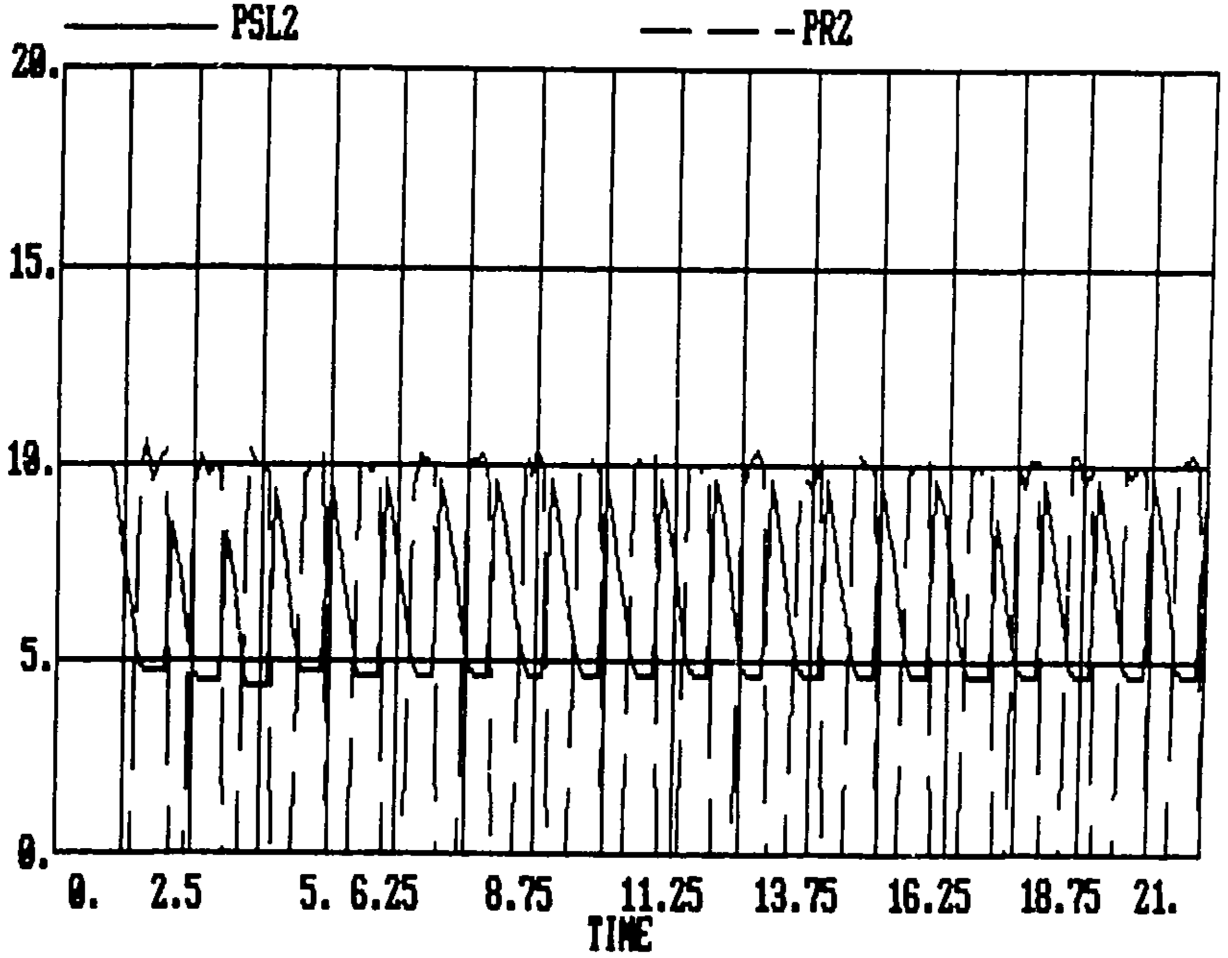

Figure 14: Nature of pull system - workstation 2

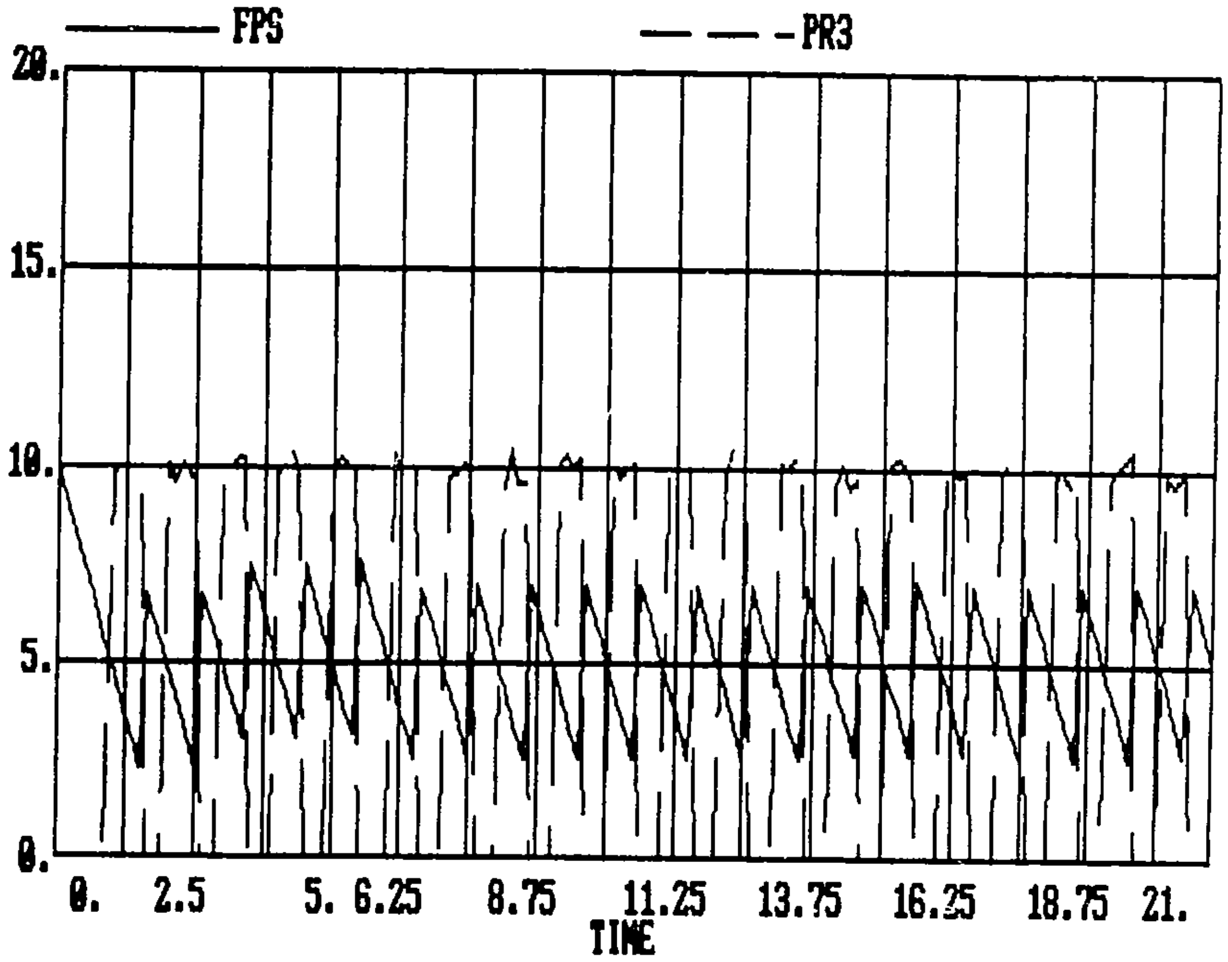

Figure 15: Nature of pull system - workstation 3

From the Figures 16 to 21 it could be seen that a smaller number of kanbans with proportionally larger container sizes produce more inventory variations, i.e. smaller lot sizes are preferable to larger ones. This is consistent with JIT principles of attaining lot sizes which approach one unit.

3.3.3 Analysis of long pull system

In this section various research topics such as: where the long pull has to be located, the span of control of each long pull and the corresponding amount of work-in-process inventory etc. were analyzed. The span of the long pull is modelled such that the moment one unit is finished at the end of the span of control we allow one more unit to enter the system. The individual buffers are not limited but the total number of units within the span of control of the long pull in the system is limited. The following parameters were used in the experiment and are defined:

Maxinv: This is the maximum work in process that is allowed in the span of control of the long pull.

Critical work-in-process level: This is MAXINV allowed within the span of the long pull. Below this level the MAXINV chosen will act as a bottleneck and decreases the throughput. For any number above this critical level the throughput remains the same.

Trig amt: This is the maximum level of WIP that is allowed in the buffer where the long pull is located. The withdrawal of one unit from this buffer will activate the long pull.

Simulation Run 1: Location of the long pull

Here, we test where the pull has to be located in a serial production system with a bottleneck work station.

System parameters:

(1) 6 workstations

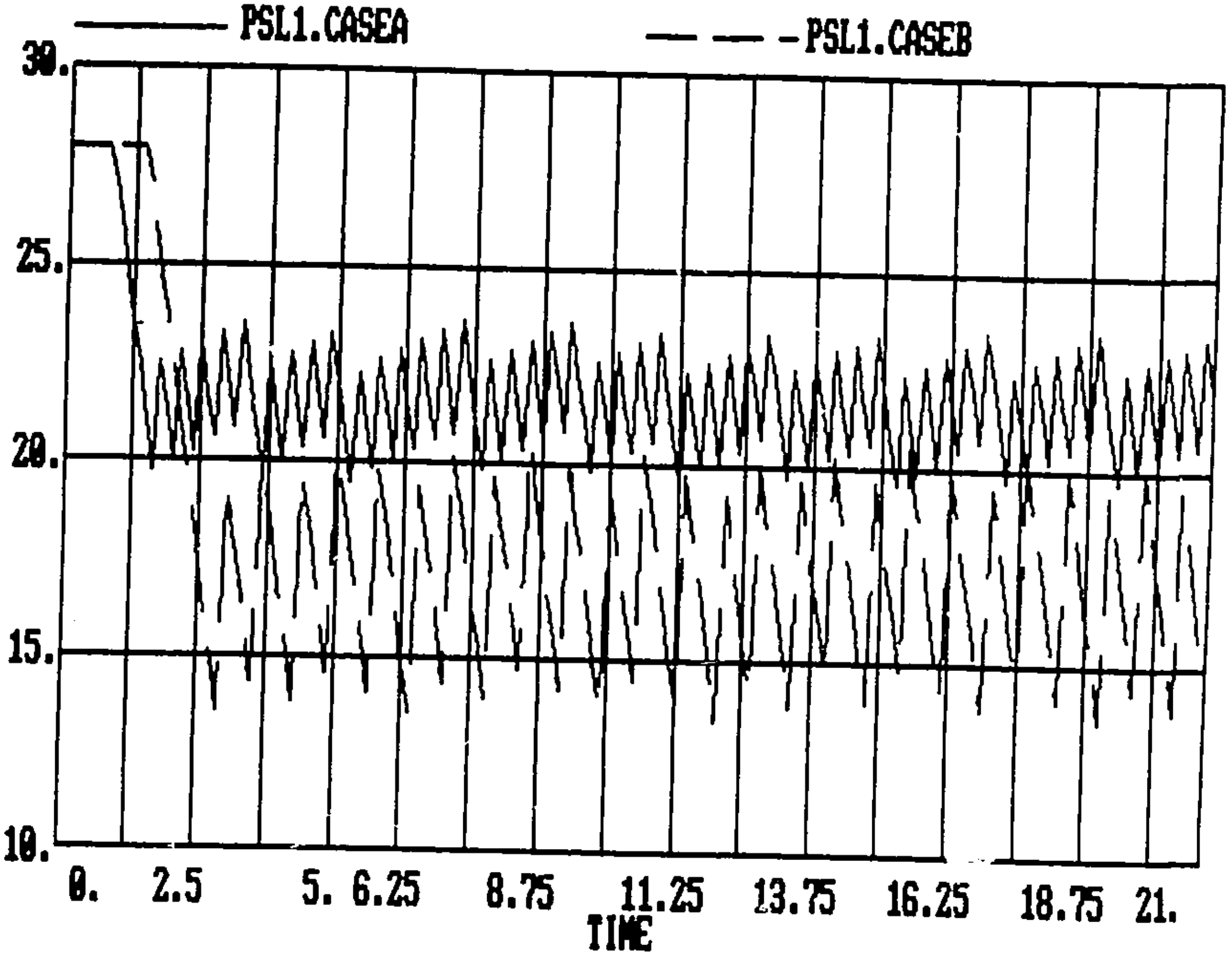

Figure 16: Variation of WIP - Case A and B (workstation 1)

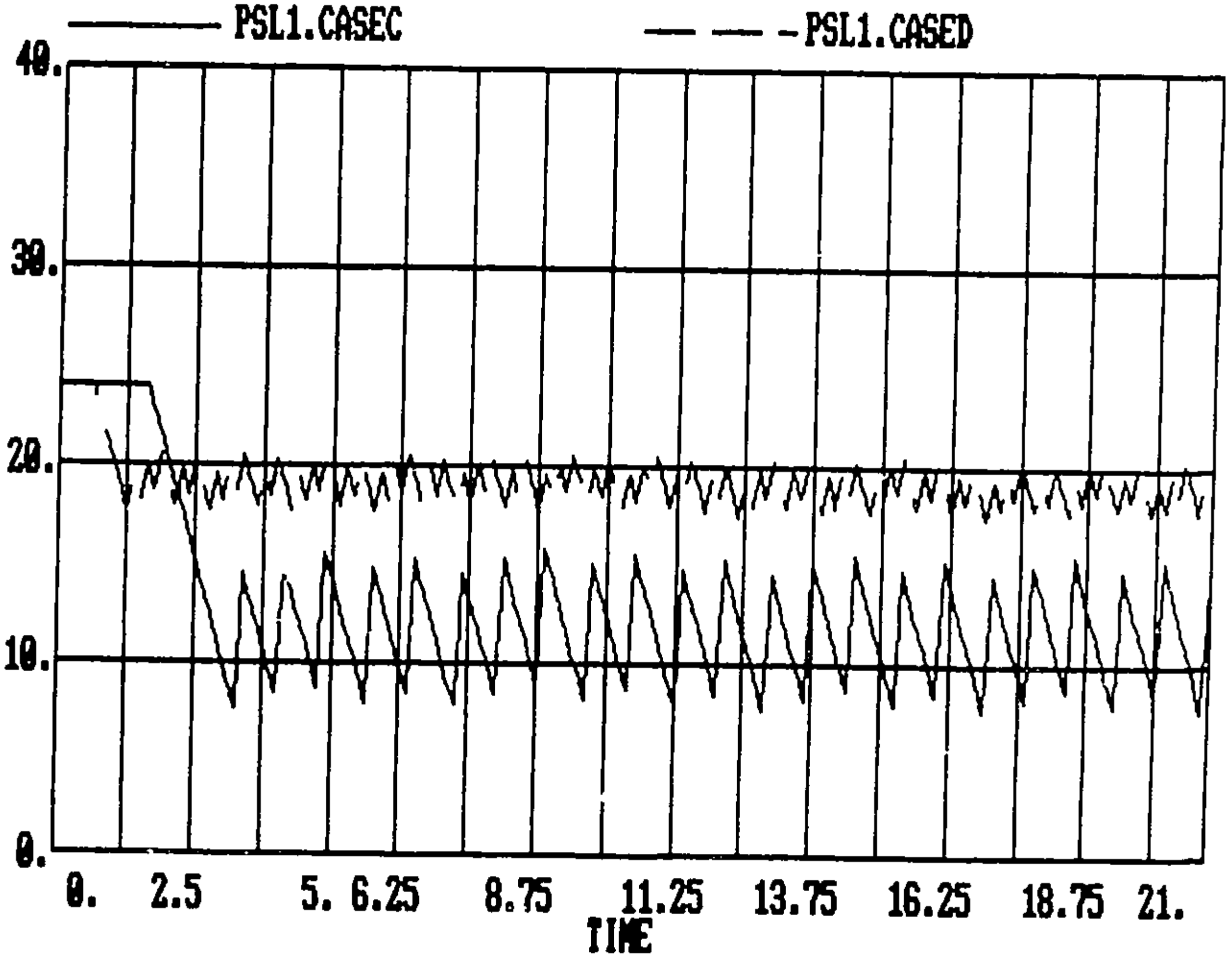

Figure 17: Variation of WIP - Case C and D (workstation 1)

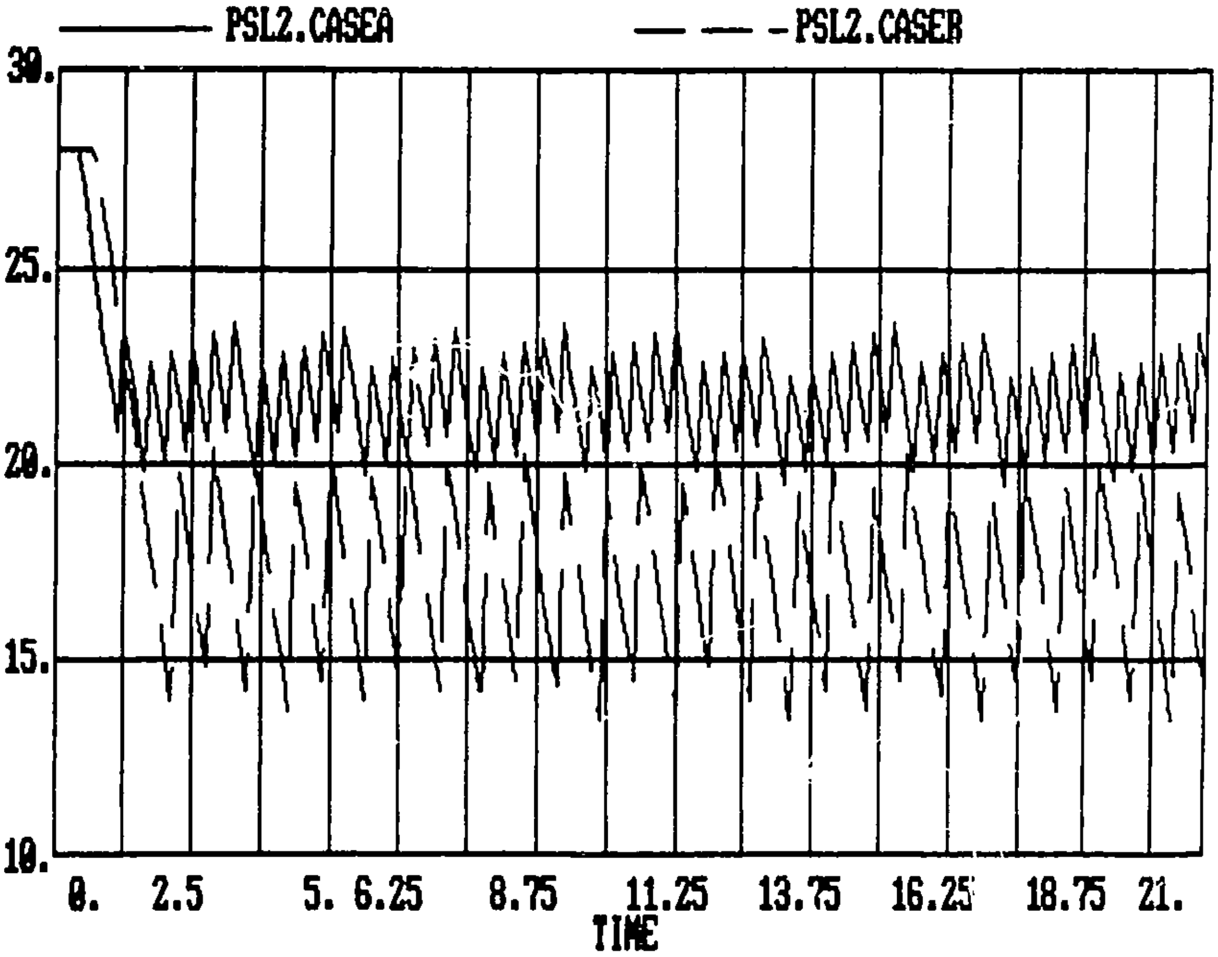

Figure 18: Variation of WIP - Case A and B (workstation 2)

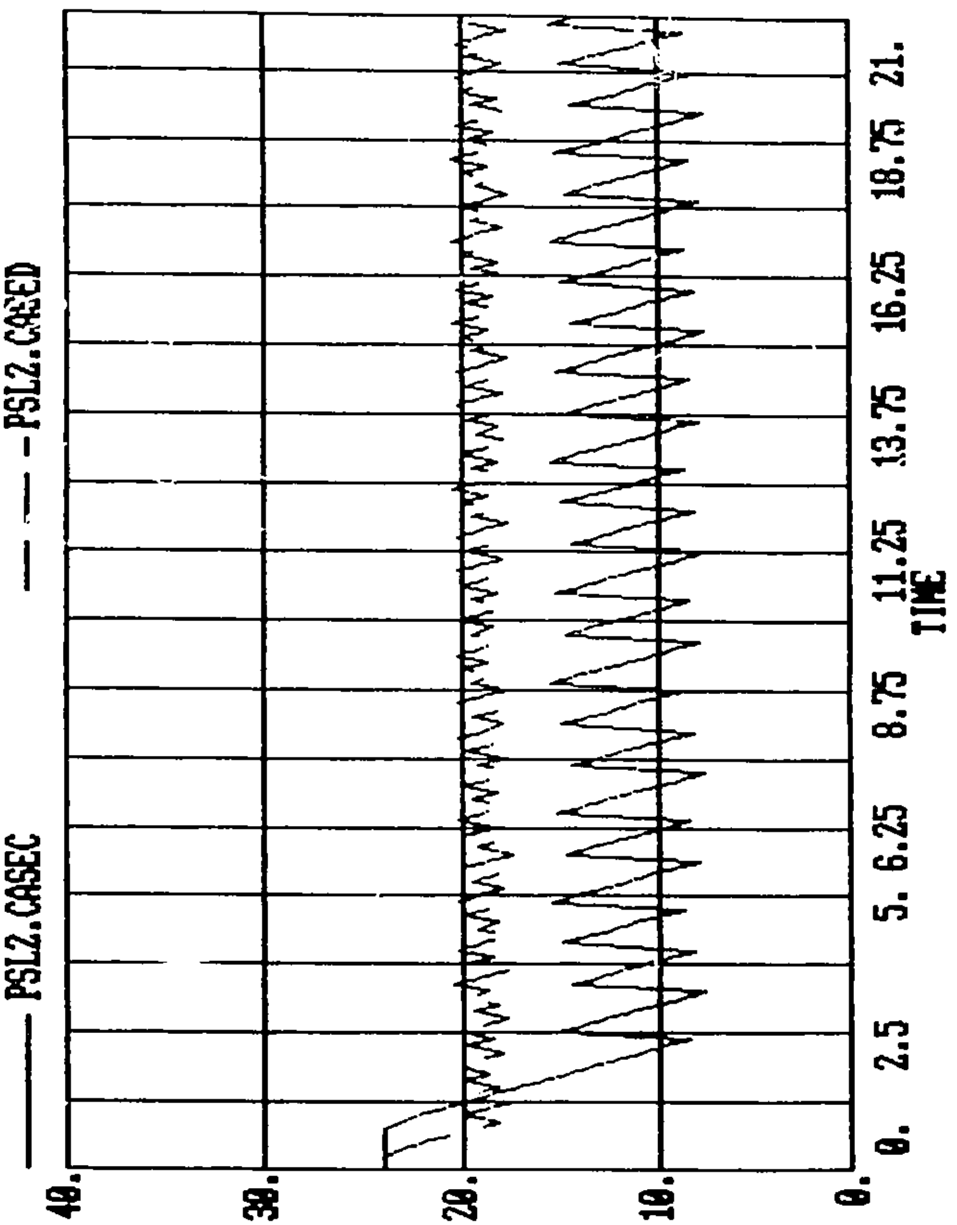

Figure 19: Variation of WIP - Case C and D (workstation 2)

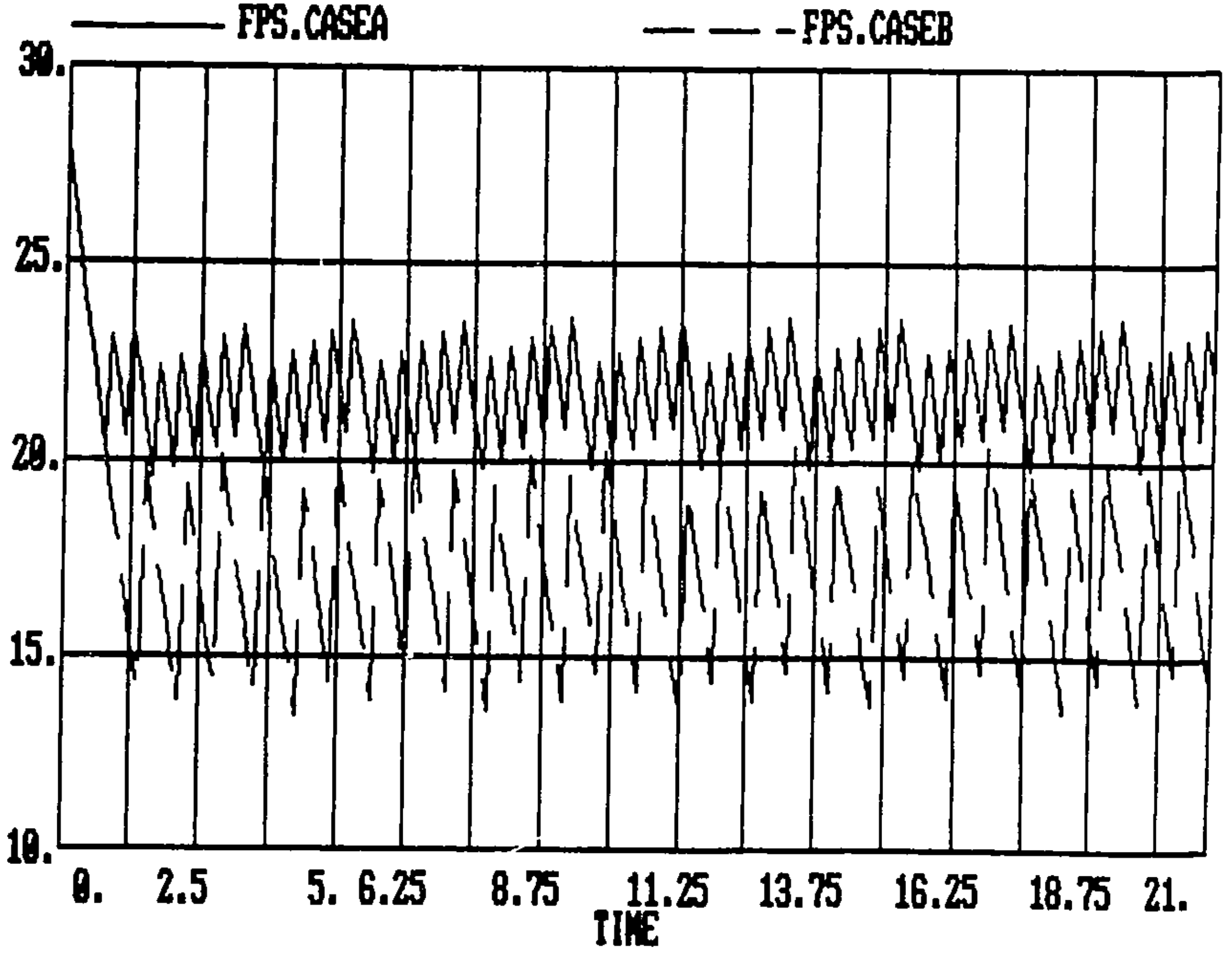

Figure 20: Variation of WIP - Case A and B (workstation 3)

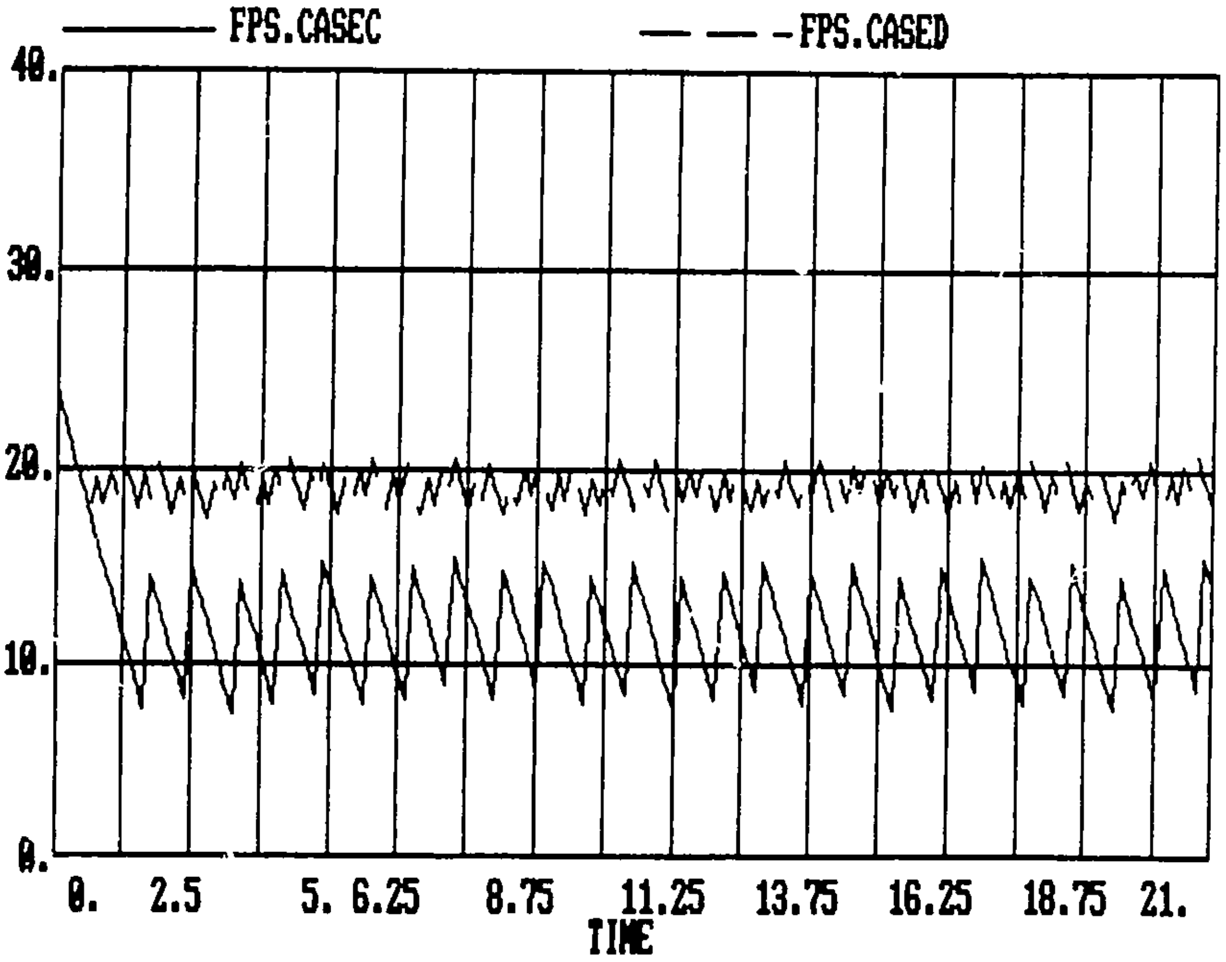

Figure 21: Variation of WIP - Case C and D (workstation 3)

(ii) Work stations 1,2,3,5 and 6 have a production rate of 15 with a standard deviation of 0.25. The bottleneck workstation (4) has a production rate of 9 with a standard deviation of 0.25.

(iii) The demand is assumed to be normally distributed with a demand of 15 with a standard deviation of 0.25.

(iv) The maximum inventory where the trigger (pull) is set to 2.

(v) Length of the run = 105

Cases analyzed: Location of the long pull

Case A: Location of long pull at station 3

Case B: Location of long pull at station 4 (at bottleneck)

Case C: Location of long pull at station 5

Case D: Location of long pull at station 6

* For all cases the span of the longpull is to station 1

Table 9a: Location of the long pull
(All variables are given for a 95% C.I.)

Cases	MaxInv	b1	b2	b3	b4	b5	$\overline{B}$	Throughput
Case A	3	0.61 ±0.01	0.61 ±0.01	0.70 ±0.01	0.60 ±0.01	0.60 ±0.01	0.62 ±0.01	784.30 ±11.59
	4	0.60 ±0.00	0.59 ±0.01	0.97 ±0.01	0.58 ±0.00	0.58 ±0.01	0.66 ±0.01	744.10 ±8.00
	* 5	0.59 ±0.01	0.59 ±0.00	1.00 ±0.01	0.58 ±0.00	0.57 ±0.00	0.67 ±0.00	728.00 ±3.09
Case B	5	0.68 ±0.00	0.68 ±0.00	0.99 ±0.00	0.68 ±0.00	0.68 ±0.00	0.74 ±0.00	936.50 ±0.61
	* 6	0.68 ±0.00	0.68 ±0.00	1.98 ±0.00	0.68 ±0.00	0.68 ±0.00	0.94 ±0.00	937.90 ±0.39
	7	0.68 ±0.00	0.68 ±0.00	2.97 ±0.00	0.68 ±0.00	0.68 ±0.00	1.14 ±0.00	937.90 ±0.39
Case C	* 7	0.68 ±0.00	0.68 ±0.00	1.40 ±0.00	0.68 ±0.00	0.68 ±0.00	0.82 ±0.00	937.90 ±0.39
	8	0.68 ±0.00	0.68 ±0.00	2.39 ±0.00	0.68 ±0.00	0.68 ±0.00	1.02 ±0.00	937.90 ±0.39
	9	0.68 ±0.00	0.68 ±0.00	3.40 ±0.00	0.68 ±0.00	0.68 ±0.00	1.22 ±0.00	937.90 ±0.39
Case D	8	0.67 ±0.00	0.67 ±0.00	1.08 ±0.02	0.66 ±0.00	0.66 ±0.00	0.75 ±0.00	907.00 ±2.11
	* 9	0.68 ±0.00	0.69 ±0.00	1.97 ±0.02	0.68 ±0.00	0.68 ±0.00	0.94 ±0.00	937.90 ±0.39
	10	0.69 ±0.00	0.69 ±0.00	2.96 ±0.03	0.68 ±0.00	0.68 ±0.00	1.14 ±0.00	937.90 ±0.39

Duncan's multiple range test was performed only for the cases asterisked (*) in the above table and the results indicate that there are significant differences at a 5 percent level between all pairs of means except for the following cases:

b1 - cases (B, C and D)

b2 - cases (B and C)

b3 - cases (B and D)

b4 - cases (B, C and D)

b5 - cases (B, C and D)

$\overline{B}$ - cases (B and D)

Throughput - cases (B, C and D)

The results given in the above table were obtained by performing the experiments in the following sequence:

RUN 1: With the pull located at workstation 4 (bottleneck) it is found that the critical WIP inventory for the span of control of the longpull is 6 since this value gives the maximum throughput and minimum average buffer content.

RUN 2: This is to test the control of each longpull and the corresponding amount of WIP. By using the principle of equal buffer allocation a MAXINV of 4, 8 and 10 were used for cases A, C and D respectively. Case B is still found to be the best in terms of throughput and average buffer content when compared to the other cases.

RUN 3: The MAXINV selected for cases C and D may not be the critical WIP. Therefore, more tests were conducted and the results are given in the above table. It is seen that for cases C and D the critical WIP levels are 7 and 9 respectively.

Now a simulation run is performed where the span of control of the long pull encompasses 3 workstations but the location of the long pull is as follows: Case A: Location of long pull from station 3 to station 1

Case B: Location of long pull from station 4 to station 2

Case C: Location of long pull from station 5 to station 3

Case D: Location of long pull from station 6 to station 4

The results of this simulation run are given below in Table 9b.

Table 9b: Location of long pull

(All variables are given for a 95% C.I.)

Cases	MaxInv	b1	b2	b3	b4	b5	$\overline{B}$	Throughput
Case A	4	0.60 ±0.00	0.59 ±0.00	0.97 ±0.01	0.58 ±0.00	0.58 ±0.00	0.66 ±0.00	744.10 ±8.00
Case B	4	312.22 ±0.37	0.68 ±0.00	1.55 ±0.00	0.69 ±0.00	0.68 ±0.00	63.15 ±0.08	939.00 ±0.48
Case C	4	1.43 ±0.12	310.26 ±0.29	1.53 ±0.01	0.68 ±0.00	0.68 ±0.00	62.91 ±0.08	940.10 ±0.41
Case D	4	1.43 ±0.12	1.43 ±0.09	309.03 ±0.30	0.68 ±0.00	0.68 ±0.00	62.69 ±0.07	941.10 ±0.41

Duncan's multiple range test was performed for the throughput and the results indicate that there are no significant differences in throughput at a 5 percent level between all pairs of means except for Case A.

In Table 9b the maximum inventory level was found in a similar manner as it was found in Table 9a. From these results the following observations can be made:

1. The long pull should contain the bottleneck workstation.
2. The average work-in-process level is higher than the results given in Table 9a due to the accumulation

of work-in-process before the beginning of the long pull.

From the results in Tables 9a and 9b the following parameters concerning the location and span of control of a long pull were observed:

(1) The long pull should be located at the bottleneck or after and span to the first workstation. If the span of the long pull does not encompass the bottleneck the throughput is greatly minimized.

(2) The critical WIP level has to be chosen carefully as shown in Table 9a.

Simulation Run 2: Effect of variability of production rates on Critical WIP

(i) 6 workstations

(ii) All work stations have a production rate normally distributed with a mean of 15. The bottleneck workstation (PR4) has a production rate normally distributed with a mean of 9.

(iii) The demand is assumed to be constant at 30.

(iv) The long pull is located at workstation 4.

(v) Length of the run = 105

Table 10: Effect of variability of production rates on Critical WIP

CV	critical WIP (trig amt = 2)	Throughput 95% C.I.	critical WIP (trig amt = 5)	Throughput 95% C.I.
0	5	938.00±0.00	5	938.00±0.00
0.1	6	938.50±1.66	6	938.00±1.43
0.3	7	937.90±3.82	7	938.70±4.17
0.5	8	916.20±5.98	7	939.10±6.64
0.7	11	877.00±6.57	8	938.40±8.51
0.9	15	824.60±8.64	10	938.70±11.72
1	20	796.80±9.87	11	937.50±12.39

Duncan's multiple range test was performed only for the throughput and the results indicate that there are significant differences at a 5 percent level between all pairs of means except for the following cases:

Trig amt 2 - cases (A, B and C)

Trig amt 5 - no significant differences

From the results it can be seen that with the trig amt of 2 the critical WIP keeps increasing as the CV increases. However, after a CV of 0.3 the trigger amount itself becomes a bottleneck after which the throughput decreases. However, if the trigger amount is higher (trig amt = 5) the critical WIP level increases whereas the throughput remains the same.

Simulation Run 3: The role of MAXINV as the bottleneck

(i) 6 workstations

(ii) All work stations have a production rate of 15. The bottleneck workstation (PR4) has a production rate with a mean of 9.

(iii) The demand is constant at 30.

(iv) Trig amt = 5

(v) Maxinv = 5

(vi) Pull is located at the bottleneck workstation

(vii) Length of the run = 105

Table 11: Role of MAXINV as the bottleneck

Cases	CV	Throughput 95% C.I.
A	0	938.00±0.00
B	0.1	933.30±1.58
C	0.3	907.20±2.33
D	0.5	853.70±4.41
E	0.7	784.30±6.88
F	0.9	718.20±6.24
G	1.0	681.80±5.42

Duncan's multiple range test was performed for the throughput and the results indicate that there are significant differences at a 5 percent level between all pairs of means except for the following cases:

Cases (A and B).

The results indicate after a CV of 0.1 MAXINV acts as a bottleneck thereby decreasing the throughput.

3.3.4 Comparative study of the various systems

A comparative study of the various systems was performed to analyze the behaviour of each system under almost similar conditions. The fact that the average inventory is different for different systems makes the study more complicated. This is because the distribution of the inventories varies from buffer to buffer depending on the allocation strategy and the system used.

Simulation Run 1: Effect of various systems on buffer allocation and throughput

Parameters used for various systems:

(i) 4 workstations

(ii) Production rates are normally distributed with a mean of 10

(iii) Demand is normally distributed with a mean of 15 and a standard deviation of .25

(iv) Length of the run = 105

(v) Buffer allocations

Push finite (equal buffers) Buffer Vector	Pull (Kanban) Buffer Vector	Longpull (Maxinv)
(5,5,5)	(5,5,5)	15

Table 12: Effect of various systems on buffer allocation and throughput

a) Pull system

Cases	CV	b1 95% C.I.	b2 95% C.I.	b3 95% C.I.	$\overline{B}$ 95% C.I.	Throughput 95% C.I.
Case A	0.1	1.83±0.24	1.53±0.21	1.50±0.16	1.65±0.15	1039.90±0.71
Case B	0.3	2.31±0.08	2.12±0.19	1.87±0.11	2.11±0.10	1027.30±2.82
Case C	0.5	2.41±0.71	2.14±0.11	1.89±0.05	2.15±0.05	1003.60±3.57
Case D	0.7	2.46±0.07	2.18±0.09	1.89±0.06	2.17±0.05	970.60±4.60
Case E	0.9	2.56±0.07	2.22±0.08	1.90±0.04	2.24±0.05	932.20±5.48
Case F	1.0	2.60±0.06	2.22±0.09	1.92±0.04	2.24±0.05	911.00±5.60

Duncan's multiple range test was performed for the above table and the results indicate that there are significant differences at a 5 percent level between all pairs of means except for the following cases:

b1 - cases (B, C, D, E and F)

b2 - cases (B, C, D, E and F)

b3 - cases (B, C, D, E and F)

$\overline{B}$ - cases (B and D) and (C, D, E and F)

Throughput - all are significantly different

b) Push system with finite buffers

Cases	CV	b1 95% C.I.	b2 95% C.I.	b3 95% C.I.	$\overline{B}$ 95% C.I.	Throughput 95% C.I.
Case A	0.1	1.85±0.26	1.65±0.31	1.52±0.21	1.68±0.17	1039.90±0.86
Case B	0.3	2.38±0.08	2.19±0.19	1.92±0.13	2.16±0.10	1027.80±2.76
Case C	0.5	2.39±0.06	2.14±0.11	1.90±0.05	2.14±0.05	1004.00±3.60
Case D	0.7	2.43±0.07	2.12±0.09	1.86±0.05	2.14±0.05	968.10±4.40
Case E	0.9	2.46±0.06	2.13±0.08	1.83±0.05	2.14±0.04	925.00±6.06
Case F	1.0	2.45±0.06	2.12±0.06	1.82±0.05	2.13±0.04	902.90±6.32

Duncan's multiple range test was performed for the above table and the results indicate that there are significant differences at a 5 percent level between all pairs of means except for the following cases:

b1 - cases (B, C, D, E and F)

b2 - cases (B, C, D, E and F)

b3 - cases (B, C, D, E and F)

$\overline{B}$ - cases (B, C, D, E and F)

Throughput - all are significantly different

c) Long pull system

Cases	CV	b1 95% C.I.	b2 95% C.I.	b3 95% C.I.	$\overline{B}$ 95% C.I.	Throughput 95% C.I.
Case A	0.1	1.89±0.33	1.67±0.34	1.51±0.17	1.70±0.18	1039.90±0.53
Case B	0.3	2.97±0.53	2.89±0.64	2.55±0.28	2.79±0.21	1031.70±0.22
Case C	0.5	3.20±0.57	2.91±0.41	2.92±0.45	3.03±0.25	1020.00±5.71
Case D	0.7	3.23±0.43	3.20±0.34	3.23±0.28	3.20±0.12	1001.80±5.49
Case E	0.9	3.23±0.34	3.23±0.32	3.28±0.20	3.25±0.10	977.30±8.33
Case F	1.0	3.25±0.32	3.24±0.30	3.30±0.18	3.26±0.09	963.70±9.15

Duncan's multiple range test was performed for the above table and the results indicate that there are significant differences at a 5 percent level between all pairs of means except for the following cases:

b1 - cases (B, C, D, E and F)

b2 - cases (B, C, D, E and F)

b3 - cases (C and D) and (D, E and F)

$\overline{B}$ - cases (C, D and E) and (D, E and F)

Throughput - all are significantly different

Push and pull have lower WIP levels as compared to longpull. All systems have lower throughput with increased variability. However, at higher levels of uncertainty longpull performs better (i.e. higher throughput). This is intuitively clear since a constraint on the system has been relaxed.

Simulation Run 2: Effect of various systems on Lost Sales (LS)

System Parameters:

(i) 4 workstations

(ii) Production rates are normally distributed with a mean of ten

(iii) Demand is normally distributed with a mean of 12 and a standard deviation of .25.

(v) Buffer allocations

Push (equal buffers) Buffer Vector	Pull (Kanban) Buffer Vector	longpull Maxinv
(3,3,3)	(3,3,3)	9

(vi) Length of the run = 21

Table 13: Effect of various systems on Lost Sales (LS)

Cases	CV	Push (finite) 95% C.I.	Pull 95% C.I.	Push (infinite) 95% C.I.	Longpull 95% C.I.
Case A	0.1	51.10±0.63	50.10±0.53	49.70±0.48	49.70±0.48
Case B	0.3	57.80±1.30	58.30±0.62	53.80±1.30	54.30±1.07
Case C	0.5	70.00±1.43	70.30±1.35	57.60±2.00	60.40±1.18
Case D	0.7	86.00±1.75	83.30±1.89	61.50±2.68	68.20±1.42
Case E	0.9	103.60±2.44	98.70±4.06	65.30±3.49	76.50±2.24
Case F	1.0	111.70±2.82	103.50±2.19	67.10±4.04	81.20±2.15

Duncan's multiple range test was performed for the above table and the results indicate that there are significant differences at a 5 percent level between all pairs of means except for the following cases:

Push (infinite) - cases (E and F)

As the variability increases the amount of demand that is not met increases in all the systems due to the decrease in throughput. At a higher level of uncertainty longpull and push with infinite buffers performs the best.

Simulation Run 3: Reaction of the different systems to demand

System parameters:

(i) 4 workstations

(ii) Production rates have a mean of ten

(iii) Case (1): Demand rate is constant with a mean of 10 for 42 time units then there is no demand for 21 time units and again there is a constant demand rate of 10 units for 42 time units

Case (2): Demand is constant with mean of ten over the entire length of the run

(iv) Buffer allocations

Push (equal buffers) Buffer Vector	Pull (Kanban) Buffer Vector	longpull Maxinv
(3,3,3)	(3,3,3)	9

(v) Maxinv = 9

(iv) Length of the run = 105

Table 14: Reaction of the different systems to demand

		b1	b2	b3	$\overline{B}$	T
Push (infinite)	Case 1	0.7802	0.7788	0.7778	0.7789	1045
	Case 2	0.7802	0.7788	0.7778	0.7789	1045
Push (finite)	Case 1	1.4518	1.4156	1.3793	1.4156	838
	Case 2	0.7802	0.7788	0.7778	0.7789	1045
Pull	Case 1	1.4518	1.3654	1.3901	1.3858	837
	Case 2	0.7802	0.7788	0.7778	0.7789	1045
Longpull	Case 1	0.6745	0.6606	0.6471	0.6674	835
	Case 2	0.7802	0.7788	0.7778	0.7789	1045

As expected push with infinite buffers does not react to the changes in demand. These results indicate that the push with finite buffers, pull and long pull systems react to the changes in demand as and when necessary.

CHAPTER 4

SYSTEM DYNAMICS MODELLING AND ANALYSIS OF A SPARK PLUG ASSEMBLY PLANT

The principles of push and pull systems were applied to develop two models for a local spark plug assembly plant. First, a description of the assembly plant processes was given and the problems faced by the plant were identified. Then, a system dynamics model of the existing assembly process (a push system) was developed with the existing company policy and the results were verified. New policies were tested and the results were compared with the existing policy. The second model was developed using system dynamics to incorporate a pull system to study the system behaviour.

4.1 DESCRIPTION OF THE SPARK PLUG ASSEMBLY

A clear description of the flow of material in the spark plug assembly plant is first discussed (see Figure 22). In addition to spark plug assembly the company under study also manufactures shell terminals and centre wires which are used in the second step of the assembly process. The raw shells are extruded from coiled steel stock which is fed through six punch and die stations progressively, to form a shell. Then the shells are chucked (decorations added), washed, counterbored, welded and threaded before being shipped to an outside source for zinc plating and chrome protection. The shell terminals (open or closed form) are manufactured on automatic screw machines through progressive

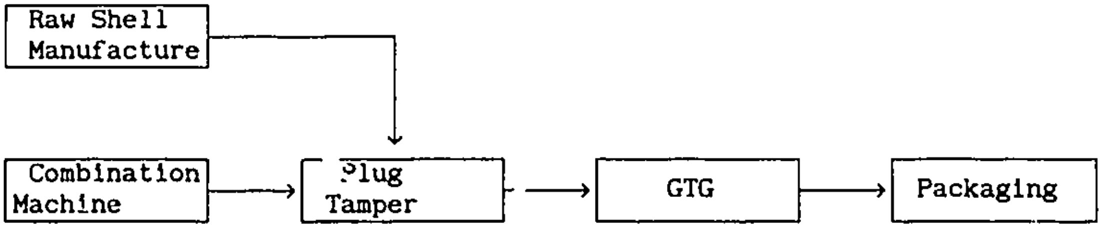

Figure 22. Structure of the spark plug assembly process

and simultaneous machining of steel or aluminum rods. Then they are sent to the same outside source as the shells for electroplating. The centre electrode wire consists of a copper coated iron wire welded to a nickel wire. The assembly of the spark plug can be divided into four main operations:

1. The core assembly (combination machines) consists of four shots of aluminum oxide powder being injected between the centre wire and insulator and tamped under high pressure to form a gas tight seal. For resistor type plugs a spring and resistor are also fed into the insulator. The last step in the core assembly is to apply cement to the terminal (also called studs) and screw it into the insulator.
2. The plug tampers assemble the finished insulators (from core assembly), gaskets and shells using aluminum oxide powder to form a seal. Automatic inspection devices reject defective plugs.
3. The GTG (Gasket, Trim and Gap) operation adds and crimps into position the attached gasket. The centre electrode is trimmed. The side of the electrode is then bent to give the precise gap for optimal plug performance and the gaskets are inspected.
4. The packaging operation consists of manually feeding the plugs

onto a conveyor where the plugs are packaged in different types of packs and then fed into boxes.

The finished plugs are either shipped or transferred to a high-bay storage system which is a computer-directed, manually-operated retriever system.

4.2 Problems observed at the plant

The most noticeable problem in the area of the spark plug assembly is the build up of inventories before the plug tamper machines. This was mainly due to the shortage of plated shells. Since the company under study manufactures a variety of parts and the policy of the company is to change over parts if the plated shells run out, inventories tend to accumulate before the plug tamper machines. Some of these inventories remained there for a month or more before being used again. This not only used up floor space but also tied up capital invested in these inventories.

The main contributing factor for these inventories to remain on the shop floor is the insufficient amounts of plated shells. This is attributed to the fluctuation in delivery times of the plated shells from an outside source and the company policy of holding minimum amounts of plated shells as inventory. Other factors include: breakdown of machines manufacturing raw shells, and efficiency of the work force (eg. absenteeism, newly hired workers, etc.).

A possible factor for the problems faced by the company maybe due to the present company scheduling policy. The schedule used currently by the company is often staggered in terms of start up times of the various machines in the assembly of a spark plug. Also, the present lead time (5 days) used in manufacturing raw shells may effect work-in-process inventories and throughput. Some of the problems faced by the company have been identified. The primary objective of this work is, therefore, to use a system dynamics approach for simulating the industrial system and identify various policies to effectively reduce the various problems faced by the company.

4.3 SYSTEM DYNAMICS MODEL OF THE ASSEMBLY PROCESS

The model presented here is of a multi stage manufacturing system. It consists of a serial production line with an assembly process in the second stage. The data was collected for the assembly of one spark plug type and modelled. The system dynamics model is shown in Figure 23. The flow diagram given shows both information flows and material flows between various rates and levels. The company under study uses a push strategy for manufacturing shells and to assemble the spark plugs. A description of all the rates, levels and auxiliary levels of the model given in Figure 23 are first given.

The manufacturing of raw shells is determined by the raw shell production rate (RSPR). The amount of shells manufactured are set to equal the demand for the part type and a correction factor (PRCORR) which indicates the number of additional units to compensate for the rejects levels at the different stages of the assembly process. The raw shells manufactured are stored in the shells for plating inventory (SFP). This inventory is depleted by the shells for plating order rate

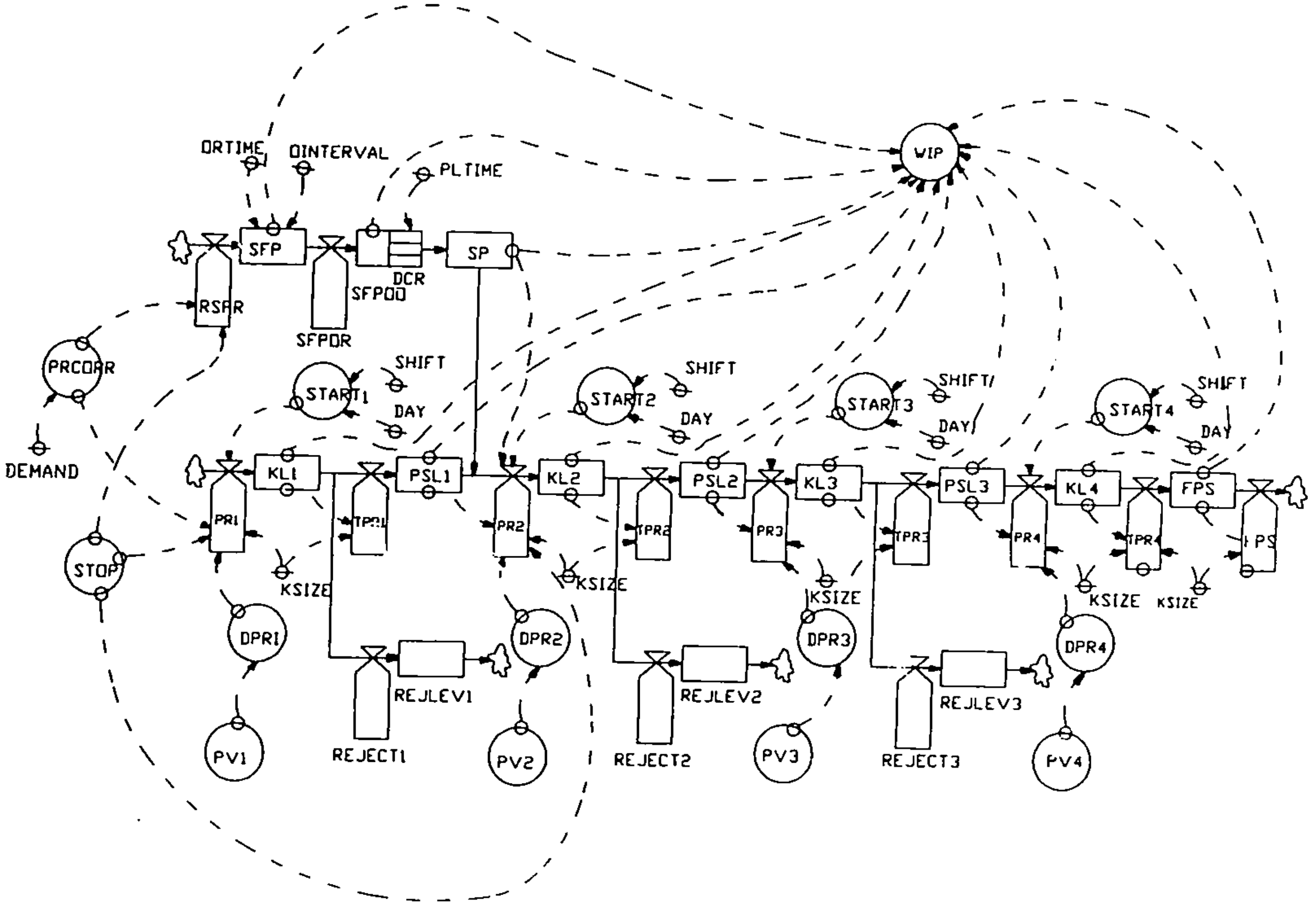

Figure 23: Flow diagram of spark plug assembly process - a push system

(SFPOR) when the shells are sent to an external source for electroplating. This rate is determined by the order time and the order interval. The policy of the company under study is to send all the shells accumulated in SFP out for plating which have been produced until the beginning of the morning shift. The ordering interval currently used is once a day. The amount of shells which are sent out for plating but have not yet returned from the external source is represented by SFPOO (shells for plating on order). The delivery completion rate (DCR) is given by a third order delay. This delay represents the time it takes the external source to return the shells after plating. The DCR is determined by the plating lead time (PLT) which is the average time it takes the external source to deliver the plated shells. The plated shells (SP) which are delivered are stored in inventory and are now ready to be used in the second process of assembling a spark plug.

The first machine in the assembly process is the combination machine which runs at a production rate (PR1) which is determined by the desired production rate (DPR1) and by production variability (PV1). Once a part is finished at PR1 it is dropped into a container (KL1) located at that station and upon reaching the container capacity (KSIZE) it is transferred (TPR1) to the storage area for the combination machines (PSL1). Parts found defective at this stage are rejected at a given rate (REJECT1) and accumulated in a bin (REJLEV1). If the plated shell inventory falls to zero and the expected delivery is late PR1 is stopped (STOP) and the machine is changed over to assemble a different part.

The second machine in the assembly process is the plug tampers machine. If there are assembled raw cores in PSL1 and plated shells in SP then the plug tampers machine can continue assembly of the part at a production rate (PR2) influenced by a desired production rate (DPR2) and production variability (PV2). The plug tamper machine (PR2) will therefore, check the level of inventory in PSL1 and the level of inventory in SP before commencing its assembly process. The assembled parts are dropped into a container (KL2) and once the container reaches capacity (KSIZE) it is transferred (TPR1) to the production storage area of the plug tamper machine (PSL2). The parts which are found defective are rejected at a given rate (REJECT2) and collected in a bin (REJLEV2). If the supply of shells (SP) are depleted then the PR2 is stopped (STOP) and the machines is changed over for another part.

The third step in the assembly is the GTG machine which produces at a rate (PR3) determined from the desired production rate (DPR3) and production variability (PV3). The assembled parts are tested and placed on racks. For the purpose of modelling, the containers are retained for this assembly process. That is, the tested parts are assumed to be placed in containers (KL3) which are then transferred (TPR3) to the production storage area of the GTG machines (PSL3).

The last step in the assembly process is the packaging of the finished product. This is done at a rate (PR4) determined from a desired production rate (DPR4) and production variability (PV4). Again, for the purpose of modelling it is assumed that these units are placed into containers (KL4). When the limits of the container are reached the finished product is transferred (TPR4) to the finished product storage (FPS) of the packaging area.

The assembly of a new spark plug type is determined by the company schedule. For PR1, PR2, PR3 and PR4 the time to start is given by START1, START2, START3 and START4 respectively, which gives the day that a new part type is started and the shift schedule for that machine. For the purposes of modelling a 21 hour day will be used since it represents the actual number of hours that are available for assembling and manufacturing parts. The morning shift is represented by hours 7-14; the afternoon shift by hours 14-21; and the night shift by hours 21-7. According to company policy and using a 21 hour day and the following shifts: the combination machine (PR1) is run during the morning shift; the plug tamper machine (PR2) is run for two shifts: morning shift and the afternoon shift; the GTG machine (PR3) is also run for two shifts: morning shift and afternoon shift; and the packaging machine (PR4) is run for one shift: morning shift. The manufacturing of raw shells is run during all three shifts.

The manufacturing of shells which are used in the second step of the assembly process is first planned since the shells require time for manufacturing in the plant and time for electroplating from an external source before they are completed and delivered. Since the external source has variable delivery times for the plated shells, the schedule provides a lead time for the manufacture of raw shells which will allow for the manufacturing process, the time taken for the material to be shipped, electroplated and delivered and a safety factor in the case of late delivery times. The schedule presently used aims for a 5 day lead time as this will ensure a sufficient time for the arrival of plated shells to be used in the second stage of assembly process (PR2). The company policy of stopping production of a specific part type if the plated shells (SP) inventory is empty will be maintained for the purposes of this study.

4.4 Model validation

The validity of the model developed is determined by comparing the simulated results with the observed data collected from the assembly plant. The observed data was collected for one particular spark plug type through its entire manufacturing and assembly process in the plant. For this particular spark plug assembly run it was found that production started according to the following schedule: the combination machine (PR1) started on day 0, the plug tamper machine (PR2) started on day 2, the GTG machine (PR3) started on day 3 and the packaging machine (PR4) on day 5. The amount of raw cores available for PR1 was 126290. It was also found that the raw shells (RSPR) for this spark plug type started the manufacturing process with a lead time of two days (LT = 2 days) before the assembly process was started on the combination machine. Also, the raw shells were sent for electroplating to the external supplier during the morning shift (ORTIME) and at an order interval (OINTERVAL) of once a day. The supplier usually delivers the raw shells at an average of 2.6 days but for the observed spark plug type there was a delivery delay (LSHOCK) of one day.

Using the same parameters (schedule, raw cores available, lead time, order interval, order time and delivery delay) as the actual data collected, a simulation run was performed on the model developed for the purpose of model validation. It was found that the simulated values of the variables compare well with the observed values as shown in Table 15.

Table 15: Observed and simulated values for a particular spark plug type

Variable Name	Actual Value	Simulated Value
Amount processed at PR1	100399	101700
Reject % of PR1	4%	4%
Output of PR1	96383	97500
PSL1	3500	2960
Amount processed at PR2	92883	94540
Reject % of PR2	0.337%	0.337%
Output of PR2	92570	94100
Amount processed at PR3	92570	94000
Reject % of PR3	11.98%	11.98%
Output of PR3	81480	83150
Amount processed at PR4	81480	83000

The difference between the raw cores available for assembly and the amount processed at PR1 is due to the company policy of stopping the assembly process if the plated shell inventory is empty.

However, in general, the schedule followed by the company for various spark plug types is as follows: The assembly process started on days 0, 2, 3 and 5 for the combination machine, plug tamper machine, GTG machine and packaging machine, respectively with a lead time of 5 days for starting the manufacture of raw shells. The order interval for sending the raw shells for electroplating is once a day during the morning shift with an average plating lead time of 2.6 days.

In the following section this general schedule was used as the base case to study the effect of various policies such as: varying lead times with and without delivery delays using different schedules, using different production rates for the assembly process, and the impact of different plating lead times and order intervals. The purpose of this analysis was to determine the best schedule and corresponding lead time and the plating order time and order interval that the company should follow.

4.5 Analysis and results of simulation runs performed for the present system

Simulation Runs 1, 2, and 3 were performed to find the best schedule and lead time for starting the manufacture and assembly of raw shells under both regular conditions and with a shock in the delivery of plated shells. The results show the levels of SFP, SFPOO, SP, throughput (FPS) and the time it takes it takes for the given throughput.

Simulation Run *1: Impact of lead time with original schedule*

The original schedule is an example of the type of schedule usually followed by the company. The company schedule to start the assembly process is: the manufacturing of raw shells is started with a lead time of approximately 5 days. In anticipation of the plated shells delivery, the combination machine (PR1) starts the manufacture of a new spark plug type and the raw cores undergo the first assembly process. Similarly PR2, PR3 and PR4 are ready to start the assembly of the new spark plug type as soon as the previous spark plug type processes are finished. This often leads to a staggered start up schedule of the assembly line machines. The original schedule in this case starts manufacturing of the raw shells with a lead time (LT) and the PR1, PR2, PR3 and PR4 are started according the schedule START1, START2, START3 and START4 respectively.

System Parameters:

(i) START1 = Day 0 + LT

(ii) START2 = Day 2 + LT

(iii) START3 = Day 3 + LT

(iv) START4 = Day 5 + LT

(v) SHOCK in the delivery completion rate occurs at time = 78 and lasts for a duration of one day during which no shells are delivered

Table 16: Impact of lead time with original schedule

LT (days)	Run	Throughput ; correponding time	Run with shock	Throughput ; correponding time
5	EX1A	95500 ; 264	EXS1A	77500 ; 246
2	EX1B	94000 ; 201	EXS1B	66500 ; 180
1	EX1C	79000 ; 176	EXS1C	56500 ; 156
0	EX1D	3000 ; 92	EXS1D	3000 ; 92

A lead time of 2 days is found to perform the best even with a SHOCK in the system as seen from work-in-process levels and throughput (See Figures 24 to 29).

Simulation Run 2: *Impact of lead time on one day difference schedule*

This experiment tests the scheduling of the assembly machines with a one day difference in start up time when a new spark plug is to be manufactured.

System Parameters:

(i) START1 = Day 0 + LT

(ii) START2 = Day 1 + LT

(iii) START3 = Day 2 + LT

(iv) START4 = Day 3 + LT

(v) SHOCK in the delivery completion rate occurs at time = 78 and lasts for a duration of one day during which no shells are delivered

Table 17: Impact of lead time on one day difference schedule

LT (days)	Run	Throughput ; correponding time	Run with shock	Throughput ; correponding time
5	EX2A	95500 ; 222	EXS2A	78500 ; 204
2	EX2B	95000 ; 158	EXS2B	56500 ; 119
1	EX2C	3500 ; 72		

The results (Figure 30 to 34) show that lead time of 2 days gives the best throughput even with a shock in delivery for one day.

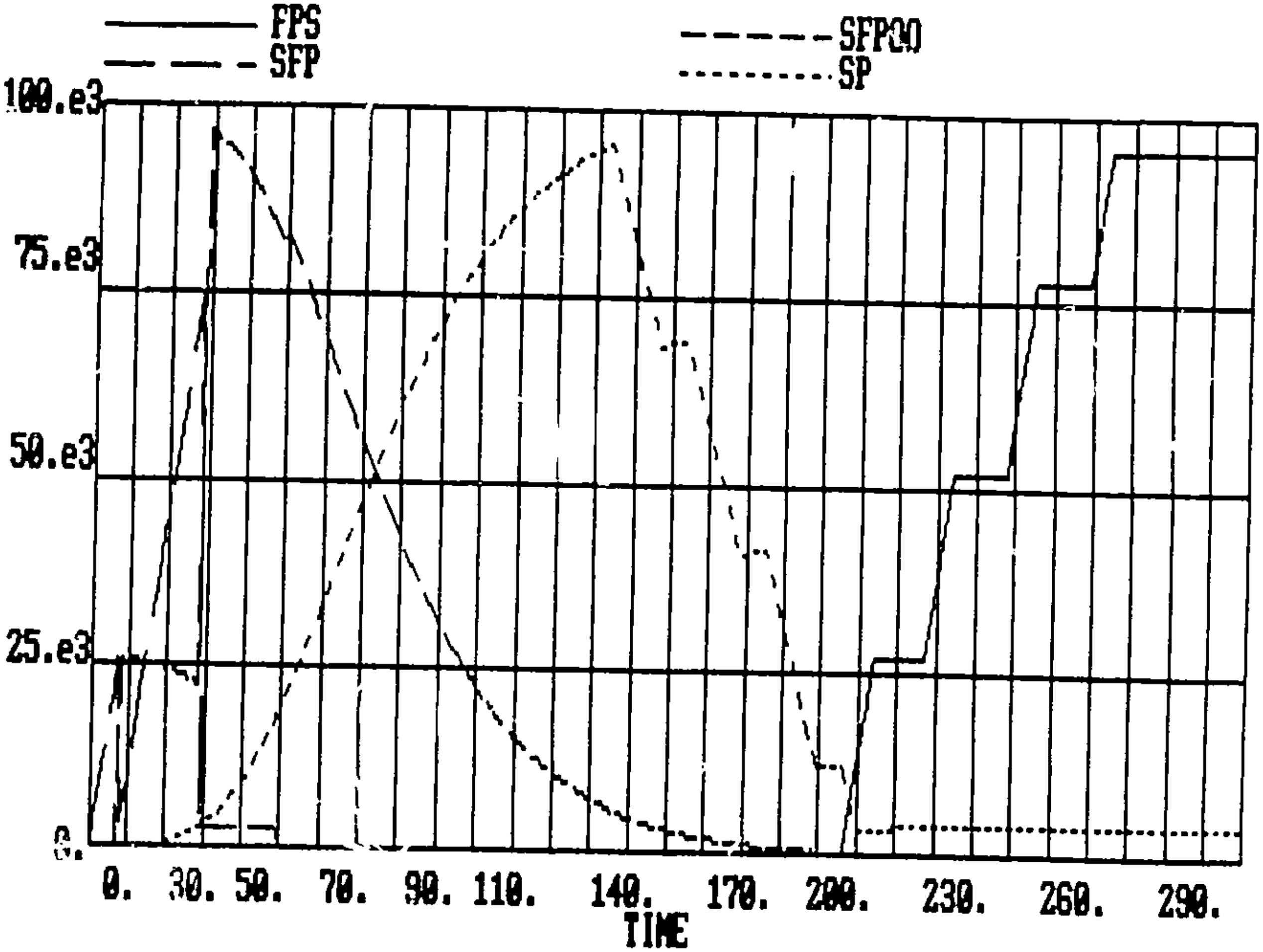

Figure 24: Impact of lead time with original schedule
(LT = 5 days)

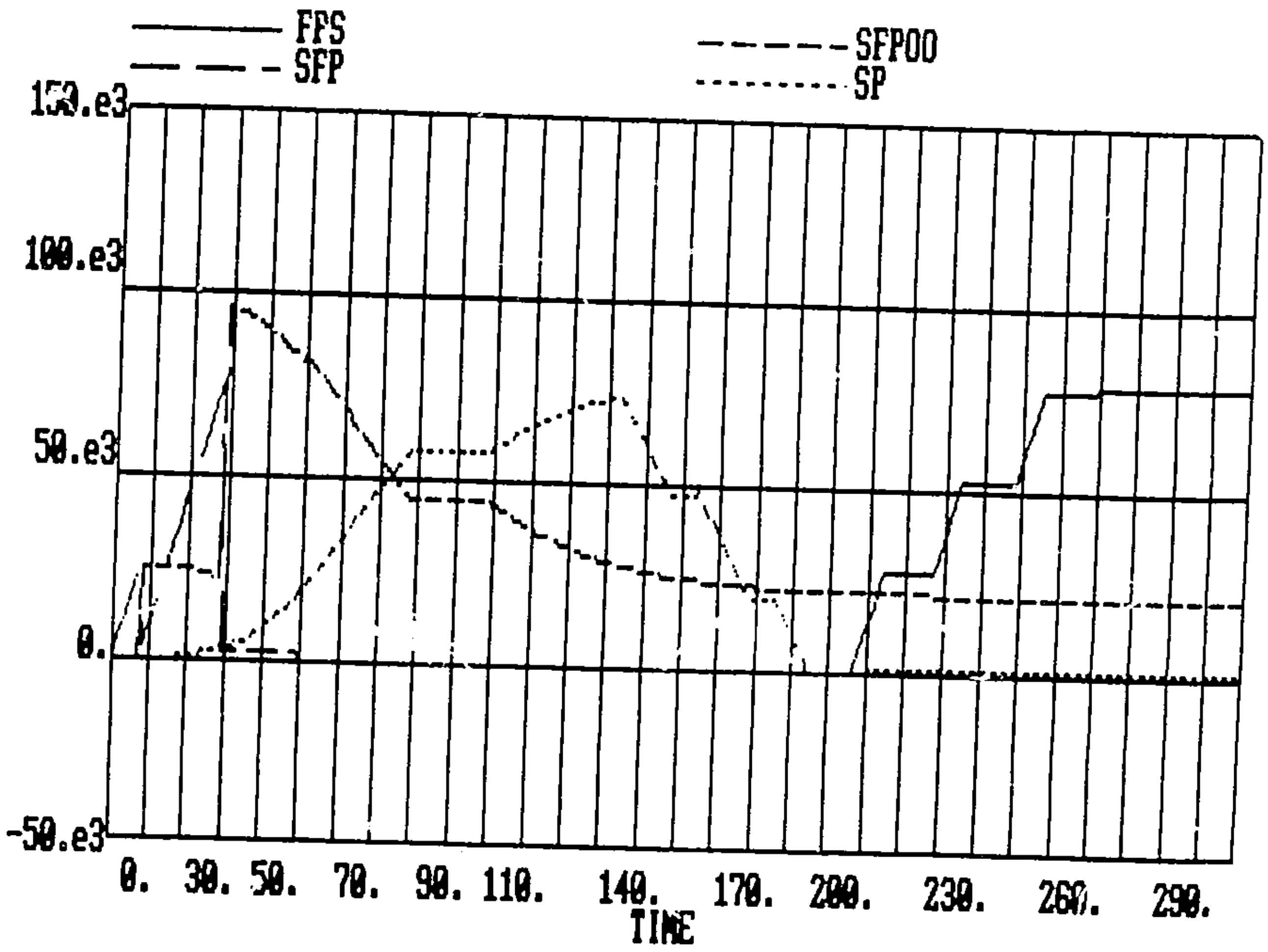

Figure 25: Impact of lead time with original schedule
(LT = 5 days with SHOCK)

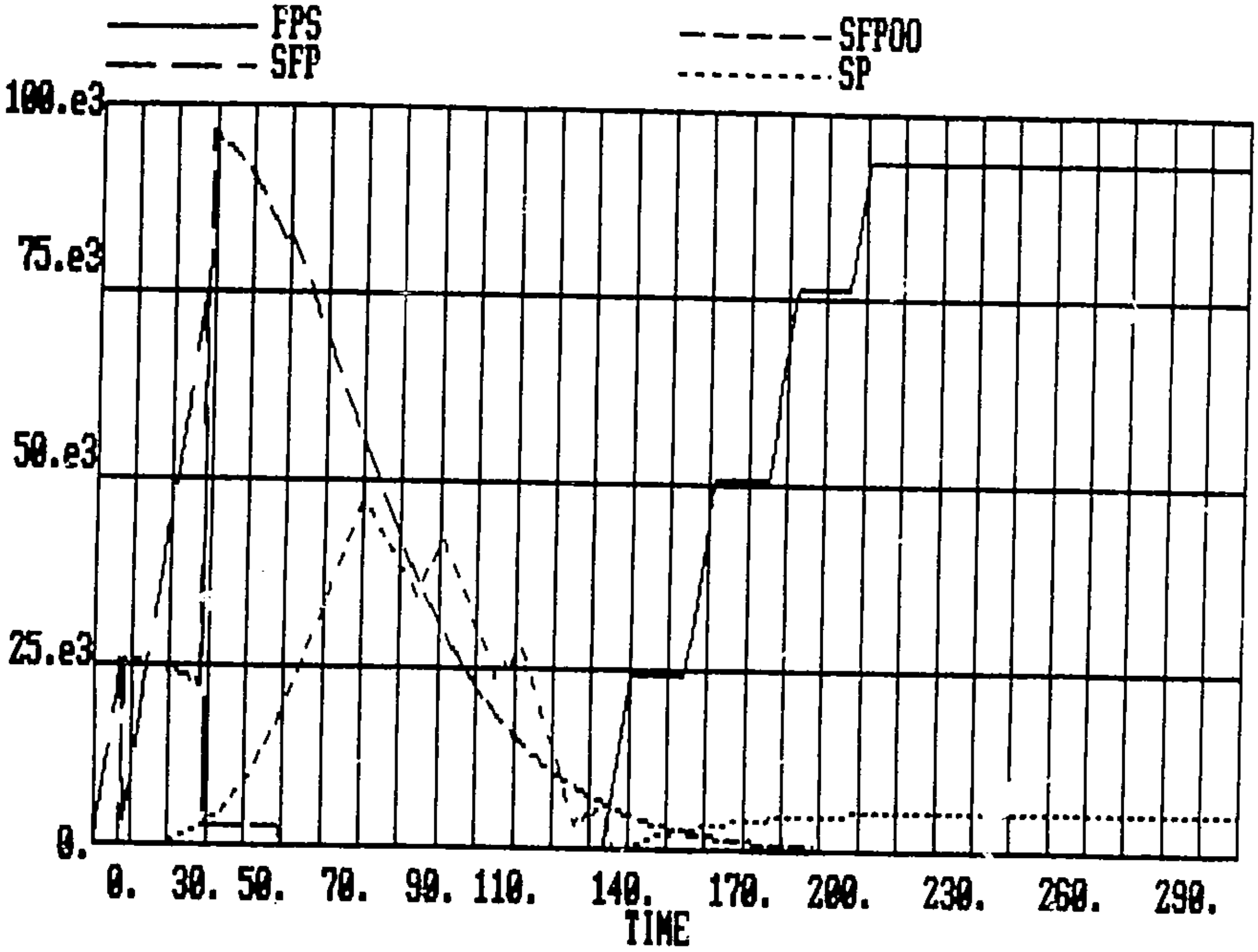

Figure 26: Impact of lead time with original schedule
(LT = 2 days)

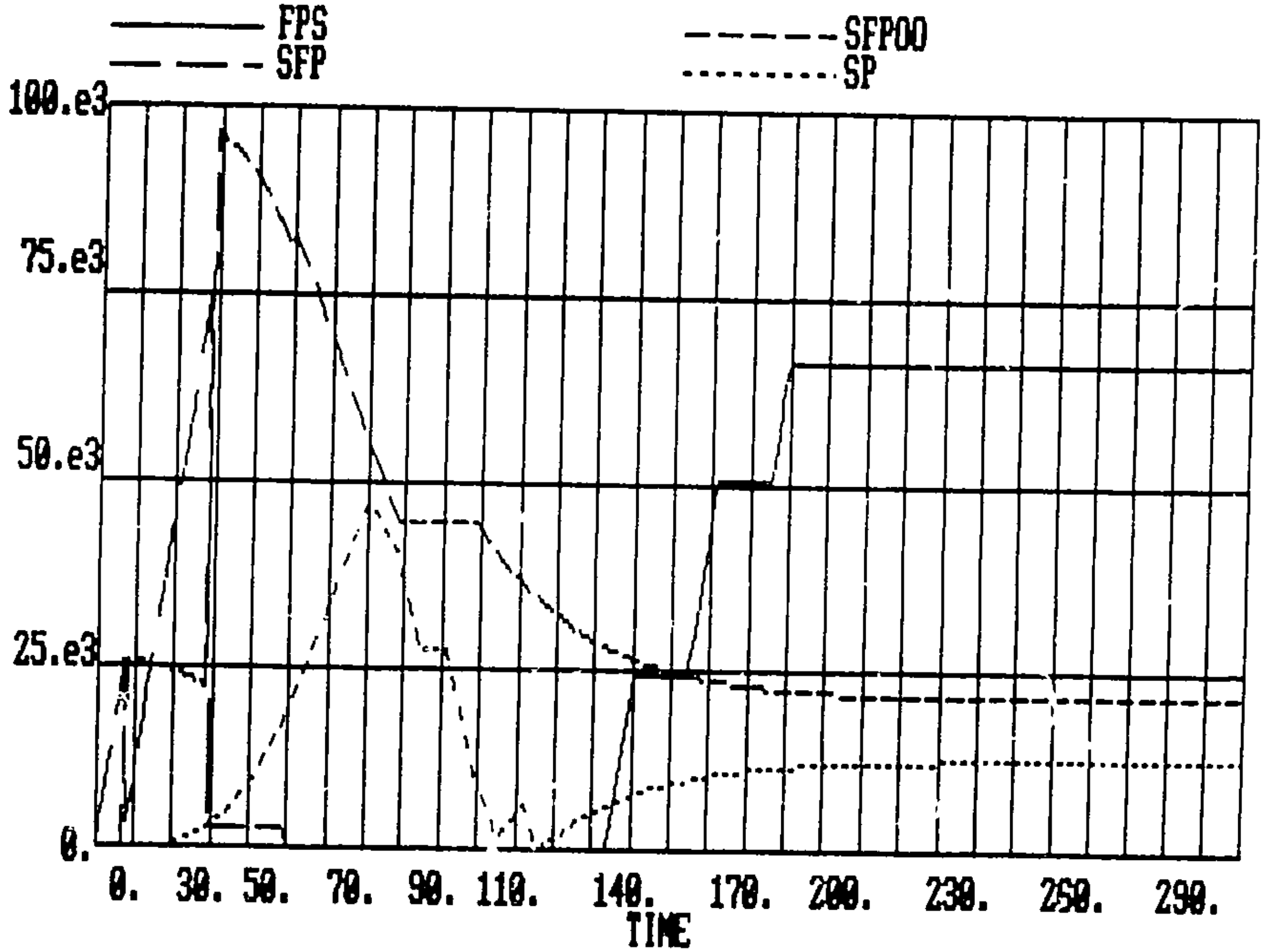

Figure 27: Impact of lead time with original schedule
(LT = 2 days with SHOCK)

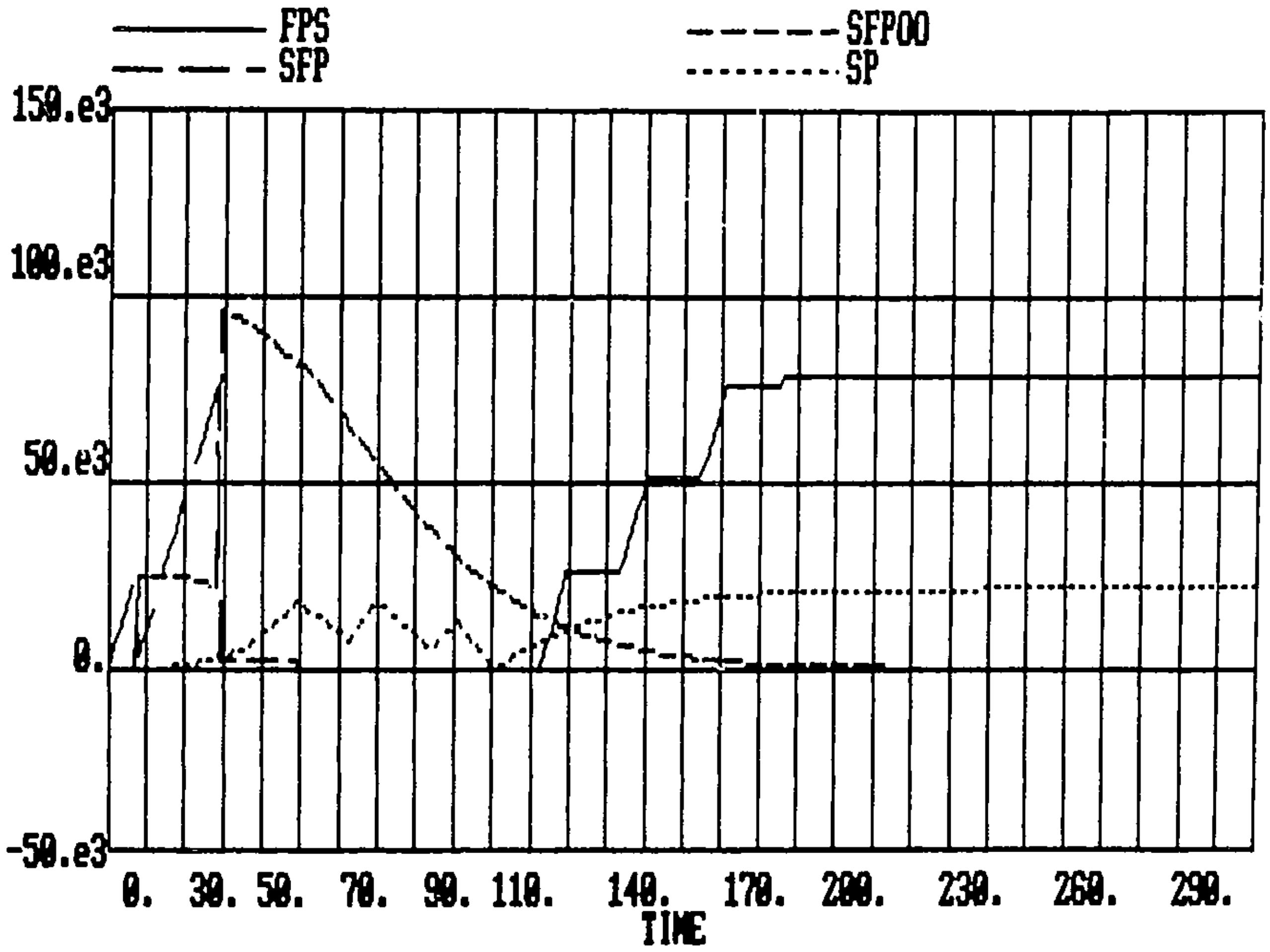

Figure 28: Impact of lead time with original schedule
(LT = 1 day)

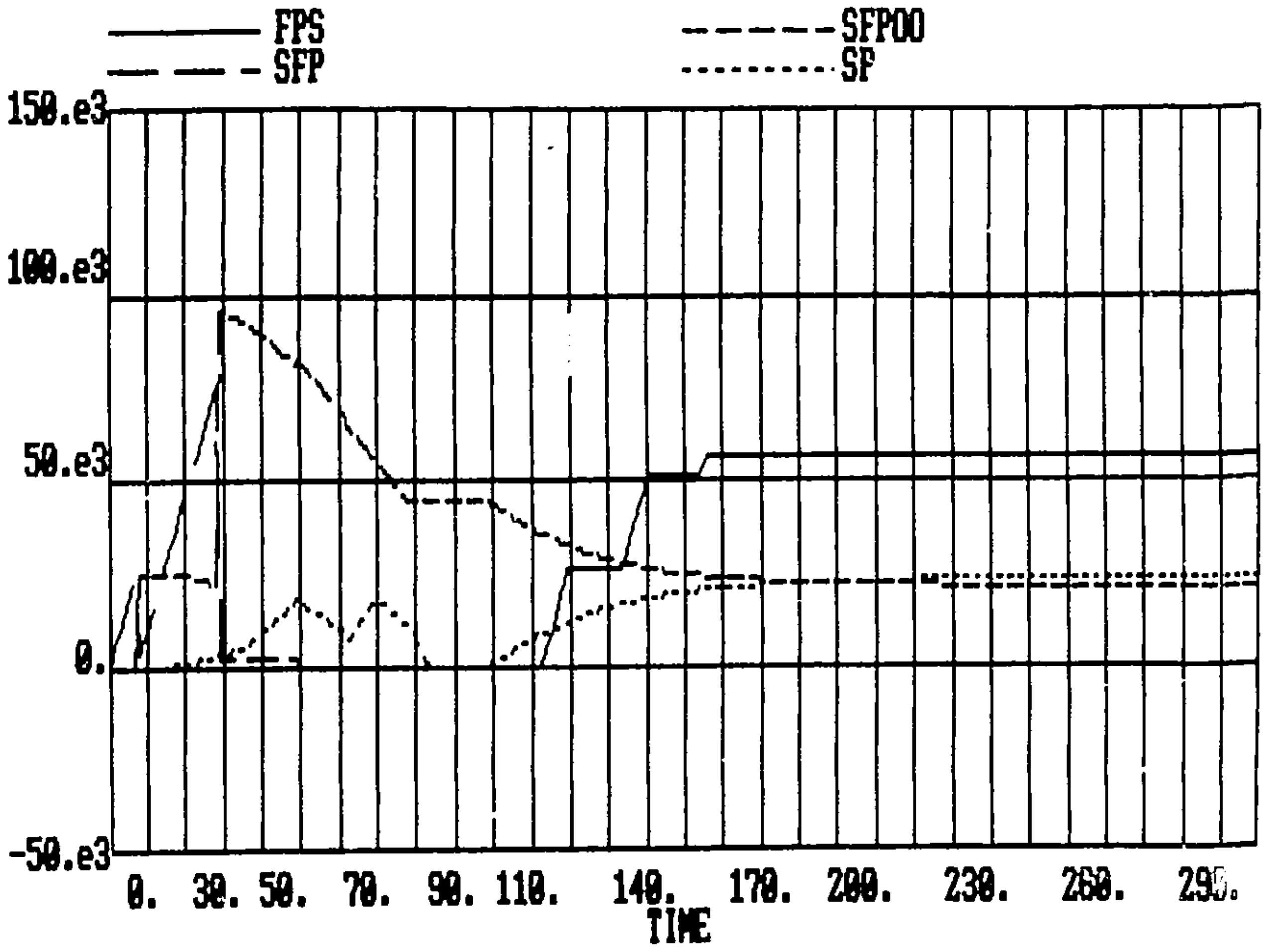

Figure 29: Impact of lead time with original schedule
(LT = 1 day with SHOCK)

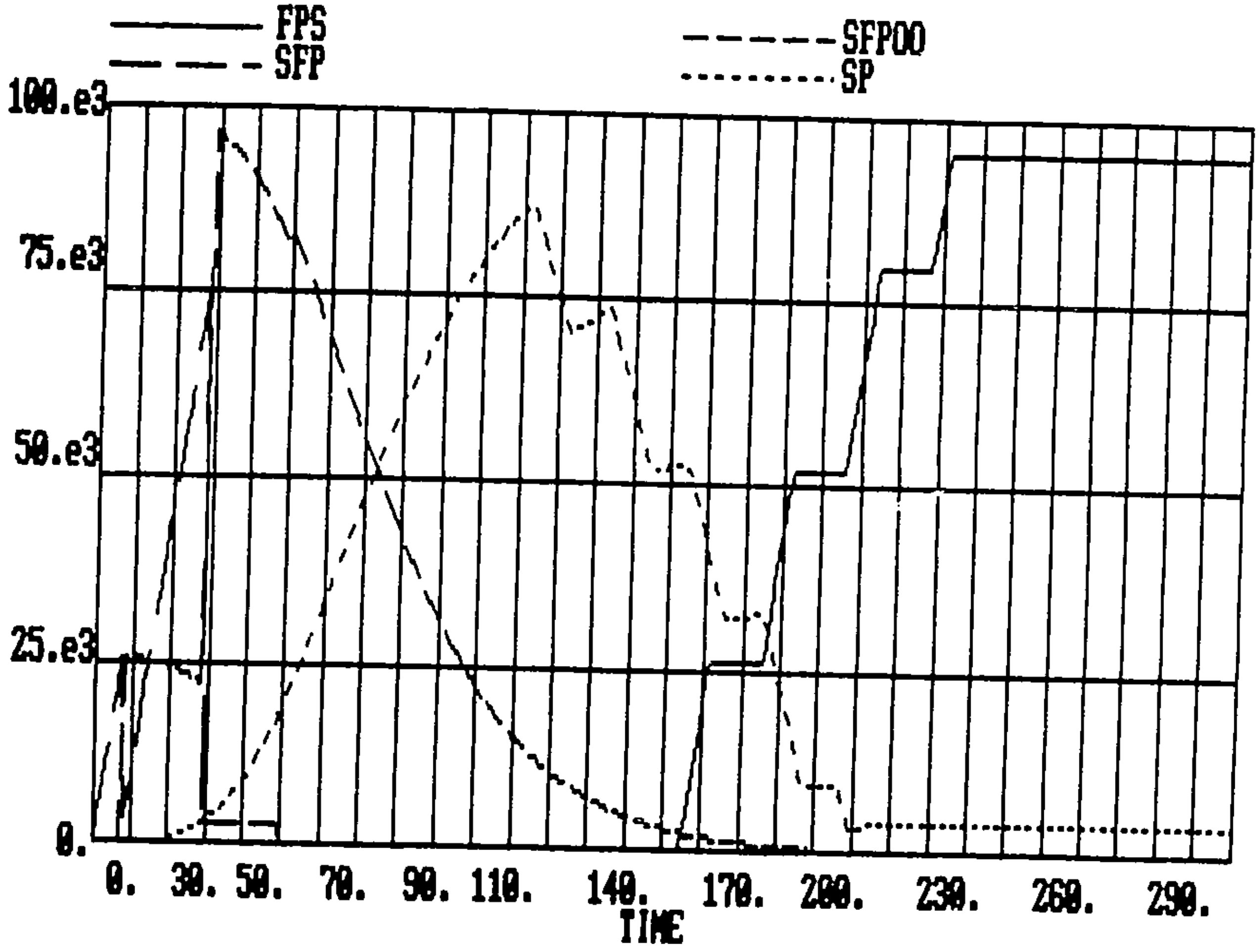

Figure 30: Impact of lead time with one day difference schedule (LT = 5 days)

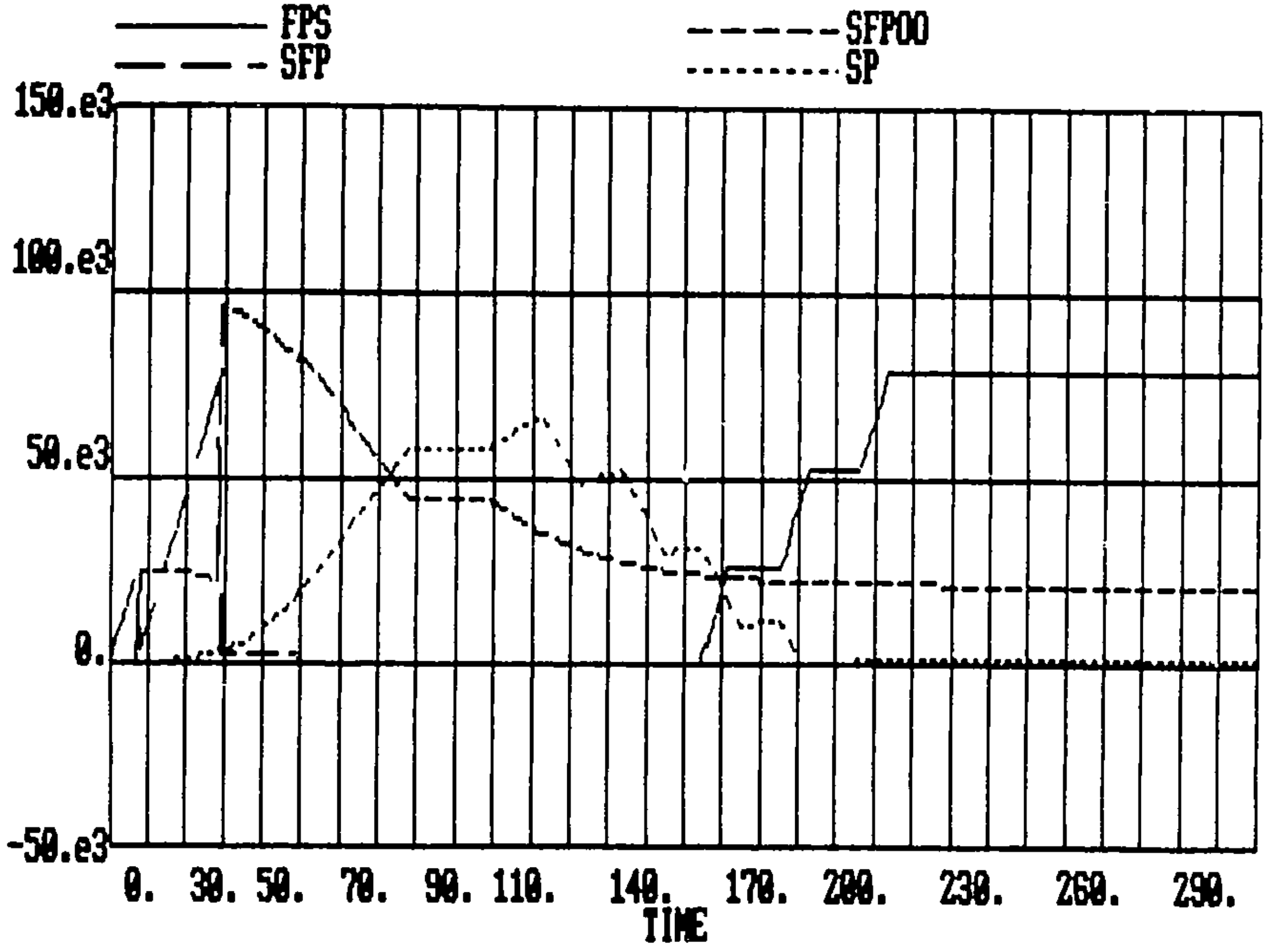

Figure 31: Impact of lead time with one day difference schedule
(LT = 5 days with SHOCK)

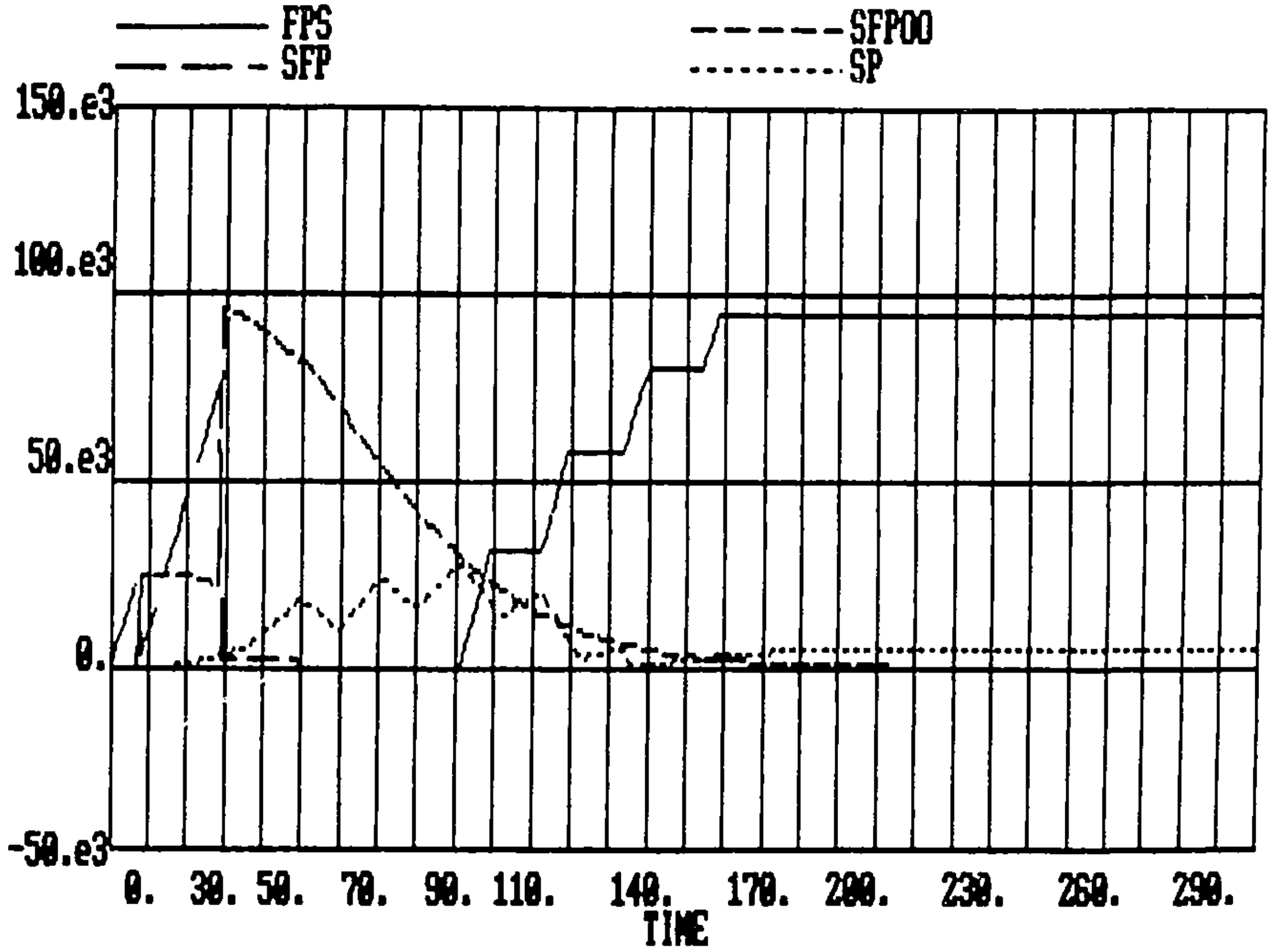

Figure 32: Impact of lead time with one day difference schedule
(LT = 2 days)

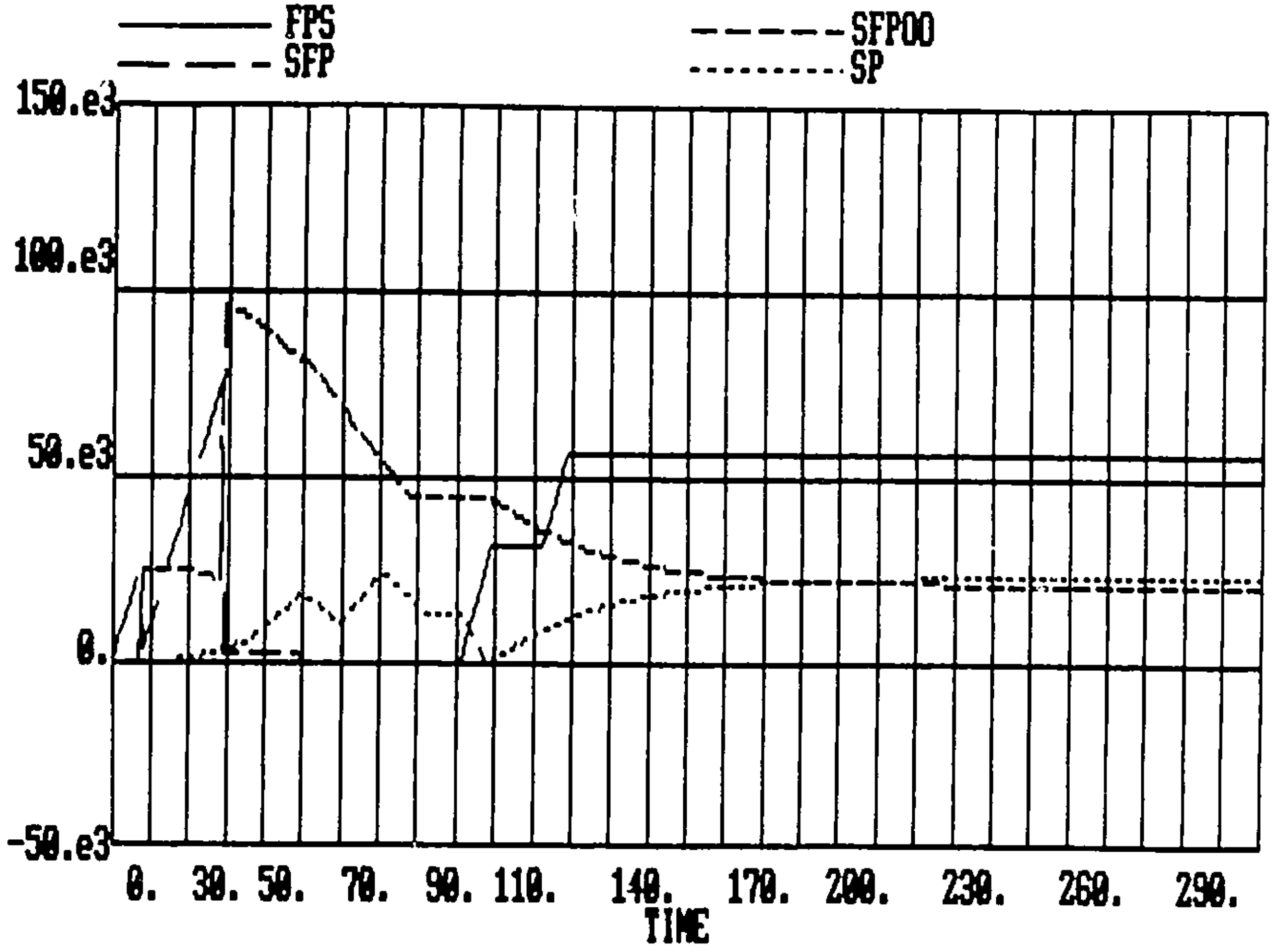

Figure 33: Impact of lead time with one day difference schedule
(LT = 2 days with SHOCK)

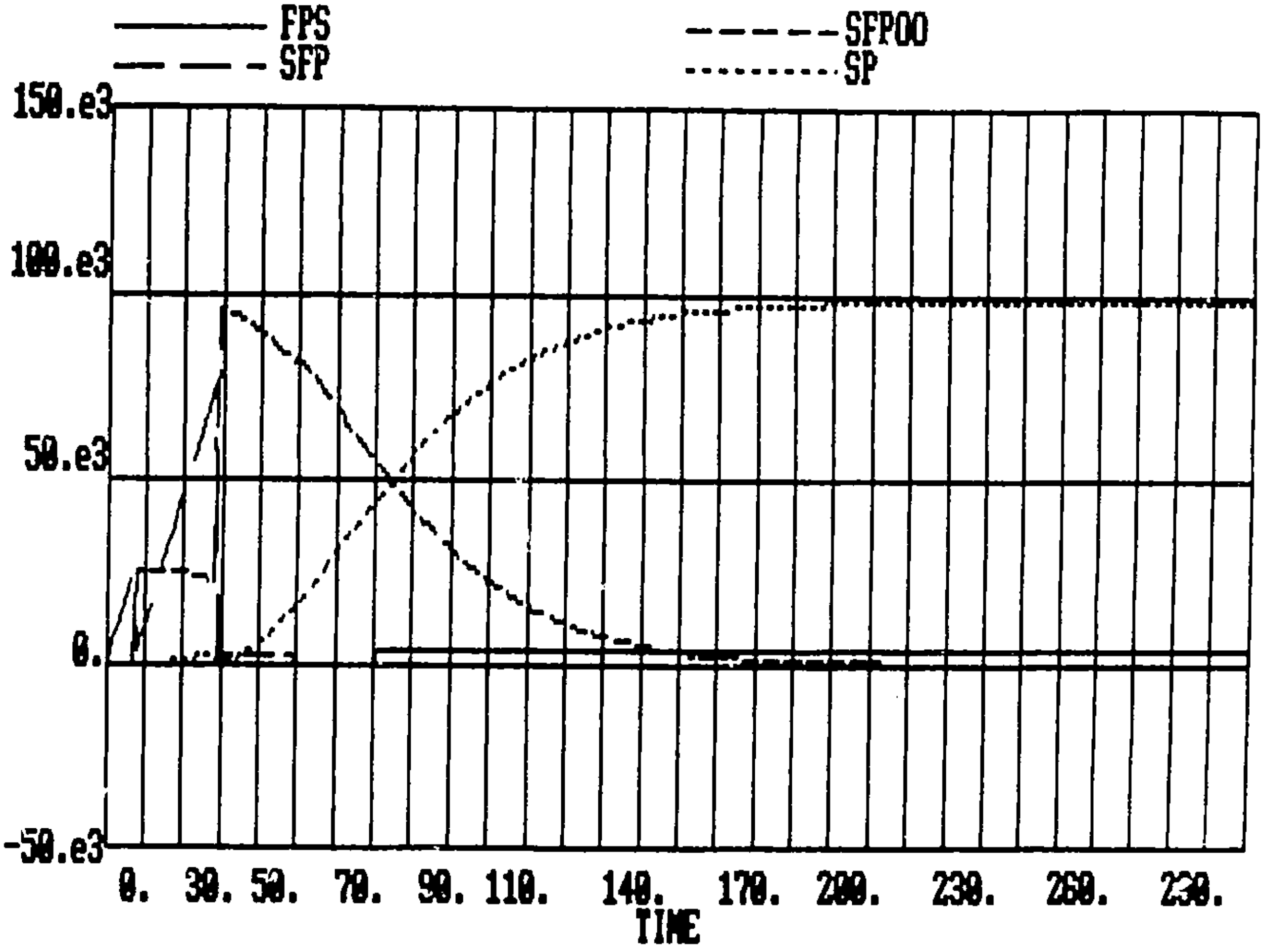

Figure 34: Impact of lead time with one day difference schedule
(LT = 1 day)

Simulation Run 3: Impact of lead time with synchronized schedule

This policy schedules the machines in the assembly process to start at the same time (synchronized schedule).

System Parameters:

(i) START1 = Day 0 + LT

(ii) START2 = Day 0 + LT

(iii) START3 = Day 0 + LT

(iv) START4 = Day 0 + LT

(v) SHOCK in the delivery completion rate occurs at time = 78 and lasts for a duration of one day during which no shells are delivered

Table 18: Impact of lead time with synchronized schedule

LT (days)	Run	Throughput ; corresponding time	Run with shock	Throughput ; corresponding time
5	EX3A	95500 ; 202	EXS2A	78500 ; 197
3	EX3B	96000 ; 160	EXS2B	73500 ; 139
2	EX3C	94500 ; 139	EXS3C	57000 ; 114
1	EX3D	3000 ; 32	EXS3D	3000 ; 32

The results (Figures 35 to 42) show that a lead time of 2 days gives the best results for throughput. Although the throughput for this best case is less (by 1000 units) than the best cases for the original and one day difference schedule, the corresponding time required to achieve a throughput of 139 is considerably less than for the original schedule (201) and for the one day difference schedule (158).

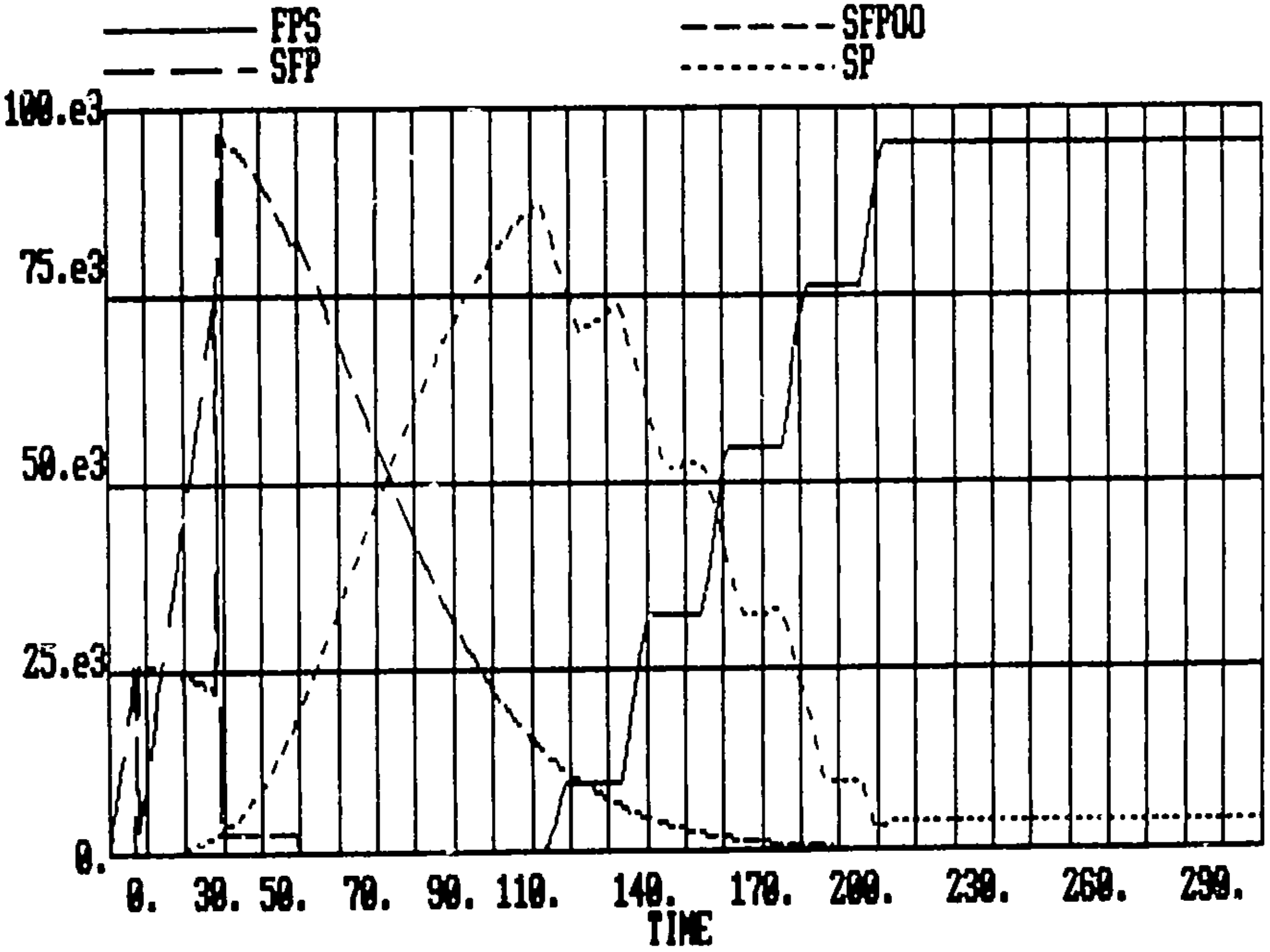

Figure 35: Impact of lead time with synchronized schedule
(LT = 5 days)

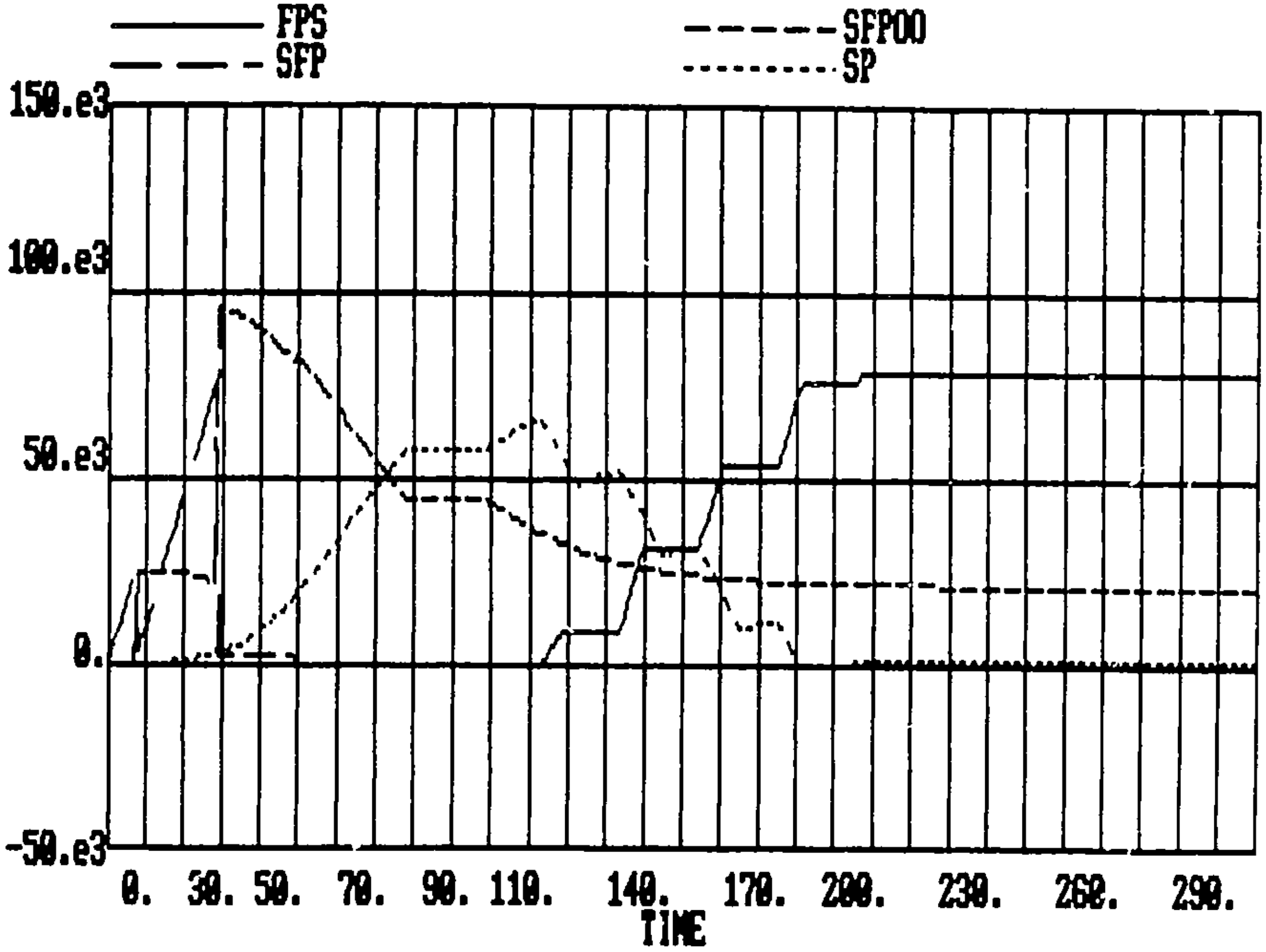

Figure 36: Impact of lead time with synchronized schedule
(LT = 5 days with SHOCK)

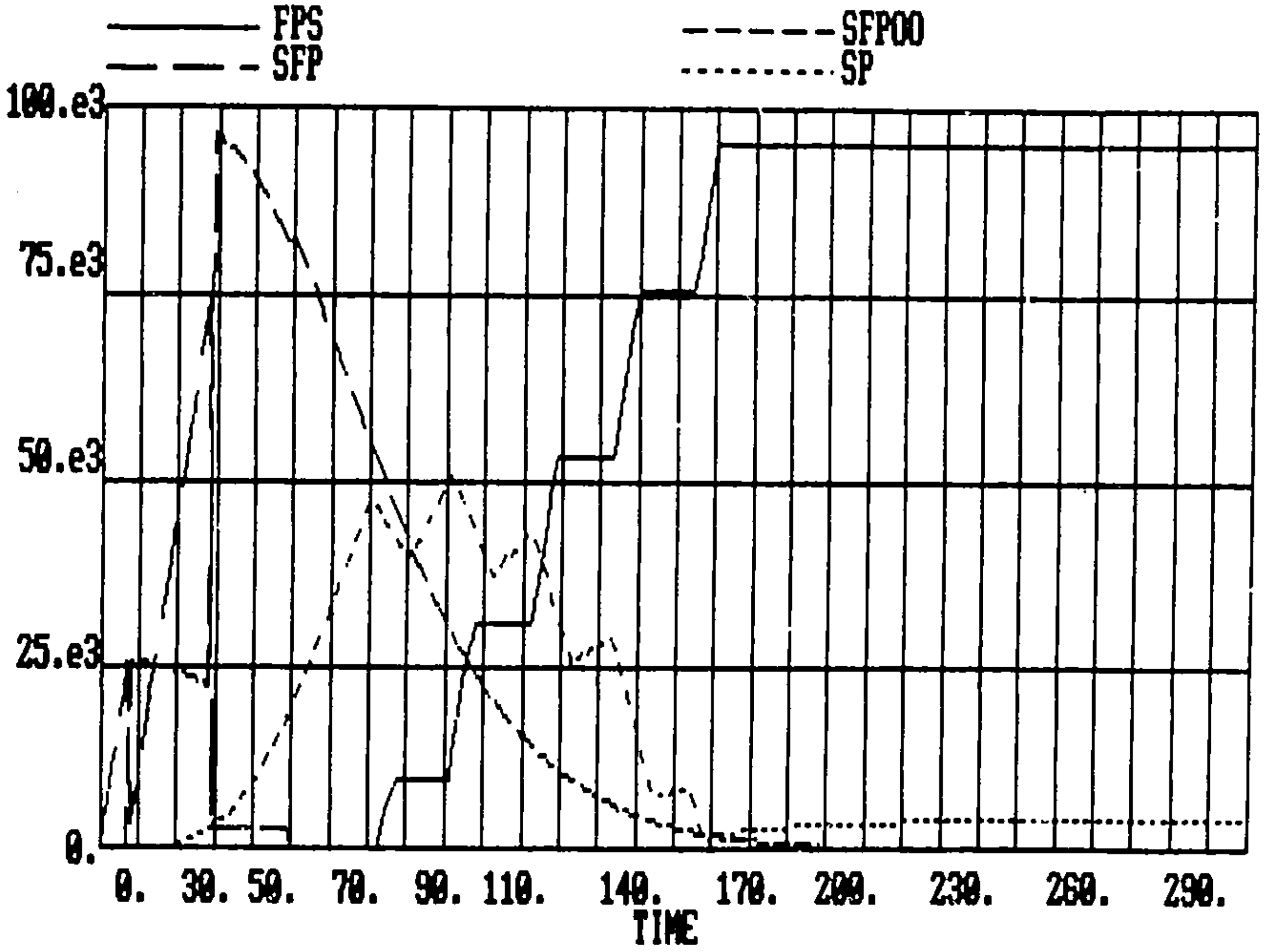

Figure 37: Impact of lead time with synchronized schedule
(LT = 3 days)

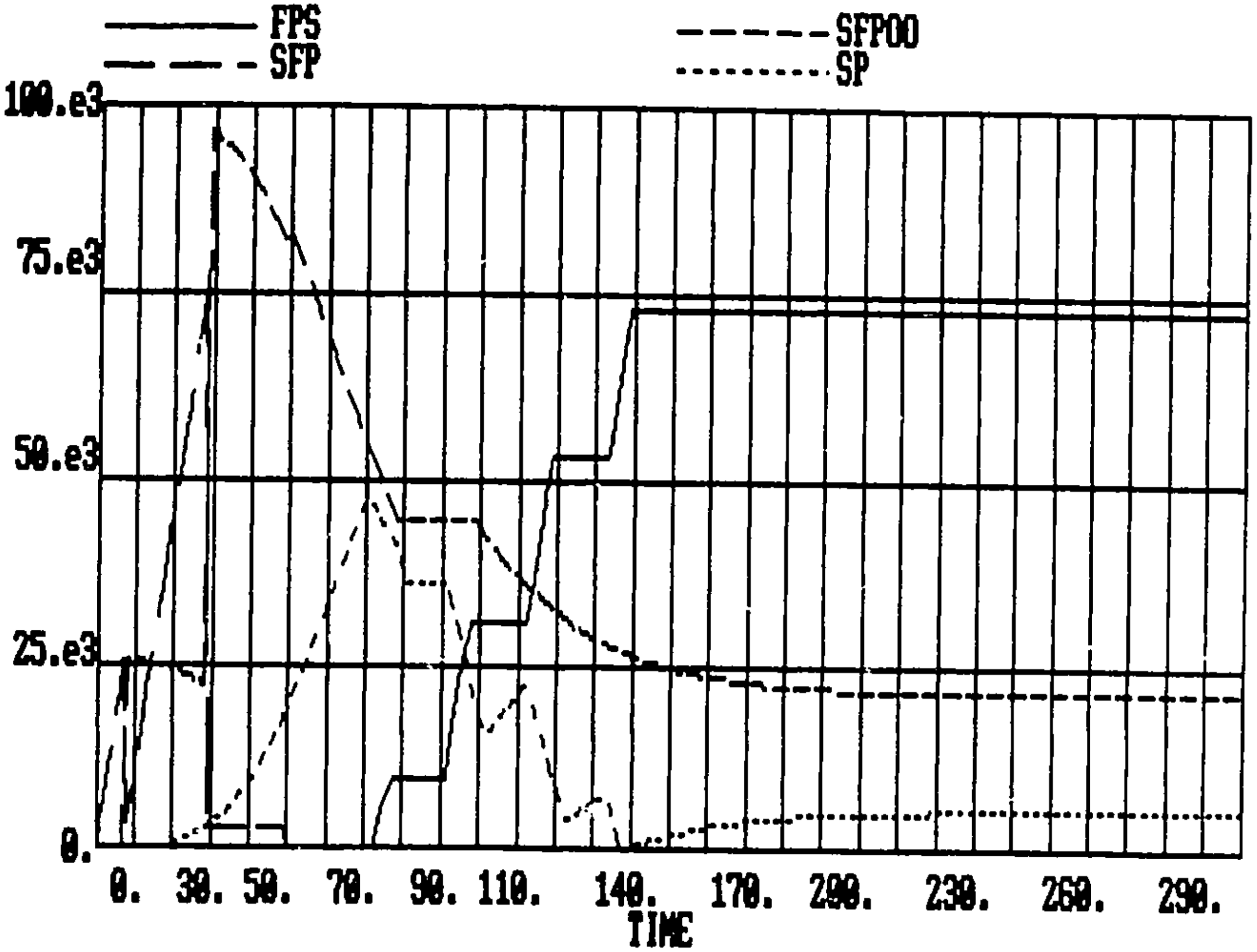

Figure 38: Impact of lead time with synchronized schedule
(LT = 3 days with SHOCK)

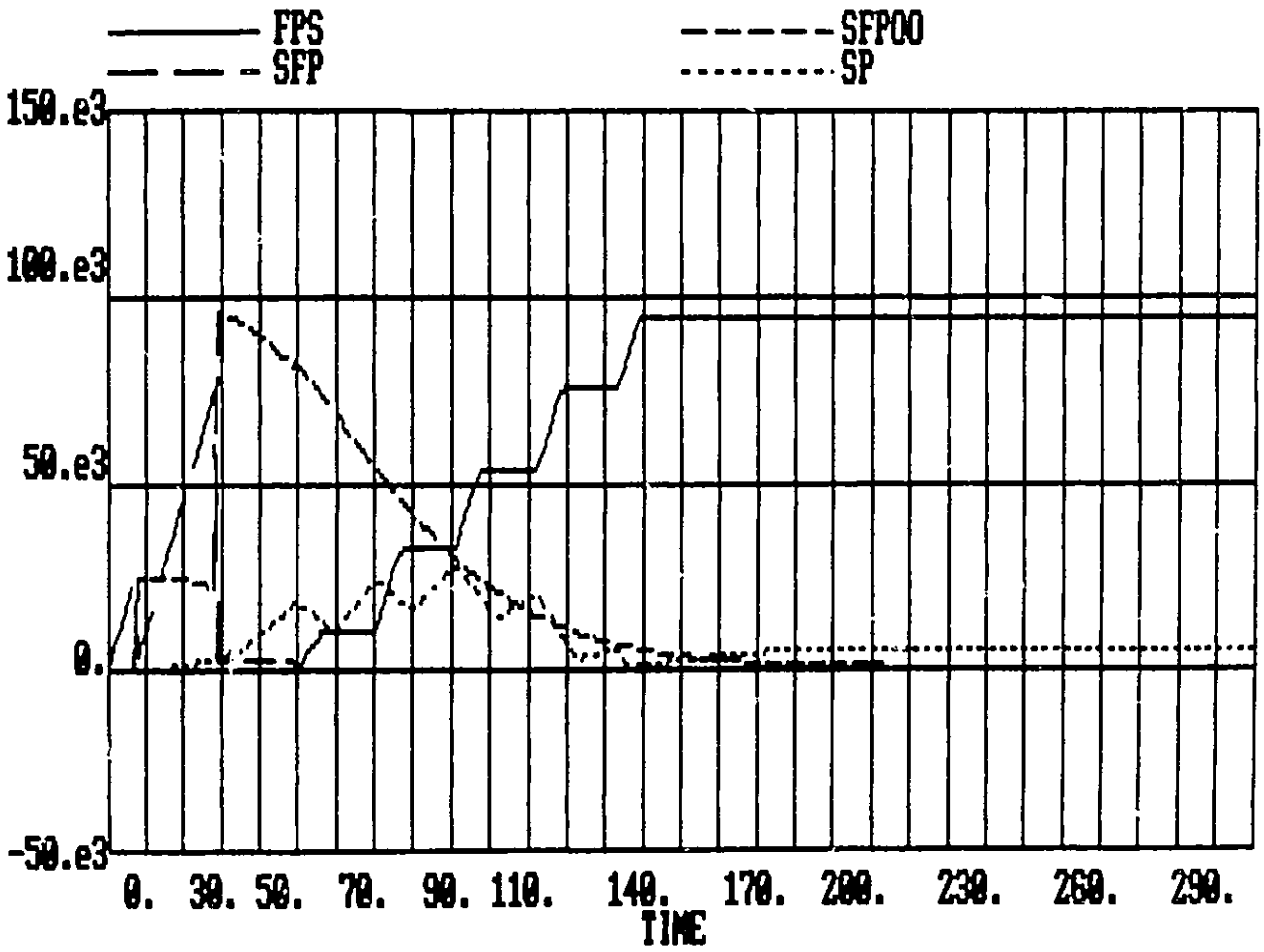

Figure 39: Impact of lead time with synchronized schedule
(LT = 2 days)

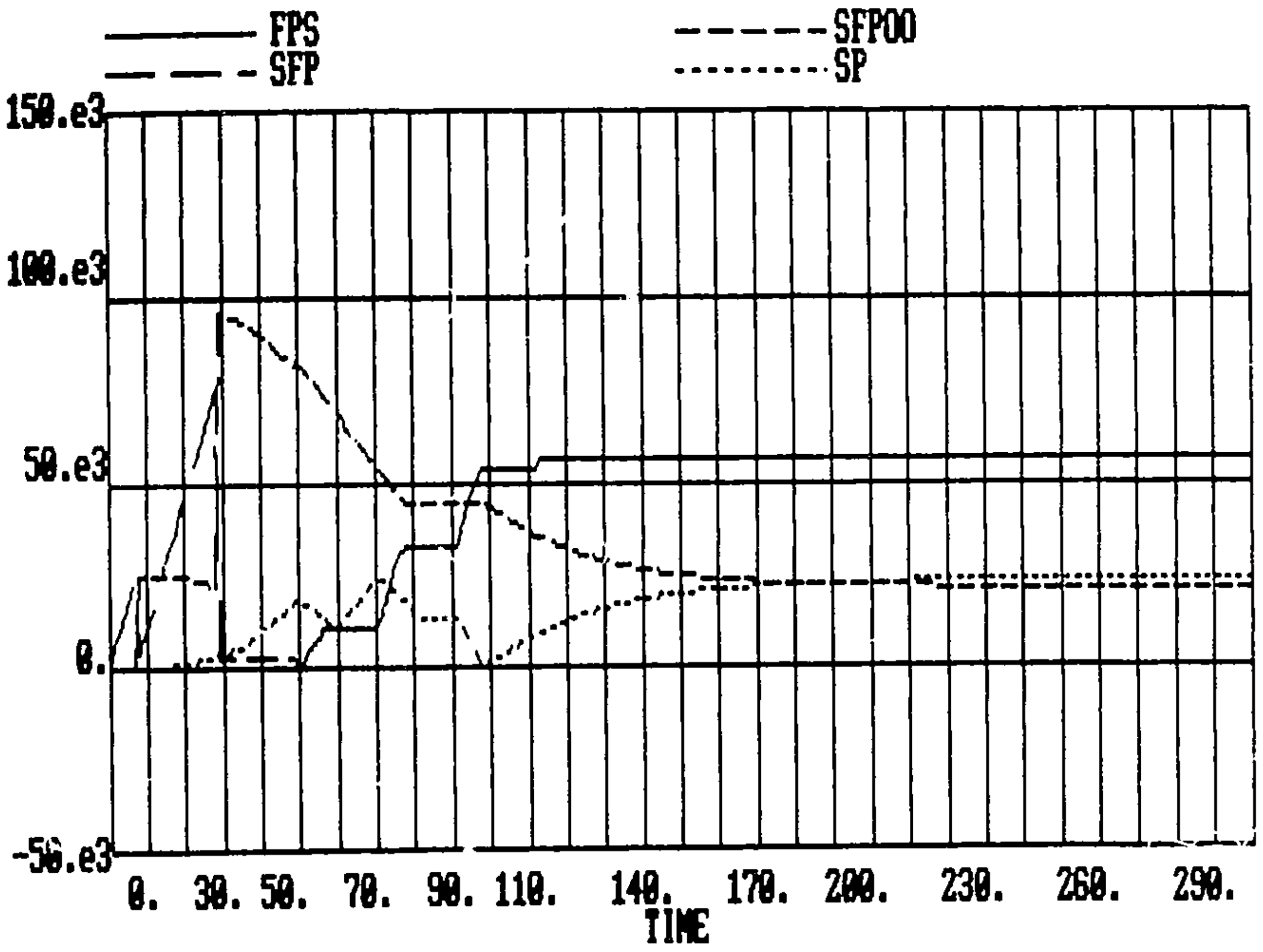

Figure 40: Impact of lead time with synchronized schedule
(LT = 2 days with SHOCK)

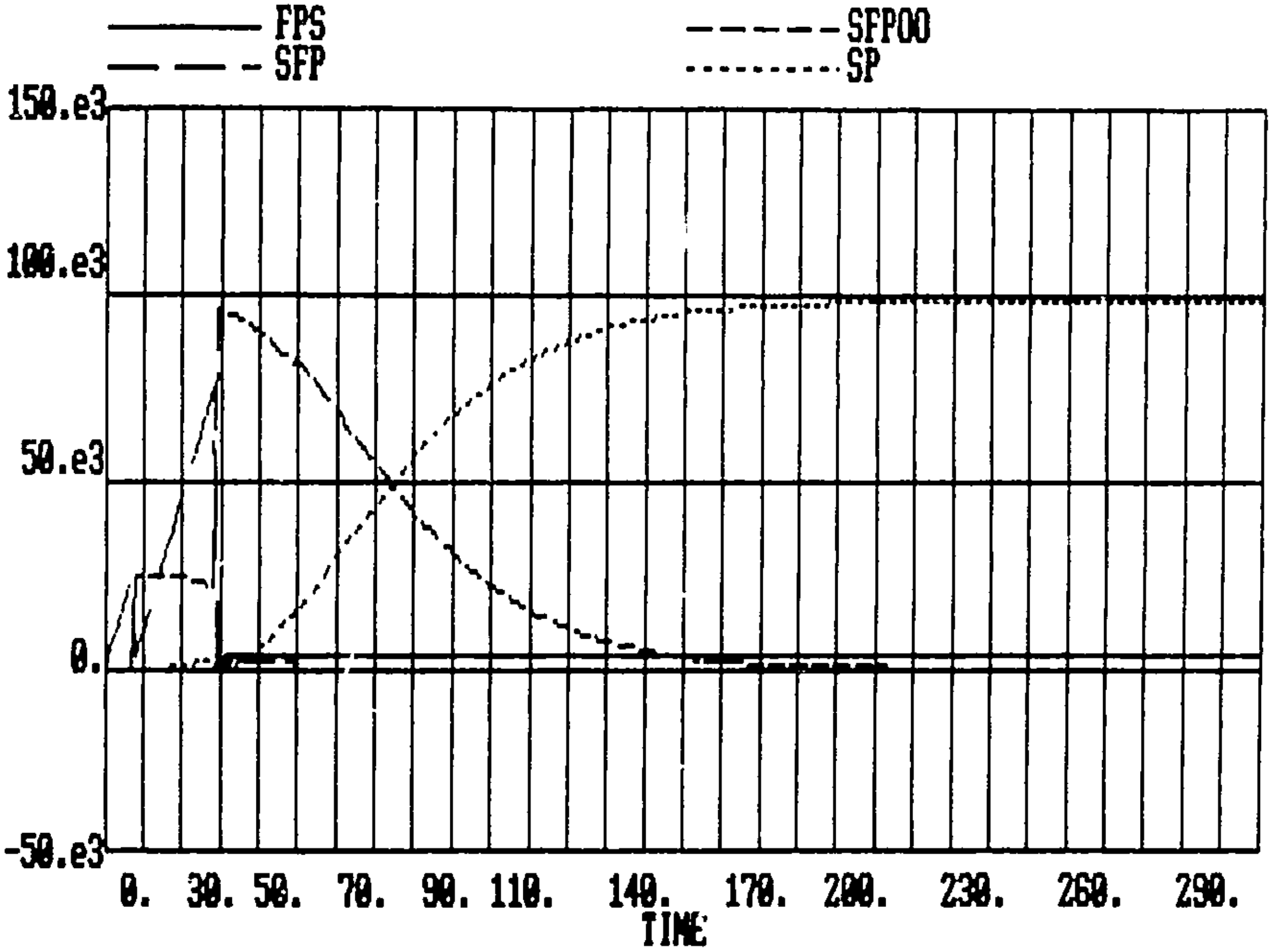

Figure 41: Impact of lead time with synchronized schedule
(LT = 1 day)

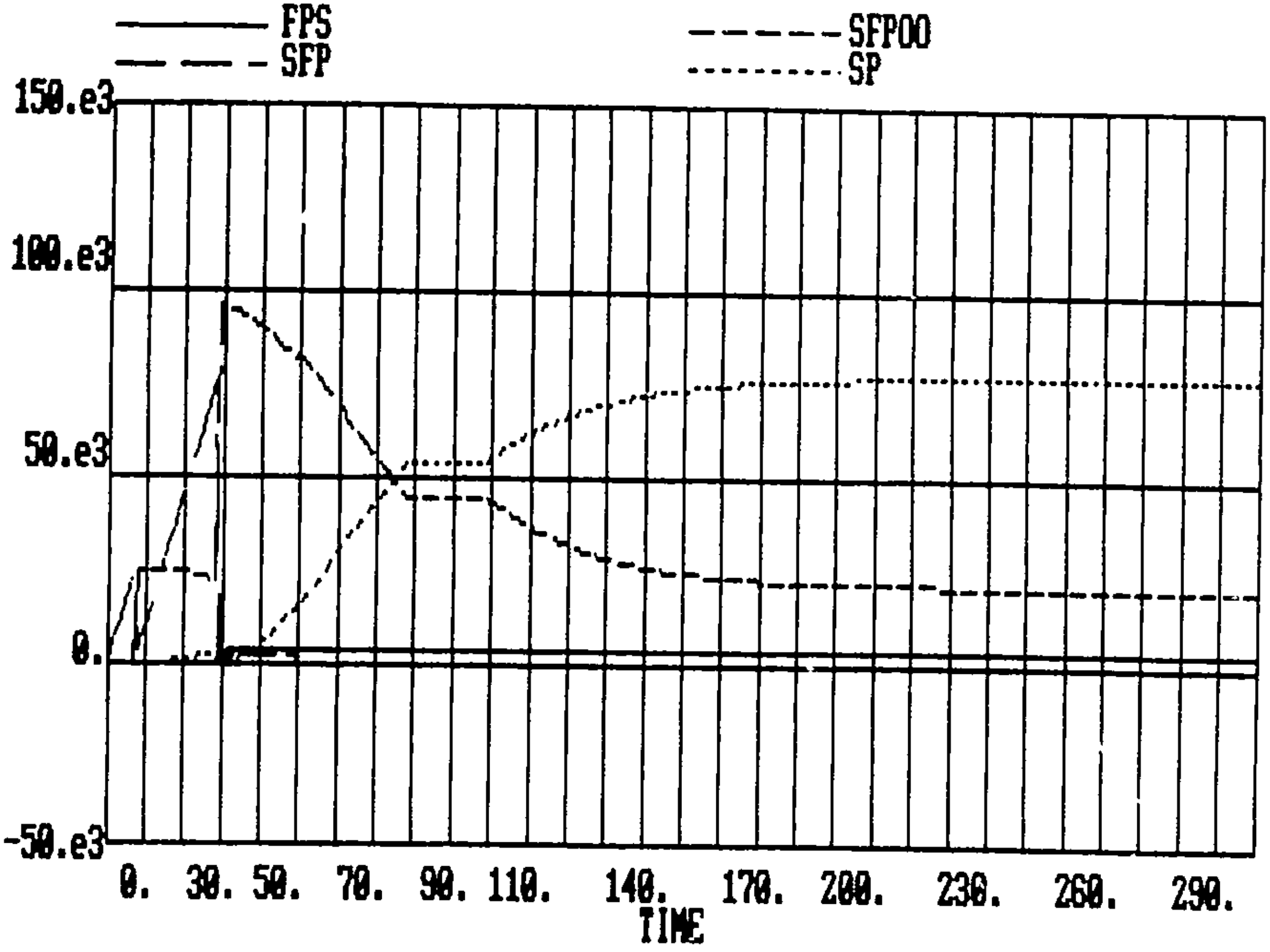

Figure 42: Impact of lead time with synchronized schedule
(LT = 1 day with SHOCK)

Simulation Run 4: Impact of current production rates on WIP and throughput

Experiment 3 was performed to test different production rate policies and the effects on WIP and throughput for the schedules in experiments 1 and 2 with a lead time of 2 days. The purpose of this experiment was to check if there was a significant improvement in the level of throughput and WIP levels with increased production rates and decreased variability.

System Parameters:

Case-1 : Original production rates of assembly machines

Machine	Mean Production Rate	CV
PR1	3403	0.31
PR2	2141	0.13
PR3	1671	0.17
PR4	3827	0.45

Case-2 : Original production rates with improved variability

Machine	Mean Production Rate	CV
PR1	3403	0.1
PR2	2141	0.1
PR3	1671	0.1
PR4	3827	0.1

Case-3 : Increase in original production rates of assembly machines

Machine	Mean Production Rate	CV
PR1	4100	0.2
PR2	2230	0.13
PR3	1949	0.17
PR4	5400	0.2

Case-4 : Production rates of assembly machines at full capacity

Machine	Mean Production Rate	CV
PR1	4920	0
PR2	2520	0
PR3	2280	0
PR4	6480	0

Table 19: Impact of current production rates on WIP and throughput (Cases analyzed)

Schedule	Case-1	Case-2	Case-3	Case-4
Original	EXA EXSA	EXB EXSB	EXC EXSC	EXD EXSD
One Day Difference	EXE EXSE	EXF EXSF	EXG EXSG	EXH EX4H
Synchronized	EXI EXSI	EXJ EXSJ	EXK EXSK	EXL EXSL

The results show WIP and throughput levels for the original schedule (Figures 43 to 46). For the original schedule Cases 1 and 2 give the same final throughput whereas, Cases 3 and 4 give slightly less final

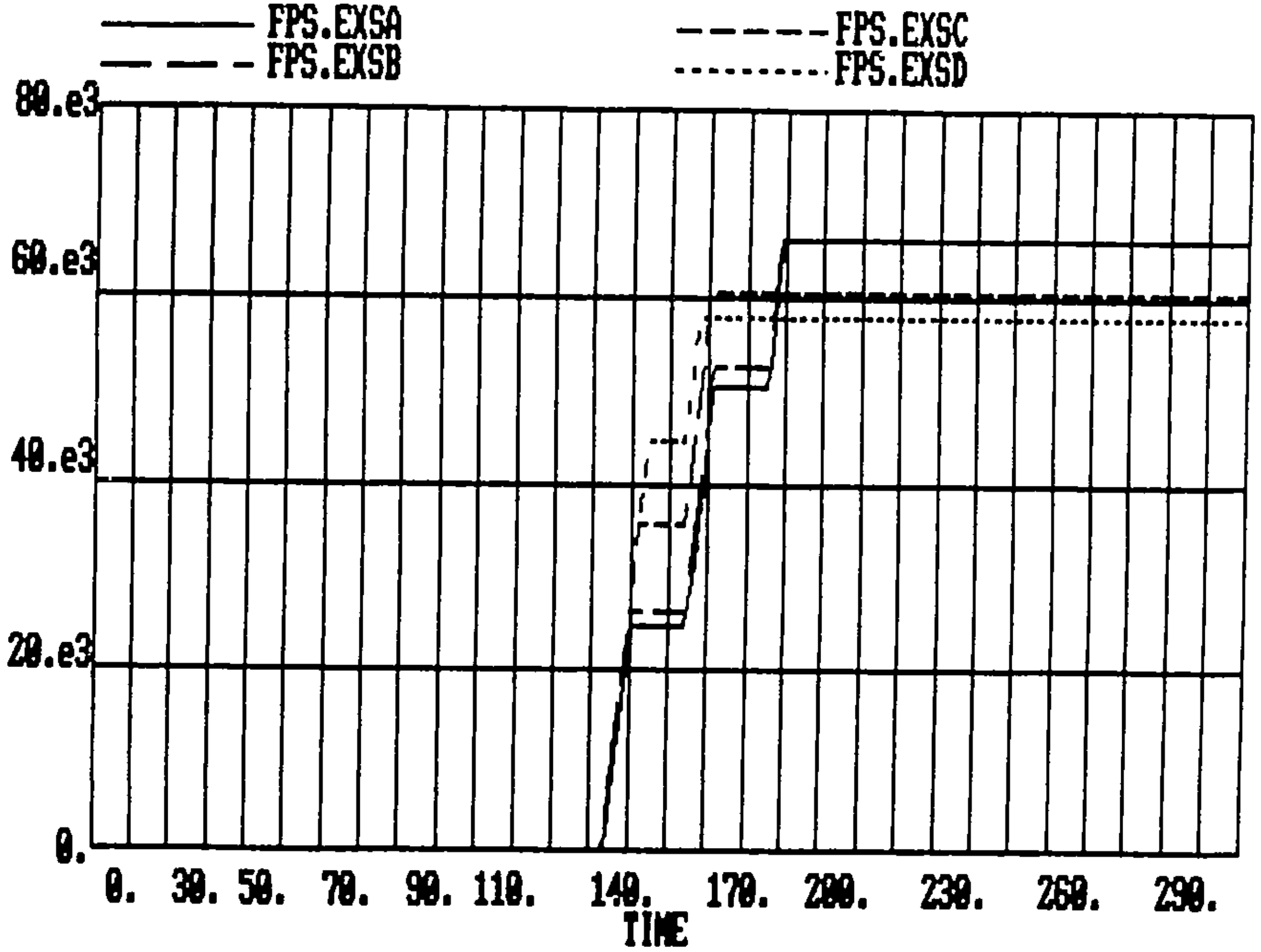

Figure 43: Impact of current production rates on WIP and throughput - original schedule (FPS)

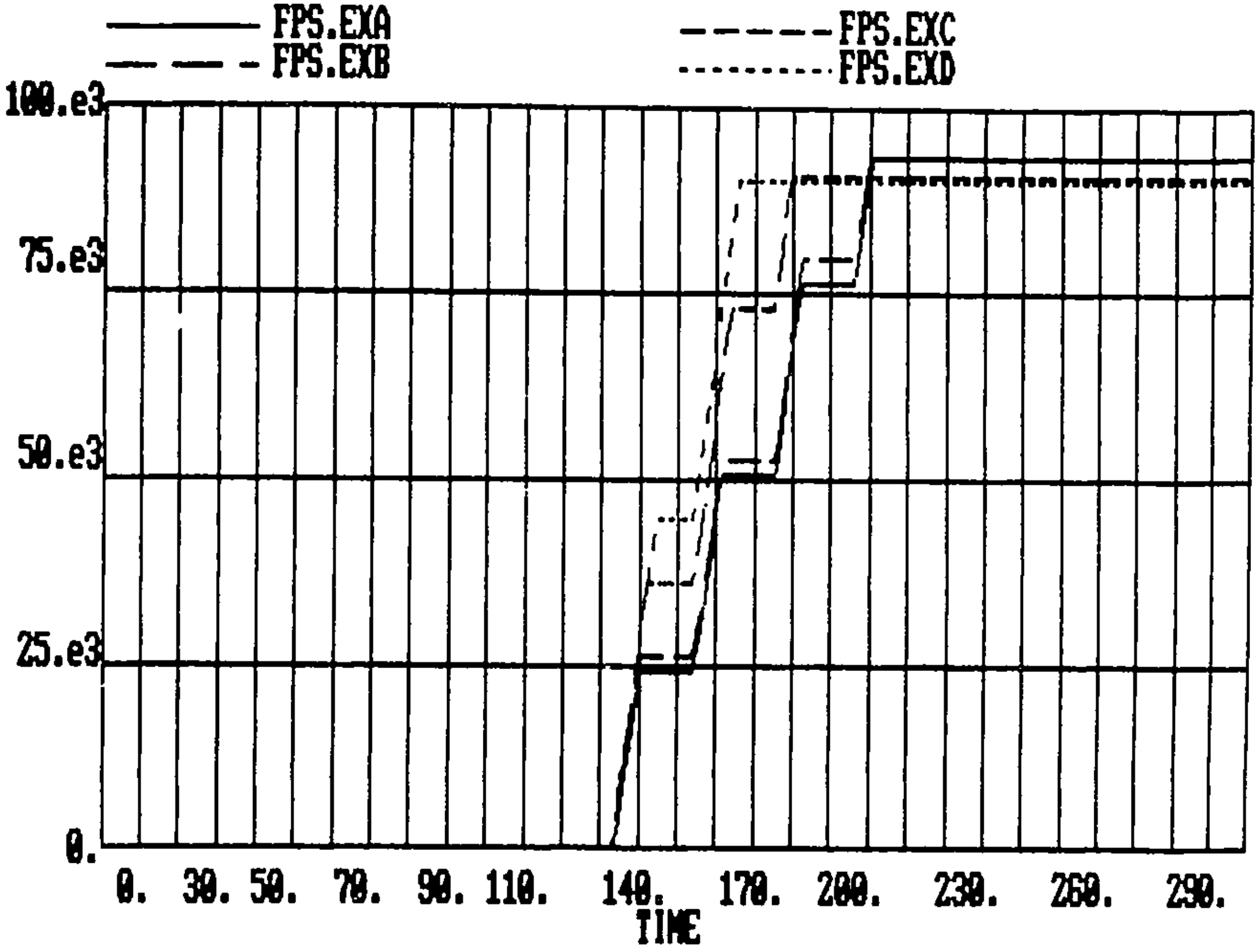

Figure 44: Impact of current production rates on WIP and throughput - original schedule (FPS with SHOCK)

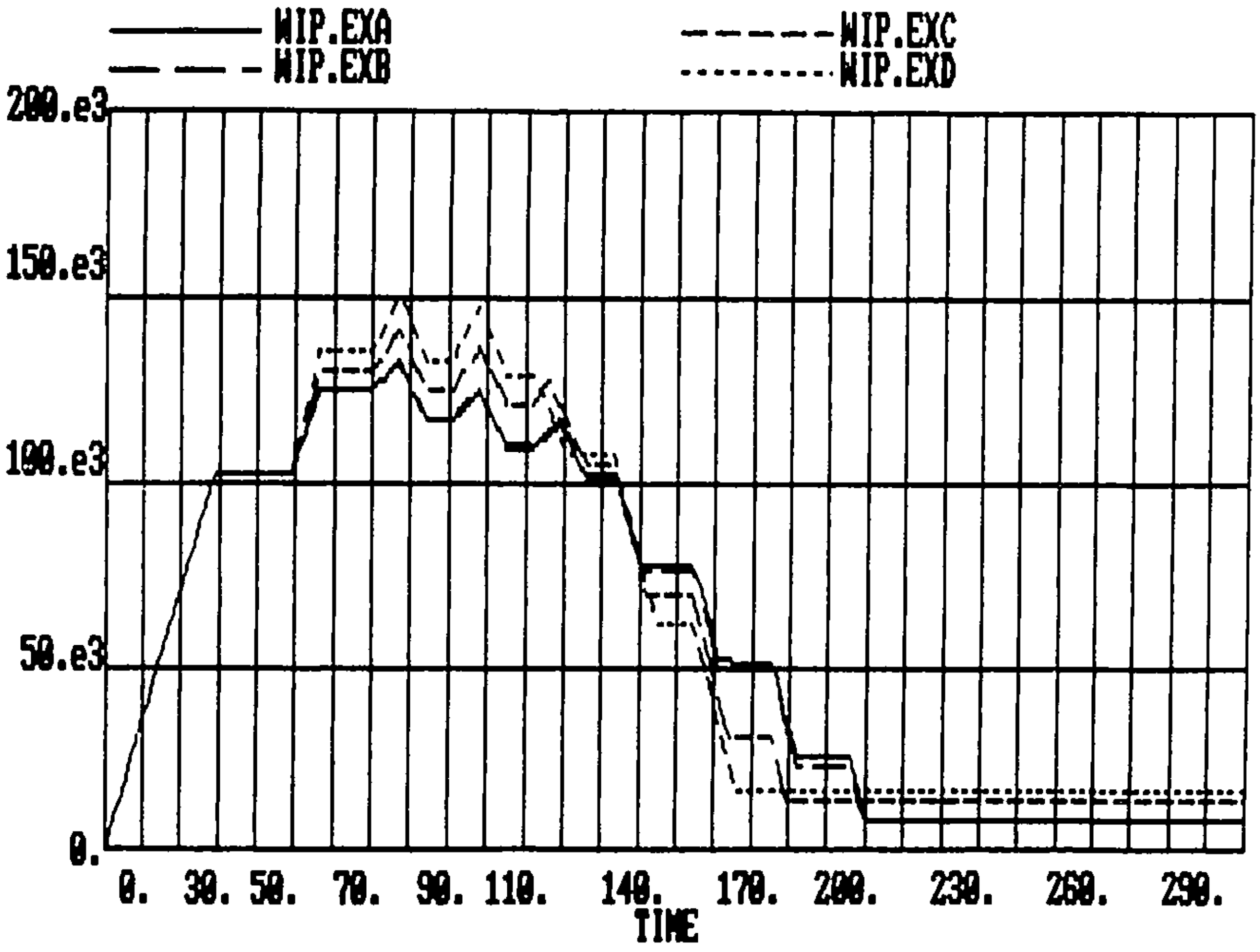

Figure 45: Impact of current production rates on WIP and throughput - original schedule (WIP)

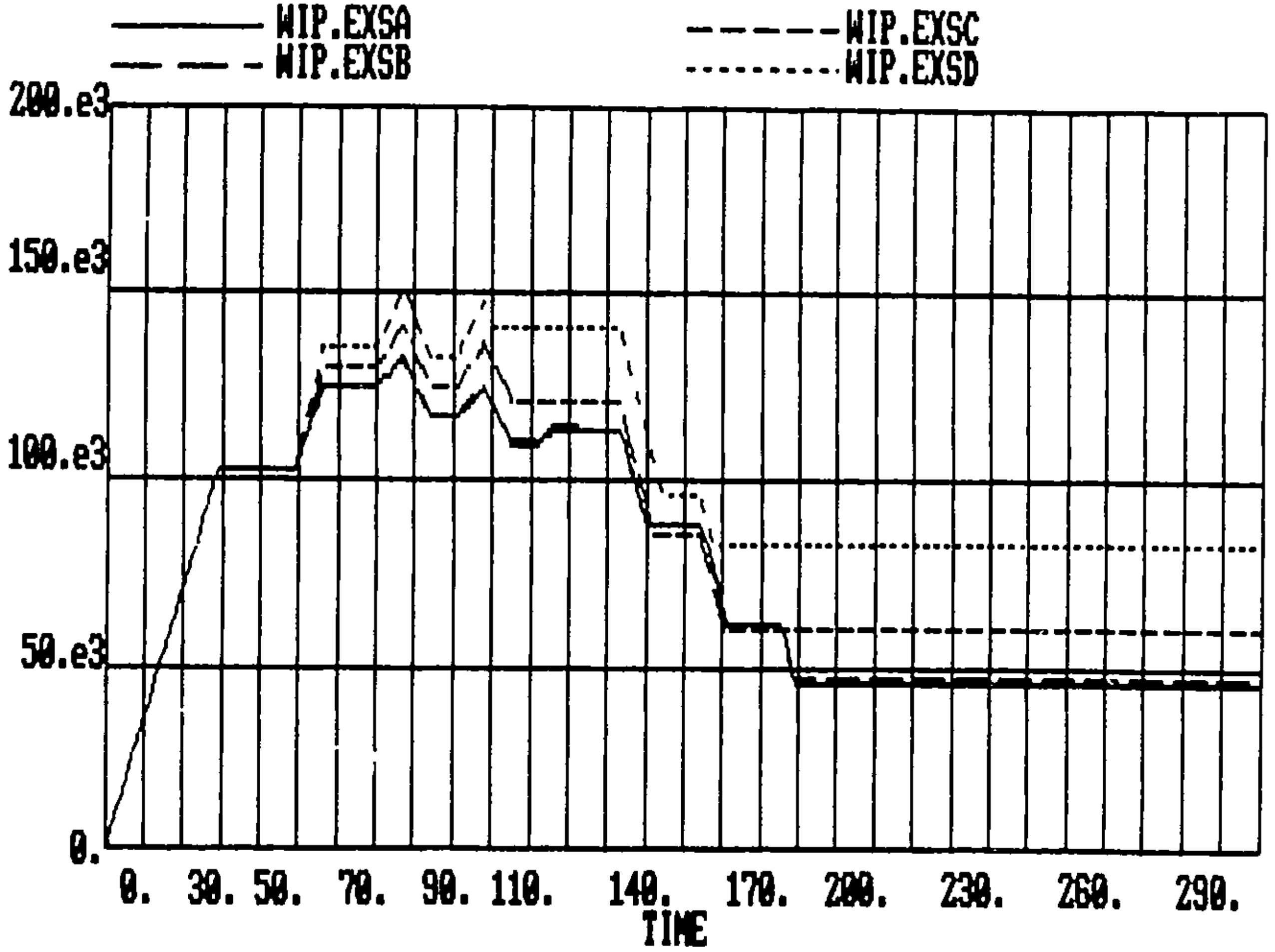

Figure 46: Impact of current production rates on WIP and throughput - original schedule (WIP with SHOCK)

throughput at an earlier time. With a shock added to the original schedule the same trend is observed but with more impact on cases 3 and 4. Cases 3 and 4 give slightly higher levels of work-in-process than cases 1 and 2 but with a shock added to the system this difference is amplified.

For the one day difference schedule (see Figures 47 to 50) it was found that Cases 1 and 2 gave the maximum level of throughput whereas, Cases 3 and 4 gave less final throughput. When a shock was added to the system all four cases gave the same level of final throughput. Similarly, the WIP levels for Case 4 and Case 3 were higher than for Cases 1 and 2. With a shock added to the system all four cases gave approximately the same levels of WIP.

For the synchronized schedule (see Figures 51 to 54) Cases 1 and 2 gave more final throughput than for Case 3 and considerably more than for Case 5. With a shock added to the system the final throughput was the same for all four cases. Similarly, the WIP level for Case 4 and Case 3 was higher than for Cases 1 and 2 and with a shock added all four cases had approximately the same levels of WIP inventory.

From these results it is seen that increasing the production rates or decreasing the variability does not produce significant improvement in throughput. Also, the level of WIP increases as the production rates are improved because there is an accumulation of WIP before each workstation.

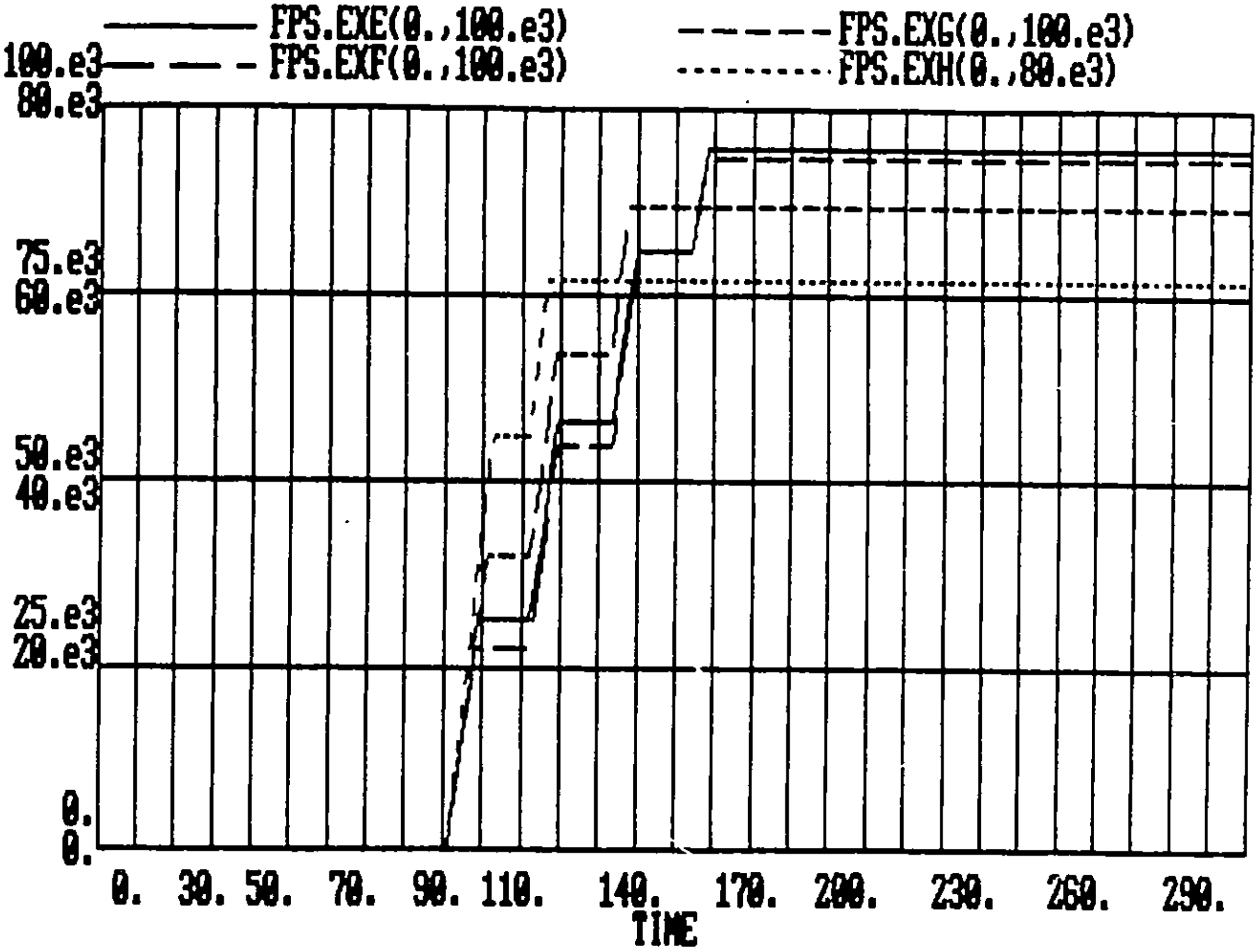

Figure 47: Impact of current production rates on WIP and throughput - 1 day difference schedule (FPS)

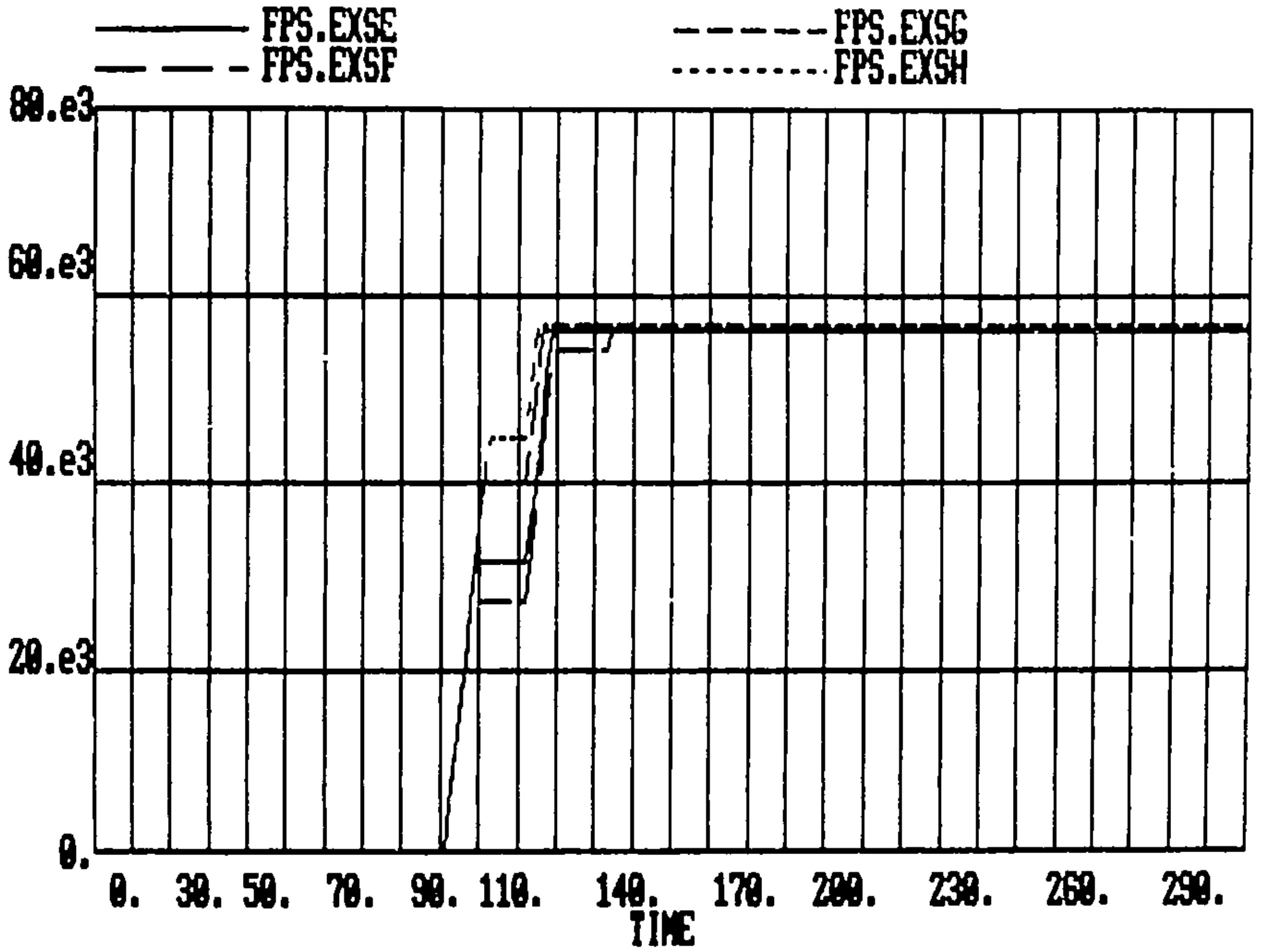

Figure 48: Impact of current production rates on WIP and throughput - 1 day difference schedule (FPS with SHOCK)

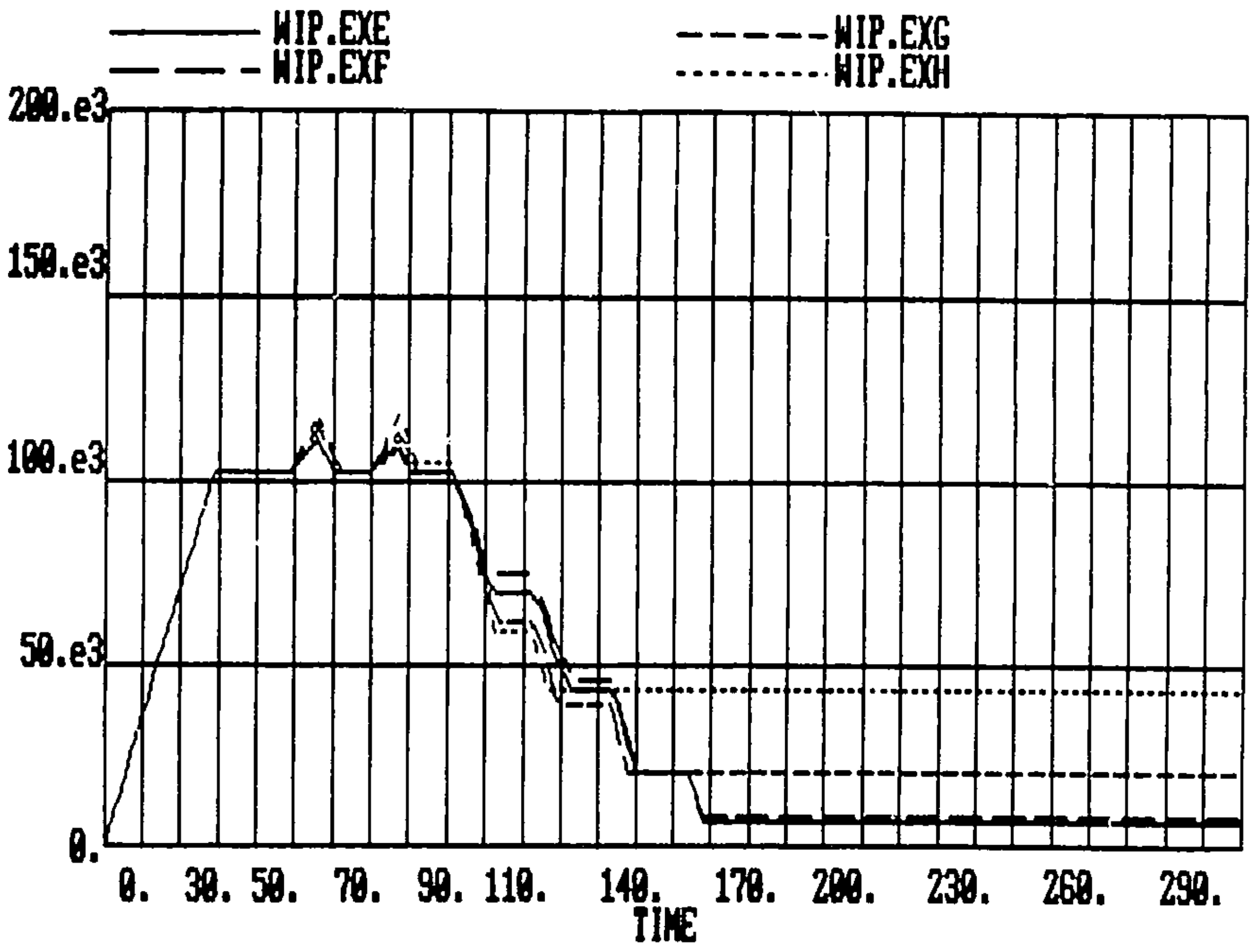

Figure 49: Impact of current production rates on WIP and throughput - 1 day difference schedule (WIP)

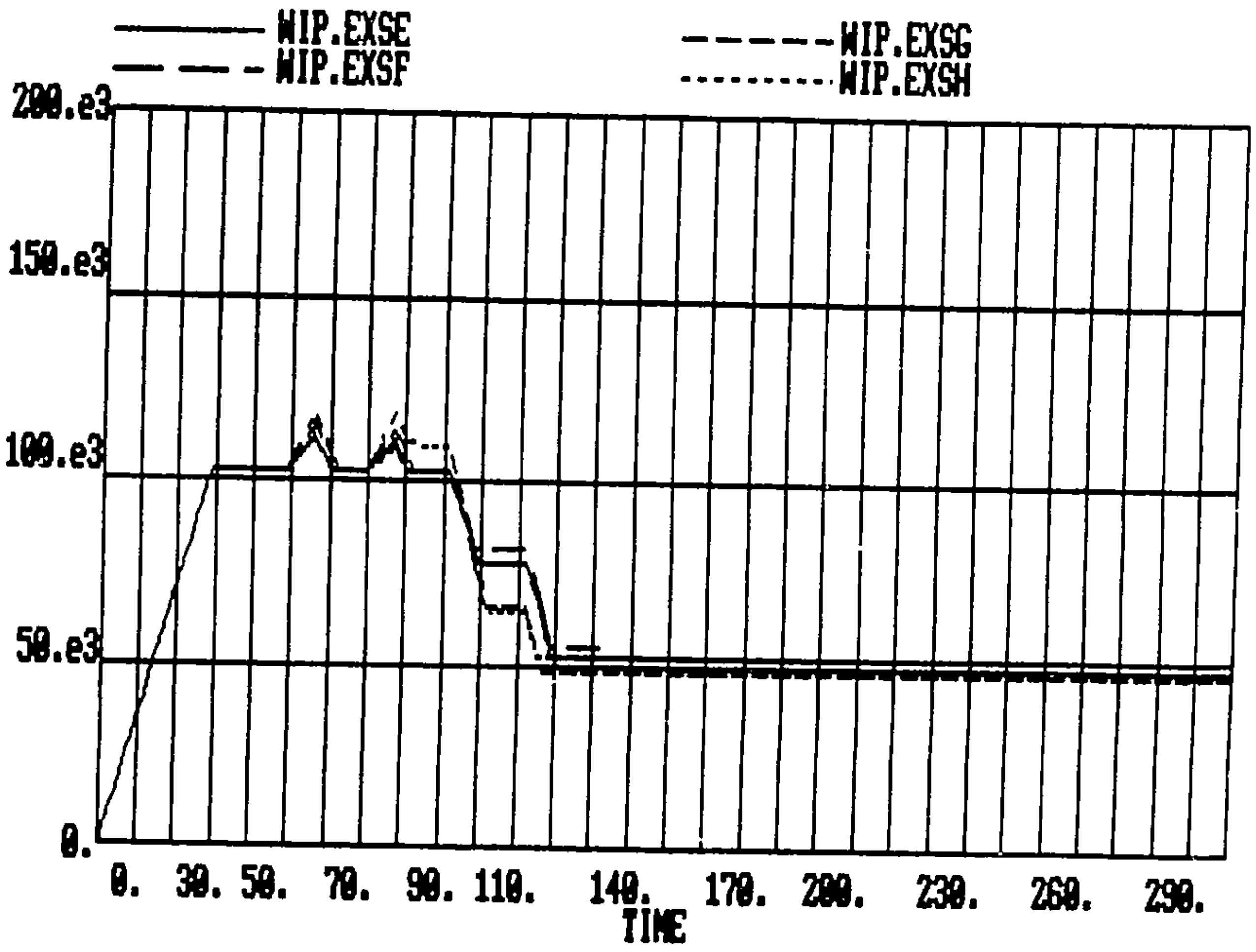

Figure 50: Impact of current production rates on WIP and throughput - 1 day difference schedule (WIP with SHOCK)

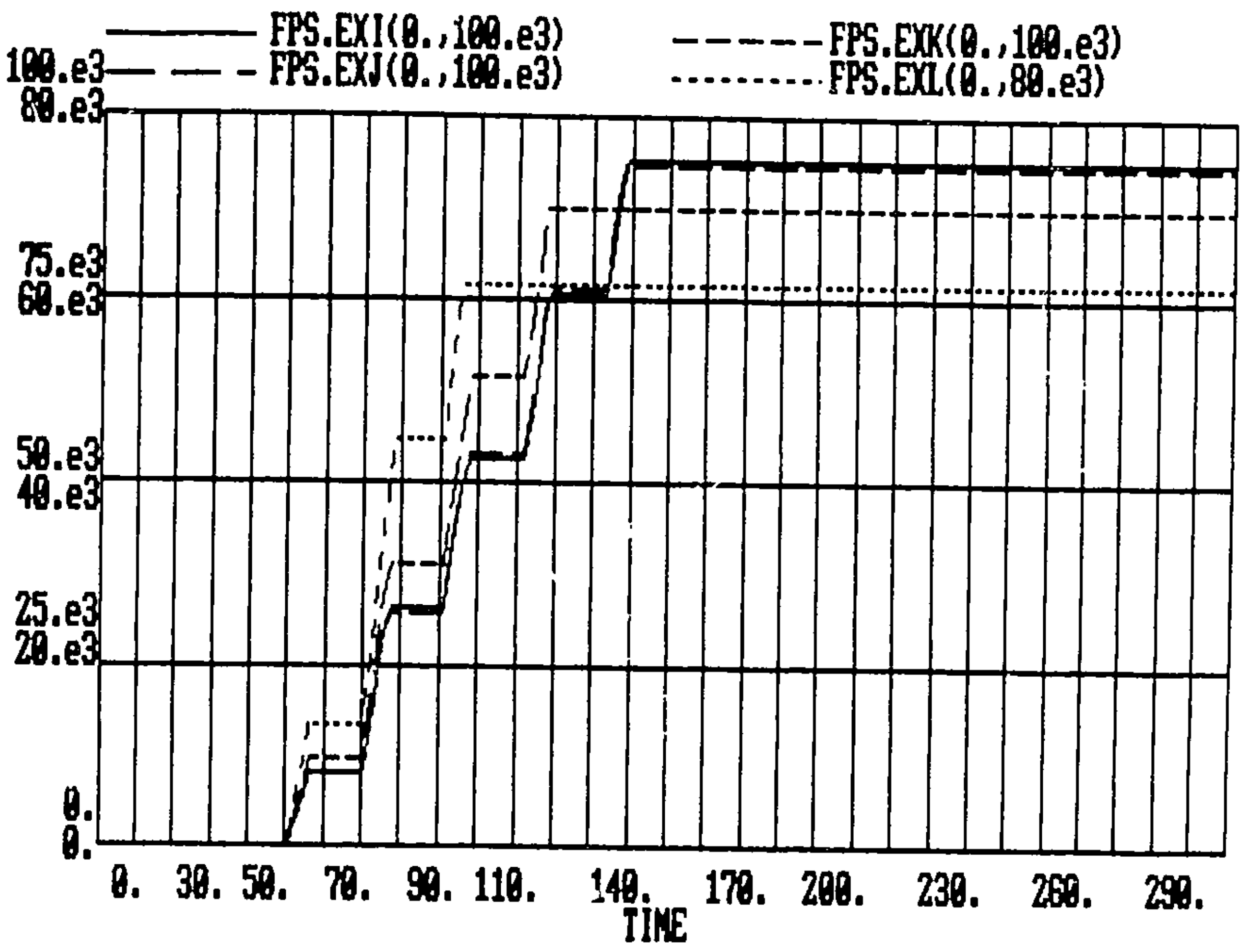

Figure 51: Impact of current production rates on WIP and throughput - synchronized schedule (FPS)

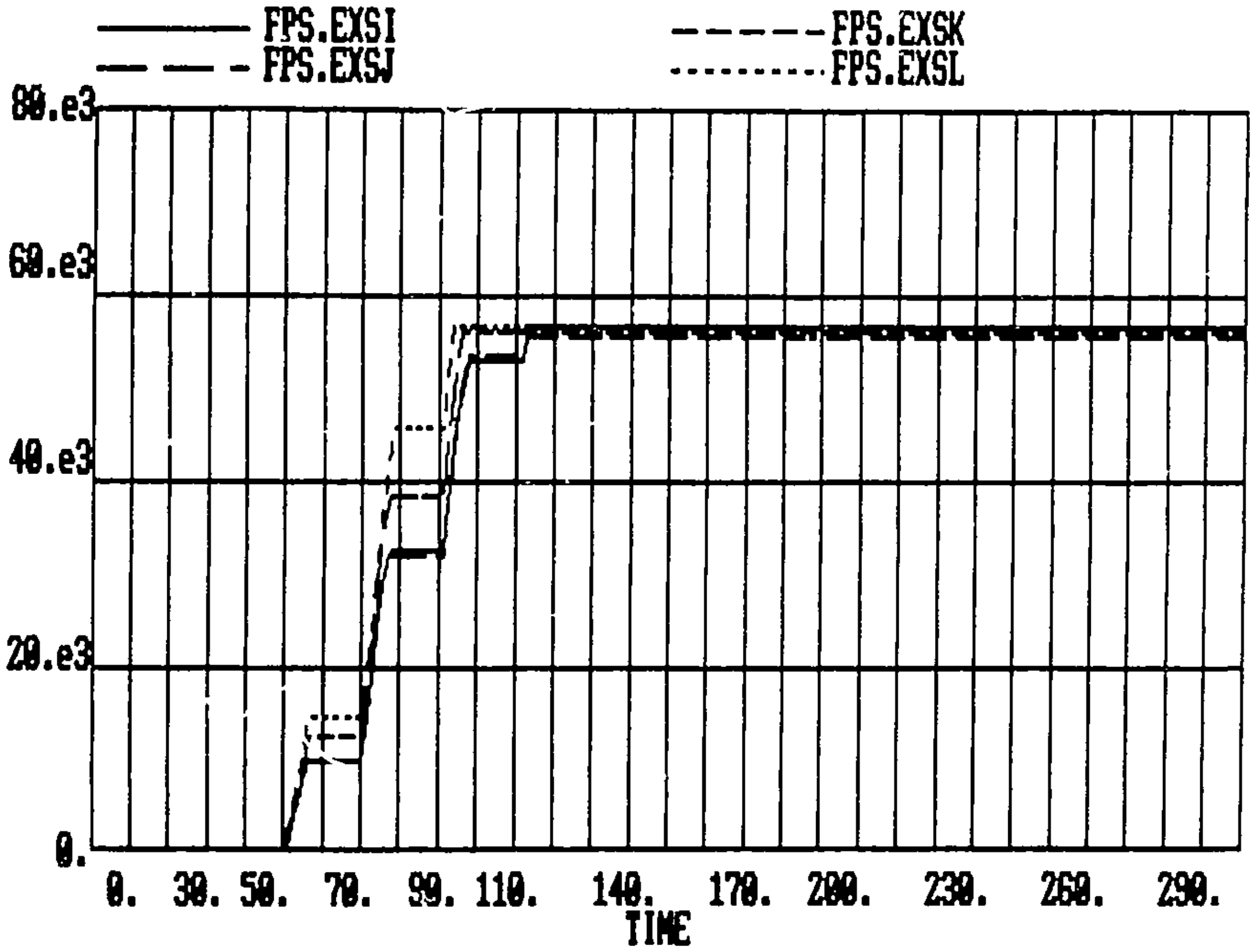

Figure 52: Impact of current production rates on WIP and throughput - synchronized schedule (FPS with SHOCK)

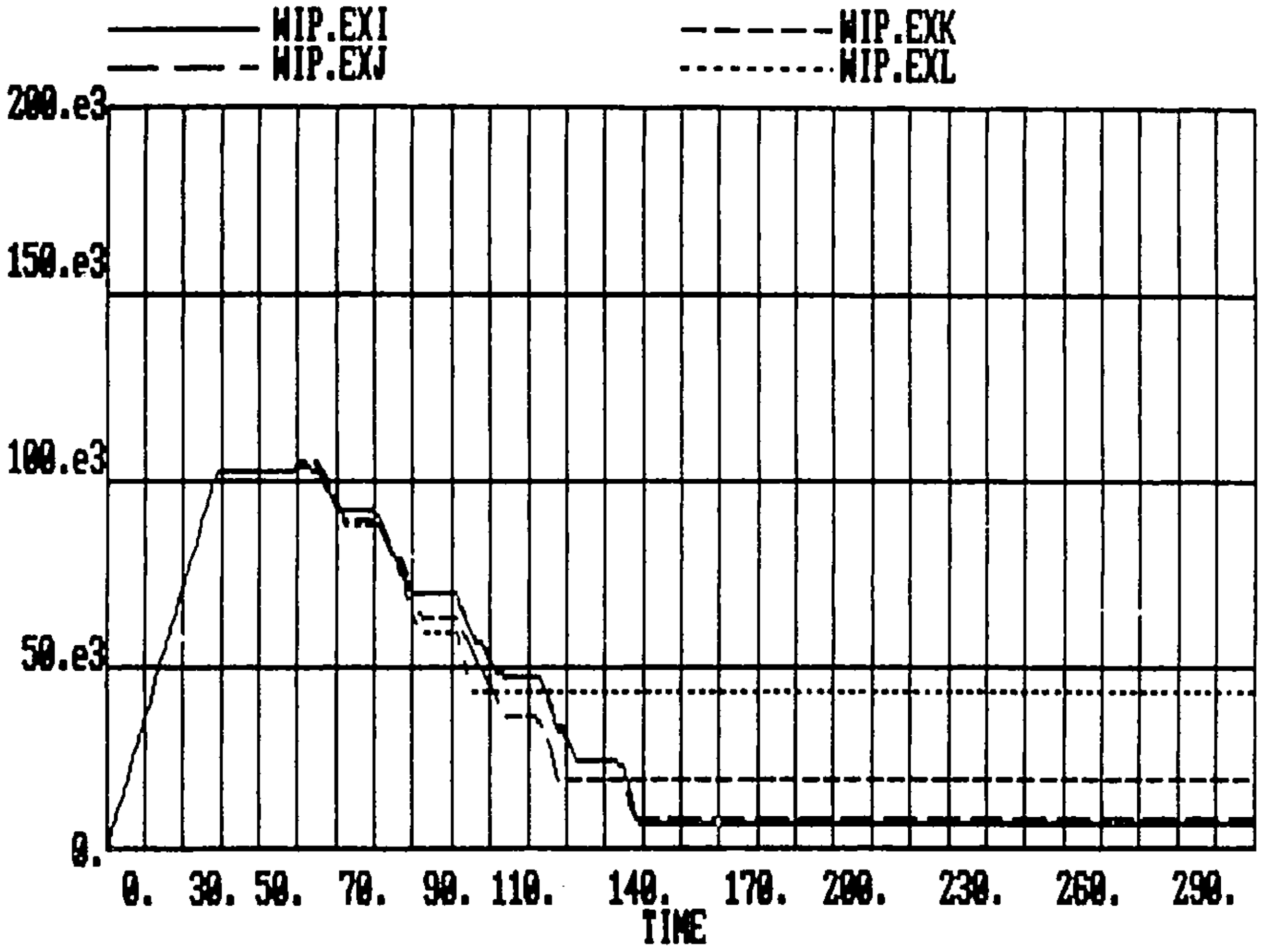

Figure 53: Impact of current production rates on WIP and throughput - synchronized schedule (WIP)

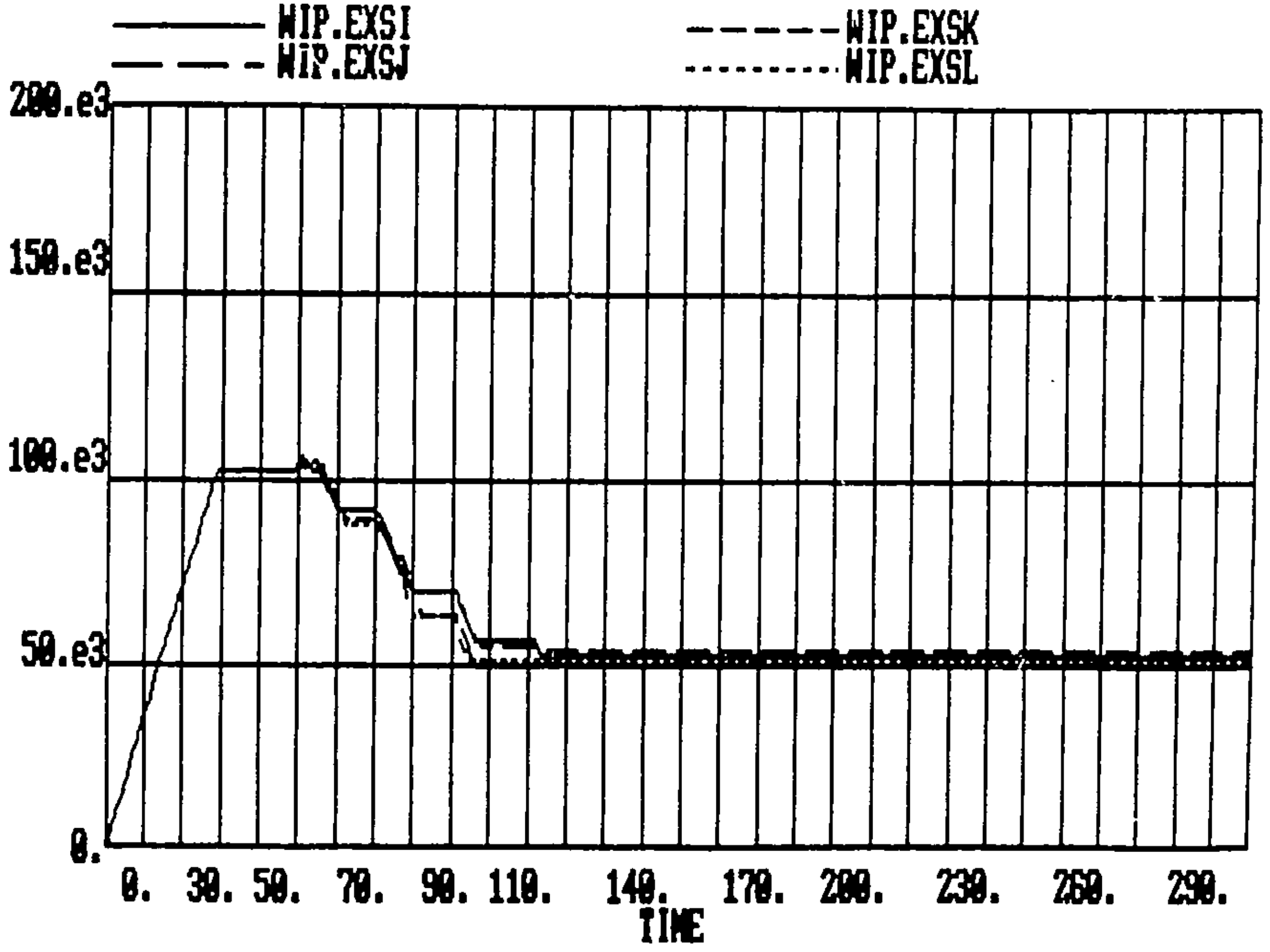

Figure 54: Impact of current production rates on WIP and throughput - synchronized schedule (WIP with SHOCK)

Simulation Run 5: Impact of plating lead time and order interval

In experiment 5 we test the effect of changing the average time for shells plated (PLT) and two order interval (OINTERVAL) policies: one a day, at the beginning of the morning shift (time = 7) and twice a day, at the beginning of the morning shift and towards the end of the afternoon shift. For the following experiments a lead time (LT) of 2 days and 1 day both with a SHOCK (no delivery for one day) and without will be tested:

Cases	PLT	OINTERVAL
Case-1	2.6	1
Case-2	2.6	2
Case-3	2.0	1
Case-4	2.0	2
Case-5	1.0	1
Case-6	1.0	2

Table 20: Impact of plating lead time and order interval
(For each schedule the first row represents throughput and the second row represents the time required to achieve this throughput)

Case A: with LT = 2 days

Schedule	Case-1	Case-2	Case-3	Case-4	Case-5	Case-6
Present	94000	95000	95500	95500	95500	95500
	201	202	202	202	202	201
One day difference	95500	95500	95500	95500	95500	95500
	158	158	159	158	159	159
Synchronized	94500	95500	95500	95500	95500	95500
	139	139	139	139	139	139

Case B: LT = 2 days with a SHOCK

Schedule	Case-1	Case-2	Case-3	Case-4	Case-5	Case-6
Present	66500	71500	80000	83500	95500	95500
	180	181	197	198	201	202
One day difference	56500	62500	79500	83500	95500	95500
	119	135	140	155	158	158
Synchronized	57000	63000	80000	84000	95500	95500
	114	115	135	136	139	139

Case C: LT = 1 day

Schedule	Case-1	Case-2	Case-3	Case-4	Case-5	Case-6
Present	79000	83500	95500	95500	95500	95500
	176	177	180	180	180	180
One day difference	3500	4000	60	11500	95500	95500
	72	72	72	74	138	138
Synchronized	3000	4500	6000	11500	95500	95500
	32	32	33	50	118	118

Case D: LT = 1 day with a SHOCK

Schedule	Case-1	Case-2	Case-3	Case-4	Case-5	Case-6
Present	56500	61500	73000	78500	95500	95500
	156	158	160	176	180	180
One day difference	3500	4000	6000	11500	95500	95500
	72	72	72	74	138	138
Synchronized	3000	4500	6000	11500	95500	95500
	32	32	33	50	118	118

The throughput and time taken to achieve the given throughput are found in the above tables. Generally, an order interval policy of twice a day gives better throughput than once a day.

4.6 System dynamics model of the assembly process using a pull system

The spark plug assembly under study was also modelled using the principles of a pull system (Figure 55). The notation used in this figure is the same as that for the push system with a few key differences: Each machine in the assembly process is not started by a specific schedule as it was for the push system. The assembly of a part is first triggered at the last stage (FPS) when there is a demand for a spark plug type. While there is a demand for a product, the FPS inventory will be depleted. When the trigger level of the FPS area is reached this will send an information flow to the production process (PR4) to replenish the units that were depleted in FPS until the trigger level is reached. The start up of PR4 will require material from the preceding station storage area (PSL3). Inventory from PSL3 will be depleted until a trigger level is reached and this will send an information flow to PR3 to replenish PSL3 until the trigger is reached. In a similar manner PSL2 is depleted and the trigger for that is activated to start the production process at PR2. At this point two checks are made: inventory must be present in both SP and PSL1 for PR2 to start the assembly process. The company policy of stopping production of a specific part type if the plated shells (SP) inventory is empty will be maintained for this model. When the trigger level of PSL1 is reached this will activate PR1 which will start after a prespecified lead time. This allows the raw shells to be manufactured

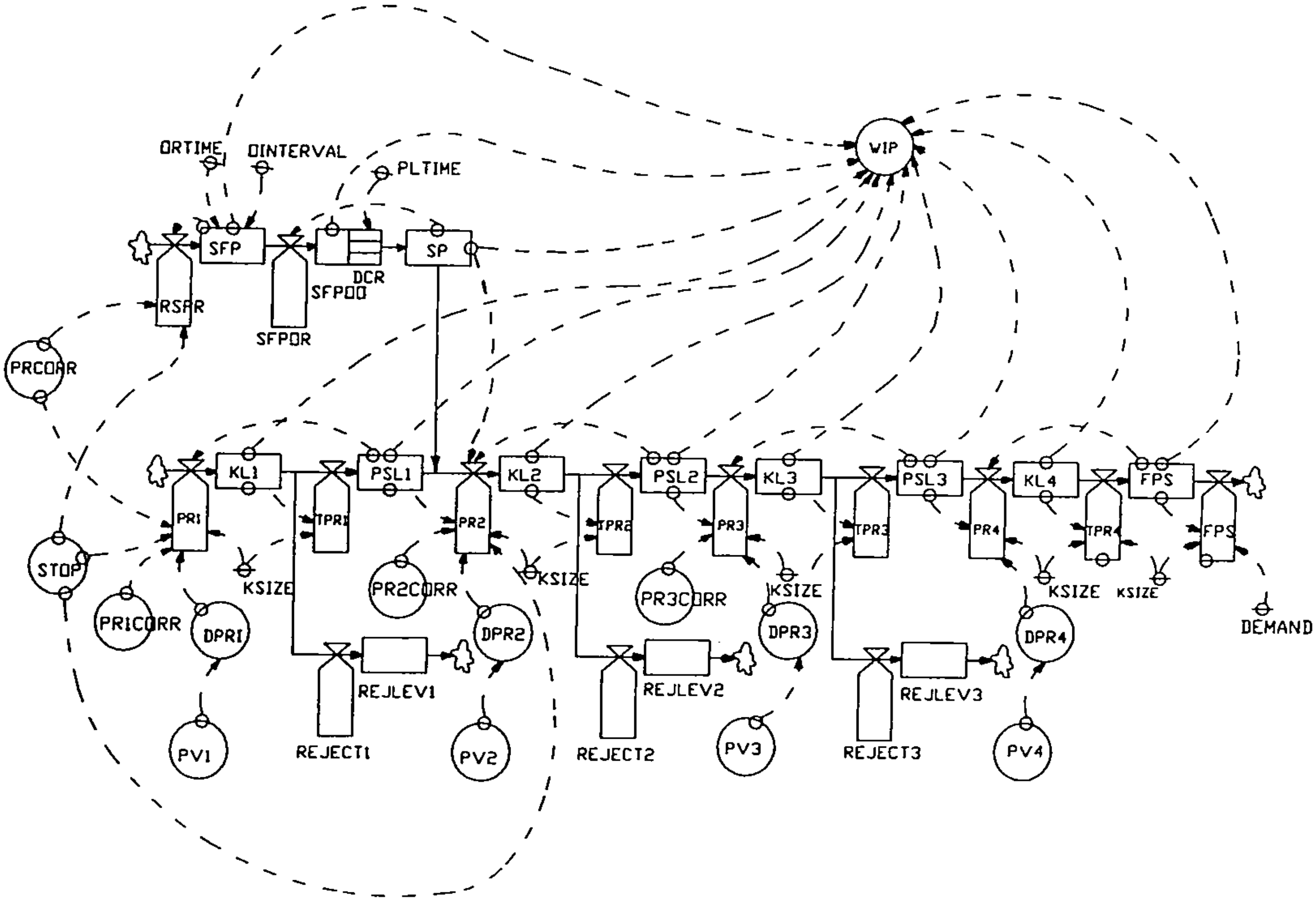

Figure 55: Flow diagram of a spark plug assembly process
- a pull system

and sent out for plating. The SP level will send an information flow to the delivery completion rate when triggered and this in turn starts to deplete the shells for plating on order (SFPOO) which will come from the raw shell inventory (SFP). The SFP inventory will be depleted and cause an information flow to travel to the raw shell manufacturing process (RSPR) when the trigger level is reached.

In the previous section where a push system was used to model the spark plug assembly process different schedules were used for the experiments and it was found that a synchronized schedule with a lead time of 2 days gave the best performance with respect to throughput and the average level of WIP. However, this involved a lengthy time consuming process of various simulation runs. Then the spark plug assembly plant was modelled using system dynamics and incorporating a pull system (see Figure 55). The advantage of using a pull approach is that the model itself gives the required schedules to be used to satisfy the demand requirements. The schedule given by the pull system was found to be a synchronized schedule and this was consistent with the best schedule found in the experimental runs using a system dynamics model with a push system. This is consistent with the JIT principle of producing "the right amount of product when required". JIT involves levelling the production schedule and this is achieved by synchronizing the production schedule. Also, it was found that the system behaviour of the pull model gave the same throughput and WIP results that the synchronized schedule in the push system did (Figure 56).

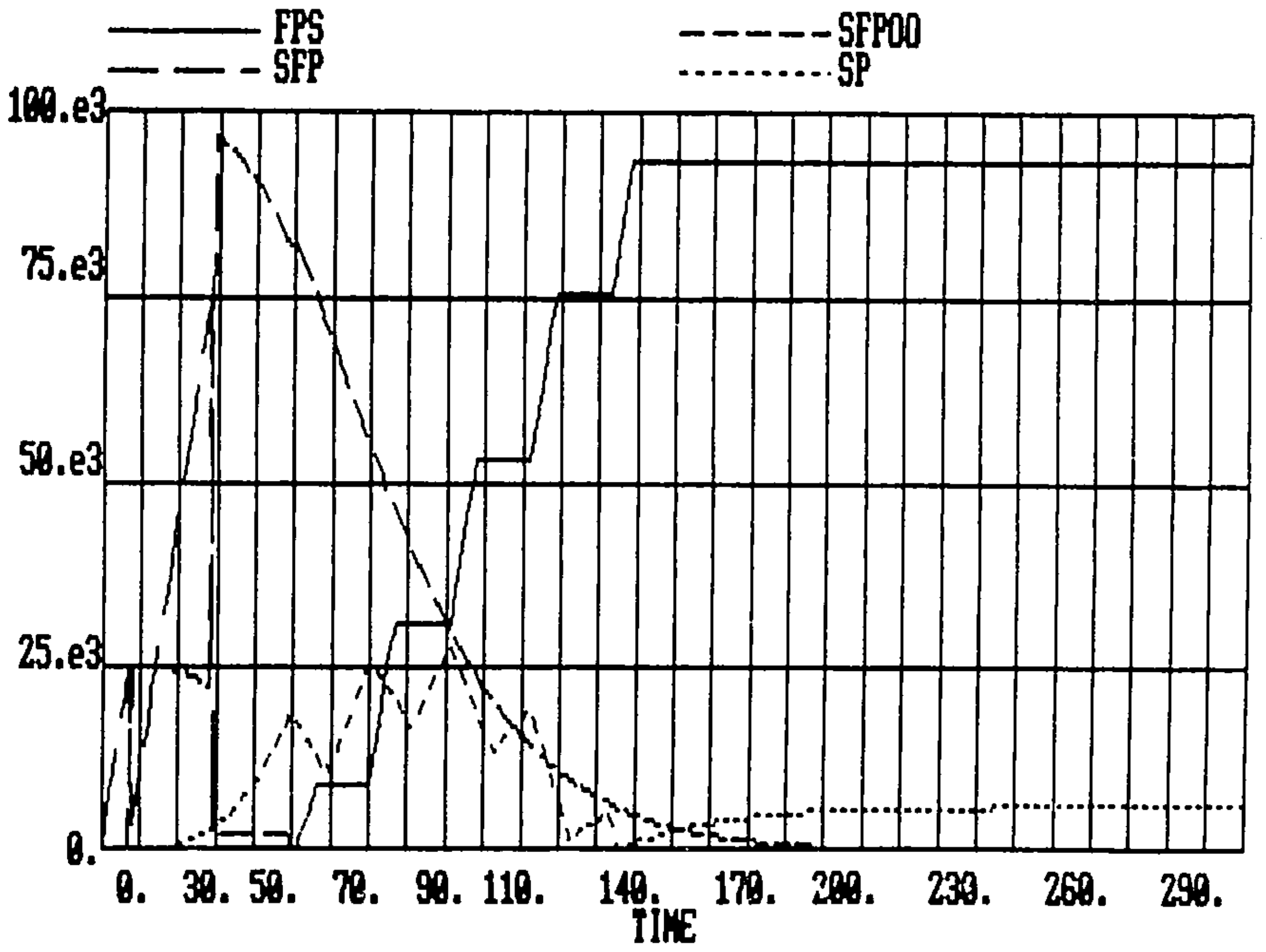

Figure 56: Throughput and WIP levels for the pull system

CHAPTER 5

CONCLUSIONS

In this research system dynamics models were developed to address the three systems: push, pull and long pull. Several simulation runs were conducted and the results analyzed. Also, a local spark plug assembly plant was studied and modelled using both the push and pull approaches. Various policies for these systems were reviewed and results were given. The proposed simulation models were obtained using the dynamic simulation software, DYNAMO (PC version 3.1).

5.1 Contributions of the research

In this work simulation models using system dynamics were developed to give a comprehensive analysis of various research issues in serial production lines. Most of the results in the literature give counterintuitive results. Also, an analysis of various factors of the long pull system such as, impact of work-in-process inventories on throughput, location of the long pull, span of control of each long pull and the corresponding amount of work-in-process inventory, was required.

In this research, an attempt was made to consider all these issues. A comprehensive analysis of the push, pull and the long pull systems was done using system dynamics. Various simulation runs were performed to study the impact of these systems on the work-in-process levels and throughput. A comparative study was performed on these systems to analyze system characteristics and to find which strategy performs the best and to remove the misconceptions of these systems. Also a simulation model using system dynamics was developed for a local spark plug assembly plant and various problems faced in the operations of the assembly system were identified. Various policies to test the performance of the plant using push and pull systems were developed and tested.

5.2 Summary of serial production lines

5.2.1 Results of push systems

1. **Effect of changes in lot size on WIP**
   a. WIP increases as lot size increases
   b. Variability in production storage areas increases as the lot size increases

2. **Effect of changes in lot size on throughput**
   a. As lot size increases, throughput decreases

3. **Effect of increased variability of production rates**
   a. Average buffer content increases as the coefficient of variation increases whereas the throughput correspondingly decreases

4. **Impact of bottleneck workstations**
   a. There is an accumulation of WIP before the bottleneck station

5. **Effect of increased variability in case of a bottleneck station**
    a. There is an accumulation of WIP before the bottleneck station
    b. As the coefficient of variation of the production rates increases the inventory before the bottleneck decreases while the other buffer contents correspondingly increase
    c. As the coefficient of variation increases throughput remains the same

6. **Placement of workstations with variable processing times**
    a. Variable workstations should be placed at the first and last stations

7. **Placement of buffers in a balanced production line**
    a. Equal allocation of buffers maximizes throughput

8. **Placement of extra buffer slots**
    a. Use an equal allocation of buffers as far as possible
    b. Use a centre weighted spread for maximizing throughput

9. **Reversibility in serial lines**
    a. Serial production lines which are mirror images of each other in terms of production rates have similar throughput and trend of buffer allocation

5.2.2 Results of pull system

1. **Nature of the pull system**
    a. The goal seeking nature of a pull system is evident by the

fluctuations in production rates caused by the system reacting to changes in demand

2. **Variation in WIP inventory**
    b. A smaller number of kanbans with proportionally larger containers produces more inventory variation

5.2.3 Results of long pull systems

1. **Location of the long pull**
    a. A long pull should be located at the bottleneck or after
    b. There exists a critical WIP level within the span of the pull

2. **Effect of variability of production rates on critical WIP**
    a. As the coefficient of variation increases, the critical WIP increases whereas the throughput remains the same

3. **The role of maximum inventory as a bottleneck**
    a. As the coefficient of variation of production rates increases, the maximum inventory (Maxinv) will become a bottleneck and thereby decrease throughput

5.2.4 Results of the comparative study of the various systems

1. **Effect of various systems on buffer allocation and throughput**
    a. The push system with finite buffers and the pull system have lower WIP levels than the long pull system
    b. All systems (push, pull and long pull) have lower throughput with increased variability in production rates
    c. At higher levels of uncertainty the long pull system gives

higher throughput

2. **Effect of various systems on lost sales**
    a. As variability of production rates increases the lost sales increases for all systems (push, pull and long pull)
    b. At higher levels of uncertainty the long pull system and the push system with infinite buffers perform the best

3. **Reaction of the different systems to demand**
    a. The push system with finite buffers, the pull system and the long pull system react to changes in demand due to the feedback control mechanisms in these systems whereas, the push system with infinite buffers does not react to changes demand

5.3 Results of the spark plug assembly plant analysis

Simulation models of a local spark plug assembly plant were developed using a system dynamics incorporating push and pull approaches. From the simulation runs conducted the following parameters gave the best performance in terms of throughput and the time required to achieve this throughput:

1. Synchronized schedule
2. A lead time of two days for the manufacture of raw shells
3. An order interval of twice a day

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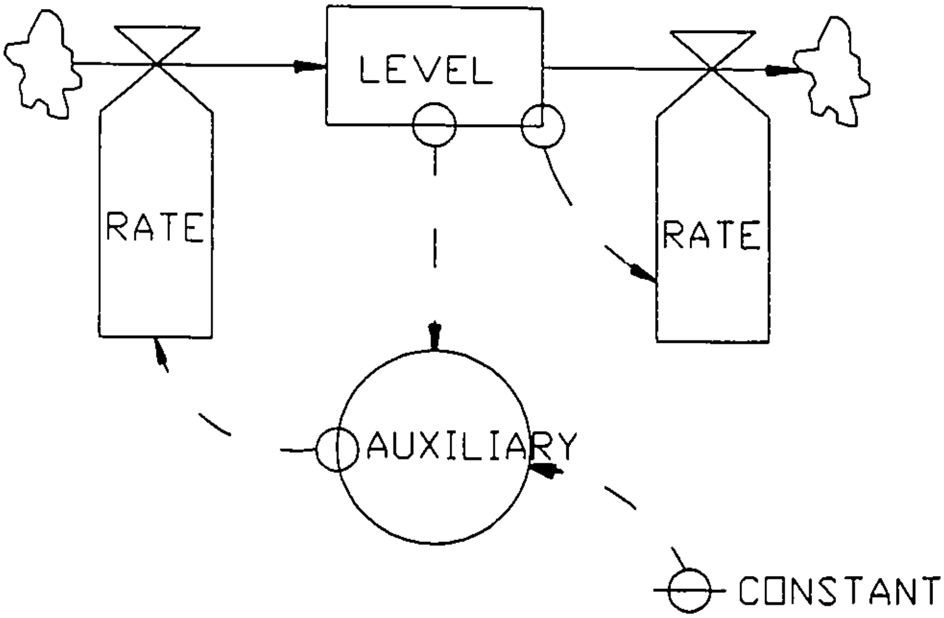
APPENDICES

APPENDIX A.1

SIMULATION WITH DYNAMO

Dynamo is a computer program which compiles and executes continuous simulation models. It is designed to be an effective aid in simulating system dynamics models whose behaviour depends more on the aggregate flows rather than the occurrence of discrete events (Pugh 1976).

There are seven equation types in Dynamo. The seven types are discussed briefly in the following paragraphs.



Level (L) equations are the integral equation types in Dynamo. They relate a quantity at the current time to its value at the previous time that calculations are made, and its rate of change during the interval between the calculations. In Dynamo the present time is indicated with a postscript .K, and the preceding time instant is represented by the postscript .J following the variable name. The incremental simulation time interval, Δt, is written as DT. Thus, a level can be written as:

$$LEV.K = LEV.J + (DT) \times (\text{Rate of change})$$

where,

LEV.K = Present value of LEV.

LEV.J = Immediate Past Value of LEV.

DT = Incremental Simulation Time Interval.

Auxiliary (A) equations are simple algebraic functions of levels and other auxiliary variables at the same time instant. Auxiliary equations may not depend upon other auxiliary variables which in turn depend on the auxiliary defined; i.e, simultaneous equations among auxiliary equations are not permitted. One form of auxiliary equations can be written as:

$$AUX.K = LEV.K \times CONST.$$

where

AUX.K = An Auxiliary Variable at Present

LEV.K = Present value of a LEV

Const = Some Constant Value

Rate (R) equations are much like auxiliary equations in that they are algebraic functions of levels and auxiliaries at the same instant. For the rate variables a double postscript .JK is used in the right hand side of the equal sign for rates that are independent variables that represent time from past to present. Thus, the LEV equations can be written as:

LEV.K = LEV.J + (DT) x (RATE.JK)

In cases where a rate is a dependant variable, its postscript is .KL, which denotes the time from present to future. A rate equation can be written as:

RATE.KL = AUX.K / CONST

where

RATE.KL = A Rate of the Next Instant

AUX.K = An Auxiliary Variable at present

CONST = Some constant value

Supplementary (S) equations are algebraic equations that are computed to provide output.

An initial value (N) equation must be provided for every level and may be provided for auxiliary or rate. A constant may also be computed initially by this equation type. (The N equation is the only equation that exists for the quantity).

A given constant (C) differs from an initially computed constant in that the right hand side is restricted to a numerical value.

A table (T) is an array of numerical values that provides the values upon which the table look-up function operates. A table function used to express a relationship between two variables.

Once all equations are written, Dynamo executes them in the following sequence: The first quantities to be calculated at the instant k are the levels. These depend on the previous value (at time J), on auxiliaries computed at time J, and on the rates computed for the interval JK. As all quantities for J and JK have already been calculated, there is no difficulty in carrying out the level computations.

Next, auxiliaries, ordered properly by Dynamo, are calculated for the instant K from levels at K and other auxiliaries calculated earlier for k.

Finally, rates are calculated for the interval KL from the levels and auxiliaries at time k. Like the levels, the rates do not provide any ordering problems.

Once the rates have been calculated, the present time is advanced DT time units, all quantities that have been calculated for time k are now considered to be values at time J; and the rates for the interval KL are now treated now as though they are JK values. The computation cycle then starts all over again with the level computations.

A.1.1 Selection of Computational Interval, DT

The choice of the size of DT requires a compromise between a large DT which demands slightly less computer time and a small DT which assures numerical accuracy. A good way to choose DT is first to select a value based on the delays in the model, and then check this choice by rerunning some run with a much smaller DT. The accuracy of any model results associated with any particular DT is almost impossible to determine except by this procedure.

A.1.2 Concluding remarks

After understanding the system dynamics methodology, it can be concluded that the methodology embodies several features and underlying viewpoints which distinguish it from other modelling approaches. These features include:

1. An emphasis on understanding the causes of dynamic behaviour
2. Inclusion of all variables relevant to the problem behaviour
3. A focus on policy design rather than decision making or forecasting

Although other modelling techniques embody some of these features, system dynamics appears to be unique in combining all these aspects.

APPENDIX A.2

PROGRAM LISTINGS

A.2.1 Push with infinite buffers

```
* WORKSTATION 1

R PR1.KL=DPR1.K

A DPR1.K=PV1.K
A PV1.K=NORMRN(PAMT1,SD1)

L KL1.K=KL1.J+DT*(PR1.JK-TPR1.JK)
N KL1=0

R TPR1.KL=CLIP(KSIZE/DT,0,KL1.K,KSIZE)

L PSL1.K=PSL1.J+DT*(TPR1.JK-PR2.JK)
N PSL1=0

* WORKSTATION 2

R PR2.KL=CLIP(DPR2.K,0,PSL1.K,DT*DPR2.K)

A DPR2.K=PV2.K
A PV2.K=NORMRN(PAMT2,SD2)

L KL2.K=KL2.J+DT*(PR2.JK-TPR2.JK)
N KL2=0

R TPR2.KL=CLIP(KSIZE/DT,0,KL2.K,KSIZE)
```

```
L PSL2.K=PSL2.J+DT*(TPR2.JK-PR3.JK)
N PSL2=0

* WORKSTATION 3

R PR3.KL=CLIP(DPR3.K,0,PSL2.K,DT*DPR3.K)

A DPR3.K=PV3.K
A PV3.K=NORMRN(PAMT3,SD3)

L KL3.K=KL3.J+DT*(PR3.JK-TPR3.JK)
N KL3=0

R TPR3.KL=CLIP(KSIZE/DT,0,KL3.K,KSIZE)

L PSL3.K=PSL3.J+DT*(TPR3.JK-PR4.JK)
N PSL3=0

* WORKSTATION 4

R PR4.KL=CLIP(DPR4.K,0,PSL3.K,DT*DPR4.K)

A DPR4.K=PV4.K
A PV4.K=NORMRN(PAMT4,SD4)

L KL4.K=KL4.J+DT*(PR4.JK-TPR4.JK)
N KL4=0

R TPR4.KL=CLIP(KSIZE/DT,0,KL4.K,KSIZE)

L FPS.K=FPS.J+DT*(TPR4.JK-UR.JK)
N FPS=0

R UR.KL=MIN(FPS.K,CDR.K)
A CDR.K=DAMT*DV.K
A DV.K=SAMPLE(NORMRN(1.0,SDD),1,1)

A WIP.K=KL1.K+PSL1.K+KL2.K+PSL2.K+KL3.K+PSL3.K
```

```
* THROUGHPUT

L THRUPUT.K=THRUPUT.J+DT*(TPR4.JK)
N THRUPUT=0

* STOCKOUT LEVEL

A DNMET.K=CDR.K-UR.KL
L CDNMET.K=CDNMET.J+DT*DNMET.J
N CDNMET=0

* NO. OF STOCKOUTS
* TNDKNMT IS TOTAL NO. OF TIMES DEMAND IS NOT MET

A NDNMET.K=CLIP(0,1/DT,0,DNMET.K)
L TNDNMT.K=TNDNMT.J+DT*(NDNMET.J)
N TNDNMT=0

* B1,B2,B3 ARE AVERAGE BUFFER SIZES

L LEVEL1.K=LEVEL1.J+DT*(PSL1.J/DT)
N LEVEL1=0
A B1.K=LEVEL1.K*DT/LENGTH

L LEVEL2.K=LEVEL2.J+DT*(PSL2.J/DT)
N LEVEL2=0
A B2.K=LEVEL2.K*DT/LENGTH

L LEVEL3.K=LEVEL3.J+DT*(PSL3.J/DT)
N LEVEL3=0
A B3.K=LEVEL3.K*DT/LENGTH

A BAVE.K=(B1.K+B2.K+B3.K)/3

L LEVEL4.K=LEVEL4.J+DT*(FPS.J/DT)
N LEVEL4=0
A B4.K=LEVEL4.K*DT/LENGTH
```

```
* CONSTANTS

C KSIZE=1
C PAMT1=10
C SD1=0.25
C PAMT2=10
C SD2=0.25
C PAMT3=10
C SD3=0.25
C PAMT4=10
C SD4=0.25
C DAMT=10
C SDD=.25

* SYSTEM PARAMETERS

SAVE PR1,KL1,TPR1,PSL1,DPR1,PR2,KL2,TPR2,PSL2,DPR2,PR3,KL3,TPR3,PSL3
SAVE DPR4,PR4,KL4,FPS,DPR3
SAVE UR,CDR,WIP,DNMET,CDNMET,NDNMET,TNDNMT,THRUPUT,B1,B2,B3,BAVE,B4
SPEC DT=0.03125/LENGTH=21/SAVPER=.125/PRTPER=.125/PLTPER=.125
```

A.2.2 Push with finite buffers

```
* MODEL PUSH4.DYN -- using four workstations to illustrate the push system
*                    with finite buffers

* WORKSTATION 1

R PR1.KL=CLIP(0,DPR1.K,PSL1.K+KL1.K+DPR1.K*DT,MAX1)
A WIP1.K=PSL1.K+KL1.K

A DPR1.K=PV1.K
A PV1.K=NORMRN(PAMT1,SD1)

L KL1.K=KL1.J+DT*(PR1.JK-TPR1.JK)
N KL1=0
```

```
R TPR1.KL=CLIP(KSIZE/DT,0,KL1.K,KSIZE)

L PSL1.K=PSL1.J+DT*(TPR1.JK-PR2.JK)
N PSL1=BUFF1

* WORKSTATION 2

R PR2.KL=CLIP(0,CLIP(DPR2.K,0,PSL1.K,BUFF1+DT*DPR2.K),^
             PSL2.K+KL2.K+DPR2.K*DT,MAX2)
A WIP2.K=PSL2.K+KL2.K

A DPR2.K=PV2.K
A PV2.K=NORMRN(PAMT2,SD2)

L KL2.K=KL2.J+DT*(PR2.JK-TPR2.JK)
N KL2=0

R TPR2.KL=CLIP(KSIZE/DT,0,KL2.K,KSIZE)

L PSL2.K=PSL2.J+DT*(TPR2.JK-PR3.JK)
N PSL2=BUFF2

* WORKSTATION 3

R PR3.KL=CLIP(0,CLIP(DPR3.K,0,PSL2.K,BUFF2+DT*DPR3.K),^
             PSL3.K+KL3.K+DPR3.K*DT,MAX3)

A WIP3.K=PSL3.K+KL3.K

A DPR3.K=PV3.K
A PV3.K=NORMRN(PAMT3,SD3)

L KL3.K=KL3.J+DT*(PR3.JK-TPR3.JK)
N KL3=0

R TPR3.KL=CLIP(KSIZE/DT,0,KL3.K,KSIZE)

L PSL3.K=PSL3.J+DT*(TPR3.JK-PR4.JK)
```

```
N PSL3=BUFF3

* WORKSTATION 4

R PR4.KL=CLIP(0,CLIP(DPR4.K,0,PSL3.K,BUFF3+DT*DPR4.K),^
            FPS.K+KL4.K+DPR4.K*DT,MAX4)


A DPR4.K=PV4.K
A PV4.K=NORMRN(PAMT4,SD4)

L KL4.K=KL4.J+DT*(PR4.JK-TPR4.JK)
N KL4=0

R TPR4.KL=CLIP(KSIZE/DT,0,KL4.K,KSIZE)

L FPS.K=FPS.J+DT*(TPR4.JK-UR.JK)
N FPS=0

R UR.KL=MIN(CDR.K,FPS.K)
A CDR.K=DAMT*DV.K
A DV.K=SAMPLE(NORMRN(1.0,SDD),1,1)

A WIP.K=KL1.K+PSL1.K+KL2.K+PSL2.K+KL3.K+PSL3.K

* THROUGHPUT

L THRUPUT.K=THRUPUT.J+DT*(TPR4.JK)
N THRUPUT=0

* STOCKOUT LEVEL

A DNMET.K=CDR.K-UR.KL
L CDNMET.K=CDNMET.J+DT*(DNMET.J)
N CDNMET=0

* NO. OF STOCKOUTS
* TNDNMT IS TOTAL NO. OF TIMES DEMAND IS NOT MET
```

```
A NDNMET.K=CLIP(0,1/DT,0,DNMET.K)
L TNDNMT.K=TNDNMT.J+DT*(NDNMET.J)
N TNDNMT=0

* B1,B2,B3 ARE AVERAGE BUFFER SIZES

L LEVEL1.K=LEVEL1.J+DT*(PSL1.J/DT)
N LEVEL1=0
A B1.K=LEVEL1.K*DT/LENGTH

L LEVEL2.K=LEVEL2.J+DT*(PSL2.J/DT)
N LEVEL2=0
A B2.K=LEVEL2.K*DT/LENGTH

L LEVEL3.K=LEVEL3.J+DT*(PSL3.J/DT)
N LEVEL3=0
A B3.K=LEVEL3.K*DT/LENGTH

A BAVE.K=(B1.K+B2.K+B3.K)/3

L LEVEL4.K=LEVEL4.J+DT*(FPS.J/DT)
N LEVEL4=0
A B4.K=LEVEL4.K*DT/LENGTH

* CONSTANTS

C KSIZE=1
C PAMT1=10
C SD1=0.25
C PAMT2=10
C SD2=0.25
C PAMT3=10
C SD3=0.25
C PAMT4=10
C SD4=0.25
C DAMT=15
C SDD=0.25
```

```
C MAX1=2
C MAX2=2
C MAX3=2
C MAX4=2
C BUFF1=0
C BUFF2=0
C BUFF3=0
C BUFF4=0
* SYSTEM PARAMETERS

SAVE PR1,KL1,TPR1,PSL1,DPR1,PR2,KL2,TPR2,PSL2,DPR2,PR3,KL3,TPR3,FPS,DPR3
SAVE UR,CDR,WIP,DNMET,CDNMET,NDNMET,TNDNMT,THRUPUT,B1,B2,B3,BAVE,B4
SPEC DT=0.03125/LENGTH=21/SAVPER=.125/PRTPER=.125/PLTPER=.125
```

A.2.3 Pull system

```
* MODEL JPULL4.DYN -- using 4 workstations illustrate pull system

* WORKSTATION 1

L KL1.K=KL1.J+DT*(PR1.JK-TPR1.JK)
N KL1=0

R TPR1.KL=CLIP(KSIZE/DT,0,KL1.K,KSIZE)

L PSL1.K=PSL1.J+DT*(TPR1.JK-PR2.JK)
N PSL1=0

R PR1.KL=CLIP(DPR1.K,0,(KNUM1*KSIZE-PSL1.K),KSIZE)

A DPR1.K=PV1.K
A PV1.K=NORMRN(PAMT1,SD1)

* WORKSTATION 2

L KL2.K=KL2.J+DT*(PR2.JK-TPR2.JK)
N KL2=0
```

```
R TPR2.KL=CLIP(KSIZE/DT,0,KL2.K,KSIZE)

L PSL2.K=PSL2.J+DT*(TPR2.JK-PR3.JK)
N PSL2=0

R PR2.KL=CLIP(CLIP(DPR2.K,0,(KNUM2*KSIZE-PSL2.K), ^
         KSIZE),0,PSL1.K,DT*DPR2.K)

A DPR2.K=PV2.K
A PV2.K=NORMRN(PAMT2,SD2)

* WORKSTATION 3

L KL3.K=KL3.J+DT*(PR3.JK-TPR3.JK)
N KL3=0

R TPR3.KL=CLIP(KSIZE/DT,0,KL3.K,KSIZE)

L PSL3.K=PSL3.J+DT*(TPR3.JK-PR4.JK)
N PSL3=0

R PR3.KL=CLIP(CLIP(DPR3.K,0,(KNUM3*KSIZE-PSL3.K), ^
         KSIZE),0,PSL2.K,DT*DPR3.K)

A DPR3.K=PV3.K
A PV3.K=NORMRN(PAMT3,SD3)

* WORKSTATION 4

L KL4.K=KL4.J+DT*(PR4.JK-TPR4.JK)
N KL4=0

R TPR4.KL=CLIP(KSIZE/DT,0,KL4.K,KSIZE)

L FPS.K=FPS.J+DT*(TPR4.JK-UR.JK)
N FPS=0

R PR4.KL=CLIP(CLIP(DPR4.K,0,(KNUM4*KSIZE-FPS.K), ^
```

```
          KSIZE),0,PSL3.K,DT*DPR4.K)

A DPR4.K=PV4.K
A PV4.K=NORMRN(PAMT4,SD4)

R UR.KL=MIN(CDR.K,FPS.K)
A CDR.K=DV.K
A DV.K=SAMPLE(NORMRN(DAMT,SDD),1,1)

S WIP.K=KL1.K+PSL1.K+KL2.K+PSL2.K+KL3.K+PSL3.K

* THROUGHPUT

L THRUPUT.K=THRUPUT.J+DT*(TPR4.JK)
N THRUPUT=0

* STOCKOUT LEVEL

A DNMET.K=CDR.K-UR.KL
L CDNMET.K=CDNMET.J+DT*DNMET.J
N CDNMET=0

* NO. OF STOCKOUTS
* TNDNMT IS TOTAL NO. OF TIMES DEMAND NOT MET

A NDNMET.K=CLIP(0,1/DT,0,DNMET.K)
L TNDNMT.K=TNDNMT.J+DT*(NDNMET.J)
N TNDNMT=0

* B1,B2,B3 ARE AVERAGE BUFFER SIZES

L LEVEL1.K=LEVEL1.J+DT*(PSL1.J/DT)
N LEVEL1=0
A B1.K=LEVEL1.K*DT/LENGTH

L LEVEL2.K=LEVEL2.J+DT*(PSL2.J/DT)
N LEVEL2=0
A B2.K=LEVEL2.K*DT/LENGTH
```

```
L LEVEL3.K=LEVEL3.J+DT*(PSL3.J/DT)
N LEVEL3=0
A B3.K=LEVEL3.K*DT/LENGTH

A BAVE.K=(B1.K+B2.K+B3.K)/3

L LEVEL4.K=LEVEL4.J+DT*(FPS.J/DT)
N LEVEL4=0
A B4.K=LEVEL4.K*DT/LENGTH

* CONSTANTS

C KSIZE=1
C KNUM1=2
C KNUM2=2
C KNUM3=2
C KNUM4=2
C PAMT1=10
C SD1=0.25
C PAMT2=10
C SD2=0.25
C PAMT3=10
C SD3=0.25
C PAMT4=10
C SD4=0.25
C DAMT=15
C SDD=0.25

* SYSTEM PARAMTERS

SAVE PR1,KL1,TPR1,PSL1,DPR1,PR2,KL2,TPR2,PSL2,DPR2,PR3,PSL3,PR4,KL4,TPR4,DPR4
SAVE KL3,TPR3,FPS,DPR3,FPS,UR,CDR,WIP,DNMET,CDNMET,NDNMET,TNDNMT,THRUPUT
SAVE B1,B2,B3,BAVE,B4
SPEC DT=.03125/LENGTH=21/SAVPER=.125/PRTPER=.125/PLTPER=.125
```

A.2.4 Long pull system

```
* MODEL LPULL4.DYN -- using FOUR workstations to illustrate the long pull
```

```
* WORKSTATION 1

R PR1.KL=CLIP(0,CLIP(DPR1.K,0,(KNUM*KSIZE-FPS.K),KSIZE),WIP.K,MAXINV)

A DPR1.K=PV1.K
A PV1.K=NORMRN(PAMT1,SD1)

L KL1.K=KL1.J+DT*(PR1.JK-TPR1.JK)
N KL1=0

R TPR1.KL=CLIP(KSIZE/DT,0,KL1.K,KSIZE)

L PSL1.K=PSL1.J+DT*(TPR1.JK-PR2.JK)
N PSL1=0

* WORKSTATION 2

R PR2.KL=CLIP(DPR2.K,0,PSL1.K,DT*DPR2.K)

A DPR2.K=PV2.K
A PV2.K=NORMRN(PAMT2,SD2)

L KL2.K=KL2.J+DT*(PR2.JK-TPR2.JK)
N KL2=0

R TPR2.KL=CLIP(KSIZE/DT,0,KL2.K,KSIZE)

L PSL2.K=PSL2.J+DT*(TPR2.JK-PR3.JK)
N PSL2=0

* WORKSTATION 3

R PR3.KL=CLIP(DPR3.K,0,PSL2.K,DT*DPR3.K)

A DPR3.K=PV3.K
A PV3.K=NORMRN(PAMT3,SD3)
```

```
L KL3.K=KL3.J+DT*(PR3.JK-TPR3.JK)
N KL3=0

R TPR3.KL=CLIP(KSIZE/DT,0,KL3.K,KSIZE)

L PSL3.K=PSL3.J+DT*(TPR3.JK-PR4.JK)
N PSL3=0

* WORKSTATION 4

R PR4.KL=CLIP(DPR4.K,0,PSL3.K,DT*DPR4.K)

A DPR4.K=PV4.K
A PV4.K=NORMRN(PAMT4,SD4)

L KL4.K=KL4.J+DT*(PR4.JK-TPR4.JK)
N KL4=0

R TPR4.KL=CLIP(KSIZE/DT,0,KL4.K,KSIZE)

L FPS.K=FPS.J+DT*(TPR4.JK-UR.JK)
N FPS=0

R UR.KL=MIN(CDR.K,FPS.K)
A CDR.K=DV.K
A DV.K=SAMPLE(NORMRN(DAMT,SDD),1,1)

A WIP.K=KL1.K+PSL1.K+KL2.K+PSL2.K+KL3.K+PSL3.K

* THROUGHPUT

L THRUPUT.K=THRUPUT.J+DT*(TPR4.JK)
N THRUPUT=0

* STOCKOUT LEVEL

A DNMET.K=CDR.K-UR.KL
```

```
L CDNMET.K=CDNMET.J+DT*DNMET.J
N CDNMET=0

* NO. OF STOCKOUTS
* TNDNMT IS TOTAL NO. OF TIMES DEMAND IS NOT MET

A NDNMET.K=CLIP(0,1/DT,0,DNMET.K)
L TNDNMT.K=TNDNMT.J+DT*(NDNMET.J)
N TNDNMT=0

* B1,B2,B3 ARE AVERAGE BUFFER SIZES

L LEVEL1.K=LEVEL1.J+DT*(PSL1.J/DT)
N LEVEL1=0
A B1.K=LEVEL1.K*DT/LENGTH

L LEVEL2.K=LEVEL2.J+DT*(PSL2.J/DT)
N LEVEL2=0
A B2.K=LEVEL2.K*DT/LENGTH

L LEVEL3.K=LEVEL3.J+DT*(PSL3.J/DT)
N LEVEL3=0
A B3.K=LEVEL3.K*DT/LENGTH

A BAVE.K=(B1.K+B2.K+B3.K)/3

* CONSTANTS

C KNUM=5
C KSIZE=5
C PAMT1=10
C SD1=0.25
C PAMT2=10
C SD2=0.25
C PAMT3=10
C SD3=0.25
C PAMT4=10
C SD4=0.25
```

```
C DAMT=10
C SDD=0.25
C MAXINV=50

* SYSTEM PARAMETERS

SAVE PR1,KL1,TPR1,PSL1,DPR1,PR2,KL2,TPR2,PSL2,DPR2,PR3,KL3,TPR3,PSL3,FPS,DPR3
SAVE PR4,KL4,TPR4,UR,CDR,WIP,THRUPUT,DNMET,CDNMET,NDNMET,TNDNMT,B1,B2,B3,BAVE
SPEC DT=0.03125/LENGTH=21/SAVPER=.125/PRTPER=.125/PLTPER=.125
```

A.2.5 Spark plug assembly plant - Push system approach

```
* MODEL CASEPUSH.DYN -- using four workstations to illustrate the case
*                       study of local spark plug assembly plant

N TIME=0

* RAW SHELL PRODUCTION RATE

R RSPR.KL=MAX(0,CLIP(0,PULSE(DSPR.K/SHIFT,SHIFT*3,0,DAY)*(1+STOP.K),^
             SFPUSE.K,PRCORR.K))
L SFPUSE.K=SFPUSE.J+DT*(RSPR.KL)
N SFPUSE=0
C DEMAND=100000
A PRCORR.K=(1+REJAMT3)*(1+REJAMT2)*(DEMAND)

* This basically stops production if shells have run out
A STOP.K=CLIP(0,-1,H1.K,0)+CLIP(0,-1,0,AMT2.K)
A SPNIL.K=CLIP(0,1,SP.K,0)
L AMT1.K=AMT1.J+DT*(SPNIL.J/DT)
N AMT1=0

A H1.K=CLIP(0,CLIP(-1,0,AMT1.K,1),AMT1.K,2)
A NOSP.K=CLIP(0,1,H1.K,0)
L AMT2.K=AMT2.K+DT*(NOSP.J/DT)
N AMT2=0
A H2.K=CLIP(-1,0,AMT2.K,0)
```

```
A DSPR.K=NORMRN(SMEAN,SSD)
C SMEAN=25000
C SSD=1667

* SHELLS FOR PLATING INVENTORY

L SFP.K=SFP.J+DT*(RSPR.JK-SFPOR.JK/DT)
N SFP=0

* SHELLS FOR PLATING ORDER RATE

R SFPOR.KL=PULSE(SFP.K,DT,ORTIME,OINTERVAL)
C ORTIME=7
C OINTERVAL=21

* SHELLS FOR PLATING ON ORDER AND DELIVERY COMPLETION RATE
*  WITH LEAD TIME OF 2.6 DAYS SD.1.2
*   CONVERTED LEAD TIME TO HOURS (7 HOUR SHIFTS) IS 54.6 DAYS SD. 25.2

L TSFPOO.K=TSFPOO.J+DT*(SFPOR.JK/DT)
N TSFPOO=0
L SFPOO.K=SFPOO.J+DT*((SFPOR.JK/DT)-(DCR.JK/DT))
N SFPOO=0
R DCR.KL=DELAY3(SFPOR.JK,PLT*DAY)*DSHOCK.K
A DSHOCK.K=1+STEP(-1,TSHOCK)+STEP(1,TSHOCK+LSHOCK)
C TSHOCK=400
C LSHOCK=21

C PLT=2.6

* SHELLS PLATED INVENTORY

L TSP.K=TSP.J+DT*(DCR.JK/DT)
N TSP=0
L SP.K=SP.J+DT*((DCR.JK/DT)-PR2.JK)
N SP=SPSTK

* LEAD TIME FOR ORDERING SHELLS TO BE MANUFACTURED (APPROX. ONE WEEK)
```

```
*   5 WORKING DAYS  5*21

C LT=105

* WORKSTATION 1 - COMBINATION MACHINES

L RCUSE.K=RCUSE.J+DT*(PR1.JK)
N RCUSE=0

R PR1.KL=MAX(0,CLIP(0,CLIP(CLIP(CLIP(MAX(0,PULSE(NORMRN(MEAN1,SD1),^
         SHIFT,SHIFT,DAY)),0,TIME.K,START1.K+LT),0,TIME.K,LT),^
         0,SP.K,0)*(1+STOP.K),RCUSE.K,PRCORR.K))

A START1.K=SHIFT*(3*DAY1-2)

L KL1.K=KL1.J+DT*(PR1.JK-TPR1.JK-REJECT1.JK)
N KL1=0

R REJECT1.KL=REJAMT1*PR1.KL
C REJAMT1=0.04

L REJLEV1.K=REJLEV1.J+DT*(REJECT1.JK)
N REJLEV1=0

R TPR1.KL=CLIP(KSIZE/DT,0,KL1.K,KSIZE)

L PSL1.K=PSL1.J+DT*(TPR1.JK-PR2.JK)
N PSL1=0

* WORKSTATION 2 - PLUG TAMPERS

R PR2.KL=MAX(0,CLIP(0,CLIP(0,CLIP(MAX(0,PULSE(NORMRN(MEAN2,SD2),^
             SHIFT*2,SHIFT,DAY)),0,TIME.K,START2.K+LT),0,SP.K),0,PSL1.K)*^
             (1+STOP.K))
A START2.K=SHIFT*(3*DAY2-2)

L KL2.K=KL2.J+DT*(PR2.JK-TPR2.JK-REJECT2.JK)
N KL2=0
```

```
R REJECT2.KL=REJAMT2*PR2.KL
C REJAMT2=0.00337

L REJLEV2.K=REJLEV2.J+DT*(REJECT2.JK)
N REJLEV2=0

R TPR2.KL=CLIP(KSIZE/DT,0,KL2.K,KSIZE)

L PSL2.K=PSL2.J+DT*(TPR2.JK-PR3.JK)
N PSL2=0

* WORKSTATION 3 - GTG MACHINES

R PR3.KL=MAX(0,CLIP(0,CLIP(MAX(0,PULSE(NORMRN(MEAN3,SD3),SHIFT*2,SHIFT,DAY)),
             0,TIME.K,START3.K+LT),0,PSL2.K))
A START3.K=SHIFT*3*(DAY3-1)

L KL3.K=KL3.J+DT*(PR3.JK-TPR3.JK-REJECT3.JK)
N KL3=0

R REJECT3.KL=REJAMT3*PR3.KL
C REJAMT3=0.018

L REJLEV3.K=REJLEV3.J+DT*(REJECT3.JK)
N REJLEV3=0

R TPR3.KL=CLIP(KSIZE/DT,0,KL3.K,KSIZE)

L PSL3.K=PSL3.J+DT*(TPR3.JK-PR4.JK)
N PSL3=0

* WORKSTATION 4 - PACKAGING

R PR4.KL=MAX(0,CLIP(0,CLIP(MAX(0,PULSE(NORMRN(MEAN4,SD4),SHIFT,SHIFT,DAY)),
             0,TIME.K,START4.K+LT),0,PSL3.K))
A START4.K=SHIFT*3*(DAY4-1)
```

```
L KL4.K=KL4.J+DT*(PR4.JK-TPR4.JK)
N KL4=0

R TPR4.KL=CLIP(KSIZE/DT,0,KL4.K,KSIZE)

L FPS.K=FPS.J+DT*(TPR4.JK)
N FPS=0

A WIP.K=SFP.K+SFP00.K+SP.K+KL1.K+PSL1.K+KL2.K+PSL2.K+KL3.K+PSL3.K+KL4.K


* CONSTANTS - NOTE PRODUCTION RATES ARE IN PARTS/HOUR

C KSIZE=500
C MEAN1=3403
C SD1=1070
C MEAN2=2141
C SD2=275
C MEAN3=1671
C SD3=276
C MEAN4=3827
C SD4=1713
C SPSTK=0

* PRODUCTION SHIFT SCHEDULE

C SHIFT=7
C DAY=21

* PRODUCTION STARTUP SCHEDULE

C DAY1=0
C DAY2=2
C DAY3=3
C DAY4=5

* ***** PROGRAM TEST BY CHECKING INDIVIDUAL LEVELS ****
```

```
L LEVEL1.K=LEVEL1.J+DT*(PR1.JK)
N LEVEL1=0
L LEVEL2.K=LEVEL2.J+DT*(PR2.JK)
N LEVEL2=0
L LEVEL3.K=LEVEL3.J+DT*(PR3.JK)
N LEVEL3=0
L LEVEL4.K=LEVEL4.J+DT*(PR4.JK)
N LEVEL4=0


* SYSTEM PARAMETERS

SAVE PR1,KL1,TPR1,PSL1,PR2,KL2,TPR2,PSL2,PR3,KL3,TPR3,
SAVE PSL3,PR4,KL4,TPR4,FPS,WIP
SAVE REJECT1,REJLEV1,REJECT2,REJLEV2,REJECT3,REJLEV3
SAVE RSPR,SFP,SFPOR,SFPOO,DCR,SP,DSPR,PLT
SAVE LEVEL1,LEVEL2,LEVEL3,LEVEL4
SAVE SPNIL,AMT1,AMT2,H1,H2,NOSP,STOP,DSHOCK,PRCORR,RCUSE,SFPUSE,TSP,TSFPOO
SPEC DT=.125/LENGTH=300/SAVPER=1/PRTPER=1/PLTPER=1
```

A.2.6 Spark plug assembly plant - Pull system approach

```
* MODEL CASEPULL.DYN -- using four workstations to illustrate the case
*                       study of local spark plug assembly plant

N TIME=0

* RAW SHELL PRODUCTION RATE

R RSPR.KL=MAX(0,CLIP(0,CLIP(PULSE(DSPR.K/SHIFT,SHIFT*3,0,DAY),0,^
               KNUMSFP*KSIZE-SFP.K,KSIZE/500)*(1+STOP.K),SFPUSE.K,PRCORR.K))
L SFPUSE.K=SFPUSE.J+DT*(RSPR.JK)
N SFPUSE=0
C DEMAND=100000
A PRCORR.K=(1+REJAMT3)*(1+REJAMT2)*(DEMAND)

A DSPR.K=NORMRN(SMEAN,SSD)
C SMEAN=25000
```

```
C SSD=1667

* This basically stops production if shells have run out
A STOP.K=CLIP(0,-1,H1.K,0)+CLIP(0,-1,0,AMT2.K)
* A SPNIL.K=CLIP(0,1,SP.K,0)
A SPNIL.K=CLIP(CLIP(0,1,SP.K,DT*DPR2.K),0,TIME.K,STARTLT)
C STARTLT=21
L AMT1.K=AMT1.J+DT*(SPNIL.J/DT)
N AMT1=0

A H1.K=CLIP(0,CLIP(-1,0,AMT1.K,1),AMT1.K,2)
A NOSP.K=CLIP(0,1,H1.K,0)
L AMT2.K=AMT2.K+DT*(NOSP.J/DT)
N AMT2=0
A H2.K=CLIP(-1,0,AMT2.K,0)

* SHELLS FOR PLATING INVENTORY

L SFP.K=SFP.J+DT*(RSPR.JK-SFPOR.JK/DT)
N SFP=0

* SHELLS FOR PLATING ORDER RATE

R SFPOR.KL=CLIP(PULSE(SFP.K,DT,ORTIME,OINTERVAL),0,KNUMSP*KSIZE-SP.K,KSIZE)
C ORTIME=7
C OINTERVAL=21

* SHELLS FOR PLATING ON ORDER AND DELIVERY COMPLETION RATE
*  WITH LEAD TIME OF 2.6 DAYS SD.1.2

L TSFPOO.K=TSFPOO.J+DT*(SFPOR.JK/DT)
N TSFPOO=0
L SFPOO.K=SFPOO.J+DT*((SFPOR.JK/DT)-(DCR.JK/DT))
N SFPOO=0
R DCR.KL=DELAY3(SFPOR.JK,PLT*DAY)*DSHOCK.K
A DSHOCK.K=1+STEP(-1,TSHOCK)+STEP(1,TSHOCK+LSHOCK)
C TSHOCK=400
C LSHOCK=400
```

```
C PLT=2.6

* SHELLS PLATED INVENTORY

L TSP.K=TSP.J+DT*(DCR.JK/DT)
N TSP=0
L SP.K=SP.J+DT*((DCR.JK/DT)-PR2.JK)
N SP=SPSTK

* LEAD TIME FOR ORDERING SHELLS TO BE MANUFACTURED
*   2 WORKING DAYS  2*21 --- NOT APPLICABLE HERE

C LT=49

* WORKSTATION 1 - COMBINATION MACHINES

L PR1USE.K=PR1USE.J+DT*(PR1.JK)
N PR1USE=0

R PR1.KL=MAX(0,CLIP(0,CLIP(0,CLIP(DPR1.K,0,KNUM1*KSIZE-PSL1.K,KSIZE), ^
             PR1USE.K,PR1CORR.K),MINSP,TSP.K)*(1+STOP.K))
*R PR1.KL=MAX(0,CLIP(0,CLIP(DPR1.K,0,KNUM1*KSIZE-PSL1.K,KSIZE), ^
*             PR1USE.K,PR1CORR.K)*(1+STOP.K))
A PR1CORR.K=(1+REJAMT3)*(1+REJAMT2)*(1+REJAMT1)*(DEMAND)
A DPR1.K=CLIP(PULSE(NORMRN(MEAN1,SD1),SHIFT,SHIFT,DAY),0,TIME.K,LT)
C MINSP=0
A PR1START.K=CLIP(0,TIME.K,0,PR1.KL)

L KL1.K=KL1.J+DT*(PR1.JK-TPR1.JK-REJECT1.JK)
N KL1=0

R REJECT1.KL=REJAMT1*PR1.KL
C REJAMT1=0.04

L REJLEV1.K=REJLEV1.J+DT*(REJECT1.JK)
N REJLEV1=0

R TPR1.KL=CLIP(KSIZE/DT,0,KL1.K,KSIZE)
```

```
L PSL1.K=PSL1.J+DT*(TPR1.JK-PR2.JK)
N PSL1=0

* WORKSTATION 2 - PLUG TAMPERS

L PR2USE.K=PR2USE.J+DT*(PR2.JK)
N PR2USE=0

R PR2.KL=MAX(0,CLIP(0,CLIP(0,CLIP(CLIP(CLIP(DPR2.K,0,SP.K,DT*DPR2.K), ^
            0,PSL1.K,DT*DPR2.K),0,KNUM2*KSIZE-PSL2.K,KSIZE), ^
            PR2USE.K,PR2CORR.K),0,SP.K)*(1+STOP.K))
A PR2CORR.K=(1+REJAMT3)*(1+REJAMT2)*(DEMAND)
A DPR2.K=PULSE(NORMRN(MEAN2,SD2),SHIFT*2,SHIFT,DAY)

L KL2.K=KL2.J+DT*(PR2.JK-TPR2.JK-REJECT2.JK)
N KL2=0

R REJECT2.KL=REJAMT2*PR2.KL
C REJAMT2=0.00337

L REJLEV2.K=REJLEV2.J+DT*(REJECT2.JK)
N REJLEV2=0

R TPR2.KL=CLIP(KSIZE/DT,0,KL2.K,KSIZE)

L PSL2.K=PSL2.J+DT*(TPR2.JK-PR3.JK)
N PSL2=0

* WORKSTATION 3 - GTG MACHINES

L PR3USE.K=PR3USE.J+DT*(PR3.JK)
N PR3USE=0

R PR3.KL=MAX(0,CLIP(0,CLIP(CLIP(DPR3.K,0,PSL2.K,DT*DPR3.K), ^
            0,KNUM3*KSIZE-PSL3.K,KSIZE),PR3USE.K,PR3CORR.K))
A PR3CORR.K=(1+REJAMT3)*(DEMAND)
A DPR3.K=PULSE(NORMRN(MEAN3,SD3),SHIFT*2,SHIFT,DAY)
```

```
L KL3.K=KL3.J+DT*(PR3.JK-TPR3.JK-REJECT3.JK)
N KL3=0

R REJECT3.KL=REJAMT3*PR3.KL
C REJAMT3=0.018

L REJLEV3.K=REJLEV3.J+DT*(REJECT3.JK)
N REJLEV3=0

R TPR3.KL=CLIP(KSIZE/DT,0,KL3.K,KSIZE)

L PSL3.K=PSL3.J+DT*(TPR3.JK-PR4.JK)
N PSL3=0

* WORKSTATION 4 - PACKAGING

R PR4.KL=MAX(0,CLIP(0,CLIP(DPR4.K,0,PSL3.K,DT*DPR4.K),FPS.K,DEMAND))
A DPR4.K=PULSE(NORMRN(MEAN4,SD4),SHIFT,SHIFT,DAY)

L KL4.K=KL4.J+DT*(PR4.JK-TPR4.JK)
N KL4=0

R TPR4.KL=CLIP(KSIZE/DT,0,KL4.K,KSIZE)

L FPS.K=FPS.J+DT*(TPR4.JK)
N FPS=0

A WIP.K=SFP.K+SFPOO.K+SP.K+KL1.K+PSL1.K+KL2.K+PSL2.K+KL3.K+PSL3.K+KL4.K


* CONSTANTS - NOTE PRODUCTION RATES ARE IN PARTS/HOUR

C KSIZE=500
C MEAN1=3403
C SD1=1070
C MEAN2=2141
C SD2=275
```

```
C MEAN3=1671
C SD3=276
C MEAN4=3827
C SD4=1713
C SPSTK=0
C KNUM1=18
C KNUM2=11
C KNUM3=25
C KNUMSP=58
C KNUMSFP=150

* PRODUCTION SHIFT SCHEDULE

C SHIFT=7
C DAY=21

* ***** PROGRAM TEST BY CHECKING INDIVIDUAL LEVELS ****

L LEVEL1.K=LEVEL1.J+DT*(TPR1.JK)
N LEVEL1=0
L LEVEL2.K=LEVEL2.J+DT*(TPR2.JK)
N LEVEL2=0
L LEVEL3.K=LEVEL3.J+DT*(TPR3.JK)
N LEVEL3=0
L LEVEL4.K=LEVEL4.J+DT*(TPR4.JK)
N LEVEL4=0


* SYSTEM PARAMETERS

SAVE PR1,KL1,TPR1,PSL1,PR2,KL2,TPR2,PSL2,PR3,KL3,TPR3,
SAVE PSL3,PR4,KL4,TPR4,FPS,WIP
SAVE REJECT1,REJLEV1,REJECT2,REJLEV2,REJECT3,REJLEV3
SAVE RSPR,SFP,SFPOR,SFPOO,DCR,SP,DSPR,PLT
SAVE LEVEL1,LEVEL2,LEVEL3,LEVEL4
SAVE DSHOCK,PR1USE,PR2USE,PR3USE,SFPUSE,TSP,TSFPOO
SAVE NOSP,STOP,PR1START
SPEC DT=.125/LENGTH=300/SAVPER=1/PRTPER=1/PLTPER=1
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VITA AUCTORIS

1966	Born in Jagroan, Punjab, India on December 16th
1984	Completed S.S.H.G. Diploma from the Annex Village Campus, Toronto, Ontario, Canada
1989	Graduated from the University of Toronto, Toronto, Ontario, Canada, with a Bachelor of Applied Science in Industrial Engineering
1991	Currently a candidate for the degree of Master of Applied Science in Industrial Engineering at the University of Windsor, Windsor, Ontario, Canada