ANALYTICAL LOADING MODELS AND CONTROL STRATEGIES IN FLEXIBLE MANUFACTURING SYSTEMS: A COMPARATIVE STUDY

A Thesis
Submitted To The Department Of Industrial Engineering
And The Institute Of Engineering And Sciences
Of Bilkent University
In Partial Fulfillment Of The Requirements
For The Degree Of
Master Of Science

By
Nureddin Kırkavak

June, 1990

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

Assoc. Prof. Cemal Dinçer(Principal Advisor)

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

Prof. Charles Falkner

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Assoc. Prof. Ömer Benli

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ABSTRACT

ANALYTICAL LOADING MODELS AND CONTROL STRATEGIES IN FLEXIBLE MANUFACTURING SYSTEMS : A COMPARATIVE STUDY

Nureddin Kırkavak
M.S. in Industrial Engineering
Supervisor: Assoc. Prof. Cemal Dinçer
June, 1990

There are three problem areas in designing and implementing a *manufacturing line* : the part family selection and grouping, *system configuration and tooling*, and the operational control of manufacturing. The manufacturing process has to be stream-lined by considering resources and products to achieve flow lines operating around product families with acceptable levels of utilization. The stream-lined processes have to be assigned to tandem machines in the manufacturing lines. Then, interactions between production and inventory levels should be controlled at the operational level. Based on this framework, first a system configuration and tooling problem is modeled. The model turns out to be a large mixed integer linear program, so that some alternative optimal seeking or heuristic techniques are used to solve the model for constructing a flow line structured *Flexible Manufacturing System*. *Push* systems of the Material Requirements Planning type or *pull* systems like the base-stock or Kanban schemes are often seen as alternatives for controlling manufacturing systems. The differentiating features of push, pull and a hybrid strategy are studied by discrete event simulation under different system and environmental characteristics for Flexible Manufacturing Systems. The impact of assignment of operations to machines on the performance of the system is also discussed.

Keywords: Flexible Manufacturing Systems, Machine Loading Problem, Mixed Integer Linear Programming, Manufacturing Control Strategies, Simulation, Statistical Analysis.

ÖZET

ESNEK İMALAT SİSTEMLERİNDE YÜKLEME MODELLERİ VE KONTROL STRATEJİLERİNİN KARŞILAŞTIRMALI ANALİZİ

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Tez Yöneticisi: Doç. Cemal Dinçer
Haziran, 1990

İmalat hattı tasarım ve uygulamalarında karşılaşılan üç problem alanı; ürün ailelerinin belirlenmesi ve gruplama, sistemin kurulması ve kesici takımlarla yüklenmesi ve operasyonel imalat kontrolüdür. Kaynaklar ve ürünler göz önüne alınarak üretim süreci kabul edilebilir doluluk oranlarında belli ürün ailelerinin üretimi için çalışan imalat hatlarına ayrılırlar. Üretim sürecinden ayrılan işlemler ilgili imalat hatlarındaki seri makinalara yüklenirler. Daha sonra, üretim ile ara stok seviyeleri arasındaki etkileşim operasyonel seviyede kontrol edilmelidir. Bu yapıya göre öncelikle, *sistemin kurulması ve makinaların kesici takımlarla yüklenmesi problemi* modellendi. Kurulan çok büyük Karışık Tamsayılı model alternatif optimal veya yaklaşık çözüm veren yöntemler ile çözüldüğünde seri akışlı *Esnek İmalat Sistemi* kurulmuş ve kesici takımlarla yüklenmiş olur. Malzeme İhtiyaç Planlamasındaki gibi *itme* ve taban stok veya Kanban tekniklerindeki gibi *çekme* stratejileri imalat sistemlerinin operasyonel kontrolünde alternatif olarak kullanılabilirler. İtme, çekme ve karışık stratejilerin değişik özellikleri benzetim yoluyla Esnek İmalat Sistemleri için değişik sistem ve çevre faktörlerine göre incelenmiştir. Ayrıca, operasyonların makinalara yüklenmesi probleminin sistemin performansına olan etkileri üzerinde de durulmuştur.

Anahtar kelimeler: Esnek İmalat Sistemleri, Makina Yükleme Problemi, İmalat Kontrol Stratejileri, Karışık Tamsayılı Doğrusal Programlama, Benzetim, İstatistiksel Analiz.

To my wife and my parents,

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I would like to extend my deepest gratitude and thanks to my family for their morale support, encouragement, especially at times of despair and hardship. It is to them that this study is affectionally dedicated, without whom it would not be possible.

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1. INTRODUCTION

After fifties, the developments in computer technology have been utilized to control automation in manufacturing industry. The production of numerically controlled machine tools has started *Computer Aided Manufacturing* (CAM). On the other hand. the design and process planning studies required to manufacture a new part are automated by *Computer Aided Design* (CAD) and *Computer Aided Process Planning* (CAPP) systems as a result of increasing graphic and programming capabilities in computers.

After seventies, *Automated Storage and Retreival Systems* (AS/RS) and *Automated Guided Vehicles* (AGV) represent the adoption of computer control for material handling and storage functions. A group of numerically controlled machines equipped with an automated material handling system, which are all operated under computer control, is called a Flexible Manufacturing System.

After eighties, those automation features have been brought together and integrated in a manufacturing system for the concept of *Computer Integrated Manufacturing* (CIM). *Flexible Manufacturing Systems* (FMS) are to be a physical implementation of CIM in manufacturing systems for achieving the efficiency of a transfer line with the flexibility of a jobshop.

In this thesis, the distinctive features of **manufacturing control strategies** for manufacturing systems composed of tandem flexible machines are investigated using sequential optimization and the discrete event simulation. The aim is to explore the potential control capability and to investigate the superiority of pull control strategy for flexible machines under various operating conditions. First, **the system configuration and tooling (loading)** problem is modeled with mixed integer linear programming. Then, the simulation model of the system is developed. The emprical results are obtained from the solutions of the loading problem and the simulated performance measures of hypothetical manufactuing systems generated for experimentation.

The following chapter considers the modeling issues and solution strategies for the loading problem. The first two sections are Introduction and Literature Review. The hypothetical system to be investigated is introduced and mixed integer linear programming formulation is given in the third section. A problem generation procedure and the design of the experiment are also included in this section. Section four discusses solution strategies available for solving this mixed integer linear program. Concluding results are summarized in the succeding section. Modeling extensions are given in the last section of this chapter.

The comparative analysis of manufacturing control strategies is discussed in the third chapter. Introduction and Literature Review are given in first two sections of the chapter. The simulation model and key performance measures are explained and the investigated simulation scenarios are introduced in the third section. The fourth section summarizes all simulation results. The general conclusion on the simulation of manufacturing control strategies is stated in the last section.

Finally, overall conclusion and suggetions for further research will be addressed in the last chapter. The accompanying tables, graphs and figures are collected in the Appendix. References are given at the end of the thesis.

2. ANALYTICAL LOADING MODELS

2.1 Introduction

2.1.1 What is a Flexible Manufacturing System ?

After midfifties, requirements for high precision in manufacturing led to the development of numerically controlled machine tools. Standing in the late seventies, manufacturing systems have been designed and developed using computer control of machine tools to produce mid-sized batches of several different parts attempting to gain both the efficiency of automated mass production and the flexibility of a job shop. These are called Flexible Manufacturing Systems if they have the following main components:

- **Machine Tool :** It requires insignificant set-up time between two operations utilizing different tools on the same machine.
- **Materials Handling System :** It is an automated and flexible system giving alternative material routing opportunuties between components of the system.
- **Computer Control System :** It supports either centralized or decentralized computer control over system components.
- **Resources to be shared by part types :** These are mainly composed of tools, pallets, carriers and fixtures .

The FMS is a result of the evolution of the use of several NC machine tools working independently, into an integrated system of CNC machine tools controlled by a central computer. As a consequence of the automatic tool interchange, the machine set-up time and hence internal set-up costs are small for an FMS, which permit less work-in-process inventory than that of a conventional manufacturing system. Generally, an FMS can process required part types to demand, in lot sizes as small as one.

2.1.2 Production Planning Problems of FMS

The design problems concern how to set up the FMS before production begins in order to make good use of the system capabilities. The typical problems can be listed as follows [23] :

- Part type selection problem,
- Machine grouping problem,
- Production ratio problem,
- Resource allocation problem,
- Loading problem.

In this chapter, we are mostly interested in machine grouping and loading problems before going into the operational problems to investigate different control strategies. First problem is to partition the machines into machine groups in such a way that each machine in a particular group is able to perform the same set of operations. The second problem is to allocate the operations and required tools for part types among the machine groups subject to the technological and capacity constraints of the system.

The general approach to the analysis of loading and operational problems of an FMS can be described pictorially as given in Figure 2.1.

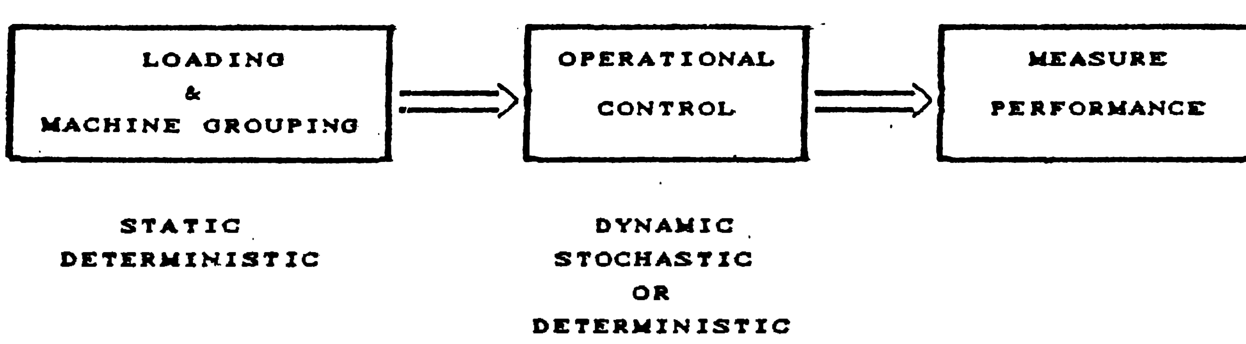

Figure 2.1: The structure of system analysis.

Recall that a solution to the loading problem is an allocation of the total amount of work for processing parts among the machines. A solution to the grouping problem is a particular configuration of the system.

2.2 Literature Review

The loading and scheduling problems in practice are handled in various ways. At present, even for some FMS's, the loading function is performed manually with an aim of finding a feasible solution [23].

Caie and Maxwell [4] have noticed that, "schedulers are usually more interested in generating a feasible part-to-tool assignment that satisfies demand ..... . A scheduler's main objective is to level the load between identical machine tools so that no machine tool is over-capacitated and demand is satisfied".

Stecke [23] have noticed that, "for systems that are simple to be able to utilize a more sophisticated loading procedure, the usual practice in industry is to balance the assigned workload among the machines ...". Software packages have been developed by several computer companies to help a shop manager perform his planning and/or control functions.

A common complaint of industrial practitioners is that theoretical approaches to their problems fall short in realism or are impractical. Analytical approaches to workload assignment methods and loading procedures will now be examined for their relevance to our research. The loading problem is defined as the allocation of given part types (or operations) to machines with limited slots in each tool magazine to minimize the number of machines required [23].

The loading problem could be viewed as a bin packing problem, Coffman et. al. [6]. One version of the problem has been found to be equivalent to the assembly line balancing problem, Greene [11], Magazine and Wee [18]. These versions of the loading problem have been shown to be NP-Complete [7].

There are many proposed procedures and algorithms which either attempt to balance or advocate balancing the workload within the job-shop environment. In these studies, it is assumed that each operation is assigned to one and only one machine.

The balancing problem in deterministic flow lines is known as the assembly line balancing problem and is stated as : given a production rate or cycle time, what is the minimum number of workstations needed without violating the constraints of the problem [11]. Application of an assembly line balancing algorithm results in a one-to-one assignment of operations to machines. The possibilities of pooling or duplication of an operation assignment, or multiple manning be largely ignored. However, Wild and Slack [29] examine the benefits from the merging of two equivalent single flow lines into a one double line, with two servers at each station. They found that the double flow line reduces machine idle time. Kleinrock [15] shows that M pooled servers are more efficient than M individual parallel servers. Conway, Maxwell and Miller [8] stated that multiple job routes and machine flexibility reduces the machine congestion and queue lengths.

FMS loading problems have brought attention to many researchers after eighties. Stecke and Solberg [24] presented five different loading policies for an existing FMS. An impact of these policies on machine scheduling is discussed. Detailed non-linear integer programming formulations of this problem are presented by Stecke [25]. These grouping and loading problems are solved through linearization approaches [25] or heuristics by Stecke and Talbot [26]. A variety of objectives are considered regarding workload, material movement, tool magazine utilization and operation priorities. Those models include a set of constraints related to a limited space of a tool magazine. Kusiak [17] introduced an additional set of tool life and part assignment constraints.

Ammons et. al. [1] developed a loading model which minimizes a number of operation-to-machine assignments while balancing the workload. The developed model is solved with three variants of the objective function. Chakravarty and Shtub [5] linked the concept of grouping parts and machines with the loading model. For one particular loading problem, Berrada and Stecke [2] developed a solution procedure to solve the non-linear integer loading problem directly.

Stecke [27] ties some previous results together by suggesting a hierarchical approach to solve actual grouping and loading problems. The actual grouping is done by modeling the problem as an optimal k-decomposition of weighted networks by Kumar et. al. [16]. Algorithms which are suitable for computer implementation and large problems are developed. Bounds on algorithm performance are constructed to give an estimate of the quality of the generated solution. Greene and Sadowski [12] solved loading and scheduling problem with a mixed integer program. Several objective functions are considered. Also, there is a discussion on the increasing number of variables and constraints necessary to solve the problem for a real sized system.

2.3 Model Development

2.3.1 Problem Statement : System Configuration and Tooling

Consider a manufacturing system composed of M machines and N different part types to be processed in that system. Suppose material handling, storage and computer control problems are solved. These are the main components of the system. Tools are required to process the parts on the machines. So, one problem is to assign tools to machines. Then, we have to assign operations of parts to the machines that possess the required tool. Therefore, we have three different sets of components to deal with. If we bring all operations required to process all parts together, we obtain the set of operations. For a specific part type, there may be alternative feasible sequences of operations for processing on machines. The feasibility of operation sequences are supplied by priority relations between operations. These alternative operation sequences increase the processing flexibility of the system. Then we have the set of machines composed of all machines in the system. They may have different set of manufacturing characteristics. The last set is the set of tools. This set is the link between operations and machines for assignment. Because, an operation can not be assigned to a machine if the required tool is not available on that machine.

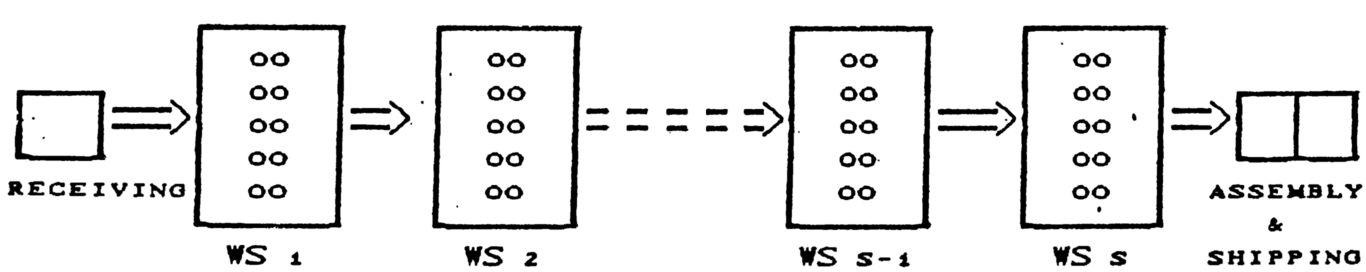

Figure 2.2: The system configuration of the original problem.

The original problem is to find an acceptable assignment of operations and tools to machines so that grouped or pooled machines construct tandem workstations. Parts can be processed on alternative machines in a workstation. Increasing the number of alternative machines in a wokstation, increases the machining flexibility of the workstations. The configuration of the system is given in Figure 2.2.

2.3.2 Problem Formulation

It is important to start with the simplest formulation of the problem. Suppose there are M machines, each one of them is assigned to a unique workstation. So, there are M number of machines and corresponding M number of workstations in the system. There are N number of different part types to be processed. Part type i requires O_i number of operations to be a complete part and ready for the assembly.

Suppose all machines are identical with the same magazine capacity, C slots per magazine. Note that, in real life all operations could not be performed in all machines. For any operation, there may be a feasible subset of all machines in which the operation could be performed. V_i is the production volume of part type i, in a period of time in which there are T time units of production planned. P_{ij} is the processing time, in time units required for the j th operation of the i th part to be processed in the system. Machine blocking set-up times are included in processing times. S_{ij} is the space requirements on the magazine in terms of slots required for the tools used in the j th operation of the i th part. X_{ijm} is a binary variable showing the assignment of j th operation of i th part to the m th machine. Several objectives could be found related with the selected performance criteria. One such simple, linear and practically interesting objective is to maximize the minimum machine utilization. The system configuration of the primary model is given in Figure 2.3.

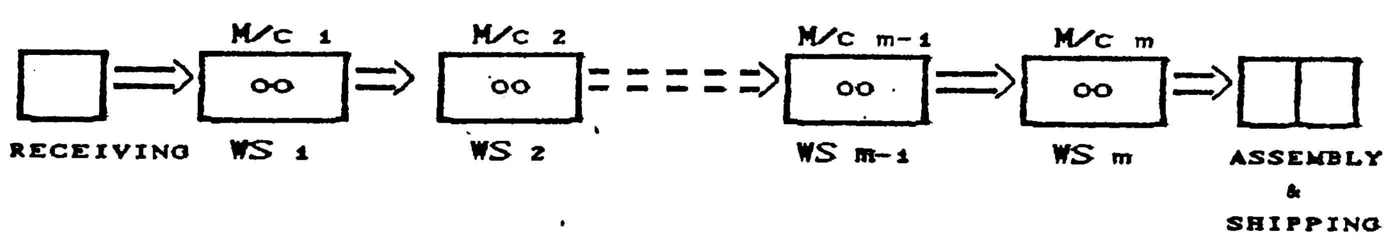

Figure 2.3: The system configuration for the primary model.

Assuming there is only one part type, the problem reduces to deterministic line balancing problem. Otherwise, it is a mixed integer linear program as follows :

$$\text{Maximize} \qquad Z_0 = Z$$

Subject to

$$\sum_{i=1}^{N}\sum_{j=1}^{O_i}\frac{X_{ijm} * P_{ij} * V_i}{T} \geq Z \qquad \forall m = 1..M \qquad (1)$$

$$\sum_{i=1}^{N}\sum_{j=1}^{O_i} X_{ijm} * S_{ij} \leq C \qquad \forall m = 1..M \qquad (2)$$

$$\sum_{m=1}^{M}(X_{ijm} - X_{i(j+1)m}) * m \leq 0 \qquad \forall i = 1..N \quad \forall j = 1..O_i - 1 \qquad (3)$$

$$\sum_{m=1}^{M} X_{ijm} = 1 \qquad \forall i = 1..N \quad \forall j = 1..O_i \qquad (4)$$

$$X_{ijm} \ \textit{is Binary} \quad \& \quad Z \geq 0 \qquad \forall i = 1..N \quad \forall j = 1..O_i \quad \forall m = 1..M \qquad (5)$$

In this model, Z denotes minimum target machine utilization in the system. Note that, objective functions considered in previous formulations of loading problem are almost non-linear. This formulation differs from the previous studies with the linear **maximin** objective. In the first constraint, Z should not exceed the assigned workloads of the machines. Second constraint is for the magazine capacity of the machines. In this formulation of the model, the tool duplications are not considered. Third constraint requires, the operations of a part type to be assigned in a flow line structure to the machines. This is another distinguishing feature of this formulation in loading a manufacturing line. That is, after the completion of j th operation of a specific part, $(j+1)$ st operation of the same part can be assigned either to the current machine or to the succeeding machines along the line. For all parts, one way flow of processing is allowed along the production line. Note that, allowing alternative flows of operations for processing in the system, increases the flexibility but this makes the control of the system much more difficult. And, fourth constraint assures one-to-one assignment of all operations of all parts to the machines in the system. Since, Z is a measure for minimum planned machine utilization, a value for Z that is greater than one shows the need for overtime at all machines. Finally, X_{ijm} is a binary decision variable showing the assignment decision of j th operation of i th part type to the m th machine.

In this model there are 1 nonnegative and ($M * \sum_{i=1}^{N} O_i$) binary variables together with ($2 * M + 2 * \sum_{i=1}^{N} O_i - N$) constraints. For moderate values of M, N and O_i the resulting problem may become computationally prohibitive in finding optimal solution. Therefore, some computationally more tractable solution procedures must be developed to attack real size problems.

2.3.3 Problem Generation

A software package is designed to test the solution capability of primary formulation for the system configuration and tooling problem with a built-in random problem generation mechanism. By the help of this software some test problems are generated and solved both by a commercially available large scale Mathematical Programming System and heuristics which are exclusively designed to solve larger problems.

In the generation procedure of problems a standard random number generator is used. That makes possible to generate the same problem by using the same input parameters if need arises. There are two kinds of input parameters to generate the system configuration and tooling problem. The first group of parameters is composed of constants which define the general characteristics of the problem. Those parameters are as follows :

- Number of machines in the system,
- Number of part types in the system,
- Machine magazine capacity in terms of slots,
- Total available time units in a planning period,
- Planned capacity utilization, required to determine the maximum throughput of the system, with generated production ratios.

The second group of parameters is some distribution parameters for the required data of the problem. The data are generated uniformly with specified lower and upper limits. The distribution parameters are as follows :

- Upper and lower limits on the number of operations required to complete a specific part type,
- Upper and lower limits on processing times of operations in time units,

- Upper and lower limits on slot requirements of tools in the system,
- Upper and lower limits on production ratios of part types.

The procedure utilized to generate the test problems is described in the flow chart given in Figure 2.4. To gain an insight in solving system configuration and tooling problem we have designed and evaluated experiments. Three control groups are considered in these experiments. Each control group is composed of several problems with similar characteristics. All problems in each control group are generated using the same random number seed, planned capacity utilization (average machine utilization) and average machine magazine utilization. The problems in each control group are comparable in size.

- **Control Group 1** problems are composed of 2-3 machines and 8-16 part types. The average number of operations of a specific part type is increased from 5 to 20 in increments of 5. There are 16 different problems in this control group. These problems are relatively computationally easier due to simplicity of machines configuration. The general parameters and the sizes of the formulations of problems are tabulated in Table A.1 in the Appendix.
- **Control Group 2** problems are composed of 4-5 machines and 5-10 part types. The average number of operations of a specific part type is increased from 5 to 20 in increments of 5. There are again 16 different problems in the second Control Group. These problems are relatively more complex, due to configuration, than previous group. The general parameters and the sizes of the formulations of problems are tabulated in Table A.2 in the Appendix.
- **Control Group 3** problems are composed of 6-7-8 machines and 3-6 part types. The average number of operations of a specific part type is increased from 5 to 20 in increments of 5. There are 24 problems in this control group. Relatively the most complex problems are in this group. The general parameters and the sizes of the formulations of problems are tabulated in Table A.3 in the Appendix.

2.4 Solution Strategies

2.4.1 Optimal Seeking Solution Technique

The experimentation started with solving Control Group 1 problems on the main frame *Data General MV/2000* by using **SCICONIC/VM V1.47**. This is a professional

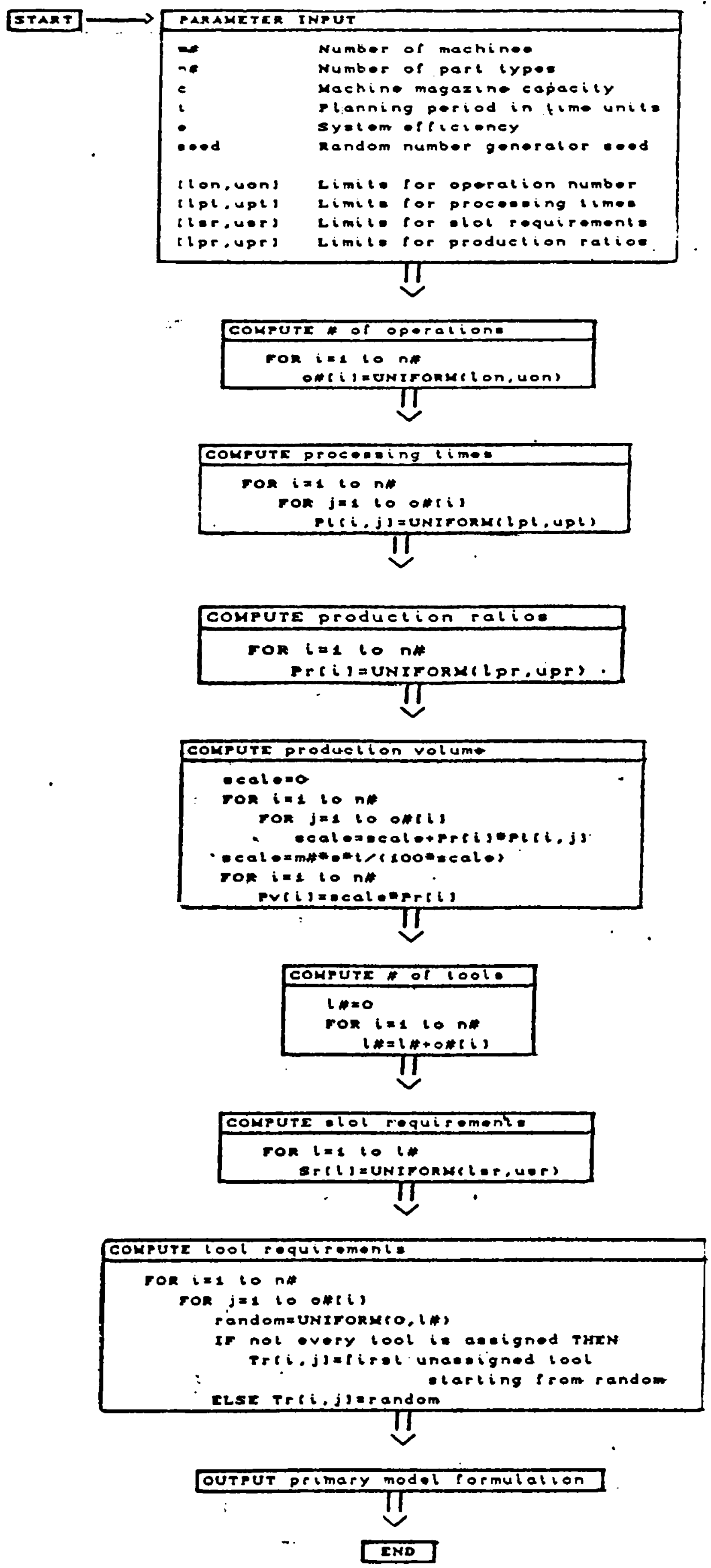

Figure 2.4: The flowchart of the problem generation procedure.

mathematical programming code for solving linear and non-linear programming problems. This code utilizes the *Branch & Bound* technique in solving integer programming problems. In all problems, since the formulation is maximization type, optimal linear solution is an upper bound on the optimal integer solution. An integer solution which has an objective value greater than 99 % of the upper bound is considered to be sufficient to stop branching. Also, the maximum number of iterations allowed in the branch and bound technique is 50000.

All problems of the first group could be solved with a 1 % maximum deviation from the upper bound in less than 50000 iterations. A total of 90 minutes of CPU Time is elapsed, to solve 16 problems in this group. Optimal linear solutions are obtained in less than 5 minutes. 30 minutes more is required to obtain the initial integer solutions. An additional 55 minutes is elapsed for improving initial integer solutions. On the average, 3 % improvement is attained in the objective functions. The details of the solutions are tabulated in Table A.4 in the Appendix.

For three problems of the second control group, the code was not able to find an initial integer solution in 50000 iterations. For other problems, the average deviation from the upper bound is 13 %. In solving these problems, a total of 9 hours of CPU Time is elapsed. Only 6 minutes of this amount is utilized for obtaining optimal linear solutions. More than 3 hours is required, to obtain initial integer solutions. Nearly 6 hours is elapsed for improving initial integer solutions to the best solutions found. An average of 9 % improvement is attained in the objective functions. The details of the solutions are tabulated in Table A.5 in the Appendix.

We conclude that, for moderately large problems acceptable feasible solutions could be found in reasonable time, but it takes too much time to improve the initial solutions or prove the optimality of the solutions.

2.4.2 Heuristic Loading Rules

There are some heuristic solution techniques to be used in obtaining an acceptable solution for the system configuration and tooling problem. All these heuristic solution techniques are myopic in the sense that they are one pass algorithms and they choose an operation from a subset of all operations with a given rule. The set of available operations consists of operations that have no unassigned preceeding operation. If an available operation finds enough empty slots on the current machine magazine, then this operation is called a feasible available operation.

The heuristics choose an operation from the feasible available operation set by considering the given criteria. Workloads and magazine capacities are the two restrictions of the problem during the solution. Heuristic solution rules differ in two points. The first is the selection criteria and the other is the maximum workload to shift the assignments to the next machine in the manufacturing line.

HEURISTIC # 1 : Select the operation from feasible available set of operations that minimizes the absolute difference between two ratios :

$$RATIO\#1 = \frac{Current\ Workload + Operation\ Processing\ Requirement}{Target\ Workload}$$

$$RATIO\#2 = \frac{Loaded\ Slots\ In\ Current\ Magazine + Operation\ Slot\ Requirement}{Target\ Magazine\ Utilization * Magazine\ Capacity}$$

The machines are loaded up to a limit where the absolute deviation of the current workload of the machine from target workload could not be less than the previous value of that absolute deviation by assigning more operations to the current machine.

HEURISTIC # 2 : Select the operation from feasible available set of operations as it is in Heuristic # 1, and load the machines up to target workload.

HEURISTIC # 3 : Select the operation from feasible available set of operations that minimizes the absolute difference between two ratios :

$$RATIO\#1 = \frac{Remaining\ Workload - Operation\ Processing\ Requirement}{Total\ Processing\ Requirement}$$

$$RATIO\#2 = \frac{Remaining\ Slot\ Requirements - Operation\ Slot\ Requirement}{Total\ Slot\ Requirements}$$

The machines are loaded up to a limit where the absolute deviation of the current workload of the machine from target workload could not be less than the previous value of that absolute deviation by assigning more operations to the current machine.

HEURISTIC # 4 : Select the operation from feasible available set of operations as it is in Heuristic # 3, and load the machines up to target workload.

BEST STRATEGY : Apply all four heuristics to the problem, then select the best solution obtained that gives the maximum of minimum workloads assigned to the machines.

Note that, if the selection of operations gives an infeasible assignment to the machines, then increase the target workload by some amount and reapply the same heuristic technique. Also, in some problems, heuristic solution techniques may not give feasible solutions at all.

2.5 Concluding Results

The system configuration and tooling problem is formulated and solved utilizing both optimal seeking and heuristic solution techniques. The solutions of optimal and heuristic techniques are evaluated by utilizing both **parametric** (Paired-t test with normality assumption) and **non-parametric** (Wilcoxon signed-rank test) tests with appropriate hypotheses. In all cases, both statistical tests resulted in the same decision. The solutions obtained from the primary formulation of the problem give a flow line structured Flexible Manufacturing System. Operational level machining flexibility is related with the number of alternative flows of processing of a specific part type in the system. Alternative flows of processing of operations is not allowed in a flow line structured flexible manufacturing system but this reduces the complexity of the control and scheduling problems in the system.

It takes substantial CPU time to solve the problem optimally. For relatively complex and large problems, after obtaining an initial feasible integer solution, convergence to optimal solution is too slow. If the workloads could be balanced within a predetermined range, it may suffice to use that solution.

- **CONTROL GROUP 1 :** An improvement of 3 % on the average, is realized over the initial integer solution by utilizing an optimal seeking *Branch & Bound* procedure. Solutions obtained by best strategy on the average are within 4 % of the optimum (or best if 50000 iterations exceeded) solutions. There is no definite dominating heuristic solution technique. Solutions obtained by heuristics 3 and 4 are significantly worse than the initial integer solutions of optimal seeking algorithm. On the other hand, best integer solution is significantly better than solutions of all four heuristics and the best strategy. Solutions of heuristics 1, 2 and the best strategy could be treated as equivalent to initial integer solutions of optimal seeking algorithm. For more detail on statistical tests, see Table A.6 and A.9 in the Appendix.

- **CONTROL GROUP 2 :** An improvement of 11 % on the average, is realized over the initial integer solution by utilizing an optimal seeking *Branch & Bound* procedure. The best solutions found are 13 % on the average less than the solutions given by LP relaxation. That shows the computational complexity of this group. Best strategy on the average gave 4 % better solutions than the best solutions obtained (in 50000 iterations of the Branch & Bound Algorithm). There is no definite dominating heuristic solution technique. Except heuristic # 1, all other heuristics gave significantly better solutions than initial integer solutions obtained by optimal seeking technique. In comparison to the best solutions attained by Branch & Bound procedure, heuristic 1 is significantly worse and the best strategy is significantly better. Other heuristics gave equivalently acceptable solutions with optimal seeking solution technique. For more detail on statistical tests, see Table A.7 and A.10 in the Appendix.

- **CONTROL GROUP 3 :** Only heuristic solution techniques are used in this control group, since the CPU time requirement of optimal seeking solution technique becomes unreasonably high. The heuristic solutions found are 8 % on the average less than the upper bound given by LP relaxations. The numerical data of the solutions are tabulated in Table A.8 in the Appendix. For three of the problems in this control group workloads could not be balanced well. These are the smallest sized problems in this group. During the generation of the problems, decreasing the total number of operations and at the same time keeping average machine and magazine utilizations close to a target value result in artificial problems which are away from reality. The relative reduction in the average number of operations per machine negatively affects the balance of the workloads.

Considering all problems of control group 1 and 2 as a pooled control group, some conclusions could be stated :

- Applying all heuristic techniques and then selecting the best solution, result in significant improvements.
- There is no significant difference between initial integer solution and solution of any one of the heuristics.
- Applying all heuristic techniques and then selecting the best solution, is equivalently as good as the best solution obtained by optimal seeking solution technique (in 50000 iterations).
- Best integer solutions found by optimal seeking solution technique (in 50000 iterations) are significantly better than the individual solutions obtained by all heuristics.
- There is no dominating heuristic rule.

Related statistical tests are tabulated in Table A.11 in the Appendix. Average power statistics for tests of hypothesis are summarized in Table A.12 in the Appendix.Note that, in statistical tests rejection decisions are more powerful than acceptance decisions.

The performance of heuristic solution rules is even better for larger problems. A medium sized machine configuration and tooling problem is generated with parameters of 10 machines, 15 part types and 12 operations on the average by utilizing 10 different random number generation seeds. Best strategy gave solutions within 2 % on the average from the upper bound of the problem. Heuristics 2 and 4 is better than the other two on the average. The numerical data of the solutions are tabulated in Table A.13 in the Appendix.

As a result, heuristic rules, in most cases, could safely be used instead of solving the current formulation of the system configuration and tooling problem by optimal seeking solution techniques such as Branch & Bound.

2.6 Model Extensions

The primary formulation of the system configuration and tooling problem is the simplest representation of the reality. It should be extended to cover some real life features of the problem. The size of the formulation increases with the addition of new features. This makes the extended formulation more complicated and difficult to solve yet more realistic.

In the primary model formulation, all machines are assumed to be identical with the same magazine capacity, C . Different machine magazine capacities could be incorporated into the model by using C_m instead of C in the primary model fomulation. Here, C_m is the machine magazine capacity of the m th machine.

Tool duplications are allowed in this formulation. Tool duplication occurs, when two operations requiring same tool assigned to the same machine. Incorporating the tool duplication problem both the number of binary variables and constraints increase. Let us separate the set of operations into two : operations that do not use the same tool with some other operations and operations that share the same tool with some other operations. D_{ij} is a matrix of binary parameters indicating either the j th operation of i th part shares the tool if the binary parameter value is zero or otherwise that operation does not share any tool. Suppose Y_{lm} is a binary variable representing the assignment of l th tool to the m th machine in the system. There are L number of different tools available. Additionally, E_l is a binary parameter showing either the tool l is required by only one operation if the value is zero, or that tool is utilized by more than one operation if the value is one. R_l is the number of slots required on the magazine by the l th tool. W_l is the number of operations using l th tool, that is, the total number of operations is ($\sum_{l=1}^{L} W_l$) . In summary, assign any tool sharing operation to a machine if the required tool is available on that machine. So, the assignment decision is extended to cover the assignment of sharing tools to the machines.

There is also, only one sequence of operations for processing in the system. It is possible to consider alternative sequences of operations. During the process planning stage of a part type, precedence relations between operations are set. This information could be summarized in a matrix of binary parameters of a specific part. If operation j_1 of part i should be processed before operation j_2 of part i, then $Pre_i(j_1, j_2)$ has a value of 1, otherwise zero. For all pairs of operations having 1 in precedence matrix, there are $(m-1)$ number of corresponding constraints for not violating the precedence relations.

Primary model formulation considers maximization of minimum machine utilization as the objective. If the average machine utilization is low, then minimizing the difference between the maximum and the minimum machine utilizations would be a better objective resulting a more balance in loading of the machines. This objective could be formulated by minimizing the difference between two linear variables. First variable, should exceed all assigned workloads to the machines and second variable, should not exceed all assigned workloads to the machines.

Modified formulation of the system configuration and tooling problem then becomes :

$$Minimize \quad Z_0 = Z_1 - Z_2$$

Subject to

$$\sum_{i=1}^{N}\sum_{j=1}^{O_i} \frac{X_{ijm} * P_{ij} * V_i}{T} \leq Z_1 \qquad \forall m = 1..M \qquad (1)$$

$$\sum_{i=1}^{N}\sum_{j=1}^{O_i} \frac{X_{ijm} * P_{ij} * V_i}{T} \geq Z_2 \qquad \forall m = 1..M \qquad (2)$$

$$\sum_{i=1}^{N}\sum_{j=1}^{O_i}(X_{ijm} * S_{ij} * D_{ij}) + \sum_{l=1}^{L}(E_l * Y_{lm} * R_l) \leq C_m \qquad \forall m = 1..M \qquad (3)$$

$$\sum_{(i,j)\in J(l)} X_{ijm} - Y_{lm} * W_l \leq 0 \qquad \forall l = 1..L \qquad (4)$$

$$\forall m = 1..M$$

$$\sum_{m=1}^{M} Y_{lm} \leq W_l \qquad \forall l = 1..L \qquad (5)$$

$$Pre_i(j_1, j_2) * \sum_{m=1}^{M} m * (X_{ij_1m} - X_{ij_2m}) \leq 0 \qquad \forall i = 1..N \quad \forall j_1 = 1..O_i \quad \forall j_2 = 1..O_i \qquad (6)$$

$$\sum_{m=1}^{M} X_{ijm} = 1 \qquad \forall i = 1..N \quad \forall j = 1..O_i \qquad (7)$$

$$X_{ijm} \,\&\, Y_{lm} \text{ is Binary and } Z_1 \,\&\, Z_2 \geq 0 \qquad \forall i = 1..N \quad \forall j = 1..O_i \quad \forall m = 1..M \quad \forall l = 1..L \qquad (8)$$

Where $J(l) = \{ (i,j) :$ if j th operation of i th part uses l th tool for processing. $\forall i = 1..N \,\&\, \forall j = 1..O_i \}$

The objective function is modified for minimizing the difference between maximum and minimum machine utilizations. First two constraints put an upper and lower bound on the machine utilizations. The modification to allow different machine magazine capacities is reflected in the third constraint. This constraint also avoids the duplication of tools. Then fourth and fifth constraints are added to dictate the assignment of tools and operations to the machines. The sixth constraint is modified to consider alternative sequences of operations in assignment. Also, there are additional binary tool assignment variables in this formulation.

The hidden objective behind maximizing minimum machine utilization or minimizing the difference between maximum and minimum machine utilizations, is balancing the workload between machines equally. An alternative objective could be to minimize the number of parts processed on different machines while keeping the balance of the workloads in an acceptable range. The hidden objective in this case is minimizing the number of intermediate buffers between machines to reduce the total inventory cost.

Suppose, Z_{im} is an additional variable showing some of the operations of i th part performed on m th machine if it takes a value of 1 and zero otherwise. A new constraint is required to assure the assignment of parts to machines in the system for some of their processing requirements.

The resulting altenative formulation of the system configuration and tooling problem is as follows :

$$Minimize \quad Z_0 = \sum_{i=1}^{N} \sum_{m=1}^{M} Z_{im}$$

Subject to

$$\sum_{i=1}^{N} \sum_{j=1}^{O_i} \frac{X_{ijm} * P_{ij} * V_i}{T} \leq K_{max} \qquad \forall m = 1..M \qquad (1)$$

$$\sum_{j=1}^{O_i} X_{ijm} \leq Z_{im} * O_i \qquad \forall m = 1..M \quad \forall i = 1..N \qquad (2)$$

$$\sum_{i=1}^{N} \sum_{j=1}^{O_i} (X_{ijm} * S_{ij} * D_{ij}) + \sum_{l=1}^{L} (E_l * Y_{lm} * R_l) \leq C_m \qquad \forall m = 1..M \qquad (3)$$

$$\sum_{(i,j) \in J(l)} X_{ijm} - Y_{lm} * W_l \leq 0 \qquad \forall l = 1..L \quad \forall m = 1..M \qquad (4)$$

$$\sum_{m=1}^{M} Y_{lm} \leq W_l \qquad \forall l = 1..L \qquad (5)$$

$$Pre_i(j_1, j_2) * \sum_{m=1}^{M} m * (X_{ij_1m} - X_{ij_2m}) \leq 0 \qquad \forall i = 1..N \quad \forall j_1 = 1..O_i \quad \forall j_2 = 1..O_i \qquad (6)$$

$$\sum_{m=1}^{M} X_{ijm} = 1 \qquad \forall i = 1..N \quad \forall j = 1..O_i \qquad (7)$$

$$X_{ijm} \ \& \ Y_{lm} \ \& \ Z_{im} \quad is \quad Binary \qquad \forall i = 1..N \quad \forall j = 1..O_i \quad \forall m = 1..M \quad \forall l = 1..L \qquad (8)$$

The objective function is altered for minimizing the number of parts processed on different machines. First constraint does not allow a machine to be overloaded since K_{max} is the maximum capacity utilization ratio. Second constraint assigns parts to machines. All other constraints of the formulation remain the same as in the modified formulation of system configuration and tooling problem. Also, there are additional binary part assignment variables in this formulation.

3. MANUFACTURING CONTROL STRATEGIES

3.1 Introduction

In manufacturing systems the strategy of keeping inventory at the minimum possible level has been recognized to be very important during the past few years. This interest has been created by the recently well publicized successes of Japanese production management techniques. The most well-known Japanese technique is *kanban* control technique implemented within the *Just-in-time* philosophy. To date, the succesfull applications of the JIT concept in Japan that have been reported are mainly for large scale assembly line operations.

The purpose of this research is to explore the potential of the pull aspect of JIT philosophy for scheduling and to compare the effectiveness of pull to the traditional push and to a hybrid control strategy *CONWIP* - constant work-in-process.

In push systems. jobs are released to the first stage to be processed, and this stage pushes the work-in-process (WIP) to the following stage and so forth until the product reaches the final stage. A forecast demand, including the allowances for lead times, is determined for each stage of the production process. The push system is thus controlled through the inventory levels at each stage in the system. An inaccurate forecast, in most cases, is overcome by the WIP inventory levels which are often inflated to include the safety stocks. This can result in unnecessarily high carrying costs. The reliance on the WIP and on-hand inventories is the primary drawback of the push strategy.

On the other hand. the Japanese pull system is designed to minimize work-in-process inventory levels and its fluctuations. This simplifies inventory controls, prevents amplified transmission of demand fluctuations from stage to stage and raises the level of shop control through decentralization. In pull systems, the succeeding stage demands and withdraws work-in-process units from the preceeding stage only at its consumption rate of the items. The ideal pull system with one unit of inventory at each stage is hardly achievable in a real manufacturing system, where a variation in processing times, imbalance of workloads between stages, demand fluctuations and machine breakdowns are inevitable.

A new pull based production system that possesses the benefits of a pull system and can be used in a wide variety of manufacturing environments is called CONWIP. In CONWIP systems, jobs are pulled into the production environment whenever an earlier job is completed and are then pushed between stages. Thus a production system operating under CONWIP strategy is a closed system.

In a sequential production line, the higher work-in-process inventory incurs cost, but it is capable of absorbing the shock of uncertainty from sudden machine breakdowns, high variation of processing times at different stages and the like. In other words, it is well accepted that these intermediate buffers increase the efficiency of the line.

In an ideal situation, the processing times at various stages are usually assumed constant and equal for a balanced production system. For such a system, the production line runs at 100 percent efficiency and the need for work-in-process inventory is zero when the system experiences no machine breakdowns.

Most of the systems in real life have complex characteristics so that it would be difficult to represent the system with an analytically tractable mathematical formulation. Even in some cases, simulation is the only tool in modelling and analysis of the systems. In Flexible Manufacturing Systems, simulation can be used to test the layout of the system and to study the effects of different control strategies, scheduling priority rules, breakdown scenarios and maintenance schemes. In this chapter, the comparative analysis of hypothetical manufacturing systems will be conducted with the help of a simulation model.

3.2 Literature Review

During the past three decades, the general sequential production line has been studied by many researchers. Most of these research studies use simulation as a tool to investigate the effects of some system parameters on the performance of the system.

In the last decade, the concept of Just-In-Time (JIT) technique has been the main focus of the poduction literature. But, very few researchers have performed analytical studies on pull systems. A review of these studies reveals that only two-or-three stages are analytically analyzed or simulated. Also, some of the findings are contradictory such as the placement of a bad stage in a production line [13]. Freeman [10] suggested that a bad (bottleneck) stage should be surrounded by good stages and a large buffer should be placed close to that stage. On the other hand, Sheskin [21] found analytically that a bad stage at the beginning or at the end of the line has little effect in case of symmetric lines with reliabilities arranged in increasing or decreasing order.

Research reported on the measurement of performance of a pull system or on its performance comparison with a push system is sparse. A unitary scheme in order to interpret and classify. with push and pull logic, and some application conditons have been considered in De Toni et. al. [9].

Spearman and Zazanis [22] offer theoretical motivations for the apparent superior performance of pull systems. They consider three conjectures:

1. Pull systems have less congestion,
2. Pull systems are inherently easier to control,
3. The benefits of a pull environment owe more to the fact that WIP is bounded than to the practice of *pulling* everywhere.

Woodruff et. al. [30] have described a pull based production control strategy called CONWIP that offers the possibility of significant improvements over other production control strategies. Karmarkar [14] has compared the procedural distinctions between push and pull systems. He noted that some pull systems actually have a push component inside.

Rees et al. [19] state that " The Japanese have demonstrated in the market place the superiority of a JIT with a Kanban system that includes reduced set-up times and costs and group technology. Many Non-Japanese companies have jumped on the Kanban **band-wagon** in the hope of remaining competetive. Companies that can not implement the group technology portion of JIT may very well be better off remaining with MRP and reducing setup costs and times within that system ".

Sarker and Fitzsimmons [20] have identified some characteristics of the pull system regarding its efficiency and the role of WIP inventory. They observed that a pull system is always better at minimal WIP levels, but on the other hand its throughput is less than the push system.

Note that, simulation analysis is an indispensible tool in designing complex systems. Discrete event simulation is a natural candidate for modeling Flexible Manufacturing Systems in which state changes occur at discrete points in time [28]. The simulation model represents the detailed operation of the system through a computer program which executes each event that would occur in the system. So, simulation modeling and analysis permits controlled experiments on complex systems.

3.3 Simulation Model

3.3.1 System Configuration

A manufacturing system with M identical and flexible machines working in series is selected. N different part types have to be processed in this hypothetical system. Part type i requires O_i number of operations to be a complete part and ready for the assembly. Machines have identical magazine capacities of C slots. For any operation, there may be a feasible subset of all machines on which the operation could be performed. V_i is the production volume of part type i in a period of time in which there are T time units. P_{ij} is the processing time in time units required for the j th operation of the i th part to be processed in the system.

3.3.2 Model Development

A comprehensive series of simulation experiments are designed to investigate the performance of push, pull and conwip control strategies on sequential production line composed of flexible machines. The problem generator introduced in Section 2.3.3, is used to generate data for different systems with different parameters. Recall that, the set of parameters associated to the problem generation is as follows:

- Number of machines,
- Number of part types,
- Distribution for the number of operation per part type,
- Capacity of the tool magazine (for all machines),
- Distribution for processing times,
- Distribution for production ratios,
- Distribution for space requirements of tools on the magazines,
- Planned capacity utilization,
- Planning period length,

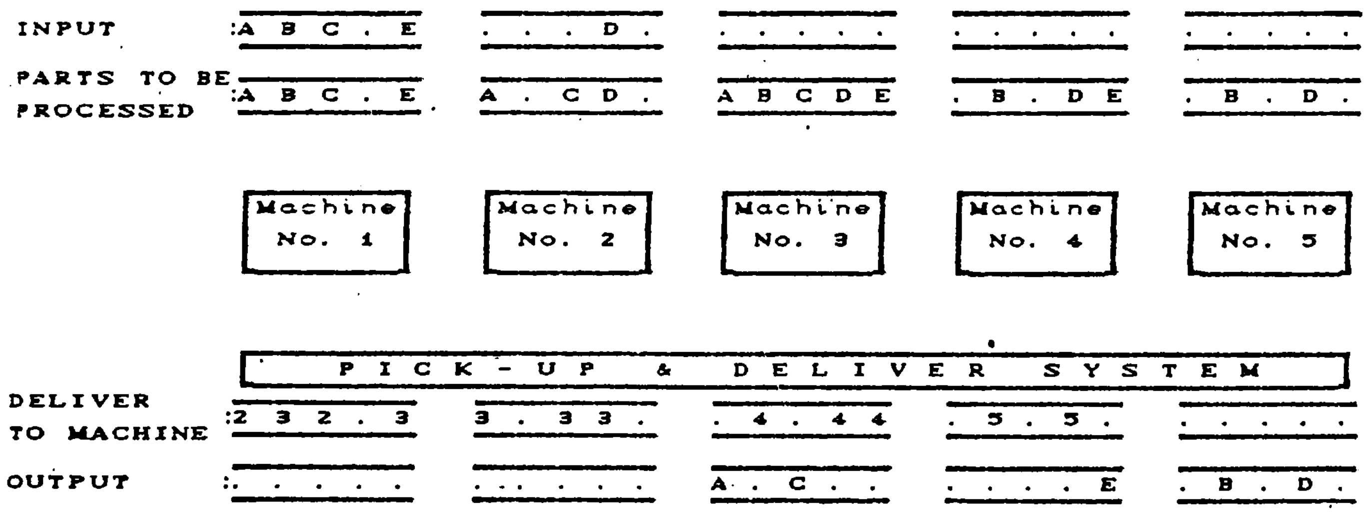

Figure 3.1: The layout of the hypothetical system.

Uniform distribution is assumed for all distributions required, since there is a lack of statistical data to determine on the input distribution type. The hypothetical system in Figure 3.1 is generated using the parameters in input file given in Figure A.1 in the Appendix. The data of the generated system can be found in Figure A.2 in the Appendix. There are some assumptions related with the operation (model) of that system :

- A part follows a unique sequence of operations. So, there is no operation flexibility of part types.
- In *system configuration and tooling (loading) problem* no alternative machine assignments are considered. All operations have to be assigned to a unique machine in the system. So, parts have no routing flexibility.
- Planning decisions related with the operation of the system are carried out periodically.
- Material handling times are supposed to be negligable compared to processing times. So. no material handling system is included in the model.
- A batch cannot be released at a machine for processing before all units are processed at the previous stage.
- There is no physical limitation on buffer storages.
- Initial input buffers are assumed to be infinite.

- When a break-down occurs at any stage, the loaded part continues its processing after repair.
- For all input buffers of the machines, *First-Come-First-Served* (FCFS) queue discipline is assumed.

Note that, eight types of flexibilities are defined for manufacturing systems in Browne et. al. [3]. These are machine, process, product, routing, volume, expansion,operation and production flexibilities. The hypothetical manufacturing system under consideration has no routing and operation flexibilities because of the assumptions in the formulation of the associated loading problem. All other flexibilities are achievable.

The set of operations in all generated problems could be assigned to machines by some optimal or heuristic procedures discussed in Section 2.4. A sample output of heuristic procedure is given in Figure A.3 in the Appendix.

There are a lot of general purpose simulation programming languages available, such as SLAM, SIMAN, XCELL+ and etc. Modeling and reporting functions are standard and less flexible to differentiate between various systems. For that reason, a simulation model is developed in Pascal Programming Language to simulate and gain insight on the system performance under different conditions. See Figure 3.2 for the general flowchart of the simulation procedure. The code of the simulation model is designed modular and structural so that any modification in the model could be easily reflected into the code. A sample file containing the simulation input parameters is given in Figure A.4 in the Appendix. The set of input parameters associated to the simulation of the problem is as follows :

- **The type of the control strategy :** This parameter determines whether the control strategy is push, pull or conwip.

  In the push system, parts are released into the system with average demand arrival rate. Whenever those released parts complete an operation, they are triggered for the next operation, so that they are released to the next operation. This way of controlling pushes the work-in-process parts through the system.

  In the pull system, whenever a demand arrival occurs, a part waiting for the last operation is triggered. When this triggered part is loaded into the machine for processing, another part at the previous stage triggered in the same manner. This trigger process goes back through the production line until the first stage is triggered. This way of controlling pulls the work-in-process parts through the system.

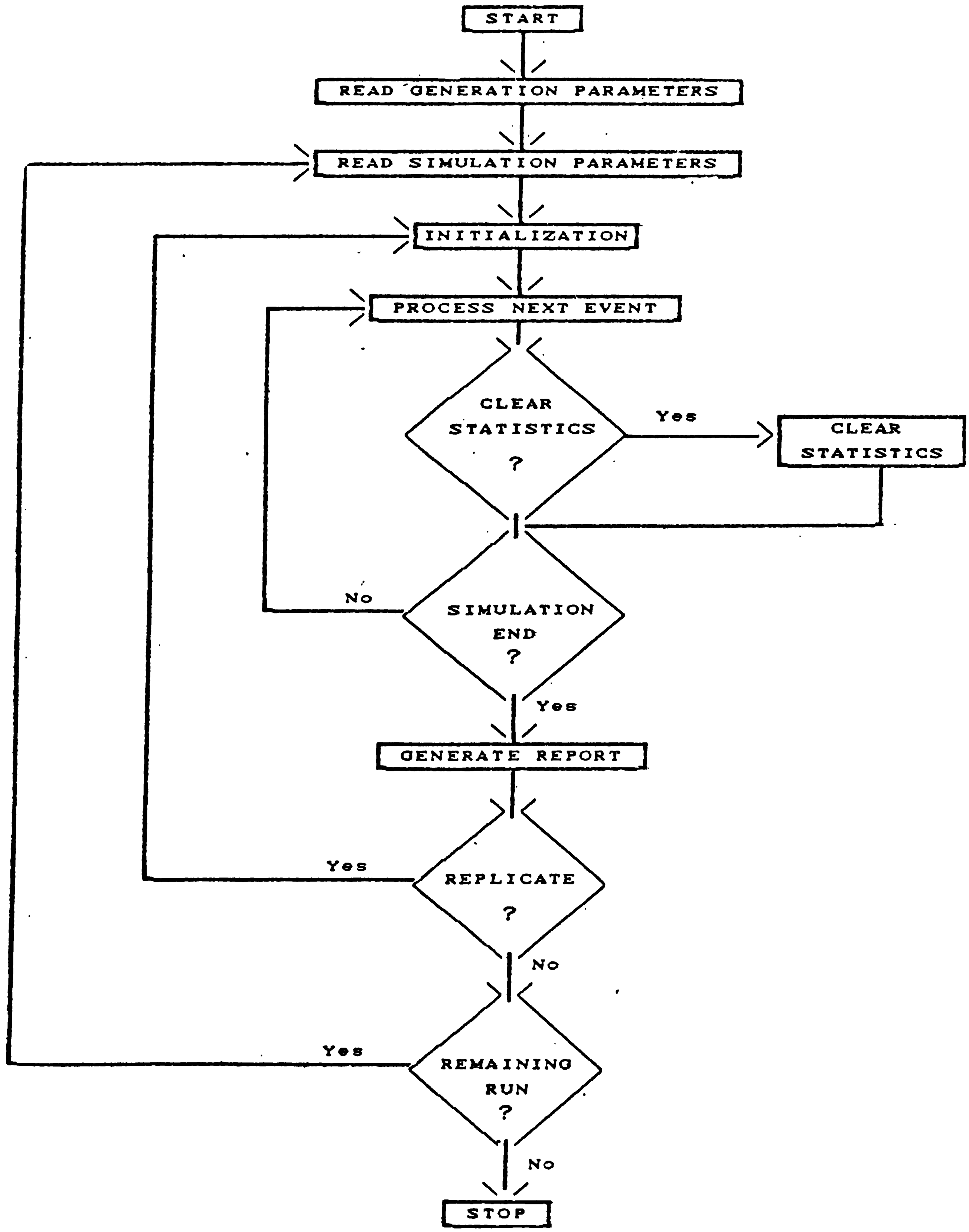

Figure 3.2: Flowchart of the simulation model.

In the conwip system, whenever a demand arrival occurs, a new part is released into the first stage. This part will be pushed through the system, as in the push system, until all of its operations are completed. This way of controlling keeps the number of parts in the system waiting for processing at a constant level.

- **Initial WIP inventory level** at buffer points,
- **Initial Safety Stock (SS) inventory level** at the buffer points after all last operations,
- **Production lot size,** is assumed to be one since machines are flexible,
- **Set-up time to processing time ratio,** is assumed to be zero since flexible machines have negligible set-up times,
- **Distribution for demand process,**
- **Distribution for processing times,**
- **Distribution for failure process,**
- **Distribution for repair process,**
- **Time for collected statistics to be cleared out,**
- **Time for stopping the simulation,**
- **Number of replicate runs.**

For all distributions, uniform, exponential, truncated normal, weibull, beta and gamma distributions are available in the code. Five key performance measures are selected for comparison of simulation results.

1. Average aggregated WIP inventory level per part type.

$$AAWIP = (\frac{1}{N}) * \sum_{i=1}^{N} WIP_i$$

where WIP_i is the sum of simulated time-average WIP inventory levels of part type i at all stages.

2. Average aggregated stockout level per part type.

$$AASO = (\frac{1}{N}) * \sum_{i=1}^{N} SO_i$$

where SO_i is the simulated time-average stockout level for part type i.

3. Average aggregated stockout period per part type.

$$AASOP = (\frac{1}{N}) * \sum_{i=1}^{N} SOP_i$$

where SOP_i is the simulated time-average stockout period for part type i.

4. Average aggregated service level.

$$AASL = 100 - (\frac{1}{N}) * \sum_{i=1}^{N} | 100 - SL_i |$$

where SL_i is the simulated service level for part type i. Note that, in this definition of service level, both underproduction and overproduction are equally penalized, since the throughputs of the systems are not actually compared. The overproduction of push control strategy could be accepted as a disadvantage.

5. Average machine utilization.

$$AMU = (\frac{1}{M}) * \sum_{m=1}^{M} MU_m$$

where MU_m is the simulated time-average utilization of machine m.

3.3.3 Simulation Scenarios

Five different simulation cases are investigated. In all these cases, the system is simulated to obtain a *behaviour curve* on the selected key performance measures. For each point in the curve, 9 different problems are generated and simulation runs are replicated 10 times. This means any point on the behaviour curve is the average of 90 simulated values. A sample simulation output is given in Figure A.5 in the Appendix.

The number of part types are set equal to the number of machines in the system. so that the workload equilibrium between machines could be preserved while increasing the number of machines. Uniform distribution is used to generate the number of operations per part type, the production ratios of part types, the data of processing times of operations and the slot requirements of tools on the magazine. Magazine capacities of machines are assumed to be 60 slots. Planned system efficiency is set to 80 %. All problems are generated for a period of 9600 time units.

In all cases, the problems are simulated for push, pull and conwip control strategies, for three consecutive periods. After the first 2400 time units the collected statistics are cleared since the variability in output rate of the systems as a function of time becomes negligible. Both demand and failure interarrival times are assumed to be exponential. Mean failure interarrival time is 1750 time units. Mean demand interarrival times are obtained from dividing period length to the production volumes of the part types. Repair times are assumed to be gamma with parameters 17.4 and 14.4. In all simulations, processing times of operations are assumed to be deterministic. The initial WIP and SS inventory levels are increased from 1 to 13 with the increments of one, to obtain the behaviour curve of the selected key performance measures.

In this simulation study, the effect of the following factors on the response of the model are considered :

- The loading techniques,
- The length of the production line,
- The average machine utilization,
- The demand variability,
- The buffer inventories.

3.4 Simulation Results

The effects of the factors described in previous section are investigated by a total of 4368 simulation runs. In total, 109 mixed-integer programs associated with loading problems are solved by heuristic balancing rules. Nine of these programs are solved by optimal seeking *Branch & Bound* technique for two alternative objectives. Approximately, 453 hours of computer time (**Data General MV/2000 Eclipse Processor**) is used. Only, 10 % of this computer time is allocated to solve some of the loading problems by optimal seeking technique. Less than one percent of the computer time is used for heuristic rules to solve all the loading problems. The simulation results are analyzed to compare the performance of control strategies applied on flexible production line.

During the evaluation of these simulation results, graphs of stockouts, stockout period, service level and machine utilization are drawn against simulated WIP inventory, so that the performance of three control strategies and various levels of input parameters could be compared at equivalent levels of WIP inventory. The impact of various factors are listed below.

3.4.1 Impact of Loading Techniques

The system configuration and tooling (loading) problem is solved by heuristic and optimal seeking techniques discussed in Section 2.4. First, the problems are solved using the heuristic loading rule which aims balancing the work-loads among machines. Then a mixed-integer model with balancing objective is solved for each problem by optimal seeking Branch & Bound technique of SCICONIC. This is a professional integer programming software available on mainframes. Finally, all problems are optimally solved by a mixed-integer model with the objective of minimizing the buffer points required in the system. As a result, the impacts of both balancing quality and alternative objectives could be investigated. Because of computer time limitations, a problem group with 5 machines is selected.

In this case, 9 test problems are generated with parameters given in Table A.14. The loading problems associated with these 9 problems are solved by heuristic rule to balance workloads and by optimal seeking technique both to balance workloads and to minimize the number of buffer points. So, for each problem there are three different assignments of operations to machines. That means three alternative loading solutions are available. Note that ;

- BS (*Best Strategy*) refers to the simulation experiment based on the solution of loading problems obtained by heuristic rule. See Section 2.4.
- OB (*Optimized Balance*) refers to the simulation experiment based on the solution of loading problems obtained by optimal seeking technique to balance the workloads among machines. See details of the formulation in Section 2.6.
- MBP (*Minimized Buffer Points*) refers to the simulation experiment based on the solution of loading problems obtained by optimal seeking technique to minimize the number of buffer points. See details of the formulation in Section 2.6.

Solution Type	Objective # 1 Balance Range		Objective # 2 Number of Buffer Points	
	Average	Coefficient of Variation	Average	Coefficient of Variation
BS	7.69	0.36	17.11	0.08
OB	3.41	0.97	15.22	0.15
MBP	25.13	0.32	9.67	0.22

Table 3.1: Evaluation of alternative loading solutions in terms of alternative objectives.

The average values of 9 problems given in Table 3.1 indicate OB is significantly better in minimizing balance range objective, and MBP is significantly better in minimizing number of buffer points objective. OB is superior in both objective values to BS. But, BS gives rather acceptable loading solutions in terms of average values of both objectives. Considering the coefficient of variation of both objective values, BS gives more robust loading solutions. For detailed information on the evaluation of alternative loading solutions in terms of objectives, see Table A.15 and Figure A.6.

The simulation parameters for this case are given in Table A.14. Nine different problems are simulated for 3 control strategies with 13 different WIP and SS inventory levels. The simulated values of key performance measures are tabulated in Table A.16. The key findings are :

- In all loading solutions, pull control strategy has less stockouts, better service levels and shorter stockout periods than the other two control strategies at equivalent WIP levels - see Figures A.10, A.11 and A.12.
- In BS loading solutions, conwip control strategy performs as good as the push control strategy in terms of stockouts at equivalent WIP inventory levels - see Figure A.10.
- In OB and MBP loading solutions, conwip control strategy has less stockouts and shorter stockout periods than push control strategy at low levels of WIP inventory. On the other hand, with increasing WIP inventory levels, conwip control strategy performs worse than push - see Figures A.11 and A.12.
- Pull control strategy is very robust for all loading solutions at high levels of WIP - see Figure A.8.
- For all control strategies, MBP loading solutions give better performance than the other loading solutions. But in push control strategy, with increasing WIP inventory level, OB loading solutions perform best and in conwip control strategy BS loading solutions give the best performance - see Figures A.7, A.8 and A.9.

In this simulation experiment, pull control strategy outperforms push and conwip. There is no evidence to say that either push or conwip control strategy performs better than the other. But, with the increase of WIP inventory level, the performance of conwip control strategy becomes worse than the push control strategy. At low levels of WIP inventory, MBP loading solutions give the best performance. For push control strategy, OB loading solutions are the best performer. For medium or high levels of WIP inventory, BS loading solutions could be well acceptable, since it preserves the representative characteristics of the problem. Note that, assigning operations to machines in the loading problem by an optimal seeking technique, improves the simulated performance of the system.

3.4.2 Impact of Length of the Production Line

In this case, heuristic loading rule is used to solve the associated loading problems. The number of machines and the number of part types in the system are increased from 5 to 20 with increments of 5. So, the impact of the number of machines in the production line on key performance measures could be investigated. 36 test problems are generated with parameters given in Table A.17. The loading problems associated with these 36 problems are solved by heuristic rule to balance the workloads.

The simulation parameters for this case are given in Table A.17. The generated problems are simulated for 3 control strategies with 13 diffirent WIP and SS inventory levels. The simulated values of key performance measures are tabulated in Table A.18. The key findings are :

- Increasing the number of machines in the problem, decreases the efficiency by shifting stockout and stockout period curves upward, but service level and machine utilization curves downward, at equivalent levels of WIP inventory - see Figures A.13, A.14 and A.15.
- At low levels of WIP inventory, the performance of conwip strategy is robust for various lengths of the production line - see Figure A.15,
- The performance of pull control strategy, for 10, 15 and 20 machines is not significantly different form each other at equivalent levels of WIP inventory - see Figure A.14.
- The performance of push control strategy, at high levels of WIP inventory, for 15 and 20 machines is better than 10 machines case - see Figure A.13. Note that, average number of operations per part is 10. Increasing the number of machines

beyond the average number of operations per part type does not decrease the efficiency significantly since a part could be assigned to machines at most the number of operations times. On the other hand, this may increase the efficiency since the balancing quality of heuristic loading rule increases with the increase of the size of the problem.

- The performance of pull control strategy is the best, irrispective of the length of the production line - see Figure A.16, A.17, A.18 and A.19.
- The performance of conwip control strategy, at very low levels of WIP inventory, is even better than the pull control strategy - see Figure A.16, A.17, A.18 and A.19.
- There is no hard evidence to say that, at medium and high levels of WIP inventory, either push or conwip control strategy is better than the other - see Figures A.16, A.17, A.18 and A.19.

In this simulation experiment, pull control strategy is again outperforms the other two strategies and increasing the number of machines in the production line, decreases the efficiency up to the number of machines which is equal to the average number of operations per part type.

3.4.3 Impact of Average Machine Utilization

The associated loading problems are solved by using aforementioned heuristic rule. The simulations are carried out with different levels of planned average system utilization. This will show the impact of average machine utilization on key performance measures. Problems with 80, 70, 60 and 50 % planned average system utilizations are generated and simulated. For all generated problems, the number of machines and part types in the system are set equal to 10.

The problem generation and simulation parameters for this case are given in Table A.19. 36 different problems are simulated for 3 control strategies with 13 different WIP and SS inventory levels. The simulated values of key performance measures are tabulated in Table A.20. The key findings are :

- For all three control strategies, decreasing the average machine utilization, shifts the performance curves downward at equivalent WIP inventory levels - see Figures A.20, A.21 and A.22.

- At low levels of WIP inventory, the performance of conwip control strategy is the best. When the average machine utilization is decreased, the performance of conwip control strategy even gets better - see Figures A.23, A.24, A.25 and A.26.
- At medium or high levels of WIP inventory, the performance of pull control strategy is the best - see Figures A.23, A.24, A.25 and A.26.
- For all levels of average machine utilization, the performance of push control strategy is the worst. A decrease in the average machine utilization makes the performance of push control strategy worse - see Figures A.23, A.24, A.25 and A.26.

In this simulation experiment, push control strategy is found to be the worst strategy. At low levels of WIP inventory, conwip control strategy performs very well. On the higher levels of WIP inventory, pull control strategy performs better than the other strategies. When the average machine utilization is decreased, the stockouts and stockout period decrease for all control strategies.

3.4.4 Impact of Demand Variability

The demand distribution is exponential for all other cases. In this case, a truncated normal distribution is selected for demand interarrival times to observe the impact of demand variability. Problems with 0.0, 0.25 and 0.5 coefficient of variation of demand interarrival times are solved. Recall that, coefficient of variation is 1 in exponential distribution. For all problems generated, the number of machines and part types in the system is 10.

The problem generation and simulation parameters for this case are given in Table A.21. Nine different problems are simulated for 3 control strategies and 4 levels of demand variability with 13 different WIP and SS inventory levels. The simulated values of key performance measures are tabulated in Table A.22.

The coefficient of variation is the parameter that is differentiated to investigate the impact of demand variability. In generating random variates from truncated normal distribution, truncation becomes very significant for coefficient of variations greater than 0.5. Since, the deviation in output parameters of normal distribution is linearly related with the mean, 100 is selected for the mean to show the percent deviations. See Table 3.2 for the deviations of output parameters for the distributions used to generate demand interarrival times, in this simulation experiment. The key findings are :

Distribution Type	Input Parameters			Output Parameters		
	Mean	Variance	Coefficient of Variation	Mean	Variance	Coefficient of Variation
Normal	100.00	25.00^2	0.25	100.36	25.36^2	0.25
Normal	100.00	50.00^2	0.50	103.00	47.99^2	0.47
Normal	100.00	75.00^2	0.75	98.95	54.20^2	0.55
Exponential	100.00	100.00^2	1.00	102.23	106.60^2	1.04

Table 3.2: The evaluation of distributions used for generating demand intearrival times.

- For all control strategies, the performance of 0.0 and 0.25 coefficient of variation in demand interarrival times is equivalent to each other. That is, 0.25 coefficient of variation in demand interarival times does not significantly affect the performance of the system. Only a slight decrease is observed in efficiency - see Figures A.27, A.28 and A.29.

- For all control strategies, the decrease in efficiency of the system for 0.5 coefficient of variation in demand interarrival times is more significant than 0.25 coefficient of variation - see Figures A.27, A.28 and A.29.

- For all strategies, increasing the level of demand variability decreases the efficiency of the system - see Figures A.27, A.28 and A.29.

- Note that, coefficient of variation of 1.0 in demand interarrival times is obtained from exponential distribution and there is no significant difference in efficiency between 0.5 and 1.0 coefficient of variation in demand interarrival times. So, the rate of decrease in efficiency with increasing level of demand variability might be different for various types of distributions - see Figures A.27, A.28 and A.29.

- For all levels of demand variability, pull control strategy gives the best performance at equivalent levels of WIP inventory - see Figures A.30, A.31, A.32 and A.33.

- At low levels of WIP inventory, with increasing variability in demand interarrival times, conwip control strategy becomes even better than the pull control strategy - see Figures A.32 and A.33.

- For all levels of demand variability, push control strategy gives the worst performance at equivalent levels of WIP inventory - see Figures A.30, A.31, A.32 and A.33.

In this simulation experiment, pull control strategy still performs better than the competitors. Increasing the variability of demand, decreases the efficiency of the system for all control strategies. At low levels of WIP inventory and high levels of demand variability conwip control strategy performes very well. Push control strategy gives the worst performance once again.

3.4.5 Impact of Buffer Inventories

In both push and conwip control strategies, the amount of WIP inventory in the system is the main control parameter. But the positions of WIP inventory at each stage of manufacturing line is not controlled. On the other hand, in pull control strategy the WIP inventory is controlled at every stage of the production line. In the pull system. the impact of WIP and SS inventory levels on key performance measures could be observed by increasing the WIP and SS inventory levels.

In this case, only one problem is generated with the parameters given in Table A.23. The associated loading problem is solved by heuristic rules to balance the workloads.

The simulation parameters for this case are given in Table A.23. The problem is simulated for only pull control strategy with 12 different WIP and 13 different SS inventory levels. The simulated values of key performance measures are tabulated in Table A.24. The key findings are :

- For pull control strategy, both WIP and SS inventory levels determine the levels of stockouts and stockout period - see Figure A.34.
- On the other hand, the service and average machine utilization levels are determined only by the level of WIP inventory - see Figure A.34.

As a result, in optimizing a pull control strategy, first the level of WIP inventory have to be fixed to a value achieving acceptable service and machine utilization levels, then according to costs of inventory carrying and stockout, the SS inventory level has to be computed.

3.5 Conclusion

More than 100 different hypothetical problems are generated at random and simulated at various levels of WIP and SS inventory to investigate the impacts of the loading solution, the length of the production line, the average machine utilization, the demand variability and the buffer inventories on the relative performance of push, pull and conwip control strategies.

Among these control strategies, almost in every simulation experiment the best is pull control strategy. That is, a manufacturing system composed of flexible machines have to be operated under pull control strategy.

On the other hand, if the WIP inventory carrying cost is very high relative to the cost of stockouts, then conwip control strategy well suits to this situation. In a system that has to carry very low level of WIP inventory, the performance of conwip control strategy is even better than the pull control strategy. The implementation of conwip control strategy is simpler than both push and pull control strategies. In the implementation of conwip control strategy, only the number of parts in the system is required. In most cases, this parameter is technologically limited to the number of material handling devices. The computational requirement for implementing a pull control strategy equals to the computation required to implement conwip control strategy multiplied by the number of machines in the production line. Note that, the scheduling problem in push control strategy is very difficult. Also, a manufacturing system operated under conwip control strategy could be assumed as a closed system. In this way, conwip control strategy is analytically more tractable.

In order to simplify the control function and decrease the load on material handling system the operations must be assigned to machines in series for configuring the production line. The loading problem is a mixed integer program with alternative linear objectives. Both optimal and heuristic solution techniques are available to solve the loading problem. Heuristic loading solution technique gives acceptable assignments of operations according to both objectives of balancing the workloads and minimizing number of buffer points. On the other hand, if computer time is available, optimal solution techniques could be used to improve the efficiency of the system.

4. CONCLUSION & SUGGESTIONS FOR FURTHER RESEARCH

In this research, a *manufacturing line* composed of flexible machines is investigated to solve related design and operational problems. A mathematical model is formulated to solve the **system configuration and tooling (loading)** problem. Some heuristic rules are developed to obtain acceptable solutions to the loading problem. Then, the differentiating features of **control strategies** are analyzed using discrete event simulation.

The loading problem of the considered manufacturing line is formulated as a mixed integer linear program. Manufacturing operations are loaded to tandem machines in the line to decrease the traffic load of Material Handling System. This serial flow of operations have no routing flexibility, but on the other hand, this greatly simplifies controllability of the system. One of the possible future research is to investigate the interactions between jobshop and flowshop structures in operation loading phase by extending the simulation model to include a Pick-up and Deliver System.

Solving mixed integer linear formulations of realistic size by optimal seeking *Branch and Bound* technique is very difficult and requires substantial amount of computer time and storage. As a result, *heuristic loading rules*, originating from assembly line balancing techniques, are developed. Since, they are one pass algorithms, they are fast and practically give very good results in terms of balancing the workload among machines. The optimal solutions of alternative formulations of loading problem with different objectives could further improve the performance of the system.

In general, **pull** control strategy is found to be better than the other strategies, in terms of carrying less WIP inventory in achieving the target production level. In pull systems, WIP inventory is controlled at every stage of the manufacturing line while in **push** systems, putting some restrictions on intermediate buffer capacities will cause blocking and decrease the efficiency of the system.

The third control strategy that is investigated by computer simulation is **conwip**. This control strategy seems to be a constrained version of push, since the number of parts in the system is kept constant. One other possible future research is to represent a conwip system by an equivalent *Closed Queueing Network Model*, to investigate an upper bound on WIP inventory above which pull control strategy becomes relatively better.

The control strategies are compared for various system parameters. Shorter manufacturing lines are found to be more productive than the longer ones. Increasing average machine utilization decreases the efficiency of the system. That is, increasing the average workload of machines, will significantly affect the WIP inventory carrying costs of the manufacturing line. On the other hand, it is observed that decreasing demand variability, increases the system efficiency.

For all simulation experiments, flexible machines with no set-up time and one unit of production lot size are considered. In another future research, the relative performance of control strategies will be investigated while incrementing the set-up time and associated production lot size.

As a conclusion, this research proposes a design for a manufacturing line composed of flexible machines. Additionally, some experience related with the operating features of the line is obtained through a series of experiments carried out by computer simulation. In this way, the load on part handling and routing functions are simplified while preserving the efficiency and throughput of the system.

APPENDIX

The *problem and matrix generator* modules, *heuristic loading solution* procedure and *simulation model* are coded on **Data General Eclipse MV/20000 Model 1 Computer System** operating under AOS/VS. The complete list of **PASCAL** Codes of all programs can be obtained from :

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Note # 1 :

M	denotes the number of machines in the problem.
N	denotes the number of part types in the problem.
O	denotes the average number of operations required for a specific part type.
Var#	denotes the number of variables in the formulation.
Con#	denotes the number of constraints in the formulation.
Density	denotes the ratio of non-zero entries to total entries in the contraint matrix.
Problem Identifier	is used to denote a specific problem for further reference.

Note # 2 :

Optimal seeking Branch & Bound Technique is used in solutions. Problem Identifier refers to a specific problem. The optimal linear, initial and best integer solutions are three different solutions tabulated for a problem. For each solution, objective value, the number of iterations performed and elapsed CPU time information are tabulated. Difference in solutions is the deviation between the linear optimal solution and the best integer solution. Sol# refers to the number of feasible integer solutions found. Total improvement is the difference between initial and best integer solutions.

Note # 3 :

Problem identifier is used to refer to a specific problem. The objective values for optimal linear solution. initial integer solution, best integer solution , solutions of heuristic rules and the solution of best strategy which is the best of four heuristics are tabulated. First difference is the difference between initial integer solution and solution obtained by best strategy. Best difference refers to the difference between the best integer solution and solution obtained by best strategy.

Note # 4 :

No optimal seeking solution technique is used for the solutions of the problems. The solutions obtained by the best strategy are within 10 % of the upper bound except for three problems.

Note # 5 :

Heuristic Rule # 1	is denoted by	H1
Heuristic Rule # 2	is denoted by	H2
Heuristic Rule # 3	is denoted by	H3
Heuristic Rule # 4	is denoted by	H4
Best Strategy	is denoted by	BS.
Initial Integer Solution	is denoted by	INITIAL
Best Integer Solution	is denoted by	BEST

Paired-t and Wilcoxon signed-rank tests are applied on the difference of means with 0.05 % level of significance. N denotes the number of observations, DF refers to degrees of freedom, t-stat denotes the computed t value, Table refers to the tabulated t value, Power corresponds to power of the test, R+ is the sum of the positive ranks, R- is the absolute value of the sum of the negative ranks and R* is the critical value for Wilcoxon signed-rank test.

Note # 6 :

Number of machines	10
Number of part types	15
Average number of operations for a specific part type	12

10 different problems are generated by different random numbers. The Best Strategy gives on the average solutions which are within 3 % of the upper bound.

Note # 7 :

Obj.1	denotes the range of the balance of workloads in a solution.
Obj.2	denotes the required # of buffer points in a solution.
Util.1	denotes the simulated average machine utilization for push.
Util.2	denotes the simulated average machine utilization for pull.
Util.3	denotes the simulated average machine utilization for conwip.
Avg.	denotes the average value of sample problems.
Std.	denotes the standard deviation of sample problems.
C.V.	denotes the coefficient of variation of sample problems.

Note # 8 :

WIP	denotes the average simulated WIP inventory level.
STKOUT	denotes the average simulated stockout level.
STKOUT PERIOD	denotes the average simulated stockout period.
%SERV.	denotes the average simulated service level.
%UTIL.	denotes the average simulated machine utilization.

Table A.1: Sizes of formulations of problems in control group 1.

See Note # 1 for further explanation.

M	N	O	Var#	Con#	Density	Problem Identifier
2	8	5	77	73	0.062	M02N08O05
2	8	10	157	153	0.031	M02N08O10
2	8	15	237	233	0.021	M02N08O15
2	8	20	317	313	0.016	M02N08O20
2	16	5	151	139	0.033	M02N16O05
2	16	10	311	299	0.017	M02N16O10
2	16	15	471	459	0.011	M02N16O15
2	16	20	631	619	0.008	M02N16O20
3	8	5	115	75	0.061	M03N08O05
3	8	10	235	155	0.031	M03N08O10
3	8	15	355	235	0.021	M03N08O15
3	8	20	475	315	0.016	M03N08O20
3	16	5	226	141	0.032	M03N16O05
3	16	10	466	301	0.016	M03N16O10
3	16	15	706	461	0.011	M03N16O15
3	16	20	946	621	0.008	M03N16O20

Table A.2: Sizes of formulations of problems in control group 2.

See Note # 1 for further explanation.

M	N	O	Var#	Con#	Density	Problem Identifier
4	5	5	113	60	0.077	M04N05O05
4	5	10	213	110	0.044	M04N05O10
4	5	15	313	160	0.030	M04N05O15
4	5	20	413	210	0.023	M04N05O20
4	10	5	189	93	0.049	M04N10O05
4	10	10	389	193	0.025	M04N10O10
4	10	15	589	293	0.017	M04N10O15
4	10	20	789	393	0.012	M04N10O20
5	5	5	141	62	0.075	M05N05O05
5	5	10	266	112	0.043	M05N05O10
5	5	15	391	162	0.030	M05N05O15
5	5	20	516	212	0.023	M05N05O20
5	10	5	236	95	0.048	M05N10O05
5	10	10	486	195	0.025	M05N10O10
5	10	15	736	295	0.016	M05N10O15
5	10	20	986	395	0.012	M05N10O20

Table A.3: Sizes of formulations of problems in control group 3.

See Note # 1 for further explanation.

M	N	O	Var#	Con#	Density	Problem Identifier
6	3	5	109	46	0.106	M06N03O05
6	3	10	199	76	0.066	M06N03O10
6	3	15	289	106	0.048	M06N03O15
6	3	20	379	136	0.037	M06N03O20
6	6	5	187	69	0.070	M06N06O05
6	6	10	367	129	0.039	M06N06O10
6	6	15	547	189	0.027	M06N06O15
6	6	20	727	249	0.020	M06N06O20
7	3	5	127	48	0.101	M07N03O05
7	3	10	232	78	0.064	M07N03O10
7	3	15	337	108	0.047	M07N03O15
7	3	20	442	138	0.037	M07N03O20
7	6	5	218	71	0.067	M07N06O05
7	6	10	428	131	0.038	M07N06O10
7	6	15	638	191	0.026	M07N06O15
7	6	20	848	251	0.020	M07N06O20
8	3	5	145	50	0.097	M08N03O05
8	3	10	265	80	0.062	M08N03O10
8	3	15	385	110	0.046	M08N03O15
8	3	20	505	140	0.036	M08N03O20
8	6	5	249	73	0.065	M08N06O05
8	6	10	489	133	0.037	M08N06O10
8	6	15	729	193	0.026	M08N06O15
8	6	20	969	253	0.020	M08N06O20

Table A.4: Solutions of problems in control group 1.

See Note # 2 for further explanation.

Problem	LP Optimum Solution			Initial Integer Solution			Best Integer Solution			Difference	Sol	Total
Identifier	Obj.Val.	Itr.	Sec.	Obj.Val.	Itr.	Sec.	Obj.Val.	Itr.	Sec.	In Solutions	#	Improve.
M02N08O05	0.888125	77	1.0	0.863541	104	3.3	0.882188	154	6.9	0.005938	3	0.0186
M02N08O10	0.873698	186	3.7	0.863125	240	11.9	0.873021	261	16.1	0.000677	2	0.0099
M02N08O15	0.861406	299	8.6	0.840208	349	26.3	0.858229	628	63.0	0.003177	4	0.0180
M02N08O20	0.854688	353	12.2	0.854688	359	25.0	0.854688	359	25.0	0.000000	1	0.0000
M02N16O05	0.875260	152	2.5	0.875000	200	11.0	0.875000	200	11.0	0.000260	1	0.0000
M02N16O10	0.858594	330	10.5	0.855417	465	65.1	0.855417	465	66.0	0.003177	1	0.0000
M02N16O15	0.829948	518	23.4	0.829896	734	165.1	0.829896	734	165.1	0.000052	1	0.0000
M02N16O20	0.792708	679	35.7	0.791667	884	190.6	0.791667	884	190.6	0.001042	1	0.0000
M03N08O05	0.890868	102	2.0	0.851979	276	8.3	0.887813	3420	76.0	0.003056	4	0.0358
M03N08O10	0.884063	244	6.5	0.753958	1216	49.3	0.879688	11331	429.9	0.004375	8	0.1257
M03N08O15	0.879306	375	14.2	0.744271	1998	129.5	0.873646	23501	1428.0	0.005660	16	0.1294
M03N08O20	0.863854	458	22.3	0.801979	1043	116.8	0.860729	3405	403.0	0.003125	4	0.0587
M03N16O05	0.881111	186	4.6	0.849792	755	32.5	0.878125	1263	55.1	0.002986	3	0.0283
M03N16O10	0.866215	477	18.9	0.840313	2199	206.9	0.860938	8823	715.8	0.005278	3	0.0206
M03N16O15	0.863819	608	36.3	0.807188	1566	328.0	0.858542	7668	1219.5	0.005278	3	0.0514
M03N16O20	0.846389	835	59.4	0.844479	2298	738.8	0.844479	2298	738.8	0.001910	1	0.0000

Table A.5: Solutions of problems in control group 2.

See Note # 2 for further explanation.

Problem Identifier	LP Optimum Solution Obj.Val.	Itr.	Sec.	Initial Integer Solution Obj.Val.	Itr.	Sec.	Best Integer Solution Obj.Val.	Itr.	Sec.	Difference In Solutions	Sol #	Total Improve.
M04N05O05	0.894896	93	2.2	0.774895	292	11.4	0.833542	10684	364.1	0.061354	5	0.0566
M04N05O10	0.892943	204	7.1	0.609063	1925	84.5	0.754688	45467	1513.6	0.138255	4	0.1456
M04N05O15	0.890339	331	15.3	0.659167	3264	220.3	0.763958	14190	920.6	0.126380	6	0.1048
M04N05O20	0.880755	347	17.7	0.535938	2880	174.1	0.682708	47430	2654.5	0.198047	7	0.1468
M04N10O05	0.893880	158	4.5	0.714375	730	21.9	0.889479	15698	413.5	0.004401	15	0.1751
M04N10O10	0.887031	334	15.4	0.666354	2614	246.4	0.823438	39710	3216.7	0.063594	12	0.1571
M04N10O15	0.881172	531	30.5	0.700729	19554	1257.4	0.773750	35145	2446.6	0.107422	7	0.0730
M04N10O20	0.872682	668	49.6	0.727813	7449	897.3	0.798333	24522	2643.9	0.074349	2	0.0705
M05N05O05	0.897708	114	3.2	0.598021	1387	36.4	0.694688	7847	182.7	0.203021	3	0.0967
M05N05O10	0.896521	223	7.9	0.613125	23273	756.1	0.796563	48660	1583.2	0.099958	3	0.1834
M05N05O15	0.894104	285	14.7	...	50000	2256.6	...	50000	2256.6	...	0	...
M05N05O20	0.889813	349	22.1	...	50000	3339.2	...	50000	3339.2	...	0	...
M05N10O05	0.894563	203	7.3	...	50000	1436.7	...	50000	1436.7	...	0	...
M05N10O10	0.890313	380	24.5	0.713646	3057	192.8	0.784688	48224	2178.2	0.105625	6	0.0710
M05N10O15	0.875896	561	44.4	0.661250	10544	747.4	0.761771	28759	1918.7	0.114125	4	0.1005
M05N10O20	0.875750	913	87.3	0.459896	4095	614.3	0.547813	35012	3979.1	0.327938	5	0.0879

Table A.6: Results of heuristics for the problems in control group 1.

See Note # 3 for further explanation.

Problem Identifier	Optimal Seeking Technique LP Optimum Obj.	Initial Obj.	Best Obj.	Heuristic Loading Rules #1 Obj.	#2 Obj.	#3 Obj.	#4 Obj.	Best Strategy	First Difference	Best Difference
M02N08O05	0.89	0.86	0.88	0.89	0.87	0.87	0.87	0.89	0.03	0.01
M02N08O10	0.87	0.86	0.87	0.86	0.88	0.81	0.81	0.88	0.01	0.00
M02N08O15	0.86	0.84	0.86	0.86	0.86	0.86	0.86	0.86	0.02	0.00
M02N08O20	0.85	0.85	0.85	0.82	0.82	0.80	0.80	0.82	-0.04	-0.04
M02N16O05	0.88	0.88	0.88	0.88	0.87	0.86	0.86	0.88	0.00	0.00
M02N16O10	0.86	0.86	0.86	0.86	0.86	0.86	0.85	0.86	0.01	0.01
M02N16O15	0.83	0.83	0.83	0.78	0.78	0.74	0.74	0.78	-0.05	-0.05
M02N16O20	0.79	0.79	0.79	0.68	0.68	0.75	0.75	0.75	-0.04	-0.04
M03N08O05	0.89	0.85	0.89	0.88	0.86	0.87	0.83	0.88	0.03	-0.01
M03N08O10	0.88	0.75	0.88	0.73	0.75	0.73	0.73	0.75	-0.01	-0.13
M03N08O15	0.88	0.74	0.87	0.84	0.85	0.69	0.69	0.85	0.10	-0.03
M03N08O20	0.86	0.80	0.86	0.70	0.71	0.72	0.72	0.72	-0.09	-0.15
M03N16O05	0.88	0.85	0.88	0.88	0.87	0.86	0.86	0.88	0.03	0.00
M03N16O10	0.87	0.84	0.86	0.86	0.86	0.83	0.83	0.86	0.02	0.00
M03N16O15	0.86	0.81	0.86	0.68	0.73	0.77	0.77	0.77	-0.04	-0.09
M03N16O20	0.85	0.84	0.84	0.71	0.70	0.72	0.72	0.72	-0.12	-0.12
AVERAGE	0.86	0.83	0.86	0.81	0.81	0.80	0.79	0.82	-0.01	-0.04

Table A.7: Results of heuristics for the problems in control group 2.

See Note # 3 for further explanation.

Problem Identifier	Optimal Seeking Technique LP Optimum Obj.	Initial Obj.	Best Obj.	Heuristic Loading Rules #1 Obj.	#2 Obj.	#3 Obj.	#4 Obj.	Best Strategy	First Difference	Best Difference
M04N05O05	0.89	0.77	0.83	0.79	0.88	0.84	0.85	0.88	0.11	0.05
M04N05O10	0.89	0.61	0.75	0.68	0.68	0.50	0.63	0.68	0.07	-0.08
M04N05O15	0.89	0.66	0.76	0.79	0.85	0.71	0.71	0.85	0.19	0.09
M04N05O20	0.88	0.54	0.68	0.48	0.54	0.63	0.63	0.63	0.10	-0.05
M04N10O05	0.89	0.71	0.89	0.79	0.79	0.82	0.82	0.82	0.11	-0.07
M04N10O10	0.89	0.67	0.82	0.66	0.66	0.83	0.83	0.83	0.16	0.00
M04N10O15	0.88	0.70	0.77	0.77	0.73	0.82	0.82	0.82	0.12	0.05
M04N10O20	0.87	0.73	0.80	0.56	0.57	0.78	0.78	0.78	0.06	-0.01
M05N05O05	0.90	0.60	0.69	0.73	0.71	0.82	0.75	0.82	0.22	0.12
M05N05O10	0.90	0.61	0.80	0.69	0.83	0.51	0.51	0.83	0.21	0.03
M05N05O15	0.89	...	...	0.87	0.86	0.63	0.57	0.87	...	...
M05N05O20	0.89	...	...	0.45	0.43	0.58	0.58	0.58	...	...
M05N10O05	0.89	...	...	0.65	0.87	0.81	0.81	0.87	...	...
M05N10O10	0.89	0.71	0.78	0.70	0.70	0.87	0.85	0.87	0.15	0.08
M05N10O15	0.88	0.66	0.76	0.86	0.86	0.86	0.84	0.86	0.20	0.10
M05N10O20	0.88	0.46	0.55	0.46	0.48	0.81	0.81	0.81	0.35	0.26
AVERAGE	0.89	0.65	0.76	0.68	0.72	0.74	0.74	0.80	0.16	0.04

Table A.8: Results of heuristics for the problems in control group 3.

See Notes # 3 & 4 for further explanation.

Problem Identifier	Heuristic Loading Rules #1 Obj.	#2 Obj.	#3 Obj.	#4 Obj.	Best Strategy
M06N03O05	0.42	0.42	0.47	0.38	0.47
M06N03O10	0.75	0.77	0.83	0.84	0.84
M06N03O15	0.82	0.84	0.85	0.83	0.85
M06N03O20	0.87	0.84	0.87	0.86	0.87
M06N06O05	0.83	0.78	0.80	0.84	0.84
M06N06O10	0.83	0.82	0.87	0.85	0.87
M06N06O15	0.87	0.85	0.87	0.86	0.87
M06N06O20	0.85	0.87	0.83	0.88	0.88
M07N03O05	0.65	0.35	0.63	0.54	0.65
M07N03O10	0.77	0.77	0.84	0.73	0.84
M07N03O15	0.69	0.78	0.85	0.83	0.85
M07N03O20	0.87	0.83	0.87	0.83	0.87
M07N06O05	0.82	0.70	0.53	0.84	0.84
M07N06O10	0.81	0.84	0.88	0.86	0.88
M07N06O15	0.82	0.86	0.85	0.85	0.86
M07N06O20	0.84	0.88	0.82	0.87	0.88
M08N03O05	0.35	0.35	0.32	0.32	0.35
M08N03O10	0.73	0.74	0.77	0.83	0.83
M08N03O15	0.79	0.72	0.81	0.80	0.81
M08N03O20	0.88	0.79	0.73	0.88	0.88
M08N06O05	0.81	0.58	0.61	0.85	0.85
M08N06O10	0.79	0.85	0.69	0.86	0.86
M08N06O15	0.87	0.85	0.87	0.86	0.87
M08N06O20	0.84	0.87	0.78	0.88	0.88
AVERAGE	0.77	0.75	0.76	0.79	0.81

Table A.9: Tests of hypothesis related with the means of objective values of the problems in Control Group 1.

See Notes #3 & 4 for further explanation.

Null Hypothesis	Alternative Hypothesis	N	DF	t-stat	Paired-t Test Table	Power	Decision	Wilcoxon Signed-Rank Test R+	R-	R*	Decision
$\mu(BS) = \mu(H1)$	$\mu(BS) \neq \mu(H1)$	16	15	2.24	±2.13	≈0.50	Reject Null	91	0	29	Reject Null
$\mu(BS) = \mu(H1)$	$\mu(BS) < \mu(H1)$	16	15	2.24	-1.75	≈0.02	Accept Null	91	-	35	Accept Null
$\mu(BS) = \mu(H1)$	$\mu(BS) > \mu(H1)$	16	15	2.24	1.75	≈0.65	Reject Null	-	0	35	Reject Null
$\mu(BS) = \mu(H2)$	$\mu(BS) \neq \mu(H2)$	16	15	2.61	±2.13	≈0.55	Reject Null	100	0	29	Reject Null
$\mu(BS) = \mu(H2)$	$\mu(BS) < \mu(H2)$	16	15	2.61	-1.75	≈0.01	Accept Null	100	-	35	Accept Null
$\mu(BS) = \mu(H2)$	$\mu(BS) > \mu(H2)$	16	15	2.61	1.75	≈0.75	Reject Null	-	0	35	Reject Null
$\mu(BS) = \mu(H3)$	$\mu(BS) \neq \mu(H3)$	16	15	2.53	±2.13	≈0.60	Reject Null	115	0	29	Reject Null
$\mu(BS) = \mu(H3)$	$\mu(BS) < \mu(H3)$	16	15	2.53	-1.75	≈0.01	Accept Null	115	-	35	Accept Null
$\mu(BS) = \mu(H3)$	$\mu(BS) > \mu(H3)$	16	15	2.53	1.75	≈0.75	Reject Null	-	0	35	Reject Null
$\mu(BS) = \mu(H4)$	$\mu(BS) \neq \mu(H4)$	16	15	2.85	±2.13	≈0.70	Reject Null	121	0	29	Reject Null
$\mu(BS) = \mu(H4)$	$\mu(BS) < \mu(H4)$	16	15	2.85	-1.75	≈0.01	Accept Null	121	-	35	Accept Null
$\mu(BS) = \mu(H4)$	$\mu(BS) > \mu(H4)$	16	15	2.85	1.75	≈0.85	Reject Null	-	0	35	Reject Null
$\mu(BEST) = \mu(H1)$	$\mu(BEST) \neq \mu(H1)$	16	15	3.13	±2.13	≈0.80	Reject Null	114	7	29	Reject Null
$\mu(BEST) = \mu(H1)$	$\mu(BEST) < \mu(H1)$	16	15	3.13	-1.75	≈0.00	Accept Null	114	-	35	Accept Null
$\mu(BEST) = \mu(H1)$	$\mu(BEST) > \mu(H1)$	16	15	3.13	1.75	≈0.90	Reject Null	-	7	35	Reject Null
$\mu(BEST) = \mu(H2)$	$\mu(BEST) \neq \mu(H2)$	16	15	3.44	±2.13	≈0.80	Reject Null	125	6	29	Reject Null
$\mu(BEST) = \mu(H2)$	$\mu(BEST) < \mu(H2)$	16	15	3.44	-1.75	≈0.00	Accept Null	125	-	35	Accept Null
$\mu(BEST) = \mu(H2)$	$\mu(BEST) > \mu(H2)$	16	15	3.44	1.75	≈0.90	Reject Null	-	6	35	Reject Null
$\mu(BEST) = \mu(H3)$	$\mu(BEST) \neq \mu(H3)$	16	15	4.42	±2.13	≈0.95	Reject Null	133	0	29	Reject Null
$\mu(BEST) = \mu(H3)$	$\mu(BEST) < \mu(H3)$	16	15	4.42	-1.75	≈0.00	Accept Null	133	-	35	Accept Null
$\mu(BEST) = \mu(H3)$	$\mu(BEST) > \mu(H3)$	16	15	4.42	1.75	≈1.00	Reject Null	-	0	35	Reject Null
$\mu(BEST) = \mu(H4)$	$\mu(BEST) \neq \mu(H4)$	16	15	4.79	±2.13	≈0.95	Reject Null	135	0	29	Reject Null
$\mu(BEST) = \mu(H4)$	$\mu(BEST) < \mu(H4)$	16	15	4.79	-1.75	≈0.00	Accept Null	135	-	35	Accept Null
$\mu(BEST) = \mu(H4)$	$\mu(BEST) > \mu(H4)$	16	15	4.79	1.75	≈1.00	Reject Null	-	0	35	Reject Null
$\mu(BEST) = \mu(BS)$	$\mu(BEST) \neq \mu(BS)$	16	15	2.90	±2.13	≈0.70	Reject Null	107	14	29	Reject Null
$\mu(BEST) = \mu(BS)$	$\mu(BEST) < \mu(BS)$	16	15	2.90	-1.75	≈0.01	Accept Null	107	-	35	Accept Null
$\mu(BEST) = \mu(BS)$	$\mu(BEST) > \mu(BS)$	16	15	2.90	1.75	≈0.85	Reject Null	-	14	35	Reject Null
$\mu(INITIAL) = \mu(H1)$	$\mu(INITIAL) \neq \mu(H1)$	16	15	1.28	±2.13	≈0.30	Accept Null	82	48	29	Accept Null
$\mu(INITIAL) = \mu(H1)$	$\mu(INITIAL) < \mu(H1)$	16	15	1.28	-1.75	≈0.03	Accept Null	82	-	35	Accept Null
$\mu(INITIAL) = \mu(H1)$	$\mu(INITIAL) > \mu(H1)$	16	15	1.28	1.75	≈0.30	Accept Null	-	48	35	Accept Null
$\mu(INITIAL) = \mu(H2)$	$\mu(INITIAL) \neq \mu(H2)$	16	15	1.21	±2.13	≈0.25	Accept Null	81	53	29	Accept Null
$\mu(INITIAL) = \mu(H2)$	$\mu(INITIAL) < \mu(H2)$	16	15	1.21	-1.75	≈0.03	Accept Null	81	-	35	Accept Null
$\mu(INITIAL) = \mu(H2)$	$\mu(INITIAL) > \mu(H2)$	16	15	1.21	1.75	≈0.25	Accept Null	-	53	35	Accept Null
$\mu(INITIAL) = \mu(H3)$	$\mu(INITIAL) \neq \mu(H3)$	16	15	3.11	±2.13	≈0.80	Reject Null	116	19	29	Reject Null
$\mu(INITIAL) = \mu(H3)$	$\mu(INITIAL) < \mu(H3)$	16	15	3.11	-1.75	≈0.00	Accept Null	116	-	35	Accept Null
$\mu(INITIAL) = \mu(H3)$	$\mu(INITIAL) > \mu(H3)$	16	15	3.11	1.75	≈0.90	Reject Null	-	19	35	Reject Null
$\mu(INITIAL) = \mu(H4)$	$\mu(INITIAL) \neq \mu(H4)$	16	15	3.66	±2.13	≈0.85	Reject Null	125	12	29	Reject Null
$\mu(INITIAL) = \mu(H4)$	$\mu(INITIAL) < \mu(H4)$	16	15	3.66	-1.75	≈0.00	Accept Null	125	-	35	Accept Null
$\mu(INITIAL) = \mu(H4)$	$\mu(INITIAL) > \mu(H4)$	16	15	3.66	1.75	≈0.95	Reject Null	-	12	35	Reject Null
$\mu(INITIAL) = \mu(BS)$	$\mu(INITIAL) \neq \mu(BS)$	16	15	0.47	±2.13	≈0.10	Accept Null	75	56	29	Accept Null
$\mu(INITIAL) = \mu(BS)$	$\mu(INITIAL) < \mu(BS)$	16	15	0.47	-1.75	≈0.05	Accept Null	75	-	35	Accept Null
$\mu(INITIAL) = \mu(BS)$	$\mu(INITIAL) > \mu(BS)$	16	15	0.47	1.75	≈0.10	Accept Null	-	56	35	Accept Null

Table A.10: Tests of hypothesis related with the means of objective values of the problems in control group 2.

See Notes #5 for further explanation.

Null Hypothesis	Alternative Hypothesis	N	Paired-t Test DF	t-stat	Table	Power	Decision	Wilcoxon Signed-Rank Test R+	R-	R*	Decision
$\mu(BS) = \mu(H1)$	$\mu(BS) \neq \mu(H1)$	16	15	4.83	±2.13	≈0.95	Reject Null	88	0	29	Reject Null
$\mu(BS) = \mu(H1)$	$\mu(BS) < \mu(H1)$	16	15	4.83	-1.75	≈0.00	Accept Null	88	-	35	Accept Null
$\mu(BS) = \mu(H1)$	$\mu(BS) > \mu(H1)$	16	15	4.83	1.75	≈1.00	Reject Null	-	0	35	Reject Null
$\mu(BS) = \mu(H2)$	$\mu(BS) \neq \mu(H2)$	16	15	3.43	±2.13	≈0.85	Reject Null	76	0	29	Reject Null
$\mu(BS) = \mu(H2)$	$\mu(BS) < \mu(H2)$	16	15	3.43	-1.75	≈0.00	Accept Null	76	-	35	Accept Null
$\mu(BS) = \mu(H2)$	$\mu(BS) > \mu(H2)$	16	15	3.43	1.75	≈0.90	Reject Null	-	0	35	Reject Null
$\mu(BS) = \mu(H3)$	$\mu(BS) \neq \mu(H3)$	16	15	2.39	±2.13	≈0.60	Reject Null	46	0	29	Reject Null
$\mu(BS) = \mu(H3)$	$\mu(BS) < \mu(H3)$	16	15	2.39	-1.75	≈0.01	Accept Null	46	-	35	Accept Null
$\mu(BS) = \mu(H3)$	$\mu(BS) > \mu(H3)$	16	15	2.39	1.75	≈0.75	Reject Null	-	0	35	Reject Null
$\mu(BS) = \mu(H4)$	$\mu(BS) \neq \mu(H4)$	16	-15	2.44	±2.13	≈0.60	Reject Null	70	0	29	Reject Null
$\mu(BS) = \mu(H4)$	$\mu(BS) < \mu(H4)$	16	15	2.44	-1.75	≈0.01	Accept Null	70	-	35	Accept Null
$\mu(BS) = \mu(H4)$	$\mu(BS) > \mu(H4)$	16	15	2.44	1.75	≈0.75	Reject Null	-	0	35	Reject Null
$\mu(BEST) = \mu(H1)$	$\mu(BEST) \neq \mu(H1)$	13	12	2.62	±2.18	≈0.60	Reject Null	76	14	17	Reject Null
$\mu(BEST) = \mu(H1)$	$\mu(BEST) < \mu(H1)$	13	12	2.62	-1.78	≈0.01	Accept Null	76	-	21	Accept Null
$\mu(BEST) = \mu(H1)$	$\mu(BEST) > \mu(H1)$	13	12	2.62	1.78	≈0.75	Reject Null	-	14	21	Reject Null
$\mu(BEST) = \mu(H2)$	$\mu(BEST) \neq \mu(H2)$	13	12	1.66	±2.18	≈0.30	Accept Null	67	25	17	Accept Null
$\mu(BEST) = \mu(H2)$	$\mu(BEST) < \mu(H2)$	13	12	1.66	-1.78	≈0.02	Accept Null	67	-	21	Accept Null
$\mu(BEST) = \mu(H2)$	$\mu(BEST) > \mu(H2)$	13	12	1.66	1.78	≈0.45	Accept Null	-	25	21	Accept Null
$\mu(BEST) = \mu(H3)$	$\mu(BEST) \neq \mu(H3)$	13	12	0.15	±2.18	≈0.05	Accept Null	44	47	17	Accept Null
$\mu(BEST) = \mu(H3)$	$\mu(BEST) < \mu(H3)$	13	12	0.15	-1.78	≈0.05	Accept Null	44	-	21	Accept Null
$\mu(BEST) = \mu(H3)$	$\mu(BEST) > \mu(H3)$	13	12	0.15	1.78	≈0.10	Accept Null	-	47	21	Accept Null
$\mu(BEST) = \mu(H4)$	$\mu(BEST) \neq \mu(H4)$	13	12	0.11	±2.18	≈0.05	Accept Null	45	46	17	Accept Null
$\mu(BEST) = \mu(H4)$	$\mu(BEST) < \mu(H4)$	13	12	0.11	-1.78	≈0.05	Accept Null	45	-	21	Accept Null
$\mu(BEST) = \mu(H4)$	$\mu(BEST) > \mu(H4)$	13	12	0.11	1.78	≈0.05	Accept Null	-	46	21	Accept Null
$\mu(BEST) = \mu(BS)$	$\mu(BEST) \neq \mu(BS)$	13	12	-1.81	±2.18	≈0.35	Accept Null	22	69	17	Accept Null
$\mu(BEST) = \mu(BS)$	$\mu(BEST) < \mu(BS)$	13	12	-1.81	-1.78	≈0.55	Reject Null	22	-	21	Accept Null
$\mu(BEST) = \mu(BS)$	$\mu(BEST) > \mu(BS)$	13	12	-1.81	1.78	≈0.02	Accept Null	-	69	21	Accept Null
$\mu(INITIAL) = \mu(H1)$	$\mu(INITIAL) \neq \mu(H1)$	13	12	-1.55	±2.18	≈0.25	Accept Null	22	68	17	Accept Null
$\mu(INITIAL) = \mu(H1)$	$\mu(INITIAL) < \mu(H1)$	13	12	-1.55	-1.78	≈0.40	Accept Null	22	-	21	Accept Null
$\mu(INITIAL) = \mu(H1)$	$\mu(INITIAL) > \mu(H1)$	13	12	-1.55	1.78	≈0.02	Accept Null	-	68	21	Accept Null
$\mu(INITIAL) = \mu(H2)$	$\mu(INITIAL) \neq \mu(H2)$	13	12	-2.25	±2.18	≈0.55	Reject Null	15	75	17	Reject Null
$\mu(INITIAL) = \mu(H2)$	$\mu(INITIAL) < \mu(H2)$	13	12	-2.25	-1.78	≈0.65	Reject Null	15	-	21	Reject Null
$\mu(INITIAL) = \mu(H2)$	$\mu(INITIAL) > \mu(H2)$	13	12	-2.25	1.78	≈0.01	Accept Null	-	75	21	Accept Null
$\mu(INITIAL) = \mu(H3)$	$\mu(INITIAL) \neq \mu(H3)$	13	12	-3.07	±2.18	≈0.75	Reject Null	12	80	17	Reject Null
$\mu(INITIAL) = \mu(H3)$	$\mu(INITIAL) < \mu(H3)$	13	12	-3.07	-1.78	≈0.85	Reject Null	12	-	21	Reject Null
$\mu(INITIAL) = \mu(H3)$	$\mu(INITIAL) > \mu(H3)$	13	12	-3.07	1.78	≈0.00	Accept Null	-	80	21	Accept Null
$\mu(INITIAL) = \mu(H4)$	$\mu(INITIAL) \neq \mu(H4)$	13	12	-3.76	±2.18	≈0.90	Reject Null	6	85	17	Reject Null
$\mu(INITIAL) = \mu(H4)$	$\mu(INITIAL) < \mu(H4)$	13	12	-3.76	-1.78	≈0.95	Reject Null	6	-	21	Reject Null
$\mu(INITIAL) = \mu(H4)$	$\mu(INITIAL) > \mu(H4)$	13	12	-3.76	1.78	≈0.00	Accept Null	-	85	21	Accept Null
$\mu(INITIAL) = \mu(BS)$	$\mu(INITIAL) \neq \mu(BS)$	13	12	-7.08	±2.18	≈1.00	Reject Null	0	91	17	Reject Null
$\mu(INITIAL) = \mu(BS)$	$\mu(INITIAL) < \mu(BS)$	13	12	-7.08	-1.78	≈1.00	Reject Null	0	-	21	Reject Null
$\mu(INITIAL) = \mu(BS)$	$\mu(INITIAL) > \mu(BS)$	13	12	-7.08	1.78	≈0.00	Accept Null	-	91	21	Accept Null

Table A.11: Tests of hypothesis related with the means of objective values of the problems in pooled control group.

See Notes #5 for further explanation.

Null Hypothesis	Alternative Hypothesis	N	Paired-t Test DF	t-stat	Table	Power	Decision	Wilcoxon Signed-Rank Test R+	R-	R*	Decision
$\mu(BS) = \mu(H1)$	$\mu(BS) \neq \mu(H1)$	32	31	4.29	±2.04	≈1.00	Reject Null	450	0	159	Reject Null
$\mu(BS) = \mu(H1)$	$\mu(BS) < \mu(H1)$	32	31	4.29	-1.70	≈0.01	Accept Null	450	-	175	Accept Null
$\mu(BS) = \mu(H1)$	$\mu(BS) > \mu(H1)$	32	31	4.29	1.70	≈1.00	Reject Null	-	0	175	Reject Null
$\mu(BS) = \mu(H2)$	$\mu(BS) \neq \mu(H2)$	32	31	3.48	±2.04	≈0.90	Reject Null	423	0	159	Reject Null
$\mu(BS) = \mu(H2)$	$\mu(BS) < \mu(H2)$	32	31	3.48	-1.70	≈0.01	Accept Null	423	-	175	Accept Null
$\mu(BS) = \mu(H2)$	$\mu(BS) > \mu(H2)$	32	31	3.48	1.70	≈0.95	Reject Null	-	0	175	Reject Null
$\mu(BS) = \mu(H3)$	$\mu(BS) \neq \mu(H3)$	32	31	3.12	±2.04	≈0.85	Reject Null	392	0	159	Reject Null
$\mu(BS) = \mu(H3)$	$\mu(BS) < \mu(H3)$	32	31	3.12	-1.70	≈0.03	Accept Null	392	-	175	Accept Null
$\mu(BS) = \mu(H3)$	$\mu(BS) > \mu(H3)$	32	31	3.12	1.70	≈0.90	Reject Null	-	0	175	Reject Null
$\mu(BS) = \mu(H4)$	$\mu(BS) \neq \mu(H4)$	32	31	3.28	±2.04	≈0.90	Reject Null	450	0	159	Reject Null
$\mu(BS) = \mu(H4)$	$\mu(BS) < \mu(H4)$	32	31	3.28	-1.70	≈0.02	Accept Null	450	-	175	Accept Null
$\mu(BS) = \mu(H4)$	$\mu(BS) > \mu(H4)$	32	31	3.28	1.70	≈0.95	Reject Null	-	0	175	Reject Null
$\mu(BEST) = \mu(H1)$	$\mu(BEST) \neq \mu(H1)$	29	28	4.05	±2.05	≈0.90	Reject Null	362	52	126	Reject Null
$\mu(BEST) = \mu(H1)$	$\mu(BEST) < \mu(H1)$	29	28	4.05	-1.70	≈0.01	Accept Null	362	-	140	Accept Null
$\mu(BEST) = \mu(H1)$	$\mu(BEST) > \mu(H1)$	29	28	4.05	1.70	≈0.95	Reject Null	-	52	140	Reject Null
$\mu(BEST) = \mu(H2)$	$\mu(BEST) \neq \mu(H2)$	29	28	3.34	±2.05	≈0.85	Reject Null	350	79	126	Reject Null
$\mu(BEST) = \mu(H2)$	$\mu(BEST) < \mu(H2)$	29	28	3.34	-1.70	≈0.01	Accept Null	350	-	140	Accept Null
$\mu(BEST) = \mu(H2)$	$\mu(BEST) > \mu(H2)$	29	28	3.34	1.70	≈0.95	Reject Null	-	79	140	Reject Null
$\mu(BEST) = \mu(H3)$	$\mu(BEST) \neq \mu(H3)$	29	28	1.87	±2.05	≈0.50	Accept Null	320	113	126	Reject Null
$\mu(BEST) = \mu(H3)$	$\mu(BEST) < \mu(H3)$	29	28	1.87	-1.70	≈0.03	Accept Null	320	-	140	Accept Null
$\mu(BEST) = \mu(H3)$	$\mu(BEST) > \mu(H3)$	29	28	1.87	1.70	≈0.60	Reject Null	-	113	140	Reject Null
$\mu(BEST) = \mu(H4)$	$\mu(BEST) \neq \mu(H4)$	29	28	2.12	±2.05	≈0.60	Reject Null	330	105	126	Reject Null
$\mu(BEST) = \mu(H4)$	$\mu(BEST) < \mu(H4)$	29	28	2.12	-1.70	≈0.02	Accept Null	330	-	140	Accept Null
$\mu(BEST) = \mu(H4)$	$\mu(BEST) > \mu(H4)$	29	28	2.12	1.70	≈0.65	Reject Null	-	105	140	Reject Null
$\mu(BEST) = \mu(BS)$	$\mu(BEST) \neq \mu(BS)$	29	28	0.02	±2.05	≈0.05	Accept Null	229	192	126	Accept Null
$\mu(BEST) = \mu(BS)$	$\mu(BEST) < \mu(BS)$	29	28	0.02	-1.70	≈0.05	Accept Null	229	-	140	Accept Null
$\mu(BEST) = \mu(BS)$	$\mu(BEST) > \mu(BS)$	29	28	0.02	1.70	≈0.05	Accept Null	-	192	140	Accept Null
$\mu(INITIAL) = \mu(H1)$	$\mu(INITIAL) \neq \mu(H1)$	29	28	-0.42	±2.05	≈0.05	Accept Null	187	239	126	Accept Null
$\mu(INITIAL) = \mu(H1)$	$\mu(INITIAL) < \mu(H1)$	29	28	-0.42	-1.70	≈0.05	Accept Null	187	-	140	Accept Null
$\mu(INITIAL) = \mu(H1)$	$\mu(INITIAL) > \mu(H1)$	29	28	-0.42	1.70	≈0.05	Accept Null	-	239	140	Accept Null
$\mu(INITIAL) = \mu(H2)$	$\mu(INITIAL) \neq \mu(H2)$	29	28	-1.10	±2.05	≈0.10	Accept Null	161	269	126	Accept Null
$\mu(INITIAL) = \mu(H2)$	$\mu(INITIAL) < \mu(H2)$	29	28	-1.10	-1.70	≈0.05	Accept Null	161	-	140	Accept Null
$\mu(INITIAL) = \mu(H2)$	$\mu(INITIAL) > \mu(H2)$	29	28	-1.10	1.70	≈0.25	Accept Null	-	269	140	Accept Null
$\mu(INITIAL) = \mu(H3)$	$\mu(INITIAL) \neq \mu(H3)$	29	28	-1.44	±2.05	≈0.30	Accept Null	175	260	126	Accept Null
$\mu(INITIAL) = \mu(H3)$	$\mu(INITIAL) < \mu(H3)$	29	28	-1.44	-1.70	≈0.02	Accept Null	175	-	140	Accept Null
$\mu(INITIAL) = \mu(H3)$	$\mu(INITIAL) > \mu(H3)$	29	28	-1.44	1.70	≈0.45	Accept Null	-	269	140	Accept Null
$\mu(INITIAL) = \mu(H4)$	$\mu(INITIAL) \neq \mu(H4)$	29	28	-1.52	±2.05	≈0.30	Accept Null	171	265	126	Accept Null
$\mu(INITIAL) = \mu(H4)$	$\mu(INITIAL) < \mu(H4)$	29	28	-1.52	-1.70	≈0.01	Accept Null	171	-	140	Accept Null
$\mu(INITIAL) = \mu(H4)$	$\mu(INITIAL) > \mu(H4)$	29	28	-1.52	1.70	≈0.45	Accept Null	-	265	140	Accept Null
$\mu(INITIAL) = \mu(BS)$	$\mu(INITIAL) \neq \mu(BS)$	29	28	-3.42	±2.05	≈0.90	Reject Null	83	347	126	Reject Null
$\mu(INITIAL) = \mu(BS)$	$\mu(INITIAL) < \mu(BS)$	29	28	-3.42	-1.70	≈0.01	Reject Null	83	-	140	Reject Null
$\mu(INITIAL) = \mu(BS)$	$\mu(INITIAL) > \mu(BS)$	29	28	-3.42	1.70	≈0.95	Accept Null	-	347	140	Accept Null

Table A.12: Average power statistics for hypothesis tests.

	Control Group I			Control Group II			Pooled Control Group		
	Total	Reject	Accept	Total	Reject	Accept	Total	Reject	Accept
$\neq$	0.63	0.75	0.22	0.56	0.76	0.20	0.59	0.86	0.22
$<$	0.01	...	0.01	0.33	0.80	0.06	0.02	0.01	0.02
$>$	0.72	0.86	0.22	0.34	0.83	0.07	0.65	0.87	0.37

Table A.13: Heuristic results for medium sized problems.

See Notes #6 for further explanation.

Problem Identifier	Heuristic1 Obj.Val.	Heuristic2 Obj.Val.	Heuristic3 Obj.Val.	Heuristic4 Obj.Val.	Best Strategy
M10N15O12-01	0.83	0.87	0.87	0.87	0.87
M10N15O12-02	0.88	0.86	0.87	0.86	0.88
M10N15O12-03	0.82	0.84	0.78	0.88	0.88
M10N15O12-04	0.82	0.84	0.79	0.87	0.87
M10N15O12-05	0.88	0.87	0.86	0.88	0.88
M10N15O12-06	0.83	0.87	0.83	0.88	0.88
M10N15O12-07	0.85	0.87	0.81	0.87	0.87
M10N15O12-08	0.87	0.86	0.87	0.86	0.87
M10N15O12-09	0.87	0.82	0.86	0.87	0.87
M10N15O12-10	0.77	0.87	0.74	0.88	0.88
AVERAGE	0.84	0.86	0.83	0.87	0.87

....	:	PROBLEM GENERATION PARAMETERS
5	:	Number of Machines in the System
5	:	Number of Part Types in the System
0	:	Number of Tool Duplications in the System
60	:	Capacity of the Tool Magazine in Slots
9600	:	Planning Period Length in Time Units
80.00	:	Planned System Efficiency for Maximum Production
8 13	:	Limits for Operation Number of a Part Type
3.0 16.0	:	Limits for Processing Times in Time Units
3 8	:	Limits for Requirements of Tools in Slots
1.0 6.0	:	Limits for Production Ratios of Part Types
123456789	:	Random Number Generator Seed
.0 0 1 1 1 1	:	Generation Flow Control Parameters

Figure A.1: The input parameter file for problem generation procedure.

Number of Machines in the System	:	5
Number of Part Types in the System	:	5
Number of Tool Duplications Requested in the System	:	0
Capacity of the Tool Magazine in Slots	:	60
Planning Period Length in Time Units	:	9600
Planned System Efficiency for Maximum Production %	:	80.00
Lower,Upper Limits of Operation Number for a Part Type	:	8 13
Lower,Upper Limits for Processing Times in Time Units	:	3.0 16.0
Lower,Upper Limits for Requirements of Tools in Slots	:	3 8
Lower,Upper Limit for Production Ratios of Part Types	:	1.0 6.0
Initial Random Number Generator Seed	:	123456784.0

Computation of # of Operations of Part Types

9 8 8 10 8

Computation of Processing Times of Part Types

Part Type	:	1	>	15.3	9.5	10.8	15.8	12.0	10.8	10.5	6.5	9.4		
Part Type	:	2	>	5.0	3.6	14.6	6.3	10.8	13.1	3.2	5.9			
Part Type	:	3	>	7.6	8.2	13.7	4.9	5.7	7.8	8.8	14.3			
Part Type	:	4	>	9.4	4.7	8.6	14.1	8.7	15.3	11.1	4.8	4.3	12.2	
Part Type	:	5	>	9.1	5.4	4.2	3.4	8.4	11.1	5.6	7.7			

Computation of Production Ratios & Production Volumes

89 106 115 128 47

Computation of Slot Requirements for Tools

7 3 6 4 4 5 3 3 7 4 6 7 7 5 3 3 7 3 6 3 4 5 6 5 4 3 7 5 4 6 3 7 7 5 7 6 3 7 6 7 3 3 3

Computation of Tool Requirements for Operations

Part Type	:	1	>	36	42	9	40	22	29	41	15	43	
Part Type	:	2	>	3	35	10	6	1	21	18	2		
Part Type	:	3	>	5	25	30	23	28	32	38	31		
Part Type	:	4	>	4	13	7	37	34	8	17	11	33	16
Part Type	:	5	>	12	39	14	20	19	24	26	27		

Computation of Duplications for Tools

1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1

Identification of Duplicted Tools

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

Identification of Sharing Operations

Part Type	:	1	>	1	1	1	1	1	1	1	1	1	
Part Type	:	2	>	1	1	1	1	1	1	1	1		
Part Type	:	3	>	1	1	1	1	1	1	1	1		
Part Type	:	4	>	1	1	1	1	1	1	1	1	1	1
Part Type	:	5	>	1	1	1	1	1	1	1	1		

Figure A.2: The generated data of a sample problem.

BEST STRATEGY SOLUTION REPORT

		Assigned Machines for operations									
Part 1	>	1	1	1	1	2	2	2	2	3	
Part 2	>	1	3	4	4	4	5	5	5		
Part 3	>	1	1	2	2	2	3	3	3		
Part 4	>	2	3	3	4	4	5	5	5	5	5
Part 5	>	1	3	3	3	3	4	4	4		

Objective : 76.53
Machine 1 > 76.53 73.33
Machine 2 > 78.54 60.00
Machine 3 > 77.90 95.00
Machine 4 > 77.44 65.00
Machine 5 > 88.09 60.00

Figure A.3: Sample output of heuristic loading procedure..

....	SIMULATION PARAMETERS
1	Control System Type : PUSH(1) / PULL(2) / CONWIP(3)
10	Work In Process Inventory Levels Between Machines
10	Safety Stock Level For Finished Product
1	Production Lot Size
0	Setup/Processing Time Ratio
2 0 0 0 0	Demand Distribution : Type / 1.Parameter / 2.Parameter
123456789	Seed For Demands
0 0 0 0 0	Processing Distribution : Type / 1.Pparameter / 2.Parameter
123456789	Seed For Processing Times
2 1750 0 0 0	Failure Distribution : Type / 1.Parameter / 2.Parameter
123456789	Seed For Failures
5 17.4 14.4 0 0	Repair Distribution : Type / 1.Parameter / 2.Parameter
123456789	Seed For Repairs
2400	Clear Statistics Time
28800	Simulation Ending Time
3	Number Of Duplicate Runs
101	Outout File Name Extension
....	PROBLEM GENERATION PARAMETERS
2	Control System Type : PUSH(1) / PULL(2) / CONWIP(3)
10	Work In Process Inventory Levels Between Machines
10	Safety Stock Level For Finished Product
1	Production Lot Size
0	Setup/Processing Time Ratio
2 0 0 0 0	Demand Distribution : Type / 1.Parameter / 2.Parameter
123456789	Seed For Demands
0 0 0 0 0	Processing Distribution : Type / 1.Pparameter / 2.Parameter
123456789	Seed For Processing Times
2 1750 0 0 0	Failure Distribution : Type / 1.Parameter / 2.Parameter
123456789	Seed For Failures
5 17.4 14.4 0 0	Repair Distribution : Type / 1.Parameter / 2.Parameter
123456789	Seed For Repairs
2400	Clear Statistics Time
28800	Simulation Ending Time
3	Number Of Duplicate Runs
201	Outout File Name Extension
....	PROBLEM GENERATION PARAMETERS
3	Control System Type : PUSH(1) / PULL(2) / CONWIP(3)
10	Work In Process Inventory Levels Between Machines
10	Safety Stock Level For Finished Product
1	Production Lot Size
0	Setup/Processing Time Ratio
2 0 0 0 0	Demand Distribution : Type / 1.Parameter / 2.Parameter
123456789	Seed For Demands
0 0 0 0 0	Processing Distribution : Type / 1.Pparameter / 2.Parameter
123456789	Seed For Processing Times
2 1750 0 0 0	Failure Distribution : Type / 1.Parameter / 2.Parameter
123456789	Seed For Failures
5 17.4 14.4 0 0	Repair Distribution : Type / 1.Parameter / 2.Parameter
123456789	Seed For Repairs
2400	Clear Statistics Time
28800	Simulation Ending Time
3	Number Of Duplicate Runs
301	Outout File Name Extension
END SIMULATION..........	

Figure A.4: The input parameter file for problem simulation procedure.

```
SIMULATION RESULTS

CONTROL SYSTEM TYPE                      PULL .
WIP INVENTORY LEVEL                          10
SS INVENTORY LEVEL                           10
PRODUCTION LOT SIZE                           1
SETUP/PROCESSING RATIO                      0.0
DEMAND DISTRIBUTION               EXPONENTIAL .
PROCESSING DISTRIBUTION              CONSTANT .
FAILURE DISTRIBUTION              EXPONENTIAL .
REPAIR DISTRIBUTION                     GAMMA .
STATISTICS CLEAR TIME                    2400.0
SIMULATION DURATION                     28800.0
TOTAL # OF SIMULATION RUNS                    3

*****************************************************************
*****SIMULATION RUN # : 1 / 3***********************************
*****************************************************************

PERIOD'S AGGREGATED STATISTICS

AGGREGATED AVERAGE INVENTORY UNIT      :   18.51
AGGREGATED AVERAGE STOCKOUT UNIT       :    2.02
AGGREGATED AVERAGE STOCKOUT PERIOD     :  168.24
AGGREGATED SERVICE LEVEL ( % )         :   95.72
AVERAGE MACHINE UTILIZATION ( % )      :   76.98

*****************************************************************
*****SIMULATION RUN # : 2 / 3***********************************
*****************************************************************

PERIOD'S AGGREGATED STATISTICS

AGGREGATED AVERAGE INVENTORY UNIT          17.17
AGGREGATED AVERAGE STOCKOUT UNIT            2.25
AGGREGATED AVERAGE STOCKOUT PERIOD        178.57
AGGREGATED SERVICE LEVEL ( % )             94.57
AVERAGE MACHINE UTILIZATION ( % )          78.02

*****************************************************************
*****SIMULATION RUN # : 3 / 3***********************************
*****************************************************************

PERIOD'S AGGREGATED STATISTICS

AGGREGATED AVERAGE INVENTORY UNIT          17.39
AGGREGATED AVERAGE STOCKOUT UNIT            1.67
AGGREGATED AVERAGE STOCKOUT PERIOD        135.82
AGGREGATED SERVICE LEVEL ( % )             98.12
AVERAGE MACHINE UTILIZATION ( % )          78.27

___________________________________________
___________________________________________

CUMMULATIVE AGGREGATED STATISTICS

AGGREGATED AVERAGE INVENTORY UNIT          17.69
AGGREGATED AVERAGE STOCKOUT UNIT            1.98
AGGREGATED AVERAGE STOCKOUT PERIOD        160.88
AGGREGATED SERVICE LEVEL ( % )             96.14
AVERAGE MACHINE UTILIZATION ( % )          77.76

___________________________________________
___________________________________________
```

Figure A.5: Sample output of simulation procedure..

Table A.14: Experimentation parameters for the impact of loading techniques.

EXPERIMENTATION PARAMETERS

IMPACT : LOADING TECHNIQUES

PROBLEM GENERATION

Number of machines	:	5
Number of part types	:	5
Number of operations	:	Uniform(8,12)
Processing times	:	Uniform(3,15)
Poduction ratios	:	Uniform(1,5)
Planning period length	:	9600
Average capacity utilization	:	80 %
Tool magazine capacity	:	60
Slot requirements	:	Uniform(3,7)
Number of tool sharings	:	0

SIMULATION

Control strategy	:	PUSH,PULL,CONWIP
Wip inventory level	:	1..13
SS inventory level	:	1..13
Production lot size	:	1
Setup/processing time ratio	:	0
Demand inter-arrival time distribution	:	Exponential(..)
Processing time distribution	:	Constant(..)
Failure time distribution	:	Exponential(1/1750)
Repair time distribution	:	Gamma(17.4,14.4)
Statistics clear time	:	2400
Simulation end time	:	28800
Number of replications	:	10

Table A.15: Evaluation of loading solutions in terms of alternative objectives.

See Note # 7 for further explanation.

	HEURISTIC LOADING					BALANCED LOADING					LOADING WITH LESS BUFFER POINTS				
No	Obj.1	Obj.2	Util.1	Util.2	Util.3	Obj.1	Obj.2	Util.1	Util.2	Util.3	Obj.1	Obj.2	Util.1	Util.2	Util.3
1	11.56	17.00	81.37	77.53	76.84	1.34	14.00	81.83	78.98	78.50	29.05	9.00	80.15	77.84	78.45
2	10.54	16.00	82.19	77.87	73.91	2.43	15.00	81.99	78.42	70.46	25.20	11.00	78.90	76.73	76.15
3	9.49	18.00	82.90	78.18	75.38	2.24	15.00	81.57	77.67	74.83	39.45	13.00	79.66	75.53	76.03
4	5.43	17.00	81.93	79.33	75.02	12.49	13.00	81.62	79.51	75.11	22.72	9.00	78.90	76.46	77.05
5	7.39	15.00	81.54	78.61	75.01	3.61	19.00	82.08	78.88	69.77	9.66	8.00	80.40	78.86	72.49
6	10.54	19.00	82.52	78.53	74.97	1.94	15.00	82.55	79.31	75.30	18.53	9.00	80.35	77.29	78.45
7	3.78	17.00	81.92	78.36	72.28	1.15	17.00	81.65	78.30	68.81	27.88	13.00	79.14	76.69	73.40
8	4.95	16.00	82.27	78.53	78.38	2.09	18.00	82.08	79.23	72.04	21.98	6.00	79.45	78.30	76.20
9	5.53	19.00	83.27	78.89	74.70	3.43	11.00	81.55	78.95	73.06	31.69	9.00	79.96	76.32	71.37
Avg.	7.69	17.11	82.21	78.43	75.17	3.41	15.22	81.88	78.81	73.10	25.13	9.67	79.66	77.11	75.51
Std.	2.73	1.29	0.58	0.50	1.61	3.30	2.35	0.31	0.55	2.96	7.96	2.16	0.56	0.99	2.39
C.V.	0.36	0.08	0.01	0.01	0.02	0.97	0.15	0.00	0.01	0.04	0.32	0.22	0.01	0.01	0.03

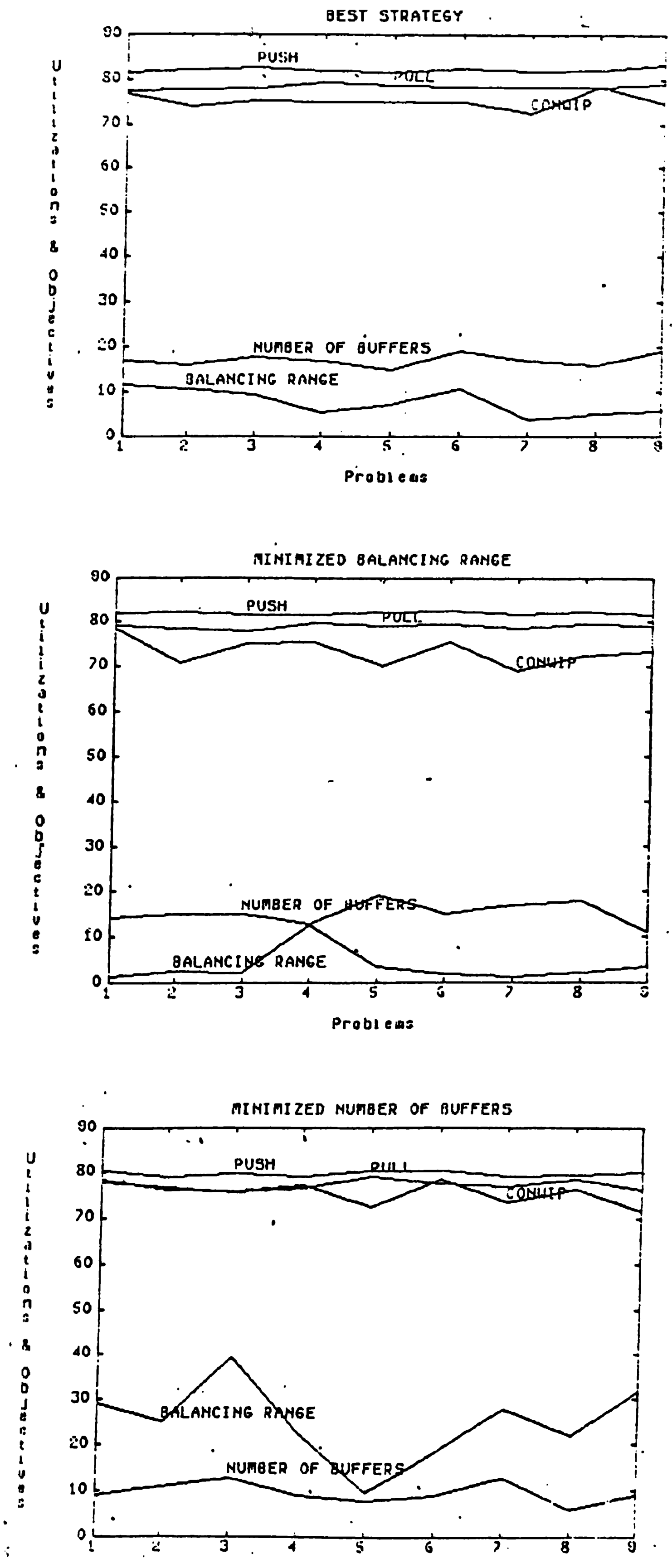

Figure A.6: Evaluation of loading solutions of sample problems according to alternative objectives.

Table A.16: Simulation results for the impact of loading techniques.

See Note # 8 for further explanation.

PUSH WITH HEURISTIC LOADING					PULL WITH HEURISTIC LOADING					CONWIP WITH HEURISTIC LOADING				
WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.
7.59	8.23	507.22	93.94	78.93	1.09	27.56	2857.00	74.91	65.53	0.65	33.20	3208.42	65.26	58.19
9.63	5.99	549.43	94.31	79.32	2.20	18.52	1872.56	84.57	71.58	1.24	24.74	2284.70	77.33	68.59
12.34	4.41	378.65	94.44	79.84	3.49	12.79	1249.80	89.17	74.54	2.05	19.92	1776.41	83.07	70.66
15.58	3.38	294.59	94.36	80.43	4.99	8.84	860.27	91.93	76.26	2.87	16.69	1440.28	86.00	72.68
19.18	2.73	210.73	94.10	81.04	6.89	6.20	555.86	93.53	77.28	3.77	14.16	1192.18	88.02	73.92
23.01	2.37	177.93	93.72	81.64	9.00	4.26	366.32	94.84	78.05	4.68	12.08	991.43	89.48	74.69
26.93	2.13	156.24	93.12	82.21	11.36	3.21	264.99	95.41	78.43	5.64	10.45	839.24	90.49	75.14
30.79	1.90	137.38	92.77	82.75	14.04	2.21	176.61	96.08	78.80	6.62	8.93	708.28	91.31	75.49
34.76	1.80	127.97	92.09	83.27	16.74	1.67	128.25	96.41	79.01	7.62	7.83	610.45	91.96	75.70
38.58	1.61	112.95	91.67	83.74	19.95	1.14	86.36	96.89	79.29	8.68	6.78	524.76	92.55	75.86
42.64	1.66	114.64	91.00	84.17	22.86	0.97	72.25	96.98	79.37	9.80	5.95	450.78	92.90	75.77
46.45	1.57	107.10	90.54	84.56	26.12	0.73	53.44	97.18	79.47	10.88	5.18	391.49	93.32	75.79
50.31	1.54	103.92	89.95	84.30	29.13	0.62	46.40	97.28	79.56	12.03	4.62	350.06	93.59	75.70

PUSH WITH OPTIMAL BALANCE					PULL WITH OPTIMAL BALANCE					CONWIP WITH OPTIMAL BALANCE				
WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.
6.32	7.46	731.51	94.35	79.15	0.84	24.77	2467.50	77.34	67.60	0.70	30.38	2609.97	62.26	57.45
8.12	5.36	492.97	94.68	79.36	1.71	16.32	1581.70	86.81	73.25	1.38	23.82	2253.56	73.72	64.70
10.51	3.87	333.61	94.88	79.77	2.78	11.09	1040.49	90.85	75.63	2.19	19.95	1834.65	78.65	67.79
13.39	2.89	233.95	94.82	80.26	4.10	7.57	689.40	93.12	77.15	3.03	17.57	1586.15	81.65	69.71
16.34	2.05	158.03	94.95	80.79	5.88	5.26	455.98	94.52	77.93	3.88	15.45	1368.25	83.93	71.14
19.83	1.77	128.35	94.24	81.34	7.80	3.84	322.01	95.33	78.35	4.78	13.65	1203.33	85.84	72.35
23.24	1.47	102.63	93.68	81.88	10.02	2.65	214.34	96.06	78.81	5.67	12.15	1054.93	87.15	73.10
26.71	1.27	90.25	93.02	82.41	12.47	1.91	150.06	96.49	79.13	6.61	11.06	944.45	88.16	73.65
30.17	1.12	75.60	92.44	82.91	15.06	1.36	104.28	96.89	79.32	7.58	9.63	816.46	89.06	74.00
33.70	1.06	70.23	91.69	83.39	17.70	1.14	86.71	97.03	79.37	8.61	8.34	691.08	90.17	74.53
37.20	1.03	67.35	91.07	83.83	20.49	0.89	65.35	97.28	79.57	9.62	7.72	638.45	90.43	74.50
40.61	0.96	62.35	90.49	84.23	22.94	0.70	51.66	97.43	79.61	10.59	6.75	551.47	91.04	74.61
43.60	0.97	63.28	89.91	84.60	25.89	0.55	40.12	97.59	79.73	11.73	5.99	478.73	91.58	74.73

PUSH WITH MINIMUM # OF BUFFERS					PULL WITH MINIMUM # OF BUFFERS					CONWIP WITH MINIMUM # OF BUFFERS				
WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.
4.82	8.28	924.44	93.76	78.20	0.49	19.04	1697.78	83.72	69.60	0.43	23.81	2271.34	73.81	65.23
6.03	6.73	635.30	94.02	78.37	1.06	13.03	1304.34	89.49	73.70	0.97	18.79	1567.48	82.21	70.51
7.53	5.56	499.57	94.19	78.59	1.73	10.10	977.97	91.44	75.06	1.56	15.71	1397.44	85.34	72.60
9.20	4.82	399.66	94.34	78.85	2.60	7.88	741.16	92.83	75.97	2.24	14.09	1231.95	87.45	73.97
11.08	4.04	334.97	94.22	79.13	3.63	6.47	593.73	93.53	76.52	3.01	12.52	1067.53	88.81	74.83
13.17	3.51	280.48	94.20	79.40	4.74	5.19	457.14	94.18	77.01	3.71	11.36	955.81	89.47	75.23
15.08	2.98	229.13	94.31	79.66	5.98	4.48	386.10	94.47	77.11	4.50	10.40	870.02	90.04	75.51
17.13	2.64	198.10	94.26	79.89	7.39	3.81	320.27	94.80	77.31	5.33	9.49	782.16	90.55	75.84
19.27	2.40	175.65	94.03	80.12	8.81	3.26	266.05	94.90	77.36	6.19	8.77	718.54	91.14	76.16
21.52	2.29	163.89	93.70	80.35	10.25	2.79	225.29	95.13	77.53	7.00	8.04	653.58	91.37	76.26
23.65	2.11	145.02	93.81	80.57	11.86	2.34	180.77	95.36	77.66	7.89	7.34	607.41	91.71	76.40
25.73	1.88	127.70	93.43	80.77	13.47	2.02	154.74	95.47	77.72	8.79	6.82	550.54	92.00	76.55
27.92	1.81	120.11	93.30	80.97	15.08	1.78	132.24	95.52	77.73	9.72	6.45	515.32	92.06	76.44

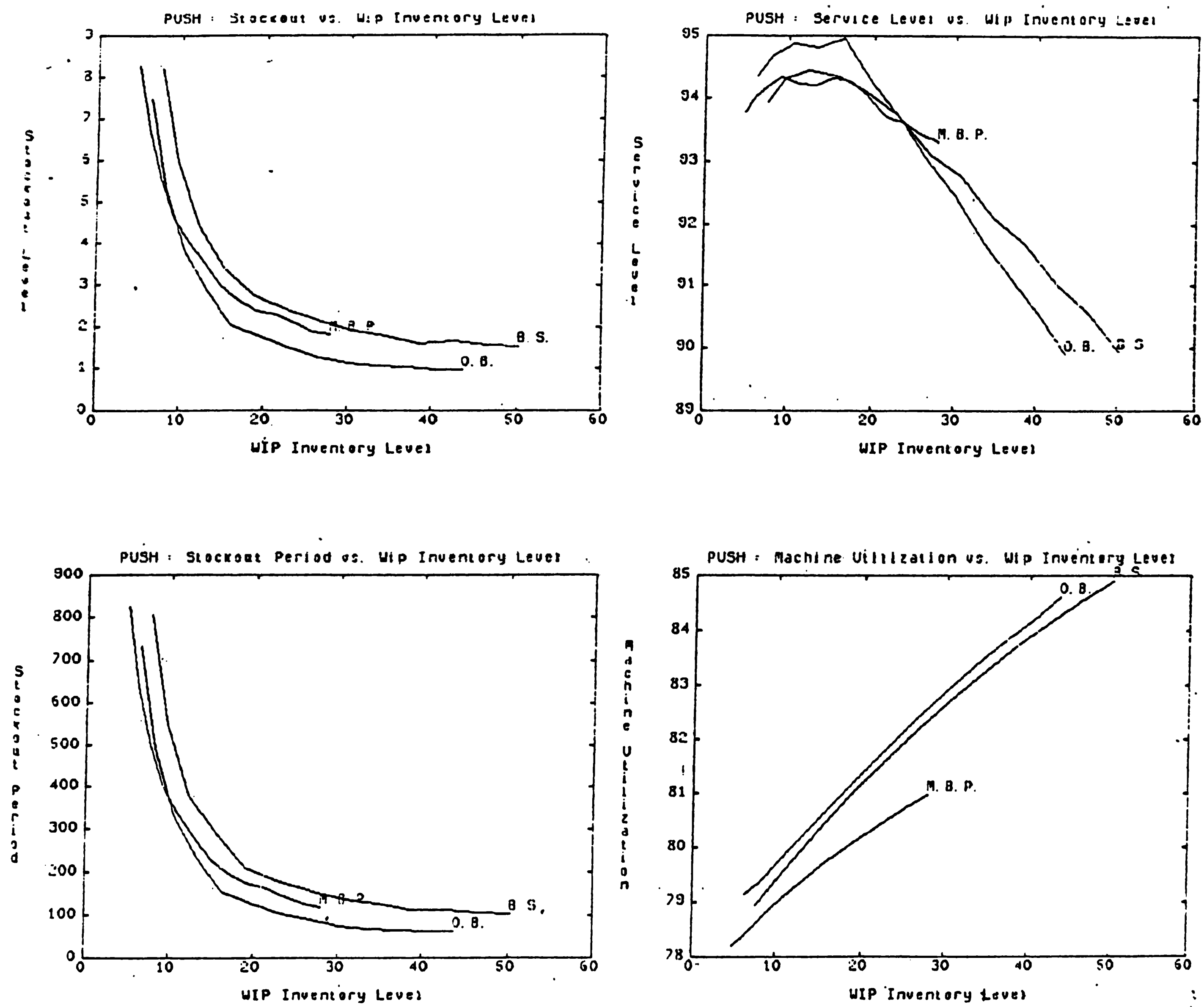

Figure A.7: Evaluation of alternative loading solutions for push control strategy.

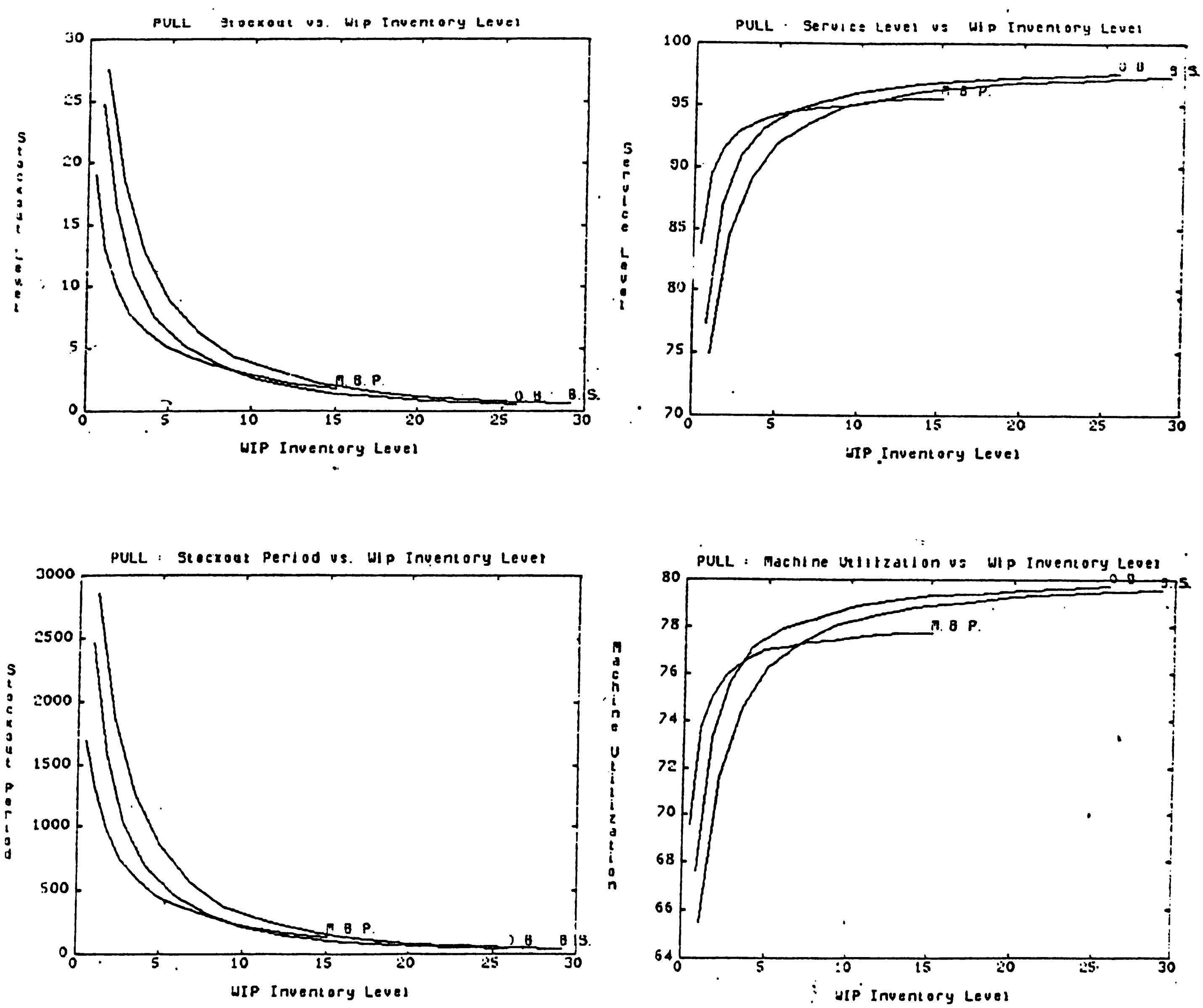

Figure A.8: Evaluation of alternative loading solutions for pull control strategy.

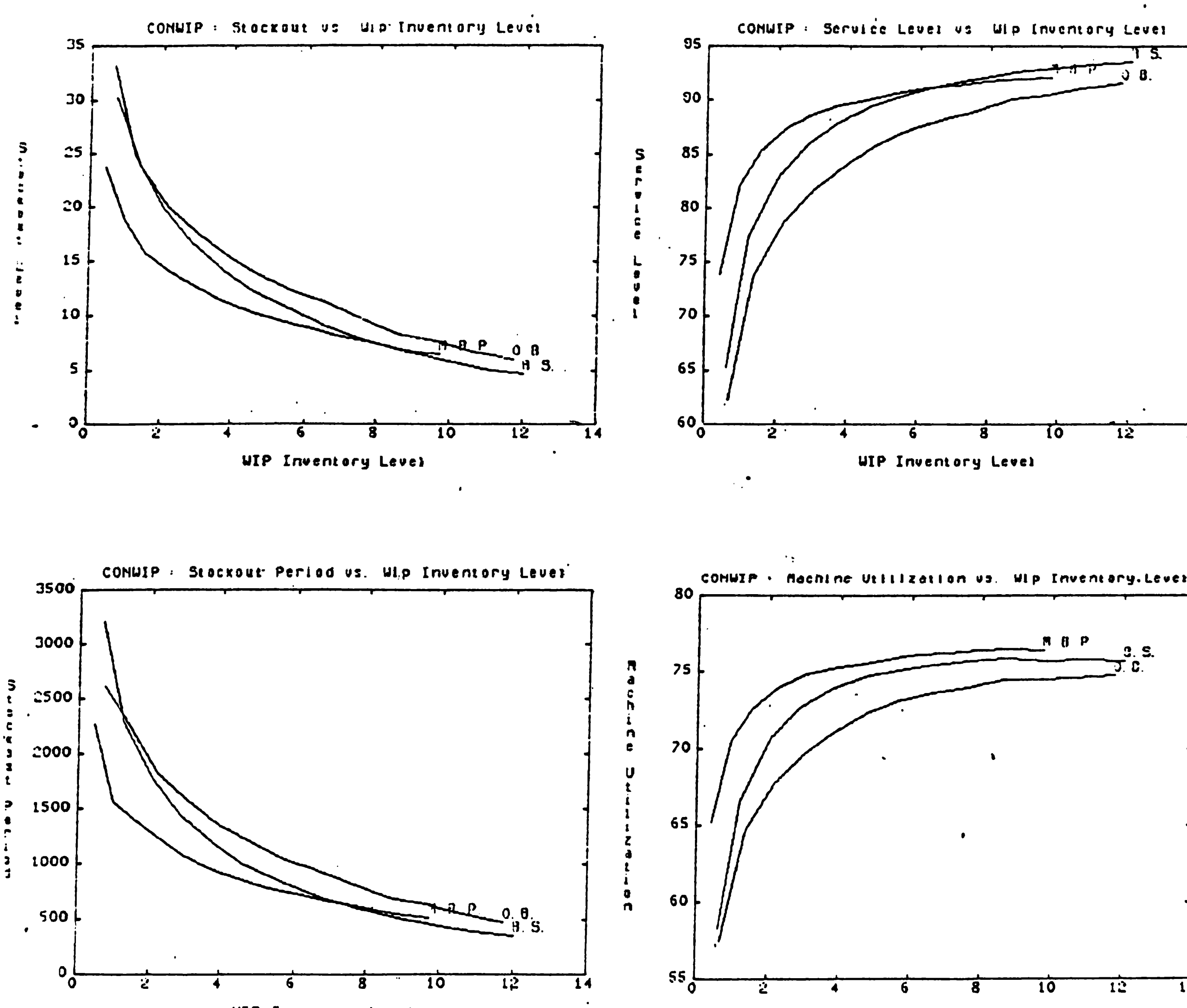

Figure A.9: Evaluation of alternative loading solutions for conwip control strategy.

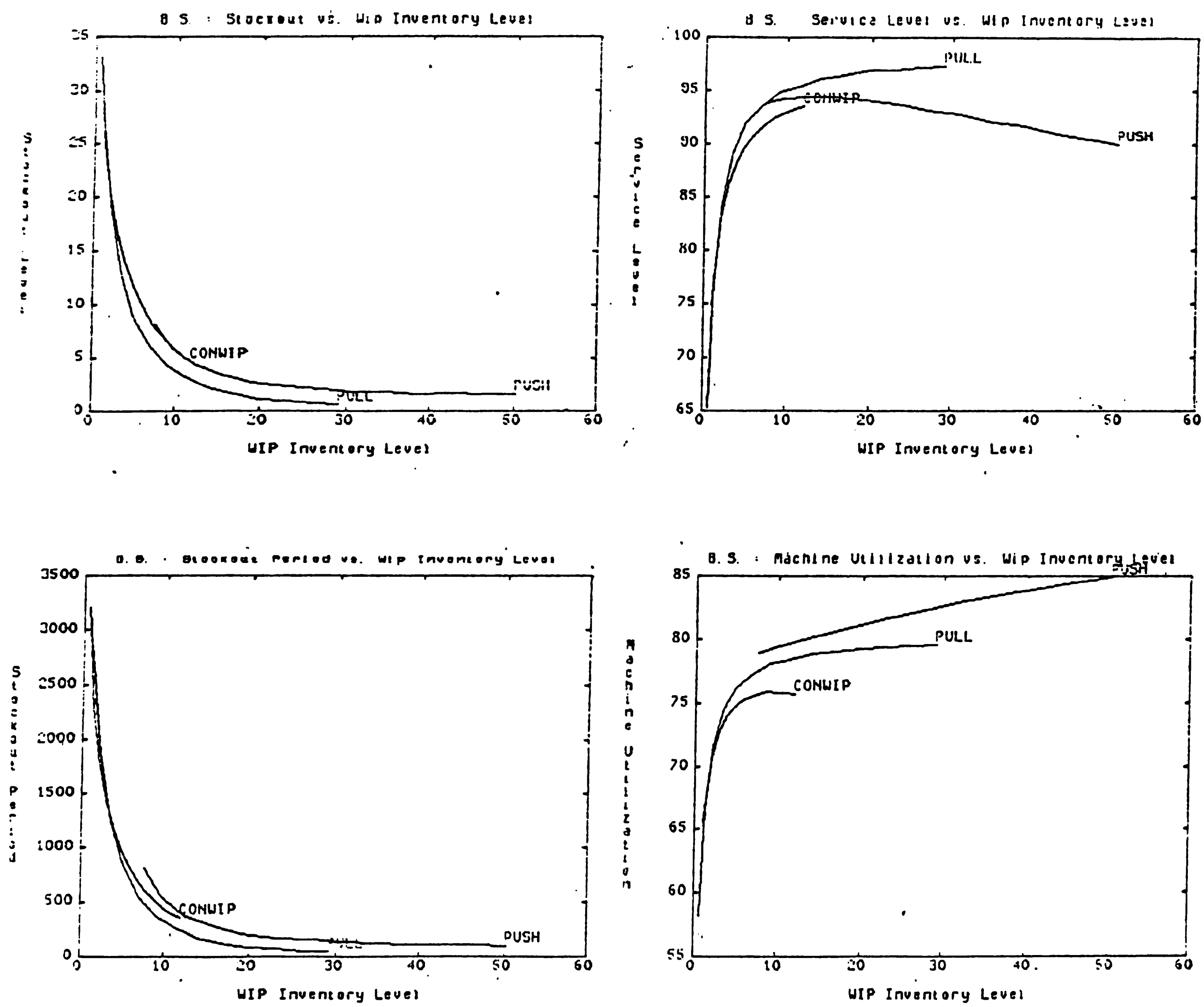

Figure A.10: Evaluation of alternative control strategies for heuristic loading solution.

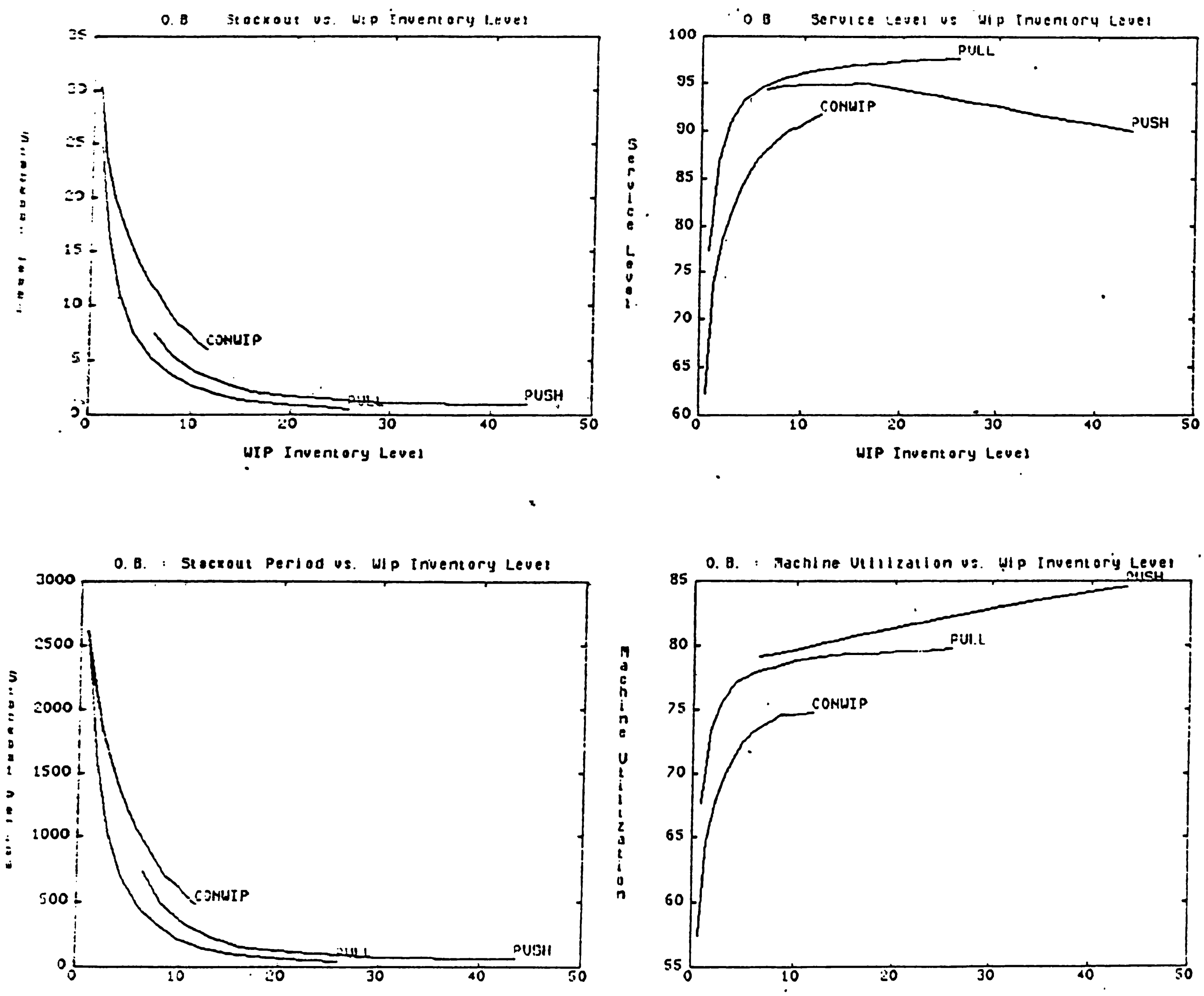

Figure A.11: Evaluation of alternative control strategies for optimized balance of workloads.

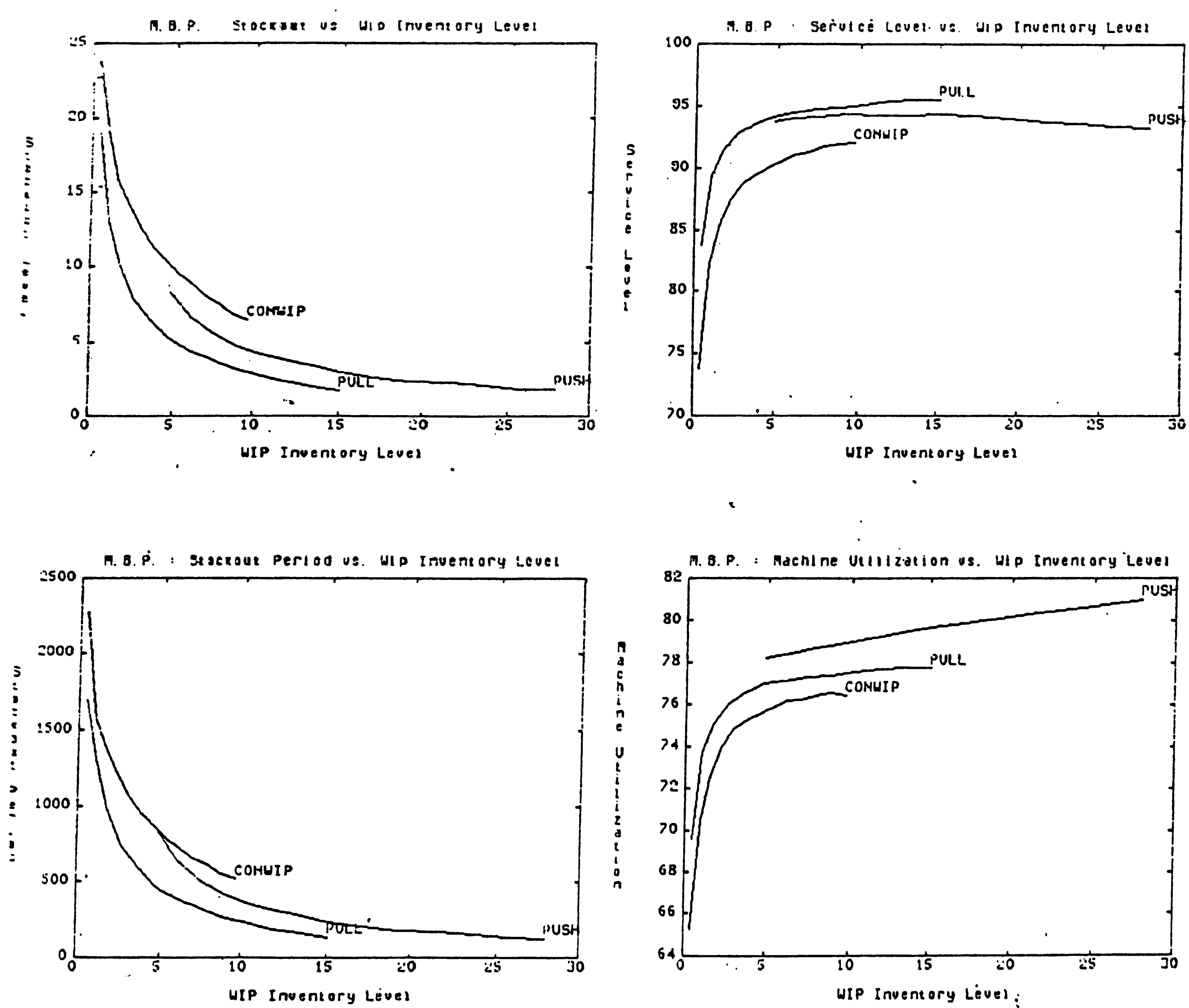

Figure A.12: Evaluation of alternative control strategies for minimized number of buffer points.

Table A.17: Experimentation parameters for the impact of length of the production line.

EXPERIMENTATION PARAMETERS

IMPACT : THE LENGTH OF THE PRODUCTION LINE

PROBLEM GENERATION

Number of machines	:	5,10,15,20
Number of part types	:	5,10,15,20
Number of operations	:	Uniform(8,12)
Processing times	:	Uniform(3,15)
Poduction ratios	:	Uniform(1,5)
Planning period length	:	9600
Average capacity utilization	:	80 %
Tool magazine capacity	:	60
Slot requirements	:	Uniform(3,7)
Number of tool sharings	:	0

SIMULATION

Control strategy	:	PUSH,PULL,CONWIP
Wip inventory level	:	1..13
SS inventory level	:	1..13
Production lot size	:	1
Setup/processing time ratio	:	0
Demand inter-arrival time distribution	:	Exponential(..)
Processing time distribution	:	Constant(..)
Failure time distribution	:	Exponential(1/1750)
Repair time distribution	:	Gamma(17.4,14.4)
Statistics.clear time	:	2400
Simulation end time	:	28800
Number of replications	:	10

Table A.18: Simulation results for the impact of length of the production line.

See Note # 8 for further explanation.

PUSH WITH 5 MACHINES					PULL WITH 5 MACHINES					CONWIP WITH 5 MACHINES				
WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.
7.59	8.23	807.22	93.94	75.93	1.09	27.56	2857.00	74.91	65.53	0.65	33.20	3208.42	65.26	58.19
9.63	5.99	549.43	94.31	79.32	2.20	18.52	1872.56	84.57	71.58	1.24	24.74	2284.70	77.33	66.59
12.34	4.41	378.65	94.44	79.84	3.49	12.79	1249.80	89.17	74.54	2.05	19.92	1776.41	83.07	73.66
15.58	3.38	294.59	94.36	80.43	4.99	8.84	860.27	91.93	76.26	2.87	16.69	1440.28	86.00	72.58
19.18	2.73	210.73	94.10	81.04	6.89	6.20	555.86	93.53	77.28	3.77	14.16	1192.18	88.02	73.92
23.01	2.37	177.93	93.72	81.64	9.00	4.26	366.32	94.84	78.05	4.68	12.08	991.43	89.48	74.69
26.93	2.13	156.24	93.12	82.21	11.36	3.21	264.99	95.41	78.43	5.64	10.45	839.24	90.49	75.14
30.79	1.90	137.34	92.77	82.75	14.04	2.21	176.61	96.08	78.80	6.62	8.93	708.28	91.31	75.49
34.76	1.80	127.97	92.09	83.27	16.74	1.67	128.25	96.41	79.01	7.62	7.83	610.45	91.96	75.70
38.58	1.61	112.95	91.67	83.74	19.95	1.14	86.36	96.89	79.29	8.68	6.78	524.76	92.55	75.86
42.64	1.66	114.64	91.00	84.17	22.86	0.97	72.25	96.98	79.37	9.80	5.95	450.78	92.90	75.77
46.45	1.57	107.10	90.54	84.56	26.12	0.73	53.44	97.18	79.47	10.88	5.18	391.49	93.32	75.79
50.31	1.54	103.92	89.95	84.90	29.13	0.62	46.40	97.28	79.56	12.03	4.62	350.06	93.59	75.70
PUSH WITH 10 MACHINES					PULL WITH 10 MACHINES					CONWIP WITH 10 MACHINES				
WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.
9.46	11.00	1138.53	92.03	78.45	1.37	31.02	3211.91	68.21	62.79	0.84	31.31	2905.50	59.11	53.57
11.95	8.53	814.17	92.75	78.88	2.80	22.31	2245.91	79.07	69.50	1.52	25.45	2241.72	70.13	50.88
15.36	6.93	616.80	93.11	79.50	4.48	16.52	1611.53	84.55	72.89	2.43	21.42	1808.58	76.69	65.63
19.40	5.95	500.61	93.19	80.18	6.38	12.35	1161.57	87.98	75.00	3.33	18.42	1514.20	80.31	67.97
23.79	5.33	427.95	93.07	80.87	8.70	9.37	847.69	90.13	76.30	4.36	15.87	1265.09	83.11	69.78
28.43	4.97	376.47	92.72	81.55	11.23	7.12	618.51	91.74	77.24	5.41	14.10	1108.91	84.89	70.98
33.19	4.76	363.05	92.25	82.19	14.17	5.44	457.70	92.93	78.00	6.55	12.51	972.90	86.30	71.66
38.07	4.69	351.46	91.68	82.79	17.17	4.63	381.42	93.42	78.28	7.74	11.15	851.75	87.50	72.14
42.82	4.57	340.11	91.23	83.31	20.43	3.71	296.31	94.11	78.74	8.99	9.99	754.44	88.40	72.34
47.78	4.66	341.15	90.47	83.78	24.05	2.98	233.56	94.60	78.99	10.32	8.98	665.03	89.18	72.48
52.56	4.65	339.77	90.12	84.19	27.74	2.61	202.68	94.94	79.26	11.70	8.16	599.94	89.77	72.46
57.42	4.72	343.52	89.56	84.55	31.13	2.18	164.37	95.16	79.41	13.16	7.64	555.89	90.22	72.34
62.22	4.78	345.81	89.14	84.85	35.04	1.97	147.15	95.35	79.50	14.69	6.87	493.48	90.79	72.27
PUSH WITH 15 MACHINES					PULL WITH 15 MACHINES					CONWIP WITH 15 MACHINES				
WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.
10.13	11.79	1224.33	91.08	78.42	1.48	31.98	3336.46	64.96	61.08	0.88	31.29	2985.88	56.77	51.30
12.64	8.97	858.72	92.01	78.98	2.94	23.56	2397.29	77.27	68.73	1.55	26.55	2406.65	66.73	58.27
16.17	7.09	634.65	92.60	79.70	4.67	17.61	1717.35	83.15	72.42	2.49	22.84	2008.34	73.71	63.38
20.43	5.93	503.75	92.82	80.49	6.80	13.17	1238.05	86.94	74.82	3.41	20.02	1723.64	77.33	65.85
25.20	5.26	433.21	92.66	81.29	9.27	9.93	896.70	89.46	76.37	4.47	17.57	1486.02	80.28	67.71
30.22	4.86	387.86	92.31	82.03	12.03	7.84	686.67	90.90	77.27	5.56	15.58	1298.61	82.24	68.79
35.40	4.66	366.67	91.73	82.69	15.29	5.93	500.92	92.36	78.15	6.77	13.84	1135.88	83.86	69.56
40.62	4.54	352.19	91.23	83.27	18.68	4.99	414.46	93.01	78.56	8.03	12.39	1006.86	85.17	70.05
45.91	4.55	349.61	90.65	83.76	22.45	3.96	320.38	93.74	79.05	9.39	11.17	898.89	86.24	70.41
51.18	4.56	347.98	90.08	84.18	26.20	3.38	269.82	94.21	79.35	10.81	9.92	788.44	87.26	70.67
56.38	4.55	347.04	89.51	84.52	30.30	2.83	222.90	94.64	79.60	12.35	9.04	715.23	87.93	70.73
61.58	4.57	347.04	88.92	84.83	34.38	2.55	199.45	94.86	79.74	13.94	8.19	641.41	88.48	70.62
66.74	4.59	347.27	88.19	85.09	38.51	2.19	170.04	95.15	79.93	15.85	7.67	594.26	89.02	70.54
PUSH WITH 20 MACHINES					PULL WITH 20 MACHINES					CONWIP WITH 20 MACHINES				
WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.
9.77	11.66	1224.01	91.69	78.49	1.48	32.08	3385.18	64.08	60.75	0.92	31.23	3015.84	56.06	50.75
12.10	8.49	835.15	92.79	79.08	3.03	23.78	2533.73	76.53	68.30	1.59	26.32	2442.59	66.16	57.77
15.50	6.34	590.89	93.47	79.85	4.80	17.53	1754.84	82.79	72.11	2.56	22.21	2003.76	73.59	63.18
19.71	4.99	445.02	93.78	80.60	6.84	13.12	1274.52	86.69	74.51	3.46	19.18	1712.39	77.34	65.67
24.48	4.18	360.09	93.71	81.48	9.35	9.70	915.84	89.33	76.10	4.55	16.67	1468.02	80.40	67.58
29.54	3.69	310.23	93.43	82.22	12.12	7.31	672.03	91.12	77.20	5.63	14.61	1272.39	82.57	68.78
34.83	3.46	284.00	92.91	82.89	15.35	5.24	470.51	92.68	78.16	6.84	12.76	1097.64	84.40	69.71
40.17	3.33	269.16	92.37	83.46	18.85	3.83	336.86	93.82	78.82	8.12	11.34	969.90	85.73	70.24
45.53	3.28	260.78	91.74	83.97	22.67	2.92	252.50	94.54	79.28	9.50	10.00	845.20	86.84	70.62
50.92	3.28	258.47	91.34	84.40	26.59	2.19	187.62	95.15	79.67	10.93	8.85	743.52	87.82	70.87
56.35	3.36	262.65	90.82	84.77	30.94	1.67	141.82	95.69	80.01	12.47	7.91	659.15	88.54	70.95
61.71	3.43	266.67	90.29	85.08	35.19	1.35	113.39	95.98	80.17	14.11	7.23	597.84	89.14	70.91
66.99	3.45	266.75	89.84	85.36	39.73	1.05	87.91	96.32	80.42	15.79	6.42	526.00	89.77	70.95

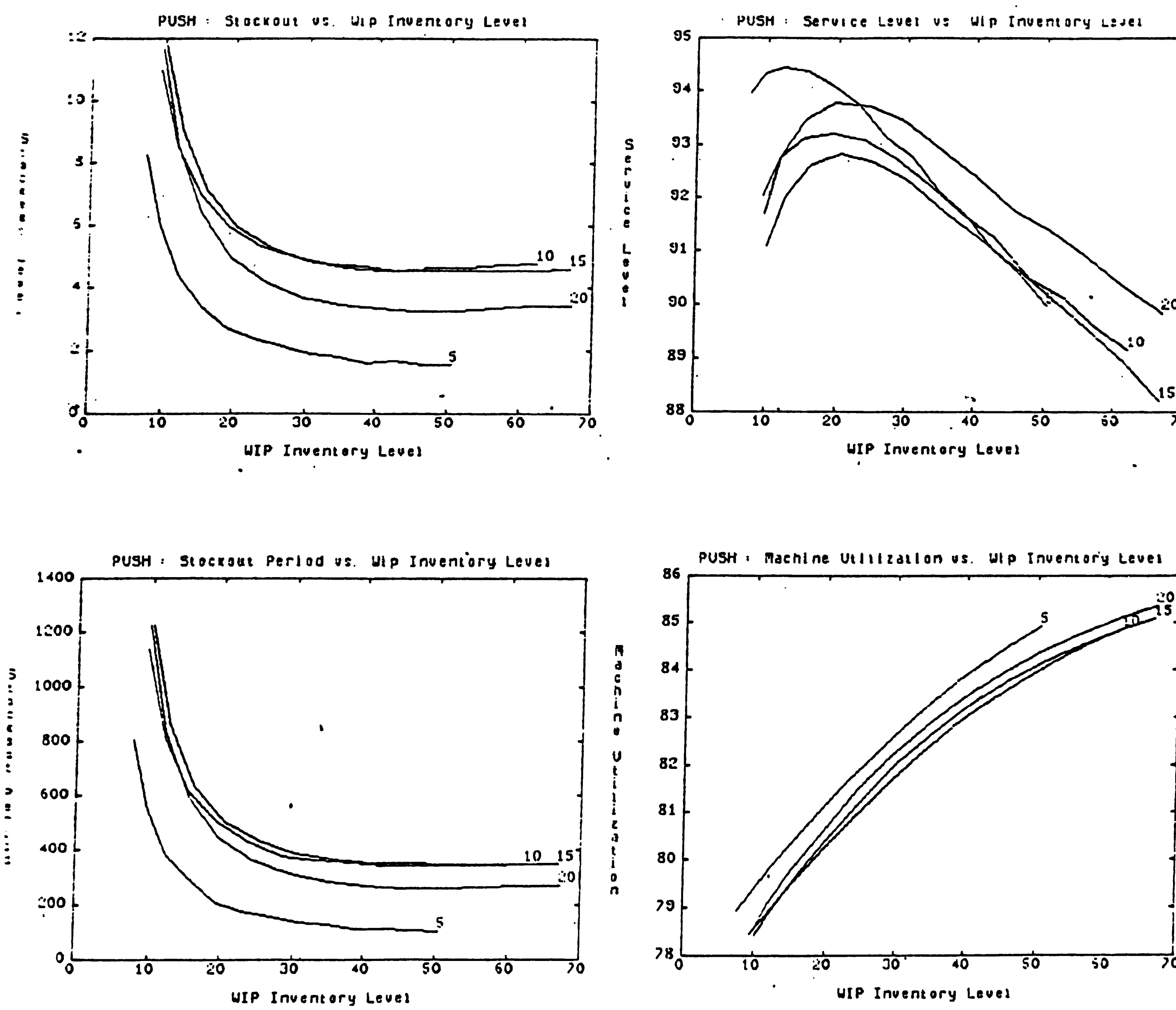

Figure A.13: Evaluation of alternative lengths of manufacturing line for push control strategy.

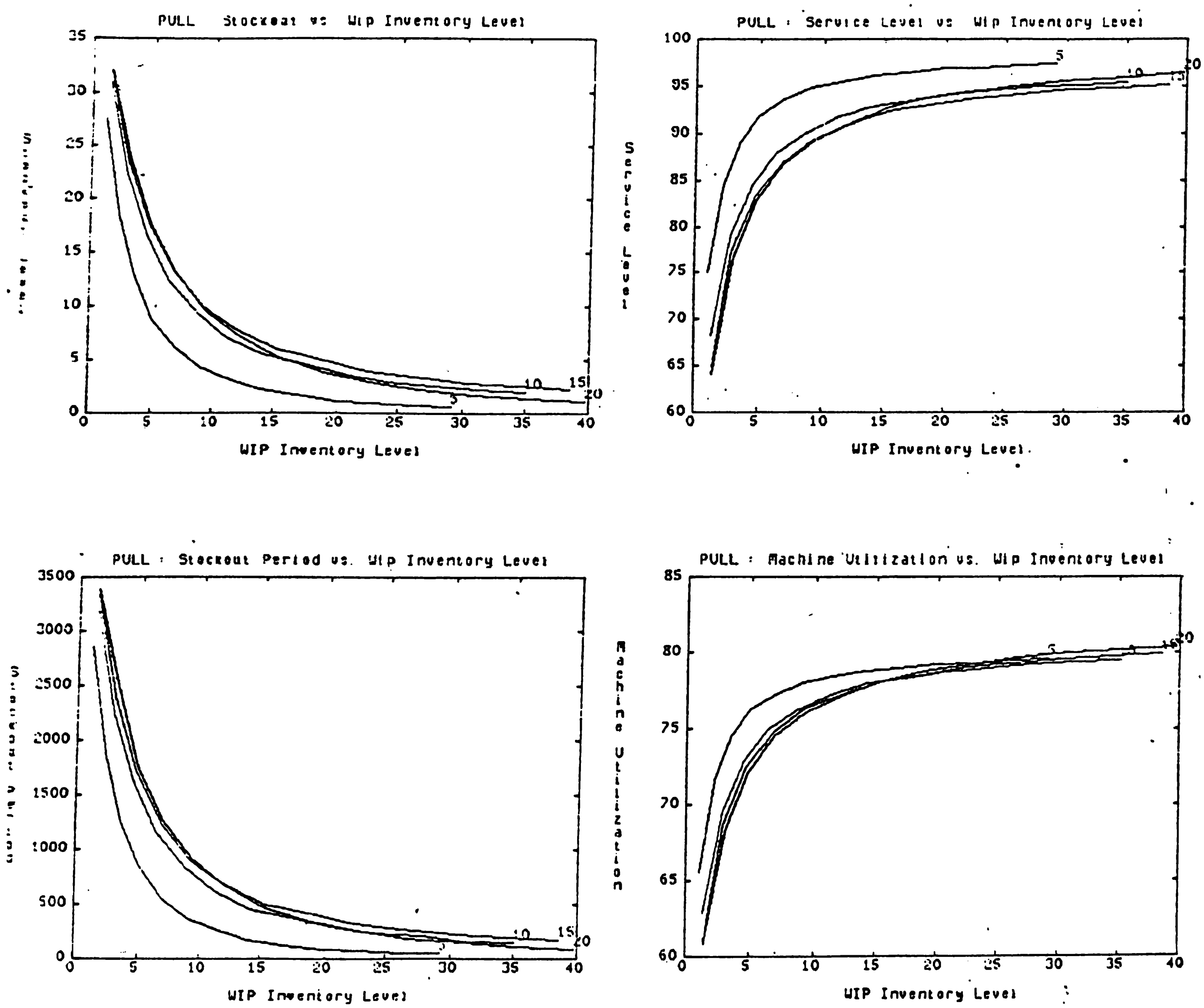

Figure A.14: Evaluation of alternative lengths of manufacturing line for pull control strategy.

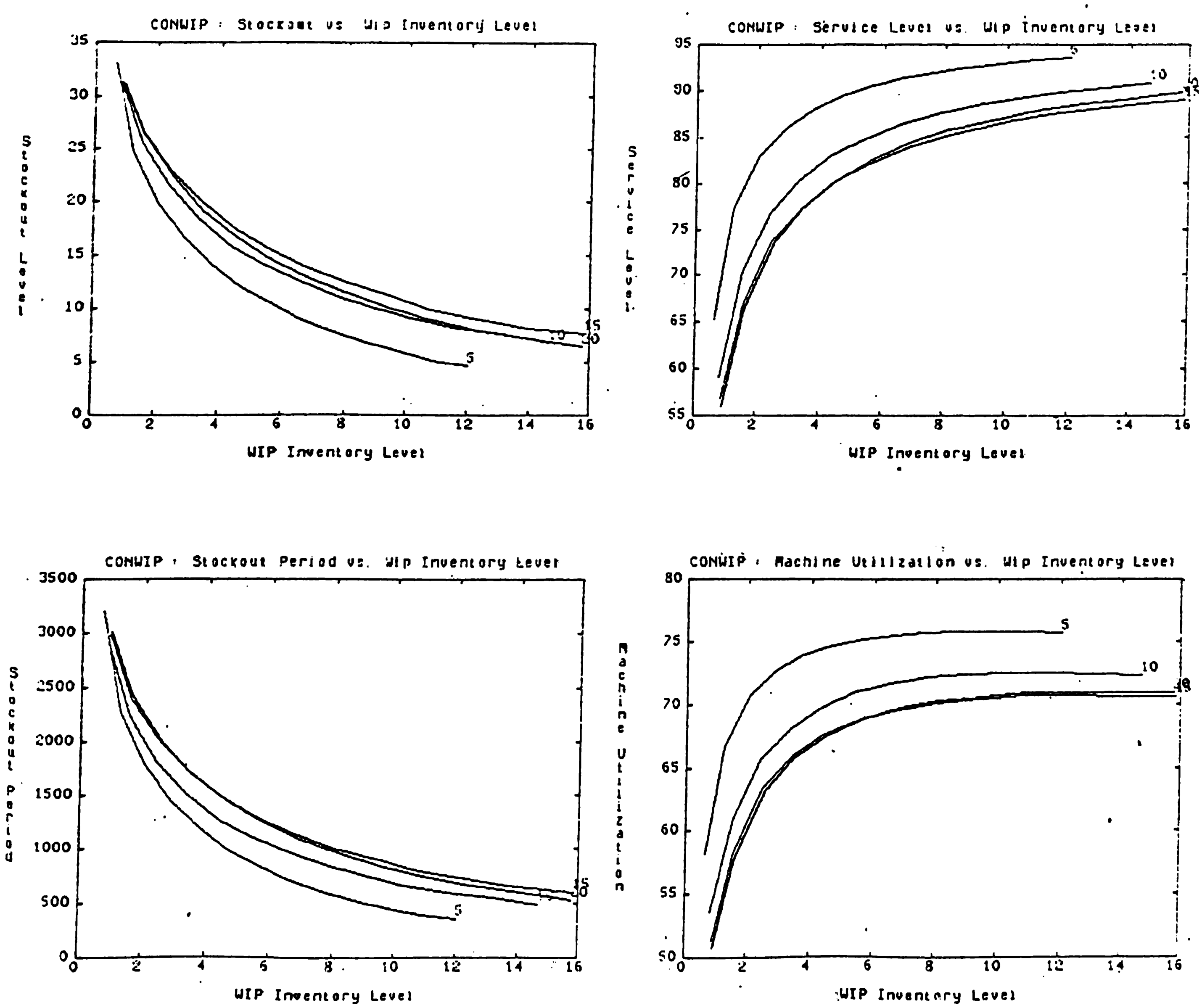

Figure A.15: Evaluation of alternative lengths of manufacturing line for conwip control strategy.

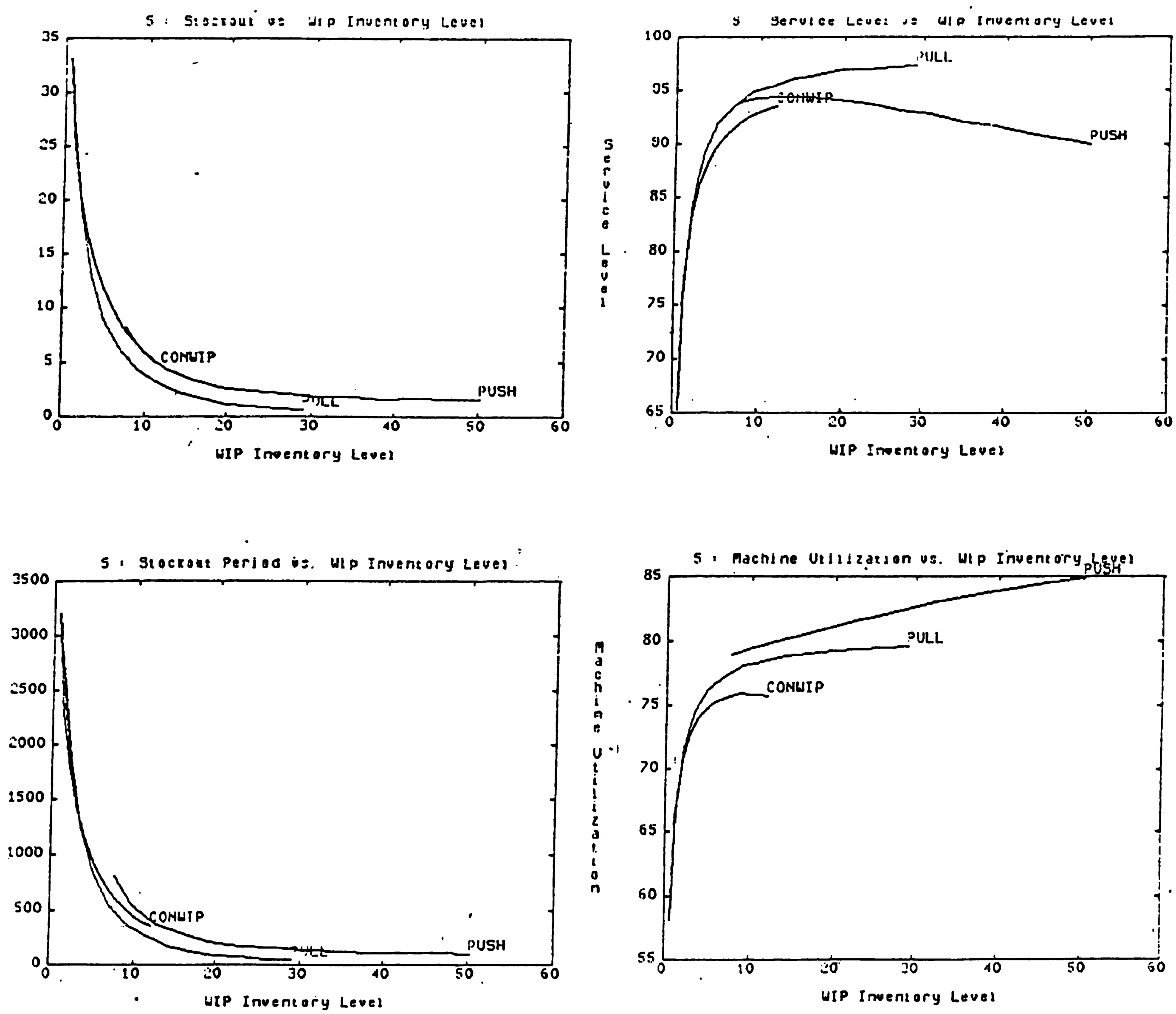

Figure A.16: Evaluation of alternative control strategies for 5 machines.

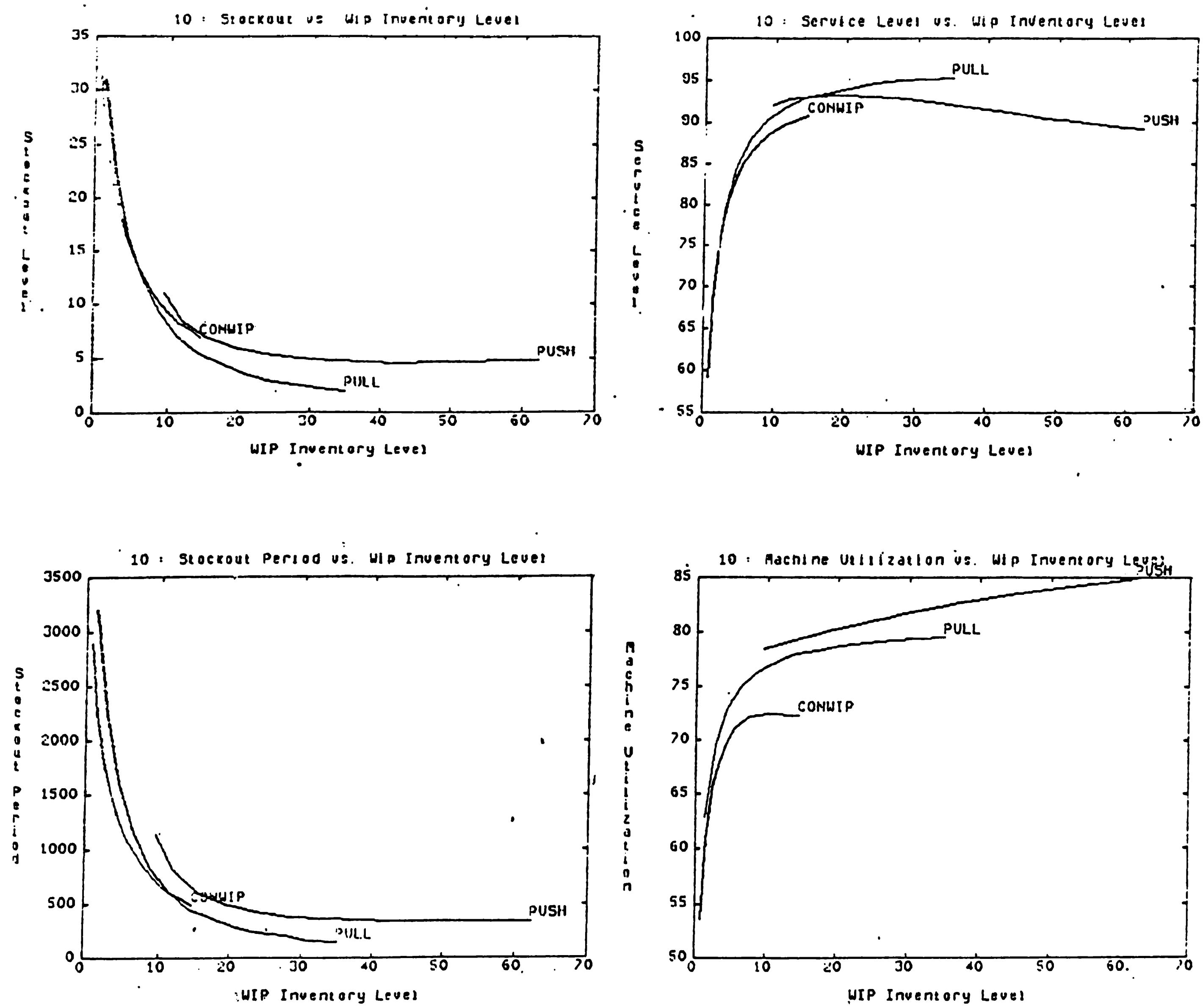

Figure A.17: Evaluation of alternative control strategies for 10 machines.

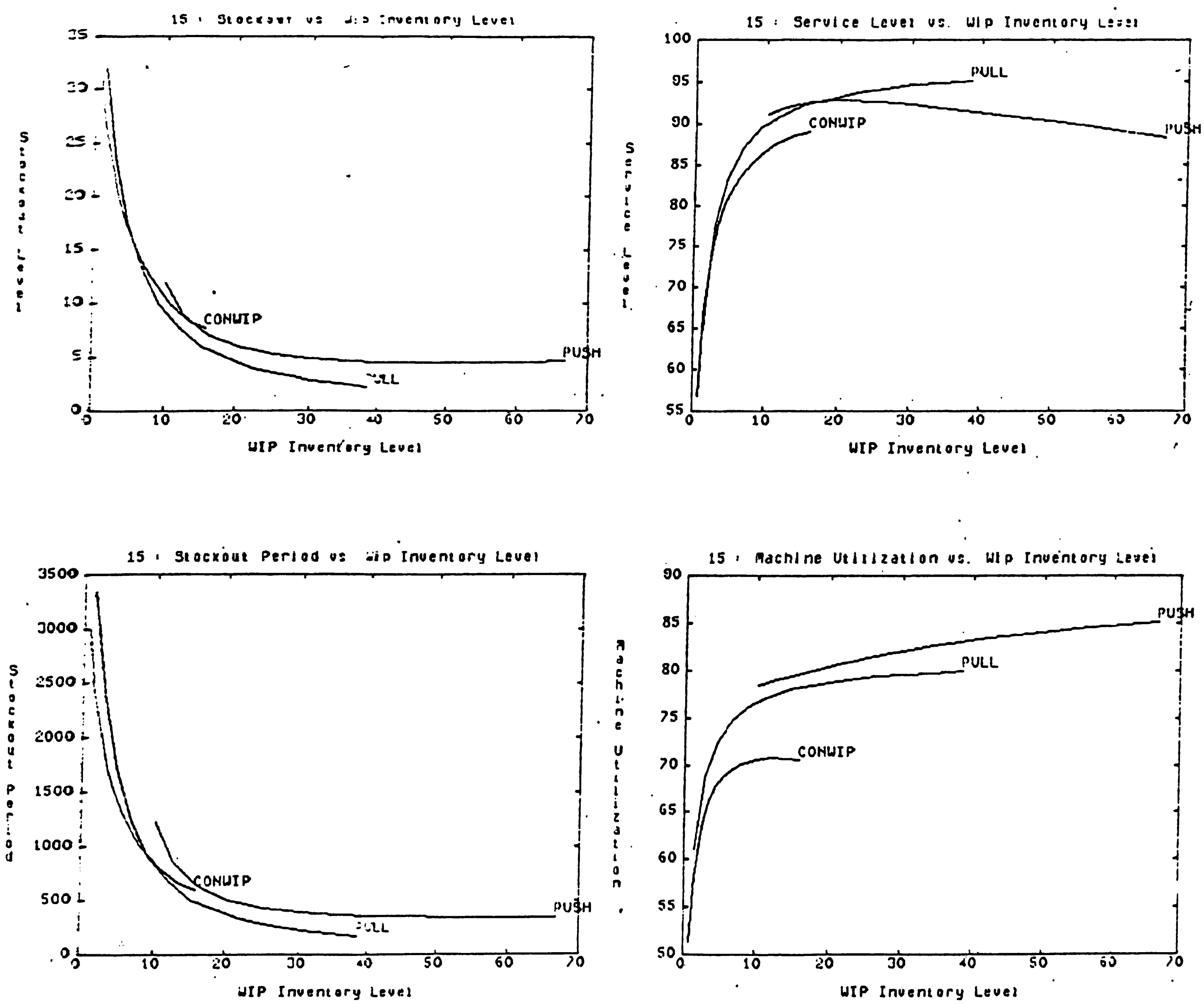

Figure A.18: Evaluation of alternative control strategies for 15 machines.

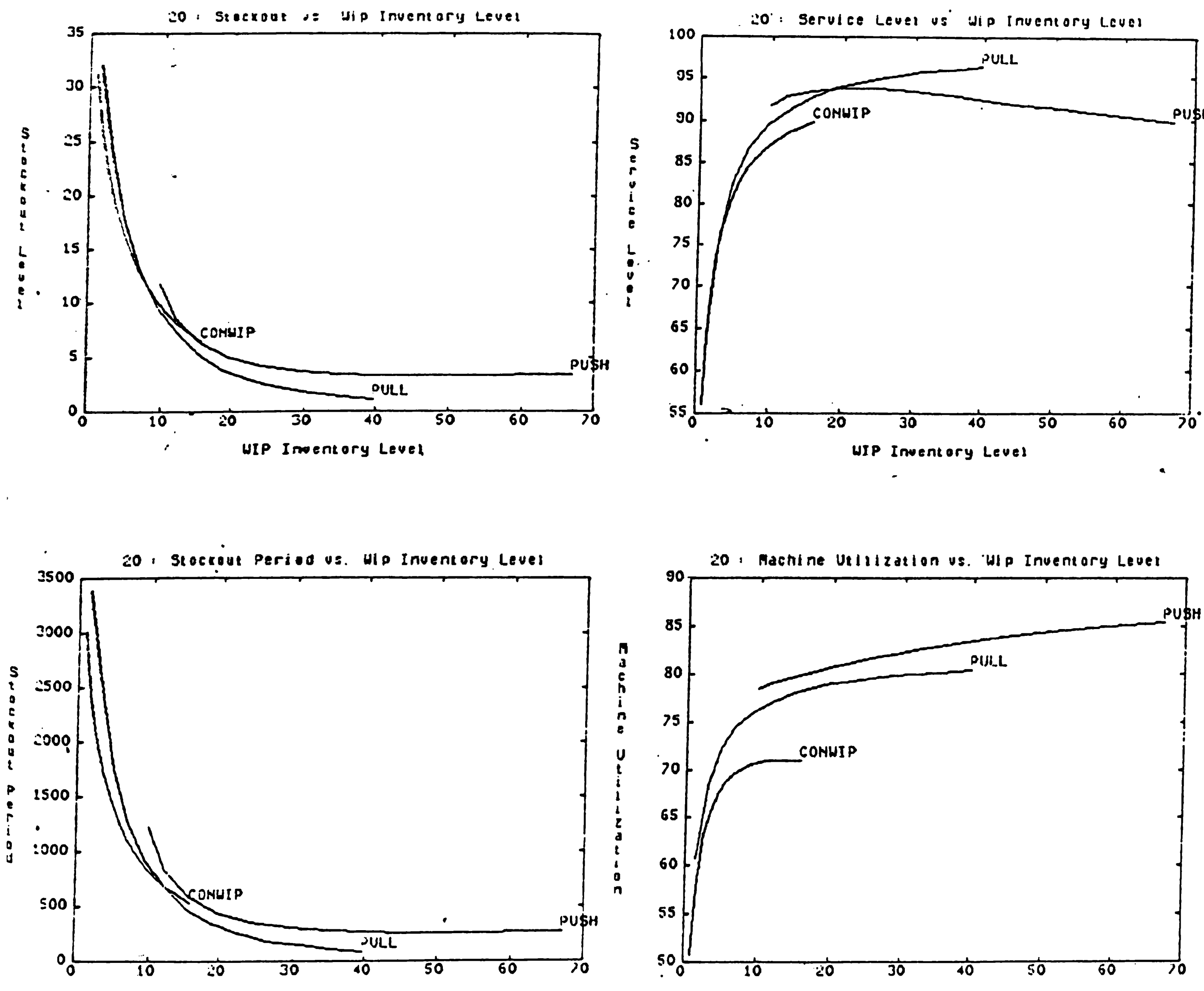

Figure A.19: Evaluation of alternative control strategies for 20 machines.

Table A.19: Experimentation parameters for the impact of average machine utilization.

EXPERIMENTATION PARAMETERS

IMPACT : AVERAGE MACHINE UTILIZATION

PROBLEM GENERATION

Number of machines	:	10
Number of part types	:	10
Number of operations	:	Uniform(8,12)
Processing times	:	Uniform(3,15)
Poduction ratios	:	Uniform(1,5)
Planning period length	:	9600
Average capacity utilization	:	80, 70, 60, 50 %
Tool magazine capacity	:	60
Slot requirements	:	Uniform(3,7)
Number of tool sharings	:	0

SIMULATION

Control strategy	:	PUSH,PULL,CONWIP
Wip inventory level	:	1..13
SS inventory level	:	1..13
Production lot size	:	1
Setup/processing time ratio	:	0
Demand inter-arrival time distribution	:	Exponential(..)
Processing time distribution	:	Constant(..)
Failure time distribution	:	Exponential(1/1750)
Repair time distribution	:	Gamma(17.4,14.4)
Statistics clear time	:	2400
Simulation end time	:	28800
Number of replications	:	10

Table A.20: Simulation results for the impact of average machine utilization.

See Note # 8 for further explanation.

PUSH WITH 80% UTILIZATION					PULL WITH 80 % UTILIZATION					CONWIP WITH 80 % UTILIZATION				
WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.
9.46	11.00	1138.53	92.03	78.45	1.37	31.02	3211.91	58.21	62.79	0.84	31.31	2905.50	59.11	53.57
11.95	8.53	814.17	92.75	78.88	2.80	22.31	2245.91	79.07	69.50	1.52	25.45	2241.72	70.13	60.88
15.36	6.93	616.80	93.11	79.50	4.48	16.52	1611.53	84.55	72.89	2.43	21.42	1808.58	76.69	65.63
19.40	5.95	500.61	93.19	80.18	6.38	12.35	1161.57	87.98	75.00	3.33	18.42	1514.20	80.31	67.97
23.79	5.33	427.95	93.07	80.87	8.70	9.37	847.69	90.13	76.30	4.36	15.87	1265.09	83.11	69.78
28.43	4.97	376.47	92.72	81.55	11.23	7.12	618.51	91.74	77.24	5.41	14.10	1108.91	84.89	70.98
33.19	4.76	363.05	92.25	82.19	14.17	5.44	457.70	92.93	78.00	6.55	12.51	972.90	86.30	71.66
38.07	4.69	351.46	91.68	82.79	17.17	4.63	381.42	93.42	78.28	7.74	11.15	851.75	87.50	72.14
42.82	4.57	340.11	91.23	83.31	20.43	3.71	296.31	94.11	78.74	8.99	9.99	754.44	88.40	72.34
47.78	4.66	341.15	90.47	83.78	24.05	2.98	233.56	94.60	78.99	10.32	8.98	665.03	89.18	72.48
52.56	4.65	339.77	90.12	84.19	27.74	2.61	202.68	94.94	79.26	11.70	8.16	599.94	89.77	72.46
57.42	4.72	343.52	89.56	84.55	31.13	2.18	164.37	95.16	79.41	13.16	7.64	555.89	90.22	72.34
62.22	4.78	345.81	89.14	84.85	35.04	1.97	147.15	95.35	79.50	14.69	6.87	493.48	90.79	72.27

PUSH WITH 70% UTILIZATION					PULL WITH 70 % UTILIZATION					CONWIP WITH 70 % UTILIZATION				
WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.
5.08	6.25	743.87	93.70	69.32	1.14	22.12	2586.36	75.40	59.62	0.85	24.03	2478.27	66.85	52.37
8.84	4.04	440.38	94.23	69.66	2.28	13.36	1486.22	85.78	64.87	1.57	17.12	1698.96	77.87	58.48
12.55	2.85	271.91	94.31	70.24	3.87	8.56	893.62	90.29	67.06	2.49	12.98	1215.26	83.66	61.98
17.05	2.07	186.46	94.02	70.95	5.90	5.40	530.60	93.15	68.51	3.44	10.45	939.54	86.83	63.79
21.68	1.74	144.78	93.42	71.67	8.34	3.52	326.83	94.81	69.29	4.48	8.68	752.65	89.04	64.89
26.64	1.61	127.88	92.57	72.41	11.23	2.25	195.87	96.04	69.86	5.57	7.14	597.30	90.57	65.47
31.68	1.57	121.28	91.54	73.14	14.33	1.58	130.62	96.74	70.16	6.74	6.01	498.20	91.82	65.79
36.78	1.60	120.79	90.39	73.87	17.69	1.11	88.13	97.25	70.30	8.00	5.04	404.98	92.77	65.90
41.87	1.64	122.77	89.19	74.60	21.22	0.77	59.25	97.58	70.62	9.30	4.32	340.67	93.46	65.88
46.95	1.68	124.94	87.96	75.33	24.76	0.61	45.19	97.90	70.76	10.71	3.73	288.27	94.00	65.71
52.02	1.74	128.80	86.71	76.05	28.37	0.50	36.17	98.03	70.81	12.15	3.19	243.28	94.55	65.57
57.02	1.75	129.28	85.49	76.76	32.03	0.38	27.61	98.19	70.92	13.68	2.76	207.62	94.88	65.33
62.08	1.84	135.90	84.30	77.45	35.79	0.29	20.37	98.32	71.00	15.28	2.58	189.17	95.14	64.98

PUSH WITH 60% UTILIZATION					PULL WITH 60 % UTILIZATION					CONWIP WITH 60 % UTILIZATION				
WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.
5.35	4.06	568.82	93.93	59.43	0.96	15.23	2014.82	80.15	53.24	0.88	15.63	1763.00	76.86	50.63
8.56	2.20	278.74	94.22	59.66	2.22	7.57	905.06	90.05	57.22	1.65	9.47	995.86	86.52	55.19
12.67	1.18	136.76	93.92	60.15	4.20	3.73	400.75	94.23	58.86	2.64	5.93	585.08	92.01	57.81
17.30	0.65	69.94	93.08	60.81	6.71	1.89	200.64	96.27	59.67	3.67	3.86	363.20	94.53	58.57
22.21	0.38	38.80	91.83	61.57	9.84	0.91	81.99	97.57	60.11	4.82	2.64	235.85	95.90	58.82
27.25	0.24	23.49	90.30	62.39	13.17	0.43	35.85	98.31	60.42	6.02	1.86	159.06	96.66	58.61
32.36	0.16	15.95	88.61	63.23	16.67	0.22	16.79	98.79	60.60	7.34	1.30	107.19	97.23	58.34
37.51	0.13	12.77	86.77	64.09	20.30	0.10	7.51	99.05	60.73	8.73	0.96	76.49	97.46	57.83
42.67	0.13	11.83	84.82	64.94	24.04	0.05	3.91	99.22	60.78	10.20	0.73	56.79	97.61	57.36
47.82	0.13	11.77	82.84	65.80	27.81	0.02	1.58	99.32	60.83	11.74	0.57	43.26	97.75	56.86
52.98	0.13	12.31	80.86	66.67	31.54	0.01	1.00	99.41	60.88	13.37	0.42	32.51	97.89	56.42
58.11	0.14	12.90	78.87	67.54	35.44	0.00	0.57	99.45	60.89	15.08	0.38	27.93	97.79	55.86
63.24	0.15	13.77	76.91	68.40	39.36	0.00	0.21	99.47	60.94	16.84	0.30	22.63	97.85	55.40

PUSH WITH 50% UTILIZATION					PULL WITH 50 % UTILIZATION					CONWIP WITH 50 % UTILIZATION				
WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.
4.98	3.03	493.45	93.57	49.45	0.79	10.26	1593.22	84.23	45.32	0.90	8.06	1038.46	88.24	47.33
8.42	1.62	236.34	93.45	49.54	2.29	4.08	546.59	93.09	48.26	1.74	3.40	390.81	95.03	49.52
12.57	0.86	116.23	92.67	49.87	4.47	1.62	190.07	96.38	49.36	2.80	1.56	161.16	97.39	50.04
17.10	0.45	57.24	91.37	50.41	7.44	0.63	65.29	97.96	49.89	3.89	0.93	93.63	98.06	49.76
21.84	0.24	29.07	89.78	51.07	10.59	0.25	23.13	98.81	50.17	5.10	0.51	50.69	98.47	49.27
26.48	0.13	15.15	87.90	51.80	13.85	0.09	7.48	99.23	50.27	6.36	0.31	31.20	98.64	48.76
31.57	0.07	8.05	85.83	52.57	17.26	0.03	2.94	99.42	50.32	7.71	0.21	21.18	98.66	48.12
36.49	0.04	4.54	83.64	53.37	20.66	0.01	0.93	99.56	50.39	9.16	0.15	14.66	98.68	47.71
41.42	0.03	2.88	81.38	54.18	24.20	0.00	0.42	99.60	50.43	10.71	0.11	11.03	98.73	46.94
46.35	0.02	2.12	79.08	55.00	27.70	0.00	0.29	99.63	50.48	12.37	0.09	9.39	98.72	46.39
51.28	0.02	1.94	76.72	55.83	31.33	0.00	0.09	99.65	50.50	14.04	0.08	7.87	98.68	45.91
56.20	0.02	1.80	74.33	56.67	34.97	0.00	0.07	99.65	50.50	15.85	0.06	6.55	98.65	45.44
61.11	0.02	1.81	71.93	57.51	38.69	0.00	0.02	99.65	50.54	17.69	0.06	5.00	98.56	45.05

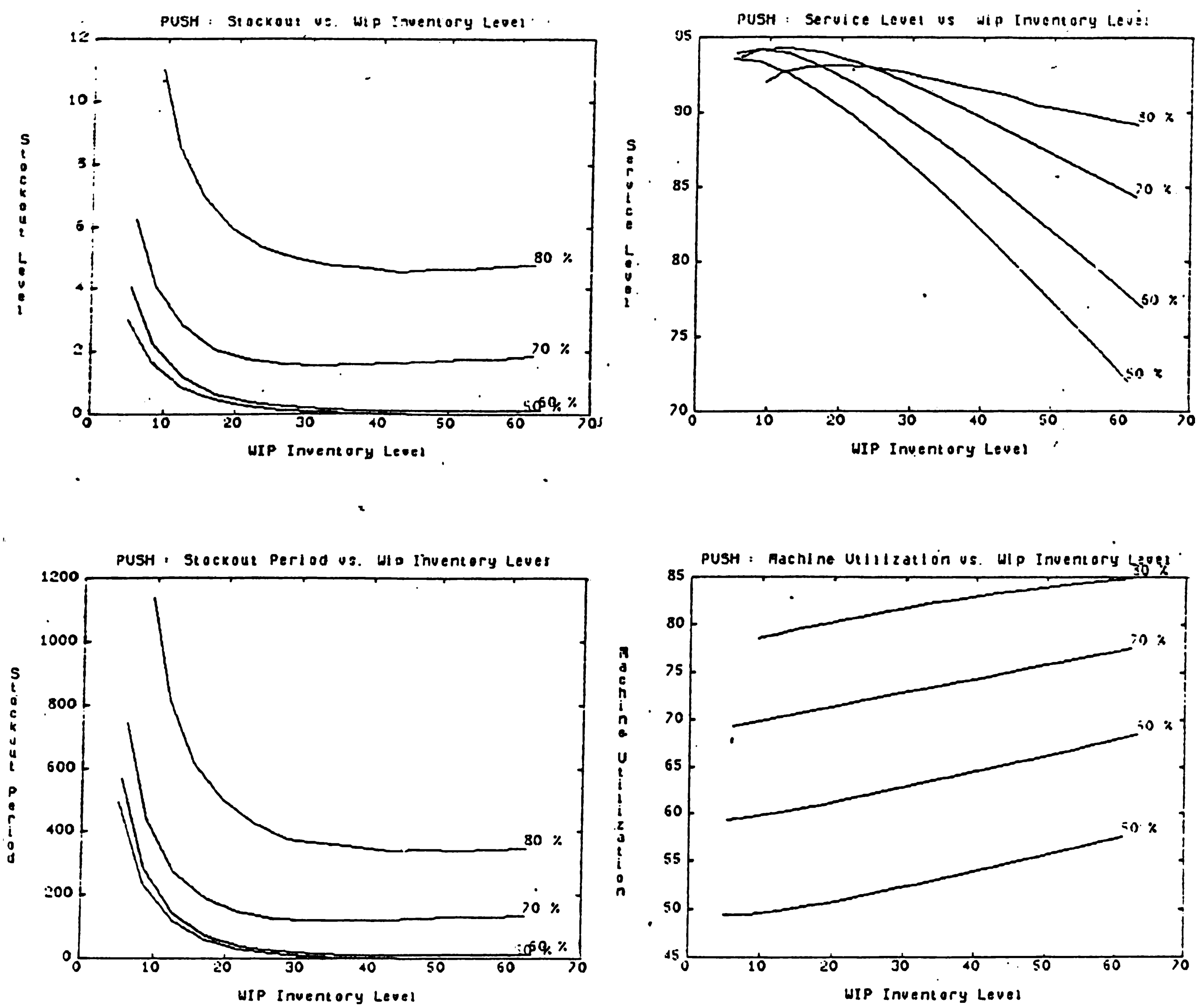

Figure A.20: Evaluation of alternative levels of average machine utilization for push control strategy.

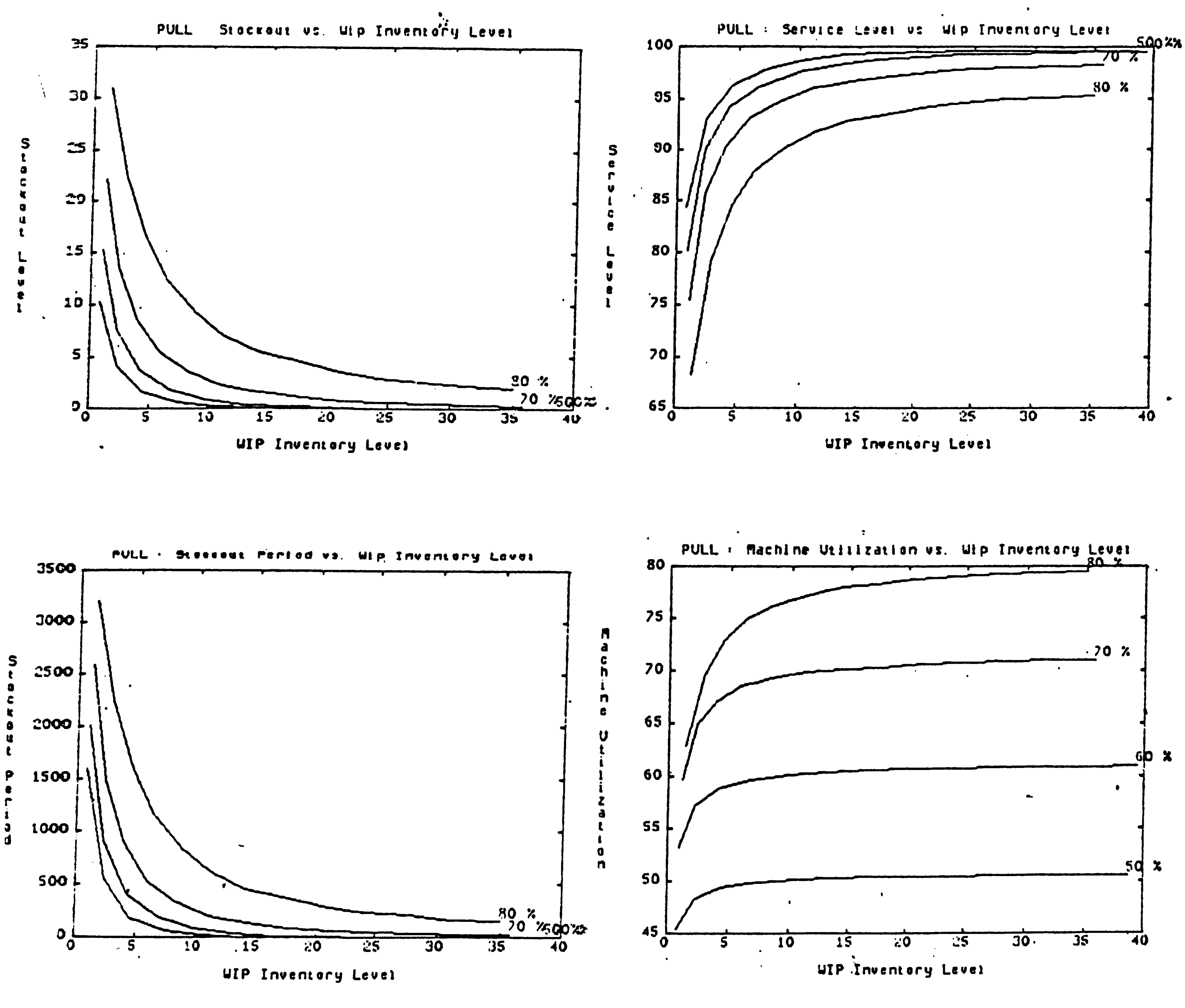

Figure A.21: Evaluation of alternative levels of average machine utilization for pull control strategy.

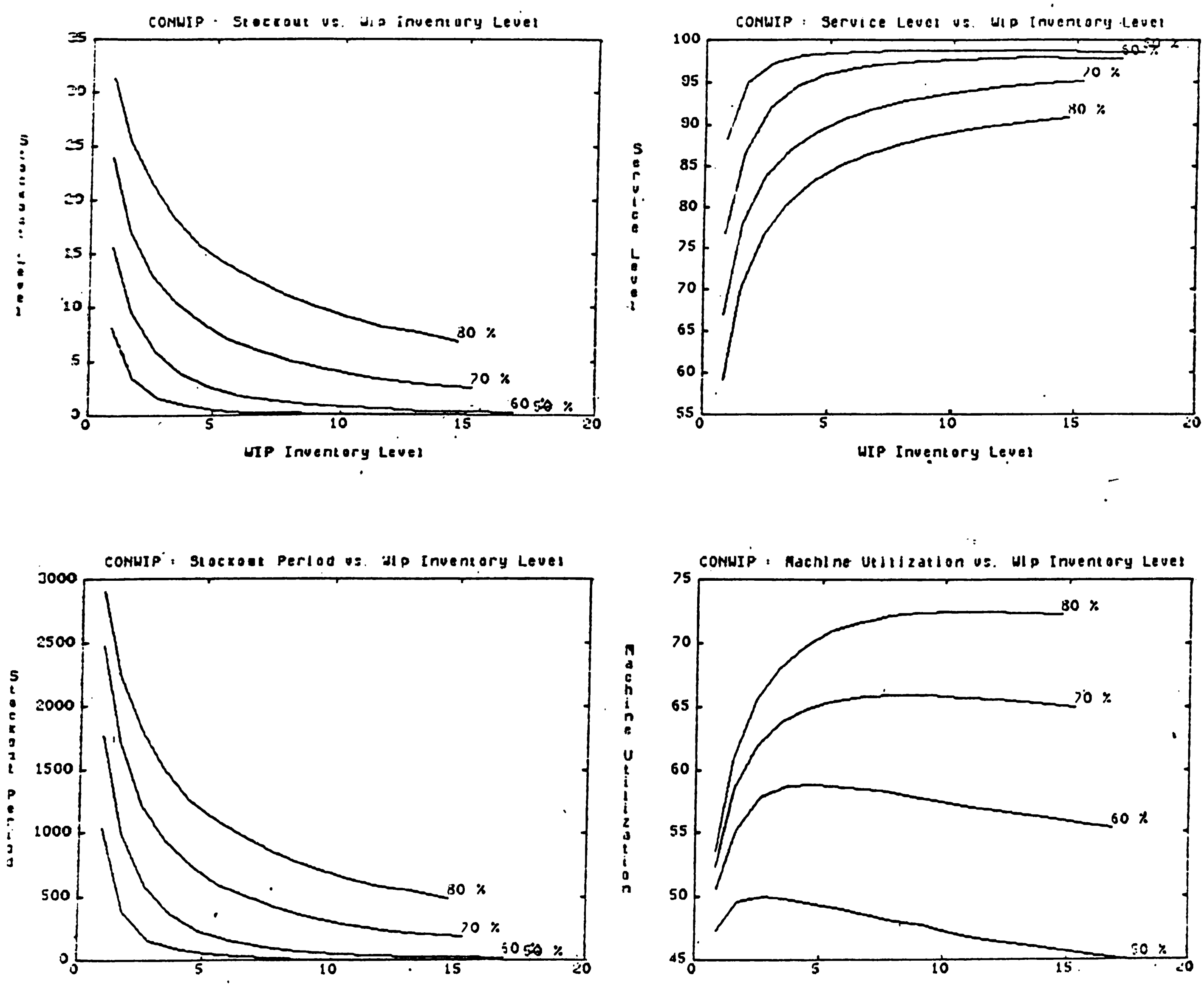

Figure A.22: Evaluation of alternative levels of average machine utilization for conwip control strategy.

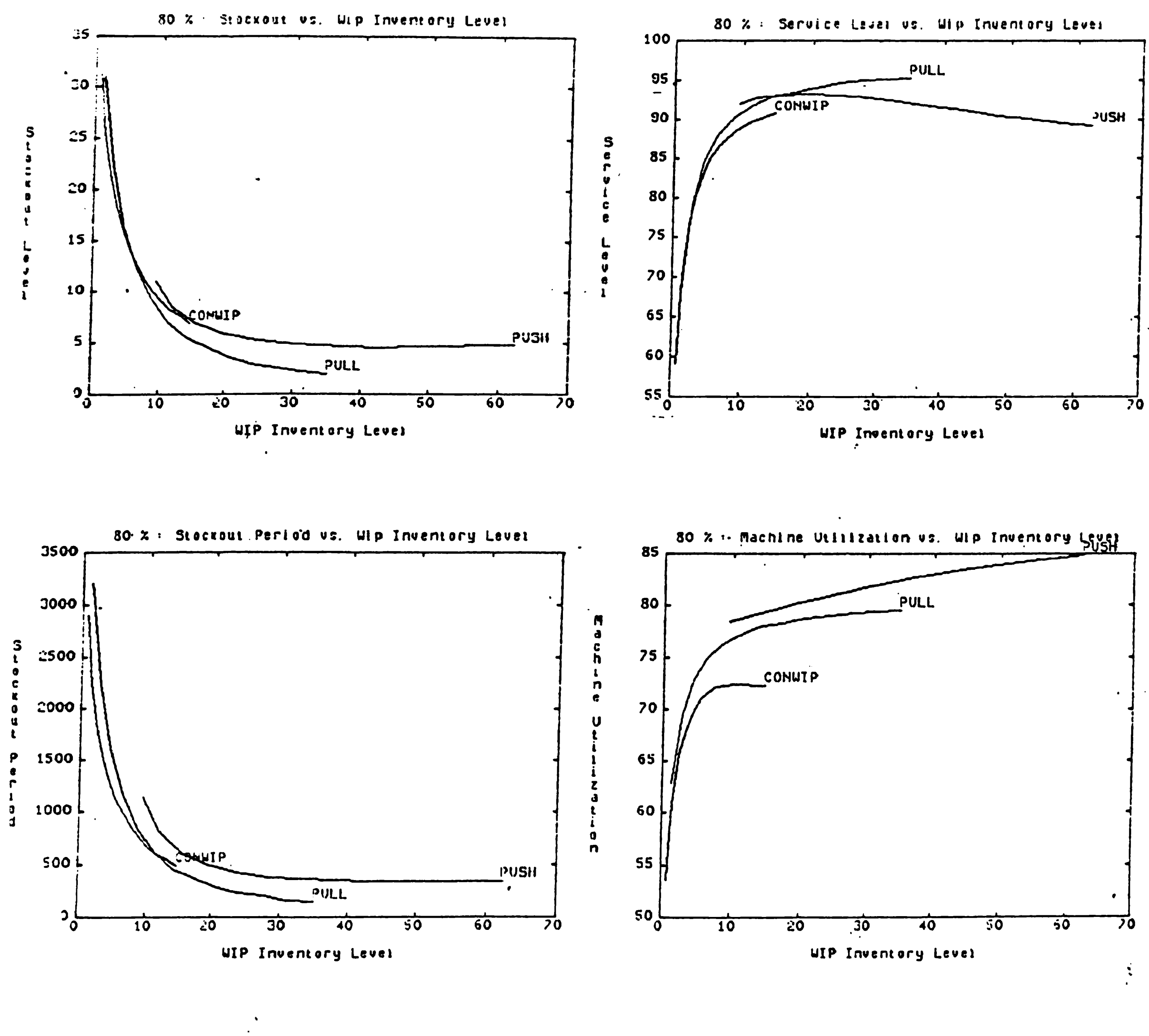

Figure A.23: Evaluation of alternative control strategies for 80 % average machine utilization.

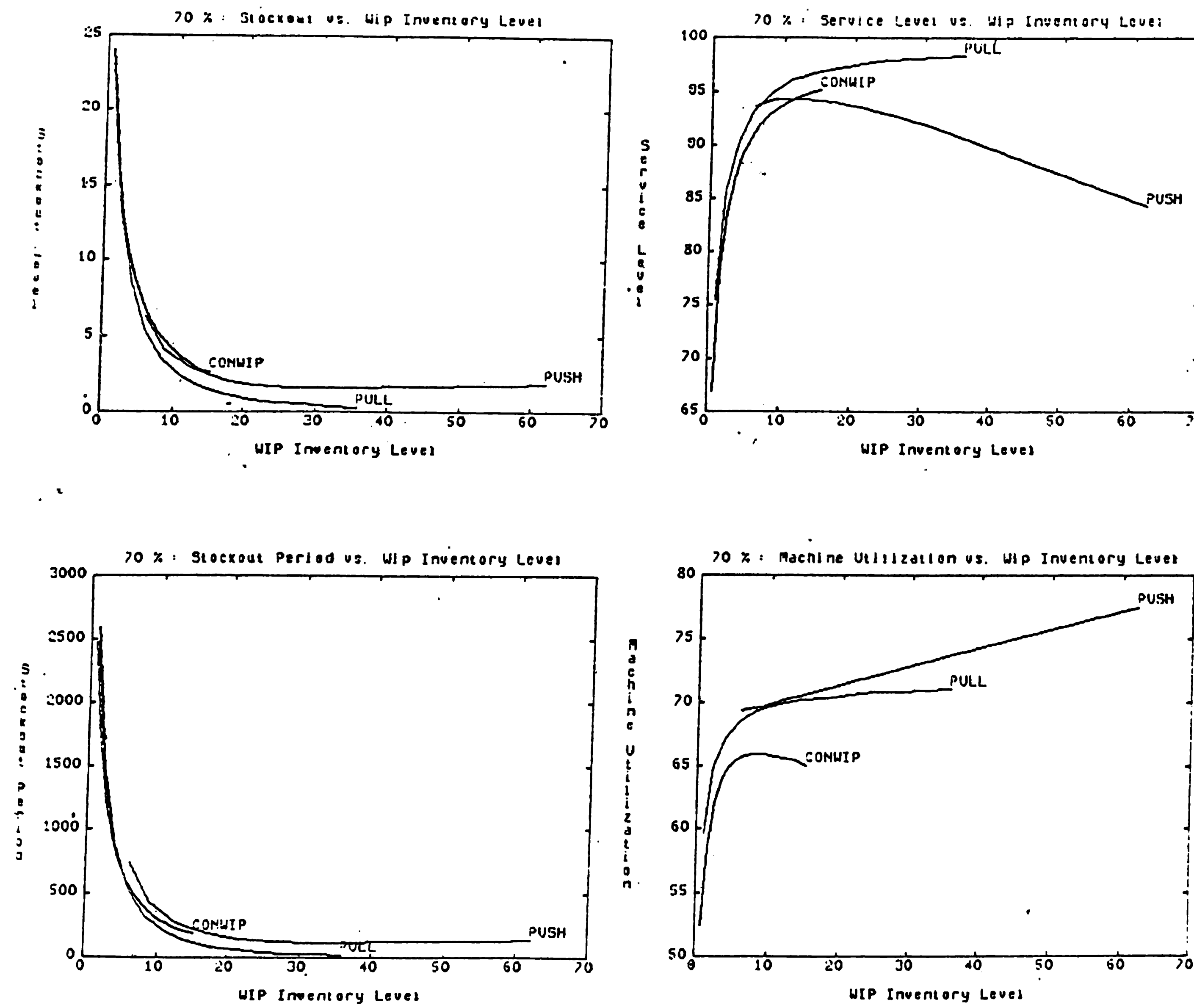

Figure A.24: Evaluation of alternative control strategies for 70 % average machine utilization.

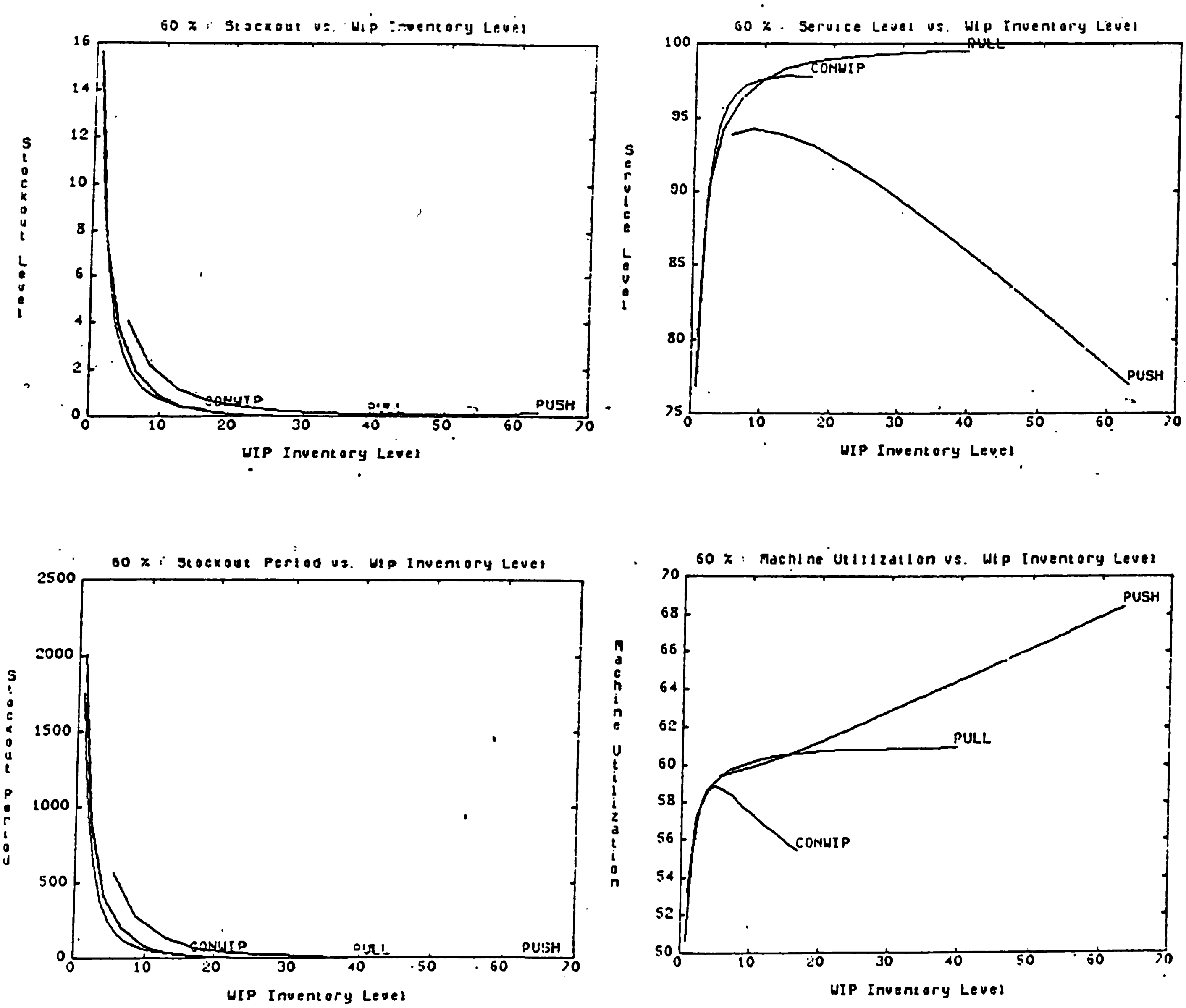

Figure A.25: Evaluation of alternative control strategies for 60 % average machine utilization.

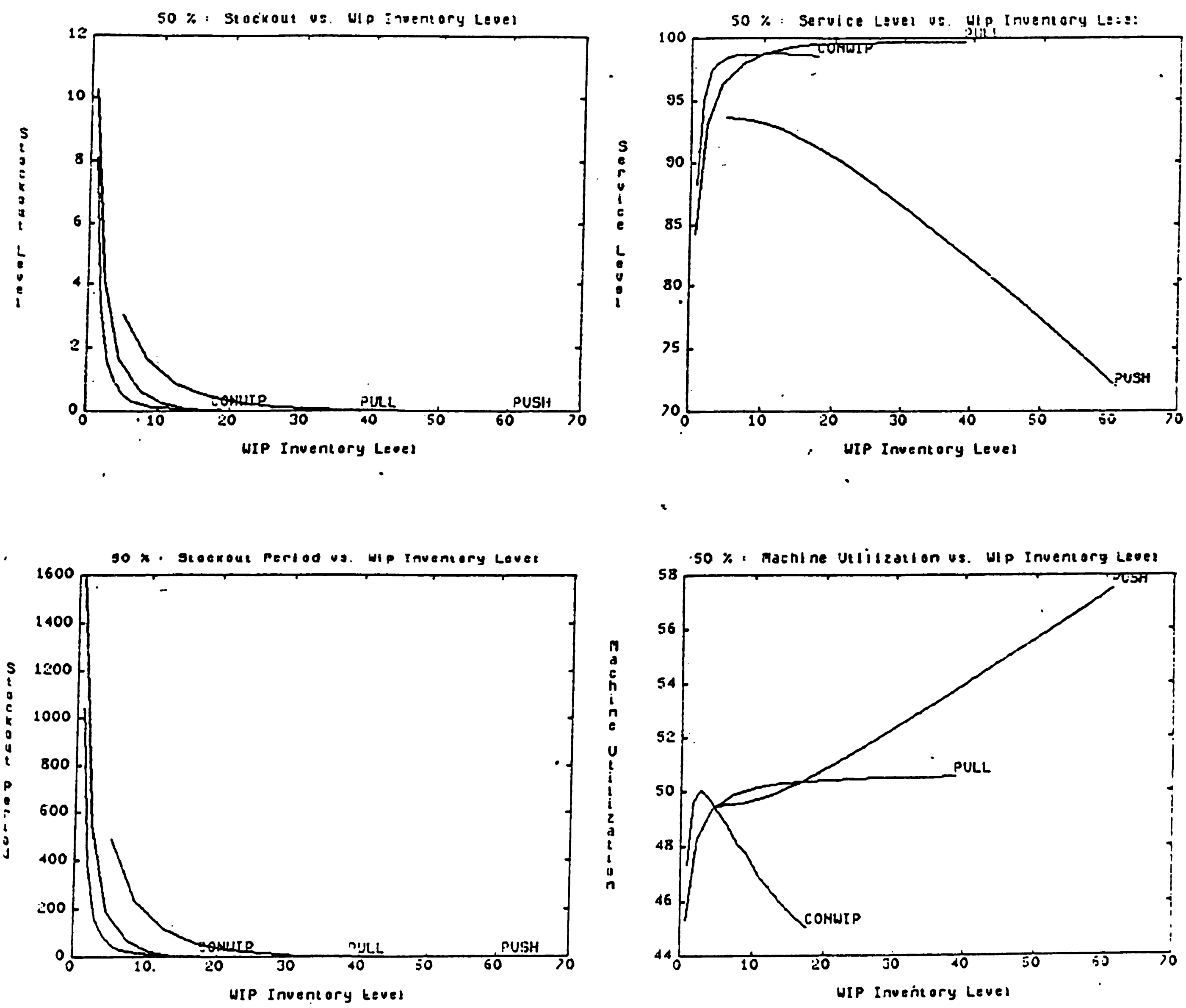

Figure A.26: Evaluation of alternative control strategies for 50 % average machine utilization.

Table A.21: Experimentation parameters for the impact of demand variability.

EXPERIMENTATION PARAMETERS

IMPACT : DEMAND VARIABILITY

PROBLEM GENERATION

Number of machines	:	10
Number of part types	:	10
Number of operations	:	Uniform(8,12)
Processing times	:	Uniform(3,15)
Poduction ratios	:	Uniform(1,5)
Planning period length	:	9600
Average capacity utilization	:	80 %
Tool magazine capacity	:	60
Slot requirements	:	Uniform(3,7)
Number of tool sharings	:	0

SIMULATION

Control strategy	:	PUSH,PULL,CONWIP
Wip inventory level	:	1..13
SS inventory level	:	1..13
Production lot size	:	1
Setup/processing time ratio	:	0
Demand inter-arrival time distribution	:	Normal(..) / Exponential(..) C.V. = 0.00, 0.25, 0.50, 1.00
Processing time distribution	:	Constant(..)
Failure time distribution	:	Exponential(1/1750)
Repair time distribution	:	Gamma(17.4,14.4)
Statistics clear time	:	2400
Simulation end time	:	28800
Number of replications	:	10

Table A.22: Simulation results for the impact of demand variability.

See Note # 8 for further explanation.

PUSH WITH DEMAND (C.V.=0.00)					PULL WITH DEMAND (C.V.=0.00)					CONWIP WITH DEMAND (C.V.=0.00)				
WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.
8.51	5.31	465.47	96.58	78.45	1.35	26.17	2764.71	73.33	64.28	0.82	28.91	2691.82	61.44	53.57
11.82	3.50	276.80	96.95	78.88	2.81	15.96	1623.42	84.66	70.98	1.49	22.57	1974.38	72.72	60.87
16.38	2.85	218.22	96.47	79.50	4.59	10.14	969.78	89.68	73.92	2.41	17.58	1511.84	79.78	65.78
21.39	2.72	206.15	95.55	80.18	6.84	6.52	583.59	92.60	75.57	3.33	14.98	1217.95	83.56	68.32
26.51	2.75	207.12	94.44	80.87	9.43	4.36	369.33	94.28	76.51	4.38	12.27	971.76	86.41	70.07
31.61	2.80	210.31	93.27	81.55	12.48	2.98	241.18	95.38	77.11	5.45	10.32	796.49	88.31	71.08
36.67	2.86	214.77	92.15	82.19	15.72	2.17	169.40	96.07	77.49	6.62	8.72	661.26	89.82	71.75
41.70	2.95	220.75	91.12	82.79	19.26	1.61	123.11	96.57	77.78	7.84	7.55	562.87	90.81	72.03
46.68	3.03	226.72	90.19	83.31	22.78	1.27	95.91	96.90	77.96	9.14	6.53	480.23	91.69	72.19
51.63	3.13	233.61	89.34	83.78	26.63	1.03	77.21	97.13	78.10	10.50	5.85	426.20	92.22	72.09
56.51	3.22	239.25	88.66	84.19	30.43	0.86	64.73	97.31	78.21	11.93	5.19	374.30	92.76	71.98
61.38	3.30	245.27	88.03	84.55	34.26	0.74	55.45	97.40	78.29	13.43	4.73	338.03	93.15	71.77
66.22	3:39	251.33	87.48	84.85	38.22	0.65	48.06	97.50	78.37	15.01	4.34	308.89	93.46	71.51

PUSH WITH DEMAND (C.V.=0.25)					PULL WITH DEMAND (C.V.=0.25)					CONWIP WITH DEMAND (C.V.=0.25)				
WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.
8.60	6.54	513.69	95.52	78.45	1.36	26.94	2837.48	72.53	64.29	0.82	29.48	2731.51	60.92	53.63
11.65	4.47	374.97	95.97	78.88	2.83	16.95	1724.38	83.93	71.13	1.49	23.24	2023.61	72.15	60.94
15.87	3.54	282.11	95.80	79.50	4.62	10.99	1054.89	88.92	74.12	2.41	18.95	1579.33	79.01	65.78
20.64	3.19	247.57	95.23	80.18	6.77	7.37	671.76	91.90	75.85	3.32	15.63	1270.83	82.93	68.41
25.61	3.08	236.28	94.42	80.87	9.37	5.00	433.37	93.70	76.88	4.36	13.01	1035.86	85.80	70.22
30.66	3.08	234.45	93.44	81.55	12.33	3.55	295.32	94.79	77.49	5.44	10.89	847.88	87.77	71.31
35.70	3.12	236.92	92.46	82.19	15.63	2.61	210.96	95.57	77.95	6.60	9.34	715.77	89.18	71.95
40.70	3.18	240.88	91.52	82.80	19.03	1.96	156.04	96.10	78.24	7.82	8.03	605.97	90.33	72.34
45.68	3.26	247.00	90.62	83.31	22.67	1.57	123.55	96.43	78.46	9.12	7.08	527.11	91.13	72.46
50.66	3.37	254.37	89.76	83.78	26.26	1.27	99.33	96.70	78.61	10.47	6.33	467.82	91.73	72.43
54.38	3.41	257.24	89.12	84.19	30.10	1.04	80.58	96.94	78.75	11.89	5.62	411.10	92.26	72.37
60.35	3.50	263.49	88.50	84.55	33.37	0.91	70.49	97.05	78.83	13.39	5.13	372.69	92.68	72.18
65.20	3.59	269.31	87.95	84.85	37.36	0.81	61.73	97.11	78.89	14.97	4.70	339.19	93.02	71.95

PUSH WITH DEMAND (C.V.=0.50)					PULL WITH DEMAND (C.V.=0.50)					CONWIP WITH DEMAND (C.V.=0.50)				
WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.
8.13	13.84	2662.30	90.03	78.45	1.39	31.54	3167.50	67.96	64.37	0.82	32.47	2918.95	57.59	54.09
9.98	10.76	966.01	91.23	78.89	2.91	22.55	2213.61	79.05	71.48	1.48	26.87	2267.90	68.48	61.59
12.87	8.72	730.43	92.12	79.50	4.69	16.46	1562.01	84.50	75.06	2.39	22.57	1839.07	75.16	66.59
16.53	7.36	586.12	92.70	80.18	6.80	12.52	1147.88	87.78	77.21	3.29	19.70	1568.81	78.74	69.12
20.65	6.47	499.10	93.07	80.87	9.19	9.58	846.00	89.91	78.61	4.31	17.17	1339.69	81.58	71.03
25.12	5.94	445.83	93.17	81.55	11.94	7.55	648.90	91.29	79.54	5.35	15.31	1178.54	83.48	72.17
29.81	5.66	419.92	93.05	82.19	14.94	6.12	514.22	92.12	80.10	6.49	13.60	1027.57	85.10	73.07
34.63	5.54	406.64	92.72	82.79	18.22	4.94	404.73	92.89	80.59	7.67	12.14	908.95	86.24	73.56
39.49	5.50	401.81	92.33	83.32	21.62	4.12	330.23	93.42	80.94	8.92	11.02	819.41	87.21	73.88
44.32	5.49	396.11	91.83	83.78	25.17	3.58	282.88	93.71	81.12	10.22	10.02	735.77	88.03	74.07
49.16	5.53	398.28	91.40	84.19	28.77	3.12	242.25	94.02	81.32	11.60	9.21	668.89	88.65	74.12
53.98	5.57	398.91	90.87	84.55	32.51	2.82	216.51	94.24	81.42	13.02	8.52	614.39	89.15	74.08
58.89	5.71	406.94	90.29	84.85	36.26	2.50	189.44	94.41	81.53	14.54	7.90	564.90	89.58	74.42

PUSH WITH DEMAND (C.V.=1.00)					PULL WITH DEMAND (C.V.=1.00)					CONWIP WITH DEMAND (C.V.=1.00)				
WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.
9.46	11.00	1138.53	92.03	78.45	1.37	31.02	3211.91	68.21	62.79	0.84	31.31	2905.50	59.11	53.57
11.95	8.53	814.17	92.75	78.88	2.80	22.31	2245.91	79.07	69.50	1.52	25.45	2241.72	70.13	60.88
15.36	6.93	616.80	93.11	79.50	4.48	16.52	1611.53	84.55	72.89	2.43	21.42	1808.58	76.69	65.63
19.40	5.95	500.61	93.19	80.18	6.38	12.35	1161.57	87.98	75.00	3.33	18.42	1514.20	80.31	67.37
23.79	5.33	427.95	93.07	80.87	8.70	9.37	847.69	90.13	76.30	4.36	15.87	1265.09	83.11	69.78
28.43	4.97	376.47	92.72	81.55	11.23	7.12	618.51	91.74	77.24	5.41	14.10	1108.91	84.89	70.98
33.19	4.76	363.05	92.25	82.19	14.17	5.44	457.70	92.93	78.00	6.55	12.51	972.90	86.30	71.66
38.07	4.69	351.46	91.68	82.79	17.17	4.63	381.42	93.42	78.28	7.74	11.15	851.75	87.50	72.14
42.82	4.57	340.11	91.23	83.31	20.43	3.71	296.31	94.11	78.74	8.99	9.99	754.44	88.40	72.34
47.78	4.66	341.15	90.47	83.78	24.05	2.98	233.56	94.60	78.99	10.32	8.98	665.03	89.18	72.48
52.56	4.65	339.77	90.12	84.19	27.74	2.61	202.68	94.94	79.26	11.70	8.18	599.94	89.77	72.46
57.42	4.72	343.52	89.56	84.55	31.13	2.18	164.37	95.16	79.41	13.16	7.64	555.89	90.22	72.34
62.22	4.78	345.81	89.14	84.85	35.04	1.97	147.15	95.35	79.50	14.69	6.87	493.48	90.79	72.27

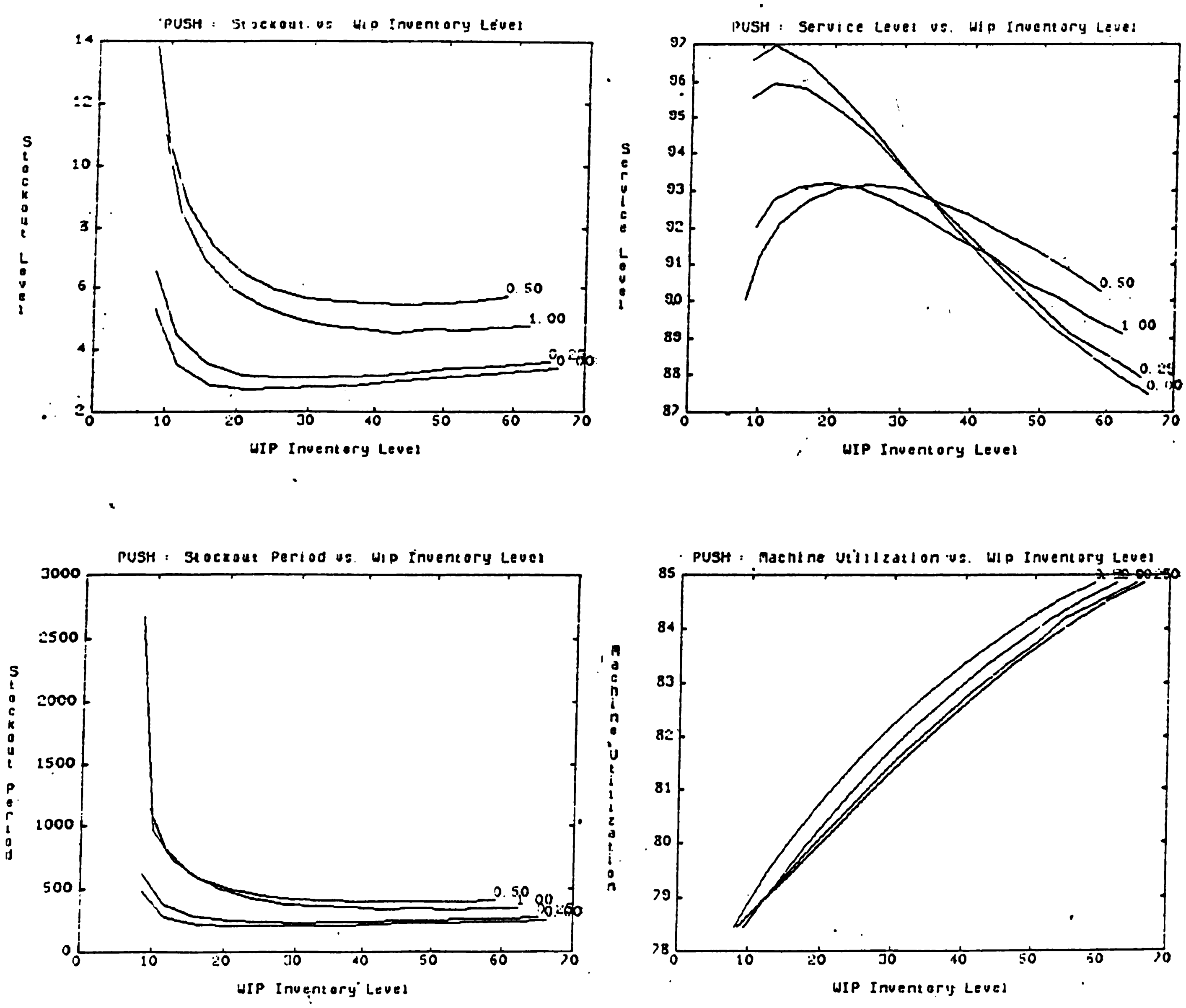

Figure A.27: Evaluation of alternative levels of demand variability for push control strategy.

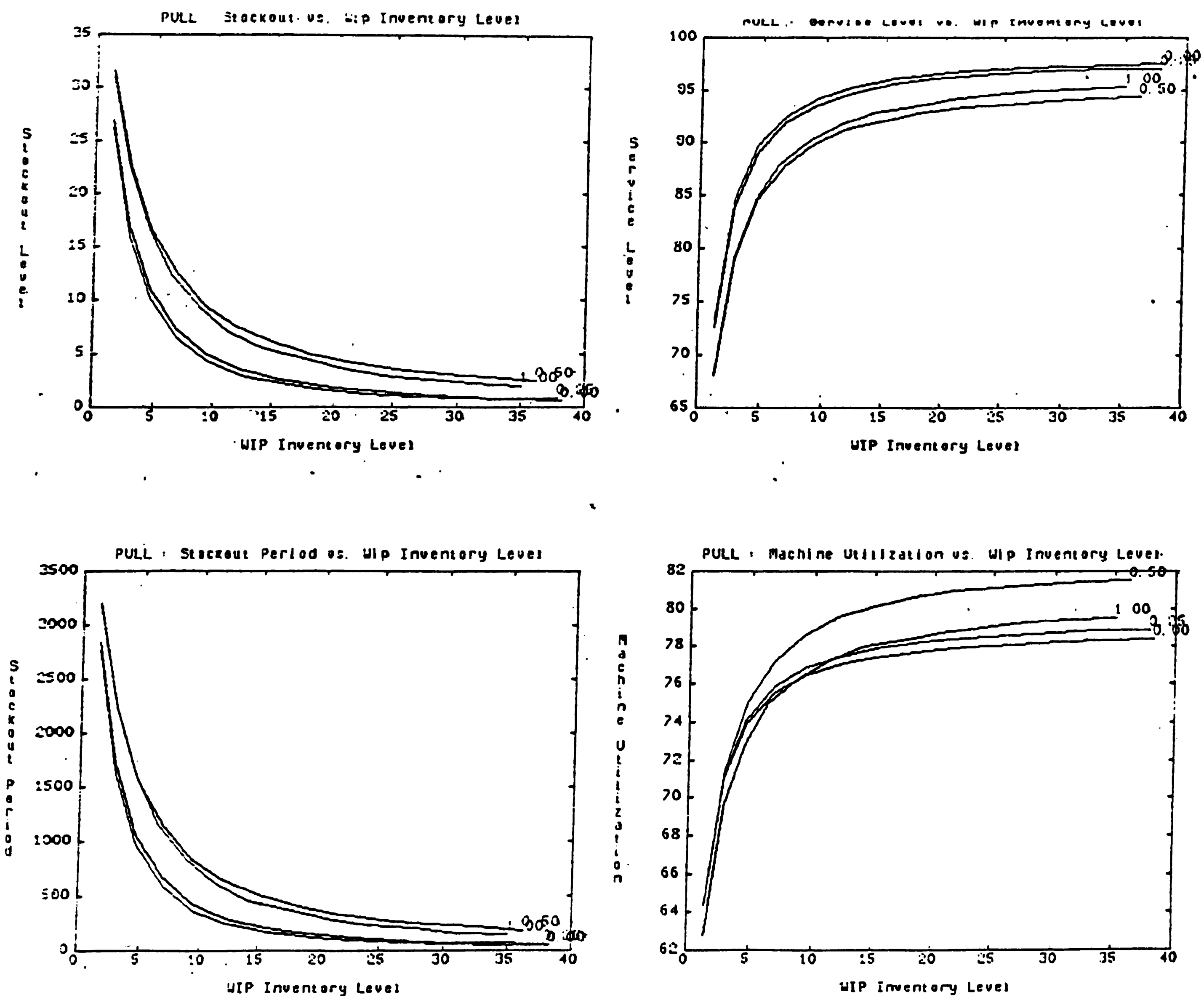

Figure A.28: Evaluation of alternative levels of demand variability for pull control strategy.

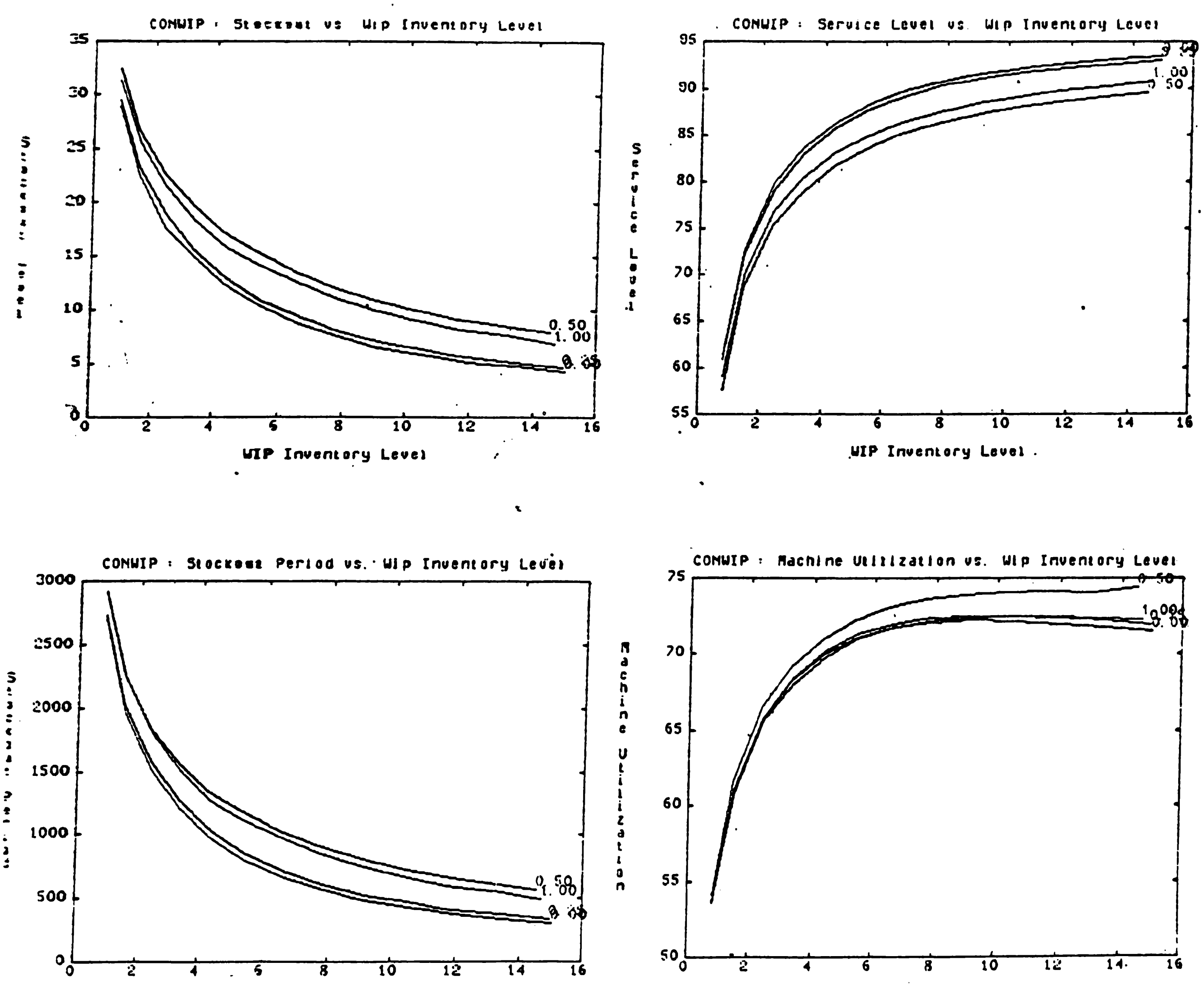

Figure A.29: Evaluation of alternative levels of demand variability for conwip control strategy.

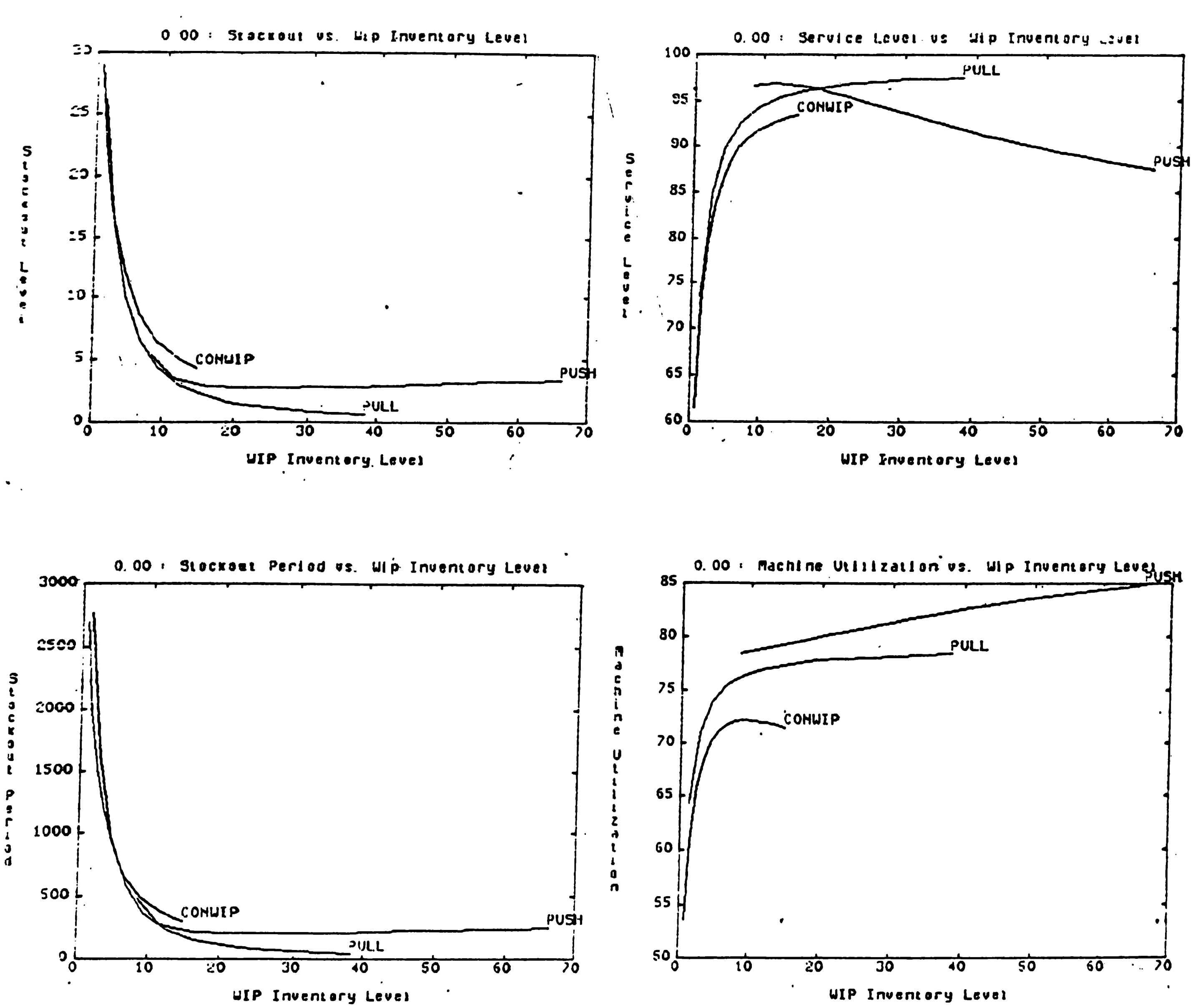

Figure A.30: Evaluation of alternative control strategies for 0.0 coefficient of variation in demand interarrival times.

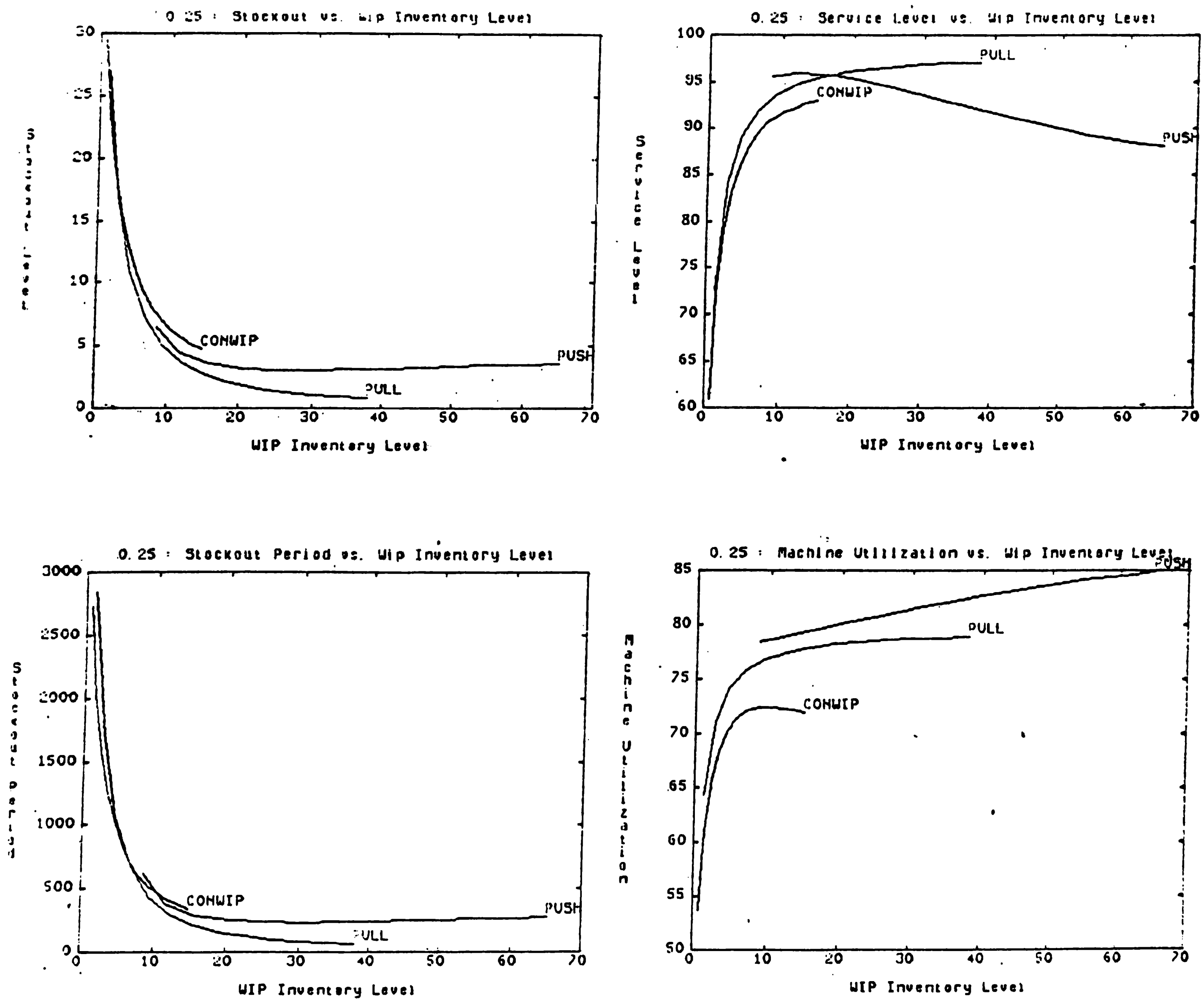

Figure A.31: Evaluation of alternative control strategies for 0.25 coefficient of variation in demand interarrival times.

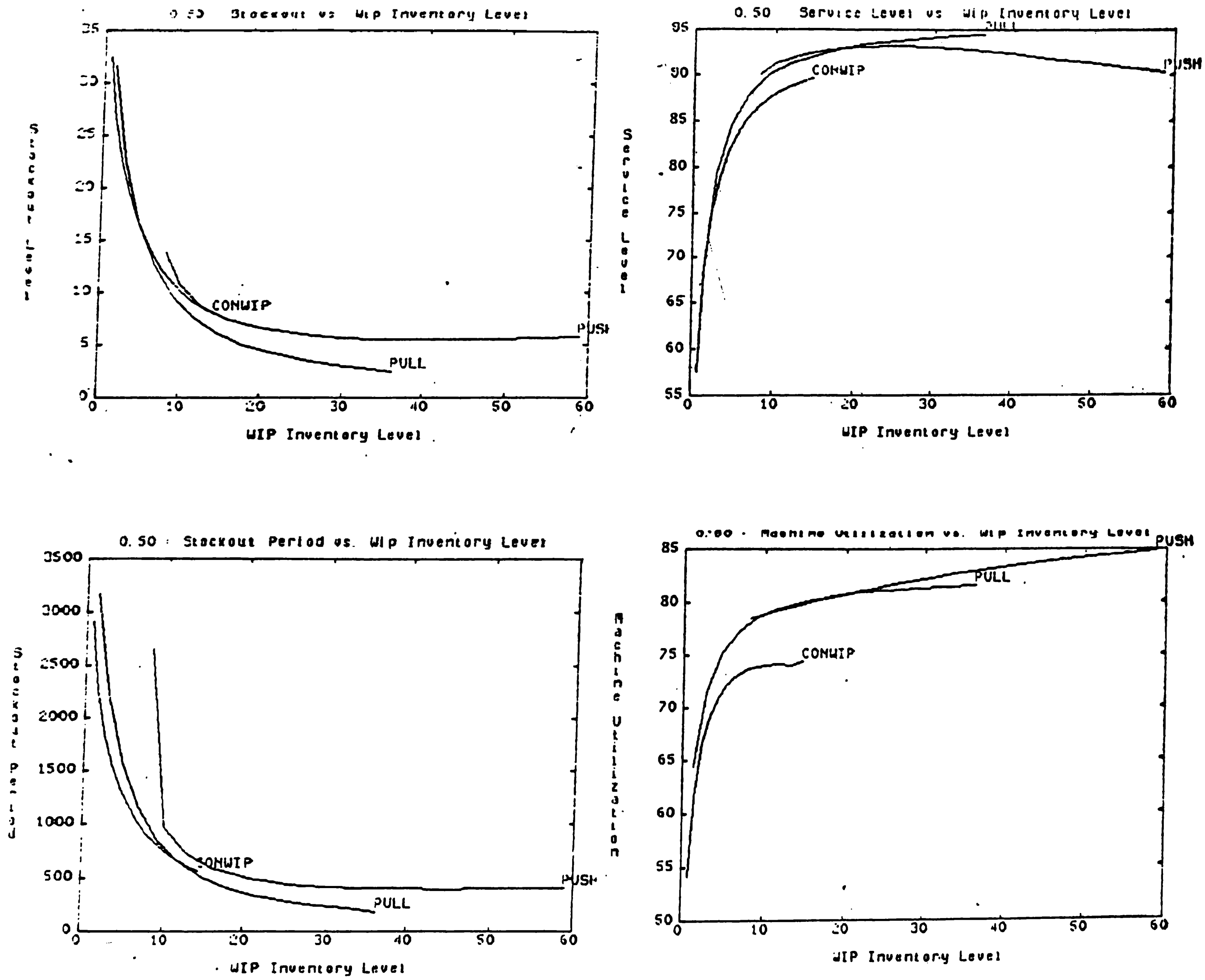

Figure A.32: Evaluation of alternative control strategies for 0.50 coefficient of variation in demand interarrival times.

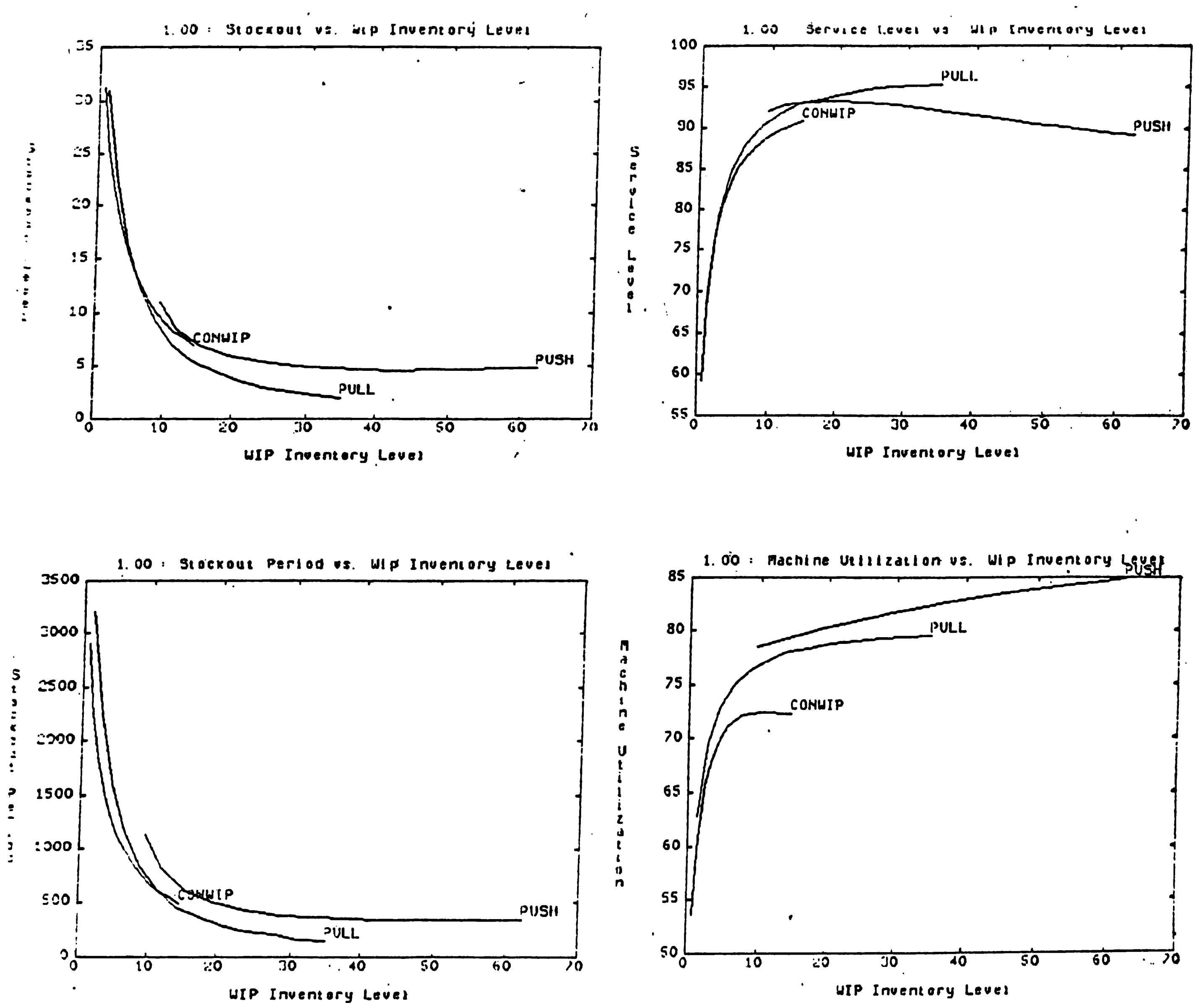

Figure A.33: Evaluation of alternative control strategies for 1.0 coefficient of variation in demand interarrival times.

Table A.23: Experimentation parameters for the impact of buffer inventories in pull control strategy.

EXPERIMENTATION PARAMETERS

IMPACT : BUFFER INVENTORIES

PROBLEM GENERATION

Number of machines	:	10
Number of part types	:	10
Number of operations	:	Uniform(8,12)
Processing times	:	Uniform(3,15)
Poduction ratios	:	Uniform(1,5)
Planning period length	:	9600
Average capacity utilization	:	80 %
Tool magazine capacity	:	60
Slot requirements	:	Uniform(3,7)
Number of tool sharings	:	0

SIMULATION

Control strategy	:	PULL
Wip inventory level	:	1..12
SS inventory level	:	1..13
Production lot size	:	1
Setup/processing time ratio	:	0
Demand inter-arrival time distribution	:	Exponential(..)
Processing time distribution	:	Constant(..)
Failure time distribution	:	Exponential(1/1750)
Repair time distribution	:	Gamma(17.4,14.4)
Statistics clear time	:	2400
Simulation end time	:	28800
Number of replications	:	10

Table A.24: Simulation results for the impact of buffer inventories in pull control strategy.

See Note # 8 for further explanation.

	PULL WITH INITIAL WIP=1					PULL WITH INITIAL WIP=5					CONWIP WITH INITIAL WIP=9				
SS	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.	WIP	STK OUT	STKOUT PERIOD	% SERV.	% UTIL.
1	1.21	29.96	3102.73	72.14	65.03	7.03	10.46	1038.97	91.83	77.33	15.21	6.78	679.12	95.41	79.39
2	1.21	29.22	3008.47	72.14	65.03	7.15	9.65	940.15	91.83	77.33	15.44	6.04	589.09	95.41	79.39
3	1.22	28.48	2915.42	72.14	65.03	7.34	8.90	849.75	91.83	77.33	15.75	5.39	510.72	95.41	79.39
4	1.24	27.75	2823.66	72.14	65.03	7.58	8.20	767.02	91.83	77.33	16.45	4.82	443.14	95.41	79.39
5	1.27	27.02	2732.84	72.14	65.03	7.87	7.54	691.54	91.83	77.33	16.62	4.31	384.86	95.41	79.39
6	1.31	26.30	2643.29	72.14	65.03	8.21	6.94	623.19	91.83	77.33	17.14	3.86	334.81	95.41	79.39
7	1.35	25.59	2555.57	72.14	65.03	8.60	6.37	560.90	91.83	77.33	17.73	3.47	291.44	95.41	79.39
8	1.42	24.89	2469.46	72.14	65.03	9.03	5.85	504.55	91.83	77.33	18.36	3.13	254.19	95.41	79.39
9	1.49	24.20	2385.00	72.14	65.03	9.50	5.37	453.36	91.83	77.33	19.04	2.83	222.64	95.41	79.39
10	1.58	23.53	2302.84	72.14	65.03	10.01	4.92	407.05	91.83	77.33	19.76	2.56	196.14	95.41	79.39
11	1.69	22.86	2222.82	72.14	65.03	10.56	4.51	365.32	91.83	77.33	20.51	2.34	173.81	95.41	79.39
12	1.82	22.21	2144.72	72.14	65.03	11.15	4.13	327.96	91.83	77.33	21.30	2.13	154.93	95.41	79.39
13	1.96	21.57	2068.93	72.14	65.03	11.78	3.79	294.92	91.83	77.33	22.11	1.96	139.25	95.41	79.39
	PULL WITH INITIAL WIP=2					PULL WITH INITIAL WIP=6					CONWIP WITH INITIAL WIP=10				
1	2.53	21.33	2168.44	81.93	71.37	8.94	9.42	931.66	93.29	78.11	17.96	6.19	627.03	95.71	79.57
2	2.56	20.52	2067.91	81.93	71.37	9.10	8.63	835.60	93.29	78.11	18.22	5.48	540.81	95.71	79.57
3	2.62	19.73	1970.26	81.93	71.37	9.32	7.90	748,42	93.29	78.11	18.58	4.86	467.55	95.71	79.57
4	2.69	18.96	1875.99	81.93	71.37	9.61	7.23	669.44	93.29	78.11	19.02	4.33	405.61	95.71	79.57
5	2.79	18.20	1784.76	81.93	71.37	9.94	6.61	598.34	93.29	78.11	19.54	3.88	353.77	95.71	79.57
6	2.91	17.47	1696.99	81.93	71.37	10.33	6.04	534.62	93.29	78.11	20.11	3.48	309.61	95.71	79.57
7	3.05	16.76	1612.68	81.93	71.37	10.77	5.52	476.91	93.29	78.11	20.74	3.13	271.48	95.71	79.57
8	3.21	16.07	1531.36	81.93	71.37	11.25	5.04	424.94	93.29	78.11	21.42	2.83	238.62	95.71	79.57
9	3.40	15.39	1453.10	81.93	71.37	11.77	4.59	378.20	93.29	78.11	22.13	2.57	210.38	95.71	79.57
10	3.62	14.74	1377.83	81.93	71.37	12.34	4.19	336.51	93.29	78.11	22.88	2.33	186.16	95.71	79.57
11	3.85	14.10	1305.59	81.93	71.37	12.94	3.82	299.53	93.29	78.11	23.66	2.13	165.36	95.71	79.57
12	4.11	13.49	1236.10	81.93	71.37	13.58	3.49	267.38	93.29	78.11	24.46	1.95	147.72	95.71	79.57
13	4.39	12.89	1169.15	81.93	71.37	14.26	3.19	239.68	93.29	78.11	25.29	1.80	132.81	95.71	79.57
	PULL WITH INITIAL WIP=3					PULL WITH INITIAL WIP=7					CONWIP WITH INITIAL WIP=11				
1	3.86	15.79	1600.07	87.12	74.41	11.02	7.97	789.83	94.12	78.58	20.42	6.00	608.82	96.07	79.88
2	3.92	14.96	1497.07	87.12	74.41	11.23	7.23	699.92	94.12	78.58	20.70	5.31	524.45	96.07	79.88
3	4.01	14.16	1399.12	87.12	74.41	11.52	6.57	621.25	94.12	78.58	21.08	4.72	453.59	96.07	79.88
4	4.13	13.39	1306.11	87.12	74.41	11.88	5.97	551.96	94.12	78.58	21.55	4.21	394.33	96.07	79.88
5	4.29	12.65	1217.60	87.12	74.41	12.31	5.43	491.38	94.12	78.58	22.09	3.78	344.86	96.07	79.88
6	4.48	11.94	1134.20	87.12	74.41	12.79	4.95	438.40	94.12	78.58	22.69	3.40	302.92	96.07	79.88
7	4.71	11.26	1055.41	87.12	74.41	13.32	4.52	391.31	94.12	78.58	23.33	3.07	266.76	96.07	79.88
8	4.97	10.62	981.13	87.12	74.41	13.90	4.12	349.36	94.12	78.58	24.02	2.78	235.34	96.07	79.88
9	5.27	10.00	911.66	87.12	74.41	14.51	3.77	311.99	94.12	78.58	24.74	2.52	208.04	96.07	79.88
10	5.60	9.42	846.60	87.12	74.41	15.17	3.45	278.84	94.12	78.58	25.50	2.29	184.22	96.07	79.88
11	5.97	8.86	785.78	87.12	74.41	15.85	3.16	249.80	94.12	78.58	26.28	2.08	163.55	96.07	79.88
12	6.37	8.34	728.94	87.12	74.41	16.57	2.90	224.44	94.12	78.58	27.08	1.90	145.98	96.07	79.88
13	6.80	7.84	675.98	87.12	74.41	17.33	2.67	202.74	94.12	78.58	27.91	1.74	131.34	96.07	79.88
	PULL WITH INITIAL WIP=4					PULL WITH INITIAL WIP=8					CONWIP WITH INITIAL WIP=12				
1	5.42	12.86	1295.13	89.76	76.07	12.98	7.47	745.70	94.84	78.97	23.22	5.79	587.62	96.20	79.94
2	5.51	12.03	1193.69	89.76	76.07	13.19	6.72	654.40	94.84	78.97	23.49	5.08	500.85	96.20	79.94
3	5.64	11.24	1098.15	89.76	76.07	13.49	6.05	573.87	94.84	78.97	23.86	4.48	428.45	96.20	79.94
4	5.80	10.49	1008.59	89.76	76.07	13.85	5.45	503.48	94.84	78.97	24.33	3.97	367.77	96.20	79.94
5	6.01	9.78	925.16	89.76	76.07	14.29	4.91	442.26	94.84	78.97	24.86	3.52	316.85	96.20	79.94
6	6.26	9.10	847.79	89.76	76.07	14.78	4.43	388.62	94.84	78.97	25.47	3.15	274.30	96.20	79.94
7	6.56	8.47	775.86	89.76	76.07	15.32	4.00	341.30	94.84	78.97	26.12	2.82	238.01	96.20	79.94
8	6.89	7.87	709.25	89.76	76.07	15.91	3.62	299.97	94.84	78.97	26.82	2.53	206.98	96.20	79.94
9	7.26	7.30	647.67	89.76	76.07	16.54	3.27	264.05	94.84	78.97	27.55	2.29	180.91	96.20	79.94
10	7.67	6.77	590.68	89.76	76.07	17.21	2.97	233.33	94.84	78.97	28.33	2.07	159.08	96.20	79.94
11	8.12	6.28	538.28	89.76	76.07	17.93	2.70	207.23	94.84	78.97	29.13	1.88	140.63	96.20	79.94
12	8.61	5.82	490.46	89.76	76.07	18.67	2.47	184.88	94.84	78.97	29.95	1.72	125.08	96.20	79.94
13	9.13	5.39	447.47	89.76	76.07	19.45	2.26	165.73	94.84	78.97	30.79	1.58	112.07	96.20	79.94

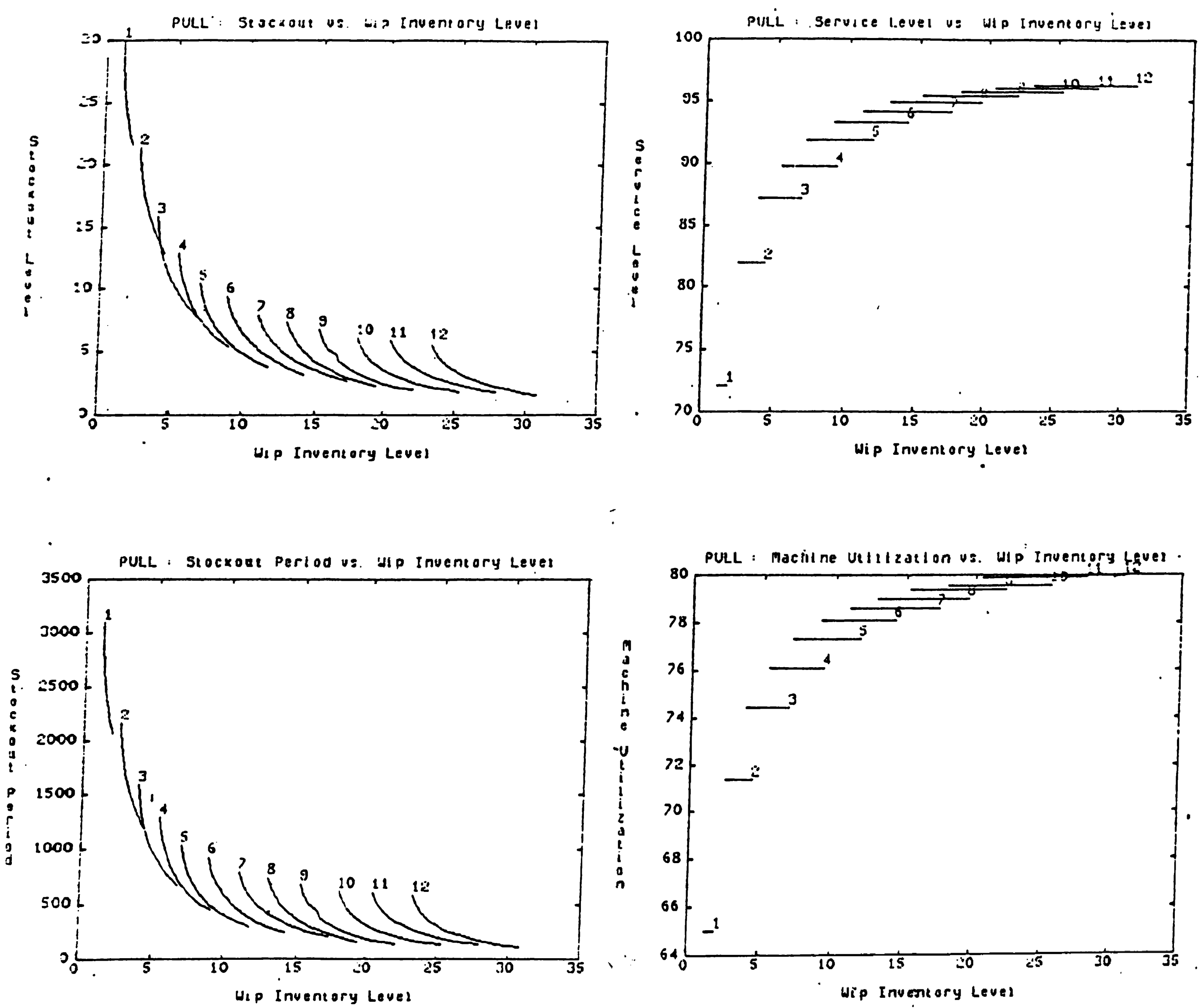

Figure A.34: Evaluation of WIP vs. SS inventories in pull control strategy.

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