May, 1982 LIDS-P-1199

# MATERIAL AND INFORMATION FLOW IN AN ADVANCED AUTOMATED MANUFACTURING SYSTEM

by

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This research was carried out at the Laboratory for Information and Decision Systems with support extended by the National Science Foundation under Grant DAR78-17826.



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## 1. Introduction

This paper surveys research performed recently at the MIT Laboratory for Information and Decision Systems in the area of manufacturing systems. Its emphasis has been the effect of the behavior of components (such as processing machines, storage buffers, etc.) on important system-wide performance measures, such as throughput and in-process inventory. Reliability has been a particular focus . When a machine fails, this failure can propagate downtime throughout the system unless specific measures are taken to prevent it.

The research to this date has been generic. As a result, this paper does not discuss applications to specific types of production. In our experience, the generic issues are important, but significant additional work is required to bring these results to practice.

This research was carried out in the M.I.T. Laboratory for Information and Decision Systems with support extended by the National Science Foundation Grant ARP76-12036 and DAR78-17826. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author, and do not necessarily reflect the views of the National Science Foundation.

## 2. Structure of an Advanced Automated Manufacturing System

In this section, the overall structure of an advanced manufacturing system is discussed. The consequences of failures are examined and methods to mitigate their effects are explored.

### 2.1 Overall Organization

Figure 2.1 represents a structure of an advanced automated production facility. It may be regarded as composed of three subsystems: the material processing and storage system, the material flow system, and the information flow system.

The material processing and storage system consists of a set of work centers or cells and a set of storage buffers. The work centers consist of one or more flexible machines, that is, machines that are capable of performing a variety of related operations on a family of related parts. In general, parts move in one direction among the work centers, but they may have different, possibly complex routes within the work centers.

In Figure 2.1, the storage buffers are displayed as located between the work centers. A single, central storage facility, involving automated storage and retrieval (AS/RS) equipment, may be used instead to serve the same purpose.

### 2.2 Failures

For the purpose of this paper, a failure is any event that causes a part of the system to be unavailable for production. This includes such causes as tool breakage. It may also be useful to include maintenance downtime in this definition.

The failures that cause difficulties are those of long duration. Short failures, when they are frequent, reduce the capacity of the system. For the purposes of this paper, however, they can be regarded as random variations of processing times.

It may be assumed that long failures are relatively infrequent for each machine. If not, the machine is a poor investment. Consequently, every machine has two states (up and down), each of which persists for a long time. If there are k machines in the system, the system has $2^k$ machine states.

If nothing is done to prevent it, the effects of failures can propogate and reduce the utilization of machines other than the failed machines. For example, upstream machines, with no place to send their products, will be blocked. Downstream machines, with no product to work on, will be starved.

There are three techniques for mitigating the propogation of failures.

Buffers allow machines upstream of a failed machine to keep operating as long as there is space in intervening buffers. They allow downstream machines to keep operating if there is material in intervening buffers. If the failure is repaired before the buffers fill or empty, respectively, the downtime is not propogated to the neighboring machines.

Buffers, then, mitigate the propogation effects by tending to decouple adjacent machines. They do it at a cost. Elaborate storage mechanisms cost money and can themselves fail. Storage takes up valuable factory floor space that could be used for other purposes. Finally, there is a cost due to in-process inventory.

Redundancy is the provision of alternative processors and production paths so that production can continue while a machine is under repair. The cost is that of purchasing machines for this purpose. It is desirable for back-up machines to be flexible so that they can perform the operations of as many machines as possible in the work center.

A third method is the distribution of machine state information. When a machine fails, its neighboring work centers are notified. If the failure limits the rate at which material of a certain kind can be processed, the upstream work centers are advised to limit their own production of that material to the same rate. In this way all affected work centers can reconfigure their routing and scheduling policies so as to increase their production rate of material that is not limited by the failure. Thus, machine utilization is kept up and in-process inventory is reduced.

The cost for this approach is that of sophisticated electronics: computers and data communication networks. Although the expenditure may be far less than than that for the other methods, it may require a relatively sophisticated work force.

All three methods can be used together. The problems facing the management of a factory are: how much and what kind of in-process inventory and processor redundancy should be obtained; how should an information flow system be configured; and how should it all be run?

## 3. Buffer Storages

### 3.1 Introduction

One of the methods listed above for mitigating the effects of failures is the provision of buffer storages between sets of operations. Buffers decouple the system so that changes from normal operating conditions at one part of the system have minimal effects on operations elsewhere. The precise effect of such storages on system-wide behavior is only partially understood.

Some progress has been reported in the literature in formulating, solving, and understanding a special class of system with storage-- the flow shop or transfer line. This class is illustrated in Figure 3.1. Workpieces enter the first machine and are processed. They are then stored in the first storage and proceed to the second machine and so forth. They leave the system after the k'th machine.

Recent research has extended the analysis to treat networks involving machines that perform assembly or disassembly operations. A network in which assembly, unitary, and disassembly operations exist appears in Figure 3.2.

One way in which buffers decouple systems is to isolate the effects of machine failures. When a machine downstream of a buffer fails, the buffer can provide space for partially manufactured pieces produced upstream, and thus allow upstream machines to continue operating. In the absence of such buffering, the upstream machines would have to stop, reducing overall productivity. Even when storages are present, a protracted failure can cause one or more storages to fill up. Similarly, a buffer can provide workpieces for the downstream part of the line when an upstream machine fails. Buffers also decouple systems in which the processing times are random. In such systems, a long processing time can act as a failure and, in the same way, cause other machines to be idle.

It is clear that storages that can hold more in-process inventory have a greater decoupling effect and thus provide a greater effective production rate (efficiency or throughput). However, increasing the sizes of such buffers leads to increased costs in the amount of space devoted to storage and in the inventory itself. In order to choose the best trade-off between these costs and the improvement in efficiency, it is necessary that efficiency be calculated as a function of storage size.

In Section 3.2, we illustrate the effects of machine reliability and buffer capacity on throughput and average in-process inventory. In Section 3.3 we present a simplified example of how these relationships can be used to optimize buffer capacity.

## 3.2 Effect of Reliability and Storage Size on Throughput and Buffer Level

This section is adopted from the MIT Master's Thesis of Irvin C. Schick (Schick and Gershwin, 1978) and the MIT Bachelor's thesis of Brenda Pomerance (1979). As shown by Ammar (1980), Ammar and Gershwin (1981) and Ibrahim (1981) the results apply to assembly/disassembly networks as well as to transfer lines.

In production lines with finite storages, the utilization of the machines is always lower than their efficiencies in isolation, since they are occasionally blocked or starved. As storage capacities are increased, the utilizations asymptotically approach the efficiency in isolation of the least efficient machine. Increasing the efficiency of an individual machine has the overall effect of increasing the production rate of the transfer line, but this effect is difficult to calculate. The utilization of the improved machine (and hence, the production rate of the transfer line) does not increase linearly with the efficiency of an individual machine. Buffer storages contribute most to the system production rate when the machines are not extremely efficient and no machine is significantly less efficient than the others (i.e., the line is balanced).

Consider a simple class of production lines in which the cycle times of all machines are the same. Assume a simple failure and repair model in which the probability of failure during a cycle in which machine i is operational is $p_i$ and the probability of a repair completion on machine i during a cycle in which it is under repair in $r_i$. The mean time between failures (MTBF) is $1/p_i$ and the mean time to repair (MTTR) is $1/r_i$. The <u>isolated efficiency</u> of machine i, which is the frequency with which it would perform operations if it were not limited to other machines and storages, is given by $e_i = r_i/(r_i+p_i)$. The <u>line efficiency</u> is the frequency with which a line produces a piece during one cycle.

Five cases of two-machine lines are illustrated in Figures 3.3-3.4. In each $p_1 = r_1 = .1$, so that the efficiency of the first machine is 50%, and $r_2 = .1$. In case 1, $p_2 = .567$ so that $e_2 = .15$. In cases 2,3,4, and 5, $p_2$ is given by .2, .1, .05, and .018 so that $e_2$ is .333, .5, .667, and .85, respectively. Note that Case 3 is that of a balanced line. In Case 1 and 2, the first machine is the bottleneck. In cases 4 and 5, the bottleneck is Machine 2.

The line efficiency is plotted against storage capacity for each of the five cases in Figure 2.3. In cases 3-5, the value of $E(\infty)$ is the same, since the least efficient machine is the first. In cases 1-2, on the other hand, the least efficient machine is the second.

For any value of storage capacity, the production rate increases with $e_2$ until $e_2 \approx e_1$, after which the first machine acts as a bottleneck and the production rate approaches an asymptote, Thus, beyond a certain point, increasing the efficiency of the second machine becomes less and less effective.

It is noteworthy that providing small amounts of storage can sometimes improve the production rate as much as increasing $e_2$. For example, $e_2 = 0.67$ and no storage gives approximately the same efficiency as $e_2$=0.6 and N=4, or $e_2$=0.5 and N=10. This is significant, because improving the efficiency of a machine may involve a great deal of research and capital investment or labor costs, and may thus be more expensive than providing a small amount of buffer capacity. It is especially important that this effect is strongest when the machines have approximately the same efficiency, i.e., when the line is balanced. This is most often the case.

In Figure 3.4, the expected number of pieces in the storage is plotted against storage capacity. In cases 1 and 2, the first machine is more efficient than the second, and the expected in-process inventory increases with storage capacity. In case 3, the two machines have equal efficiencies, and the expected inventory increases linearly with storage capacity. In cases 4 and 5, the second machine is more efficient than the first, and the expected inventory approaches an asymptote.

Figure 3.5 shows how variations in the failure probability of machine 3, $p_3$, affect line efficiency, E, of a three-machine transfer line. The curves represent different values of $p_2$, the failure probability of machine 2. All other input parameters are constant, as indicated.

An increase of .1 in $p_3$ produces the greatest change in E when $p_2$ and $p_3$ are low. When the efficiencies in isolation of all machines are high, as is the case for low values of $p_2$ and $p_3$, the line is very efficient. As $p_3$ increases, the production rate of machine 3 becomes less than that of the other machines. The first two machines are limited by the third machine; they are not permitted to produce workpieces faster than machine 3 can remove them from the line. When $p_2$ or $p_3$ is high, the corresponding machine is a bottleneck.

Figure 3.6 shows how variations of $p_2$ and $p_3$ affect expected in-process inventory, I. As the third machine becomes less efficient, I increases. For constant $p_3$, increasing $p_2$ decreases I. For constant $p_3$ , increasing $p_2$ decreases I. As the second machine becomes less efficient, we expect $\bar{n}_1$, the average amount of material in the first buffer, to rise. We expect $\bar{n}_2$ to decrease, because machine 3 has the same rate of removing workpieces, but machine 2 deposits them less frequently. Since I, which is the sum of $\bar{n}_1$ and $\bar{n}_2$, is decreasing, we conclude that $\bar{n}_2$ decreases faster than $\bar{n}_1$ increases when machine 2 becomes less efficient. This qualitative behavior is determined by the parameters of this line. For other values of $r_i$, $p_i$, and $N_i$, I may increase with $p_2$.

### 3.3 Example

R. Paul Wiley, in his MIT Master's Thesis (1981), studies analysis methods for reliable and unreliable three-machine transfer lines with exponentially distributed processing times. In an example of a reliable line, all three machines have equal production rates of 10 operations/time unit. The two buffers have identical capacity of N. The variations in system production rate and in in-process inventory are shown in Figure 3.7. Note that in in-process inventory increases linearly (because of symmetry) while the production rate rapidly levels out. The limiting production rate, as both buffer capacities approach infinity, is 10 pieces per time unit. Thus with buffers of size 9, the production rate is within 15 percent of the maximum.

If each finished workpiece returns \$2.00 and the cost c holding a workpiece for one unit of time in the buffers is \$1.00, then the monetary return of the products can be calculated. This return is shown in Figure 3.8. To maximize the return, we would pick N=4. Note that the production rate that gives the optimal return is far from the limiting value. This is why it is important to study models ith finite buffers.

3.4 State of the Art

The results displayed here were calculated using exact analytic methods for two- and three-stage systems (Gershwin and Schick, 1980; Wiley; 1981. See also Gershwin and Berman, 1981; Ward, 1981.) In our judgment, however, such methods will not readily be extended to larger systems. This is because of the rapid growth of the state space.

In these models, the state consists of two lists of numbers, one indicating the current repair state of each machine (1 or 0 representing up or down), and the other for the amount of material in each buffer. The size of the state space is

$$S = 2^M \prod_{i=1}^{B} (1+N_i)$$

if there are M machines and B buffers and the storage capacity of buffer i is $N_i$. The computational effort increases with S in various ways, depending on the numerical method used. The increase in S with B and the increase in effort with S are so rapid that no advance in computer technology can be expected to allow the extension of the exact two-and three-stage analysis methods to larger systems.

Simulation methods have been widely used. While simulation should certainly be employed as a test on proposed system configuration, it can be unwieldy as a design tool. It is often time-consuming and yields only statistical quantities. Recent research has shown the potential for increasing the power of simulation (Ho, Eyler, and Chien, 1979) but is has only been applied to a limited class of problems.

Approximated analytic methods are required. One simple technique is illustrated by a four-machine, three-buffer line whose machine parameters are all $p_i = .05$, $r_i = .45$, $i = 1,2,3,4$, and whose buffers all have capacity $N_i = 5$. An upper bound on production rate is achieved by ignoring one of the machines and one of the buffers. The three-machine method yields a production rate of .832 parts/cycle. A lower bound is obtained by assuming that the first buffer has zero capacity. The first-two machines then form one compound machine which is down when either machine is down. Failure and repair rate parameters for the new first machine can be found and again, the resulting three-machine system can be analyzed. Its production rate is .783. The actual production rate is thus between .783 and .832 parts/cycle, which are not far apart.

While this method produces acceptable results for four-machine systems, it cannot be expected to work well for larger systems. For example, the same upper bound would have been produced for lines of any length whose machines and buffers are given by the above parameters.

One class of methods that is often considered is to treat several adjacent machines and buffers as a single machine, and thereby reduce the size of the system that must be analyzed. This grouping can continue until a two-or three-machine system is reached, which is then analyzed by exact methods. See, for example, the Bachelor's Thesis of Paul M. Dishop (1981).

There are several difficulties with this approach. There are no general results to indicate whether it produces a bound, or how good an approximation it is. It is not even clear what the parameters of the reduced system should be. These methods, like the bounding method above, tend to focus on production rate. It is not known how to calculate mean buffer levels.

It is fair to conclude, however, that it is in this direction or in further advances in simulation that future progress will be made.

## 4. Control of a Single Cell

### 4.1 Introduction

In this section, the other two of the methods for limiting the effects of machine failures are discussed: redundancy and distributing failure information. We focus on a single cell; the extension of the control methods to a system such as that illustrated in Figures 2.1-2.3 is an important research topic.

For the purpose of this paper, a cell, or work center, or flexible manufacturing system is a set of material processors, transportation devices, and a controller that together can process a family of types of material with little or no time lost for change-over. While such a system may be fully or partly automated or not automated at all, questions of routing and scheduling must be treated explicitly in the design of automated systems. The performance of manual systems can be improved by the addition of a computer-based information processing system. Such a system will calculate optimal routes and schedules, keep track of parts, and support two-way communication with workers (about operations to be performed and the state of the system, for example) by means of computer terminals and other devices on the factory floor.

The material is this section is based on the doctoral thesis of Joseph G. Kimemia (1982). See also Kimemia and Gershwin (1981).

### 4.2 Current State of Research

A manufacturing system may be large and complex. It is natural therefore to divide its control or management into a hierarchy. Higher levels in the hierarchy typically have long horizons and use aggregated data, while lower levels have short planning horizons and make use of more detailed information. The natural of uncertainties of each level of control also varies.

The management of a manufacturing firm makes production plans for finished items by considering sales and demand forecasts, inventory and plant capacity. From the master production plan, the requirements for all the components that go into the finished products can be determined. The various departments responsible for the manufacture of the components then schedule their activities so as to meet requirements dictated by the master production plan (Hitomi, 1979; Halevi, 1980; Orlicky, 1975).

The overall information flow within the cell control system is described in Figure 4.1. The central feature is the short term production planning module. This module has one major purpose: to translate long term production REQUIREMENTS that are imposed on it into dispatch commands that it imposes on the material processors and the transportation system (MANUFACTURING UNITS).

In order for it to serve this function, a feedback loop is required. This is because of the random events (machine failures and repairs, material unavailability, worker absences) that are inevitable in a real factory. Information from the manufacturing units is collected and processed (SYSTEM STATUS) and used by the production planning algorithm.

Information is also made available to humans or computers outside of the work center. QUERIES can be expected on the current status of the system, on the short term scheduling decisions, or on the future of the system (PROJECTIONS) assuming a given mode of operation. The latter is based on a mathematical model or a computer simulation.

Figure 4.2 represents an approach to short term production planning and scheduling. It may be viewed as a transducer, whose input information is a set of production requirements for a part family and whose output is a sequence of load, operate, and move commands to the material processors and the transportation system. Details can be found in Kimemia and Gershwin (1980, 1981) and Kimemia (1982).

GENERATE DECISION TABLES

The inputs to this module are of two kinds: requirements and production system descriptions. Requirement information describes the production demands on the system. In the current formulation, requirements must be known; constant production rates or known functions of time. We hope to extend this to unknown stochastic functions.

The description of the system includes the configuration: the list of machines and their operations and the topology of the transport system. This is expected to be known and unchanging. It also includes such parameters as operation times, failure rates, and repair rates. These quantities may not be as well known and may change with time.

The output of this module is control law information, in the form of decision tables, that is used by the lower modules. This includes short term production rate tables (described below) and the set of routes (i.e., feasible sequences of machines) that are available for each part type.

This module is called when the system is started for the first time, when requirements change, or when data are collected that indicate that the current system parameters are inaccurate. Because it involves a great deal of computation, it should be executed on a large computer away from the work center. This computer should be connected to the work center by a data communications network.

CALCULATE SHORT TERM PRODUCTION RATES

This module uses decision tables already generated to calculate the best set of short term production rates that will guarantee meeting the long term production requirements imposed on the system. It uses two kinds of on-line information: machine operating conditions and the degree to which production is ahead of or behind demand.

The machine operating conditions, which indicate which machines are currently operational and which have failed, characterize the set of possible production rates for each of the different parts. If the production of some parts is ahead of demand and the production of others is behind, the system will tend to devote most of its capacity to the latter parts.

CALCULATE ROUTE SPLITS

More than one route (sequence of processors) may be available to some of the parts being produced. This module calculates the fraction of each part that takes each available route to meet the short term production rates already determined. This module also may incorporate on-line process planning.

SCHEDULE TIMES AT WHICH TO DISPATCH PARTS

At this point, the desired flow rate of each part type on each route has been determined. This module issues dispatch commands to the processors and transportation system so that actual flow rates achieve those values. It may use information on the current location of each part.

4.3 Example

4.3.1 Description of System

To demonstrate the application of the hierarchical controller, consider the flexible transfer line of Figure 4.3. Each stage has two identical machines. Two part types are produced. The first type requires two operations, one at each stage, while the second part requires a single operation which can only be performed at the first stage.

The operation times and reliability data for the system are assumed known. They are given in Table 1. In this example, there are nine possible machine states. We will discuss only three of them, all machines up ($\alpha=(2,2)$), one type A failed ($\alpha=(1,2)$) are one type B failed ($\alpha=(2,1)$). (Here, $\alpha$ is a list of the numbers of operational machines at each stage.)

A production constraint set is a set of feasible production rates. The production constraint set depends on the current set of operational machines. The production constraint sets for the machine states (2,2), (2,1), and (1,2) are shown in Figure 4.4. The different effects of type A and type B failures is evident.

The demand rates d for the two parts are 2.5 type 1 and .125 type 2 parts per minute. The production rate can exceed the demand rate only in machine states (2,2) and (2,1). In all other machine states, the demand rate is beyond the capacity of the system.

The module called CALCULATE SHORT TERM PRODUCTION RATE in Figure 4.2 is characterized by Figure 4.5. It is a set of partitions of $(x_1, x_2)$ space where the vector $(x_1(t), x_2(t))$ is the difference between cumulative production and cumulative demand for each part type. When $x_k(t)$ is positive, the system has produced more of type i parts than has been demanded of it up to time t; when $x_i(t)$ is negative, it has produced less.

In each partition, the short term production rate vector is determined by the corresponding corner in Figure 4.4. The boundaries between the regions are determined by a dynamic programming calculation which is described in Kimemia and Gershwin (1981) and Kimemia (1982). This calculation is performed by the GENERATE DECISION TABLES module in Figure 4.2.

Also shown in Figure 4.5 is the behavior of the downstream buffer state trajectory (i.e., the history of the cumulative difference between requirements and production). Initially, the system has all machines operating and the buffer state x(0) is 0 (the origin of Figure 4.5a). The point x(0) happens to lie on the boundary between two regions. (This is not always the case.) The production vectors in the two neighboring regions both drive the trajectory towards the boundary. The trajectory moves in the positive direction as an inventory of parts is built up as a hedge against future failures. At point (i) production equals demand and the trajectory remains constant.

When a type A machine fails, the new production is found at point (ii) in Figure 4.5b. Initially only type 1 parts are produced, resulting in an increase in the buffer level of type 1 parts. The level of type 2 parts, as a consequence, drops. At point (iii) the trajectory meets the boundary and a mix of both parts is produced, keeping the trajectory on the boundary. After approximately 25 minutes, the failed machine is repaired with the buffer levels at point (iv). The production rate is found at point v of Figure 4.5a. Type 2 parts are produced at the maximum rate to clear the backlog caused by the failure. Production of type 1 parts resumes at point (vi) and the trajectory follows the boundary to the point (i) where once again production is at the demand rate. A similar set of events can be constructed for any other sequence of failures and events.

4.3.2 Simulation Results

The system was simulated with the scheduling being performed by the hierarchical controller. Each stage had a buffer with a capacity for 5 pieces and a last-in-first-out discipline. The model was run for the equivalent of 14 hours.

The availability and utilization of available time at each machine is given in Table 2. Stage A is the bottleneck stage. The controller is able to attain utilizations of 94% and 85% of available time for the two stage A machines. Stage B, on the other hand, is lightly loaded with only 55% and 36% of the available time being used.

Production statistics are shown in Table 3. On average, the production was 5.2 pieces behind demand for part 1 and 4.2 for part 2. The average in-process inventory in the system is small, 3 type 1 pieces and 1.2 type 2 pieces. At the end of the simulation, the system had produced the required number of type 2 parts and was two type 1 parts short of target. Thus the algorithm was able to track demand and at the same time keep the number of pieces inside the system small.

## 5. Conclusion

This paper has outlined some of the issues that arise in considering the affects of machine failures on a manufacturing system. When a failure occurs, it effect can be more than local, since starvation and blockage can reduce the utilization of machines which themselves have not failed. Buffers, redundancy, or modern electronics can help to reduce these effects, at different costs. This paper has surveyed some recent work in assessing the cost of buffers and of optimally operating certain systems with redundancy and advanced computer control systems.

Research is needed in both these areas: to improve the computation of the effects of buffers and to enlarge the class of systems to which the control method of Section 4 can be applied. In addition, the collection of reliability information is critical. Methods must be devised and implemented which will supply MTBF's and MTTR's for all machines in the system. The effects of workpiece inspection, rework, and rejection on system operations, throughput, and in-process inventory levels should also be incorporated into the models described here.

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| Part | Stage A | Stage B |
|---|---|---|
| 1 | .33 | .33 |
| 2 | .67 | not re[illegible]ired |

Processing Time for the Parts in minutes.

| Stage | MTBF | MTTR |
|---|---|---|
| 1 | 300 | 30 |
| 2 | 300 | 30 |

Reliability data

MTBF - Mean time between failures (in minutes)
MTTR - Mean time to repair (in minutes)

TABLE 1 SYSTEM DATA

| Stage | Machine | Availability | Utilization |
|---|---|---|---|
| A | 1 | .95 | .94 |
| A | 2 | .91 | .85 |
| B | 1 | .92 | .55 |
| B | 2 | .92 | .36 |

TABLE 2: MACHINE AVAILABILITY AND UTILIZATION FOR THE SIMULATION RUN

| Part | Average In-Process Inventory | Mean Buffer State | Number of Parts Required | Number of Parts Produced |
|---|---|---|---|---|
| 1 | 3.0 | -5.2 | 2083 | 2081 |
| 2 | 1.2 | -4.2 | 1042 | 1042 |

TABLE 3: PRODUCTION RESULTS FOR THE SIMULATION RUN

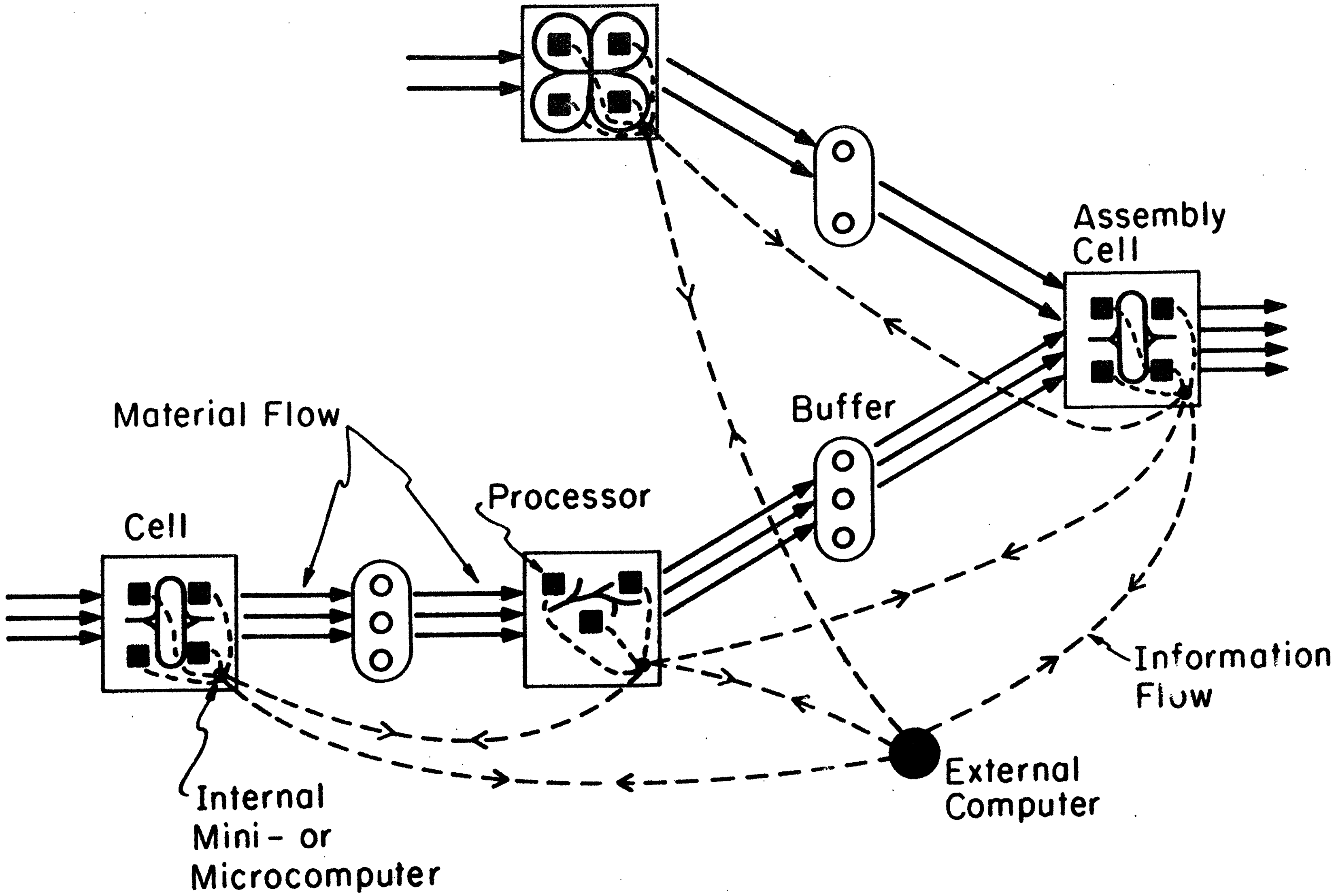



Fig. 2.1 Production System

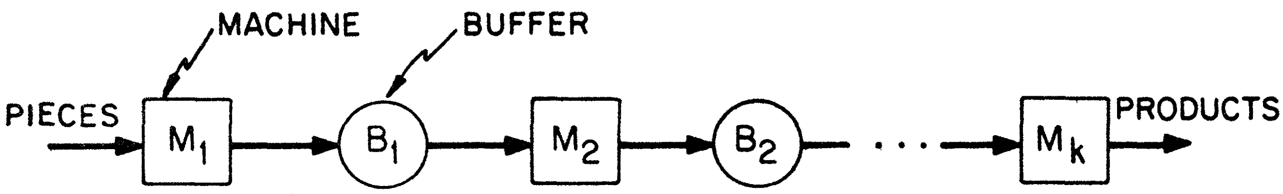



Fig. 3.1: Transfer or Production Line

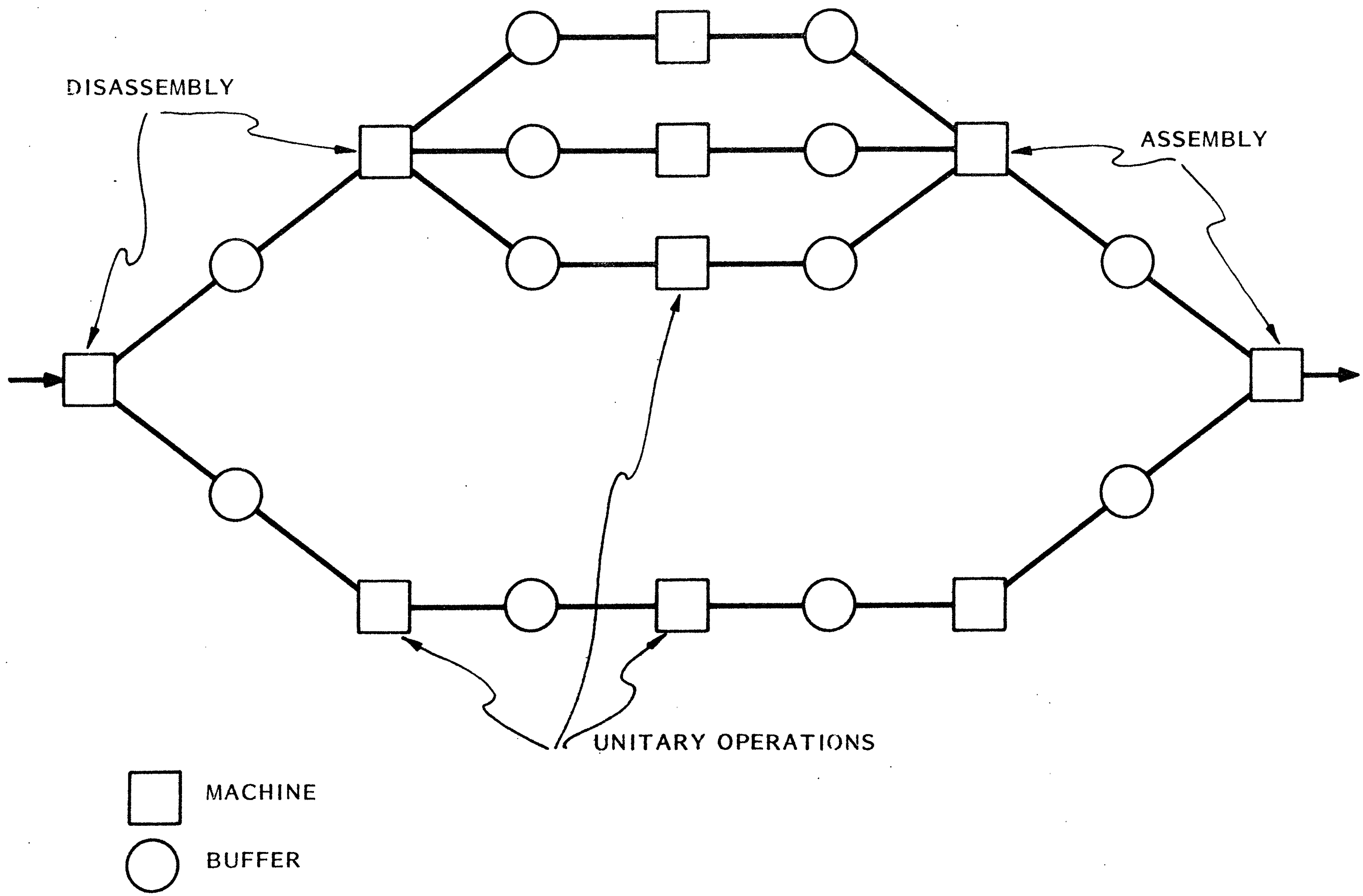



Fig. 3.2: Assembly/Disassembly Network

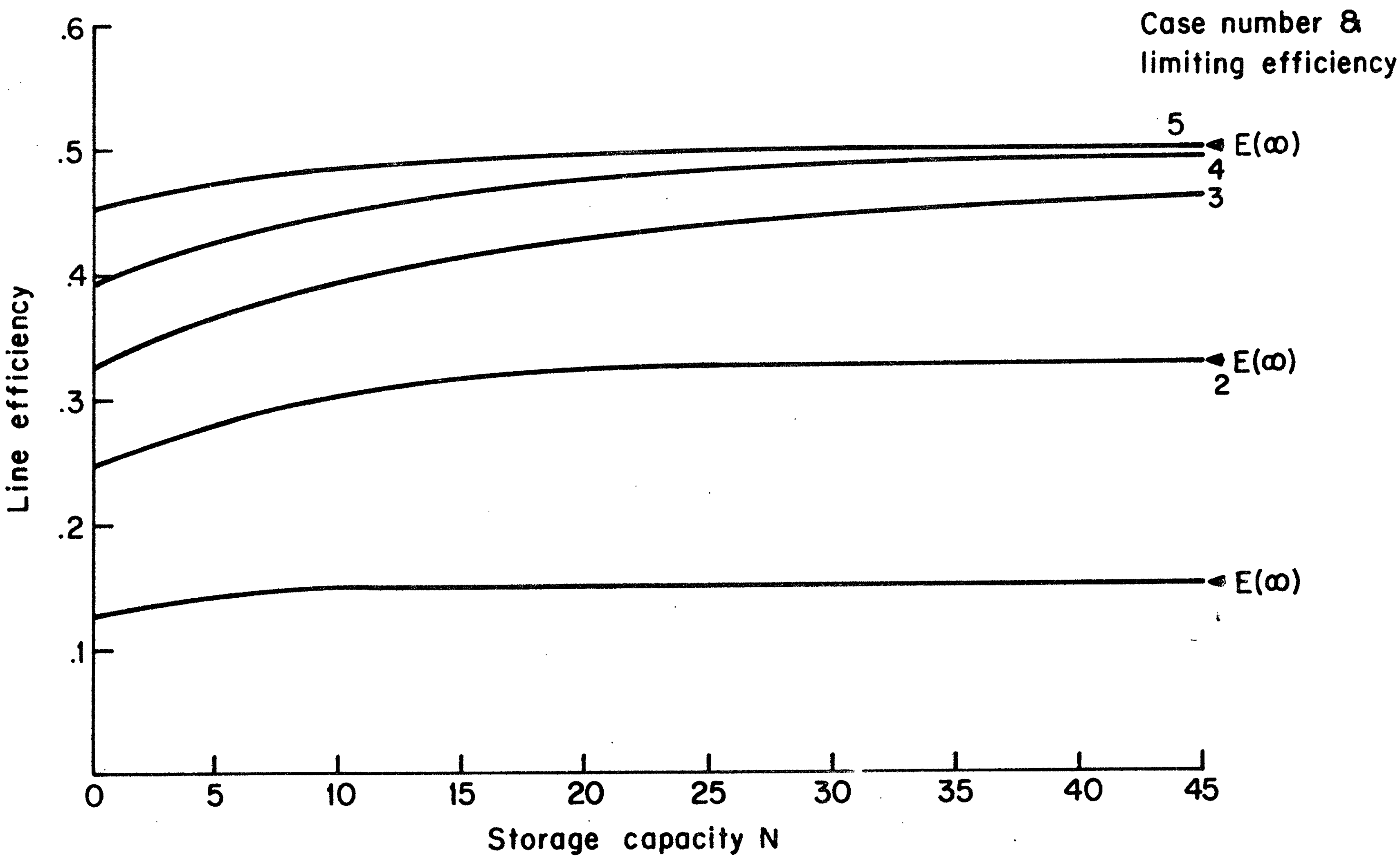



Fig. 3.3: Line efficiency for a set of two-machine lines.

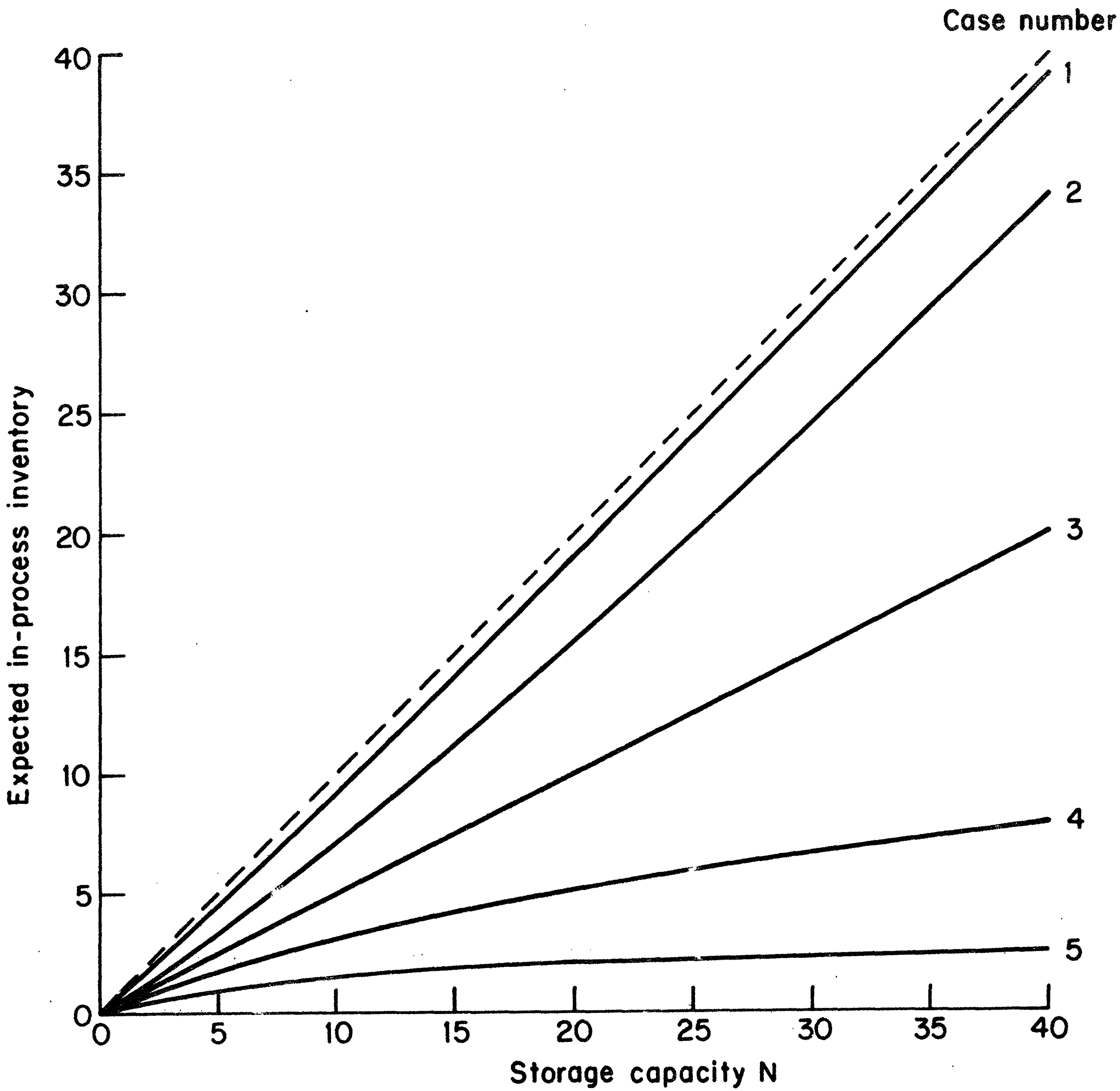



Fig. 3.4: Expected in-process inventory for a set of two-machine lines.

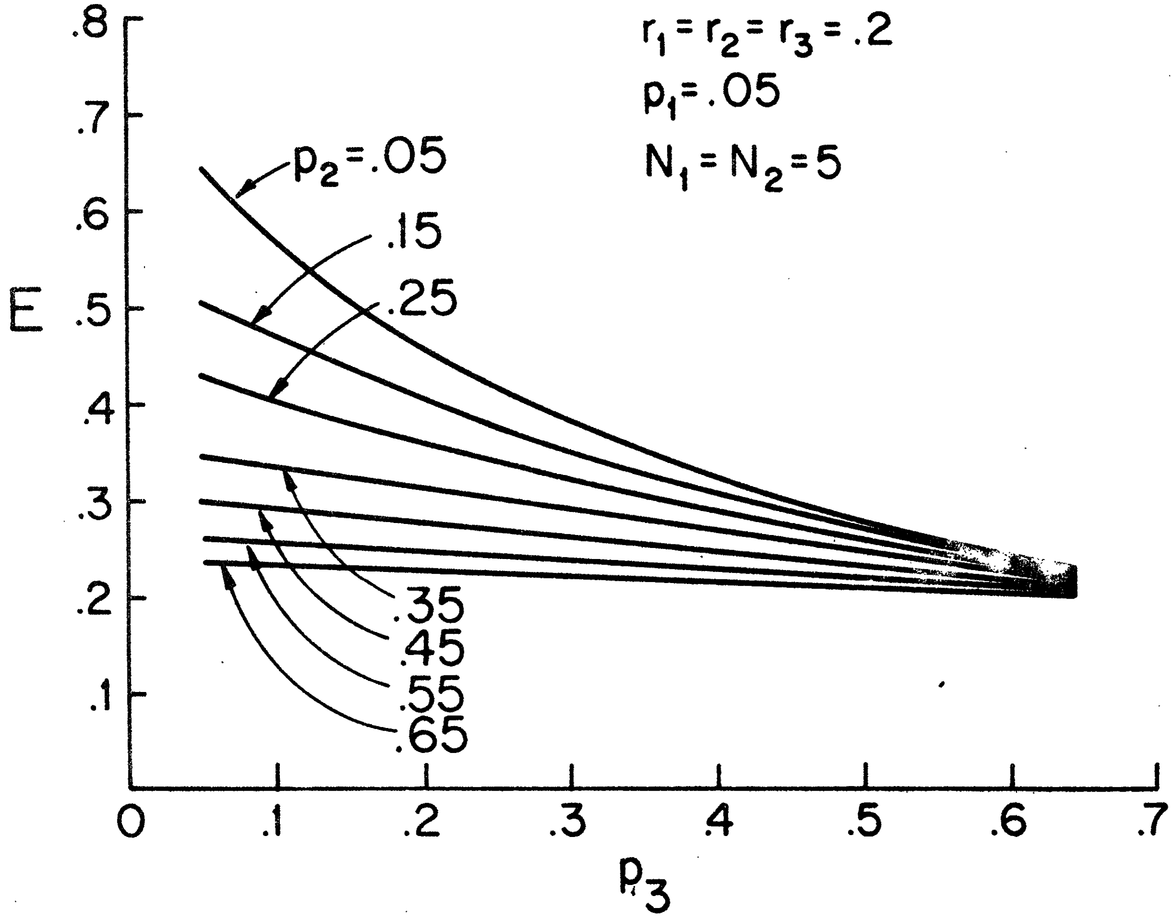



Fig. 3.5: Line efficiency for a set of three-machine lines.

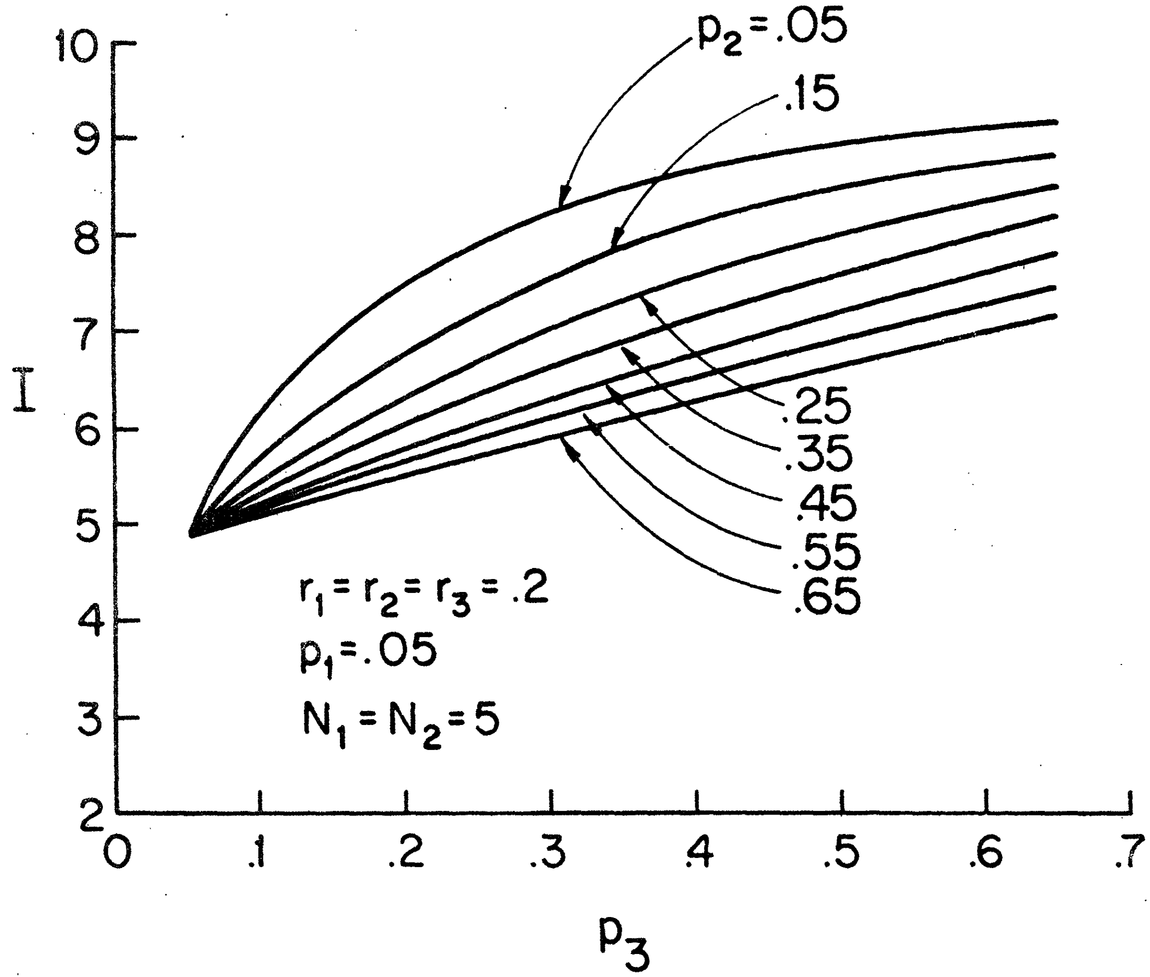



Fig. 3.6: Expected In-process inventory for a set of three-machine lines.

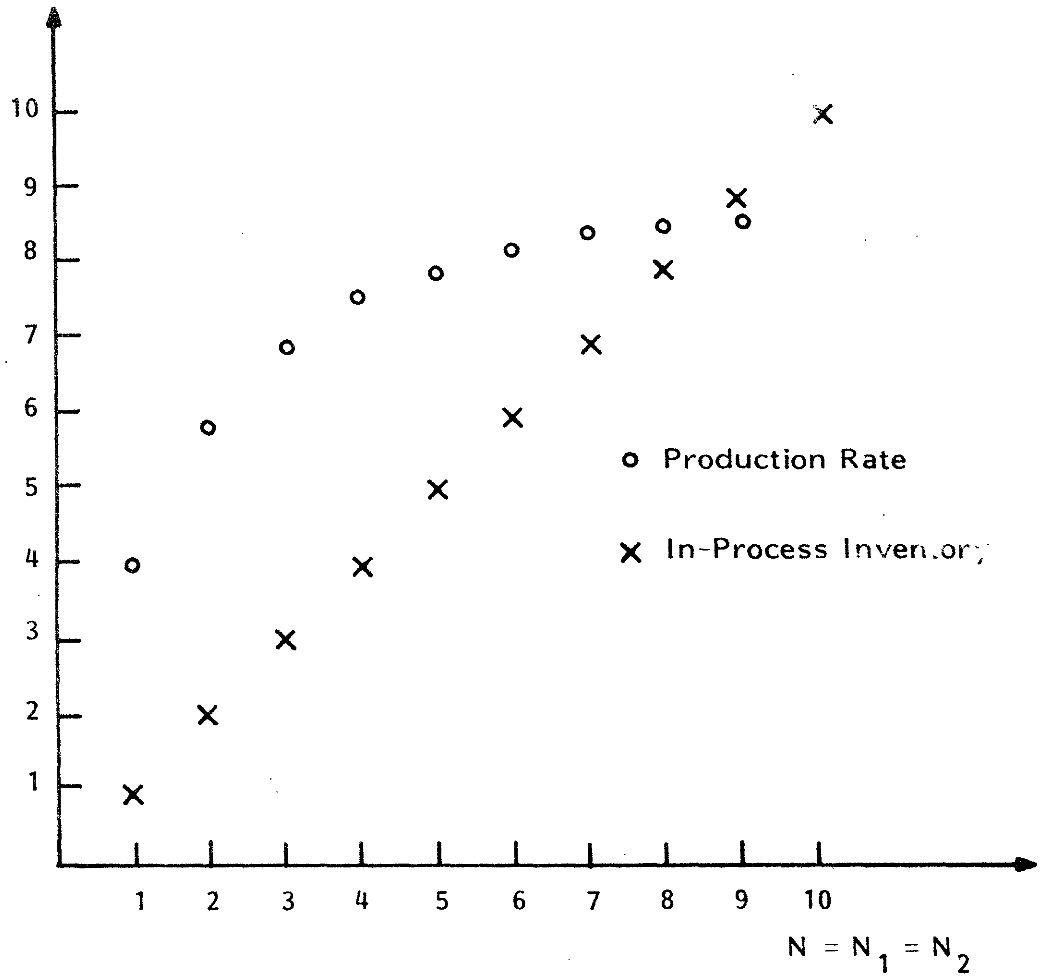



Fig. 3.7: Performance Measures of a Three-Machine Line.

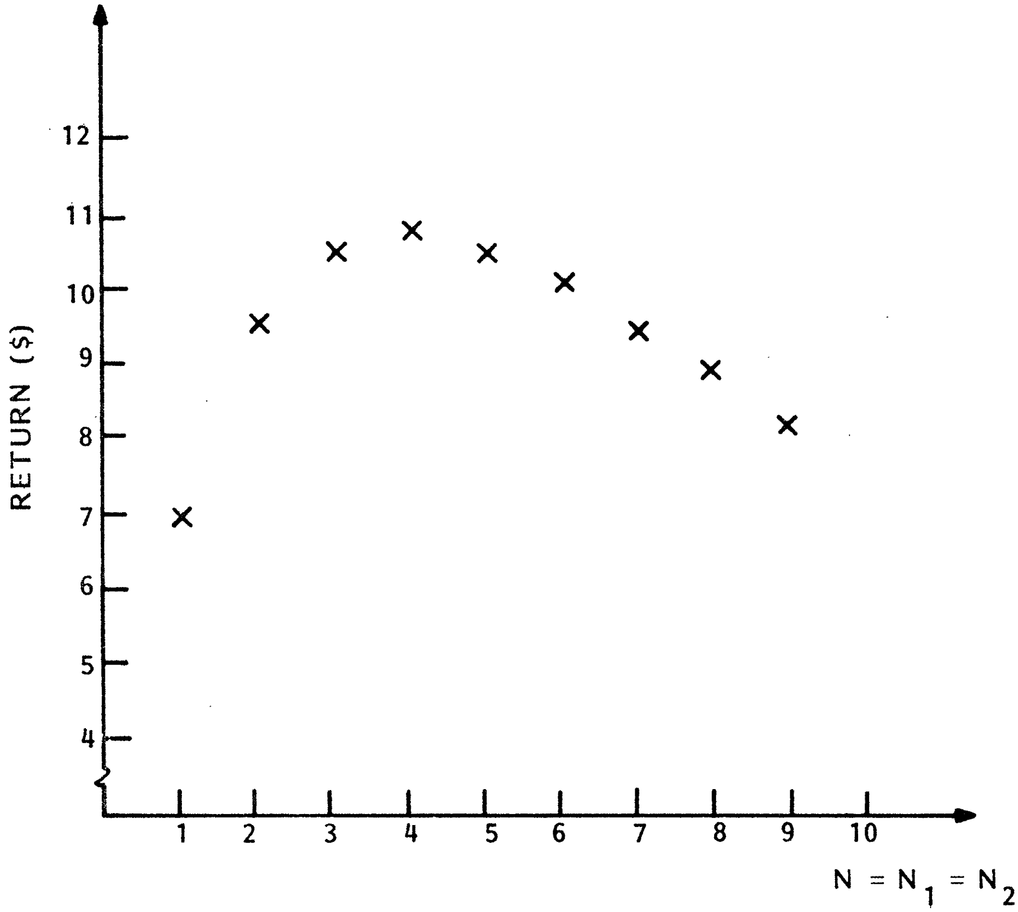



Fig. 3.8: Rate of return of a set of three-machine lines

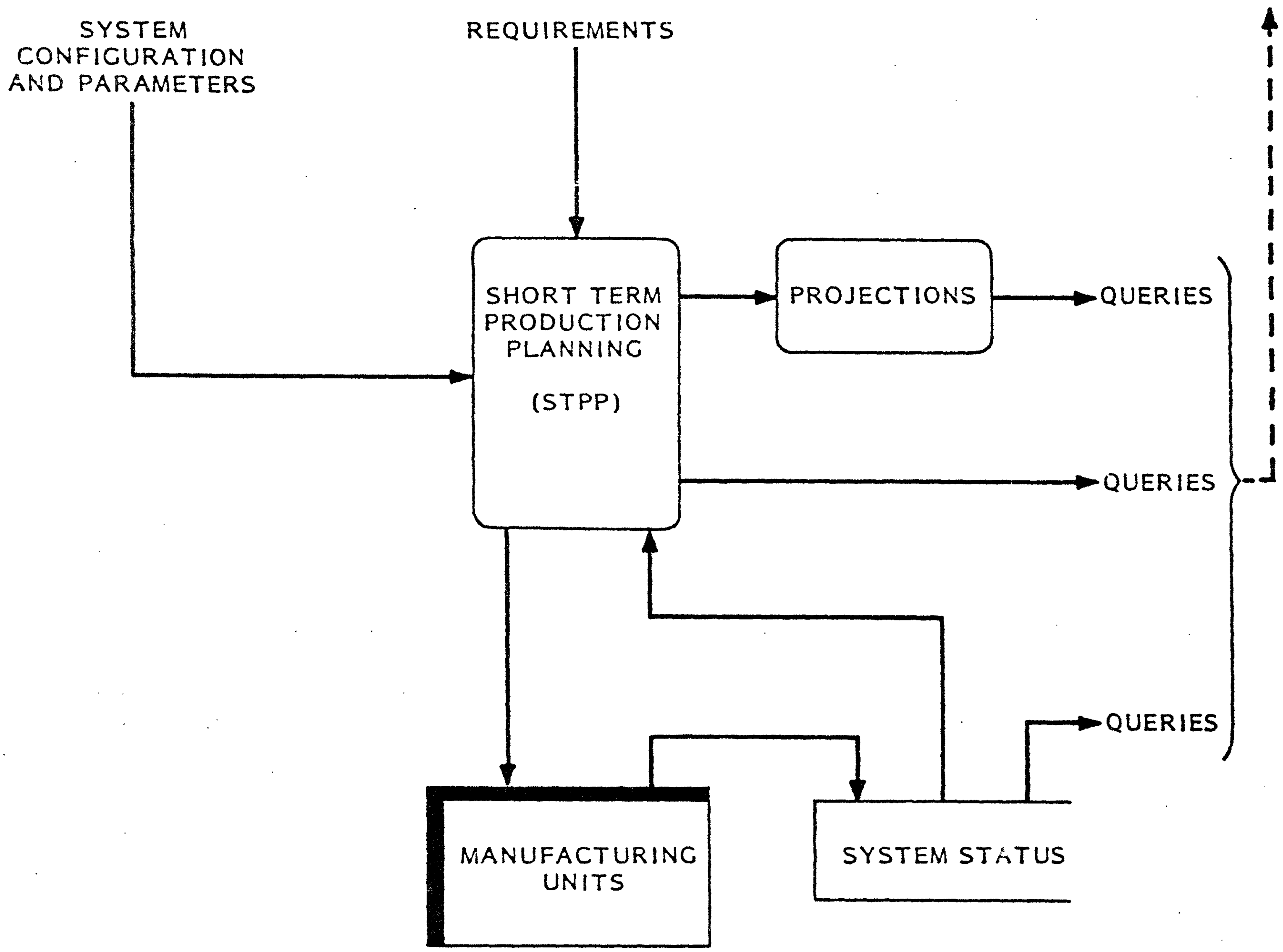



Fig. 4.1: Overall Organization of Work Center Control

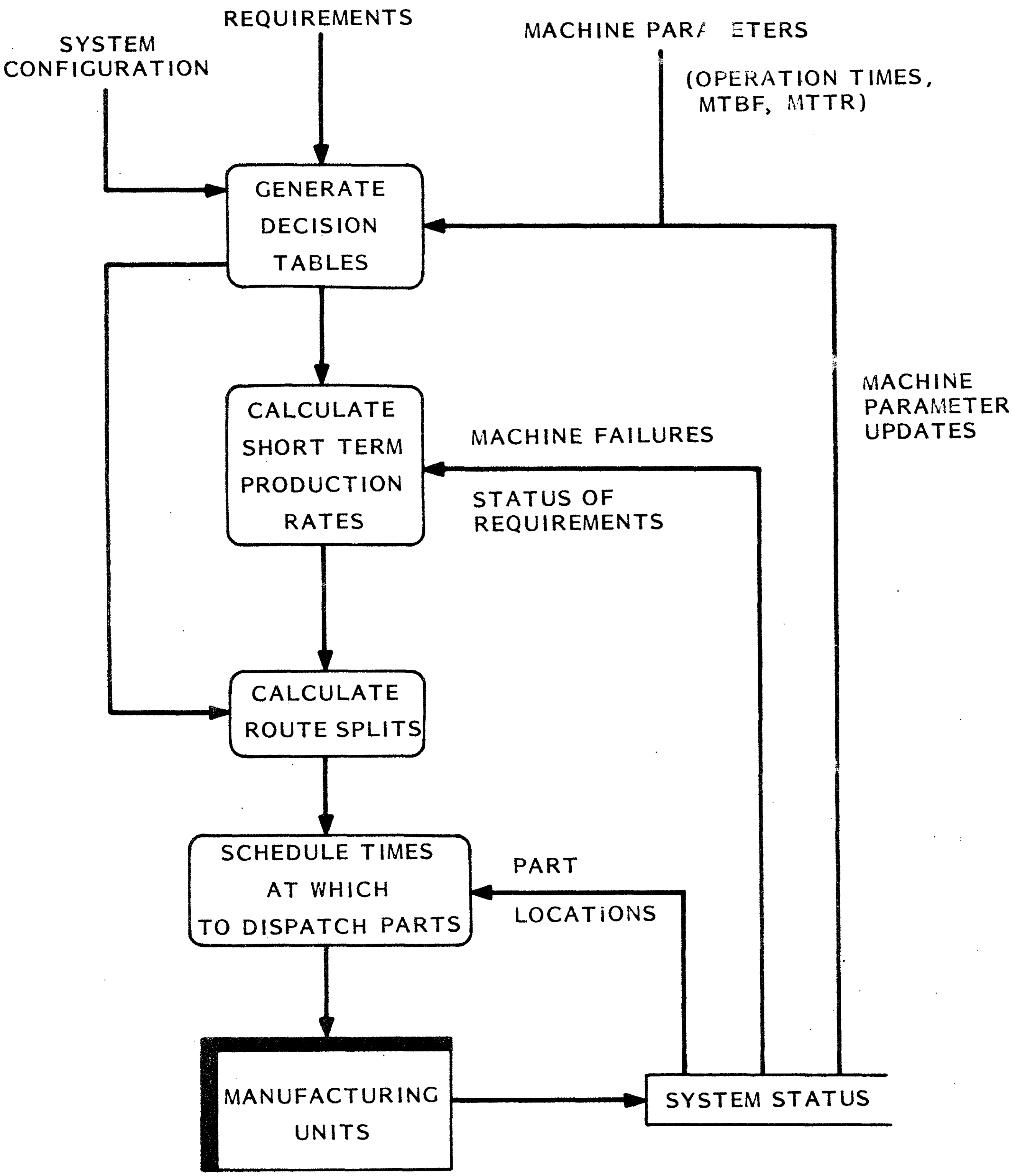



Fig. 4.2: Hierarchical Approach to Short Term Production Planning

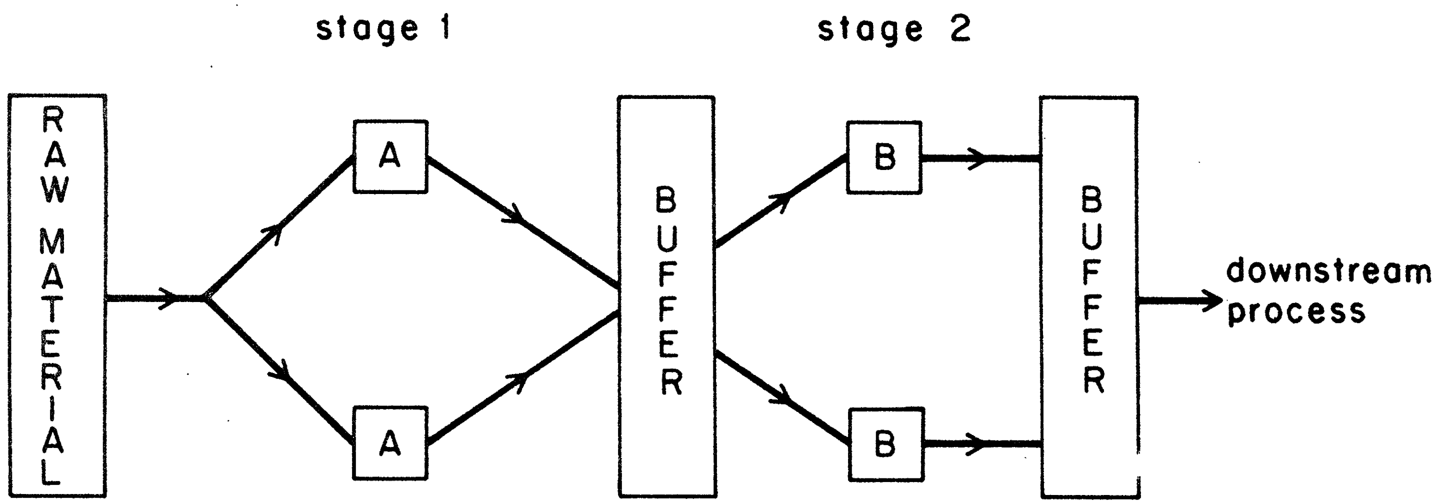
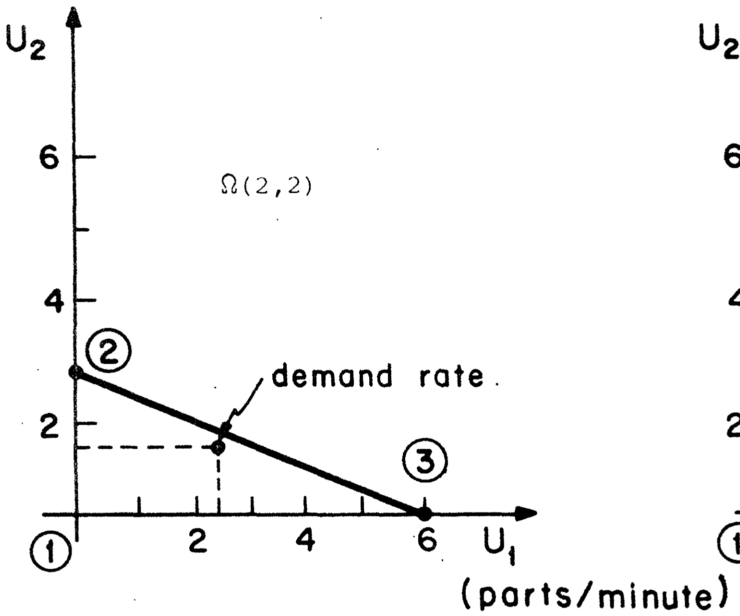
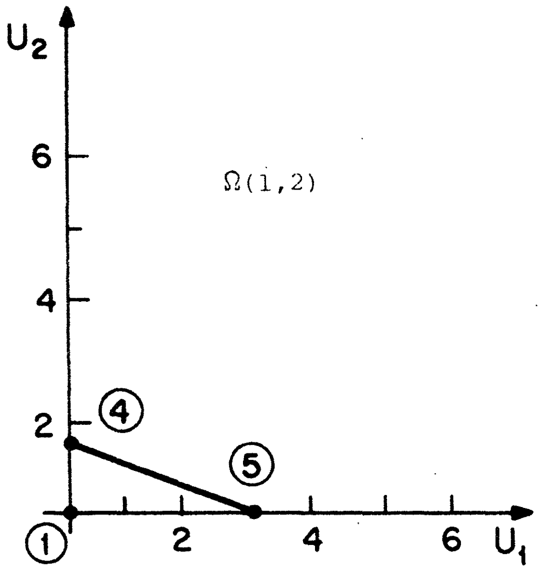


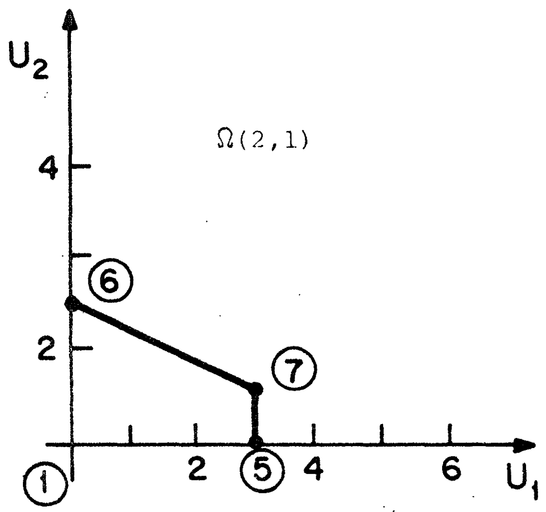

Fig. 4.3: Two-Stage Four-Station System




(a) All machines up
Machine state (2,2)

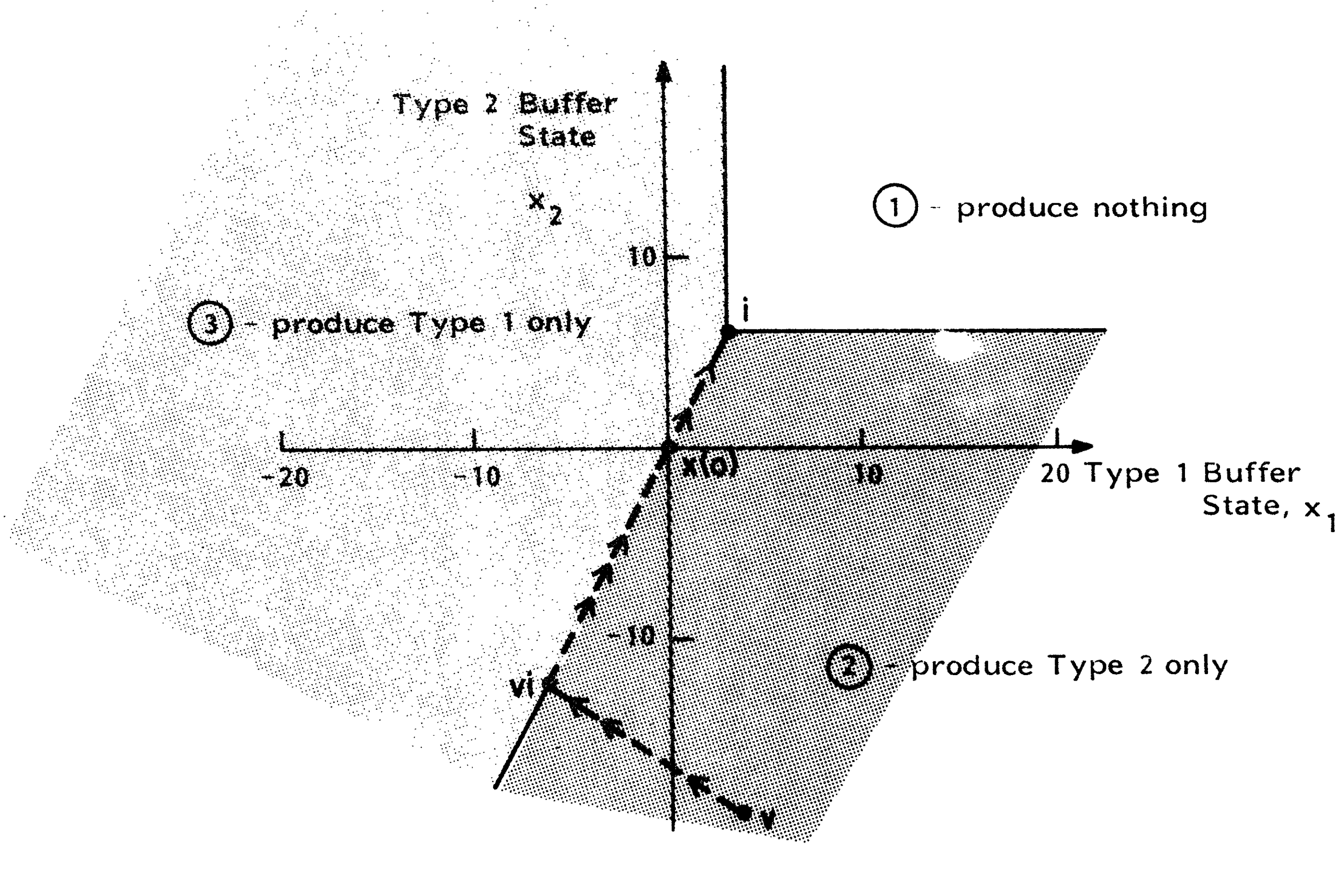



(b) One Type A down
Machine state (1,2)

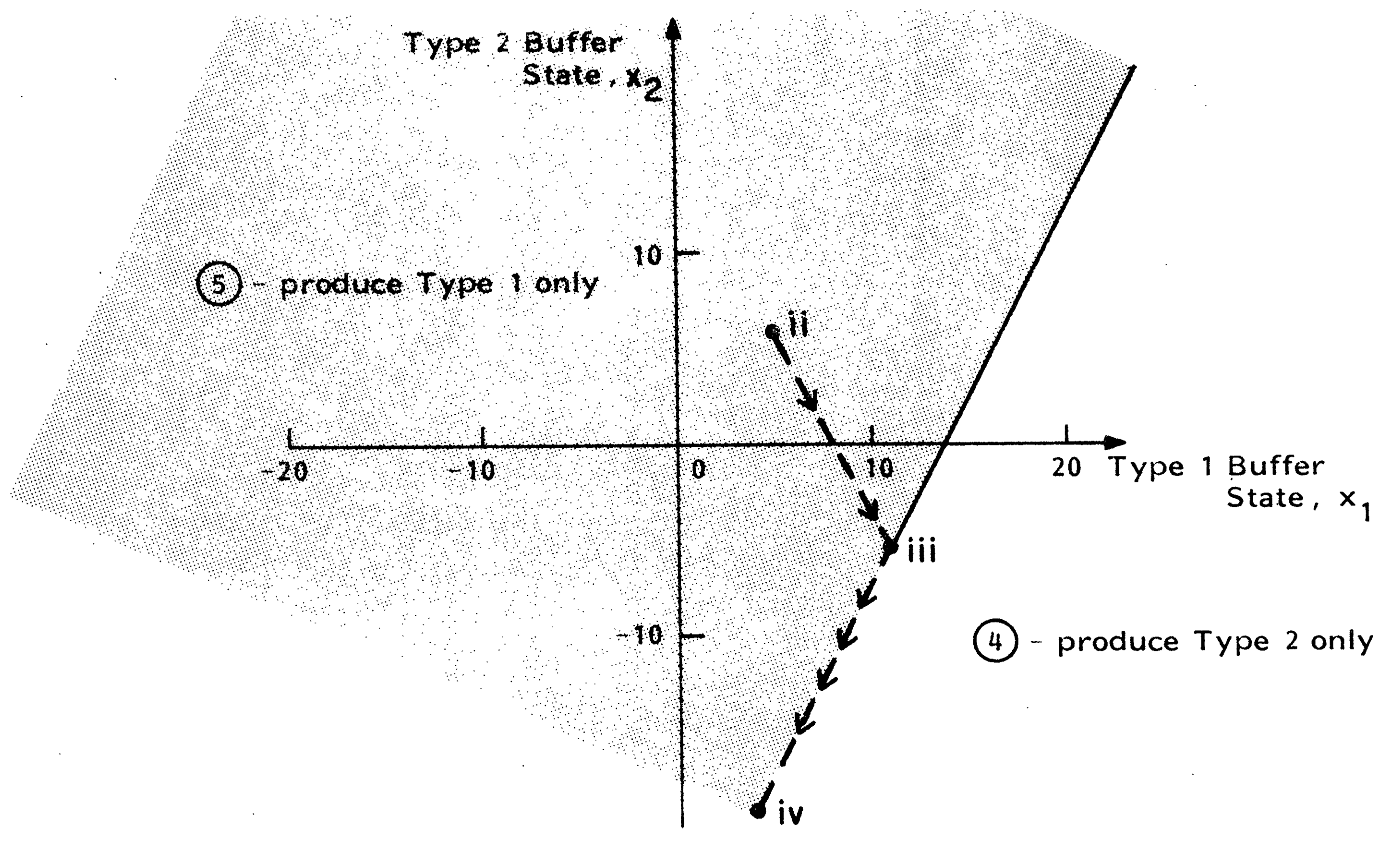



(c) One Type B down
Machine state (2,1)

Fig. 4.4: Production Constraint Sets

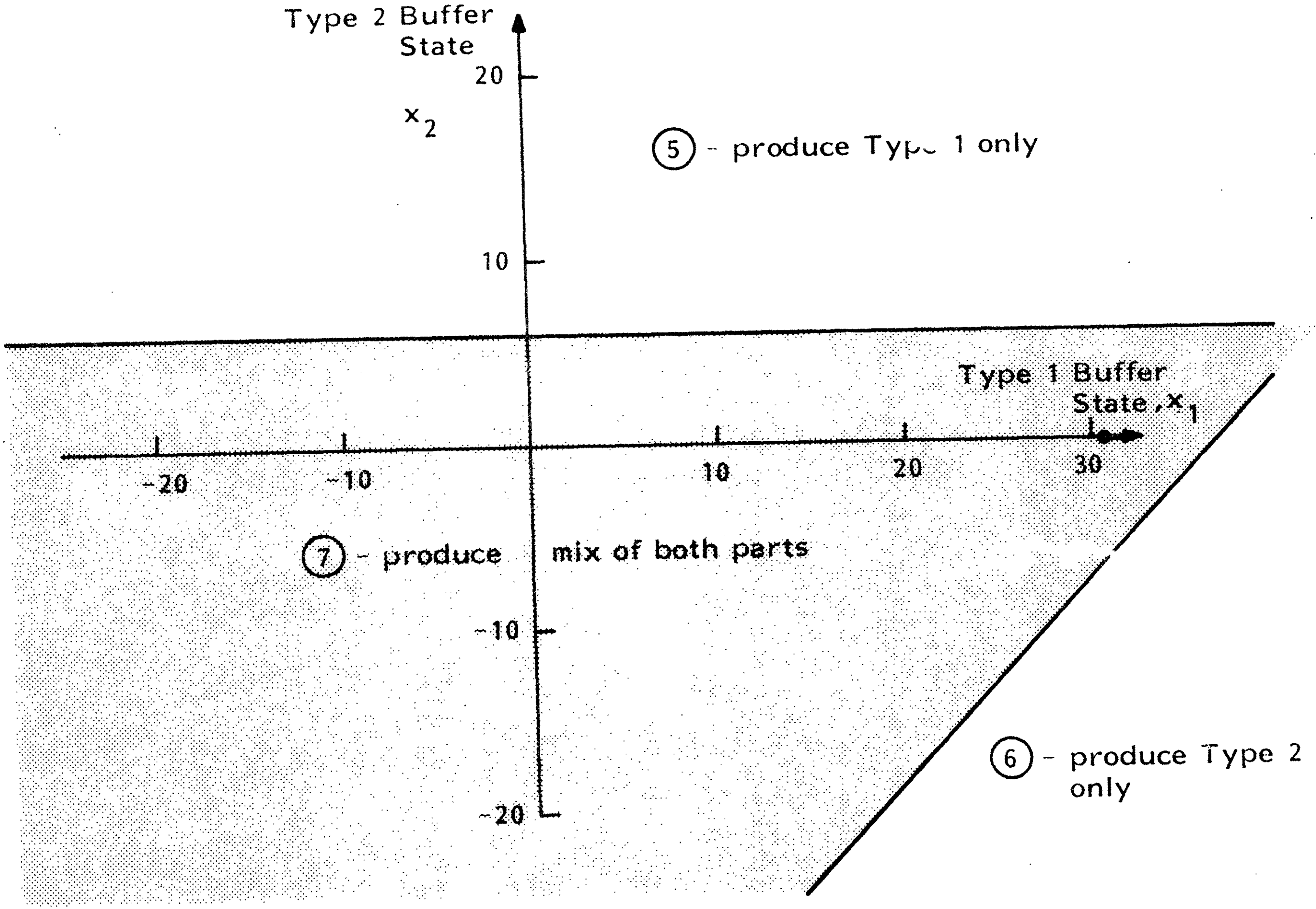



(a) All machines up (2,2)




(b) One Type A down (1,2)

Fig. 4.5: Control Regions




(c) One Type B down (2,1)

Key:

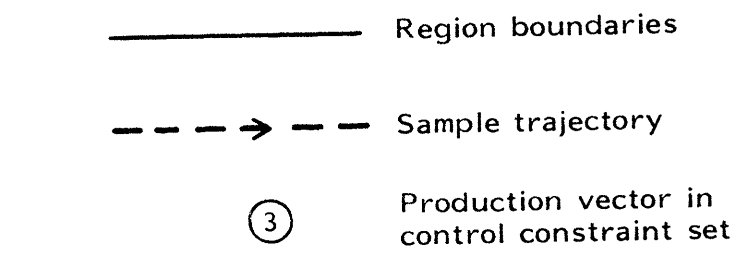



Fig. 4.5: Continued