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DECISION AIDS FOR FMS PART TYPE SELECTION USING AGGREGATE PRODUCTION RATIOS TO STUDY POOLED MACHINES OF UNEQUAL SIZES

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ABSTRACT

The short-term production planning function for setting up a flexible manufacturing system (FMS) prior to production has to be developed so as to interact well with the operation of the system over some time horizon. During FMS operation, planning for system set-up has to be performed somewhat periodically, for example, when the part mix is changed, or when the production requirements are finished for some part type, or when a machine breaks down. A flexible approach for system setup can lead to better system utilization and allow adequate coping of the dynamic situation of operation.

This paper suggests a possible flexible approach to short-term production planning. The impact of an existing mathematical programming procedure that determines balanced (or unbalanced) production ratios for part types on another planning problem of selecting part types to be machined together over the upcoming time period is analyzed. A simulation model is developed to demonstrate how unbalancing workloads can be better in a realistic flexible flow system (FFS) having pooled machines of unequal sizes. The implementation of the suggested decision procedures in an FFS is demonstrated. In addition, the advantages of the suggested flexible approach over strictly batching is demonstrated via simulation. Comparisons and extensive computational results are presented. Further research needs are also discussed.

§ 1. *INTRODUCTION*

An FMS is an automated manufacturing system. In the metal-cutting industry, an FMS consists of computer numerically controlled machine tools capable of performing multiple functions. The machine tools have automatic tool interchange capabilities and are linked together with automatic material handling equipment. All components are hierarchically computer-controlled.

A future goal of Computer Integrated Manufacturing System (CIMS) is to integrate several FMSs and other aspects of automation into more automated factories. However, this attractive combination of automation and flexibility has necessitated an improvement in the efficiency of production planning in a dynamic situation. This is because production management becomes more complex and a goal is to cope well with dynamic situations so as to attain the potential FMS efficiency. Five interrelated production planning problems were defined in Stecke [1983] to help managers set up an existing system for subsequent efficient production.

The short-term production planning function for setting up an FMS prior to production has to be implemented so as to interact well with an on-line control over some time horizon. The following five planning problems are reviewed here.

(1) **Part Type Selection Problem:**

Determine a subset of part types for immediate and simultaneous processing over the upcoming period of time.

(2) **Machine Grouping Problem:**

Partition the machines of similar types into identically tooled machine groups. Each machine in a particular group is then able to perform the same operations.

(3) **Production Ratio Problem:**

Determine the relative part type mix ratios at which the selected part types should be produced over time.

(4) **Resource Allocation Problem:**

Allocate the (minimum number of) pallets and fixtures of different fixture types required to maintain the production ratios found.

(5) **Loading Problem:**

Allocate the cutting tools of all operations of the selected part types to some machine's limited capacity tool magazine.

There have been several research studies to date dealing with some of these planning problems. Some mathematical programming approaches to part type selection include studies by Whitney and Gaul [1984], Hwang [1986], and Rajagopalan [1986]. They partition the part types having production requirements into batches to be machined one batch at a time. These aim to minimize the frequency of tool changeovers. Chakravarty and Shtub [1984] apply group technology techniques to identify families of part types that require similar processing requirements. Their aim is to group the part types and tools together so as to increase the production efficiency. Using less detail, Kusiak [1983] suggests a coding system based on the similarity between parts to select part types. This coding system is used to minimize the total sum of distances between the part types' attributes.

Some research on grouping, loading, and other related problems usually assumes that either the part mix to be machined together and/or their relative ratios have already been found (i.e., see Afentakis [1986], Akella et al. [1985], Berrada and Stecke [1986], Dar-El and Sarin [1984], Erschler, Lévêque and Roubellat [1982], Hildebrant [1980], Hitz [1980], Pinedo, Wolf, and McCormick [1986], Shanthikumar and Stecke [1986], and Stecke [1985a]). Mathematical programming and queueing networks have been used to address these problems.

In one study of systems of groups of pooled machines of unequal sizes, Stecke and Solberg [1985] show by using a closed queueing network model that unbalanced workloads are better than balanced to maximize expected production rate at an aggregate level of detail. However, extensive studies to test these theoretical and aggregate results on a realistic system have not been performed to date.

This paper presents a possible flexible approach to short-term production planning, to be implemented over some time horizon and in advance of actual production. The use of existing procedures that determine aggregate production ratios of part types is investigated to also select the parts to be machined together and on a dynamic basis. A simulation model is introduced to first show advantages of unbalancing machine workloads in a realistic flexible flow system (FFS) containing pooled machines of unequal sizes. Secondly, the uses and benefits of the suggested flexible approach is demonstrated with simulation and then compared to an alternative batching approach. A part input procedure for an FFS is suggested. Lastly, the sensitivities of transportation times as well as of the number of carts in the system are examined for unbalanced part mix ratios.

The suggested concepts and approaches are appropriate for more general FMS types. The particular implementation examined here is for a flexible flow system, where the part routings are unidirectional. In general, there are no scheduling problems for these types of systems other than determining the procedures by which parts are input into the system. Methods of determining a part input sequence for FFSs under various assumptions and for various objectives have been developed by Hitz [1980], Erschler et al. [1982], Akella et al. [1985], Afentakis [1986], and Pinedo et al. [1986], for example. These studies differ in the sizes of the buffers that are allowed, whether or not breakdowns and capacity are considered, and whether or not machines are allowed to be bypassed as parts follow the fixed route through the system. In virtually all of these studies, periodic production requirements (for example, weekly) for all part types are scaled down into a proportional minimal part set (MPS). An MPS defines *operational production ratios* that are the smallest integer multiple of the production requirements for every part type. A (usually periodic) part input sequence is developed as some permutation of these production ratios.

Under ideal conditions (infinite buffer at each station and no breakdowns), the maximum production is defined by the bottleneck machine. Under more general conditions, where orders continually arrive and breakdowns are considered, the bottleneck can shift (and hence immediately change the production rate). In fact, Afentakis [1986] notes that under the ideal conditions, *any* part input sequence will maximize production.

However, many studies are also concerned with decreasing WIP, which *is* affected by the part sequence. For example, Akella et al. [1985] provide an approach to determine the input of parts that *nearly* meets the production requirements while effectively decreasing WIP. Afentakis [1986] also addresses this issue. Pinedo et al. [1986] notes that there can be a scheduling issue to address if there is a buffer in front of each machine and parts can be resequenced. However, most studies assume FCFS in the buffer and so there is no scheduling problems. For example, the application of Akella et al. [1985] has 30 buffers in front of 4 machines, yet there are no scheduling decisions (other than part input) because FCFS is followed.

This paper differs in that issues are addressed other than determining part input into an FFS. First, more flexibility (and hence operating advantages) can be obtained by determining production ratios independent of the production requirements to maximize production rate or utilization. We discuss when each approach is appropriate in §**2**. Secondly, advantages of pooling machines has not been adequately addressed in the literature. Thirdly, selecting a subset of parts to be immediately produced has been addressed in a general FMS, but not in FFS studies. Finally, a method is suggested to determine a part input sequence to schedule the FFS although this is not the focus of this study. The part input sequence problem here differs from the previous FFS studies in that:

1. Groups of pooled machines are considered;
2. Pallet and fixture limitations are considered;
3. The part types to be input continuously change.

In addition, travel time and finite buffers are considered.

This paper is organized as follows. §**2** begins by describing the flexible approach to implement solutions to the FMS planning problems over time and usually in advance of actual machining. §3 first reviews solution methodology that determines aggregate production ratios for the operating objectives of balancing (or unbalancing, if applicable) workloads. These ratios can also be used to help select the part types to be produced simultaneously over the immediate flexible time horizon. §4 illustrates these procedures to solve these FMS planning problems on FFSs and provides some computational results on the algorithm that selects parts and determines production ratios. In §**4.1**, the theoretical and aggregate results on the optimality of unbalancing workloads (see Stecke and Solberg [1985]) are examined on realistic, detailed models of FFSs. In particular, for groups of pooled machines of unequal sizes, balancing and unbalancing are compared via simulation. §**4.2** demonstrates the use and advantages of the suggested flexible approach. Comparisons to an alternative part type selection approach are made with simulation. In §**4.3**, simulations of different data sets of travel times and number of carts in the system are performed for unbalanced aggregate part mix ratios. Conclusions and future research needs are provided in §**5**.

§2. *FLEXIBLE APPROACH TO SHORT-TERM PRODUCTION PLANNING*

An FMS is highly capital-intensive. Many FMS users (i.e., Caterpillar Tractor, Celakovice, Vought Aerospace, Yamazaki) express concern about achieving a high system utilization. This indicates that one appropriate objective of production planning is to maximize production rate or system utilization. The flexible approach to short-term production planning that will be suggested here follows these objectives. The algorithms used in this approach should be efficient to allow better integration with the subsequent FMS operation over some flexible time period.

A suggestion of a flexible approach to part type selection is as follows. When the production requirements for some part type(s) are finished, space in the tool magazines is freed up and some new part type(s) can be introduced into the system if this input can help make the system more balanced and more highly utilized.

Generally, using a fixed production horizon at an aggregate planning level should not result in higher machine utilizations than a flexible production horizon. This is because a fixed environment is less able to cope well with dynamic situations, such as changes in orders or arrival of an urgent order. On the other hand, a flexible approach to short-term production planning could be defined to be easily able to adapt to dynamic situations as well as help lead to increased system utilization. This indicates that a more flexible FMS operation can help reduce system cost by resulting in a more efficient system utilization. This beneficial effect of more flexible planning on system utilization can also help facilitate the use of real-time scheduling for system control.

The flexible approach is implemented by updating the solutions to the FMS production planning problems whenever events such as the following occur:

. The production requirements for some part type(s) are finished;

. Some urgent order(s) arrive;

. Some production order(s) change;

. One or more new part types are to begin production;

. A machine tool goes down and will remain down for a long enough period of time;

. Preventative maintenance is to be performed.

Note that the whole system does not always have to be set up again whenever these events that change the system environment occur. Like tool replacement due to breakage and wearing, the cutting tools required by the input of some new part type(s), for some systems, can be changed in a small amount of time without stopping the whole system and sometimes even while a machine is running. If the complete mix of part types is changed, the system would usually be idle for a significant length of time for this changeover. If only one or few part types in the mix are changed, this system changeover time can be quite smaller or even nil.

There are two distinct general FMS production environments. If the FMS is a subsystem of the factory that produces parts for later assembly, the FMS planning function may receive its production requirements and due dates from the factory wide production planning system. If there are certain part types *required* in particular relative ratios, then an appropriate FMS operating objective is to start and complete those part types at the same time. When all requirements are met by producing at certain relative production ratios, and output is proportional to the production requirements, then all magazines are then set up again for the next production batch. This is the scenario for most of the previous FFS studies. However, if the *demand* for the part types (or for a subset of the part types) is *independent*, FMS production planning can be developed in a more flexible manner. There can be more freedom in determining the relative ratios at which a part mix could be machined together. This freedom, in conjunction with the operating objective of balancing machine workloads, can be applied to help attain a higher production rate. In some situations, both objectives (simultaneous completion of parts and balancing workloads) may be appropriate simultaneously and both objectives might be satisfied.

§3 first shows how to both determine part mix ratios and select part types for the objectives of balancing and unbalancing workloads. Unbalancing workloads among machine types may be appropriate for systems of pooled machines of unequal sizes. As noted by Stecke and Solberg [1981] using a multiserver closed queueing network model, expected production rate is maximized by unbalancing workloads among groups of unequally sized pooled machines. For a given number of parts in the system, the unbalanced optimal aggregate and average workloads (see Stecke and Solberg [1981]) are used here in the objective function in an integer formulation provided in Stecke [1985b] to determine aggregate production ratios. Those part types with near zero ratio values in the optimal solution are not selected to be in the part mix to be machined together over the upcoming period. The zero production ratios indicate that these part types are not compatible with respect to (un)balancing machine workloads among the different machine types. The optimal production ratios could result in over- or underloading the average workload on some machine type(s). The over- or underload parameter for each machine type can be weighted to result in different sets of *optimal* ratios. A limitation on the numbers of fixtures of each type is incorporated by adding a constraint which restricts the maximum ratio values for each part type that is being produced in the system.

In the simulation studies of §4, the flexible approach is implemented as follows: whenever the production requirements of some part type(s) are finished, a current simulation run usually terminates. When one or more new part types are selected to be input into the system, new ratios that balance aggregate workloads are found to begin the next run. Otherwise, if no new part type is to enter, the current simulation run continues. However, new "optimal" production ratios are found for the reduced set of part types. Each run can result in a minor tool changeover. The cutting tools no longer required are unloaded and new ones are loaded.

The following rule to prevent too frequent (and unnecessary) tool changeovers is suggested and used here. If the total processing time required to complete the remaining requirements of any one part type is less than four hours after the completion of requirements of some other part type(s), the simulation run is not terminated until the remaining requirements of that part type are finished. The ratios of the remaining part types are updated.

§3. *SOLUTION METHODOLOGY*

The types of systems that are considered here are those that machine independent part types with varying numbers of production requirements. This is because there are more operating options available that a flexible approach to FMS operation can take advantage of. In particular, there can be more freedom in determining the relative ratios at which a particular part mix could be machined together. Because there can be more operating options (than in a dependent demand situation), the planning problems become more complex.

Table I reviews the notation of Stecke [1985b]. Given the aggregate production and

TABLE I.

Notation.

i	part types,	$i=1,\ldots,N$
j	machines,	$j=1,\ldots,M$
k	machine types,	$k=1,\ldots,K$
a_i	production ratio of part type i	
r_i	production requirement for part type i	
p_{ij}	processing time of part type i on machine j	
m_k	number of machines of type k	
pw_{ik}	average workload required by part type i on machine type k $=p_{ij}/m_k$	
W_k	constant value indicating an aggregate, (un)balanced workload on machine type k over time	
x_{k1}	load over (un)balanced, W_k, on machine type k	
x_{k2}	load under (un)balanced, W_k, on machine type k	
C_{k1}	weight assigned to the potential overload (x_{k1})	
C_{k2}	weight assigned to the potential underload (x_{k2})	
f_i	maximum number of fixtures dedicated to part type i	
n	total number of pallets in the system	

processing time requirements of each part type on each machine type, the problem to determine aggregate ratios is reviewed as the following integer formulation, Problem (P1).

(P1)

$$\text{Minimize} \quad \sum_{k=1}^{K} C_{k1}\, x_{k1} + \sum_{k=1}^{K} C_{k2}\, x_{k2}$$

subject to

$$\sum_{i=1}^{N} a_i\, pw_{ik} - x_{k1} + x_{k2} = W_k, \qquad k=1,\ldots,K \qquad (1)$$

$$a_i \le f_i, \qquad i=1,\ldots,N \qquad (2)$$

$$a_i \ge 0 \text{ and integer}, \qquad i=1,\ldots,N \qquad (3)$$

$$x_{k1},\, x_{k2} \ge 0, \qquad k=1,\ldots,K \qquad (4)$$

The objective function can be changed by weighting the overload (C_{k1}) and underload (C_{k2}) on each machine type differently. This provides alternative sets of optimal ratios. Constraint **(1)** describes the average workload on each machine type, which is sometimes specified to be unbalanced for those systems having pooled machines of unequal sizes. Constraint **(2)** restricts the maximum ratio values (maximum number of parts of each type) to be maintained in the system. This would be caused by a limitation on the number of fixtures of each type. Constraints such as due date or tool magazine capacity are not yet considered here.

The following algorithm selects the subset of part types to be machined together and determines their aggregate production ratios over the upcoming flexible time period:

PART TYPE SELECTION/ PRODUCTION RATIO ALGORITHM

Step 1. Formulate and solve Problem **(P1)** for a particular set of parameters W, C_{k1}, C_{k2}. If all requirements for all part types are completed, **STOP.**

Step 2. For those part types with positive ratio values in the optimal solution (i.e., $a_i \geq 1$), produce at those ratios until some event, such as the completion of the requirements of some part type(s), occurs.

Step 3. Update the part mix ratios by introducing the following constraints:

$a_{i_1} \geq 1$, where i_1 = {part types that have not yet completed their requirements}

$a_{i_2} = 0$, where i_2 = {part types that have completed their requirements}

Go to **Step 1.**

The algorithm is reiterated until the requirements of all part types are completed. At **Step 2**, the part types with near zero ratio values are not selected to be produced simultaneously over the upcoming time horizon. **Step 3** updates the part mix as well as their ratios, if the input of one or more new part types makes the machine tools' aggregate workloads more balanced. Otherwise, only the mix ratios of the same set of part types are updated. The part types that do not complete their requirements continue production over the next horizon without cutting tool changeovers.

If the total processing times required by some of the part types with remaining requirements are relatively small after the completion of requirements of some other part type(s), it could be more effective to continue production of these part types with small processing requirements at updated ratios, rather than considering the introduction of new part types. This saves an unnecessary changeover. Then a bound on the total remaining processing time of any one part type, such as half of one shift (i.e., four hours), is suggested here before any cutting tools are changed. In reality, different bounds could be determined either off-line or on-line by considering the ease and time of tool changeovers, the length of shifts, and the short tool changeovers already required for wearing or worn tools, etc. In addition, the maximum ratio values of those part types with small requirements should not be larger than their remaining requirements. In this case, additional constraints similar to constraint **(2)** are introduced. These are illustrated in the next section.

§4. *ILLUSTRATIONS*

To demonstrate the solution procedure to determine aggregate ratios of §3, consider the following problem sets of Tables II and III. There are two sets of ten and twelve part types ordered to be produced on an FMS having pooled machines of unequal sizes. In particular, there are pooled drills and VTLs, each group having two identical machines. There is only one mill. Two different sets of processing times and three different sets of production requirements for each set of processing times are provided for this system of three machine types and five machines. Processing times are in minutes. The problem sets were chosen to cover a variety of realistic scenarios. For example, in Problems 1 and 4 of Tables II and III, the total average processing times ($\Sigma pw_{ik}\, r_i$, k=Mill, Drill, VTL) are distributed more to the pooled drills and VTLs than to the mill. In Problems 2 and 5, the mill is more heavily loaded. Finally, the total average workloads are relatively equally distributed in the third and sixth Problems.

Problem **(P1)** is re-solved over time, as production requirements are completed and new part types are to begin production. (Usually, new production orders would also be considered for input into the system.) Initially, the values of parameters W, C_{k1}, and C_{k2} are specified as 100, 1, and 1, respectively. (Workloads are balanced.) The integer programs **(P1)** are run using LINDO on an AMDAHL 5860.

When the requirements of one or more part types are completed, the part mix ratios are determined again, both with and without fixture limitations, as follow. First, Problem **(P1)** is solved without the fixture limitations. Unless all ratio values are always less than four, **(P1)** is again solved after adding the constraints which restrict the maximum ratio values.

The FMS configuration is provided in Figure 1. It is an FFS with uni-directional transportation. There are one mill, two pooled drills, and two pooled VTLs. There are three buffer spaces, one after the mill and two in between the drills and lathes. All part types share the load/unload station having five storages. Other system resources are fix-

TABLE II.
Processing Times and Production Requirements for Ten Part Types on Three Machine Types with Five Machines.

Part Type	Mill(1)	Drill(2)	VTL(2)	Production Requirements		
				Problem 1	Problem 2	Problem 3
PT1	10*	60	50	65**	40	60
PT2	15	20	40	55	60	50
PT3	40	10	30	20	30	20
PT4	30	20	20	20	30	30
PT5	10	50	20	40	45	35
PT6	10	30	20	50	55	45
PT7	20	10	10	20	15	15
PT8	15	20	30	10	15	25
PT9	25	10	20	20	35	30
PT10	5	40	40	70	60	50

TABLE III.
Processing Times and Production Requirements for Twelve Part Types on Three Machine Types with Five Machines.

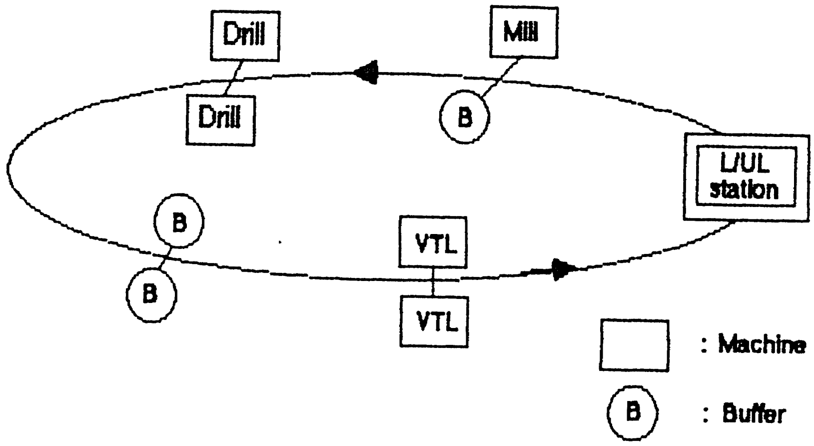
Part Type	Mill(1)	Drill(2)	VTL(2)	Production Requirements		
				Problem 4	Problem 5	Problem 6
PT1	11	50	58	35	15	29
PT2	20	40	20	24	29	35
PT3	35	30	10	10	20	20
PT4	25	20	12	14	18	10
PT5	15	18	40	30	40	35
PT6	16	30	20	21	33	28
PT7	30	20	38	14	17	25
PT8	20	10	10	14	28	20
PT9	5	30	34	50	44	30
PT10	7	36	40	40	24	33
PT11	10	52	44	55	30	34
PT12	15	20	30	20	8	10

(*) Processing times are in minutes.
(**) Production requirements are in number of parts.

tures of different types, pallets, and carts (wire-guided vehicles). There are five carts. (This is too many. To study system utilization and blocking, etcetera, we did not want to confound these with cart restrictions. This is relaxed in §4.3, to show the additional effect of not having enough carts. This issue is also investigated in a related production ratio study (Schriber and Stecke [1986])). There are two cases of fixture limitations. First, the number of fixtures of each type is limited for each part type to be four ($f_i=4$, i=1,...,10 or 12). The second case requires no restriction on this value ($f_i<\infty$, i=1,...10 or 12). A fixed number of parts (the pallet limitations) of mixed types having nonzero production ratio values is always in the system. Transportation times in the system are a linear function of the distance being traveled. Travel times are one minute between all links, i.e., between: L/UL-mill; mill-drill; buffer-drill; drill-buffer; buffer-VTL; VTL-L/UL (see Figure 1). The simulation models of the FFS are developed in GPSS/H.

FIGURE 1.

System Configuration.



There was no precise algorithm to be found in the literature that finds a good part input sequence into a flow shop having pooled machines. The part input sequence into the FFS here is determined by using a combination of a modified Johnson's algorithm (see Campbell, Dudek, and Smith [1970]) and the current production ratios as follows.

PART INPUT SEQUENCE ALGORITHM

Step 1. All part types having production requirements are ordered according to a modified Johnson's algorithm.

Step 2. Whenever new production ratios are found, the part input sequence follows the new ratios exactly, in the order specified at **Step 1.**

For example, in the simulation, the selected part types are always input to the system according to the following sequence found using a modified Johnson's algorithm: 10, 2, 6, 8, 5, 1, 4, 3, 9 and 7 for Table II, and 9, 5, 10, 11, 1, 2, 7, 12, 6, 3, 4 and 8 for Table III. Then, when the part mix ratios of part types 5, 6, 7, and 10 are 1:2:2:2 (Run 2 UB(b) of Table IV), for example, the part input sequence is 10, 10, 6, 6, 5, 7, 7. The input sequence is followed, regardless of which type of part just left the system.

When a machine and cart become available, a part can be moved. When two or more parts wait for the machine, FCFS in the buffer is used.

§4.1. Unbalancing Versus Balancing

In this section, unbalancing and balancing are compared using a realistic simulation model of an FFS of groups of pooled machines of unequal sizes. For all of these studies, the flexible approach to select part types is used. The simulation results are provided in §**4.1.2**. A comparison to batching is reported in §**4.2**.

Initially, the numbers of parts (pallets) in the system are fixed as seven for Problems 1, 2, and 3 of Table II and as eight for Problems 4, 5, and 6 of Table III. For these problems of Tables II and III and the system of three groups of 1, 2, and 2 machines each, the unbalanced average workloads that provide the maximum expected production (i.e., [80:105:105] for $n=7$ and [84:104:104] for $n=8$ –– see Stecke and Solberg [1981]) are used for the unbalancing objective in the integer Problem **(P1)** that provides aggregate part mix ratios. These determined ratios will then unbalance aggregate workloads, as the theoretical unbalanced optimum suggests.

For demonstration purposes, the two different sets of ten and twelve part types are considered here. The problems considered here are static (i.e., orders are not arriving). A series of problems is solved, until all requirements of all part types are completed. The objective function value of Problem **(P1)** for the last of each series of runs depends on the fixed distribution of the total workloads per machine among the three machine types. The last of each set of runs is hence, not representative. These ending conditions bias the apparent results and would not appear in reality. The more usual situation where our approaches are applicable is dynamic, as production orders arrive and the finished orders leave.

§4.1.1. Part Type Selection/Production Ratios

One difficulty in trying to compare the results of balancing and unbalancing machine workloads is the following. The same numbers of the same part types with given production requirements are not produced for these objectives over the same time horizon. There is no regeneration point. In order to provide common bases for comparison purposes, two different methods of *selecting part types* are considered here.

For the first method, the integer formulation for balancing attempts to select the *same* part types as those selected by the unbalanced problem in hope of machining the same part mix during each run if possible. However, the sets of selected parts are usually identical only for the first run. Even then, the production ratios are not the same.

The second method to select part types is introduced to reduce the dependence of the objective function value for the *last run* upon the distribution of the total workloads per machine. This second method attempts to select the part types and their mix ratios with the best objective function values of both unbalancing and balancing workloads for a given number of pallets. With this method, the sets of selected parts are *not* the same. Then the determined best part mix ratios for both unbalancing and balancing machine workloads are compared using simulation.

First, Method 1 of selecting part types is applied to the six Problems of Tables II and III. This method attempts to select the same part types for the unbalancing and balancing objectives as much as possible, to try to make comparisons straightforward. Tables IV and V provide both the unbalanced and balanced part mix ratios and also demonstrate the use of the flexible approach to selecting part types. The rules labeled as (b), (c), and (d) in Tables IV and V indicate that these ratios are updated with no new part type entering, although the requirements of some part type(s) are completed. The rules labeled (a) imply that new part types also enter. These new part types are noted in boldface. The label (-2) of Table V indicates that Problem **(P1)** is solved without fixture limitations. The label (-1) indicates that **(P1)** is again solved after adding the constraint that restricts the maximum ratio values to be no larger than four.

In Problems 2 and 5 of Tables IV and V, the sixth (last) objective function values are very large. This is because the remaining workloads to finish all requirements of all ten or twelve part types are much higher on the unpooled mill. This results in large overload values on the mill. In the third and sixth Problems, the last objective function values are very large only for the unbalancing objective. This is because the total workloads per machine in these Problems was selected to be *balanced* about equally on the three machine types. This would tend to not occur in the more typical situation, in which random orders arrive.

The following additional observations can be made from Tables IV and V, which use Method 1 for selecting part types.

(1) For both balancing and unbalancing runs, most solutions suggest various combinations of 3–5 part types that are compatible for immediate and simultaneous machining.

(2) Setting W = 100 (a relatively low number) in Problem **(P1)** allows the production ratio values to be small enough to be workable in the realistic situation with a limited number of pallets and dedicated fixtures. These low ratios values are then directly useful to help solve subsequent scheduling problems, such as determining a good part input sequence (see Stecke [1985b]). (Recall that our part input se-

TABLE IV.

Integer Optimum Solutions Using Method 1 to Select Part Types for the Objectives of Balancing/Unbalancing Workloads When Seven Pallets are in the System.

a. PROBLEM 1

Run	Rule	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
1	UB(a)[(1)]	**2,5,6,8,10**	2:1:2:1:1	0	3.583
	B(a)[(2)]	**2,5,6,8,10**	1:1:1:3:1	20	1.501
2	UB(a)	2,5,6,**7**,10	2:1:1:1:2	0	0.942
	(b)	5,6,7,10	1:2:2:2	25	0.992
	B(a)	2,5,6,**7**,10	2:1:2:2:1	10	2.080
3	UB(a)	**3**,5,6,10	1:1:1:3	15	0.960
	(b)	3,5,6	1:3:2	55	1.042
	B(a)	2,**3**,5,6,10	2:1:1:2:1	10	1.504
4	UB(a)	**1**,3,**4**	3:1:1	25	0.738
	B(a)	**1**,2,3,**4**,5,10	1:1:1:1:1:1	10	1.121
	(b)	1,3,4,5,10	1:1:1:2:1	30	1.337
5	UB(a)	1,4,**9**	3:1:1	15	0.636
	(b)	1,9	3:2	15	0.699
	B(a)	1,4,5,**9**,10	1:1:1:2:1	20	1.853
	(b)	1,4,9,10	2:1:2:1	5	1.244
	(c)	1,4,10	1:3:2	15	1.722
	(d)	1,10	3:1	75	1.253

b. PROBLEM 2

Run	Rule	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
1	UB(a)	**2,5,6,8,10**	2:1:2:1:1	0	3.583
	B(a)	**2,5,6,8,10**	1:1:1:3:1	20	1.501
2	UB(a)	2,5,6,**7**,10	2:1:1:1:2	0	0.942
	B(a)	2,5,6,**7**,10	2:1:2:2:1	10	2.080
3	UB(a)	**3**,5,6,10	1:1:1:3	15	0.960
	B(a)	2,**3**,5,6,10	2:1:1:2:1	10	1.504
4	UB(a)	**1**,3,5,6	2:1:1:1	20	1.056
	(b)	1,3,5	3:1:1	20	1.102
	B(a)	**1**,2,3,5,10	1:2:1:1:1	15	1.086
5	UB(a)	1,3,**9**	3:1:1	25	1.337
	B(a)	1,3,5,**9**,10	1:1:1:1:2	10	1.153
	(b)	1,5,9,10	1:1:3:2	20	1.254
6	UB(a)	3,4,9	1:1:1	170	1.588
	(b)	4,9	2:1	160	1.023
	B(a)	1,4,9,10	2:1:2:1	5	1.122
	(b)	1,4,9	3:1:1	25	1.050
	(c)	4,9	2:2	140	1.536

c. PROBLEM 3

Run	Rule	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
1	UB(a)	**2,5,6,8,10**	2:1:2:1:1	0	3.583
	(b)	2,5,8,10	1:2:2:1	10	2.090
	(c)	2,5,10	3:2:1	20	1.600
	B(a)	**2,5,6,8,10**	1:1:1:3:1	20	1.501
2	UB(a)	**1**,5,**9**,10	1:1:2:2	10	2.574
	B(a)	**1**,2,5,6,**9**,10	1:1:1:1:2:1	15	1.105
3	UB(a)	1,**4**,9,10	1:1:1:3	0	1.781
	(b)	1,4,9	3:1:1	15	1.029
	B(a)	1,2,**4**,5,6,10	1:1:1:1:1:1	35	1.317
4	UB(a)	1,4,**7**	3:1:1	15	1.343
	(b)	4,7	2:1	160	0.964
	B(a)	1,2,4,6,**7**,10	1:1:1:2:1:1	5	1.443
5	UB(a)	**3**,4,7	1:1:1	170	1.037
	(b)	3,4	1:1	180	1.341
	B(a)	1,2,**3**,4,7,10	1:1:1:1:1:2	40	1.317
	(b)	1,2,3,4,7	2:1:1:1:1	35	1.104
	(c)	1,3,4	3:1:1	5	1.106
	(d)	1,3	2:2	60	0.524

0 indicates the new part types to be introduced for the upcoming run.

(1) UB refers to the unbalanced integer Problem **(P1)** specifying that $W_{mill}=80$, $W_{drill}=105$, and $W_{vtl}=105$.

(2) B refers to the balanced integer Problem **(P1)** specifying that $W_{mill}=100$, $W_{drill}=100$, and $W_{vtl}=100$.

quence, for simulation purposes, is a permutation of the ratios and based on a modified Johnson's algorithm.) The summation of the ratios for each run of Tables IV and V is always less than nine. If W=1000 were used, for example, the sums of the ratio values would all be less than 90, which is too large (and unnecessary) to work with.

(3) The total number of dedicated fixtures required by the balanced mix ratios is similar to that required by each unbalanced run. When there are no fixture limitations, the numbers required for each part type range from one to seven (see Table V).

(4) The objective function values tend to get larger with the number of runs. This is because the problems here are static, having fixed orders. In the more typical dynamic situation of orders arriving to an FMS continuously, a better objective function value can be anticipated.

(5) Most of the CPU times are less than four seconds. The balanced problems have

TABLE V.

Integer Optimum Solutions Using Method 1 to Select Part Types for the Objectives of Balancing/Unbalancing Workloads When Eight Pallets are in the System.

a. PROBLEM 4

Run	Rule	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
1	UB(a)(1)	**3,8,9,10**	1:1:2:3	2	16.873
	B(a)(2)	**3,8,9,10**	1:2:4:1	8	1.327
	(b)	3,9,10	2:4:1	13	2.142
2	UB(a)	**2**,8,9,10,**12**	1:1:1:3:1	6	10.270
	B(a)	**2**,9,10,**12**	2:1:1:3	8	1.286
3	UB(a)	2,**5**,9,12	2:1:3:1	3	5.328
	B(a)	2,**5**,9,10	2:3:1:1	20	1.397
4	UB(a)	2,5,**11**,12	1:1:2:2	4	1.791
	B(a)	5,9,10,**11**	1:1:1:2	60	1.555
5	UB(a)	**1**,5,**6**,11	1:1:3:1	4	3.406
	B(a)	**1**,5,**6**,10,11	1:1:2:1:1	44	1.294
	(b)	1,10,11	2:1:1	67	1.547
6	UB(a)	1,**4**,5,11	1:2:1:2	15	2.073
	B(a)	1,**4**,11	2:3:1	15	1.226
7	UB(a)	1,5,**7**.11	1:1:1:2	24	1.182
	(b)	1,7,11	1:2:2	21	1.454
	(c)	1,11	2:2	44	1.046
	B(a)	1,**7**,11	1:2:2	23	1.491
	(b)	1,11	2:2	62	1.316

b. PROBLEM 5

Run	Rule	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
1	UB(a)	**3,8,9,10**	1:1:2:3	2	16.873
	B(a)	**3,8,9,10**	1:2:4:1	8	1.327
2	UB(a)	**1**,3,8,9	1:1:1:4	6	3.282
	(b)	1,3,8	3:1:1	20	2.468
	(c)	3,8	2:1	164	1.049
	B(a)	**1**,3,8,10	1:1:1:1	15	2.040
	(b)	1,3,10	1:2:3	12	1.365
	(c)	1,10	3:1	74	1.150
3	UB(a)	8,**11,12**	1:3:2	8	2.423
	(b)	8,11	2:4	20	1.065
	B(a-1)(3)	**11,12**	2:4	32	1.069
	(a-2)(4)	**11,12**	2:5	26	1.680
4	UB(a)	**2,5,6**,11	1:2:1:2	3	2.553
	(b)	2,5,6	3:3:1	43	1.643
	(c)	5,6	3:4	46	1.255

Run	Rule	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
	(d-2)	6	7	63	0.969
	B(a)	**2**,**5**,**6**,11	2:2:1:1	13	1.842
5	UB(a)	6,**7**	4:1	89	1.001
	B(a)	5,6,**7**,11	1:2:1:2	7	1.722
	(b-1)	5,6,7	2:4:1	37	1.121
	(c-1)	5,7	1:3	89	1.019
6	UB(a)	**4**,7	1:2	135	0.989
	B(a-1)	**4**,7	1:3	112	0.991
	(a-2)	**4**,5,6,7	1:2:3:1	55	1.451
	(b-2)	4,5,7	1:1:2	97	0.969
	(c-2)	4,7	1:3	112	0.991

c. PROBLEM 6

Run	Rule	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
1	UB(a)	**3**,**8**,**9**,**10**	1:1:2:3	2	16.873
	B(a)	**3**,**8**,**9**,**10**	1:2:4:1	8	1.327
	(b)	3,8,10	1:2:4	11	1.151
2	UB(a)	**1**,3,8,9	1:1:1:4	6	3.282
	(b)	1,3,8	3:1:1	20	2.468
	B(a)	**1**,3,10	1:2:3	12	1.365
	(b)	1,10	3:1	74	0.966
3	UB(a)	1,**6**,**12**	2:3:1	5	4.550
	B(a)	1,**6**,**12**	1:3:3	8	1.352
4	UB(a)	**2**,**5**,6,**11**,12	1:1:1:2:1	9	2.013
	(b)	2,5,6,11	1:2:1:2	3	1.504
	(c)	2,5,6	3:3:1	43	1.155
	(d)	2,5	4:2	56	1.017
	B(a)	1,**2**,**5**,6,**11**	1:1:1:2:1	23	1.488
5	UB(a)	2,**7**	4:1	85	1.387
	B(a)	1,2,5,**7**,11	1:1:2:1:1	22	1.223
6	UB(a)	**4**,7	1:2	135	0.989
	B(a)	2,**4**,5,7,11	1:1:1:1:2	12	1.187
	(b)	2,4,7,11	2:1:1:1	52	1.220
	(c)	2,4,7	4:1:1	70	0.955
	(d)	2,7	4:1	61	0.967

0 indicates the new part types to be introduced for the upcoming run.
(1) UB refers to the unbalanced integer Problem **(P1)** specifying that $W_{mill}=84$, $W_{drill}=104$, and $W_{vtl}=104$.
(2) B refers to the balanced integer Problem **(P1)** specifying that $W_{mill}=100$, $W_{drill}=100$, and $W_{vtl}=100$.
(3) specifies the limit of four fixtures of each type.
(4) specifies no fixture limitations.

shorter CPU times than the unbalanced. This is because for the balanced integer Problem **(P1)**, the ratio values of those part types not selected by the previous unbalancing Problem **(P1)** are now set equal to zero. This reduces the size of the balanced **(P1)**, which reduces the CPU time.

We now demonstrate the use of Method 2 to select part types. Problems **(P1)** are run again using the processing time data of Tables II and III. Here, we are only *demonstrating part type selection* (for both balancing and unbalancing) for the first run only. Hence the production requirements are not considered and no simulations are performed. (The simulation results are presented in §**4.1.2.**) The first runs for Problems 1, 2, and 3 will always be the same (see Table IV). Tables VI and VII present part mix ratios using Method 2, which selects part types with the best objective function values for both the unbalanced and balanced Problem **(P1)** for a given number of pallets in the system [n=6, 7, 8, 9, 10, 11, 12 and 13]. The theoretical unbalanced optimal workloads provided in Stecke and Solberg [1981] are used to select part types and determine their mix ratios. The unbalanced part mix ratios are different for each value of n, the number of pallets in the system.

TABLE VI.

Integer Optimum Solutions Using Method 2 to Select Part Types for the Objectives of Balancing/Unbalancing Workloads for Problems 1, 2, and 3.

n	Rule	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
6	UB(1) B(2)	1,7,8,10 1,3,4,6,10	2:1:2:1 1:1:1:1:2	3 0	5.216 4.555
7	UB(3)	2,5,6,7,10	2:1:1:1:2	0	4.493
8,9	UB(4)	2,5,7,9,10	1:1:1:1:3	3	6.516
10,11	UB(5)	5,8,9,10	1:1:2:3	6	10.688
12,13	UB(6)	1,4,6,8	2:1:1:2	5	7.096

(1) specifies $W_{mill}=76$, $W_{drill}=106$, $W_{vtl}=106$.

(2) Balanced mix ratios are the same for n= 6,...,13.

(3) specifies $W_{mill}=80$, $W_{drill}=105$, $W_{vtl}=105$.

(4) specifies $W_{mill}=84$, $W_{drill}=104$, $W_{vtl}=104$.

(5) specifies $W_{mill}=88$, $W_{drill}=103$, $W_{vtl}=103$.

(6) specifies $W_{mill}=90$, $W_{drill}=102.5$, $W_{vtl}=102.5$.

TABLE VII.

Integer Optimum Solutions Using Method 2 to Select Part Types for the Objectives of Balancing/Unbalancing Workloads for Problems 4, 5, and 6.

n	Rule	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
6	UB(1)	2,5,9,11,12	1:1:1:2:1	1	9.842
	B(2)	3,8,9	1:2:5	0	13.499
7	UB(3)	1,6,8,9	1:2:1:3:2	0	9.409
8,9	UB(4)	3,8,9,10	1:1:2:3	2	16.873
10,11	UB(5)	1,2,8,9,10	1:1:2:2:1	0	22.874
12,13	UB(6)	2,3,5,9	1:1:1:4	2	38.985

(1) specifies $W_{mill}=76$, $W_{drill}=106$, $W_{vtl}=106$.
(2) Balanced mix ratios are the same for $n= 6,\ldots,13$.
(3) specifies $W_{mill}=80$, $W_{drill}=105$, $W_{vtl}=105$.
(4) specifies $W_{mill}=84$, $W_{drill}=104$, $W_{vtl}=104$.
(5) specifies $W_{mill}=88$, $W_{drill}=103$, $W_{vtl}=103$.
(6) specifies $W_{mill}=90$, $W_{drill}=102.5$, $W_{vtl}=102.5$.

The part mix ratios for the balancing problem have zero objective function values. Also, for the balancing objective, the *same* part types are always selected in the *same* ratios, for all values of n. This is because the workload parameter, W, is never changed. W is always 100, for each machine type.

The following observations can be made from Tables VI and VII.

(1) The unbalanced problems usually have longer CPU times. This is because processing times are not scaled similar to the theoretical unbalanced optimal average workloads.

(2) For all runs of unbalancing (and balancing) workloads, the solutions suggest various combination of 3–5 part types that are compatible for subsequent simultaneous machining.

(3) Although the unbalanced workloads change only slightly as n increases, the selected part types and their production ratios are quite different. However, these are just one of many optimal sets of ratios.

There is no discernible advantage to using Method 2 instead of Method 1. Method 1 has been perceived to favor unbalancing when selecting part types. However, no differences were observed.

§4.1.2. Simulation Results for Unbalancing and Balancing

In this section, we present simulation results to investigate unbalancing and balancing using both Methods 1 and 2. First, the simulation studies are performed using Methods 1 for two cases. One case allows only four fixtures of each type. The second has no fixture limitations. The number of pallets in the system is fixed, as seven for Problems 1, 2, and 3 of Table II and, as eight for Problems 4, 5, and 6 of Table III. The ratios found in Tables IV and V are used in the simulation.

Processing (*transportation*, *blocking*) *utilizations* are found for each machine type. For example, see Table VIII. These indicate the proportions of total processing (transportation, blocking) times to total makespan. *Machine utilization* is expressed as the sum of processing, transportation, and blocking utilizations, for each machine type: Mill, Drill, and VTL. *System utilization* is a weighted average of the *processing* utilizations of the three machine types and is a measure of overall system usage. System utilization is equal to the sum of the Mill processing utilization, twice the Drill processing utilization, and twice the VTL processing utilization, and divided by five.

The machine (system) utilizations in all of the subsequent Figures 2–7 are average values. These are cumulative utilizations and calculated as requirements are completed after each run. The difference between machine and system utilizations provides the average amount of time spent in transportation and blocked. The *all machines* utilization (see Figure 2) is calculated as the sum of the Mill machine utilization, twice the Drill machine utilization, and twice the VTL machine utilization, and divided by five.

Tables VIII, IX, X, XI, XII, and XIII provide simulation results on the machine, processing, and system utilizations as well as makespan. The higher utilizations and lower makespans are noted in boldface. Figures 2–7 also show the cumulative machine and system utilizations for each of the distinct runs required to finish requirements of all part types for the two cases, with and without fixture limitations. Tables IX, X, XII, and XIII provide the average utilizations both for all runs *and* for all runs except for the last run.

The following observations can be made from the results from Tables VIII—XIII and Figures 2–7.

(1) Both of the utilization measures (system and machine) are better when unbalancing than when balancing, for Problems 1 and 4 (see Tables VIII and XI).

(2) For Problems 2, 3, 5, and 6, the cumulative system utilization for the last run of each unbalancing problem is lower than balancing because of the end condition of finishing all requirements for all part types. See Tables IX, X, XII, and XIII and

TABLE VIII.

Simulation Results Using Method 1 After the Completion of All Production Requirements of All Ten Part Types for Problem 1.

Comparison	Four Fixtures		No Limitations	
	UB	B	UB	B
Makespan (minutes)	**7054**	7436	**7044**	7419
Mill Utilization	**.927**	.883	.948	**.953**
Processing Utilization	**.734**	.695	**.734**	.697
Transportation Utilization	.072	.069	.072	.070
Blocking Utilization	.121	.119	.142	.186
Drill Utilization	**.916**	.871	**.918**	.873
Processing Utilization	**.886**	.840	**.887**	.842
Transportation Utilization	.030	.031	.030	.031
Blocking Utilization	.000	.000	.001	.000
VTL Utilization	**.887**	.849	**.888**	.853
Processing Utilization	**.847**	.803	**.848**	.805
Transportation Utilization	.040	.046	.040	.048
Blocking Utilization	.000	.000	.000	.000
System Utilization	**.840**	.796	**.841**	.798
Average Buffer Utilization	.340	.205	.359	.218
Cart Utilization	.060	.057	.059	.058
Number of Dedicated Fixtures	30	31	35	37
CPU Time (seconds)	3.182	2.442	2.325	2.265

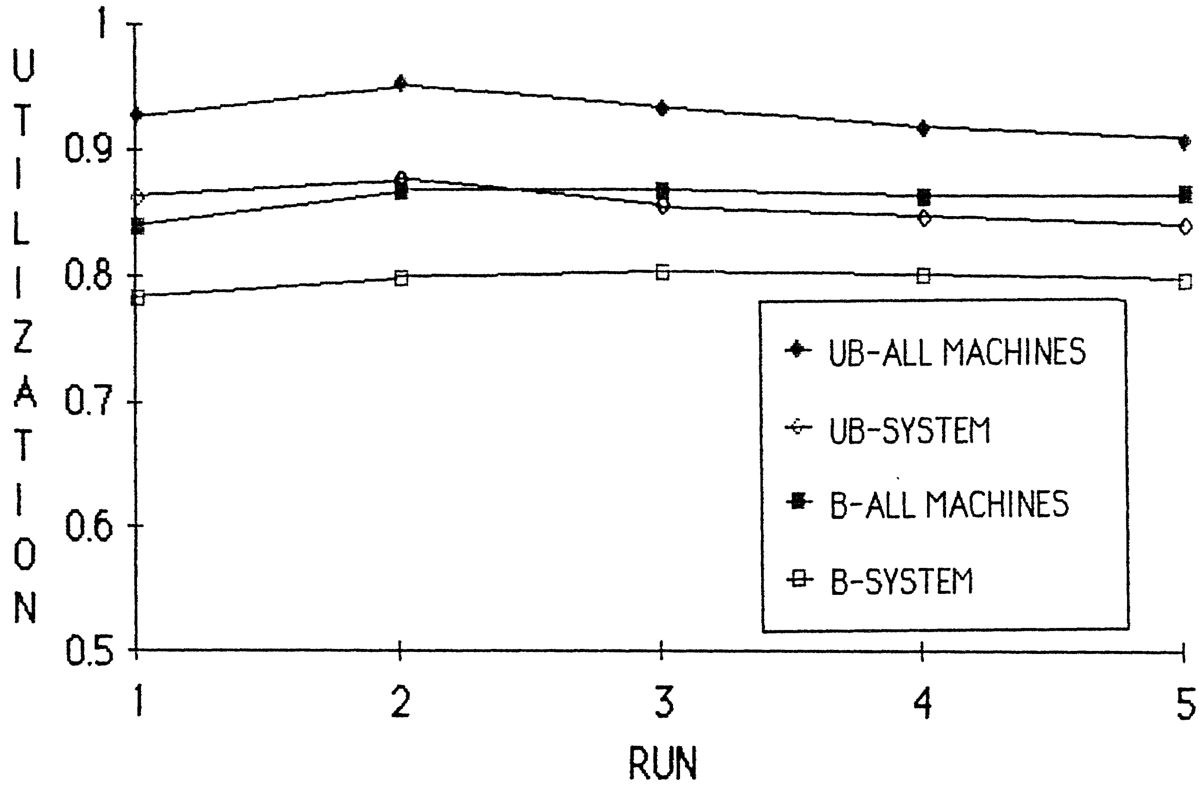
Figures 3, 4, 6, and 7. This would not happen in dynamic situations. A particular reason for the lower utilizations for unbalancing for the last run in these four problems is because the total workloads per machine are distributed equally or more to the mill. This results in worse optimal objective values for the last run (of both objectives) when solving Problem **(P1)** to select part types and determine their mix ratios. The remaining requirements have to be finished. The results of the last run are not representative of the typical FMS operating mode.

(3) However, for Problems 2, 3, 5, and 6, Tables IX, X, XII, and XIII also provide the cumulative utilizations while *excluding* the last run. These utilizations are more representative of the actual operating situation, as the ending conditions are now

FIGURE 2.

Cumulative Utilizations of the Unbalancing and Balancing Objectives for Problem 1.

a. The Number of Fixtures of Each Type is Limited to be Four.



b. No Fixture Limitations.

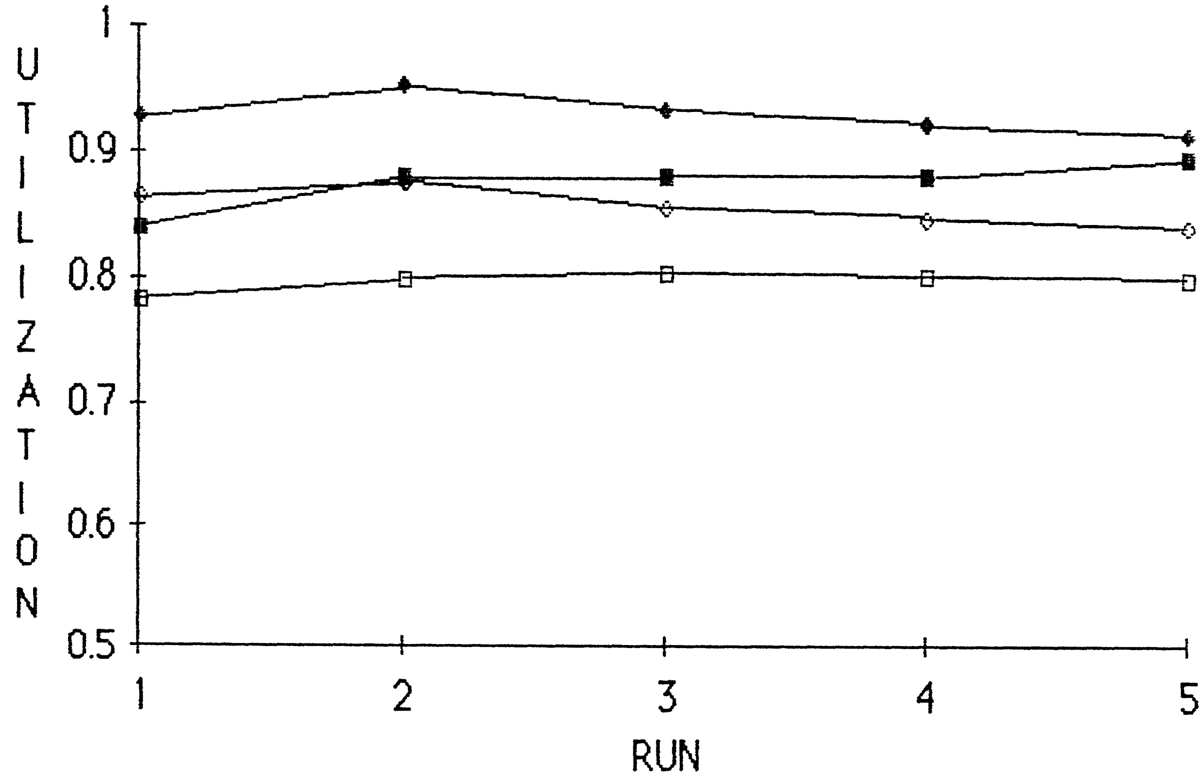


TABLE IX.

Simulation Results Using Method 1 After the Completion of All Production Requirements of All Ten Part Types for Problem 2.

Comparison	Four Fixtures		No Limitations	
	UB	B	UB	B
Makespan (minutes)	8090	**7533**	8090	**7524**
Mill Utilization	.921 (.898)	**.939** (**.938**)	.932 (.913)	**.946** (**.938**)
Processing Utilization	.754 (.682)	**.809** (**.791**)	.754 (.682)	**.810** (**.791**)
Transportation Utilization	.059 (.069)	.071 (.079)	.060 (.070)	.073 (.079)
Blocking Utilization	.108 (.147)	.059 (.068)	.118 (.161)	.063 (.068)
Drill Utilization	.743 (**.922**)	**.801** (.850)	.743 (**.923**)	**.803** (.850)
Processing Utilization	.716 (**.892**)	**.769** (.815)	.716 (**.892**)	**.770** (.815)
Transportation Utilization	.027 (.030)	.032 (.035)	.027 (.031)	.032 (.035)
Blocking Utilization	.000 (.000)	.000 (.000)	.000 (.000)	.001 (.000)
VTL Utilization	.800 (**.889**)	**.822** (.870)	.839 (**.890**)	**.841** (.870)
Processing Utilization	.716 (**.850**)	**.769** (.821)	.716 (**.850**)	**.770** (.821)
Transportation Utilization	.038 (.039)	.047 (.049)	.038 (.040)	.047 (.049)
Blocking Utilization	.046 (.000)	.006 (.000)	.085 (.000)	.024 (.000)
System Utilization	.724 (**.833**)	**.777** (.813)	.724 (**.833**)	**.778** (.813)
Average Buffer Utilization	.271 (.368)	.190 (.195)	.288 (.393)	.200 (.195)
Cart Utilization	.052 (.059)	.059 (.065)	.052 (.060)	.060 (.065)
Number of Dedicated Fixtures	31	33	40	40
CPU Time (seconds)	2.914	2.840	2.956	2.949

( ) indicates cumulative utilizations minus the last run.

excluded. These results, in conjunction with the associated Figures, all show unbalancing to be consistently better, *until* the last run forces completion of all requirements.

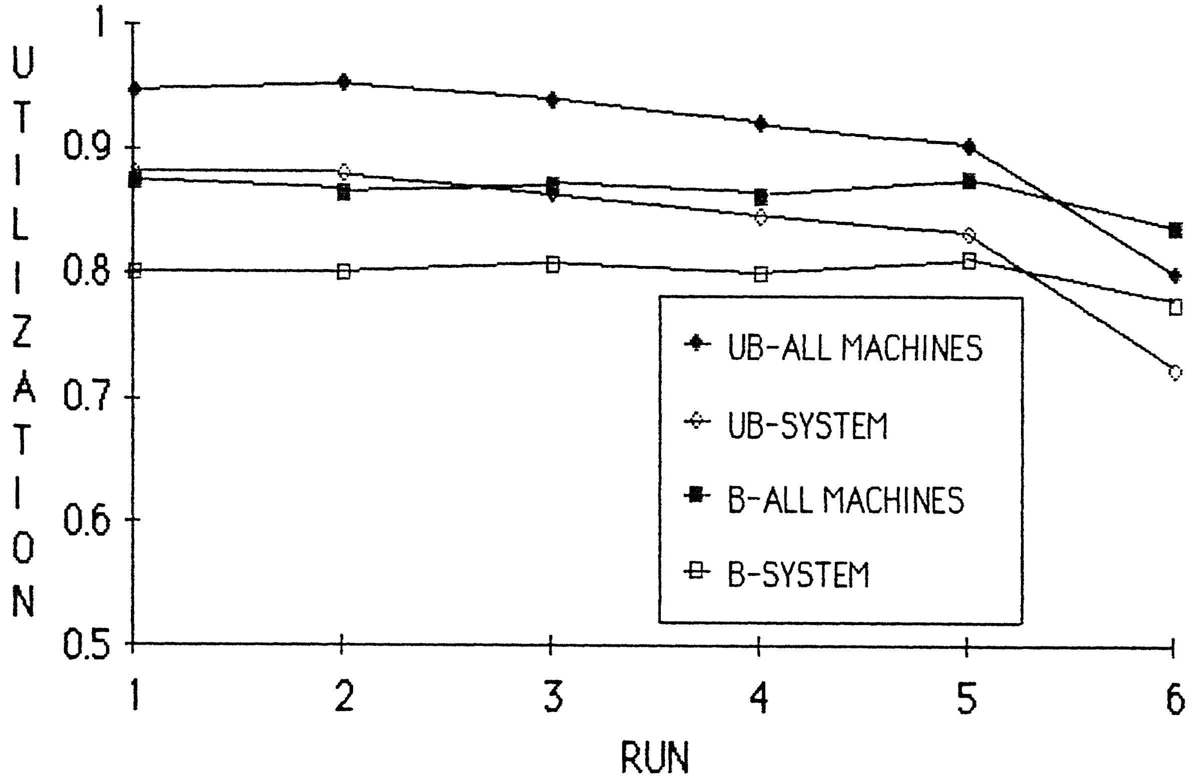
(4) The amount of blocking for the mill is usually larger when unbalancing than when balancing (except when there are no required fixture limitations for Problems 1 and 4). For example, see Table IX.

(5) The amount of blocking for the drills and VTLs as well as the number of dedicated fixtures required in the unbalanced situations are similar to those required by the balanced. For example, see Table VIII.

FIGURE 3.

Cumulative Utilizations of the Unbalancing and Balancing Objectives for Problem 2.

a. The Number of Fixtures of Each Type is Limited to be Four.



b. No Fixture Limitations.

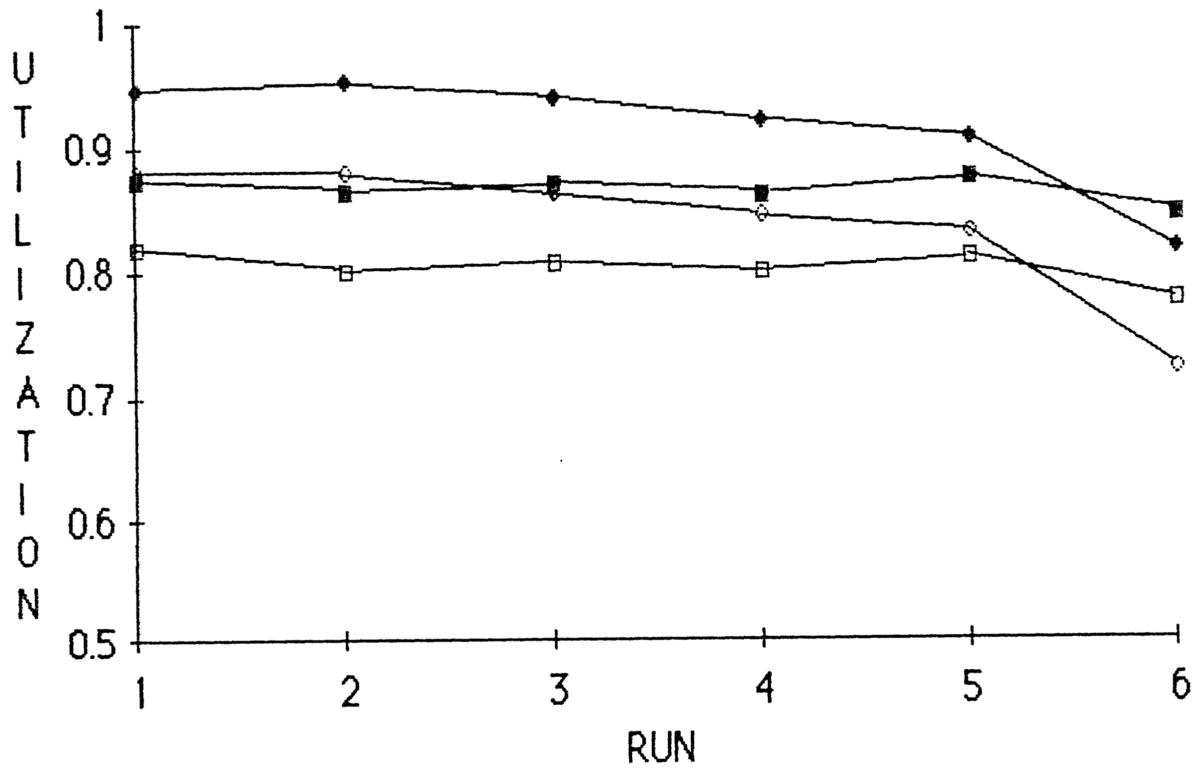


TABLE X.

Simulation Results Using Method 1 After the Completion of All Production Requirements of All Ten Part Types for Problem 3.

Comparison	Four Fixtures		No Limitations	
	UB	B	UB	B
Makespan (minute)	7338	**6921**	7350	**6921**
Mill Utilization	.925 (.915)	**.935** (**.920**)	**.941** (**.936**)	.935 (.920)
Processing Utilization	.752 (.710)	**.798** (**.753**)	.751 (.709)	**.798** (**.753**)
Transportation Utilization	.057 (.062)	.065 (.070)	.057 (.063)	.065 (.070)
Blocking Utilization	.116 (.143)	.072 (.097)	.133 (.164)	.072 (.097)
Drill Utilization	.807 (**.947**)	**.857** (.920)	.806 (**.946**)	**.857** (.920)
Processing Utilization	.780 (**.917**)	**.827** (.888)	.778 (**.915**)	**.827** (.888)
Transportation Utilization	.026 (.029)	.030 (.032)	.027 (.029)	.030 (.032)
Blocking Utilization	.001 (.001)	.000 (.000)	.001 (.002)	.000 (.000)
VTL Utilization	.842 (**.909**)	**.860** (.887)	.857 (**.907**)	**.860** (.887)
Processing Utilization	.769 (**.871**)	**.816** (.840)	.768 (**.869**)	**.816** (.840)
Transportation Utilization	.036 (.038)	.044 (.047)	.036 (.038)	.044 (.047)
Blocking Utilization	.037 (.000)	.000 (.000)	.052 (.000)	.000 (.000)
System Utilization	.770 (**.857**)	**.817** (.842)	.769 (**.855**)	**.817** (.842)
Average Buffer Utilization	.325 (.399)	.295 (.338)	.338 (.414)	.295 (.338)
Cart Utilization	.052 (.058)	.059 (.063)	.053 (.058)	.059 (.063)
Number of Dedicated Fixtures	35	29	42	30
CPU Time (seconds)	2.542	2.670	2.946	2.458

( ) indicates cumulative utilizations minus the last run.

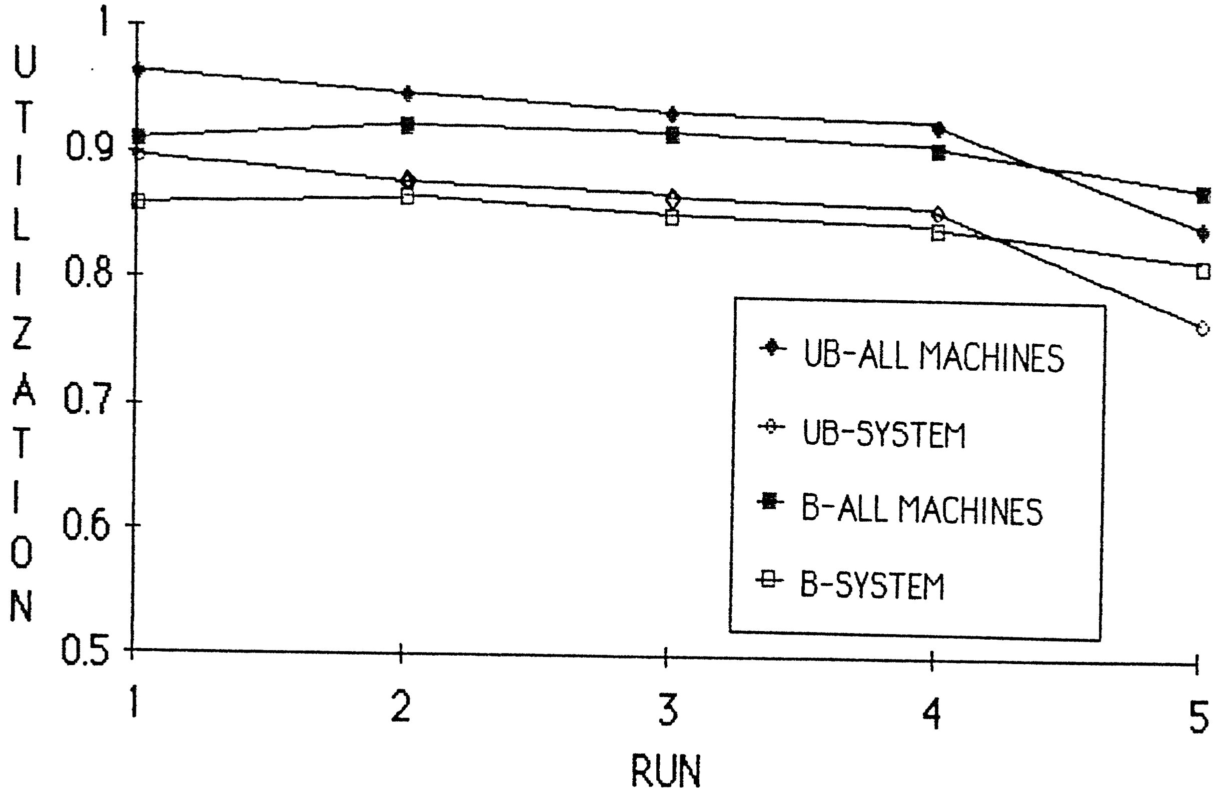
(6) The utilizations for unbalancing workloads decrease quicker with the number of runs in Problems 2, 3, 5, and 6 than in Problems 1 and 4. For example, see Figures 2 and 3. This is because the workloads are distributed more to the pooled drills and VTLs in Problems 1 and 4. This allows the optimal objective function value for unbalancing to be maintained better until the last run.

We can conclude from these that unbalancing workloads results in higher overall utilizations than balancing. All of the Figures showed unbalancing to be better than balancing until the last run. These *last run* ending conditions would not occur in reality, as orders would continuously arrive to the system.

FIGURE 4.

Cumulative Utilizations of the Unbalancing and Balancing Objectives for Problem 3.

a. The Number of Fixtures of Each Type is Limited to be Four.



b. No Fixture Limitations.

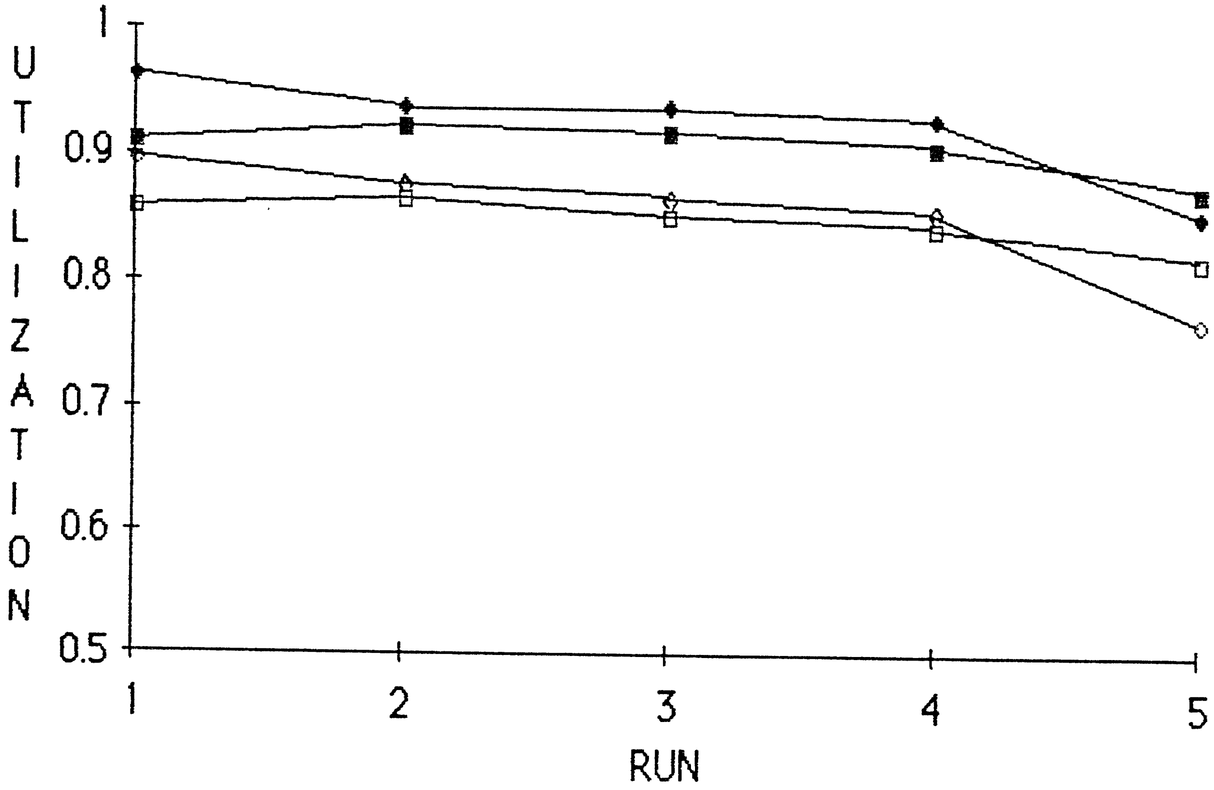


TABLE XI.

Simulation Results Using Method 1 After the Completion of All Production Requirements of All Twelve Part Types for Problem 4.

Comparison	Four Fixtures		No Limitations	
	UB	B	UB	B
Makespan (minutes)	**6486**	6744	**6476**	6704
Mill Utilization	**.892**	.857	**.901**	.882
Processing Utilization	**.683**	.657	**.684**	.660
Transportation Utilization	.076	.070	.076	.071
Blocking Utilization	.133	.130	.141	.151
Drill Utilization	**.901**	.865	**.902**	.868
Processing Utilization	**.854**	.821	**.855**	.826
Transportation Utilization	.029	.030	.030	.030
Blocking Utilization	.018	.014	.017	.012
VTL Utilization	**.916**	.885	**.917**	.889
Processing Utilization	**.878**	.844	**.879**	.849
Transportation Utilization	.038	.040	.038	.040
Blocking Utilization	.000	.001	.000	.000
System Utilization	**.829**	.797	**.830**	.802
Average Buffer Utilization	.432	.426	.442	.436
Cart Utilization	.060	.058	.060	.059
Number of Dedicated Fixtures	42	44	50	55
CPU Time (seconds)	1.798	1.857	1.733	1.794

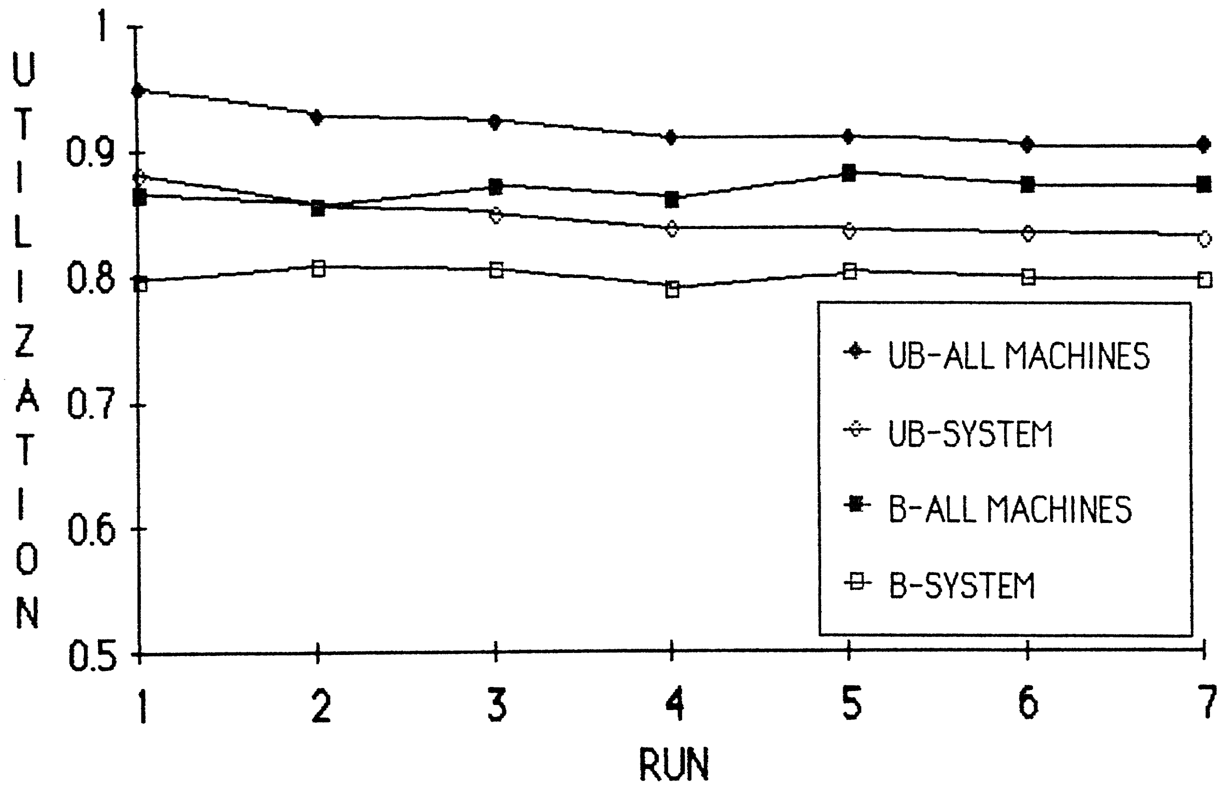
Method 2 attempts to select part types and their mix ratios with the best objective function values of unbalancing and balancing workloads for a given number of pallets. Simulation runs are performed again using Method 2 for a variety of n=6, 7, 8, 9, 10, 11, 12, and 13 and for 50 simulated hours. The ratios found in Tables VI and VII are used in the simulation. The production requirements are not considered here because part mix ratios are determined for the first run only.

Tables XIV and XV provide simulation results for the unbalancing and balancing objectives when there are no fixture limitations. For both the unbalancing and balancing rules, Figures 8 and 9 also show the machine and processing utilizations and their stand-

FIGURE 5.

Cumulative Utilizations of the Unbalancing and Balancing Objectives for Problem 4.

a. The Number of Fixtures of Each Type is Limited to be Four.



b. No Fixture Limitations.

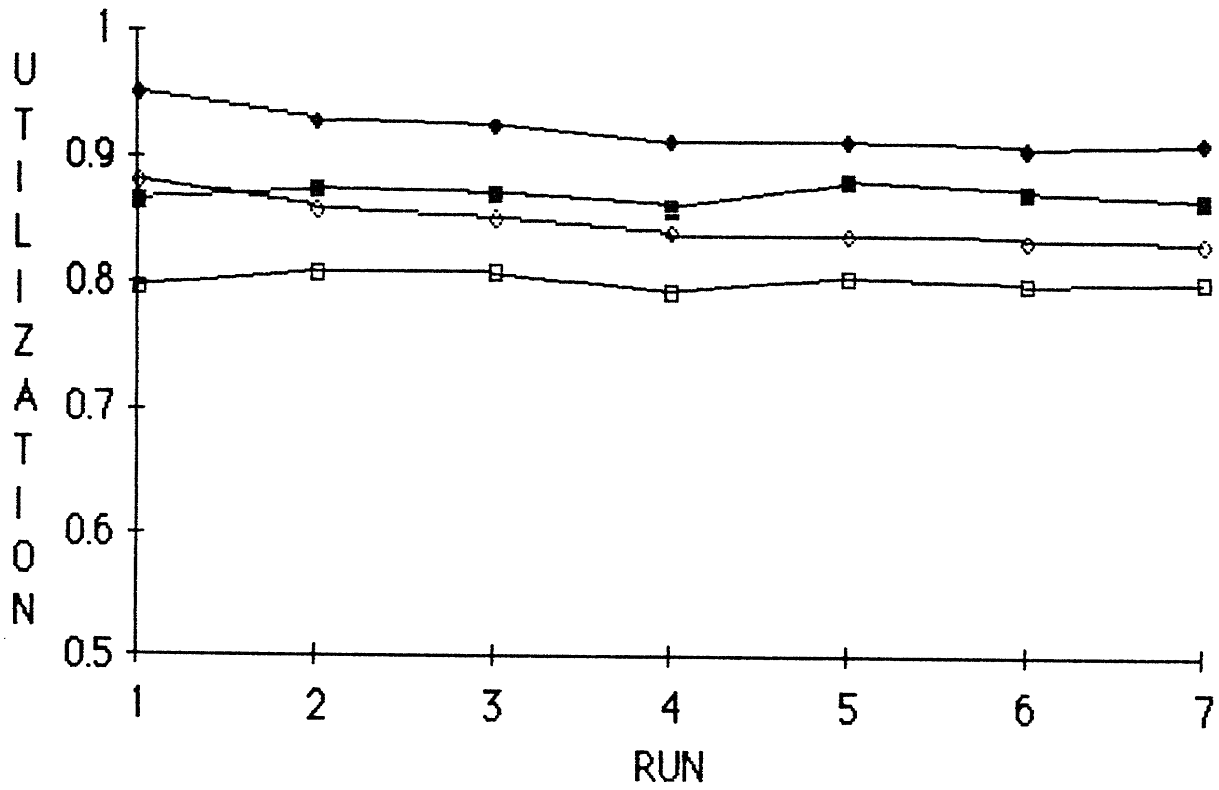


TABLE XII.

Simulation Results Using Method 1 After the Completion of All Production Requirements of All Twelve Part Types for Problem 5.

Comparison	Four Fixtures		No Limitations	
	UB	B	UB	B
Makespan (minute)	6046	**6008**	**6037**	6076
Mill Utilization	**.937 (.933)**	.919 (.915)	**.949 (.947)**	.914 (.904)
Processing Utilization	.810 (.790)	**.815 (.801)**	**.811 (.792)**	.806 (.781)
Transportation Utilization	.064 (.069)	.061 (.065)	.066 (.071)	.062 (.066)
Blocking Utilization	.063 (.074)	.043 (.049)	.072 (.084)	.046 (.057)
Drill Utilization	.786 (**.865**)	**.791** (.849)	**.787 (.863)**	.780 (.853)
Processing Utilization	.752 (**.828**)	**.757** (.813)	**.754 (.826)**	.749 (.820)
Transportation Utilization	.030 (.032)	.033 (.031)	.029 (.032)	.029 (.030)
Blocking Utilization	.004 (.005)	.001 (.005)	.004 (.005)	.002 (.003)
VTL Utilization	.795 (**.859**)	**.799** (.857)	**.841 (.858)**	.834 (.851)
Processing Utilization	.749 (**.814**)	**.754** (.811)	**.751 (.814)**	.746 (.804)
Transportation Utilization	.043 (.045)	.041 (.042)	.041 (.044)	.041 (.044)
Blocking Utilization	.003 (.000)	.004 (.004)	.049 (.000)	.047 (.003)
System Utilization	.762 (**.815**)	**.767** (.810)	**.764 (.814)**	.759 (.806)
Average Buffer Utilization	.222 (.263)	.196 (.336)	.239 (.271)	.199 (.233)
Cart Utilization	.057 (.061)	.056 (.059)	.057 (.061)	.055 (.059)
Number of Dedicated Fixtures	47	54	69	63
CPU Time (seconds)	1.520	1.795	1.545	1.518

( ) indicates cumulative utilizations minus the last run.

ard deviations.

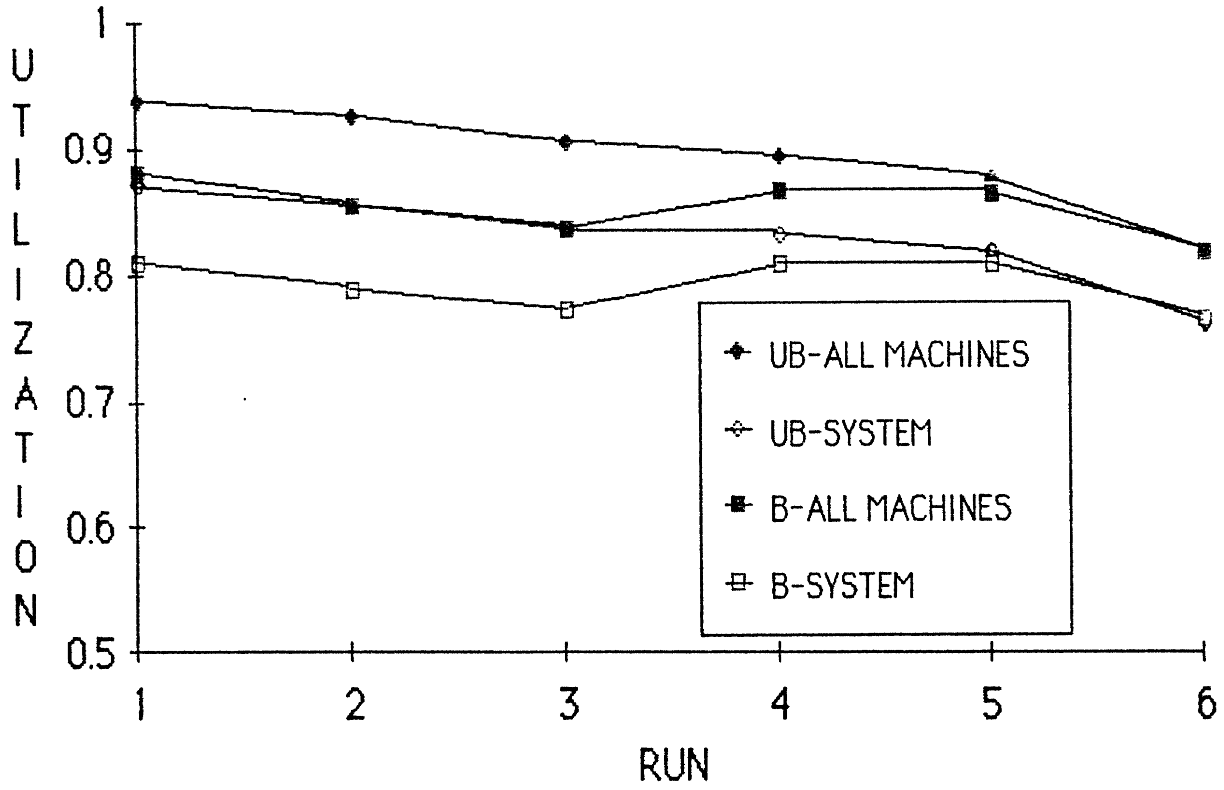
The following observations can be made from the results in Tables XIV and XV and Figures 8 and 9.

(1) The processing utilizations for the drills and VTLs are always better when unbalancing than when balancing, until the system becomes saturated with 11 or 12 pallets.

FIGURE 6.

Cumulative Utilizations of the Unbalancing and Balancing Objectives for Problem 5.

a. The Number of Fixtures of Each Type is Limited to be Four.



b. No Fixture Limitations.

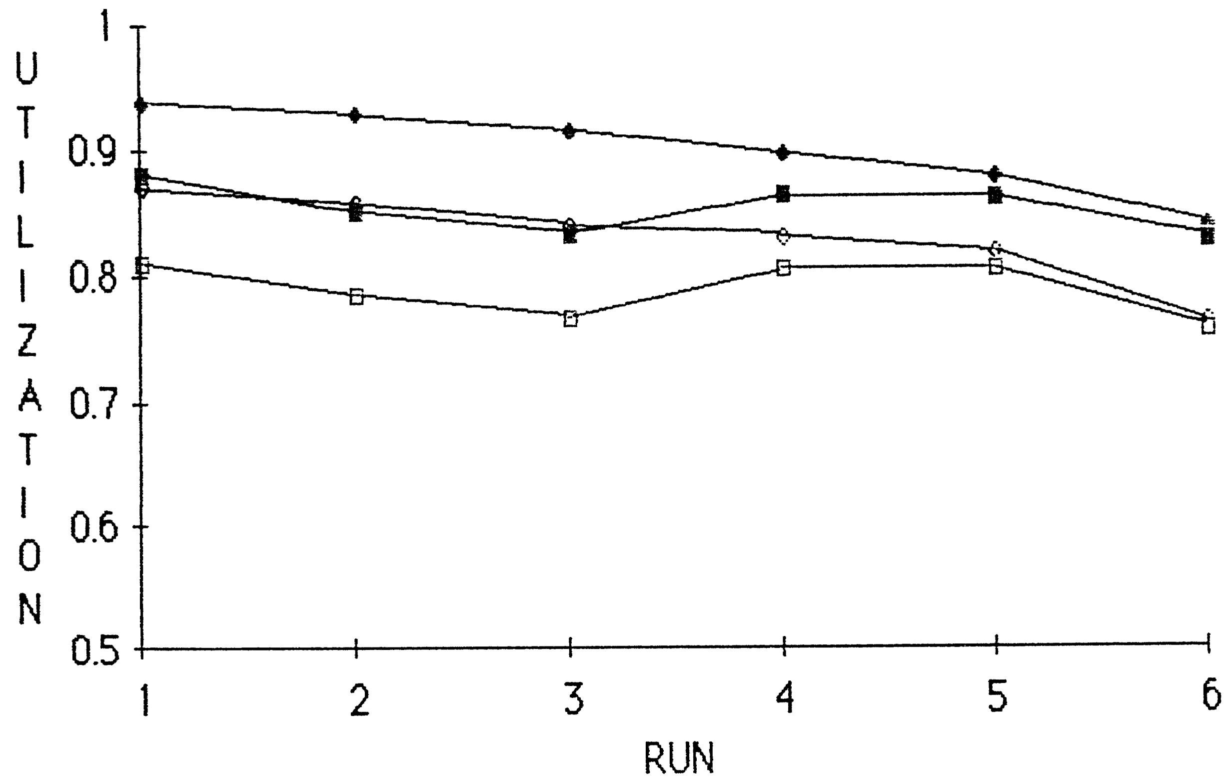


TABLE XIII.

Simulation Results After the Completion of All Production Requirements of All Twelve Part Types for Problem 6.

Comparison	Four Fixtures		No Limitations	
	UB	B	UB	B
Makespan (minutes)	6317	**6247**	6294	**6224**
Mill Utilization	**.920** (**.916**)	.914 (.898)	**.928** (**.926**)	.919 (.907)
Processing Utilization	.785 (**.761**)	**.794** (.754)	.788 (**.764**)	**.797** (.763)
Transportation Utilization	.064 (.071)	.063 (.069)	.066 (.072)	.065 (.070)
Blocking Utilization	.071 (.084)	.057 (.075)	.074 (.090)	.057 (.074)
Drill Utilization	.810 (**.904**)	**.834** (.857)	.819 (**.915**)	**.844** (.866)
Processing Utilization	.781 (**.872**)	**.790** (.806)	.784 (**.876**)	**.793** (.806)
Transportation Utilization	.027 (.030)	.028 (.030)	.028 (.031)	.028 (.030)
Blocking Utilization	.002 (.002)	.016 (.021)	.007 (.008)	.023 (.030)
VTL Utilization	.825 (**.887**)	**.838** (.863)	**.882** (**.892**)	.845 (.869)
Processing Utilization	.787 (**.847**)	**.796** (.820)	.790 (**.851**)	**.799** (.827)
Transportation Utilization	.038 (.040)	.041 (.042)	.038 (.041)	.040 (.041)
Blocking Utilization	.000 (.000)	.001 (.001)	.054 (.000)	.006 (.001)
System Utilization	.784 (**.840**)	**.793** (.801)	.787 (**.844**)	**.796** (.806)
Average Buffer Utilization	.257 (.307)	.281 (.326)	.297 (.343)	.293 (.339)
Cart Utilization	.055 (.060)	.055 (.058)	.056 (.061)	.056 (.058)
Number of Dedicated Fixtures	41	45	57	54
CPU Time (seconds)	1.588	1.577	1.585	1.601

( ) indicates cumulative utilizations minus the last run.

(2) For n=10 of Table XIV, the unbalanced problem results in less VTL machine utilization than the balanced, but has more processing utilization. This indicates that the higher machine utilization from balancing results from more blocking.

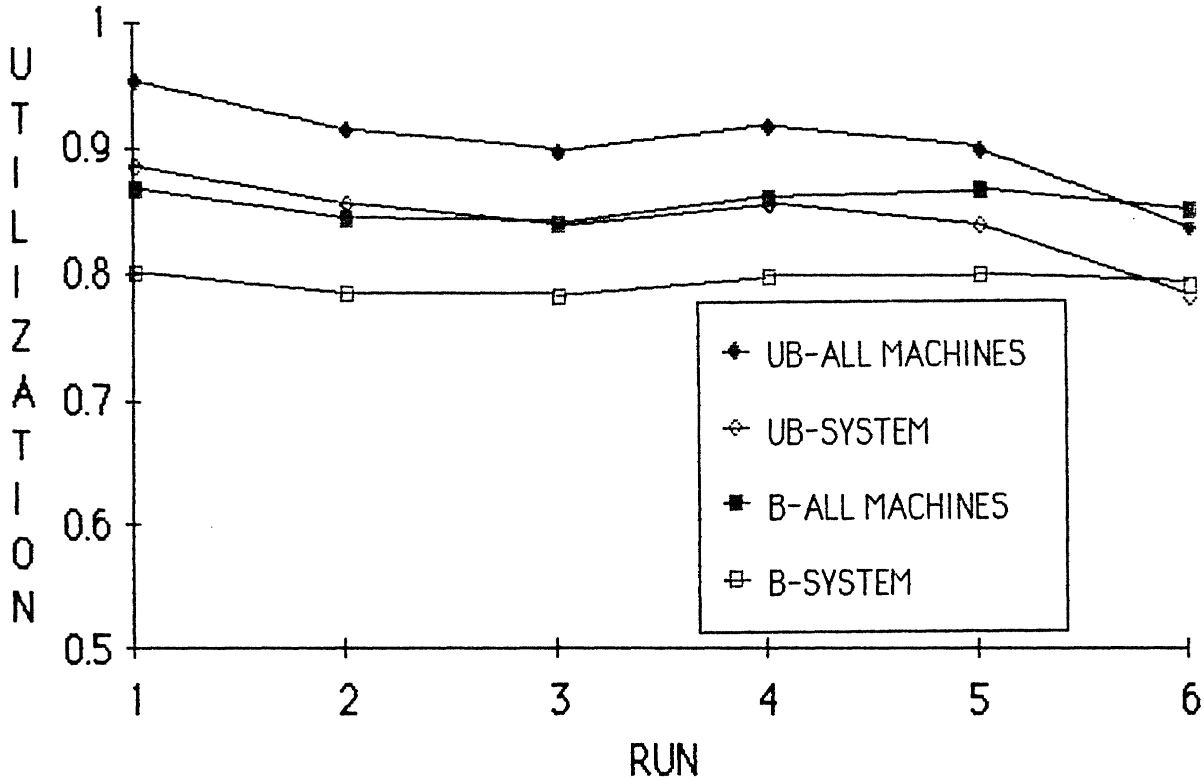
(3) The *machine utilizations* for the balancing objective are unbalanced among the three machine types. But unbalancing workloads leads to balanced machine utilizations among the three machine types pooled unequally. This is mainly because the pooled identical machines with more workloads share the total transportation time required by finishing all requirements for all part types.

(4) The *processing utilizations* are in general more balanced for the balancing objective.

FIGURE 7.

Cumulative Utilizations of the Unbalancing and Balancing Objectives for Problem 6.

a. The Number of Fixtures of Each Type is Limited to be Four.



b. No Fixture Limitations.

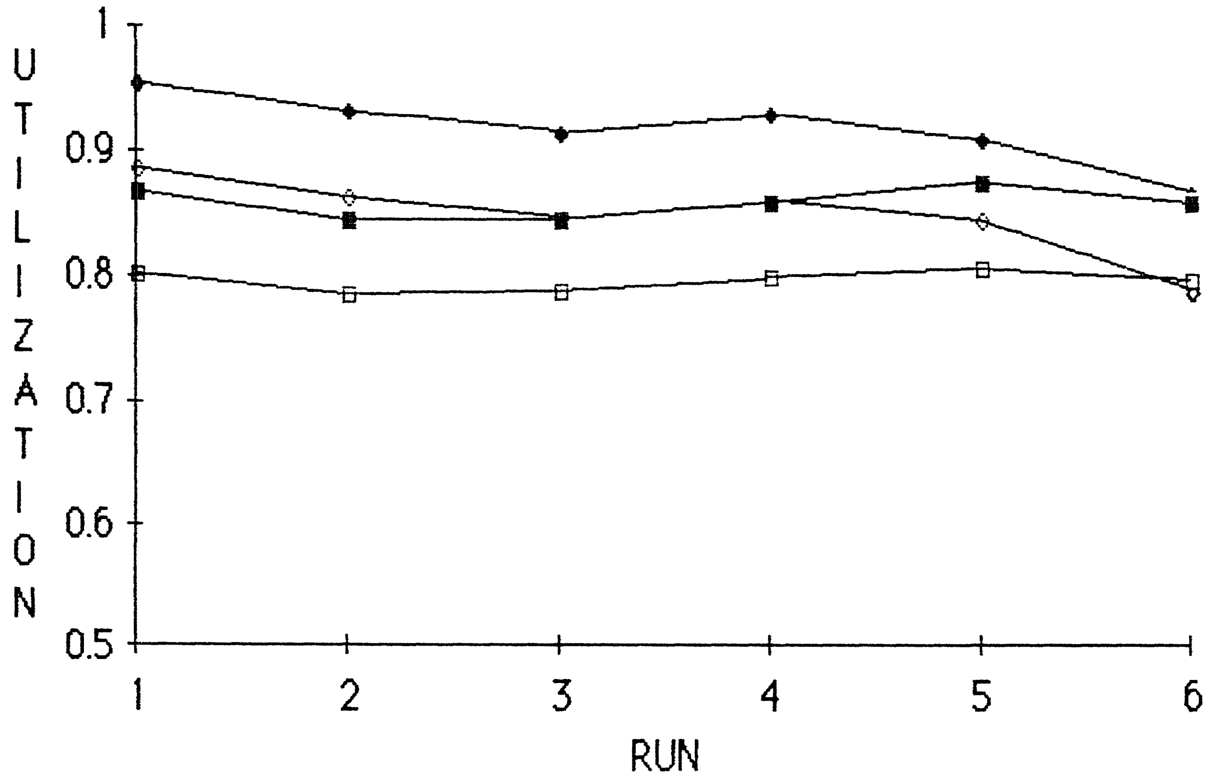


TABLE XIV.

50-hour Simulation Results Using Method 2 for Balancing/Unbalancing Objectives for Problems 1, 2, and 3.

Comparison	n=6		n=7		n=8		n=9	
	UB	B	UB	B	UB	B	UB	B
Mill Utilization	.840	**1.00**	.987	**1.00**	.999	**1.00**	**1.00**	**1.00**
Processing Utilization	.668	**.833**	.742	**.833**	.760	**.834**	.755	**.835**
Transportation Utilization	.071	.066	.067	.066	.082	.067	.107	.053
Blocking Utilization	.101	.101	.178	.101	.157	.099	.138	.112
Drill Utilization	**.959**	.863	**.989**	.863	**.968**	.864	**.972**	.858
Processing Utilization	**.924**	.831	**.957**	.831	**.929**	.831	**.923**	.832
Transportation Utilization	.035	.032	.032	.032	.035	.033	.044	.026
Blocking Utilization	.000	.000	.000	.000	.004	.000	.005	.000
VTL Utilization	**.944**	.874	**.980**	.874	**.963**	.874	**.962**	.912
Processing Utilization	**.905**	.817	**.946**	.817	**.915**	.818	**.908**	.818
Transportation	.039	.057	.034	.057	.048	.056	.054	.041
Blocking Utilization	.000	.000	.000	.000	.000	.000	.000	.053
System Utilization	**.865**	.826	**.910**	.826	**.890**	.826	**.883**	.827
Average Buffer Utilization	.302	.113	.446	.214	.404	.117	.424	.136
Cart Utilization	.061	.057	.064	.057	.071	.057	.080	.050
Number of Dedicated Fixtures	8	7	9	9	11	12	13	12
CPU Time (seconds)	1.465	1.490	1.571	1.393	1.592	1.500	1.565	1.544

TABLE XIV (CONTINUED).

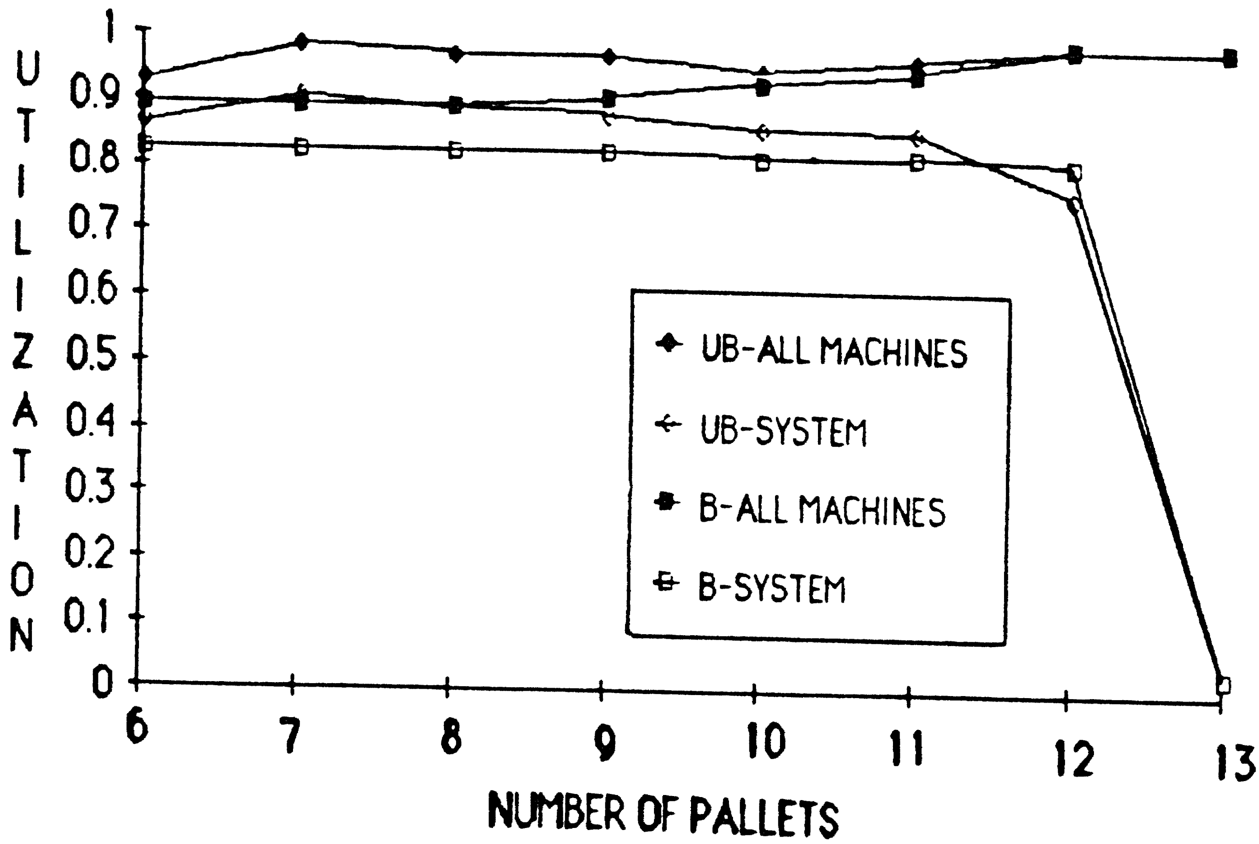
50-hour Simulation Results Using Method 2 for Balancing/Unbalancing Objectives for Problems 1, 2, and 3.

Comparison	n=10		n=11		n=12		n=13	
	UB	B	UB	B	UB	B	UB	B
Mill Utilization	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
Processing Utilization	.767	**.823**	.762	**.835**	.705	**.822**	**.047**	.045
Transportation Utilization	.093	.065	.102	.056	.099	.088	.005	.005
Blocking Utilization	.140	.112	.136	.109	.196	.090	.948	.950
Drill Utilization	**.934**	.858	**.938**	.892	.990	**.991**	.990	**.991**
Processing Utilization	**.896**	.827	**.892**	.832	.806	**.823**	**.043**	.041
Transportation Utilization	.038	.031	.041	.040	.023	.024	.001	.001
Blocking Utilization	.000	.000	.005	.020	.161	.144	.946	.949
VTL Utilization	.941	**.972**	**.979**	**.979**	**.981**	.979	**.981**	.979
Processing Utilization	**.878**	.808	**.873**	.809	.749	**.794**	.010	**.016**
Transportation	.055	.033	.045	.030	.035	.025	.001	.001
Blocking Utilization	.008	.131	.061	.140	.197	.160	.970	.962
System Utilization	**.863**	.819	**.858**	.823	.763	**.811**	.031	**.032**
Average Buffer Utilization	.360	.282	.522	.490	.758	.725	.961	.960
Cart Utilization	.075	.056	.077	.058	.060	.056	.002	.002
Number of Dedicated Fixtures	14	12	11	11	16	12	14	13
CPU Time (seconds)	1.576	1.744	1.643	1.864	.961	1.556	.966	1.626

FIGURE 8.

No Fixture Limitations for Problems 1, 2, and 3.

a. Utilizations of the Unbalancing and Balancing Objectives.



b. Standard Deviation of Utilizations.

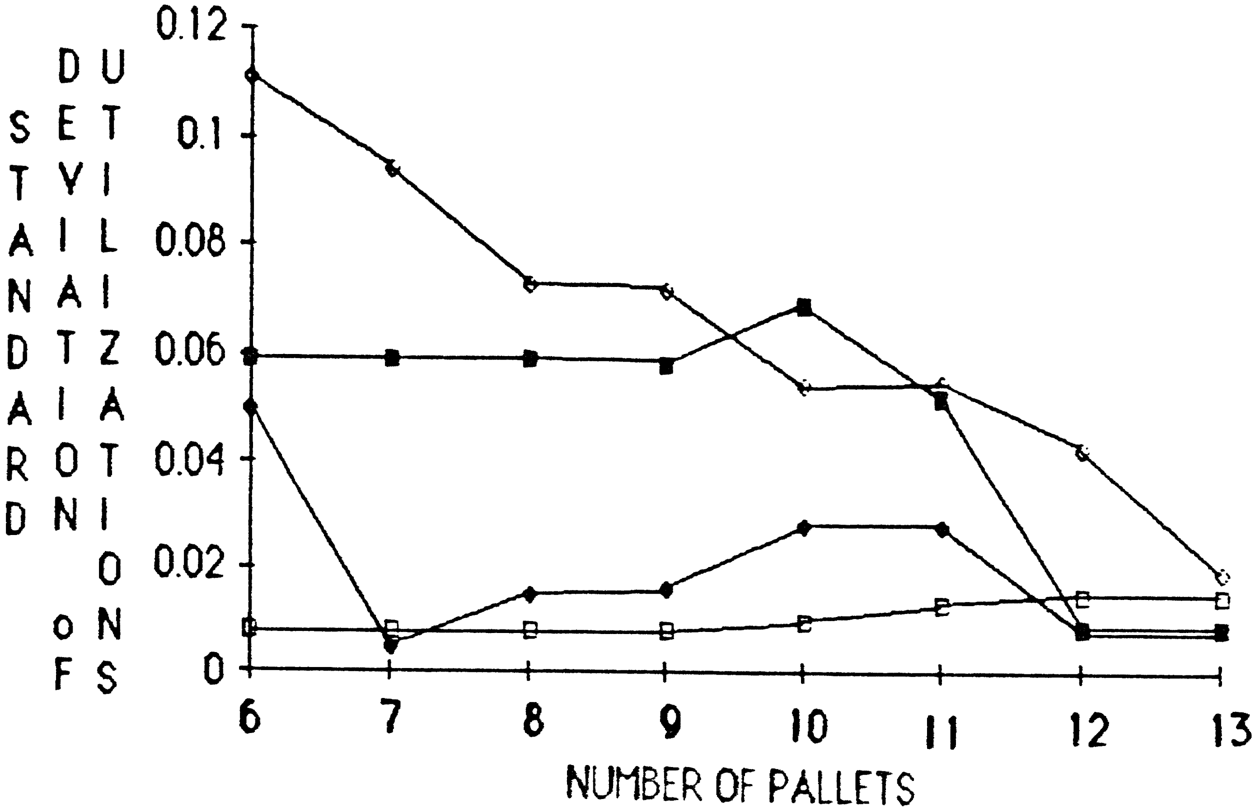


TABLE XV.

50-hour Simulation Results Using Method 2 for Balancing/Unbalancing Objectives for Problems 4, 5, and 6.

Comparison	n=6		n=7		n=8		n=9	
	UB	B	UB	B	UB	B	UB	B
Mill Utilization	.794	**1.00**	.943	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
Processing Utilization	.665	**.817**	.720	**.817**	.795	**.817**	.796	**.817**
Transportation Utilization	.063	.082	.068	.081	.094	.081	.094	.081
Blocking Utilization	.066	.101	.155	.102	.111	.102	.110	.102
Drill Utilization	**.966**	.860	**.996**	.860	**.993**	.860	**.995**	.860
Processing Utilization	**.933**	.819	**.963**	.819	**.957**	.819	**.958**	.819
Transportation Utilization	.033	.041	.033	.041	.036	.041	.037	.041
Blocking Utilization	.000	.000	.000	.000	.000	.000	.000	.000
VTL Utilization	**.952**	.856	**.979**	.856	**.981**	.856	**.981**	.857
Processing Utilization	**.916**	.807	**.945**	.807	**.943**	.807	**.944**	.807
Transportation Utilization	.036	.049	.034	.049	.038	.049	.037	.049
Blocking Utilization	.000	.000	.000	.000	.000	.000	.000	.001
System Utilization	**.873**	.814	**.907**	.814	**.919**	.814	**.920**	.814
Average Buffer Utilization	.346	.243	.538	.243	.337	.239	.341	.239
Cart Utilization	.057	.073	.064	.073	.073	.073	.073	.073
Number of Dedicated Fixtures	7	8	9	8	10	9	13	11
CPU Time (seconds)	1.090	1.038	1.172	1.074	1.065	1.082	.988	.903

TABLE XV (CONTINUED).

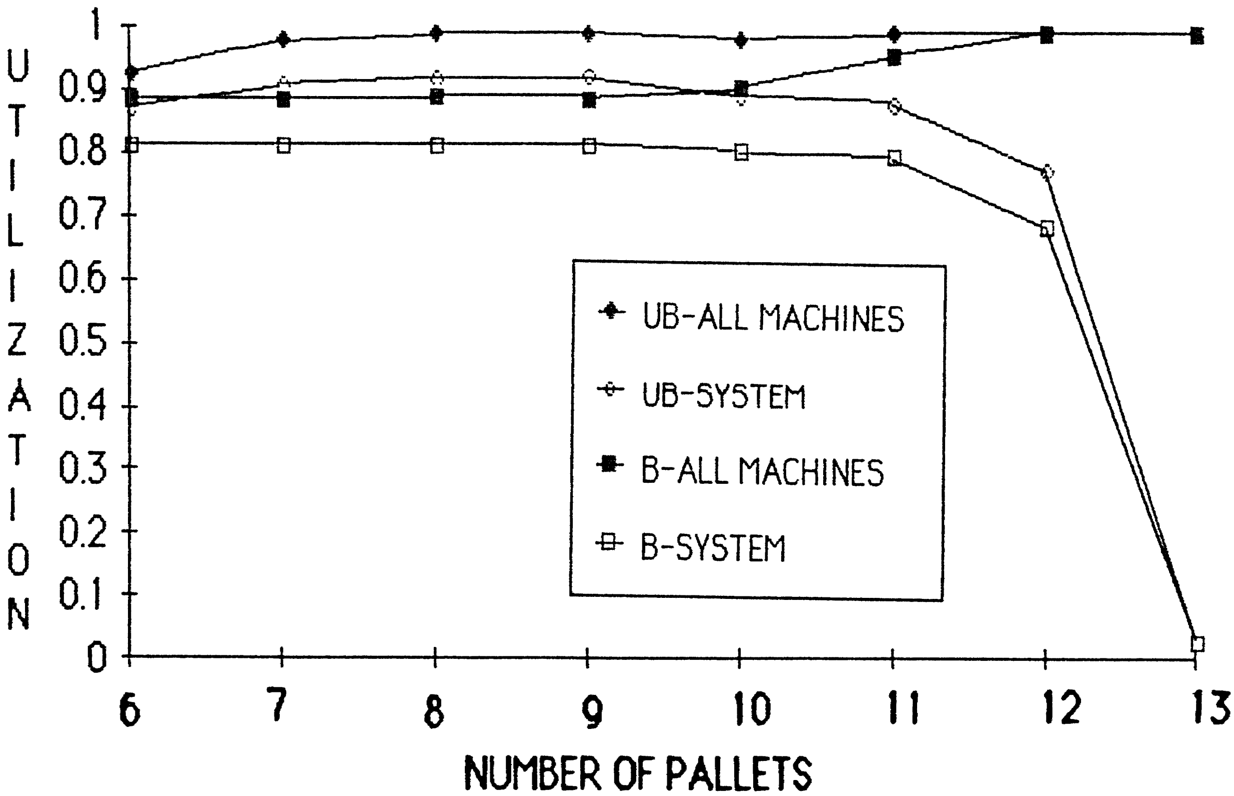
50-hour Simulation Results Using Method 2 for Balancing/Unbalancing Objectives for Problems 4, 5, and 6.

Comparison	n=10		n=11		n=12		n=13	
	UB	B	UB	B	UB	B	UB	B
Mill Utilization	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
Processing Utilization	.793	**.803**	.781	**.799**	**.696**	.690	.039	**.041**
Transportation Utilization	.122	.105	.126	.083	.127	.124	.005	.005
Blocking Utilization	.085	.092	.093	.118	.177	.186	.956	.954
Drill Utilization	**.992**	.847	**.993**	.906	**.996**	.995	**.996**	.995
Processing Utilization	**.924**	.807	**.911**	.796	**.805**	.696	**.037**	**.037**
Transportation Utilization	.035	.040	.035	.051	.027	.028	.001	.001
Blocking Utilization	.033	.000	.047	.059	.164	.271	.958	.957
VTL Utilization	**.958**	.913	**.980**	.979	**.983**	**.983**	**.983**	**.983**
Processing Utilization	**.906**	.794	**.894**	.784	**.775**	.673	**.014**	**.014**
Transportation Utilization	.052	.055	.045	.044	.028	.028	.001	.001
Blocking Utilization	.000	.064	.041	.151	.180	.282	.968	.968
System Utilization	**.891**	.801	**.878**	.792	**.771**	.686	.028	**.029**
Average Buffer Utilization	.556	301	.614	.519	.798	.754	.970	.973
Cart Utilization	.081	.080	.081	.079	.068	.068	.002	.002
Number of Dedicated Fixtures	14	13	15	14	14	15	13	13
CPU Time (seconds)	.989	.972	.949	1.026	1.182	1.079	.870	.900

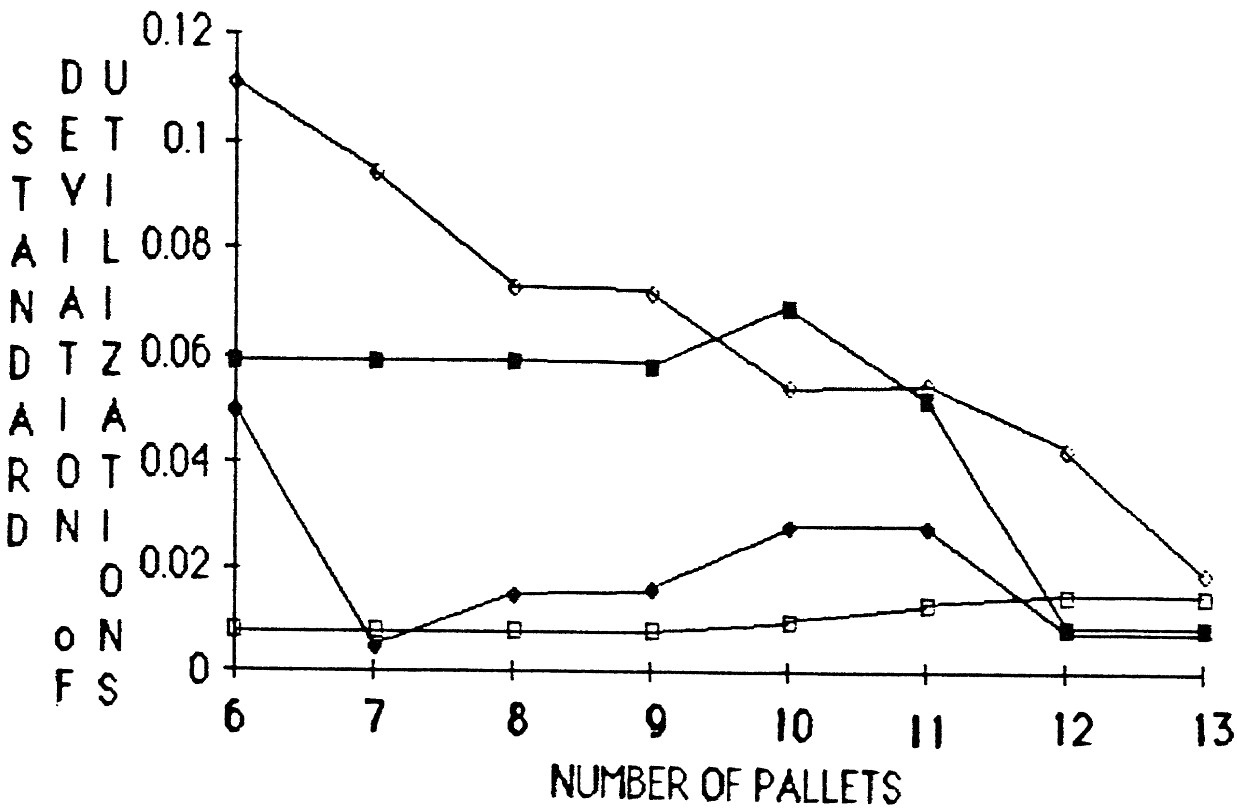
FIGURE 9.

No Fixture Limitations for Problems 4, 5, and 6.

a. Utilizations of the Unbalancing and Balancing Objectives.



b. Standard Deviation of Utilizations.



(5) The *system utilization* is *better* when *unbalancing*, for six to eleven pallets in the system.

(6) The amount of blocking as well as the number of dedicated fixtures required in the unbalanced situations are similar to those required by the balanced.

(7) The overall *best system utilization* occurs when there are seven pallets in the system for Problems 1–3 and nine pallets in the system for Problems 4–6 (see Tables XIV and XV). For the unbalancing objective, performance deteriorates as more pallets are added. For balancing, the results are almost the same for 6, 7, 8, and 9 pallets.

(8) It can be seen in Figures 8 and 9 and Tables XIV and XV that the average *machine* and *system utilizations* are *less sensitive* to the number of pallets when balancing than when unbalancing. This implies that the appropriate number of pallets in the system should be determined in advance for a given system, in order to maximize system utilization.

(9) When unbalancing, the processing utilizations of the pooled drills and VTLs with more workloads tend to increase, then decrease with the number of pallets in the system after a particular saturation point is reached (for example, n=7 in Table XIV).

(10) For thirteen pallets in the system, the processing utilizations are almost zero. This is because the system has deadlocked. Most of the machine utilization consists of blocking. This does happen in practice, and policies to prevent deadlock need to be determined.

Therefore, it can be seen with these examples that the overall *system utilization* has always been better (except when the ending conditions are considered) when unbalancing the assigned machine workloads.

§4.2. Flexible Versus Batching Approach

In this section, the suggested flexible approach is compared to batching. The batching approach used here tries to favor batching by minimizing the frequency of system setup by avoiding the input of some new part type(s) that could make the system more highly utilized. In particular, for batching, whenever the requirements for a part type in a particular batch are completed, new ratios are found for the remaining part types that aim to (un)balance machine workloads as optimally as possible. This attempts to implement batching as favorably as possible. Therefore, the selected part types are machined until all requirements are completed, by following the ratios that are continuously updated as any one part type completes its requirements.

The six problems of Tables II and III are run again as Problem **(P1)** to find the part mix ratios to compare both the flexible and batching approaches for a given number of pallets in the system. Computational results on optimal solutions to Problem **(P1)** using the unbalancing objective are provided in Tables XVI and XVII.

In Problems 1, 2, and 3 of Table II, for all ten part types, there are two total tool changeovers for all tools in all magazines for the batching approach (i.e., there are three batches). (See Table XVI.) There are four minor tool loadings (many fewer cutting tools would be involved) for the flexible approach in both Problems 1 and 3, and five minor changeovers for the flexible approach in Problem 2. For the three Problems of Table III having twelve part types, there are three or four total changeovers for batching. (See Table XVII.) There are six minor tool reloadings for the flexible approach for Problem 4 and five changeovers for both Problems 5 and 6. In addition, the objective function values for batching deteriorate as new ratios for the remaining part types in a particular batch are found. This will lead to lower processing utilization as the system operates. This deterioration occurs because new ratios are found continuously without the potentially advantageous introduction of some new part type(s) which can make the system more highly utilized.

Now we present simulation results to investigate the flexible/batching approaches. The scenario is again the flexible flow shop of Figure 1. Simulations are performed for each of the three Problems of Tables II and III and for the two cases, with and without fixture limitations. Tables XVIII, XIX, XX, XXI, XXII, and XXIII provide computational results on the system, machine, processing, and transportation utilizations, as well as makespan. Figures 10, 11, 12, 13, 14, and 15 show the cumulative machine and processing utilizations for each distinct run as all requirements of all part types are finished for Problems 1, 2, 3, 4, 5, and 6, respectively. The simulation results demonstrate how much the system and processing utilizations are improved by using the flexible approach.

The following observations can be made from Tables XVIII to XXIII and Figures 10 to 15.

(1) For all Problems except Problem 5, the *flexible approach results in higher system utilization than batching*. This is consistent with the decrease in makespan for the flexible approach.

(2) It can be seen in Figure 14 of Problem 5 that the system utilization for the flexible approach is better than batching until the sixth run. The system utilization for the flexible approach for the last (sixth) run is poorer again because of the ending conditions. These ending conditions result in most of the overall machine and processing utilizations from batching in Table XXII to be better. With the

TABLE XVI.

Integer Optimum Solutions for the Objective of Unbalancing Workloads When Seven Pallets are Allowed in the System.

a. PROBLEM 1

Run	Approach	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
1	FLEX(a)(1)	**2,5,6,8,10**	2:1:2:1:1	0	3.583
	BATCH(a)(2)	**2,5,6,8,10**	2:1:2:1:1	0	3.583
	(b)	2,5,6,10	3:1:2:1	5	1.266
	(c-1)(3)	5,6,10	1:3:3	55	1.143
	(c-2)(4)	5,6,10	1:6:1	50	1.549
	(d)	5,10	1:4	65	1.312
2	FLEX(a)	2,5,6,**7**,10	2:1:1:1:2	0	0.942
	(b)	5,6,7,10	1:2:2:2	25	0.992
	BATCH(a)	**1,4,7**	3:1:1	15	1.534
3	FLEX(a)	**3**,5,6,10	1:1:1:3	15	0.960
	(b)	3,5,6	1:3:2	55	1.042
	BATCH(a)	**3,9**	1:2	170	1.083
4	FLEX(a)	**1,3,4**	3:1:1	25	0.738
5	FLEX(a)	1,4,**9**	3:1:1	15	0.636
	(b)	1,9	3:2	15	0.699

b. PROBLEM 2

Run	Approach	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
1	FLEX(a)	**2,5,6,8,10**	2:1:2:1:1	0	3.583
	BATCH	**2,5,6,8,10**	2:1:2:1:1	0	3.583
	(b)	2,5,6,10	3:1:2:1	5	1.266
	(c-1)(3)	5,6,10	1:3:3	55	1.143
	(c-2)(4)	5,6,10	1:6:1	50	1.549
	(d)	5,10	1:4	65	1.312
2	FLEX(a)	2,5,6,**7**,10	2:1:1:1:2	0	0.942
	BATCH(a)	**1,4,7**	3:1:1	15	1.534
	(b)	4,7	2:1	160	0.964
3	FLEX(a)	**3**,5,6,10	1:1:1:3	15	0.960
	BATCH(a)	**3,9**	1:2	170	1.083
4	FLEX(a)	**1**,3,5,6	2:1:1:1	20	1.056
	(b)	1,3,5	3:1:1	20	1.102
5	FLEX(a)	1,3,**9**	3:1:1	25	1.377
6	FLEX(a)	3,**4**,9	1:1:1	170	1.588
	(b)	4,9	2:1	160	1.023

c. PROBLEM 3

Run	Approach	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
1	FLEX(a)	**2,5,6,8,10**	2:1:2:1:1	0	3.583
	(b)	2,5,8,10	1:2:2:1	10	2.090
	(c)	2,5,10	3:2:1	20	1.600
	BATCH(a)	**2,5,6,8,10**	2:1:2:1:1	0	3.583
	(b)	2,5,8,10	1:2:2:1	10	2.090
	(c)	2,5,10	3:2:1	20	1.585
	(d)	5,10	1:4	65	1.312
2	FLEX(a)	**1,5,9,10**	1:1:2:2	10	2.574
	BATCH(a)	**1,4,7**	3:1:1	15	1.534
	(b)	1,4	3:2	25	1.227
3	FLEX(a)	1,4,9,10	1:1:1:3	0	1.781
	(b)	1,4,9	3:1:1	15	1.029
	BATCH(a)	**3,9**	1:2	170	1.083
4	FLEX(a)	1,4,**7**	3:1:1	15	1.343
	(b)	4,7	2:1	160	0.964
5	FLEX(a)	3,4,7	1:1:1	170	1.037
	(b)	3,4	1:1	180	1.341

0 indicates the new part types selected to be machined simultaneously over the upcoming time period.

(1) FLEX refers to the suggested flexible approach.

(2) BATCH refers to the batching approach.

(3) specifies the limit of four fixtures of each type.

(4) specifies no fixture limitations.

(5) Unbalancing rule specifies that $W_{mill}=80$, $W_{drill}=105$, and $W_{vtl}=105$.

last run of Problem 5 (the ending conditions) deleted, the flexible approach provides better system performance. See the parenthetical values of Table XXII.

(3) When there are no required fixture limitations, the flexible approach requires many fewer dedicated fixtures than batching. This is because when all requirements of the selected part types in a particular batch except for one part type are completed, batching has only the remnants of that single part type having remaining requirements to process. These few remaining requirements then require additional fixtures for that part type to be finished.

(4) The utilizations decrease quicker with the number of runs in Problems 2, 3, 5, and 6 than in Problems 1 and 4. This is because the workloads are distributed more to the pooled drills and VTLs in Problems 1 and 4. This allows the optimal objective function value for Problems 1 and 4 for unbalancing to be maintained better for each run.

TABLE XVII.

Integer Optimum Solutions for the Objectives of Unbalancing Workloads When Eight Pallets are in the System.

a. PROBLEM 4

Run	Rule	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
1	FLEX(a)(1)	**3,8,9,10**	1:1:2:3	2	16.873
	BATCH(a)(2)	**3,8,9,10**	1:1:2:3	2	16.873
	(b)	8,9,10	3:3:2	15	1.700
	(c)	9,10	2:4	58	1.213
2	FLEX(a)	2,8,9,10,12	1:1:1:3:1	6	10.270
	BATCH(a)	**2,5,6,11**	1:2:1:2	3	6.194
	(b)	2,6,11	1:2:3	34	1.986
	(c)	2,11	3:2	42	1.062
3	FLEX(a)	2,5,9,12	2:1:3:1	3	5.328
	BATCH(a)	**1,4**	3:2	15	1.557
4	FLEX(a)	2,5,**11**,12	1:1:2:2	4	1.791
	BATCH(a-1)(3)	**7,12**	1:4	85	1.033
	BATCH(a-2)(4)	**12**	7	56	1.156
5	FLEX(a)	**1,5,6**,11	1:1:3:1	4	3.406
	BATCH(a-2)	**7**	3	127	0.996
6	FLEX(a)	1,4,5,11	1:2:1:2	15	2.073
7	FLEX(a)	1,5,7.11	1:1:1:2	24	1.182
	(b)	1,7,11	1:2:2	21	1.454
	(c)	1,11	2:2	44	1.046

b. PROBLEM 5

Run	Rule	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
1	FLEX(a)	**3,8,9,10**	1:1:2:3	2	16.873
	BATCH(a)	**3,8,9,10**	1:1:2:3	2	16.873
	(b)	3,8,9	1:2:4	51	1.692
	(c)	3,8	2:1	165	1.087
2	FLEX(a)	**1**,3,8,9	1:1:1:4	6	3.282
	(b)	1,3,8	3:1:1	20	2.468
	(c)	3,8	2:1	164	1.049
	BATCH(a)	**2,5,6,11**	1:2:1:2	3	6.194
	(b)	2,5,6	3:3:1	43	1.667
	(c)	2,6	2:4	68	1.063
3	FLEX(a)	8,**11,12**	1:3:2	8	2.423
	(b)	8,11	2:4	20	1.065
	BATCH(a)	**1,4**	3:2	15	1.557
4	FLEX(a)	**2,5,6**,11	1:2:1:2	3	2.553
	(b)	2,5,6	3:3:1	43	1.643

Run	Rule	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
	(c)	5,6	3:4	46	1.255
	(d-2)	6	7	63	0.969
	BATCH(a-1)	**7,12**	1:4	85	1.033
	(a-2)	**12**	7	56	1.156
5	FLEX(a)	6,**7**	4:1	89	1.001
	BATCH(a-2)	**7**	3	127	0.966
6	FLEX(a)	4,7	1:2	135	0.989

c. PROBLEM 6

Run	Rule	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
1	FLEX(a)	**3,8,9,10**	1:1:2:3	2	16.873
	BATCH(a)	**3,8,9,10**	1:1:2:3	2	16.873
	(b)	3,8,9	1:2:4	51	1.692
	(c)	3,8	2:1	165	1.087
2	FLEX(a)	**1**,3,8,9	1:1:1:4	6	3.282
	(b)	1,3,8	3:1:1	20	2.468
	BATCH(a)	**2,5,6,11**	1:2:1:2	3	6.194
	(b-1)	2,5,6	4:1:1	61	1.600
	(b-2)	2,5,6	1:1:5	55	1.300
	(c)	2,6	2:4	68	1.063
3	FLEX(a)	1,**6,12**	2:3:1	5	4.550
	BATCH(a)	**1,4**	3:2	15	1.557
4	FLEX(a)	**2,5**,6,**11**,12	1:1:1:2:1	9	2.013
	(b)	2,5,6,11	1:2:1:2	3	1.504
	(c)	2,5,6	3:3:1	43	1.155
	(d)	2,5	4:2	56	1.017
	BATCH(a-1)	**7,12**	1:4	85	1.033
	BATCH(a-2)	**12**	7	56	1.156
5	FLEX(a)	2,**7**	4:1	85	1.387
	BATCH(a-2)	**7**	3	127	0.966
6	FLEX(a)	4,7	1:2	135	0.989

0 indicates the new part types selected to be machined simultaneously over the upcoming time period.
(1) FLEX refers to the suggested flexible approach.
(2) BATCH refers to the batching approach.
(3) specifies the limit of four fixtures of each type.
(4) specifies no fixture limitations.
(5) Unbalancing rule specifies that $W_{mill}=84$, $W_{drill}=104$, and $W_{vtl}=104$.

(5) In Problem 3, the system utilizations for both of the flexible and batching approaches are slightly less when there are no fixture limitations than when there is

TABLE XVIII.

Simulation Results After the Completion of All Production Requirements of All Ten Part Types for Problem 1.

Comparison	Four Fixtures		No Limitations	
	FLEX	BATCH	FLEX	BATCH
Makespan (minutes)	**7054**	7855	**7044**	7850
Mill Utilization	**.927**	.800	**.948**	.920
Processing Utilization	**.734**	.658	**.734**	.659
Transportation Utilization	.072	.053	.072	.063
Blocking Utilization	.121	.089	.142	.198
Drill Utilization	**.916**	.824	**.918**	.826
Processing Utilization	**.886**	.795	**.887**	.796
Transportation Utilization	.030	.026	.030	.028
Blocking Utilization	.000	.003	.001	.002
VTL Utilization	**.887**	.805	**.888**	.853
Processing Utilization	**.847**	.760	**.848**	.761
Transportation Utilization	.040	.036	.040	.041
Blocking Utilization	.000	.009	.000	.051
System Utilization	**.840**	.754	**.841**	.755
Average Buffer Utilization	.340	.324	.359	.376
Cart Utilization	.060	.050	.059	.055
Number of Dedicated Fixtures	30	31	35	47
CPU Time (seconds)	3.182	2.237	2.325	2.165

the limit of four fixtures of each type. This is because there is more blocking. (See Table XX.)

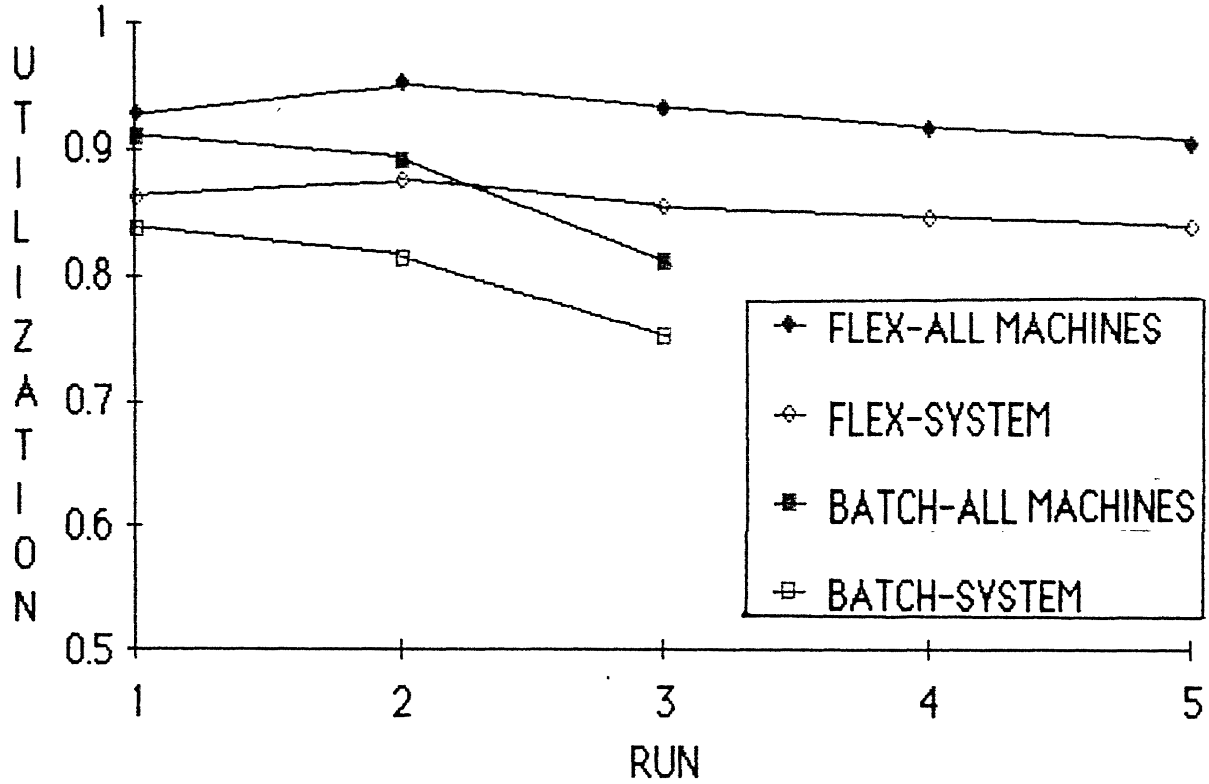
(6) In Problems 4, 5, and 6, the makespans for batching are longer when there are no fixture limitations than when there is the limit of four fixtures of each type. This is also because there is more blocking.

(7) In all Figures, the decreasing slopes on the cumulative utilizations of the batching approach are steeper than those of the flexible approach. This means that the use of the flexible approach enables the system to be utilized more constantly to finish all requirements of all part types.

FIGURE 10.

Cumulative Utilizations of the Flexible and Batching Approaches for Problem 1.

a. The Number of Fixtures of Each Type is Limited to be Four.



b. No Fixture Limitations.

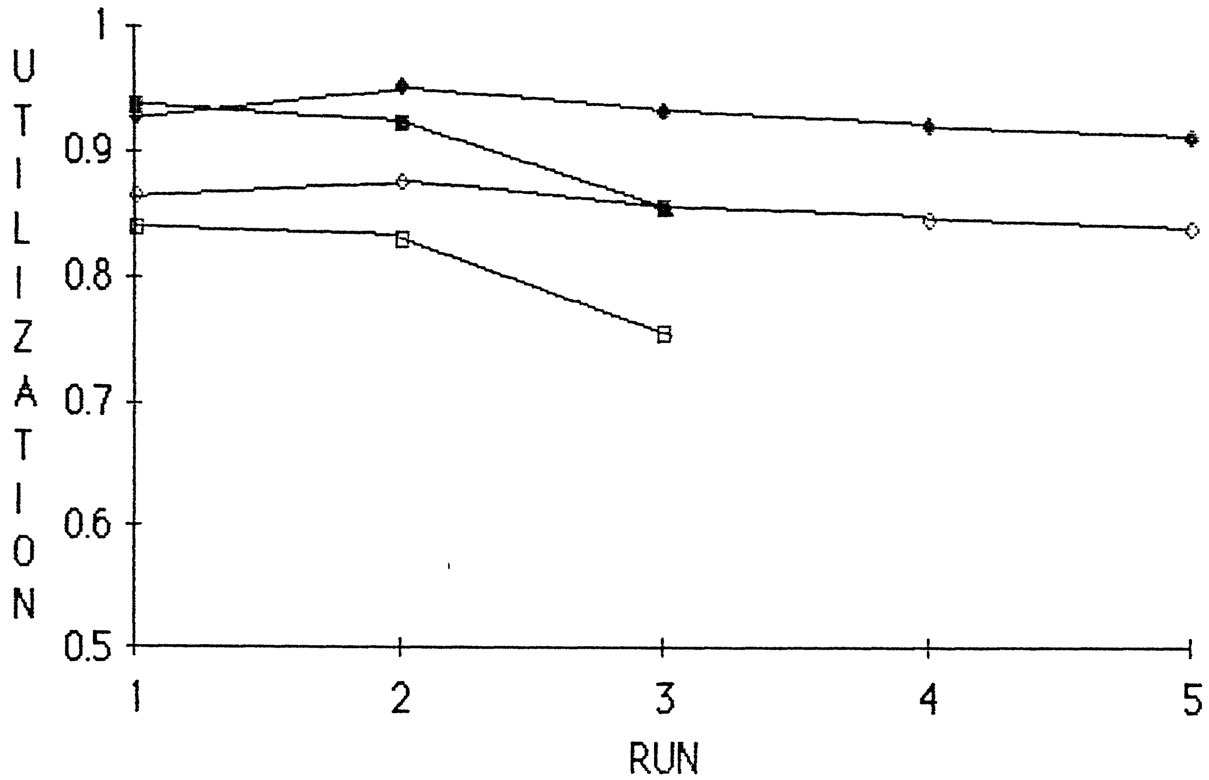


TABLE XIX.

Simulation Results After the Completion of All Production Requirements of All Ten Part Types for Problem 2.

Comparison	Four Fixtures		No Limitations	
	FLEX	BATCH	FLEX	BATCH
Makespan (minutes)	**8090**	8344	**8090**	8340
Mill Utilization	**.921**	.859	**.932**	.940
Processing Utilization	**.754**	.731	**.754**	.731
Transportation Utilization	.059	.052	.060	.055
Blocking Utilization	.108	.076	.118	.154
Drill Utilization	**.743**	.722	**.743**	.723
Processing Utilization	**.716**	.695	**.716**	.695
Transportation Utilization	.027	.025	.027	.026
Blocking Utilization	.000	.002	.000	.002
VTL Utilization	**.800**	.741	**.839**	.829
Processing Utilization	**.716**	.695	**.716**	.695
Transportation Utilization	.038	.035	.038	.038
Blocking Utilization	.046	.011	.085	.096
System Utilization	**.724**	.702	**.724**	.702
Average Buffer Utilization	.271	.289	.288	.318
Cart Utilization	.052	.048	.052	.050
Number of Dedicated Fixtures	31	33	40	53
CPU Time (seconds)	2.914	2.390	2.956	2.235

Therefore, it can be seen in Figures 10 to 15 that the flexible approach increases overall system utilization, at least in the situations examined to date. Further studies are required, however.

§4.3. Different Simulated Settings

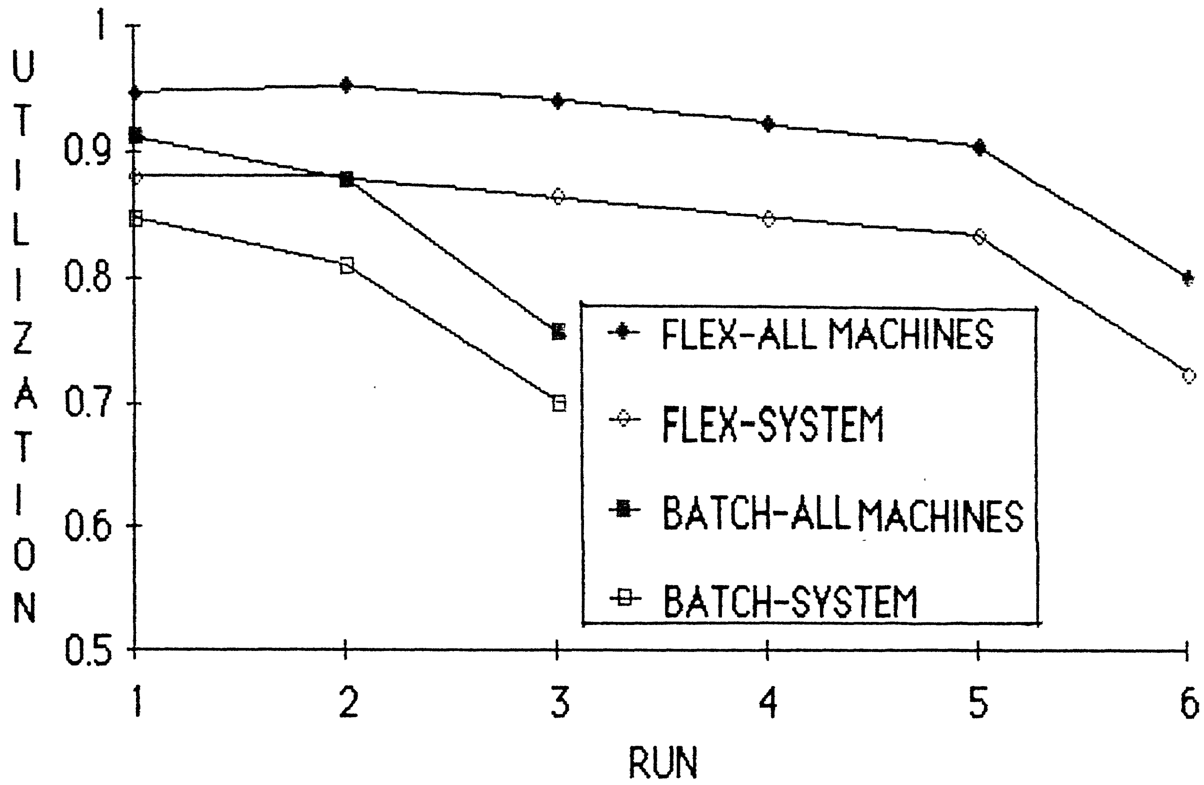
In this section, the simulations are reported that vary both the number of carts and the travel times in the system. These use the unbalanced part mix ratios for Problem 4. This study was performed in order to investigate the effects of both having cart restrictions and different travel times on system performances.

The number of carts in the system is varied as two, three, four, and five. Two dif-

FIGURE 11.

Cumulative Utilizations of the Flexible and Batching Approaches for Problem 2.

a. The Number of Fixtures of Each Type is Limited to be Four.



b. No Fixture Limitations.

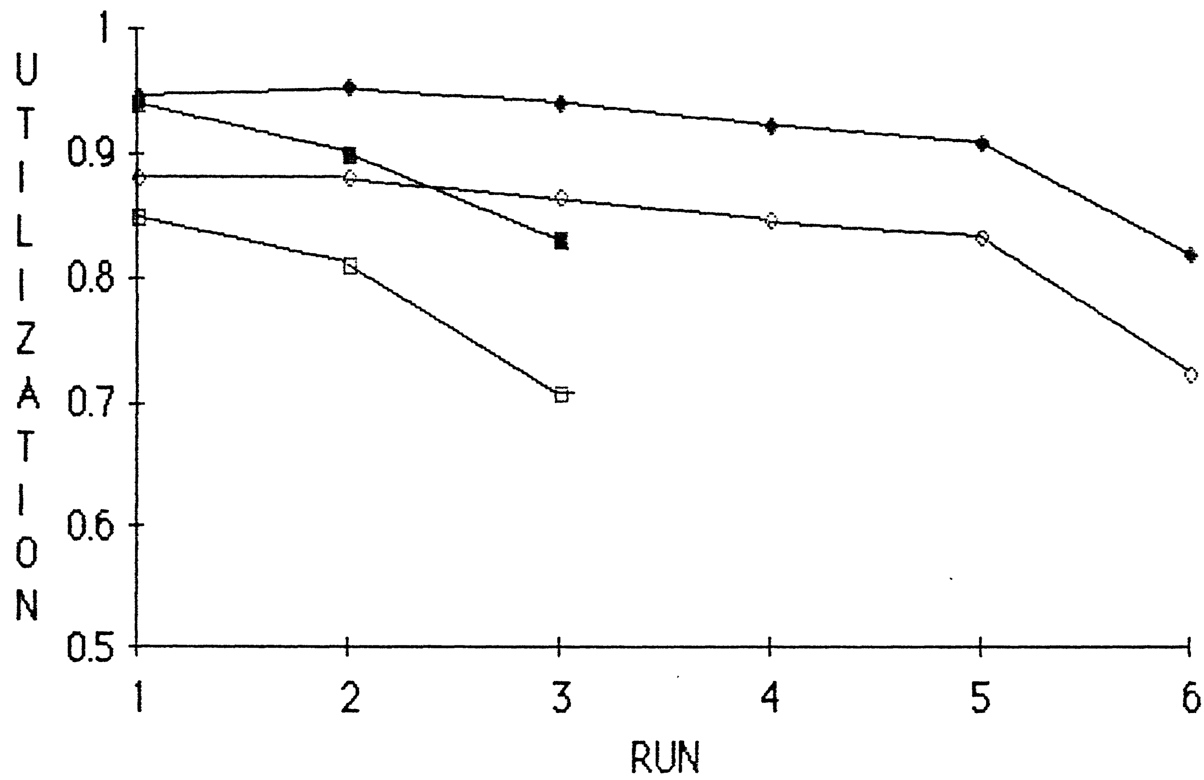


TABLE XX.

Simulation Results After the Completion of All Production Requirements of All Ten Part Types for Problem 3.

Comparison	Four Fixtures		No Limitations	
	FLEX	BATCH	FLEX	BATCH
Makespan (minute)	**7338**	7490	**7350**	7506
Mill Utilization	**.925**	.893	.941	**.962**
Processing Utilization	**.752**	.737	**.751**	.736
Transportation Utilization	.057	.052	.057	.059
Blocking Utilization	.116	.104	.133	.167
Drill Utilization	**.807**	.789	**.806**	.789
Processing Utilization	**.780**	.764	**.778**	.762
Transportation Utilization	.026	.025	.027	.027
Blocking Utilization	.001	.000	.001	.000
VTL Utilization	**.842**	.801	.857	**.859**
Processing Utilization	**.769**	.754	**.768**	.752
Transportation Utilization	.036	.035	.036	.038
Blocking Utilization	.037	.012	.052	.069
System Utilization	**.770**	.755	**.769**	.753
Average Buffer Utilization	.325	.297	.338	.334
Cart Utilization	.052	.049	.053	.053
Number of Dedicated Fixtures	35	34	42	45
CPU Time (seconds)	2.542	2.129	2.946	2.240

ferent travel times between all links are considered: one and two minutes. The simulation results are provided in Table XXIV, from which the following observations can be made.

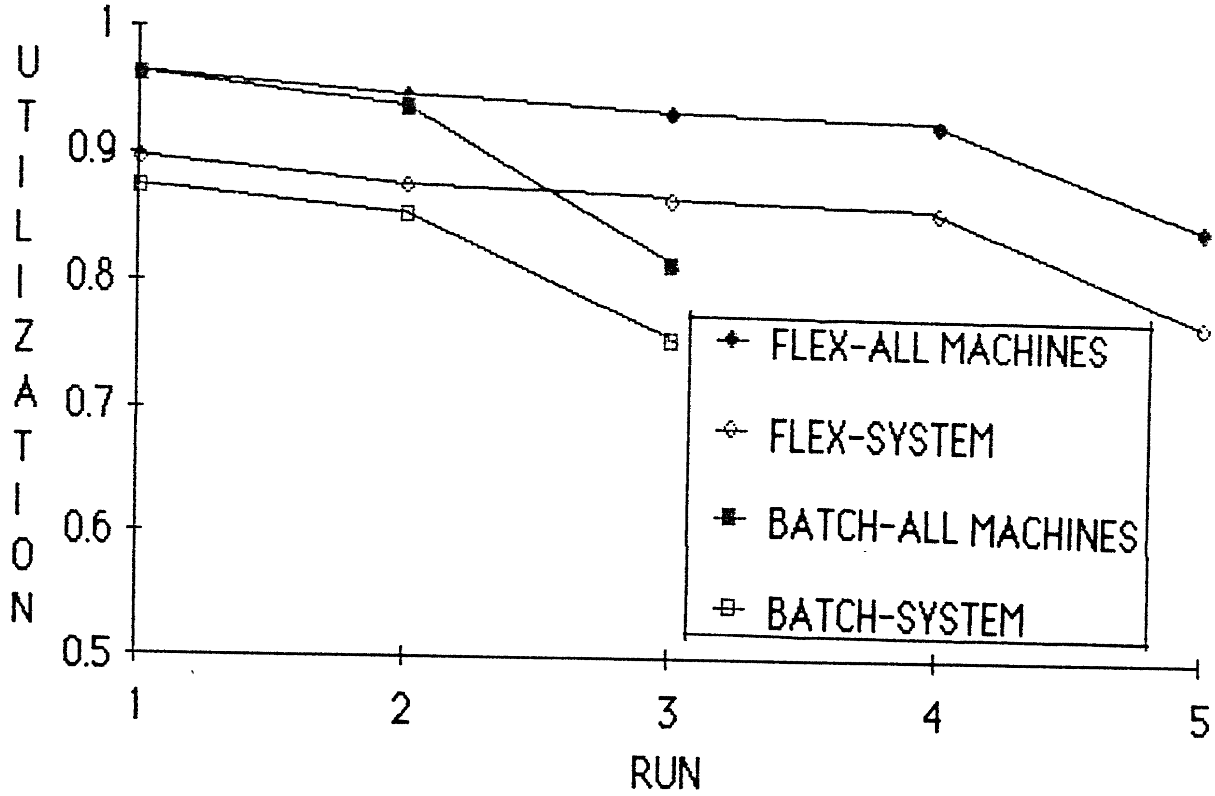
(1) Decreasing the number of carts results in significantly lower system utilization. Also, makespan increases.

(2) Increasing the number of carts leads to lower machine utilizations for the mill and VTLs, when there is a limit of four fixtures of each type. However, processing utilizations increase. This is because the amount of time spent in transportation and blocking decreases.

(3) The increase in travel times, from one to two minutes between all links, leads to longer makespan as well as increased cart utilization.

FIGURE 12.
Cumulative Utilizations of the Flexible and Batching Approaches for Problem 3.

a. The Number of Fixtures of Each Type is Limited to be Four.



b. No Fixture Limitations.

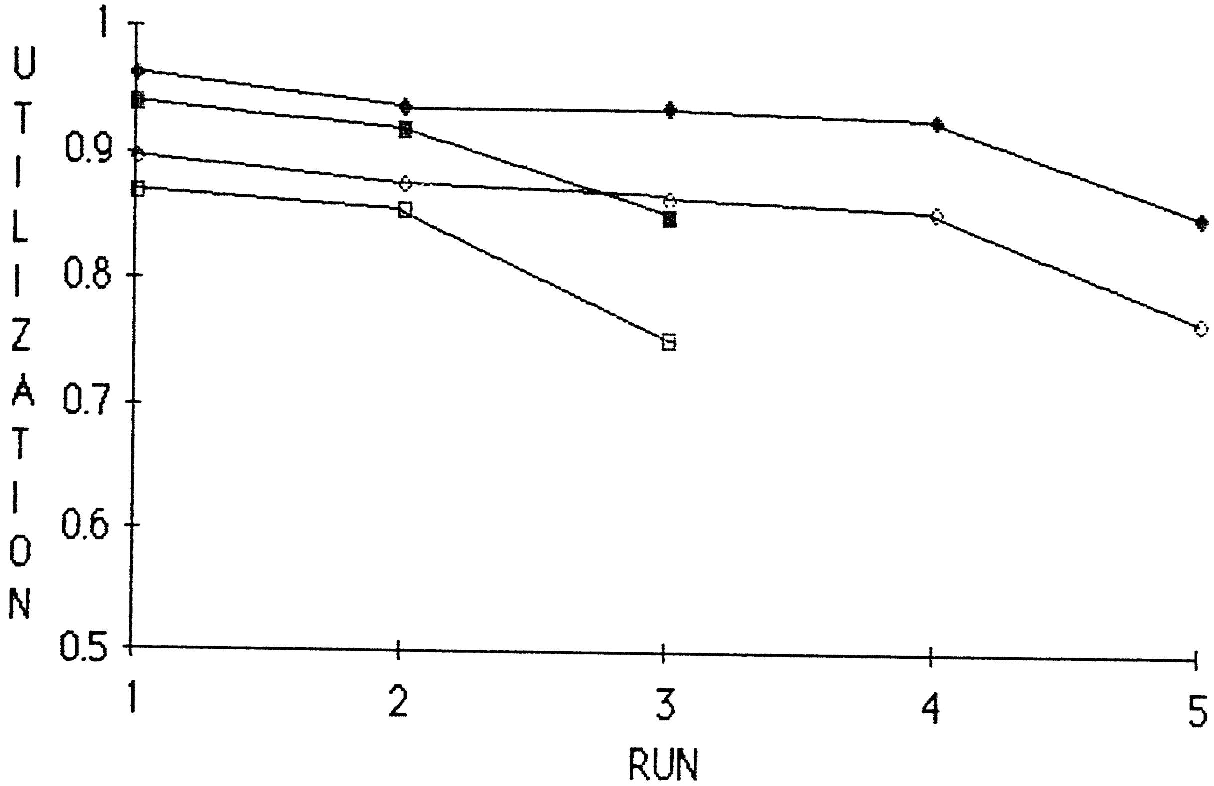


TABLE XXI.

Simulation Results After the Completion of All Production Requirements of All Twelve Part Types for Problem 4.

Comparison	Four Fixtures		No Limitations	
	FLEX	BATCH	FLEX	BATCH
Makespan (minutes)	**6486**	6678	**6476**	6689
Mill Utilization	**.892**	.826	.901	**.918**
Processing Utilization	**.683**	.663	**.684**	.662
Transportation Utilization	.076	.064	.076	.070
Blocking Utilization	.133	.099	.141	.186
Drill Utilization	**.901**	.859	**.902**	.868
Processing Utilization	**.854**	.829	**.855**	.828
Transportation Utilization	.029	.029	.030	.030
Blocking Utilization	.018	.001	.017	.010
VTL Utilization	**.916**	.890	**.917**	.902
Processing Utilization	**.878**	.852	**.879**	.851
Transportation Utilization	.038	.037	.038	.039
Blocking Utilization	.000	.001	.000	.012
System Utilization	**.829**	.805	**.830**	.804
Average Buffer Utilization	.432	.249	.442	.364
Cart Utilization	.060	.054	.060	.057
Number of Dedicated Fixtures	42	43	50	72
CPU Time (seconds)	1.798	1.542	1.733	1.543

(4) The cart and buffer utilizations are higher when there is no fixture limitation than when the number of fixtures of each type is limited to be four.

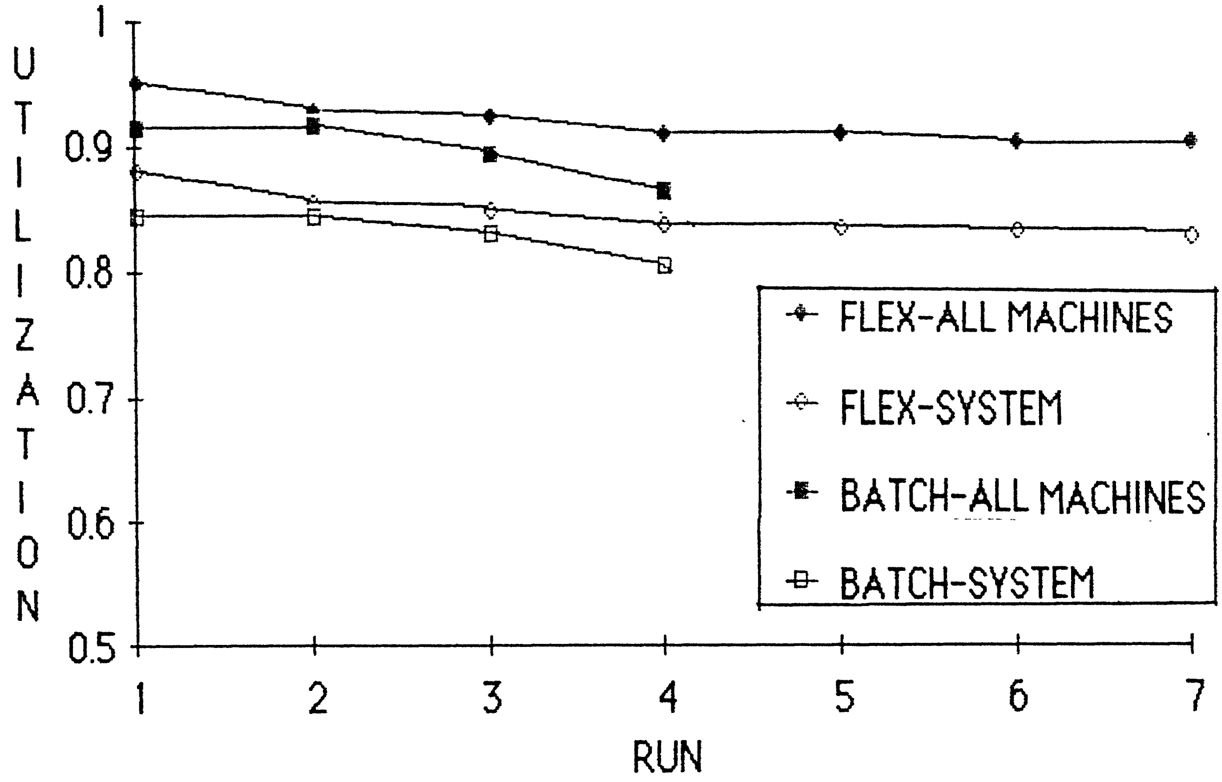
(5) Having no limitation on the number of fixtures of each type (except for the case of five carts in the system) does not lead to either a better makespan or a better system utilization when the travel time between all links is two minute.

(6) The total numbers of dedicated fixtures that are required for the different travel times and different numbers of carts in the system are similar.

(7) Increasing the number of carts results in smaller amount of time spent in blocking for the drills and VTLs, but blocking for the mill is minimized when three carts are utilized.

FIGURE 13.
Cumulative Utilizations of the Flexible and Batching Approaches for Problem 4.

a. The Number of Fixtures of Each Type is Limited to be Four.



b. No Fixture Limitations.

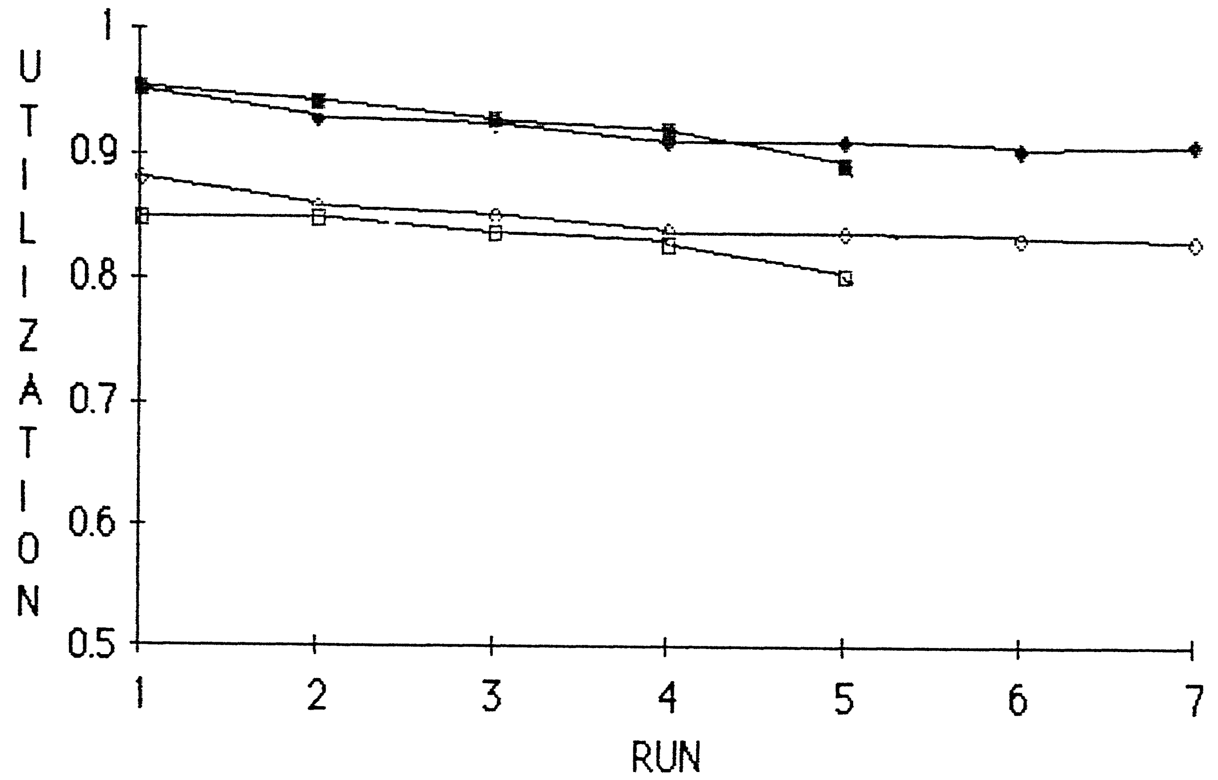


TABLE XXII.

Simulation Results After the Completion of All Production Requirements of All Twelve Part Types for Problem 5.

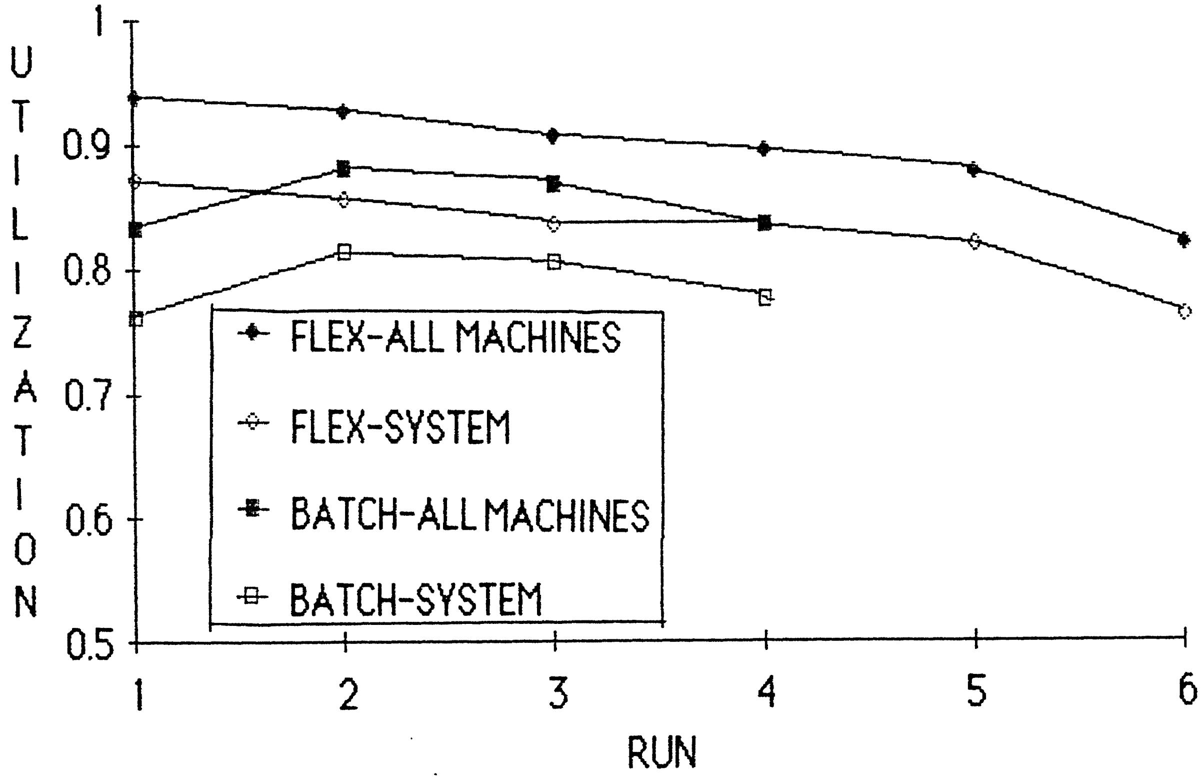
Comparison	Four Fixtures		No Limitations	
	FLEX	BATCH	FLEX	BATCH
Makespan (minute)	6046	**5945**	6037	**5998**
Mill Utilization	.937 (.933)	**.959** (**.965**)	.949 (.947)	**.961** (**.968**)
Processing Utilization	.810 (.790)	**.824** (**.816**)	.811 (.792)	**.817** (**.811**)
Transportation Utilization	.064 (.069)	.064 (.069)	.066 (.071)	.067 (.071)
Blocking Utilization	.063 (.074)	.071 (.080)	.072 (.084)	.077 (.086)
Drill Utilization	.786 (**.865**)	**.798** (.857)	.787 (**.863**)	**.793** (.846)
Processing Utilization	.752 (**.828**)	**.765** (.822)	.754 (**.826**)	**.758** (.810)
Transportation Utilization	.030 (.032)	.032 (.033)	.029 (.032)	.032 (.033)
Blocking Utilization	.004 (.005)	.001 (.002)	.004 (.005)	.003 (.003)
VTL Utilization	.795 (**.859**)	**.809** (.831)	**.841** (**.858**)	.823 (.830)
Processing Utilization	.749 (**.814**)	**.762** (.782)	.751 (**.814**)	**.755** (.778)
Transportation Utilization	.043 (.045)	.041 (.042)	.041 (.044)	.040 (.042)
Blocking Utilization	.003 (.000)	.006 (.007)	.049 (.000)	.028 (.010)
System Utilization	.762 (**.815**)	**.776** (.805)	.764 (**.814**)	**.769** (.797)
Average Buffer Utilization	.222 (.263)	.207 (.223)	.239 (.271)	.222 (.241)
Cart Utilization	.057 (.061)	.057 (.060)	.057 (.061)	.058 (.061)
Number of Dedicated Fixtures	47	48	69	75
CPU Time (seconds)	1.520	1.400	1.545	1.438

( ) indicates cumulative utilizations minus the last run.

One might suggest from this study that the appropriate number of carts for this system might be three. This is because the largest marginal improvement in system utilization is attained when three carts are utilized. However, as the number of carts increases to five, system utilization does increase significantly. Even though cart utilization is extremely low, the additional production and resultant decrease in transportation time, waiting time, and blocking may make five carts the most desirable choice. An economic evaluation would be required to analyze these trade-offs.

FIGURE 14.
Cumulative Utilizations of the Flexible and Batching Approaches for Problem 5.

a. The Number of Fixtures of Each Type is Limited to be Four.



b. No Fixture Limitations.

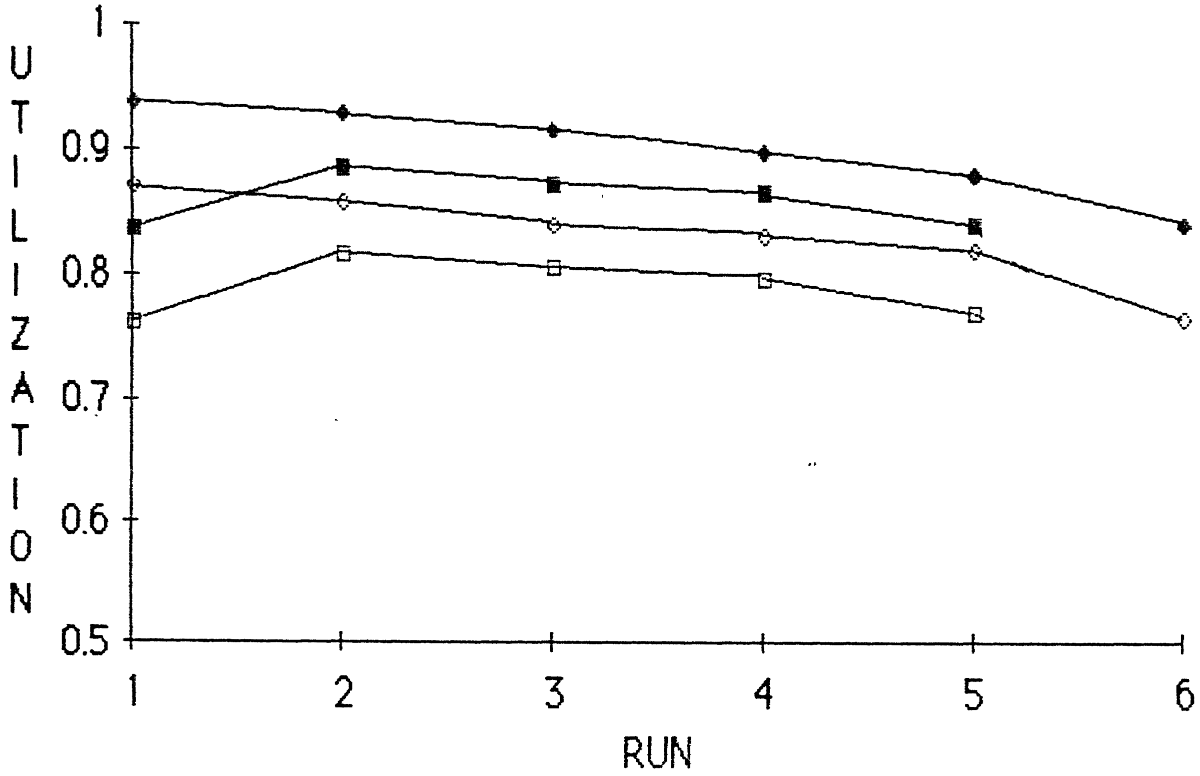


TABLE XXIII.

Simulation Results After the Ccmpletion of All Production Requirements of All Twelve Part Types for Problem 6.

Comparison	Four Fixtures		No Limitations	
	FLEX	BATCH	FLEX	BATCH
Makespan (minutes)	**6317**	6360	**6294**	6399
Mill Utilization	**.920**	.908	.928	**.937**
Processing Utilization	**.785**	.780	**.788**	.775
Transportation Utilization	.064	.063	.066	.066
Blocking Utilization	.071	.065	.074	.096
Drill Utilization	**.810**	.805	**.819**	.803
Processing Utilization	**.781**	.776	**.784**	.771
Transportation Utilization	.027	.029	.028	.029
Blocking Utilization	.002	.000	.007	.003
VTL Utilization	.825	**.826**	**.882**	.857
Processing Utilization	**.787**	.782	**.790**	.777
Transportation Utilization	.038	.038	.038	.037
Blocking Utilization	.000	.006	.054	.043
System Utilization	**.784**	.779	**.787**	.774
Average Buffer Utilization	.257	.204	.297	.266
Cart Utilization	.055	.054	.056	.055
Number of Dedicated Fixtures	41	47	57	74
CPU Time (seconds)	1.588	1.345	1.585	1.594

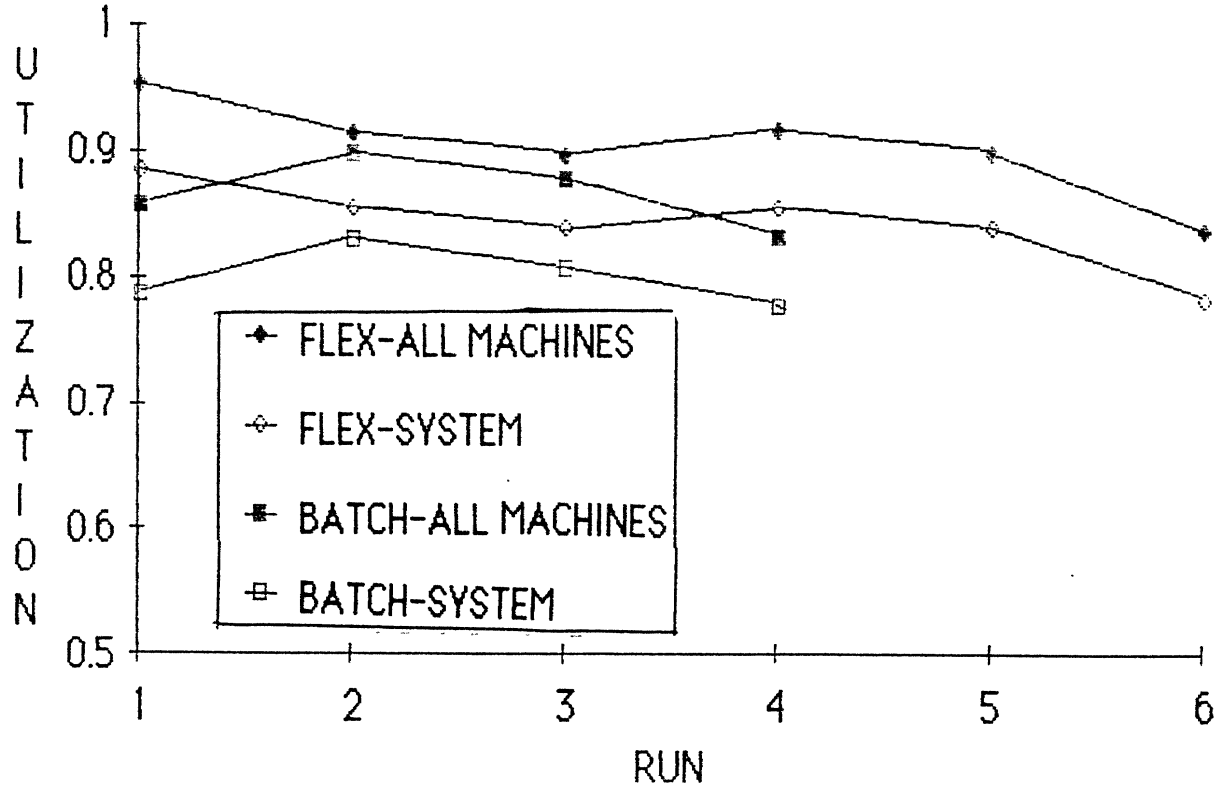
§5. *SUMMARY AND CONCLUSIONS*

This paper demonstrates how to implement a flexible approach to short-term FMS production planning. Also, this paper shows how existing decision procedures regarding the determination of the relative production ratios of the part types ordered to be produced on an FMS contributes also to selecting the part mix to be machined simultaneously in an FMS that manufactures relatively independent part types. This paper also demonstrates how these same production ratios can be useful in determining a part input sequence.

For the types of systems that machine independent part types with varying numbers of production requirements, the operating objectives of balancing or unbalancing

FIGURE 15.
Cumulative Utilizations of the Flexible and Batching Approaches for Problem 6.

a. The Number of Fixtures of Each Type is Limited to be Four.



b. No Fixture Limitations.

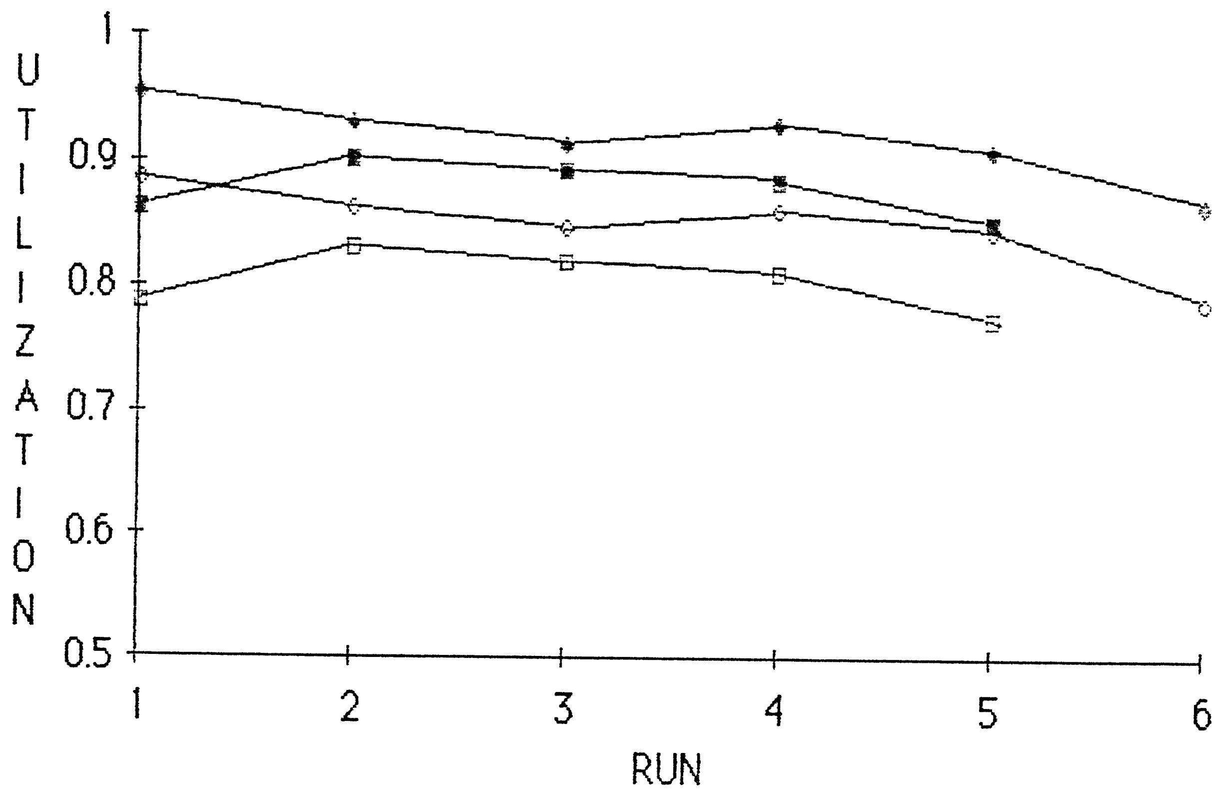


TABLE XXIV.

Simulation Results Varying Both the Number of Carts and Travel Times for Problem 4.

Comparison (Four Fixtures)	2 Carts		3 Carts		4 Carts		5 Carts	
	T=1 [1]	T=2 [2]	T=1	T=2	T=1	T=2	T=1	T=2
Makespan	8140	10191	7004	7812	6652	7091	6486	6816
Mill Utilization	.904	.916	.896	.903	.896	.897	.892	.893
Processing Utilization	.544	.434	.632	.567	.666	.624	.683	.650
Transportation Utilization	.246	.380	.172	.291	.116	.204	.076	.158
Blocking Utilization	.114	.102	.092	.045	.114	.069	.133	.085
Drill Utilization	.909	.909	.886	.872	.897	.881	.901	.890
Processing Utilization	.680	.543	.790	.709	.832	.781	.854	.812
Transportation Utilization	.090	.150	.067	.122	.045	.083	.029	.063
Blocking Utilization	.139	.216	.029	.041	.020	.017	.018	.015
VTL Utilization	.944	.947	.934	.940	.919	.916	.916	.915
Processing Utilization	.699	.558	.813	.729	.856	.803	.878	.835
Transportation Utilization	.111	.179	.083	.147	.061	.107	.038	.080
Blocking Utilization	.134	.210	.038	.064	.002	.006	.000	.000
System Utilization	.660	.527	.768	.689	.808	.758	**.829**	**.789**
Average Buffer Utilization	.737	.791	.517	.538	.438	.403	.432	.414
Cart Utilization	.359	.573	.182	.320	.102	.183	.060	.112
Number of Dedicated Fixtures	41	42	42	45	42	43	42	42
CPU Time (seconds)	1.986	1.882	1.928	2.246	1.884	1.945	1.798	2.135

(1) "T= 1" means that the travel time between all links is one minute.
(2) "T=2" means that the travel time between all links is two minutes.

TABLE XXIV (CONTINUED).

Simulation Results Varying Both the Number of Carts and Travel Times for Problem 4.

Comparison (No Limitations)	2 Carts		3 Carts		4 Carts		5 Carts	
	T=1[(1)]	T=2[(2)]	T=1	T=2	T=1	T=2	T=1	T=2
Makespan	8206	10322	6994	7855	6650	7100	6476	6812
Mill Utilization	.911	.924	.905	.909	.905	.902	.901	.902
Processing Utilization	.539	.429	.633	.564	.666	.624	.684	.650
Transportation Utilization	.250	.390	.173	.295	.117	.202	.076	.159
Blocking Utilization	.122	.105	.099	.050	.122	.076	.141	.093
Drill Utilization	.912	.912	.886	.871	.898	.879	.902	.891
Processing Utilization	.675	.536	.792	.705	.833	.780	.855	.813
Transportation Utilization	.092	.151	.064	.122	.045	.082	.030	.063
Blocking Utilization	.145	.225	.030	.044	.020	.017	.017	.015
VTL Utilization	.946	.949	.937	.940	.921	.914	.917	.916
Processing Utilization	.694	.551	.814	.725	.856	.802	.879	.836
Transportation Utilization	.113	.177	.084	.150	.062	.106	.038	.080
Blocking Utilization	.139	.221	.039	.065	.003	.006	.000	.000
System Utilization	.655	.521	.769	.685	.809	.758	**.830**	**.790**
Average Buffer Utilization	.759	.820	.544	.558	.450	.412	.442	.425
Cart Utilization	.364	.579	.182	.323	.103	.183	.060	.123
Number of Dedicated Fixtures	48	50	50	49	50	51	50	51
CPU Time (seconds)	1.916	1.963	1.880	1.960	1.839	2.217	1.733	1.771

(1) "T=1" means that the travel time between all links is one minute.
(2) "T=2" means that the travel time between all links is two minutes.

machine workloads are applied to select part types and determine aggregate production ratios. Those part types with near zero ratio values in the optimal solutions to Problem **(P1)** are not selected to be in the part mix to be machined together over the immediate (and flexible) time period.

Extensive computational results on the suggested solution procedures indicate that the determination of the appropriate mix ratios provides guidelines in selecting part types to be machined together on a dynamic basis. Simulations are performed to compare the flexible and batching approaches. They show that the use of the flexible approach to short-term production planning helps to enable the system to be more highly utilized as well as to be utilized more constantly over a flexible time horizon.

Another research issue investigated here is the appropriateness of unbalancing the workload per machine for realistic systems having groups of pooled machines of unequal sizes. It is demonstrated with simulation studies of FFSs that the overall system utilization is better when unbalancing. It is also observed that balanced part mix ratios conversely leads to unbalanced machine utilizations among machine types pooled unequally. This is in part because the total transportation times are shared by the identical machines of each group. There are more advantages to pooling a job shop type of FMS, where alternative routes are available. Unbalancing needs to be investigated in these situations.

In order to maximize system utilization or production rate, the appropriate number of pallets in the system should be examined for a given system in advance of either unbalancing or balancing. This is because system utilization seems to be sensitive to the number of pallets in the system especially when unbalancing (see Figures 8 and 9). Finally, it can be concluded that for the variety of situations examined here, unbalancing workloads is better than balancing for systems of pooled machines of unequal sizes until the ending conditions are considered.

There are further research needs along these lines. The studies reported here are for a flexible flow line type of system. However, these approaches should be appropriate for more general FMSs, having alternative routes. Similar studies should be done in a job shop environment as well as in a more dynamic situation, for example, when there are often changes in production orders or random machine failures. Implementation of the results here in the more general situations is being developed.

Other constraints, such as tool magazine capacity and due dates, should also be considered when determining the most appropriate part mix. Fortunately, there are many sets of optimal ratios, so that secondary criteria can be considered. Determining the appropriate approach to selecting production ratios is also needed when the demand for part types is dependent and certain relative output ratios are required. Other issues that need to be addressed regarding aggregate production ratios are the interactions of these mix ratios with subsequent FMS planning and operating problems.

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