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A STUDY OF FMS PART TYPE SELECTION APPROACHES FOR SHORT-TERM PRODUCTION PLANNING

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ABSTRACT

This research compares seven approaches from the literature to select part types for simultaneous production over the next time horizon. A flexible approach to both select part types and to determine their mix ratios simultaneously so as to balance aggregate machine workloads is presented. Constraints on tool magazine capacity are considered. Simulation studies are conducted on realistic, detailed models of flexible flow systems (FFSs) configured as pooled machines of equal sizes. The simulated settings are constructed to evaluate the impact of such factors as blocking, transportation, buffer utilizations, and fixture requirements and limitations of various types.

One of the goals of this study is to encourage industry to relax, for those FMS types for which the procedure is appropriate, what is essentially an artificial constraint: that tool changing be isolated in time, to a period between batches. For other types of FMSs, batching may be appropriate.

The results indicate that using the flexible approach enables the system to be more highly utilized. It is also observed that the batching approaches tend to require more fixtures of each type than the flexible. The system utilizations for the batching approaches seem to be sensitive to restrictions on the number of fixtures of each type. Further research needs are also discussed.

§1. INTRODUCTION

The short-term production planning function for setting up a flexible manufacturing system (FMS) prior to production should be performed so as to interact well with the operation of the system over an upcoming time horizon. *FMS production planning problems* are defined as system set-up decisions that have to be made *before* an FMS can begin to produce part types. The solutions to these planning problems result in all cutting tools required for each operation of the selected part types to be loaded into the appropriate machines' limited capacity tool magazines. Then the parts have to be scheduled through the system. Production planning should be developed to set up an FMS for subsequent efficient production.

There have been some research studies to date that address the FMS part type selection problem. This problem is to select a subset of the part types that have been ordered to be produced on an FMS, often with due dates and/or production requirements, for simultaneous machining over some upcoming period of time. This dynamic part type selection problem of short-term planning is not to be confused with the problem of selecting the part types early in the design phase that an FMS will be able to produce. Some algorithms to solve this static, design part type selection problem can be found in Kusiak [1985] and Whitney and Suri [1985], for example.

During FMS operation, planning for system set-up has to be performed somewhat periodically, for example, when the production requirements are completed for some part type(s), when the part mix is changed, when some production order needs an expedited entry into the system, or when a machine breaks down. The solution approaches to the part type selection problem can be broadly classified.

A *Flexible Approach* to select part types can be implemented as follows: When the production requirements of some part type(s) are finished, space in the tool magazine is freed up. Perhaps some new part type(s) can be introduced into the system for immediate and simultaneous processing, if this input can help the system be more highly utilized. (See Stecke and Kim [1986a].)

A *Batching Approach* partitions the part types into separate sets, called batches, and distinct machining horizons. The selected part types in a particular batch are produced continuously until all of the production requirements are completed. Then, the system set-up time consists of unloading all of the cutting tools that are no longer required by the current batch and reloading all new tools to perform the operations of all part types of the next scheduled batch. (See Whitney and Gaul [1984], Hwang [1986], and Rajagopalan [1986].)

To date, research on batching approaches to select part types has been either optimal-seeking or heuristic:

I) *Integer Programming Models*: The objective function of Hwang [1986] aims to minimize the number of tool changeovers (i.e., the number of batches). Since this part type selection formulation is intractable, the suggested approach attempts to maximize the number of part types in each batch as a reasonable greedy approximation. The formulation to minimize the frequency of tool changeovers seems to postpone selecting the part types with the most number of required cutting tools as late as possible. In a related study, Rajagopalan [1986] partitions the part types having production requirements into batches. A formulation to minimize total makespan is developed under the assumption of a constant system changeover time. Such an optimization formulation is NP-complete. Hence, several heuristics are suggested.

II) *Heuristic Methods*: Whitney and Gaul [1984] also partition part types into separate batches and distinct machining horizons. The goal is to minimize the number of batches and then balance workloads within each batch sequentially. The approach is iterative and uses estimated performance indices. The functional values of these indices are not obvious and depend upon the subjective judgement of a user in order to be implemented in a realistic system. Rajagopalan [1986] also suggests heuristic rules using concepts of m-dimensional bin-packing for selecting part types.

However, no extensive studies to compare these batching approaches on a realistic system have been performed to date. There are at least three questions concerning the implementation of the existing approaches to select part types in FMSs. 1) For a particular type of FMS, which approach tends to perform better, flexible or batching? 2) Which batching approach performs better? 3) Can a batching approach be implemented using a flexible approach? The first issue has been dealt with partly in Stecke and Kim [1986a]. The first and second questions are addressed here. The third question is a subject for future research.

A main issue in comparing flexible and batching approaches to FMS part type selection is *tool changeover time*. Suppose, for example, that a typical FMS consists of eight to ten machine tools, each having a tool magazine capacity of sixty slots. Implementing a batching approach usually requires taking out *all* cutting tools in all magazines and replacing these with a new set of cutting tools. (This is a total and major tool changeover.) Each individual cutting tool interchange can take about one minute. Changing all tools in between batches can take almost a shift or more.

On the other hand, the flexible approach, although requiring more frequent tool changes, the *time* required for each *tool changeover* is *greatly* reduced. When a part type finishes production, *only those affected tools* need to be changed. (This can be called a partial or minor tool changeover.) Also, since the remaining part types are still being processed, as those few tools affected are being changed in a particular tool magazine, the *remaining machine tools can continue to cut metal.* In addition, if a current operation using a particular cutting tool is to take an hour or more to complete, *perhaps even some tools in that operating machine can be changed during the cutting.* (This is not always possible. Sometimes tools cannot be changed during cutting because of safety reasons or OSHA regulations. This is possible in some systems, though.)

It can be seen that although the total time taken to change all tools may be the *same* for both the flexible and batching approaches, the lost, *idle time* due to tool changeover will be considerably less for the flexible approach.

Another consideration and savings are due to *labor.* Most of the time, there will be a constant number of set-up people on the system. The flexible approach to system set-up can be seen to *smooth* the use of these people, rather than requiring all of their attention for a large and focused period of time. Cutting tools wear and break randomly, so operators have to be present at all times anyway. The flexible approach can allow for the changing of tools for a part type *when* the worn and broken tools are to be changed.

Many of these advantages to implementing a more flexible approach may be intuitive. However, most of the researchers as well as FMS users have followed a batching approach and there are reasons for this. The *advantages* of *batching* over the flexible approach are that the *frequency* of tool changeovers is less for batching. In addition, batching may be *easier to implement* in a real system. (The necessary changeover functions are obvious if all tools have to be unloaded. If only a few are removed, it may not be as automatic (although still easy).)

For the remainder of this paper, the time and labor saving advantages from following the flexible approach are *not* considered. Any further benefits are in addition to those just described.

This paper analyzes the performances of flexible and various batching approaches over time using a simulation of a realistic flexible flow system (FFS) containing pooled machines of equal sizes. For the batching approaches, the *FMS production ratio problem* is solved to determine the mix ratios of the selected part types to maintain workload balance in the system. The determined production ratios are the relative numbers of parts of the selected part types that are to be in the system together over time. These determined mix ratios of the part types selected by the various approaches are analyzed.

The types of systems that are considered here are those that machine *independent* part types, each having particular production requirements. There can be more freedom, and hence benefits, in determining the relative production ratios at which a particular set of part types could be machined together. If the requirements of part types are *dependent,* say perhaps for subsequent assembly, then production ratios and hence bottlenecks are prespecified. (See Stecke [1985].)

The cutting tools required to perform the operations of all part types, and hence tool magazine capacities, are considered here. Duplication of cutting tools shared by several operations is considered, but the possibilities of capacity savings from the overlapping placement of tools in a tool magazine are not modeled here. Due dates are not considered here, since some of the proposed batching approaches do not consider due dates.

This paper is organized as follows. In §2.1, the mathematical programming formulation that selects part types and determines their mix ratios for the flexible approach is presented. §2.2 reviews solution procedures that determine aggregate part mix ratios for balancing and unbalancing workloads using the flexible approach. In §3.1, Hwang's integer formulation to select part types is reviewed. Next, we suggest a different formulation for the same objective of minimizing the number of batches. Also, both Whitney and Gaul's and Rajagopalan's heuristics to select part types are reviewed. §3.2 demonstrates how mix ratios of the part types selected using batching approaches are determined. The FMS scenario that is used for the comparisons is described in §4.1. §4.2 provides computational results on finding mix ratios of the part types selected by the various approaches. These are subsequently input into simulations of FFSs. Simulated settings are described in §5.1. In §5.2, computational results of the simulation studies are analyzed. Conclusions and future research needs are given in §6.

§2. A PART TYPE SELECTION / PRODUCTION RATIO MODEL USING A FLEXIBLE APPROACH

In this section, we show how to both select part types and determine their mix ratios for the objectives of balancing or unbalancing workloads using a suggested *flexible* approach. In §2.1, the mathematical programming formulation that selects part types and determines their mix ratios under constraints on tool magazine capacity is presented. §2.2 reviews a previous solution procedure that determines aggregate part mix ratios for balancing and unbalancing workloads. This procedure is used to also select the part types to be produced next.

§2.1. Integer Formulation

This section presents the formulation to select both part types and part mix ratios. Notation is provided in Table I. Given the types of cutting tools, number of slots occupied by each cutting tool, tool magazine capacity, and aggregate production and processing time

TABLE I.

Notation.

	INDICES	
i	part types,	$i=1,\ldots,N$
j	machines,	$j=1,\ldots,M$
k	machine types,	$k=1,\ldots,K$
c	cutting tool types,	$c=1,\ldots,C$
	INPUT PARAMETERS	
r_i	production requirements for part type i	
p_{ij}	processing time of a part of type i on machine j	
s_k	number of machines of machine type k	
pw_{ik}	average workload required by a part of type i on a machine of type k $=p_{ij}/s_k$	
d_{ck}	number of slots required in a tool magazine (of each machine of type k) for holding cutting tool c	
b_{ick}	$\begin{cases} 1, & \text{if part type } i \text{ requires tool } c \text{ (on a machine of type } k) \\ 0, & \text{otherwise} \end{cases}$	
t_k	capacity of the tool magazine for any machine of type k	
W_k	constant value indicating an aggregate, (un)balanced workload on machine type k	
f_i	maximum number of fixtures dedicated to part type i	
n	total number of pallets in the system	
M	large constant value	
C_{k1}	weight assigned to the potential workload overload (x_{k1})	
C_{k2}	weight assigned to the potential workload underload (x_{k2})	
	DECISION VARIABLES	
a_i	production ratio of part type i	
x_{k1}	load over (un)balanced, W_k, on machine type k	
x_{k2}	load under (un)balanced, W_k, on machine type k	
z_i	$\begin{cases} 1, & \text{if part type } i \text{ is selected in the batch} \\ 0, & \text{otherwise} \end{cases}$	
y_{ck}	$\begin{cases} 1, & \text{if cutting tool } c \text{ is loaded on a machine of type } k \\ 0, & \text{otherwise} \end{cases}$	

requirements of each part type on each machine type, the model to select part types and determine their production ratios is presented as the following integer formulation, Model (M1).

(M1)

Minimize $\sum_k C_{k1} x_{k1} + \sum_k C_{k2} x_{k2}$

subject to

$$\sum_c d_{ck} y_{ck} \leq t_k, \qquad \text{all } k \qquad (1)$$

$$b_{ick} a_i \leq M y_{ck}, \qquad \text{all } c \text{ and } k \qquad (2)$$

$$\sum_i pw_{ik} a_i - x_{k1} + x_{k2} = W_k, \qquad \text{all } k \qquad (3)$$

$$a_i \leq f_i, \qquad \text{all } i \qquad (4)$$

$$a_i \geq 0 \text{ and integer}, \qquad \text{all } i \qquad (5)$$

$$y_{ck} = 0 \text{ or } 1 \qquad \text{all } c \text{ and } k \qquad (6)$$

$$x_{k1}, x_{k2} \geq 0, \qquad \text{all } k \qquad (7)$$

Each operation type can be performed by only one machine type. For simplicity of presentation and notation, this formulation assumes that all of the machines of each machine type are pooled and that each operation is assigned to all machines of the particular machine type that can perform that operation. The cutting tools for that operation are placed in each machine's tool magazine of the correct machine type. This assumption can be easily relaxed.

The objective function can be changed by weighting the overload and underload on each machine type differently to generate alternative balanced solutions. The over- or underload parameter for each machine type can be weighted arbitrarily to result in different sets of *optimal* ratios. The optimal production ratios could result in over- or underloading the average workload on some machine type(s).

Constraint (1) describes the tool magazine capacity on each machine (and hence machine type). The cutting tool assignment is duplicated at each machine of the same machine type. Hence, the tool magazine capacity constraint for a group of machines is identical to the capacity constraint of any single machine in the group. Constraint (2) ensures that if a part type is selected, all of its required cutting tools are loaded in some machine's tool magazine. This constraint also considers tool duplication to ensure that if several operations require some cutting tools in common, those common tools are loaded only once into the appropriate tool magazine(s). Constraint (3) describes the average workload on each machine type (which can be specified to be unbalanced for systems having pooled machines of unequal sizes (see Stecke and Kim [1987a])). The workload parameter, W_k, can be selected arbitrarily. The relative ratios of workloads on machine types are calculated by using the closed queueing network model, CAN-Q, for groups of pooled machines of unequal sizes (see Stecke and Solberg [1985]). We recommend using a small value for W_k. For example, for the problem sets of §4, all W_k are 100, to result in a balanced workload distribution over all machines. This small value for W_k results in single-digit production ratios, which may be desirable for operating purposes. Constraint (4) restricts the maximum ratio values (maximum number of parts of each type) to be maintained in the system. This could be caused by a limitation on the number of fixtures of each type.

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 those selected, with respect to machine utilizations.

Notice that the production requirements for each part type have not yet been considered. These are monitored during system operation.

§2.2. Solution Procedure to Select Part Mix Ratios

In this section, the implementation of the flexible approach using the integer formulation (**M1**) is described. The following algorithm selects the subset of part types to be machined together and determines their aggregate production ratios over some upcoming flexible time period:

PART TYPE SELECTION/ PRODUCTION RATIO ALGORITHM

Step 1. Formulate and solve Model (**M1**) for a particular set of parameters W_k, C_{k1}, C_{k2}.

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

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}

$a_{i_3} \geq 0$, where i_3={part types that can be considered for upcoming production}

Step 4. If all requirements for all part types are completed, **STOP.**

Otherwise, 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 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 tool changeovers.

The maximum ratio value of each part type should not be larger than the remaining requirements. In this case, additional constraints similar to constraint (2) are introduced. At **Step 3**, if the total remaining processing times required by some part types having few remaining requirements are small after the completion of requirements of some other part type(s), it could be more effective to continue production of the remaining part types at updated ratios, rather than considering the introduction of new part types. This saves an unnecessary tool 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 in various situations, either off-line or on-line by considering the ease and time of tool changeovers, the length of shifts, and the timings of the short tool changeovers already required for wearing or worn cutters.

§3. BATCHING APPROACHES

In this section, we present various batching approaches to select part types. The batching approach tries to minimize the frequency of system set-up. In §3.1, four batching approaches are presented, three from the literature and one suggested here. §3.2 reviews how to determine mix ratios of the part types selected by batching.

§3.1. Part Type Selection By Batching

§3.1.1 reviews Hwang's [1986] formulation to select part types for the objective of maximizing the number of part types in a batch. A different integer formulation for the objective of minimizing the number of batches is suggested in §3.1.2. The heuristic method developed by Whitney and Gaul is reviewed in §3.1.3. §3.1.4 reviews Rajagopalan's heuristics.

§3.1.1. Hwang's Integer Formulation

Given the tools required by each operation of each part type, the number of slots occupied by each tool, and tool magazine capacity of each machine (type), Hwang's formulation to select part types is reviewed as Model **(M2)**.

(M2)

$$\text{Maximize} \quad \sum_i z_i$$

$$\text{subject to} \quad \sum_c d_c \, y_c \le t, \qquad (8)$$

$$b_{ic} \, z_i \le y_c, \qquad \text{all i and c} \qquad (9)$$

$$z_i = 0 \text{ or } 1, \qquad \text{all i} \qquad (10)$$

$$y_c = 0 \text{ or } 1, \qquad \text{all c} \qquad (11)$$

Hwang's model **(M2)** considers a system of identical machines, all of the same machine type. However, the extension to the case of multiple machine types is immediate, if each operation can be performed on only one machine type. The objective function maximizes the number of part types in a batch. Constraint **(8)** describes the tool magazine capacity of each machine (and hence machine type). Constraint **(9)** ensures that if a part type is selected, all cutting tools required for all operations of the selected part type are loaded in the tool magazine on each machine of the correct machine type.

This formulation appears to postpone the selection of those part types requiring the larger numbers of tool slots as late as possible, since the objective function maximizes the number of part types in a batch. This leads to a reduced consideration of tool duplication, which can result in an increase in the total number of batches needed to produce all part types. This indicates that Model **(M2)** may not always perform well for the original objective of minimizing the frequency of tool changeovers. In order to eliminate this possibility, the following integer formulation is suggested.

§3.1.2. Our Extension of Hwang's Formulation

To better satisfy Hwang's chosen criterion, we offer the following alternative objective function in Model **(M3)**. The coefficient of each part type in the objective function is the number of tool slots required for all operations of that part type. In contrast to Hwang's Model **(M2)**, this objective function aims to select part types with the *most* number of required tool slots early. This model can reinforce consideration of tool duplication by selecting part types with the largest number of required tool slots (and hence more potential tool overlap can be considered) as early as possible.

(M3)

$$\text{Maximize} \qquad \sum_i \left(\sum_c b_{ic} d_c\right) z_i$$

$$\text{subject to} \qquad (8),\ (9),\ (10),\ \text{and}\ (11).$$

An eight-part type example is introduced in Table II to compare the two models for a single machine problem. As noted in Table II, three batches are required by Model **(M2)** to produce all part types, but only two set-ups for the system are required by Model **(M3)**.

TABLE II.

Comparison of Models **(M2)** and **(M3)** for Part Type Selection for the Objective of Minimizing the Number of Batches.

Part Type	Types of Cutting Tool Required(1)	Results and Comparison
PT1	a	Model **(M2)**
PT2	b	-Batch 1: PT1,2,3,4,5,6
PT3	c	-Batch 2: PT7
PT4	d	-Batch 3: PT8
PT5	a,b	
PT6	c,d	Model **(M3)**
PT7	f,g	-Batch 1: PT2,3,4,6,8
PT8	b,c,d,e	-Batch 2: PT1,5,7

(1) It is assumed that every tool occupies only one slot. Also, the number of slots defining the tool magazine capacity is four. There is one machine.

Model **(M2)** seems to be myopic. Even if the first batch selects more part types, this can lead to a larger than necessary total number of batches to produce all part types. For example, Model **(M2)** misses the opportunity that most of the tools required for part type 8 are shared with the tools required for part types 2, 3, 4, and 6 (see Table II).

On the other hand, Model **(M3)** tends to consider tool duplication to select part types for a batch. For the example of Table II, part type 8, having the largest number of required slots, is selected first in the first batch. Therefore, this batch can also include part types 2, 3, 4, and 6 which share the same tools with part type 8. These models are analyzed more extensively on larger problems and realistic systems in §4.

The extension of Model (M3) to the case of multiple machine types is immediate. In this case, the coefficient of each part type in the objective function is the number of tool slots required for all operations of that part type that is required by the largest *weighted* machine type. The *weight* for each machine type is the current ratio of tool slots required (for the remaining part types that are to be produced) to its tool magazine capacity.

This objective function is now:

$$\text{Maximize} \sum_i \left(\sum_c b_{ic\bar{k}}\, d_{c\bar{k}}\right) z_i .$$

Here, the largest weighted machine type, $\bar{k}$, is such that: $\bar{k} = \text{Max}_k \left(\sum_i \sum_c b_{ick} d_{ck}/t_k\right)$.

§3.1.3. **Whitney and Gaul's Method**

Whitney and Gaul use a program, called BATCHBAL, to select part types, which accounts for tool allocation and capacity as well as workload balancing. The main objective of partitioning part types is to minimize the total makespan to produce all part types. Since this part type selection problem is intractable, they use the following two surrogate criteria, which can be conflicting: First, the number of batches is minimized. Second, the average utilization of all machines is maximized. The second criterion tends to balance workloads.

BATCHBAL is set up as follows: BATCH attempts to minimize the number of batches. As soon as a batch is determined, BAL investigates whether the batch workloads can be assigned to each machine. If any tool constraints are violated, then BATCH tries again with an alteration, such as a reduction in the tool capacity. The input of BATCHBAL requires the types of cutting tools, number of slots occupied by each cutting tool, tool magazine capacity, and aggregate production and processing time requirements of each part type on each machine type. Cutting tool duplication is considered.

The BATCHBAL program is implemented here in two ways: First, the number of batches is attempted to be minimized using only the BATCH option. Second, both BATCH and BAL options are utilized to balance workloads while minimizing the number of batches. The output of the BATCHBAL programs are analyzed in §4.

§3.1.4. **Rajagopalan's Heuristics**

Rajagopalan develops six heuristics of two types to solve the part type selection problem. The first type aims to *minimize the number of system set-ups* and the second type tries to *balance workloads*. For both types, the problem to select part types is considered as an m-dimensional bin packing problem, where 'm' is the number of machines. The number of tool slots required by all operations of a part type on a machine is the size of an item. Stecke and Talbot [1985] suggest bin packing type heuristics for loading FMSs.

In this paper, the following two heuristics, which have been shown by Rajagopalan

[1986] to perform better than his other suggested heuristics, are examined for comparison purposes:

Heuristic I (*RHI*): That part type (from the remaining part types that can be assigned) is selected, which requires the maximum total *weighted* tool slot requirements *over all machines*. Here, the *weight* for each machine is the current ratio of tool slot requirements for all operations of all the remaining part types to tool magazine capacity. (That is, the *weight* for machine j is w_j, where $w_j = \sum_i \sum_c b_{icj} d_{cj} / t_j$. The part type i is selected such that: $i = \mathrm{Max}_i \sum_j w_j (\sum_c b_{icj} d_{cj})$.) This selection procedure is iterated until the slots required for all operations of the selected part types satisfy the tool magazine capacity on all machines.

Heuristic II (*RHII*): That part type is selected (from the remaining part types that can be assigned), which minimizes total differences between the ratios of processing time assigned on the different machines to that on the bottleneck machine (in the current batch of part types) and the ratios of processing time *remaining* on the various machines to that on the bottleneck machine. The processing times of each part type on each machine are weighted by the production requirements. This selection procedure is iterated until the slots required for all operations of the selected part types satisfy the tool magazine capacity on all the machines.

Heuristic I considers the *number of tool slots required by each machine* to help select part types for an operating objective that tries to minimize the *number of major tool changeovers*. Heuristic II considers the *total production and processing time requirements* of all part types on each machine for an operating objective of *balancing workloads*. These are both relevant and useful considerations, for the purpose of efficient machine tool packing. Berrada and Stecke [1986] consider both in the branch and bound code for FMS loading. These two heuristics are investigated for flexible flow systems of pooled machines of equal sizes in §4.

§3.2. Production Ratio Determination

In this section, we show how to determine production ratios of the part types selected by various batching approaches for the objectives of balancing or unbalancing workloads.

Given aggregate production and processing time requirements of each part type on each machine type, the *batching* method for determining production ratios is reviewed as the following integer formulation, Model **(M4)**.

(M4)

$$\text{Minimize} \quad \sum_k C_{k1} x_{k1} + \sum_k C_{k2} x_{k2}$$

subject to

$$a_i \geq 1 \text{ and integer}, \qquad \text{all } i \qquad \textbf{(12)}$$

(3), (4) and (7).

Constraint **(12)** ensures that the part types selected by batching always have positive integer production ratio values.

The batching approach is implemented as follows. Whenever the requirements for a part type in a particular batch are completed, new production ratios are found for the remaining part types that aim to balance machine workloads as optimally as possible. This attempts to implement batching as favorably as possible.

§4. PART TYPE SELECTION EXPERIMENTS

In this section, the results of the seven approaches to part type selection are compared using a realistic FMS scenario having pooled machines of equal sizes. §4.1 describes the problem sets. In §4.2, computational results on *finding mix ratios* of the part types selected by the various approaches are provided. The *performances* of the seven part types selection approaches are compared in §5.

§4.1. Scenario Investigated

The problem set of Table III is used to demonstrate the performances of the seven suggested approaches to select part types. There are ten part types with associated production requirements that are ordered to be produced on an FMS having three groups of pooled machines of equal sizes. In particular, there are pooled mills, drills and VTLs, each group having two identical machines. The processing times (in minutes) and production requirements for each part type are provided in Table III for this system of three machine types and six machines. Each part type requires between 4 to 8 different cutting tools on each machine type. Each cutting tool occupies 1 or 3 slots. The total number of cutting tools required by all ten part types is 14. The number of tool slots required by all ten part types is 26, 28, and 32 for mills, drills, and VTLs, respectively. detailed input data is omitted here for space considerations, but is available upon request.) The tool slot capacities of mills, drills, and VTLs are specified as 30, 35, and 20, respectively. Tool overlapping is not considered here, but tool duplication is.

There are two cases of fixture limitations that are considered here. First, the

TABLE III.

Processing Times and Production Requirements for Ten Part Types on Three Machine Types with Six Machines.

Part Type	Mill(2)	Drill(2)	VTL(2)	Production Requirements
PT1	40(1)	50	50	40(2)
PT2	20	20	40	8
PT3	40	60	40	30
PT4	20	30	30	50
PT5	20	50	20	20
PT6	50	60	10	14
PT7	30	30	60	85
PT8	30	10	20	10
PT9	50	10	30	25
PT10	50	30	40	35

(1) Processing times are in minutes.

(2) Production requirements are in number of parts.

number of fixtures of each type is limited to be four. The second case requires no restrictions on fixtures. One reason is to compare the effects of having a limited number of fixtures available. A fixed number of parts (the pallet limitation) of mixed types having nonzero production ratio values is always in the system.

Initially, the number of parts (pallets) in the system is nine for the problem of Table III. The values of parameters W_k, C_{k1}, and C_{k2} of Models **(M1)** and **(M4)** are specified as 100, 1, and 1, respectively, as workloads are to be balanced. These balanced workloads maximize expected production rate for systems of pooled machines of equal sizes. (See Stecke and Morin [1985] and Shanthikumar and Stecke [1986].) The integer programs **M1**, **M2**, **M3**, and **M4** are run using LINDO on an AMDAHL 5860.

Only the one problem of Table III is presented here in all detail, for space considerations. However, the results from this problem are representative of the results typically found using these algorithms.

§4.2. Calculation of The Selected Part Mix Ratios

Mix ratios are determined, both with and without fixture limitations, as follows. First, Models **(M1)** and **(M4)** are solved without the fixture limitations. Unless all ratio values are always less than four, **(M1)** and **(M4)** are again solved after adding the constraints which restrict the maximum ratio values.

The following tables provide representative results that are typically found by using the various algorithms. The tables were constructed as follows. For each table, first the corresponding part type selection/production ratio model was run to select part types and their mix. Then a simulation, to be described in §5, was run to see which part type finished its requirements first. With this part type deleted and the remaining part types left on the system, the model was run again to determine new mix ratios and potentially new part types to enter. This iteration continues until all requirements of all part types of Table III are finished.

Table IV provides the part mix ratios for the batches selected using both Hwang's Model **(M2)** and the production ratio Model **(M4)**. Table V provides the part mix ratios for the batches selected using both the suggested Model **(M3)** and **(M4)**.

The rules labeled (a) of Tables IV, V, VI, VII, and VIII imply that new part types are scheduled to enter the system. These new part types are noted in boldface. The rules labeled as (b) indicate that the current ratios are updated with no new part type entering. If any part type requires more than four fixtures, then **M1** and **M4** are again solved after adding the constraint that restricts the maximum ratio values to be no larger than four. This occasional second run is labeled (-1). Label (-2) is used to note that **M1** and **M4** are solved without fixture limitations.

TABLE IV.

Optimum Part Mix Ratios Using Hwang's Batching Formulation **(M2)** and Model **(M4)**.

Run	Rule	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
1	M(2)&(4)(a) M4(b)	**3,5,6** 5,6	3:1:1 1:3	75 105	6.791 0.429
2	M(2)&(4)(a) M4(b)	**1,7,9** 7,9	3:1:1 2:3	25 65	3.416 0.480
3	M(2)&(4)(a)	**2,8**	4:4	60	2.100
4	M(2)&(4)(a)	**4**	7	40	1.683
5	M(2)&(4)(a)	**10**	5	50	1.581
Total CPU(1)					16.480

0 indicates the new part types to be introduced for the upcoming run.
(1) This is the total CPU time taken using **(M2)** and **(M4)** only for $a_i \leq 4$.

TABLE V.

Optimum Part Mix Ratios Using the Suggested
Batching Formulation **(M3)** and Model **(M4)**.

Run	Rule	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
1	M(3)&(4)(a) M4(b)	**3,5,6** 5,6	3:1:1 1:3	75 105	6.791 0.429
2	M(3)&(4)(a)	**8,9,10**	1:1:4	75	3.841
3	M(3)&(4)(a-1)(1) M(3)&(4)(a-2)(2)	**2,4** **2,4**	2:4 1:6	60 40	2.392 2.289
4	M(3)&(4)(a)	**1,7**	3:1	40	1.607
Total CPU(3)					15.060

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

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

(2) specifies no fixture limitations.

(3) This is the total CPU time taken using **(M3)** and **(M4)** only for $a_i \leq 4$.

Table VI provides the part mix selected in each batch using BATCH as well as BATCH and BAL. Table VI also demonstrates the use of Model **(M4)** to determine production ratios of the selected part types. BATCH tries to minimize the number of batches that are required to produce all part types. On the other hand, using BATCH and BAL examines whether the workloads for the selected part types in a batch can be balanced on each machine type whenever that batch is determined.

Table VII provides the part mix ratios for the batches selected using both of Rajagopalan's heuristics, (*RHI*) and (*RHII*), and Model **(M4)**. Table VIII provides the balanced mix ratios of the part types selected using the flexible approach, Model **(M1)**.

The following observations can be made from Tables IV, V, VI, VII, and VIII.

(1) Each run dictates a *total and significant tool changeover*, for the batching approaches. For these, there are four total and major system set-ups (tool changeovers) for Hwang's model, three total for the suggested model, four total for the BATCH option, five total for both BATCH and BAL options, and four total for both of Rajagopalan's heuristics.

(2) There are five minor tool reloadings for the flexible approach.

(3) Our suggested Model **(M3)** leads to the *smallest* number of batches required to

TABLE VI.

Part Mix Ratios Using the BATCHBAL program and Model (**M4**).

Run	Rule	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
1	BATCH&**M4**(a)(1)	**3,5,6**	3:1:1	75	0.451(5)
	M4(b)	5,6	1:3	105	0.429
	BATBAL&**M4**(a)(2)	**3**	5	50	0.298
2	BATCH&**M4**(a)	**8,9,10**	1:1:4	75	0.441
	BATBAL&**M4**(a)	**1**	4	20	0.286
3	BATCH&**M4**(a-1)(3)	**4,7**	4:2	60	0.344
	BATCH&**M4**(a-2)(4)	**4,7**	5:1	50	0.426
	BATBAL&**M4**(a)	**5,10**	2:3	30	0.358
4	BATCH&**M4**(a)	**1**	4	20	0.389
	BATBAL&**M4**(a-1)	**4,9**	4:3	45	0.463
	BATBAL&**M4**(a-2)	**4,9**	5:2	20	0.436
5	BATCH&**M4**(a)	**2**	6	100	0.302
	BATBAL&**M4**(a)	**6,7**	2:3	10	0.420
6	BATBAL&**M4**(a)	**2,8**	4:4	60	0.496
CPU(6)	BATCH				1.694
	BATBAL				1.490
Total CPU(7)	BATCH				4.050
	BATBAL				3.811

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

(1) BATCH refers to the use of only the BATCH option.

(2) BATBAL is short for BATCHBAL and refers to using both BATCH and BAL options.

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

(4) specifies no fixture limitations.

(5) This is the CPU time for Model (**M4**) using LINDO.

(6) This is the CPU time required to partition all part types into batches using the BATCHBAL program and using BATCH alone.

(7) This is the total CPU time taken using BATCH (BATCHBAL) and (**M4**) only for $a_i \leq 4$.

produce all part types among the seven part type selection approaches, six of which are batching.

(4) The objective function values (that measure the extent of system balance) for the *batching approaches* deteriorate as new ratios for the remaining part types in a

TABLE VII.

Part Mix Ratios Using Rajagopalan's Heuristics and Model (**M4**).

Run	Rule	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
1	*RHI*&M4(a)(1)	**3,5,6**	3:1:1	75	0.451(5)
	M4(b)	5,6	1:3	105	0.429
	RHII&M4(a)(2)	**1,5,10**	2:1:2	5	0.631
	M4(b)	1,5	3:1	45	0.328
2	*RHI*&M4(a)	**1,10**	3:1	30	0.457
	RHII&M4(a-1)(3)	**4,8**	4:4	20	0.424
	RHII&M4(a-2)(4)	**4,8**	6:2	20	0.519
3	*RHI*&M4(a)	**2,7**	3:3	100	0.349
	RHII&M4(a)	**2,7**	3:3	100	0.349
4	*RHI*&M4(a-1)	**4,9**	4:3	45	0.474
	RHI&M4(a-2)	**4,9**	5:2	20	0.436
	RHII&M4(a)	**3,9**	3:2	20	0.447
5	*RHI*&M4(a)	**8**	9	100	0.298
	RHII&M4(a)	**6**	4	100	0.291
CPU(6)	*RHI*				0.066
	RHII				0.101
Total CPU(7)	*RHI*				2.524
	RHII				2.571

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

(1) *RHI* refers to Rajagopalan's heuristic I.

(2) *RHII* refers to Rajagopalan's heuristic II.

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

(4) specifies no fixture limitations.

(5) This is the CPU time for Model (**M4**) using LINDO.

(6) This is the CPU time required to partition all part types into batches using the *RHI* and *RHII*.

(7) This is the total CPU time taken using *RHI* (*RHII*) and (**M4**) only for $a_i \leq 4$.

particular batch are found (see Tables IV, V, VI, and VII). This will usually lead to lower system utilization as the system operates. (This will be seen in §5.2.) This deterioration occurs because new ratios are found continuously without the potentially advantageous introduction of some new part type(s) which can let the system be more highly balanced and utilized.

(5) The objective function values of the *flexible approach also* deteriorate with the

TABLE VIII.

Optimum Part Mix Ratios Using the Flexible Approach (**M1**).

Run	Rule	Selected Part Types	Production Ratios	Objective Function Value	CPU Time (seconds)
1	**M1**(a)	**5,7,8,10**	2:1:1:2	0	85.466
2	**M1**(a)	**3**,7,**9**,10	2:1:1:1	15	16.833
3	**M1**(a-1)(1) **M1**(a-2)(2) **M1**(b)	**4**,7,9 **4**,7,9 **4**,7	3:1:2 5:1:1 4:2	40 35 60	22.204 16.054 31.344
4	**M1**(a)	**6**,7	2:3	10	3.288
5	**M1**(a)	**1**,7	4:1	50	3.276
6	**M1**(a-1) **M1**(a-2)	**2**,7 **2**,7	2:2 7:2	100 100	1.371 1.179
Total CPU(3)					163.782

0 indicates the new part types to be introduced for the upcoming run.
(1) specifies the limit of four fixtures of each type.
(2) specifies no fixture limitations.
(3) This is the total CPU time taken using **(M1)** only for $a_i \leq 4$.

number of runs. This is because the problem here is static, having fixed orders. In the more typical dynamic situations of orders arriving to an FMS continuously, a better utilization can be anticipated.

(6) The CPU time of the *flexible approach* for the first run is large. This is because tool magazine capacity constraints are considered here *concurrently* with part type and mix ratio selection for this run. The CPU time decreases with the number of runs. The batching approaches consider tool magazine capacity with part type selection *separately* from the production ratio determination. The two problems are solved separately.

It should be noted that the objective function values (measuring the extent of system balance) of the determined mix ratios for the flexible approach are better than those for the other six batching approaches (except sometimes for the last run). Also, system set-up time (tool changeover time) is usually smaller by following a flexible approach. This because only the few tools affected are changed in a particular tool magazine. Often, the other machine tools can continue to operate.

§5. SIMULATED SETTINGS

In this section, various approaches to select part types are compared by simulating an FFS of groups of pooled machines of equal sizes. The simulation model is developed in GPSS/H. Schriber [1985] and Schriber and Stecke [1986, 1987] have also used a detailed GPSS/H model of an FFS to examine the usefulness of the aggregate production ratios of Stecke [1985] when system realities such as finite numbers of buffers, congestion, blocking, and a finite number of AGVs are considered. §5.1 outlines the various parameters of the simulation model. In §5.2, the simulation results are analyzed.

§5.1. The Simulation Model

The FMS configuration is provided in Figure 1. The following specifications are used for the subsequent experiments.

(1) The FFS has uni-directional transportation.

(2) Workstations: 6; two pooled mills, two drills, and two VTLs.

(3) Buffer spaces: 4; two in between the mills and drills and two in between the drills and lathes.

(4) Load/unload stations: 5.

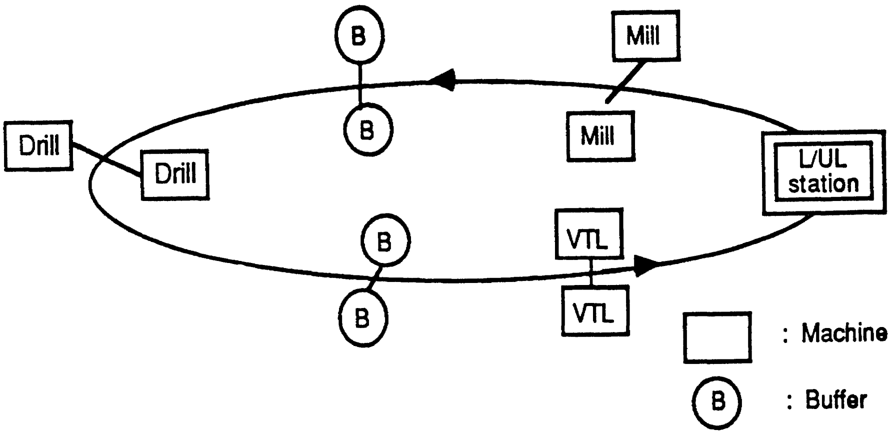
(5) Carts: 5 (wire-guided vehicles).

(6) Travel times are one minute between all links, i.e., between: L/UL-mill;mill-buffer; buffer-drill; drill-buffer; buffer-VTL; VTL-L/UL (see Figure 1).

(7) Fixture limitations: First, the number of fixtures of each type is limited for each part type to be four ($f_i = 4$, $i = 1,\ldots,10$). A second case requires no restriction on this value ($f_i < \infty$, $i = 1,\ldots 10$).

(8) Number of pallets in the system : 9.

FIGURE 1. System Configuration.



A fixed number of parts of mixed types having nonzero production ratio values is always in the system. For the flexible approach, a current simulation run is usually terminated whenever the production requirements of some part type(s) are finished. When one or more new part types are selected to be input into the system (as specified in Table VIII), new ratios 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. On the other hand, for all of the various batching approaches, a current simulation run continues until all requirements of all part types in one batch are finished. As any part type(s) of a particular batch complete the requirements, new production ratios are found for the remaining part types to balance workloads as optimally as possible.

The part input sequence into the FFS here is determined by using a combination of a modified Johnson's algorithm (Campbell, Dudek, and Smith [1970]) and the calculated part mix ratios. (See Stecke and Kim [1986b] for a detailed description of this.) In particular, for the part types of Table III, the selected part types are always input to the system according to the modified Johnson's algorithm. When a machine and cart become available, a part can be moved. When two or more parts wait for a machine, FCFS in the buffer is used.

§5.2. The Simulation Results

Now we present the simulation results to investigate the flexible and batching approaches. Simulations are performed for the problem of Table III and for the two cases, with and without fixture limitations. Tables IX and X provide computational results on the *system, machine, processing*, and *transportation utilizations*, as well as *makespan*.

Processing (*transportation, blocking*) *utilizations* are found for each machine type. These indicate the proportions of total processing (transportation, blocking) times to total makespan. *Processing utilization* is calculated as the ratio of total actual machining time to total makespan, for each machine type: Mill, Drill, and VTL. *Machine utilization* is expressed as the sum of processing, transportation, and blocking utilizations, for each machine type. *System utilization* is an average of the *processing* utilizations of the three machine types and is a measure of overall system usage. The difference between machine and processing utilizations provides the average amount of time spent in transportation and blocked.

The simulation results demonstrate how much the *system* and *processing utilizations* are improved by using the flexible approach. The boldface values in Tables IX and X note the best performances among the seven approaches. The following observations can be made.

TABLE IX.

Simulation Results After the Completion of All Production Requirements of All Ten Part Types When the Number of Fixtures of Each Type is Limited to be Four.

Comparison	**Batching Approaches**						**Flexible**
	Hwang	**E-Hwang**	BATCH	BATBAL	*RHI*	*RHII*	**(M2)**
Makespan (minutes)	8766	8745	8900	8611	8635	8146	**7479**
Mill Utilization	.686	.687	.675	.655	.696	.700	**.760**
Processing Utilization	.622	.623	.612	.633	.631	.669	**.729**
Transportation Utilization	.021	.021	.020	.021	.021	.023	.031
Blocking Utilization	.043	.043	.043	.001	.044	.008	.000
Drill Utilization	.703	.681	.672	.691	.696	.737	**.820**
Processing Utilization	.641	.643	.632	.653	.651	.690	**.752**
Transportation Utilization	.032	.032	.030	.032	.033	.033	.037
Blocking Utilization	.030	.006	.010	.006	.012	.014	.031
VTL Utilization	.772	.776	.760	.787	.785	.830	**.905**
Processing Utilization	.742	.743	.730	.755	.753	.798	**.869**
Transportation Utilization	.030	.033	.030	.032	.032	.032	.036
Blocking Utilization	.000	.000	.000	.000	.000	.000	.000
System Utilization	.668	.670	.658	.680	.678	.719	**.783**
Average Buffer Utilization	.183	.160	.186	.065	.148	.188	.308
Cart Utilization	.046	.046	.044	.046	.047	.050	.062
Number of Dedicated Fixtures	40	39	40	40	40	40	38

(1) The *flexible approach results in higher system utilization than batching.* This is consistent with the decrease in *makespan* for the flexible approach.

(2) When there are no required fixture limitations, the flexible approach requires *many fewer* dedicated fixtures than batching. (See Table X.) 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 would require additional fixtures (if they were available) for that part type to be finished (or alternatively, longer makespan).

(3) The *system utilizations* for various batching approaches are much better when

TABLE X.

Simulation Results After the Completion of All Production Requirements of All Ten Part Types When There Are No Limitations on the Number of Fixtures of Each Type.

Comparison	**Batching Approaches**						**Flexible**
	Hwang	**E-Hwang**	BATCH	BATBAL	*RHI*	*RHII*	**(M2)**
Makespan (minutes)	8217	8395	8450	7764	8107	7815	**7383**
Mill Utilization	.788	.808	**.827**	.813	.780	.751	.790
Processing Utilization	.663	.649	.645	.702	.672	.698	**.738**
Transportation Utilization	.024	.021	.033	.029	.025	.026	.038
Blocking Utilization	.101	.138	.149	.082	.083	.027	.014
Drill Utilization	.893	.842	.834	.891	.895	.913	**.881**
Processing Utilization	.684	.670	.665	.724	.693	.719	**.761**
Transportation Utilization	.027	.025	.028	.033	.029	.028	.036
Blocking Utilization	.182	.147	.141	.134	.173	.166	.084
VTL Utilization	.822	.808	.805	.875	.834	.863	**.919**
Processing Utilization	.791	.774	.769	.837	.802	.832	**.881**
Transportation Utilization	.031	.029	.031	.038	.032	.031	.038
Blocking Utilization	.000	.005	.005	.000	.000	.000	.000
System Utilization	.713	.698	.693	.754	.722	.750	**.793**
Average Buffer Utilization	.568	.554	.507	.498	.599	.587	.526
Cart Utilization	.050	.047	.054	.059	.053	.055	.068
Number of Dedicated Fixtures	71	65	72	71	69	63	54

there are no fixture limitations than when there is the limit of four fixtures of each type. This indicates that utilization when batching seems to be *sensitive* to fixture limitations.

(4) The amount of *blocking* for all three machine types is larger for the *batching approaches* than for the *flexible approach* when there are no required fixture limitations.

(5) Even though the BATCH option is better than both BATCH and BAL options simultaneously in terms of the number of tool changeovers (see Table VI), the use of both BATCH and BAL options leads to better machine utilizations. This is because BATCH and BAL options attempt to balance workloads while partitioning the part types into batches.

(6) Among the six *batching approaches*, Rajagopalan's heuristic II and both BATCH and BAL options used together lead to higher system utilization. This seems to be because these batching approaches to select part types consider the processing time requirements of each part type to *balance workloads* on machines. On the other hand, the remaining batching approaches that select part types only try to minimize the number of tool changeovers.

Therefore, it can be noted that the flexible approach increases overall system utilization and decreases system makespan also, at least in the situations examined to date. These positive results are in addition to the savings in tool changeover times. Further studies are required, however. Suggestions for these are contained in §6.

§6. CONCLUSIONS

This paper investigates and compares the performances of seven different approaches to select part types for simultaneous production for a flexible flow system having groups of pooled machines of equal sizes. This paper also suggests a global procedure for solving part type selection and production ratio determination problems together and over time using a flexible approach to implement the short-term production planning function while balancing machine workloads.

Simulation results are performed to compare the flexible and various batching approaches. They demonstrate that the use of the flexible approach tends to help the system to be more highly utilized. It is observed that the batching approaches require more fixtures of each type than the flexible. The system utilizations for the batching approaches seem to be sensitive to restrictions on the number of fixtures of each type. It can be concluded that this flexible approach to part type selection can lead to better system utilization and can more easily cope with dynamic situations during operation, for the types of FMSs considered so far.

FMS users should consider following such a more flexible approach to selecting part types dynamically in systems for which the approach may help system performance. For example, if the production requirements for some part types are independent, mix ratios proportional to the requirements will usually hurt system performance.

Among the six *batching approaches*, the second heuristic of Rajagopalan (*RHII*) and using both BATCH and BAL options in the BATCHBAL program, (which consider the processing time requirements of each part type to balance workloads on machines) lead to better system utilization than the other batching approaches. The suggested extension of Hwang's formulation leads to the smallest number of batches to produce part types among the seven part type selection approaches.

There are further research needs concerning FMS part type selection problems. For example, the results presented here are only for one general type of problem. This problem *is* representative of the general tendencies of the performances of the various procedures. However, additional extensive studies should be performed in order to conclude which methods are appropriate under what conditions and for what types of systems. Both performance and/or computational times of the algorithms *may* be important, depending on the frequency of application.

Also, similar studies should be performed in a more dynamic situation, when there are often changes in production orders or random machine failures. Implementation of some of the results here in more general situations is being developed. Also, the appropriateness of implementing a batching objective using a flexible approach is being further examined.

Similar studies of the various FMS part type selection approaches should be performed when due dates are considered. For most of the approaches that have been compared here, *due dates* have not yet been incorporated into the algorithms, yet this is an important application. For example, some systems produce the same parts all the time to maintain certain buffer levels. Due date consideration may be less important here. Customer due dates are important in other FMSs. In fact, considering due dates is more important during part type selection than during scheduling. Those part type selection approaches that do not yet account for due dates should incorporate these considerations into the algorithms.

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