On the System Setup and the Scheduling Problem in a Flexible Manufacturing System (FMS)

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In this paper we present a model which unifies several existing models with respect to two phases of the planning process of a Flexible Manufacturing System. These phases are the system setup phase and the scheduling phase and in literature they usually are considered separately. We give a mathematical formulation encompassing both phases. From this formulation several existing approaches can be deduced. We also describe some heuristic methods for our model and present the computational results.

Key Words & Phrases: Hierarchical planning, batching, flexibility, combinatorics, heuristics

1. Introduction

The purpose of this paper is to give a combined formulation of two phases in the planning process of a Flexible Manufacturing System (FMS), namely the system setup and the scheduling problem. In literature the following decision hierarchy in the planning process of an FMS is usually assumed:

1. Economic justification
2. Design
3. Aggregate planning
4. System setup
5. Scheduling
6. Control

For a more detailed discussion of this hierarchy we refer to Kiran and Tansel (1986), Stecke (1985) and Suri and Whitney (1984). Usually, the phases 4 and 5 are considered separately, though the interdependence is recognized. The

emphasis lies mostly on the system setup phase. In this paper we will start with an outline of some of the approaches to the system setup phase (see section 2). In section 3 we will give a formulation for the system setup and the scheduling problem combined. It turns out that our model unifies several of the existing approaches, since they straightforwardly can be deduced as special instances of our model.
In section 4 some heuristics for our model are presented and we will give the computational results of a number of testproblems. Section 5 will conclude with some comments on the model and the use of the different approaches.
This section describes an FMS and we will give some definitions of related objects (see also COOK, 1975, DRAPER LAB. 1984 and ZIJM, 1987).

What does a typical FMS look like? It consists of a number of machines. These machines are connected by a material handling system which is able to carry (product-) parts through the system. Each machine has a tool-magazine in which several tools can be placed. To be more precise: a toolmagazine has a number of slots, a tool occupies several slots, so the number of tools in a magazine depends on the choice of the tools. A machine can only use one tool at a time. A tool can be interchanged for another tool from this magazine automatically in negligible time. It is also possible to replace the tools in the toolmagazine out of a central tooldepot. The time needed for such a replacement cannot be ignored. An operation can be defined as the consecutive use of a number of tools from a toolmagazine to process a part on some machine. For an operation to be performed adequatly, an exact positioning of a part is necessary. To achieve this exact positioning, fixtures are used. An average FMS consists of 2-10 computer numerically controlled (CNC) machines.
The most important characteristic of an FMS is its capability to interchange tools fast. In this way it is possible to combine the efficiency of mass-production with the flexibility of job-shop production. Thus, important savings in inventories, throughput time etc. are achievable. Another characterizing feature of an FMS is its capability to produce different part types. A succesful FMS produces more than 100 different part types per year and introduces at least 25 new part types (VAN VLIET and VAN WASSENHOVE, 1989).
The application of FMS-technology started in the late seventies in the metal-working industry. The number of FMS's is still limited but growing. Several lines of development evolved. For more detailed information and recent trends we refer to the survey paper of JAIKUMAR (1986). The number of applications in the Netherlands can be estimated as very small.
In this paper we will use the following notions: A part is defined as an elementary unit which has to undergo a series of operations in order to finish as the desired end-product. Parts can be classified according to a number of part-types. Parts A and B of the same type have the same production-characteristics, which means:

- a fixture suitable for part A is suitable for part B and vice versa,
- any operation to be carried out on part A must be carried out on part B and vice versa,

- if a certain sequence of operations on part A is specified, then this sequence also holds for part B.

The production-order is a set of orders. An order specifies the part-type and the number of parts to be produced of that part-type.
Before an FMS starts producing, a number of decisions has to be made. These decisions concern the system setup problem and the scheduling problem, or, as we will refer to those two problems combined: the production operations problem (POP). Usually, the system setup phase is considered to consist of four related issues (compare KIRAN and TANSEL, 1986)

- part-type selection: to decide at which moments which parts are selected to enter the system.
- tool-loading: to decide which tools are attached to which machines during which period so that the required operations can be performed.
- fixture allocation: to allocate fixtures to parts.
- operations-assignment: to assign operations to machines.

The scheduling problem involves the scheduling of the operations on a machine, i.e. to determine a sequence of operations for every machine. In a feasible solution of the POP, which will be called a production-plan, all the above mentioned problems are solved. Several objectives for selecting a production-plan are possible. Often, one tries to find a production-plan which minimizes the time needed to produce all parts (see for instance STECKE, 1983). We will also use this performance measure.
Summarizing: the production operations problem involves to select, given a production-order, a production-plan which minimizes the time needed to produce all parts in the production-order.
Two usual and basic assumptions are the following (see for instance HWANG, 1986):

- Each part has to undergo a known set of operations and each operation corresponds to a known set of tools. As a consequence, it is known precisely which tools are needed to process a part.
- A part which entered the system to be processed is not allowed to leave the system unfinished.

Both assumptions are somewhat artificial. For instance, it is not possible that parts, depending on the outcome of certain operations, undergo additional operations. In the remainder of this paper we will assume that these assumptions hold.

2. DIFFERENT APPROACHES TO SOLVE THE SYSTEM SETUP PROBLEM

It is possible to classify methods used to solve the system setup problem according to answers to the following questions:

1) Does the method include forming batches, i.e. subsets of parts such that the parts of such a subset can be processed simultaneously?

2) In case of an affirmative answer to question 1, does the method solve the part-type selection problem and the tool-loading problem simultaneously?

On the basis of answers to these questions we distinguish three different approaches. Central is the choice for batching or continuous production (question 1). Continuous production (or the so-called flexible approach) uses the concept of tool-replacements during production, while the batching approach only allows tool-replacements when all parts of a batch are finished. A batching approach can be split up into two different categories: the part-type selection problem is solved separately from the tool-loading problem or those problems are solved simultaneously (question 2). We will refer to the first case as a hierarchical approach, to the second case as an extended batching approach. In the remainder of this section we will discuss these approaches in more detail.

2.1 The hierarchical approach

In this approach the system setup problem is divided into a number of hierarchically coupled subproblems. Usually these subproblems resemble, among others, the already mentioned part-type selection problem and the tool-loading problem. The advantage of this approach is that solving a number of solvable problems is more attractive than solving one difficult problem. However, the solution of one subproblem can lead to infeasibility of another subproblem (not to mention the loss of optimality). As a consequence, iterative procedures can be necessary to find a good solution to the system setup problem. Some methods that only solve the part-type selection problem, use clustering methods to identify families of part-types. Clustering algorithms require some sort of distance between part-types, which is usually defined as an average of differences between attribute values of some characteristics of a part-type (see KUSIAK, 1985a). Another typical example of a hierarchical approach can be found in the important paper of STECKE (1983). She divides the system setup problem into five subproblems, namely part-type selection, machine grouping, determining production-ratio's (see also STECKE, 1988), fixture allocation and operation/tool-loading problem. Assuming the part-type selection problem is solved, she tries to find a feasible solution for the tool-loading problem under various objectives (e.g. minimizing the number of part movements, (un) balancing the workload etc.).
Other examples of papers addressing subproblems are KUSIAK (1985b), KUMAR et al. (1986), GREENE and SADOWSKI (1986) and CHAKRAVARTY and SHTUB (1984).

2.2 The extended batching approach

In this approach the part-type selection problem and the tool-loading problem are solved simultaneously. The idea is to divide the parts into batches. After the processing of a batch a tool-replacement takes place (don't confuse this

tool-replacement with tool interchanges!) and the next batch will enter the system. Clearly, models of methods using this approach are larger and more difficult to solve than models of the hierarchical approach. Using heuristics or simplifying the model are means of dealing with this difficulty. Several variants can be distinguished:
In KIRAN and TANSEL (1986) a fixed time period is given. Their objective function results in producing as many parts as possible in that time period under tooling- and fixture constraints. In HWANG (1986) a model is presented which forms a batch in the following way: maximize the number of different part-types in a batch under tooling constraints; all parts of the selected part-types are added to the batch. When considering total time needed to produce all parts as an objective function, both models have a common disadvantage: they are essentially greedy methods. Sequentially, by solving repeatedly the model, batches are formed. Under the objective functions (mentioned above) 'bad' part-types are selected late, or in case of a rolling production-order not selected at all. Clearly, this can significantly prolong total production time. An example of this phenomenon and an improvement of Hwang's model can be found in STECKE and KIM (1988).
Another variant is the model in RAJAGOPALAN (1986). He presents, under the simplifying assumption that all operations of a part are performed on the same machine, a complete model of the system setup problem. In his model batches are formed with the objective that total production time is minimized.

2.3 The flexible approach

Recently STECKE and KIM (1988) proposed a so called flexible approach towards solving the system setup problem. Their idea is to let parts 'gradually flow' into the system. Even more, it is assumed that it is possible to replace tools while the system is in operation. The objective in their model tries to balance the workload of the machines. This is achieved by computing production-ratio's for the different part-types, expressing the relative rates at which parts of the part-types are fed into the system. The model is solved iteratively. As soon as production of all parts of some part-type is finished (or some other event takes place, like machine failure) the model is solved again to decide if (and eventually which) part-type (s) can be fed into the system. Clearly, the major advantage of this approach is that, while replacing tools on one machine, production on other machines continues. This implies that tool-replacements are spread in time, which on one hand, leads to a more efficient handling of this replacement; on the other hand, in a practical situation this increases the organizational complexity which results in a greater demand on the control system of the FMS.

3. A FORMULATION OF THE PRODUCTION OPERATIONS PROBLEM

The importance of the scheduling problem is emphasized in e.g. MORTON and SMUNT (1986). They state: "The need to schedule the FMS for maximum

effectiveness is great due to the high capital investment involved for such manufacturing processes.". In this section we present a formulation of the system setup problem and the scheduling problem combined and we show how the approaches described in section 2 relate to our model.
In addition to the assumptions mentioned in section 1 we further assume:

* deterministic processing times
* no machine-failure
* transfer times are included in processing time
* discretized time
* tool-replacement time is constant
* no precedence constraints
* no fixture constraints
* no due dates on parts

The last four assumptions are often too strict. Without any difficulty we can formulate a model with tool-dependent tool-replacement times, with precedence constraints, with fixture constraints and release and due dates. However, we think that the necessary notational burden will not clarify our model. In fact in our testproblems (cf. section 4) we allow for precedence constraints and tool-dependent tool-replacement times. Define the following parameters of the model:

m = number of machines (index r)
T = upper limit on number of time-units needed to process the production order
K = number of tools (index k)
L = number of operations to be carried out (index i)
C_k = number of toolslots occupied by tool k
S_r = toolslot capacity of machine r
P_i = processing time of operation i
T_i = $T-P_i$ (index t)
S = time needed for a tool-replacement.
part(i) = set of operations i' which have to be processed on the same part as operation i
forb(r) = set of operations i which machine r is unable to perform
tool(i) = set of tools k needed to perform operation i

and the following decision variables:

X_{irt} = 1 if operation i starts at time t on machine r
0 elsewhere
Y_{krt} = 1 if tool k is attached to machine r during the interval $[t, t+1)$
0 elsewhere
Z_t = 1 if some operation is being carried out at time t
0 elsewhere

It is important to realize that in this formulation the operation index i also

specifies the part on which that operation is to be carried out.
The model:

$$\min \sum_{t=0}^{T} Z_t$$

such that

$$\sum_{r=1}^{m} \Sigma_{t=0}^{T_i} X_{irt} = 1 \quad \forall i \qquad (1)$$

$$X_{irt} = 1 \rightarrow Y_{krt} = 1 \quad \forall i,r,t,\ \forall k \in \text{tool}(i) \qquad (2)$$

$$X_{irt} = 1 \rightarrow X_{i'rs} = 0 \quad \forall i,i',r,t,\ \forall s = t+1,\dots,t+P_i-1 \qquad (3)$$

$$X_{irt} = 1 \rightarrow |Y_{krs} - Y_{krs+1}| = 0 \quad \forall i,r,k,t, \forall s = t,\dots, t+P_i-2 \qquad (4)$$

$$X_{irt} = 1 \rightarrow X_{i'r's} = 0 \quad \forall i,r,r',t, \forall i' \in \text{part } (i), \qquad (5)$$

$$\forall s = t,\dots,t+P_i-1$$

$$\Sigma_{i=1}^{L} X_{irt} \leqslant 1 \quad \forall r,t \qquad (6)$$

$$\Sigma_{k=1}^{K} C_k Y_{krt} \leqslant S_r \quad \forall r,t \qquad (7)$$

$$|Y_{krt} - Y_{krt+1}| = 1 \rightarrow X_{irs} = 0 \quad \forall i,r,k,t, \qquad (8)$$

$$\forall s = t+1,\dots,t+S$$

$$X_{irt} = 0 \quad \forall i \in \text{for } b\ (r),\ \forall r,t \qquad (9)$$

$$X_{irt} = 1 \rightarrow Z_s = 1 \quad \forall i,r,t \qquad (10)$$

$$\forall s = t,\dots,t+P_i-1$$

$$X_{irt}, Y_{krt}, Z_t \in \{0,1\} \quad \forall i,k,r,t \qquad (11)$$

Constraint (1) ensures that every operation is started at some moment. To make sure that the needed tools for an operation are present at the start of that operation constraint (2) is necessary. Constraint (3) represents the fact that no operation can start on a machine while another operation is being carried out on that machine. Constraint (4) ensures that no tool can be replaced during an operation and constraint (5) represents the fact that if an operation is carried out on some part no other operations on that part can be started. Constraint (6) ensures that at any moment only one operation on a certain machine can start. Constraint (7) represents the well-known toolmagazine capacity constraint and constraint (8) ensures that when a tool-replacement has taken place, no operations on that machine are possible during the tool-replacement period. Constraint (9) represents the fact that some machines are unable to perform some operations and constraint (10) ensures that when at a certain moment an operation is being carried out, the objective function is increased. Constraint (11) represents the integrality constraints. Clearly, constraints (2), (3), (4), (5), (8) and (10) can be formulated as linear inequalities.
It is possible to relate this formulation to the earlier mentioned approaches.

Let us first take a look at the core of this model by removing the scheduling aspect of the model (delete the t-index and the constraints (3), (4), (5), (6), (8), (9), (10)).

The core:

$$\Sigma_{r=1}^{m} X_{ir}=1 \qquad \forall i \tag{1'}$$

$$X_{ir}=1 \rightarrow Y_{kr}=1 \qquad \forall i,r, \forall k \in \text{tool}\,(i) \tag{2'}$$

$$\Sigma_{k=1}^{K} C_k Y_{kr} \leqslant S_r \quad \forall r \tag{7'}$$

$$X_{ir}, Y_{kr} \in \{0,1\} \qquad \forall i,k,r \tag{11'}$$

(The definition of X_{ir} and Y_{kr} are adapted in an obvious way.)

Hierarchical Approach:
Suppose the part-type selection problem is solved. Then the operations to be performed are known and the constraints of the core model above are equivalent with Stecke's tool-loading model described in STECKE (1983).

Extended Batching Approach:
To find the model of HWANG (1986) we have to delete (1'). Remember that in his model one batch is formed, so not every operation has to be carried out. However, it is required that all parts of a part-type are added to the same batch. Hence, we have to add a constraint which ensures that if an operation i of a part belonging to a certain part-type is selected, then all operations of all parts belonging to this part-type have to be performed (notation: part- type(i)).

$$X_{ir}=1 \rightarrow \sum_{r'=1}^{m} X_{i'r'}=1 \qquad \forall i' \in \text{part-type}(i), \forall r \tag{12}$$

The model consisting of the constraint (2'), (7'), (12) and (11') is equivalent to Hwang's set of constraints. KIRAN and TANSEL (1986) require a weaker version of constraint (12), namely they only require that all operations of a part belong to the same batch:

$$X_{ir}=1 \rightarrow \sum_{r'=1}^{m} X_{i'r'}=1 \quad \forall i' \in \text{part}\,(i),\ \forall i,r \tag{12'}$$

The model of KIRAN and TANSEL consist of (2'), (7'), (11'), (12') and a constraint which fixes a time period:

$$\Sigma_{i=1}^{L} P_i X_{ir} \leqslant a_r \qquad \forall r \tag{13}$$

with a_r: available time on machine r.
Their model also incorporates fixture constraints.

As already mentioned in section 2, RAJAGOPALAN (1986) has proposed a model which solves all issues of the system setup problem (see section 1) simultaneously. In that sense his approach resembles ours. However, the

scheduling aspect is ignored. In his model two starting-points are essential, leading to a solution of a special structure. Namely, the assumption that each part uses from each machine type at most one machine and furthermore that the production should take place in batches (and tool-replacements can only occur between batches). The former starting-point implies that for every part its operations on a certain machine type can be aggregated, leading to one operation, being the lump sum of its true operations.
When in the constraints (1), (2), (7), (9) and (11) the index t is associated with the t-th batch (and the index i is associated with its aggregate operation on the machine type to which r belongs), then the model of Rajagopalan consists of the constraints (1), (2), (7), (9) and (11), extended with a constraint which determines the length of the t-th batch:

$$\Sigma_{i=1}^{L} P_i X_{irt} \leqslant h_t \qquad \forall r,t \tag{14}$$

Flexible Approach:
The model of STECKE and KIM (1988) is equivalent to an iterative solving of a model consisting of the constraints (7'), (11'), (12') and an adaption of (2') in order to cope with the production-ratio's, extended with workload and fixture constraints. Depending on the state of the system at a particular iteration some of the X_{ir} take on prescribed values (if operation i has been carried out $\rightarrow X_{ir}=0$; if some part is in process, then for all operations i of this part not yet performed $\rightarrow \Sigma_r X_{ir}=1$; else $X_{ir} \in \{0,1\}$). Unlike our model and the model of Rajagopalan, the model of Stecke and Kim does not take into account the time needed for toolreplacement.

4. HEURISTIC APPROACHES

In section 3 we developed a general model for the system setup and scheduling problem. For illustrational purposes we present in this section some heuristic methods to solve these models. We will consider two solution methods. The first one adds consequtively operations to machines based on a number of rules of thumb. The second one uses a procedure which solves the toolloading and scheduling problem in a number of iterations.

Method 1.
A lot of research effort (BUXEY, 1989, FRENCH, 1982) has been put into developing rules for solving scheduling problems in a job-shop environment. The possible necessity of toolreplacements between operations on machines prevents straightforward application of these results to our model. It may be sensible to postpone or to give priority to certain operations, because of savings in tool-replacement time. We developed some rules of thumb, which decide which operation to schedule next on which machine. Then, at each time a machine becomes idle, two issues have to be decided about: first, which operation shall enter that machine and second which tools shall be replaced to perform that operation. We implemented 4 different rules, characterized by
(i) Longest processing time first.

(ii) Shortest processing time first.
(iii) Largest workload remaining.
(iv) Longest processing time first combined with minimal tool-replacements.

The methods (i), (ii) and (iii) are well-known as heuristics for scheduling problems. We extended them to our situation where toolreplacements are allowed. Method (iv) selects the job for which the ratio R/P is minimal with R the time needed for toolreplacements, P the processing time.
After the selection of an operation tools have to be replaced. The ones that have to be added are evident. We used the following rule to remove tools: remove those tools which have the lowest workload left. Hence in this way tools that are needed more often in future stay in the system.
Next a final improving step is implemented, by application of the "Keep Tool Needed Soonest" (KTNS)-procedure of TANG and DENARDO (1988). The KTNS-procedure yields the minimal number of toolreplacements, given a sequence of operations on a machine.

Method 2.
Our second heuristic consists of four consecutive phases. In phase 1, the initializing part, the operations are divided between the machines in such a way that the workloads of all the machines are more or less equal. During phase 2 a feasible solution is constructed. Phase 3 is concerned with the bottleneck machine and it is tried to reduce the makespan of this machine. Finally, during phase 4 operations on different machines are interchanged, after which the procedure starts again in phase 2.
Phase 1 is executed by the following simple rule: order the operations according to their processing times in decreasing order. If there are m machines, assign operation 1 to machine 1, operation 2 to machine 2, . . ., operation m and $m+1$ to machine m, operation $m+2$ to machine $m-1$,..., operation $2m$ and $2m+1$ to machine 1 etc. This procedure was proposed by STECKE and TALBOT (1985).
For phase 2 we adapted the algorithm of TANG and DENARDO (1988). Their algorithm minimizes the number of toolreplacements of a one machine problem by first finding an appropriate sequence for the operations and next applying the above mentioned KTNS-procedure on this sequence.
Since we allow for more than one machine and because the operations on the different machines are interrelated by precedence constraints we adapted the Tang/Denardo-algorithm in the following way.
Order the machines according to their workload in decreasing order, schedule machine 1 by the Tang/Denardo-algorithm. After this schedule is finished, update the release and due dates of the other operations in order to satisfy the precedence constraints. Next take machine 2 and repeat the above procedure. When all machines are scheduled we have got a feasible solution. To keep computing time reasonable we apply a rather strong criterion in our check whether an appointed operation by the Tang/Denardo-algorithm is feasible with respect to the precedence constraints. In phase 3, where we look at the

bottleneck machine this criterion is relaxed for this machine as much as possible resulting in more freedom in applying the Tang/Denardo-algorithm. This generally results in a better schedule for the bottleneck machine and if it turns out that another machine has become the bottleneck machine then this relaxed criterion is applied there, etc. During phase 4 we look for interchanges of operations between machines. A criterion, based on the places of the operations in the linear orderings selects an operation out of the bottleneck machine and an operation out of the machine with smallest workload, which are interchanged next. Then our algorithm returns to phase 2. If no better solution can be found in this way, the algorithm stops.

Results.
The above mentioned methods are tested on a set of testproblems for different numbers of machines, parts and operations. These problems have been generated using a random procedure. We investigated 4 groups of 5 problems with respectively 2,3,4 and 6 machines, respectively 4,4,8 and 8 part-types, respectively 2,2,4 and 4 parts per part-type and respectively 2,2,4 and 4 operations per unit. So the total number of operations is respectively 16,16, 128 and 128. In addition to the model described in section 3 we imposed the following three assumptions:

a) Every machine is capable of performing every operation.
b) There exists a linear ordering between the operations of a part.
c) Time needed for tool-replacement depends on the number of tools to be replaced.

The objective is of course to minimize the makespan (of the bottleneck machine). The results can be found in table 1. For the different methods the makespan is given. To establish a measure of quality, we also introduce a ratio showing the performance of the best solution to a lowerbound. This lowerbound is computed by summing the processing times of the operations and dividing this by the number of machines.

TABLE 1. Results method 1 and 2

Testproblem		Method 1				Method 2		
number of machines	problem	Longest Proc Time	Shortest Proc Time	Most Work Remaining	R/P	Phase 1 + Phase 2	Phase 1-4	ratio best solution and lowerbound
2	1	73	75	77	69	71	71	1.17
	2	60	64	64	62	62	62	1.24
	3	64	66	70	58	66	59	1.16
	4	93	91	93	87	87	87	1.19
	5	74	66	74	68	68	64	1.14
3	1	54	49	51	61	59	46	1.15
	2	46	43	46	43	40	39	1.15
	3	48	50	48	44	39	39	1.15
	4	68	65	67	58	58	55	1.12
	5	53	49	48	47	45	45	1.18
4	1	298	290	310	284	282	282	1.22
	2	299	281	285	269	279	275	1.18
	3	330	306	332	300	307	300	1.21
	4	297	269	299	267	277	273	1.19
	5	325	297	333	289	291	284	1.25
6	1	202	191	208	179	187	182	1.15
	2	215	193	199	171	184	180	1.12
	3	231	197	224	193	199	193	1.16
	4	202	193	204	180	188	184	1.20
	5	214	213	220	185	201	195	1.21

It is not possible to compare our results to other approaches in literature, since as far as we know scheduling of operations integrated with the toolloading problem was never done before.
The results in table 1 indicate that from the heuristic rules the fourth one (based on the ratio tool-replacementtime/processingtime) is the favorite one. The results from method 2 are comparable to this rule. However, this method needs more computer time. Table 1 also shows that application of the iterative procedure may improve the solution in phase 1 and 2.

5. CONCLUSIONS

In this paper we have presented a model which combines two important phases in the planning process of an FMS, namely, the system setup phase and the scheduling phase. It turns out that this model generalizes and unifies approaches that deal with the system setup problem. In practical problem instances the model will normally be too large to search for an optimal solution. However, the results from our heuristic approach indicate that it is possible to formulate reasonable iterative algorithms for solving the combined scheduling and tool-loading problems. Experiments with the models of HWANG (1986) and RAJAGOPALAN (1986) also show that heuristics are necessary (see also STECKE and TALBOT (1985) and BERRADA and STECKE (1986)). STECKE and KIM (1988) claim that solutions of models of the flexible approach give a smaller makespan than solutions resulting from the extended batching approach. However, solving iteratively an on-line 0-1 model can be difficult to implement. Further research is necessary to judge the merits of the different approaches. From a practical viewpoint the hierarchical approach is probably most attractive. However, the links between the submodels are of great importance and this aspect of the hierarchical approach seems to be somewhat underexposed. The natural hierarchical structure in the system setup problem is probably responsible for the large attention to the hierarchical approach.

Topics for further research include:
- to find a classification of problem instances into classes of instances suited for a particular approach;
- to relax assumptions in section 1;
- to improve solution methods which solve the production operations problem.

We hope and trust that current research activities in this area will result in an improvement of solutions of FMS production planning problems.

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