INT. J. PROD. RES., 1988, VOL. 26, NO. 4, 585–598

Quasi on-line scheduling procedures for flexible manufacturing systems†

J. SLOMP‡, G. J. C. GAALMAN‡ and W. M. NAWIJN‡

This paper presents three quasi on-line scheduling procedures for FMSs consisting of work stations, transport devices, and operators. In the scheduling, different types of decisions are taken to perform a particular operation, i.e. the selection of (*a*) a work station, (*b*) a transport device and (*c*) an operator. Further, (*d*) the scheduling sequence of the operations has to be determined. The three developed procedures differ in the way these four decision problems are solved hierarchically. Several dispatching rules (SPT, SPT.TOT, SPT/TOT and EFTA) are available to solve the last mentioned decision problem. Limited buffer capacities in an FMS may cause deadlock in the procedures as well as in practice. The scheduling procedures involve a buffer handling method to avoid deadlock. A case study is presented to demonstrate the three procedures and to show some of its properties. Based on simulation tests, some conclusions are drawn about the performance of the scheduling procedures and the various dispatching rules.

1. Introduction

Present users have installed FMSs to achieve the efficiency of automated high volume mass production while retaining the flexibility of low volume job shop production. Several problems arise for the design and operation of an FMS. Stecke (1984) discerns problems in design, planning, scheduling and control which are strongly interrelated. FMS-scheduling includes determining the input sequence of parts into the system and the processing sequence at each station.

Scheduling procedures can be classified as either off-line or on-line. An off-line method is applied at the beginning of a scheduling period and results in a complete schedule for that period (Stecke 1981). For operators in an FMS, it is preferable to have a fixed schedule before work is started. In this way they can anticipate the expected orders. The supervisory control computer (SCC), which controls the actions in the FMS, follows the off-line schedule as long as possible. In case of a significant deviation between the schedule and the actual progress, the schedule has to be revised. In contrast with an off-line procedure, an on-line scheduling procedure evolves in real time, in an event-controlled way.

In this paper three scheduling procedures are presented. Explicit attention is devoted to buffer handling methods in order to avoid deadlock. The developed procedures are based on an activity-model of the real system. In this model the operations (consisting of several activities) are scheduled as time progresses. There is no backtracking in the scheduling procedures. The philosophy of the developed procedures can be used in event-controlled systems. Therefore the procedures can be

Received March 1987.

† Originally published in *Information Control Problems in Manufacturing Technology*, edited by A. A. Tal, Pergamon Press 1987 (Proceedings of IFAC Symposium, 1986).

‡ Department of Mechanical Engineering, Group Production Management and Operations Research, Twente University of Technology, Enschede, The Netherlands.

seen as quasi on-line, although the scheduling is done in advance of real production. Related studies include the work done by Stecke and Solberg (1981), Iwata *et al.* (1982) and Murotsu *et al.* (1983).

This paper is organized in six main sections. The activity-model of FMSs is described in the second section. The third section contains the principal features of the developed scheduling procedures. A method to handle deadlock situations caused by limited buffer capacities is given in the fourth section. The fifth section presents a case study to demonstrate the three procedures. Results of several simulation tests are summarized in the sixth section. Finally, some conclusions are drawn.

2. Activity-model of an FMS

The scheduling procedures are based on an activity-model of an FMS. The main components of this FMS-model are:

(*a*) Work stations (WSs). The conception of WSs includes load and unload stations, machine tools and auxiliary equipment such as wash and inspection stations. An WS can handle only one part at a time.

(*b*) Transport devices (TDs). Transport in FMSs can be done by automated guided vehicles (AGVs). In this model only transports of single parts is assumed.

(*c*) Local buffers. These buffers are placed in front of each work station. The buffer capacities of the local buffers can be any integer, including zero. In the model also a central buffer may be present.

(*d*) Operators. Operators can be assigned to several activities done within the FMS. Their activities can be, for instance, loading and unloading, tool set up and attending a machine tool.

The total transformation of a part consists of several successive processing stages, for example loading, milling, drilling, boring, washing and unloading. For each processing stage alternative WSs can be available.

In a processing stage several activities have to be performed. Four partly overlapping activities are distinguished:

(I) a TD moves to the place where the part is located;

(II) the TD transports the part to the WS or to the local buffer in front of the WS, if one is present;

(III) tools are set up on the WS; and

(IV) the WS transforms the part.

These four activities together will be called an operation (Fig. 1).

Figure 1 shows the relation between the activities in a Gantt chart. The interval between T2 and T4 is waiting time: Activity II can only start if the previous processing stage of the part is finished. At T5 the transport device is free to execute other transports. Between T5 and T7 the part is in the buffer in front of the workstation. In Fig. 1 the work of the operator consists of tool set up and attending the process.

Depending on the kind of transformation (activity IV) and the actual state of the FMS some of the four activities are excluded from the operation. For instance at loading stations, actitities I, II and III are not present. In case of transforming the second, third etc. part of a batch, activity III only occurs in the operation of the first part.

In this activity-model no explicit attention is paid to material handling activities as the loading of the part onto the TD, the unloading of the part from the TD, the loading

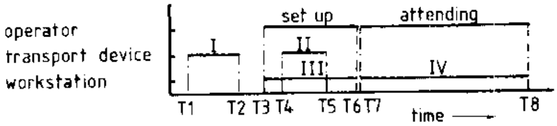


Figure 1. An operation schedule.

of the part onto the WS and the unloading from the WS. These activities have to be included into activities I, II and IV.

The route of a part through the FMS can be seen as a chain of operations. The scheduling procedures have to compose operations and have to determine the sequence in which these operations must be executed.

3. The scheduling procedures

An important property of the procedures is that an operation cannot be scheduled if the operations of the previous processing stages of the part have not been scheduled yet. As a consequence, the procedures start with scheduling an operation at a loading station and end with scheduling an operation at an unloading station. Operations are scheduled one by one and therefore form a sequence: *the scheduling sequence*. This sequence is generated during a scheduling procedure.

In each of the developed scheduling procedures *four basic functions* can be distinguished:

(A) choosing a WS upon which one or more processing stages might be executed;
(B) selecting a TD for the transport activities (I and II) of an operation;
(C) assigning an operator to one or more activities of an operation; and
(D) determining which operation must be placed in the scheduling sequence next.

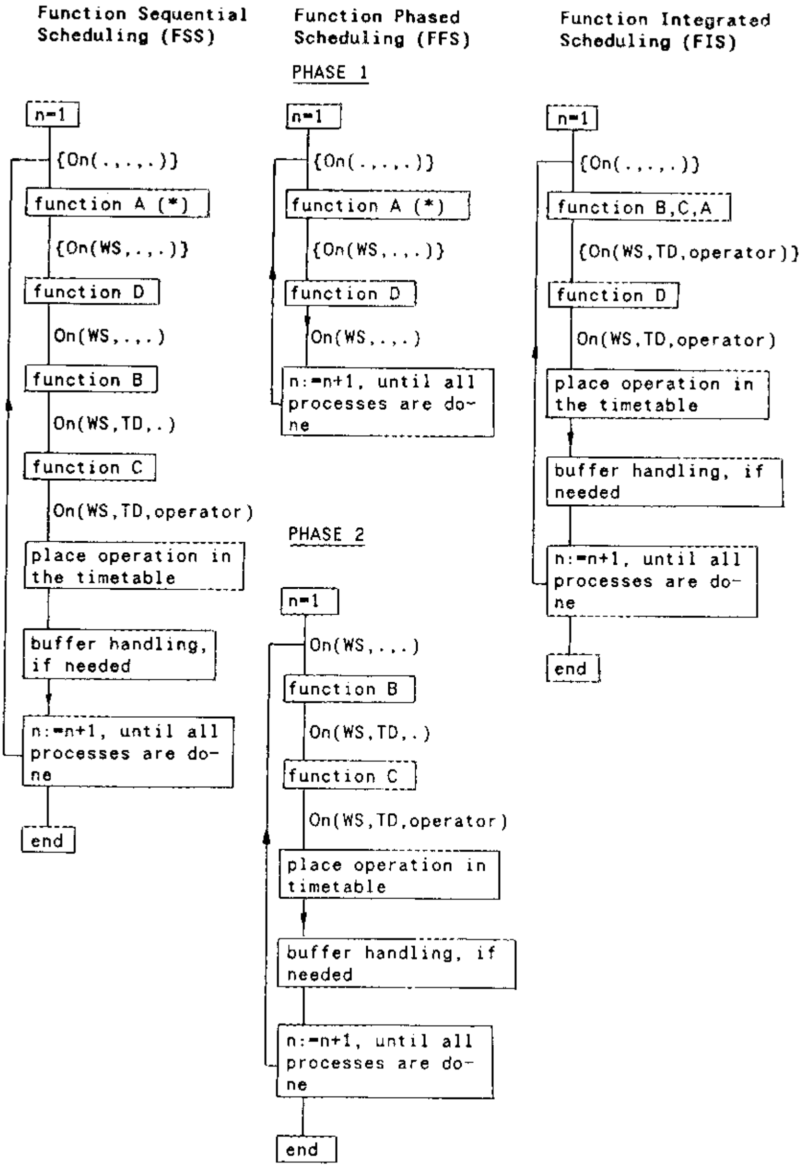
Dispatching rules needed for the execution of these functions will be dealt with later on in this section.

The three scheduling procedures, called Function Sequential Scheduling (FSS), Function Integrated Scheduling (FIS) and Function Phased Scheduling (FPS), differ in the way the four interconnected functions (A, B, C and D) are handled hierarchically. The procedures are schematically presented in Fig. 2. To understand this figure some definitions are introduced:

n : position number of an operation in the scheduling sequence.

{On(WS, TD, operator)}: set of all operations that can be scheduled as the nth operation in the scheduling sequence. For all the operations in this set a WS, a TD and an operator are known. They can be different for different operations in the set. The operation On(WS, TD operator) is related with a particular processing stage of a particular part. When instead of 'WS', 'TD' or 'operator' a dot is given, the 'WS', 'TD' or 'operator' to perform the operation, is not known at that moment in the scheduling procedure.

To explain the procedures a simple example is presented. Figure 3 shows a situation in which three operations are already scheduled. These operations represent respectively the loading (1) and milling (2) stage of part X and the loading (3) stage of part Z. The next operation to be placed in the scheduling sequence, O4(.,.,.), refers to either the drilling stage of part X, the loading stage of part Y or the drilling stage of part Z; O4(.,.,.) $\in$ {O4(.,.,.)}.



(*) Upon determining the information for the dispatching rule it is assumed that a TD and an operator are available at desired time.

Figure 2. Scheduling procedures.

	processing stage 1	processing stage 2	processing stage 3	processing stage 4	processing stage 5
part X	loading (1)	milling (2)	drilling	washing	unloading
part Y	loading	boring	unloading		
part Z	loading (3)	drilling	milling	unloading	

Figure 3. Processing scheme example.

In the FSS procedure first a WS is chosen upon which one or more processing stages might be executed (function A; {O4(.,.,.)}→{O4(WS,.,.)}). Suppose a drilling machine is chosen to perform either the third stage of part *X* or the second stage of part *Z*. This means that {O4(WS,.,.)} contains two operations. Then one of the two operations is selected to be placed in the scheduling sequence (function D; {O4(WS,.,.)}→O4(WS,.,.)). Next a TD (function B) and an operator (function C) are assigned to the operation (O4(WS,.,.)→O4(WS,TD,.)→O4(WS,TD,operator)). Finally the established operation will be placed in the timetable (see below).

In the example of Fig. 3, the FIS procedure starts with 'collecting' all WSs that can handle one or more of the three processing stages. In the example, all drilling and loading stations are put in the 'collection'. For each O4(.,.,.), related to one of these WSs, a TD (function B) and an operator (function C) is selected ({O4(.,.,.)}→{O4(WS,TD,operator), all possible WSs}). Out of all possible WSs, a WS is chosen upon which one or more processing stages might be executed (function A; {O4(WS,TD,operator), all possible WSs}→{O4(WS,TD,operator)}). When here a drilling machine is chosen to perform either the third stage of part *X* or the second stage or part *Z*, then {O4(WS,TD,operator)} consists of two operations. Next, one of these two operations is selected to be placed in the scheduling sequence (function D; {O4(WS,TD,operator)}→O4(WS,TD,operator)). Finally, the selected operation will be placed in the timetable (see below).

The FPS procedure consists of two phases. The first phase starts like the FSS procedure: In the example of Fig. 3, a WS is chosen upon which one or more processing stages might be performed (function A: {O4(.,.,.)}→{O4(WS,.,.)}). Suppose a drilling machine is chosen to execute either the third stage of part *X* or the second stage of part *Z*. Now {O4(WS,.,.)} consists of two operations. Then, as in the FSS procedure, one of these two operations is selected to be placed in the scheduling sequence (function D: {O4(WS,.,.)}→O4(WS,.,.)). After this the first phase repeats this procedure for {O5(.,.,.)}, etc. The first phase can be summarized symbolically by: ({On(.,.,.)}→On(WS,.,.)$\forall n$). In the second phase TDs (function B) and operators (function C) are sequentially assigned to the operations in the scheduling sequence (On(WS,.,.)→On(WS,TD,.)→On(WS,TD,operator)$\forall n$). Established operations will be placed in the timetable.

In each of the three procedures, selected operations have to be placed in the timetable. All three procedures use the same principle. When, in the example of Fig. 3, O4(WS,TD,operator) has to be placed in the timetable, then three operations are already scheduled: the loading and milling operation of part X and the loading operation of part Z. Starting and finishing times of their activities are determined. So it is known when the WS, TD and operator can start with the activities of O4(WS,TD,operator). Taking into account these earliest possible starting times, the activities of O4(WS,TD,operator) are placed in the timetable. If, as a consequence of all this, the buffer in front of the WS is used up, then the buffer handling method of the next section comes into in action.

In contrast with the FSS and the FPS procedure, the FIS procedure takes into account the consequences of choosing a TD and an operator before an operation is selected to be placed in the scheduling sequence. Therefore it is expected that the FIS procedure is better in situations where the workload of the TDs and/or operators is heavy. On the other hand, the FIS procedure might need high CPU times. Moreover, it is expected that the CPU times of the FIS procedure will be sensitive to the number of parts, WSs, TDs and operators. To preclude this disadvantage, the FSS procedure is developed. Here the selection of an operation, to be placed in the scheduling sequence, depends only on the state of the WSs. In the FPS procedure the scheduling sequence of the operations and the routing of the parts is fixed in the first phase of the procedure. This feature might offer advantages with respect to the buffer handling method (see § 4).

Execution of functions A, B, C and D is done by dispatching rules. Simple rules are used for functions A, B and C:

A: The WS that can start at the earliest possible moment, is chosen. (This rule also limits the set of schedulable operations on the WS to those that can start at that particular moment.)

B: The TD that can finish its activity at the earliest moment is chosen. When there are several TDs with the same finishing time, the TD with the least moving time is picked out;

C: The operator who can finish his activities at the earliest moment is selected for the operation. If several operators have the same finishing time, the operator who needs the least walking time is chosen.

For function D several dispatching rules are available. In the examined situations the following dispatching rules are used:

SPT: Shortest Processing Time;

SPT/TOT: Shortest Processing Time divided by the TOtal processing Time (Stecke 1981);

SPT.TOT: Shortest Processing Time multiplied by the TOtal processing Time (Stecke 1981);

EFTA: Earliest Finishing Time with Alternatives considered; the schedulable operations are extended with their alternatives. An alternative operation refers to the same processing stage on another machine. The operation with the earliest finishing time is chosen (Iwata *et al.* 1980).

4. Buffer handling

In an FMS the use of buffers is desirable. Buffers (local and/or central) are needed to smooth the production flow. In practice the capacities of the buffers are limited. Therefore, in the model, the capacities of the local buffers can be set to any integer, including zero. Limited buffer capacities, however, cause the risk of deadlock in the procedures as well as in practice, see e.g. Carrie *et al.* (1983).

In the procedures deadlock would occur if there is no $On(.,.,.,.) \in \{On(.,.,.,.)\}$ that can be scheduled. This situation arises if for every $On(.,.,.,.) \in \{On(.,.,.,.)\}$ it is impossible to determine the earliest starting and finishing time of at least one of its activities. Fully occupied buffers are the cause. This can be demonstrated with the example of Fig. 4.

In Fig. 4 the four underlined operations are already scheduled. The next operation to be scheduled has to refer either to the drilling stage of part X, the loading stage of part Y or the milling stage of part Z. Suppose the buffers in front of the drilling machines and the milling machines are fully occupied. Then it will not be possible to schedule an operation $O5(.,.,.,.)$ which relates to the third stage or part X or the third stage of part Z. Perhaps a TD is available to fulfil activity I and II of one of these operations. However it is impossible to free the TD since the buffer in which the part has to be placed, is fully occupied. Therefore the finishing time of activity II cannot be determined and consequently scheduling is impossible. As a consequence $O5(.,.,.,.)$,

	processing stage 1	processing stage 2	processing stage 3	processing stage 4	processing stage 5
part X	loading	milling	drilling	washing	unloading
part Y	loading	boring	unloading		
part Z	loading	drilling	milling	unloading	

Figure 4. Processing scheme example.

O6(.,.,.) and O7(.,.,.) will refer to the first, second and third stage of part *Y*, respectively. O8(.,.,.), however, is blocked because of the buffer situation and deadlock occurs. It should be noted that blocking in the procedures occurs regardless of the number of transport devices.

The following method is developed to prevent deadlock in the scheduling procedures. Consider the situation in which all operations O*n*(.,.,.) can be scheduled. When an operation O*n*(WS*, TD*, operator*) is scheduled and the buffer belonging to WS* becomes fully occupied, then all O$n+k$(WS*,.,.) [$k \geq 1$] are blocked until a part is removed from the buffer. In the scheduling procedures this situation is not accepted; after the scheduling of O*n*(WS*,TD*,operator*) an action is undertaken to remove a part out of the buffer. The part in the buffer of WS* that has already undergone a processing at this WS*, is loaded onto TD*. If there are more parts available in this buffer, then the part with the earliest finishing time on WS* is selected†. TD* is now loaded with the selected part.

The question arises what to do with the part loaded onto TD*. In the FSS and FIS procedure there are two possibilities related to situations with and without a central buffer:

1. With a central buffer. The part stays on TD* until the operation of its next processing stage has been scheduled. If, however, it is advantageous to use TD* for the transport activities of another operation, at an earlier moment, then TD* brings the part to the central buffer (The extra move to the central buffer has to be taken into account.).
2. Without a central buffer. The part stays on TD* until the operation of its next processing stage has been scheduled. Until that moment TD* cannot be assigned to other operations‡.

In the FPS procedure an extra possibility to handle the part on the TD* is present. In the first phase of the procedure the routing of the parts through the FMS has already been determined. So the next station where the part has to be processed, is known. This offers the possibility of bringing the part directly to this station. This action is not executed if the local buffer of that WS becomes full. In that case the same buffer handling method of the FSS and FIS procedure is adopted.

Possibility 2 can be problematic for the FPS procedure: When all TDs are holding parts it might be impossible to schedule the operations in the sequence determined in the first phase of the procedure. In that case intervention in the second phase of the

† In case of no local buffer, TD* waits until the part associated with O*n*(WS*,TD*,operator*) is ready on WS*. This part is then loaded onto TD*. In case of a loading operation, for which no TD is needed, a transport device has to move to WS* to load a processed part.

‡ Consequently, if all TDs are holding parts, then the next operation that will be scheduled (O$n+1$(.,.,.)), has to relate to a part on one of the TDs. This effects the selection freedom of function A (selection of a WS) in the procedures.

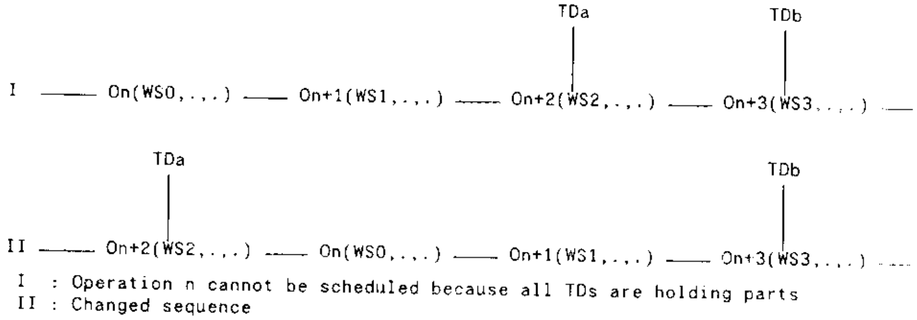


Figure 5. Example of intervention in the scheduling sequence.

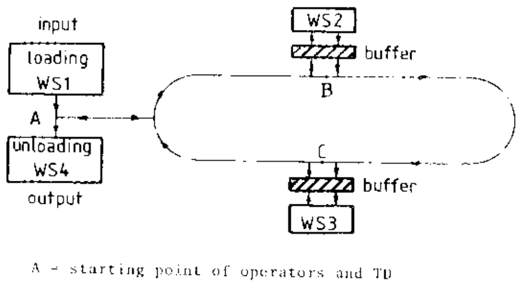
procedure is necessary. Figure 5 shows an example of how this intervention is done. There are two TDs in this example: TDa and TDb. Both TDs are holding parts. The next operations associated with these parts are, for example: $On+2$(WS2,..,.) and $On+3$(WS3,..,.). It is now impossible to find a free TD for On(WSO,..,.) in the second phase of the PHS roccdure. Intervention is now done by moving the position of $On+2$(WS2,..,.) to the front of the scheduling sequence as indicated in Fig. 5.

5. Case study

Before installing an FMS, computer simulation is desirable to determine the dimensioning parameters of the FMS and to choose the most effective scheduling procedure and dispatching rules. The usefulness of the developed procedures is shown by a case study.

The FMS of this case study consists of a load station (WS1), an unload station (WS4) and two machining centres (WS2 and WS3). The machining centres can perform the same processes. WS3, however, is less sophisticated than WS2: the processing times on WS2 are smaller. There are local buffers in front of each machining centre with the capacity of two parts. The layout of the system is given in Fig. 6. The part types to be produced on the FMS and their processing schemes are shown in Fig. 7. Tool setup time, Table 1, is dependent on the machine tool and the processing stage of the part type. With the bottleneck model, see Solberg (1981), it can be shown that one transport device and at least two operators are needed. The operators are identical. Moving times of the TD and the operators are given in Tables 2 and 3.

In this case parts are sequentially admitted to the system according to the part type sequence: 1 4 5 2 3 1 4 5. This sequence can be repeated as often as needed. The above



A = starting point of operators and TD

Figure 6. Layout of the FMS.

part type	PS1	PS2	PS3	PS4
1	1(10)	2(30)/3(35)	2(5)/3(10)	4(10)
2	1(12)	2(10)/3(15)	2(25)/3(30)	4(12)
3	1(8)	2(15)/3(20)	2(15)/3(20)	4(8)
4	1(10)	2(15)/3(25)	4(10)	
5	1(5)	2(20)/3(25)	4(5)	

PS : processing stage
x(y) : x=workstation; y=transformation time (IV)
/ : shows that there is an alternative station that can handle the processing stage

Figure 7. Machining scheme of the part types.

WS	PS	part types 1	2	3	4	5
2	2	10	5	5	5	10
2	3	5	5	5	5	5
3	2	10	5	5	5	10
3	3	5	5	5	5	5

(PS: processing stage).

Table 1. Tool set up times.

From	To A	B	C
A	0	1	3
B	3	0	2
C	1	2	0

Table 2. Moving times of the TD.

From	To A	B	C
A	0	0·5	0·5
B	0·5	0	1
C	0·5	1	0

Table 3. Moving times of operators.

sequence shows that the part type ratio in this case is 2 : 1 : 1 : 2 : 2 for part types 1 to 5, respectively. The total number of parts simultaneously present in the system can be set to a limit. In this case study the maximum number to be chosen is 5.

Figure 8 (*a*) gives some results of tests in which the total number of parts that have to be produced and the scheduling procedures are varying. All results are obtained using the SPT rule. The results are presented by means of the makespan divided by the total number of parts produced. The makespan is defined as the total time required by the system to produce the parts. The FIS procedure is better than the other procedures. Apparently, in this case, it is important to look at the states of the TD and the operators before an operation will be placed in the scheduling sequence. In contrast with the other procedures, the FIS procedure does just this.

Compared with the other procedures, the FPS procedure performs much worse. This is caused by the buffer handling method used in this procedure. Because of the small local buffers, intervention in the scheduling sequence is often necessary. This intervention disturbs the scheduling sequence determined in the first phase of the procedure and consequently, increases the makespan. It also causes the irregularity of the results.

In the case studied, it appears that the workload of the operators is heavy, regardless of the total number of parts. For that reason some tests are done with three operators. Figure 8 (*b*) shows some results. Beside the fact that the overall results are better, it can be seen that the differences between the procedures become smaller.

The CPU times are mentioned in Table 4. The FSS procedure required the least CPU time. However, only a small difference can be noted between the CPU times for the FSS and the FIS procedure. In case of more WSs, TDs, operators and parts (in the system) this difference is greater. The CPU time for the FPS procedure is strongly dependent on the total number of parts that has to be produced.

Figure 9 shows a Gantt chart of the situation in which only part types 1, 2 and 3 have to be produced. The input sequence of part types is: 1 3 1 2. The outcome is obtained from the FIS procedure in which the SPT rule executes function D. The Gantt chart is generated by a separate program. In this Gantt chart an effect of the buffer handling method can be seen. At time 54 the TD arrives at WS3, carrying part type 1, number 1. Because of a fully occupied buffer, part type 3, number 1, will be loaded onto the TD. Until time 68 the TD acts as a temporary buffer of WS3.

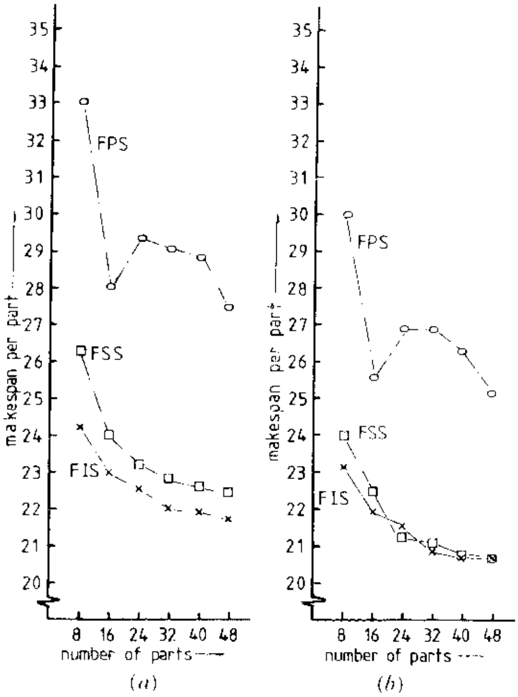
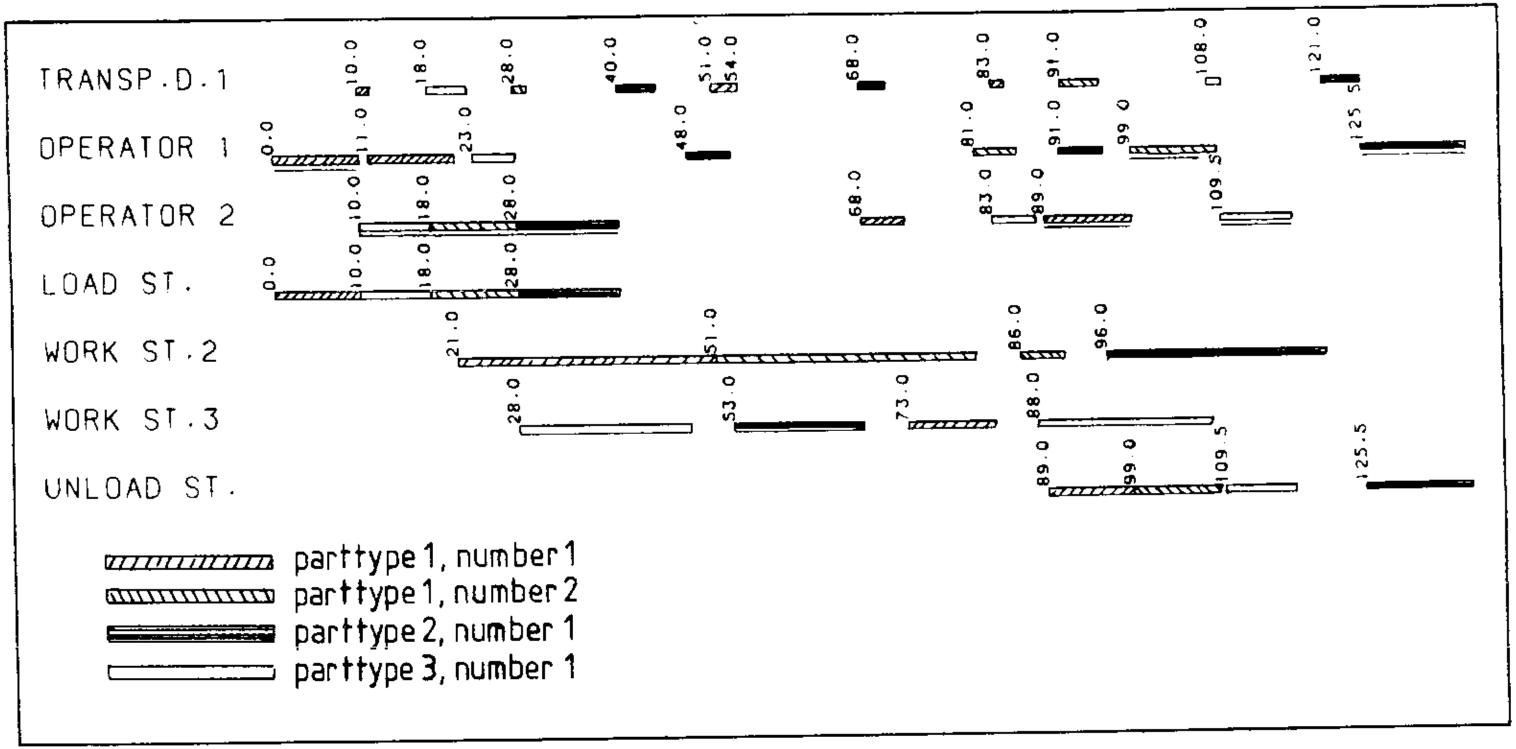


Figure 8. Results of the case study. (*a*) Two operators. (*b*) Three operators.

	Total number of parts that has to be produced					
	8	16	24	32	40	48
FSS	0·2	0·5	0·9	1·4	2·0	2·7
FIS	0·3	0·6	1·1	1·6	2·2	3·0
FPS	0·4	1·9	4·6	9·3	16·1	25·5

Table 4. CPU-times (seconds).



- A line under the operators schedule means a loading or unloading activity
- Only the starting times of the activities are noted here

Figure 9. Gantt chart with respect to FIS-SPT.

6. Simulation tests

Several tests are done to get an idea about the behaviour of the developed procedures. Special attention is given to the relative performances of the dispatching rules (SPT, SPT.TOT, SPT/TOT and EFTA). The studied FMS situations are randomly generated. Table 5 presents the most important characteristics of the generated FMS problems.

In each simulation, scheduling starts with an empty system. The workload of the TDs and operators in neither case forms a bottleneck. Altogether, 20 different situations are tested. The system performance is presented by means of makespan and mean flow time. The mean flow time is defined as the mean time that a part is in the system, measured from the moment that the loading operation of the part starts.

The outcomes of each test are normalized with respect to FIS—SPT. Averaged results of all (normalized) tests are shown in Tables 6 and 7. The number between the brackets shows how many times a dispatching rule performs best by using a particular procedure. It appears that the results from the FSS and FIS procedure are almost the same. This is caused by the light workload of the TDs and operators. The results of the FPS procedure are inferior compared to the other procedures. The SPT/TOT rule performs better when the makespan is taken as performance measure. This result is

Number of machines	: 5–10
Number of machine types	: 3
Capacity of the local buffers	: 1
Number of loading and unloading stations	: enough to form no bottleneck
Number of parts to be produced	: 10–50
Number of different part types	: 5–10
Number of processing stages of parts	: 3–6
Transport time of TDs	: 1·6–2·8 min.
Tool set up times	: 0
Machining times	: 5–25 min.

Notes: 1. There is a central buffer;
2. Parts are cyclically (dependent on the part type ratio) introduced in the system; and
3. No limit is set to the number of parts simultaneously present in the system.

Table 5. Characteristics of the generated FMS problems.

	SPT	SPT.TOT	SPT/TOT	EFTA
FSS	100·3(3)	102·0(2)	97·3(16)	100·3(4)
FIS	100·0(2)	100·3(3)	97·1(14)	99·8(4)
FPS	102·8(2)	103·2(2)	98·7(15)	102·9(3)

Table 6. Makespan results.

	SPT	SPT.TOT	SPT/TOT	EFTA
FSS	99·4(10)	99·1(13)	104·2(2)	99·4(8)
FIS	100·0(6)	99·5(14)	104·3(1)	99·9(6)
FPS	103·4(11)	102·6(12)	106·9(0)	103·3(11)

Table 7. Mean flow time results.

comparable with the results of Stecke and Solberg (1981). The SPT/TOT rule, however, causes relatively high mean flow times. The SPT.TOT rule provides the opposite result: the makespan is relatively bad and the mean flow time good. In the situations considered, there is almost no difference between the SPT and EFTA rule. The preference for the EFTA rule, as found by Iwata *et al.* (1980), is not confirmed by our results.

Besides these tests, supplementary tests are done which confirm the results of the case study in the last section.

7. Conclusions

Three quasi on-line scheduling procedures for FMSs are presented in this paper. The philosophy of these procedures can be used in event-controlled systems.

Limited buffers may cause deadlock in the procedure as well as in practice. This paper presents a method to avoid deadlock. The method is integrated in the procedures. The developed procedures are useful to measure the effects of varying the dimensioning parameters of an FMS. For instance, in the case study, the consequence of using three instead of two operators is shown.

The following conclusions can be drawn about the performance of the procedures and the dispatching rules:

1. In case of a heavy workload of the transport devices and/or operators the FIS procedure is preferred.
2. If the workload of the transport devices and operators is not heavy, then the FSS procedure is preferable because of the low CPU time.
3. In comparison with the other procedures, the FPS procedure performs worse.
4. The SPT/TOT rule leads to better makespan results than the other rules.

References

CARRIE, A. S., ADHAM, E., STEPHENS, A., and MURDOCH, I. C., 1984, Introducing a flexible manufacturing system. *International Journal of Production Research*, **22**, 907–916.

IWATA, K., MUROTSU, Y., and OBA, F., 1980, Solution of large-scale scheduling problems for job-shop type machining systems with alternative machine tools. *Annals of the CIRP*, **29**, 335–338.

IWATA, K., MUROTSU, Y., OBA, F., and YASUDA, K., 1982, Production scheduling of flexible manufacturing systems. *Annals of the CIRP*, **31**, 319–322.

MUROTSU, M., OBA, F., IWATA, K., and YASUDA, K., 1983, A production scheduling system for flexible manufacturing systems. In E. A. Warman (Ed.), *Computer Applications in Production and Engineering* (North-Holland Publishing Company), pp. 957–971.

SOLBERG, J. J. (1981). Capacity planning with a stochastic workflow model. *AIIE Transactions*, **13**, 116–122.

STECKE, K. E., 1981, Production planning problems for flexible manufacturing systems. Ann. Arbor (Mich): University, *Diss. Purdue University*.

STECKE, K. E., 1984, Design, planning, scheduling, and control problems of flexible manufacturing systems. *Proceedings of the First ORSA/TIMS Special Interest Conference of Flexible Manufacturing Systems*, pp. 1–7.

STECKE, K. E., and SOLBERG, J. J., 1981, Loading and control policies for a flexible manufacturing system. *International Journal of Production Research*, **19**, 481–490.

Cet article présente trois procédures de programmation quasi-directes destinées à des systèmes de fabrication flexibles qui consistent en postes de montage, dispositifs de transport et opérateurs. Au cours de la programmation, il est pris divers types de décisions afin d'exécuter une opération donnée, à savoir sélectionner (*a*) un poste de montage, (*b*) un dispositif de transport et (*c*) un opérateur. En outre, la séquence de programmation des opérations (*d*) doit être établie. Les trois procédures élaborées diffèrent dans la manière de résoudre hiérarchiquement ces 4 problèmes de décision. L'on dispose de plusieurs régles d'envoi (SPT, SPT.TOT, SPT/TOT et EFTA) pour résoudre le dernier de ces problèmes. Des capacités tampon limitées au niveau d'un système de fabrication flexible risquent d'entraîner une impasse au niveau des procédures et de l'exécution. Les procédures de programmation ont recours à une technique de traitement tampon afin d'éviter l'impasse. Il est présenté une étude de cas pour démontrer les trois procédures et indiquer certaines propriétés. Sur la base d'essais de modélisation, des conclusions sont tirées quant à la performance des procédures de programmation et aux règles d'envoi.

Dieser Beitrag stellt drei quasiprozeßgekoppelte Ablaufplanungsverfahren für flexible Fertigungssysteme (FMS) vor, die aus Bearbeitungsstationen, Fördermitteln und Bedienungspersonal bestehen. Bei der Ablaufplanung müssen zur Ausführung eines bestimmten Arbeitsvorgangs verschiedenartige Entscheidungen getroffen werden, d.h. zunächst muß die Wahl (*a*) einer Bearbeitungsstation, (*b*) eines Fördermittels und (*c*) einer Bedienperson erfolgen, und dann muß (*d*) die Ablauffolge der Arbeitsvorgänge festgelegt werden. Die drei entwickelten Verfahren unterscheiden sich durch die Art und Weise, in der diese vier Entscheidungsprogleme hierarchisch gelöst werden. Zur Lösung des letztgenannten Entscheidungsproblems gibt es verschiedene Abfertigungsregeln (SPT, SPT.TOT, SPT/TOT und EFTA). Begrenzte Werkstückspeichermöglichkeiten in einem FMS können jedoch einen Totpunkt in das Verfahren und in die Praxis bringen. Die vorgeschlagenen Ablaufplanungsverfahren enthalten eine Methode zur Verwalthung des Werkstückspeichers, die einen Totpunkt vermeidet. Anhand einer Fallstudie werden die drei Planungsverfahren vorgeführt und werden einige ihrer Merkmale aufgezeigt. Auf Grund von Simulationstests werden dann einige Folgerungen über die Leistungsfähigkeit der Ablaufplanungsverfahren und der verschiedenen Abfertigungsregeln gezogen.