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PRODUCTION CONTROL FOR A FLEXIBLE MANUFACTURING CELL

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Production Control for a Flexible Manufacturing Cell
- Case Study: Stork Plastics Machinery B.V. -

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ABSTRACT

This paper describes the production control issues of a flexible manufacturing cell (FMC) consisting of a machining center, a pallet storage, a rail-guided transport vehicle for pallets, and one clamping/unclamping station. The current production control system of the particular firm shows several deficiencies with respect to the FMC. This paper proposes a change in the current production control hierarchy and the introduction of some new methods to solve major production control problems.

The approach and methods described in this paper differ from the usual literature because they take real-life aspects into consideration, such as due dates, limited number of available fixtures, limited floor space for waiting parts, and the use of an unpersonned shift. Furthermore, several organizational aspects are considered in this paper.

There is some evidence that the approach and methods proposed in this paper offer significant improvements over the firm's current practice. This conclusion, however, is somewhat premature since the approach and methods are not yet implemented.

1. STORK PLASTICS MACHINERY B.V. AND ITS FMC

Stork Plastics Machinery B.V. is an independent subsidiary within the Stork group of companies, one of Europe's largest producers of capital goods and industrial services. Founded in 1967, Stork Plastics Machinery quickly grew to become a well-known manufacturer of injection moulding machines. With a wide range of market-oriented products, Stork is an important manufacturer of innovative injection moulding machines.

Each injection moulding machine represents a value of between 300,000 and 1.5 million Dutch guilders. The firm is able to assemble and ship 2 to 4 moulding machines per week. In 1990, 132 injection moulding machines were sold, which represent a turnover of about 100 million Dutch guilders. The world market share is about 4%. About 80% of the machines are exported to Germany.

In 1990, the production and sales of a new range of injection moulding machines started, the so-called Stork SX-T injection moulding machines. The firm expects a significant increase in demand in the coming years.

Most of the about 1300 components needed in the assembly of the moulding machines are purchased. Only 50 components, concerning the more voluminous part types, are processed in the firm's own manufacturing department. All purchasing and manufacturing activities are customer order driven.

In 1990, the firm installed an FMC (see Figure 1) in their manufacturing department as a replacement for two horizontal milling machines. The cell consists of a CNC machining center with a 110-slot capacity tool magazine, a parts pallet storage with a capacity of 6 FMC pallets, a rail-guided pallet transport vehicle, and one clamping/unclamping station. Both the exchange of cutting tools in the tool magazine and the clamping and unclamping of parts on the pallets is done manually. Near the clamping/unclamping station, a special area is reserved for raw materials, in-process parts, and finished parts. This area has a capacity of about 20 pallet boards; the raw material needed for one order is generally held by one pallet board. A hoist is installed for the transportation of the heavy parts to and from the clamping/unclamping station.

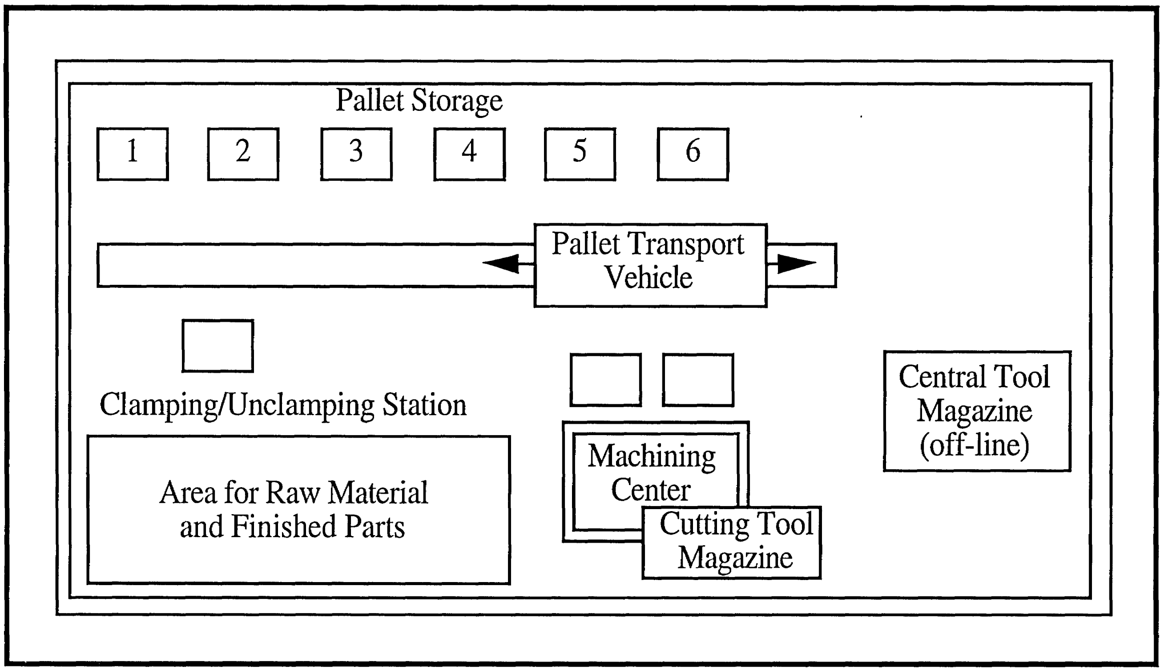

Figure 1. Schematic representation of the FMC at Stork Plastics, Hengelo, The Netherlands.

The parts assigned to the FMC often need some customer-specific processing. Therefore, the number of different NC programs increases steadily. To date, there are over 1000 NC programs for about 20 part type families, which need over 200 different cutting tools, and more of each will be required in the future.

Production requirements range from 1 to 12 parts per order, with an average of 2.5. Parts are made of cast iron. Each part requires 1, 2, or 3 refixturings, in order to manufacture more than one side of the part. Sometimes, parts in different stages of refixturing can be placed on the same pallet, but mostly another pallet is needed for refixturing. The manufacturing process that has to be performed on the parts loaded on a pallet, is called an operation. The FMS operates with 7 pallets/fixtures: 3 columns, 2 flat plates, and 2 angle plates. Operation times per loaded pallet/fixture (=operation) range from 10 minutes to about 120 minutes. The number of cutting tools required per operation range from 5 to 25; each tool takes 1 (90%) or 3 (10%) slots. Tool life varies from 10 to 40 minutes of cutting time.

The FMC works in two personned shifts, with one operator per shift. The operators are, among other things, responsible for clamping/unclamping, deburring, the assembly and disassembly of cutting tools, tool changing, and some quality checks. NC programs are written in the Process Planning department. During the day shift (see Figure 2), an extra operator does some clamping/unclamping activities. To date, the FMC is not running unattended during the night shift. However, an imminent future third shift is planned, with unpersonned operation. The employees of the planning and process planning department are only present during the day shift.

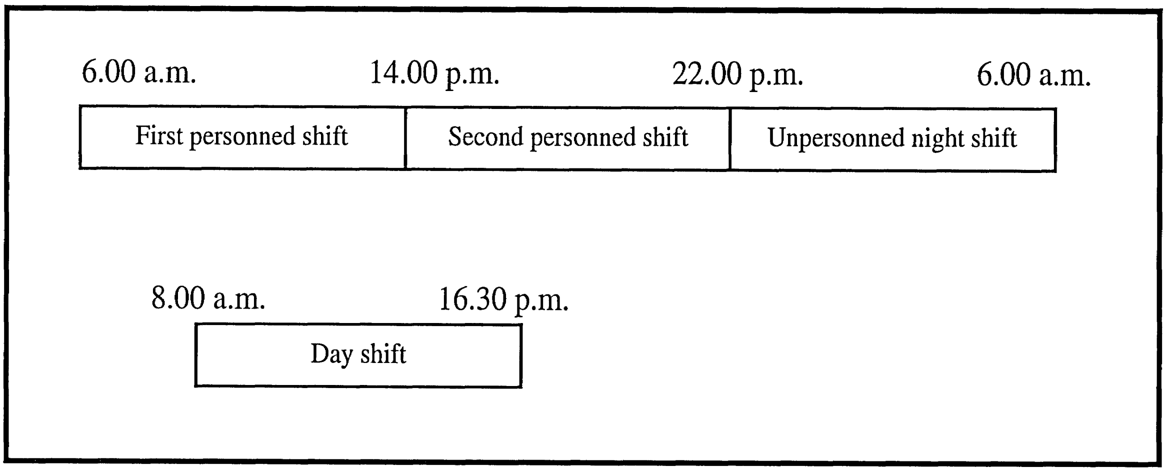

Figure 2. Shifts at Stork Plastics Machinery B.V.

Since the installation of the FMC in 1990, several technical problems have been solved. For instance, some part types which initially had been planned to be processed in one operation, had to be processed in two or more operations (= refixturings), due to some instability of the machine. Most technical problems are presently solved. Recently, attention is focused on changes that should be made in the production control system, in order to improve the efficiency and effectiveness of the FMC. The next two sections deal with the current production control system and the proposed improvements, respectively.

Section 2 describes the current production control system and shows why it is not satisfactory. Section 3 proposes a new production control hierarchy, where at each level of the hierarchy one or more production control problems have to be solved. One of the most complex problems is on the Shop Floor Control Level and concerns the selection and sequencing of operations. Section 4 describes and discusses briefly some ways of solving these problems. In Appendix A the proposed methods are described in detail. These methods are illustrated by means of an example worked out in detail. Section 5 presents the main conclusions of the research presented in this paper.

2. THE CURRENT PRODUCTION CONTROL SYSTEM

This section describes the current production control system of Stork Plastics Machinery B.V. and overviews the impact of the system on the functioning of the FMC.

2.1 Current Production Control System

The production control of the firm consists of three hierarchical control levels: a *Master Planning Level*, a *Production Management Level*, and a *Shop Floor Control Level.* The *Master Planning Level* is basically responsible for generating orders for the FMC. On a strategic level, it is decided that 2 to 4 injection moulding machines per week can be assembled and shipped to customers. As mentioned before, the purchasing of components and raw materials, the manufacturing, and the assembly are customer-order controlled. Each injection moulding machine has customer-specific parts (mostly variants of specific part types). Engineering makes drawings for these parts. Process Planning subsequently determines the routings of the parts through the manufacturing department and estimates the required processing times. After this, the Bill of Materials (BoM) of a particular injection moulding machine is known, and the information will be processed by IBM's MAPICS. MAPICS is running weekly. The estimated planned lead times for assembly, manufacturing, and purchasing are depicted in Figure 3. As can be seen, manufacturing is planned so that all of the components for a particular machine are available and can be kitted two weeks before the day that the assembly of the particular injection moulding machine is supposed to begin. These two weeks are the safety lead time and are built in mainly because of problems with the delivery of raw material. The activities are then scheduled backwards by MAPICS.

The second level of the production control system is the *Production Management Level.* At this level, an important objective is to realize the internal due dates of the orders in an efficient way. Therefore, the Production Management Level has to turn the manufacturing capacity into the order flow. The Production Management Level receives weekly information from MAPICS about the capacity needed for each machine, including the FMC, covering a period of eight weeks. Based on this information, capacity decisions can be made regarding overtime, weekend work, and/or subcontracting.

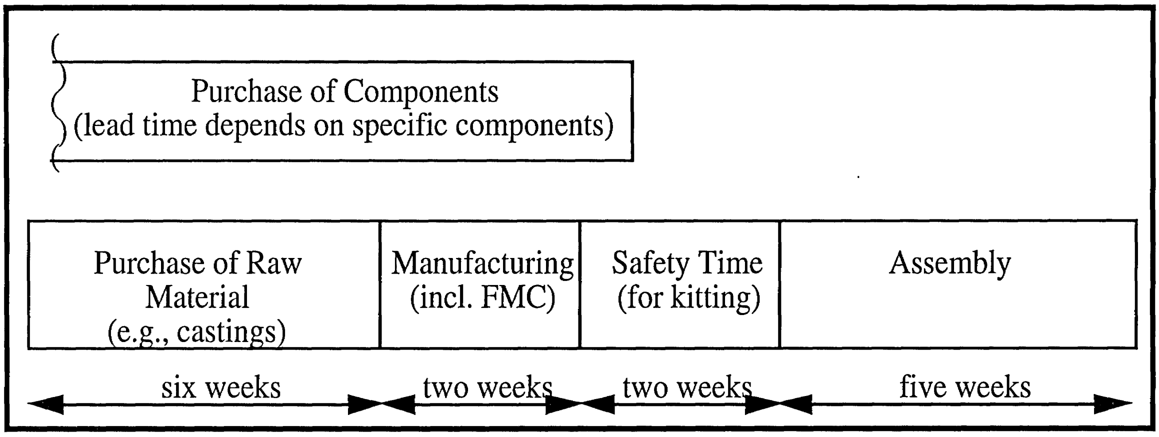

Figure 3. Lead times for the assembly, the manufacturing, and the purchasing.

The third level of the production control system is the *Shop Floor Control Level.* The flow of parts through the manufacturing department is controlled by the Shop Floor Control Level. Input to this level is a daily MAPICS list of orders. During the night, the MAPICS list is automatically updated: Finished orders, barcoded for MAPICS use, are removed from the list, and new orders, for which material is available and previous operations are done, are added to the list. Each machine has its own MAPICS list. Orders are sequenced on the list according to a critical ratio rule (see Vollmann et al., 1992 and Nahmias, 1993) that considers internal due dates (that is, the day manufacturing is scheduled to be finished) and the cumulative processing time required for an order in the manufacturing department. The total processing time of an order needed on the FMC includes the machining time, clamping and unclamping time, refixturing time, and the expected inefficiency in machining. This processing time is also used for the workload calculations at the Production Management Level. *This creates a calculation error from MAPICS* because most clamping, unclamping, and refixturing occurs while the machine is processing a different part. Operators have the task of processing the orders as much as possible according to the sequence determined by MAPICS. The orders on the MAPICS list of the FMC represent a cumulative workload of one, two, or sometimes even three weeks on the machining center.

2.2 FMC Production Control Problems

Each level of the production control system has a certain impact on the performance of the FMC. This subsection describes the problems of the FMC caused by the activities on each of the production control levels.

On the *Master Planning Level*, there are plans to decrease the safety time from two weeks to one week (see Figure 3). This will demand a higher delivery performance from the FMC and other machines in the manufacturing department. Furthermore, the strategic input (2-4 injection moulding machines per week) of the Master Planning Level will probably change because of increased sales of the new SX injection moulding machines. This fact will stress the need to use the FMC optimally. It is also important to prepare the FMC for the imminent implementation of a third unpersonned night shift.

The *Production Management Level* has to load the FMC in such a way as to realize a high utilization of the machining center while meeting the internal due dates of orders. The capacity module of MAPICS gives some information about the capacity required for all of the orders, but this information is not accurate. As mentioned in Section 2.1, there is an error in the calculation of the workload. Furthermore, it is frequently difficult for the Production Management Level to realize the due dates of orders because of unforeseeable events, such as machine breakdowns, rush orders, and the missing of raw material. An additional importance of implementing a third unpersonned shift is emphasized at the Production Management Level because of the technical depreciation of another milling machine.

The most serious problem on the *Shop Floor Control Level* concerns the sequence in which the orders will be processed. As already mentioned, operators are supposed to process the orders according to the sequence given in the MAPICS list, which is based on the critical ratio rule. There are, however, several good reasons why they choose to deviate from the suggested due date-oriented schedule:

- Required raw material may not yet be in the designated area. This area can hold approximately 20 orders, which reflects about 2 days' work;

- Part programming for a new part type may not yet be finished;

- Required fixtures may be already in use for other orders/operations. The number of fixtures of each type is limited. Several orders/operations may need the same type of fixture. These orders/operations cannot be simultaneously in process, due to the limited number of this type of fixture;

- Too many tools may have to be changed if the orders/operations were processed according to the given MAPICS sequence. The capacity of the tool magazine is limited. Manual change of tools is unavoidable. The time needed for the assembly of a (modular) tool, presetting, and exchange is about 10 minutes. Although some of this can be done during machining time[1], it is desirable to minimize the time needed for these tasks. In practice, idle time frequently occurs on the machining center because of the required number of tool changes (with accompanying assembly/disassembly, presetting, and exchange activities); and

- Cutting tools may not be available. Cutting tools may be broken or may need to be refurbished or replaced. Tool life is limited. At the beginning of a process (operation), the control computer of the FMC gives a message if there is not enough time left for the cutting tool to finish the process. Refurbishing of a cutting tool takes about 3 to 5 minutes. In practice, the setting of tool lives is conservative, and refurbishing is done during the processing of the next operation, which hopefully doesn't need the cutting tool. Cutting tools which are needed frequently, are duplicated in the tool magazine of the machining center.

There are also personal reasons why operators may choose to deviate from the MAPICS sequence. Operators may prefer, for instance, to avoid complex or difficult tasks, to do interesting things first, or to balance their workload with the load of the next shift.

Another problem with the MAPICS list is that the workload of the FMC varies considerably in terms of the number of orders (i.e., processing hours) on the list. As a consequence, the throughput times of the released orders are not easily predictable, and expediting is quite normal in the firm.

3. IMPROVING THE PRODUCTION CONTROL SYSTEM

Section 2 shows the need for improvements in the production control system for the FMC. Subsection 3.1 gives an overview of the most relevant issues which are of importance for the improvement of the current production control system. Subsection 3.2 presents the proposed production control hierarchy.

3.1 Production Control Issues

Table 1 lists the major issues which cause the complexity of the production control problems. Three categories of issues can be distinguished: (1) the *goals* of the production control function; (2) the *limitations* with respect to the redesign of the production control system; and (3) the *control problems* which have to be addressed.

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1) At the beginning of a process (operation), the system computer of the FMC provides information about which cutting tools needed for processing a part are missing from the tool magazine. If the operator only uses this information, then idle time on the machining center results, due to the exchange of tools. This was the case in the first year after the implementation of the cell. At the moment a simple software program is available, which provides the information to the operators earlier.

Table 1. Major Production Control Issues.

Goals:

- A high utilization of the FMC;
- A high delivery performance of the cell.

Design Limitations:

- The Master Planning Level has to be seen as unchangeable. The number of orders per week and the planned lead times are determined on this level;

Control Problems:

- How to deal with all of the reasons of the operators to deviate from the suggested due date-oriented order List (see Subsection 2.2) ?
- How to use the unpersonned night shift optimally, in the near future ?
- How to deal with rush orders and machine breakdowns ?

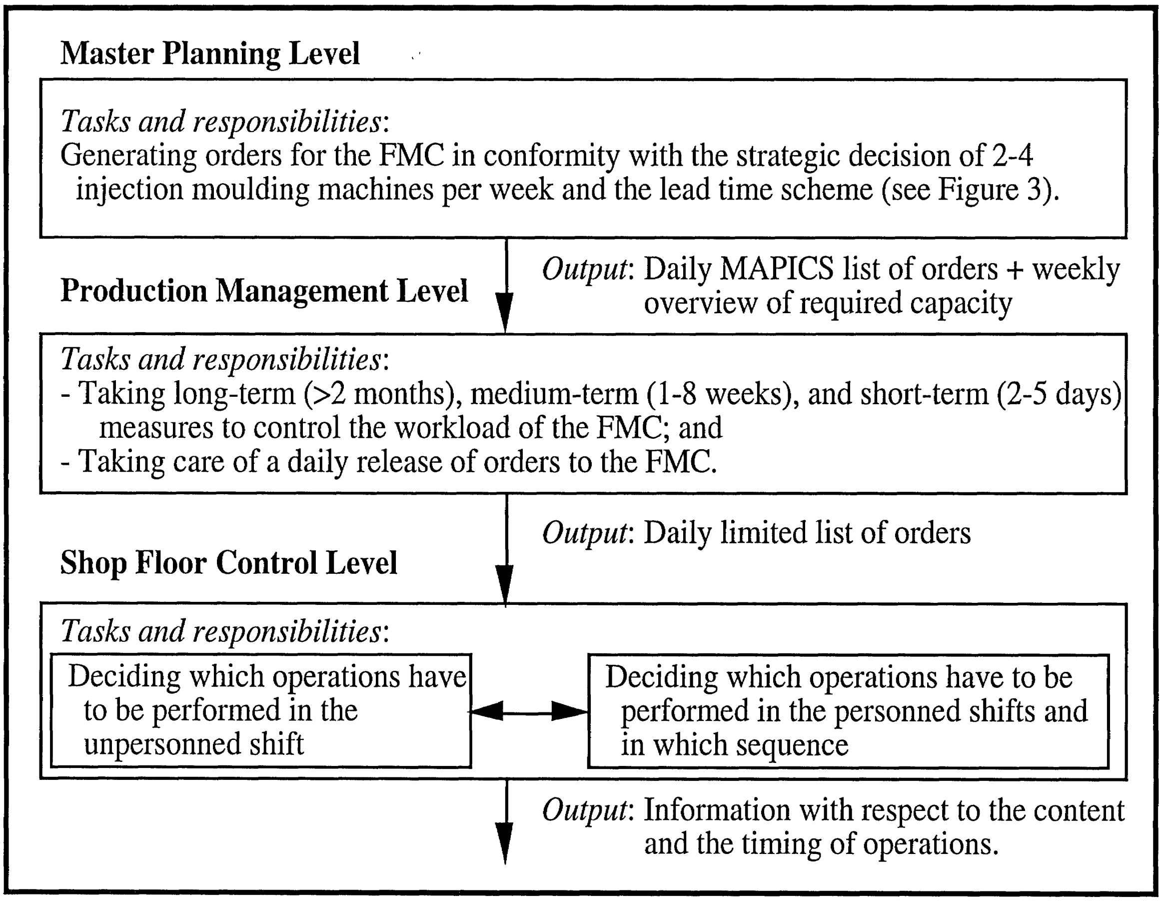
The design limitations determine the system boundaries of the redesign problem. These limitations are debatable. The order-acceptance procedure and the planned lead times determine, to a certain extent, the variation of the workload of the FMC. Therefore, it may also be wise to consider adaptations to the order-acceptance procedure and the planned lead times. Order characteristics are determined by the Process Planning Department and should be seen as basic information which has to be used in the production control. Several authors suggest a simultaneous optimization of process planning and production control (see, e.g., Gray et al., 1993 and Van Houten, 1992). In this case study, however, the order-acceptance procedure, the planned lead time, and the order characteristics are seen as unchangeable in order to limit the scope of changes in the production control.

Other important production control problems, not mentioned before, concern the question of how to deal with rush orders, the testing of new NC part programs, and the random machine breakdowns.

3.2 The Proposed Production Control Hierarchy

This subsection describes a production control hierarchy which addresses the production control issues previously mentioned. The suggested hierarchy consists of three levels, which are the same as that of the current hierarchy. However, the tasks and responsibilities differ at the various levels (see Figure 4 for an outline of the proposed hierarchy).

The *Master Planning Level* remains the same. The decisions taken at this level cannot be changed in order to improve the production control of the FMC (see Table 1). The Master Planning Level generates orders for the FMC in conformity with the lead time scheme, see Figure 3, and the strategic decision to produce 2-4 injection moulding machines per week. The output of the Master Planning Level is a daily list of MAPICS orders.



Master Planning Level

Tasks and responsibilities:
Generating orders for the FMC in conformity with the strategic decision of 2-4 injection moulding machines per week and the lead time scheme (see Figure 3).

Output: Daily MAPICS list of orders + weekly overview of required capacity

Production Management Level

Tasks and responsibilities:
- Taking long-term (>2 months), medium-term (1-8 weeks), and short-term (2-5 days) measures to control the workload of the FMC; and
- Taking care of a daily release of orders to the FMC.

Output: Daily limited list of orders

Shop Floor Control Level

Tasks and responsibilities:

Deciding which operations have to be performed in the unpersonned shift

Deciding which operations have to be performed in the personned shifts and in which sequence

Output: Information with respect to the content and the timing of operations.

Figure 4. Production control hierarchy proposed.

The proposed *Production Management Level* is responsible for controlling the workload of the FMC and the release of orders to the cell. The Production Management Level can take three types of measures to control the workload: (1) long-term measures, such as the purchase of another machining center and the establishing of a third shift; (2) medium-term measures, such as subcontracting and changing process plans in order to manufacture some parts on other machines; and (3) short-term measures, such as overtime and weekend work. The long-term measures need information on the capacity required over several months. The strategic decision of starting 2-4 injection moulding machines per week is of importance as well as the annual forecast. The medium-term measures can be based on the existing 8 weeks MAPICS' overview of required capacity. The error in the workload calculation has to be removed. Short-term measures require information on the capacity available and the capacity required over a period of about 5 days. This information is obtainable from the daily MAPICS list and the actual status of the FMC. Based on this information, decisions are taken with respect to overtime, weekend work, and the release of orders to the *Shop Floor Control Level.* The proposed procedure for this release of orders is now explained precisely.

Each morning, the planner of the manufacturing department, who works on the day shift (see Figure 2), receives a MAPICS list of orders (output from the Master Planning Level). MAPICS is updated automatically during the night shift. During the personned shifts, the operators report finished orders by means of barcoding. Based upon the workload of the unfinished orders previously released to the FMC, the planner decides which orders on the MAPICS list will be released next. The proposed order release is based on the following parameter settings: (i) a maximum workload of two days for the released and not yet finished orders, (ii) an internal FMC lead time of three days, and (iii) a release frequency of once a day. An example will illustrate the suggested release procedure and the accompanying parameters.

Table 2 gives an example of the daily MAPICS list of orders which may cover a period of one, two, or sometimes even three weeks. The planner arrives at work at 8.00 a.m. (see Figure 2) and studies the list at the beginning of his/her working day. As can be seen, order A is overdue and is not yet released. If the planner decides to release order A, then the Release Status will change from minus to plus. Because of the lead time parameter, the 'FMC Due Date generated by the planner' will then get the value of X+2. This means that the operators have to finish order A before the end of (the personned shifts of) day X+2[1]. Order B is also late, but this order cannot be released because of the lack of resources (Order Status -). Order C has already been released on day X-2 (Release Status + and FMC due date X) and has to be produced during day X. It is even

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1) It should be noted that an overdue order does not automatically generate a rush order. As mentioned in Section 2, about 1300 components are needed in the assembly of a plastic moulding machine of which only about 50 have to be processed in the firm's own manufacturing department. The overdue order therefore is not necessarily the most problematic one in causing due date problems.

possible that order C has already been finished during the unpersonned night shift of day X-1. According to the MAPICS list, order D urgently needs to be released in order to realize the MAPICS due date (critical ratio < 1). However the required resources for this order are not available at the start of day X. Therefore, this order cannot be released by the planner of the manufacturing department. Order E can be released by the planner.

Table 2. Order List Available to the Planner of the Manufacturing Department at the Beginning of the Day Shift of Day X.

Orders	Order Status*	Machining Time Needed on the Cell	Critical Ratio**	Release Status***	FMS Due Dates Generated by the Planner	Cumulative Load with Order Status:		
						+	-	Total
A	+	6 hours	-	-	-	6		6
B	-	4 hours	-	-	-		4	10
C	+	10 hours	0.3	+	X	16		20
D	-	8 hours	0.9	-	-		12	28
E	+	12 hours	1.1	+	X+1	28		40
F	-	6 hours	2.0	-	-		18	46
G	+	10 hours	2.5	+	X+1	38		56
H	-	8 hours	4.0	-	-		26	64
....	....	....	....	....	....	..		..

* **Order Status**: a minus sign (-) means that the order cannot be produced because of the lack of resources, such as material, cutting tools, and NC programs. A plus sign (+) means that the order can be taken into production.

** **Critical Ratio**: a minus sign (-) means that the order is overdue. A ratio smaller than one means that, without overtime and/or weekend work, the order will be overdue.

*** **Release Status**: a minus sign (-) means that the order is not released for the flexible manufacturing cell before day X. A plus sign (+) means that the order is released before day X

Based upon the cumulative load, the planner of the manufacturing department decides whether or not overtime or weekend work has to be organized. The planner is able to judge the orders with the minus Order Status; in other words, he/she knows whether or not the required resources for the orders will be available in the near future.

Based upon the order list and a chosen maximum allowable workload of two days for the FMC (say 40 hours), the planner decides which orders will be released for the FMC each day. In this example, only order A can be released, which leads to a total of 38 hours of released workload. (In this example, it is assumed that an 'over-release' (> 40 hours) needs to be avoided by the planner.) As already mentioned, the newly released order gets an internal due date of X+2. This enables the operator to fit the order in smoothly. In practice, it may happen that the planner demands the order be finished earlier. In that case, he/she can decide to give the newly released order an earlier due date, for instance X+1 or X. If this would lead to a situation where not all due dates can be realized by the operators, then the planner has to change some of the due dates of other released orders.

As a consequence of the release procedure, the daily limited list of orders which enters (in the morning of day X) the *Shop Floor Control Level* consists of three parts: orders with internal due date X, orders with internal due date X+1, and orders with internal due date X+2. These due dates are not generated by MAPICS!, but by the production control system proposed in this paper. At the Shop Floor Control Level, the FMC has to manufacture the released orders in time. The dominant tasks on the Shop Floor Control Level concern the determination of operations that have to be done in the unpersonned night shift and the selection and sequencing of operations for the personned shifts. These two tasks may be performed by the operators of the FMC. Figure 5 shows a possible timing of the decision tasks. The selecting and sequencing task at the beginning of the second shift of day X does not automatically generate idle time on the machining center. It

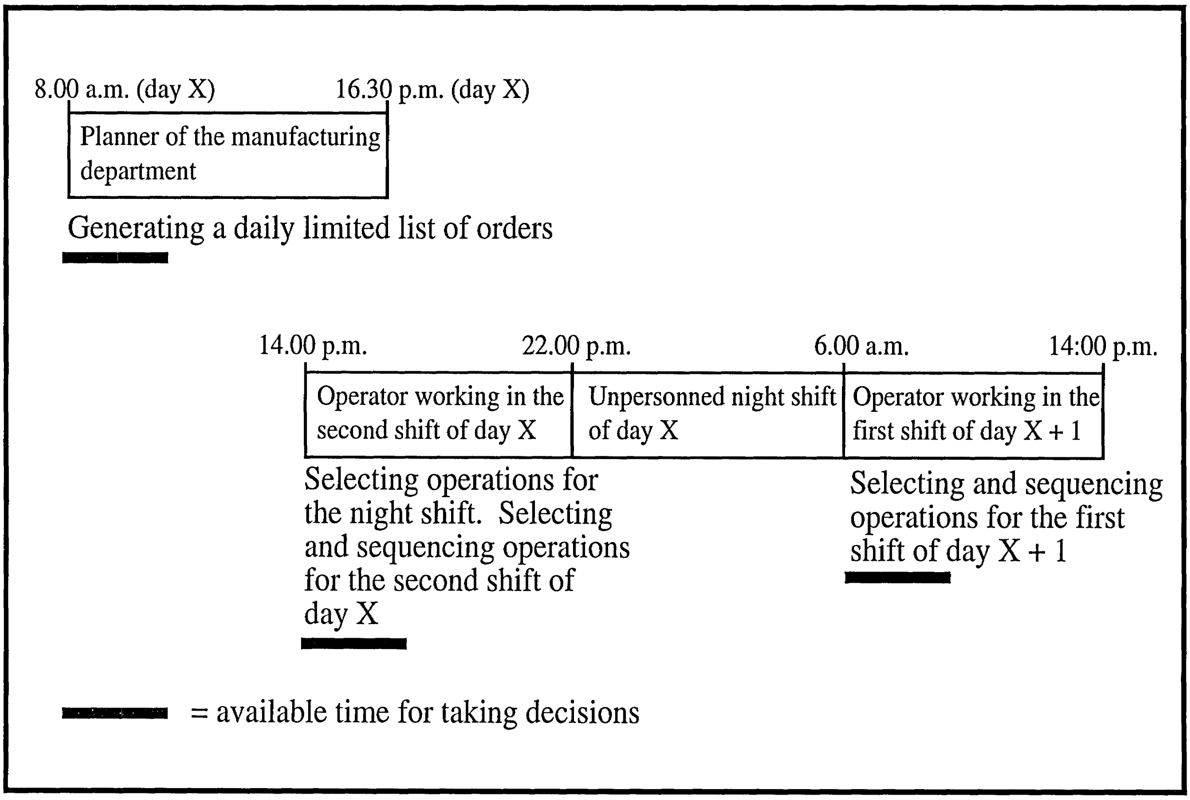

Figure 5. Possible timing of the decision tasks.

is likely that an operation from the previous shift is still running during the selecting and sequencing task. Furthermore, during day time, an extra operator does some clamping/unclamping tasks. The selecting and sequencing task at the beginning of the first shift of day X+1 can also be performed earlier.

Unforeseen events, such as a breakdown, may result in the tasks being performed at the Shop Floor Control Level again. The decisions taken at the Production Management Level do not need to be changed, since the difference between the maximum workload (2 days) and the lead time (3 days) may be able to absorb the disturbances. Each time the decision tasks have to be performed at the Shop Floor Control Level, the limited list of orders/operations has to be updated with respect to work previously done.

The selection and sequencing of operations for the personned shifts and the selection of operations for the night shift can be done in either order. For example, it is possible to select first a list of operations to be processed in the night shift and then to select the operations for personned shifts. Alternatively, it is possible to first draw up a schedule for the second personned shift of day X, then to select a set of operations for the night shift, and finally to draw up a schedule for the first personned shift of day X+1. A third possibility is to perform all of the tasks simultaneously. The three possibilities are depicted schematically in Figure 6.

An advantage of the first possibility is that a larger set of operations is under consideration for the night shift. This may be an important advantage because of the tight restrictions in the night shift: no tool change or refixturing is possible. This possibility, however, entails several difficulties. Choosing to perform some operations in the unpersonned shift, for instance, requires that some previous operations have to be scheduled in the second personned shift of day X. Further, the operations selected for the night shift need a specific set of cutting tools. This may require a significant number of cutting tool changes at the end of the second personned shift. The advantages and disadvantages of the second possibility of Figure 6 are the opposite of those just mentioned. The third possibility, in which both of the tasks of the Shop Floor Control Level are performed simultaneously, is probably the best, but also the most complicated.

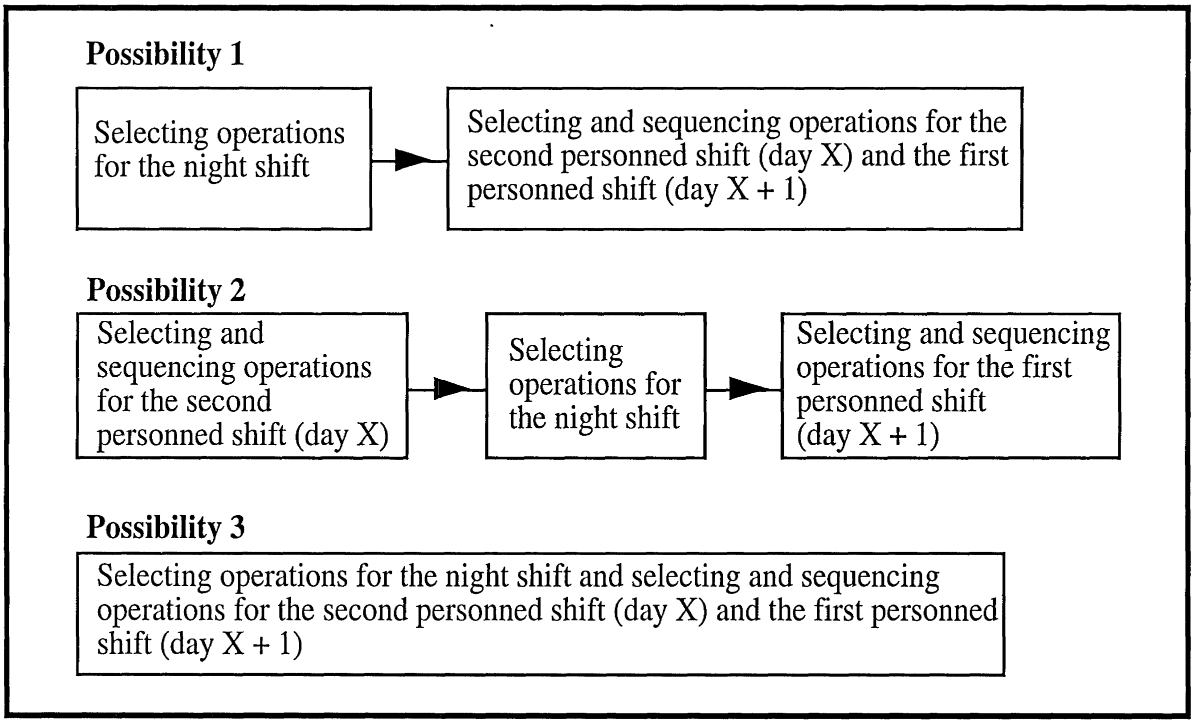

Figure 6. Three possible ways of dealing with the tasks on the Shop Floor Control Level.

In practice, at Stork Plastics Machinery B.V., a variant of the first possibility seems to be the most suitable. This is because it is almost always the case in practice that certain operations are known to be very suitable for the unpersonned night shift. These operations have long processing times and rarely cause manufacturing problems, such as the breakage of cutting tools. Long processing times are especially important when the maximum production time during the unpersonned night shift is limited by the capacity of the pallet storage, as is the case here. It is reasonable to select these operations first for the unpersonned night shift. Some other operations can be selected in addition for the night shift.

After this, the selection and sequencing of operations for the second personned shift on day X and for the first personned shift on day X+1 can be performed sequentially. Figure 7 depicts the decision steps of the proposed procedure. It is possible to exchange decision steps 2 and 3. The proposed sequence, however, has the advantage in that a larger set of operations can be considered for decision step 2 which is subject to more restrictions (see the earlier discussion).

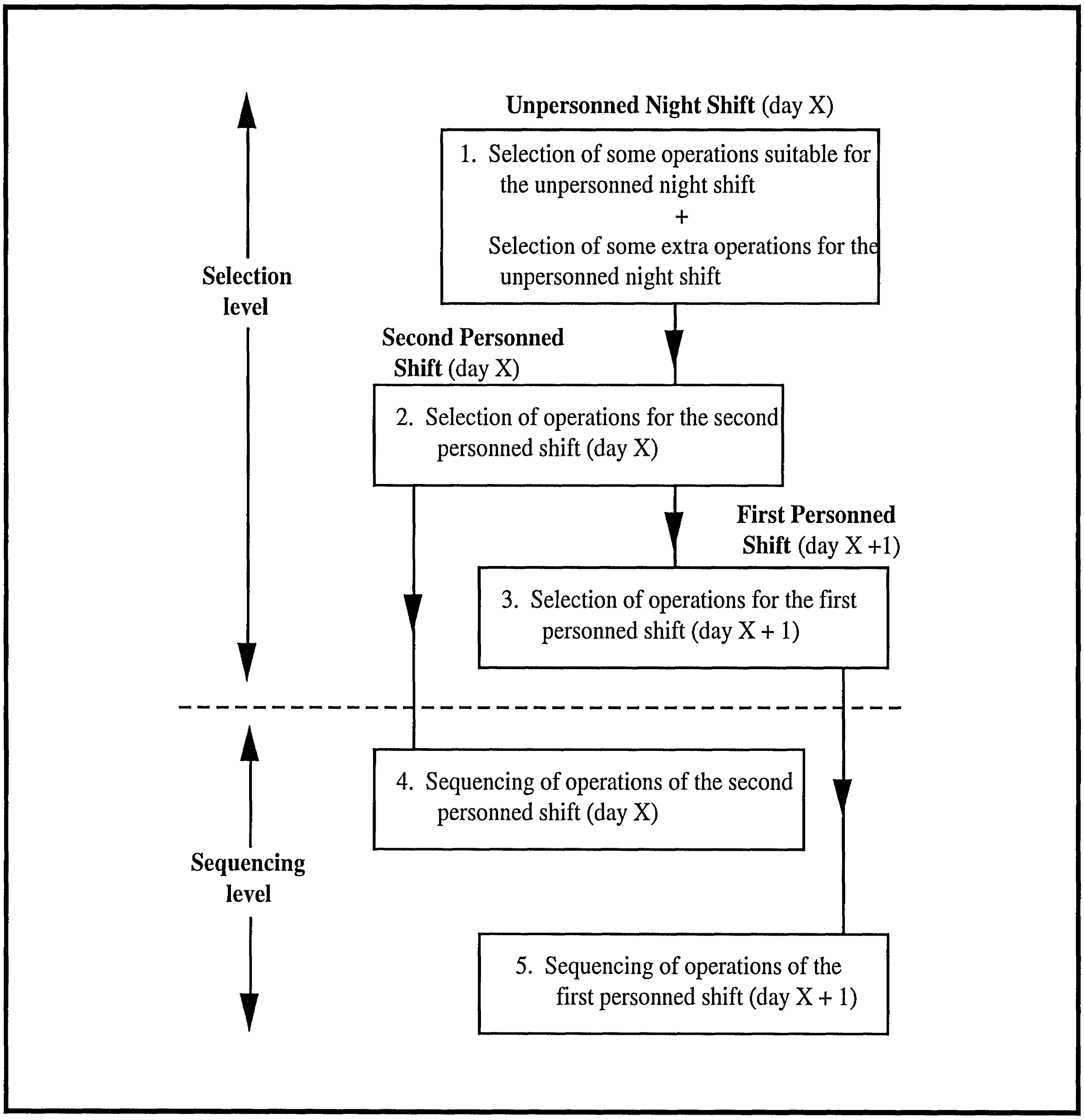

Figure 7. Decision hierarchy for the tasks of the Shop Floor Control Level.

4. METHODS FOR THE SHOP FLOOR CONTROL LEVEL

This section describes some methods which may support the decision tasks at the *Shop Floor Control Level* of Stork Plastics Machinery B.V. Subsection 4.1 briefly discusses the complexity of the decision tasks. Subsection 4.2 and 4.3 present the outlines of some methods which are designed to support the decision making at the Shop Floor Control Level. In Appendix A the methods are further elaborated and illustrated by means of an example. Appendix B illustrates the performance of the proposed methods by means of a comparison with another, greedy method. This comparison suggests that the methods described in Appendix A offer significant improvements over current practice. This conclusion, however, is somewhat premature since the methods are not yet implemented.

4.1 The Complexity of the Decision Tasks

As can be seen in Subsection 2.2, the complexity of the tasks on the Shop Floor Control Level is largely due to the limited number of fixtures and the limited capacity of the tool magazine. Both limitations should be reflected in the methods for selecting and sequencing operations. In the literature, much attention is devoted to the impact of the limited capacity of the tool magazines on the selection and sequencing problems (see e.g., Stecke and Kim, 1988 and Crama et al., 1994). However, this is not the only complicating issue at the Shop Floor Control Level. Several complicating aspects which occur in the Stork Plastics Machinery case are neglected in most of the literature:

- *An organizational goal.* As described in Section 3, each order has to be finished before a certain due date. Meester and Zijm (1993) integrate this organizational goal in a scheduling algorithm, which also attempts to minimize the number of required tool changes;

- *A partial precedence restriction.* In the Stork Plastics Case, not all operations can be treated independently. Operations on the same part usually have to be performed in a certain order, determined by technology (process planning);

- *An availability restriction.* Pallets/fixtures are limited resources. More than one order may need the same pallet/fixture; and

- *Some technological and operator preference aspects.* The methods proposed in the literature usually assume a starting situation in which the tool magazine is empty. In reality, one may have to deal with a resident tool set in the starting situation. In the case of selecting operations for the second personned shift of day X, there is even a required tooling at the end of this personned shift in order to be able to start the night shift. If possible, one should avoid an accumulation of required tool changes at these moments. Another preference aspect concerns the sequence of operations. Operations on the same part, or operations which need the same pallet/fixture should ideally not be scheduled sequentially. If these operations are scheduled sequentially, then idle time on the machining center will occur, due to the time needed for unclamping, clamping, and transportation. Finally, recall that operators prefer some tasks before others.

Despite the fact that the literature does not deal with all of the complicated issues often met in practice, it may provide some useful ideas for solving the complex selection and sequencing problems of Stork Plastics Machinery B.V.

4.2 The Selection of Operations

As can be seen in Figure 7, there are basically three selection problems. These problems differ in character. The selection of operations for the unpersonned night shift may be based on maximizing the total operating time. Important restrictions for the night shift are the limited capacities of the pallet storage and the tool magazine of the machining center. The selection problems concerning the two personned shifts differ only slightly from each other. Basically, they refer to the problem of selecting operations in such a way as to minimize the number of tools that has to be handled during a shift, while performing all orders in time. The differences between the two selection problems are due to their relationship with the night shift and their relative position in the day.

Despite the differences between the selection problems, one type of approach is proposed in Appendix A. Operations are selected sequentially based upon a particular rule, which differs for each situation. For the night shift, the rule focuses on an optimal use of the tool slots in the tool magazine. This rule is related to the extension of Hwang's Formulation given by Stecke and Kim (1988). The capacity of the tool magazine is the major constraint in maximizing the operating time in the unpersonned period. In the personned shifts, the rule focuses on minimizing the total number of required tool slots. Important conditions which are furthermore integrated into the selection algorithms concerns the due date and fixture constraints. Appendix A describes the heuristic algorithms in detail.

4.3 Sequencing Operations

The problem of sequencing operations on the flexible machining center basically consists of two parts: (a) the determination of a part input sequence and (b) the determination of an associated sequence of loadings for the tool magazine, such that the total number of tool switches is minimized. Crama et al. (1994) show that the input sequencing subproblem (a) is NP-hard. Tang and Denardo (1988^a) prove that a particular single-machine tooling subproblem (= problem b above), given a certain sequence of operations, can be solved optimally in O(MN) operations by applying the so-called Keep Tool Needed Soonest (KTNS) policy. This policy prescribes that, whenever room has to be made in the tool magazine for new cutting tools, those tools which are needed the soonest for a future operation should be removed last.

Within each shift, the operations have to be sequenced in such a way so as to minimize firstly the machine idle time caused by precedence relations between operations and secondly the number of cutting tool changes required. In the night shift, all sequences are acceptable since there are no precedence relations between operations and no cutting tool changes are needed. In the reality of Stork Plastics Machinery B.V., the number of operations per shift is limited (6 to 10 operations per shift) since the processing times per pallet vary between 0.5 and 1.5 hours. Each operation, therefore, only has a limited number of possible successors. The algorithm proposed in Appendix A (Section 4) sequences the operations successively and attempts to minimize the number of future tool changes (which are needed for the remaining operations that have to be scheduled). The KTNS policy is integrated into the algorithm.

5. CONCLUSIONS

The following conclusions can be drawn from the Stork Plastics Machinery case:

- *The complexity of the production control problems.* Even the smallest flexible manufacturing system, such as the one described in this paper, may cause complex production control problems. Several authors have dealt with subproblems (see, e.g., Stecke and Kim, 1988, Crama et al., 1994, and Tang and Denardo, 1988a and b). They propose and compare several heuristic algorithms for the subproblems. However, it appears to be difficult to apply one of the proposed methods as is in practice: several practical aspects which complicate the production control problems are rarely addressed in theory;

- *The need for sophisticated methods.* Appendix B presents a comparison of two methods for selecting and sequencing operations. The more sophisticated method, presented in Appendix A, performs significantly better than a previously suggested 'greedy' method, which resembles current practice;

- *The impact of the organization on the production control system.* Subsection 3.2 has proposed a new production control hierarchy for the FMC of Stork Plastics Machinery B.V. The responsibilities for the production control are divided among the planning department of the firm (Master Planning Level), the planner of the manufacturing department (Production Management Level), and the operators (Shop Floor Control Level). The working hours at the Production Management Level are of importance for the specific selection and sequencing problems that have to be solved at the Shop Floor Control Level. If, for instance, the daily limited list of orders (= output from the Production Management Level) could be drawn up before the start of the first personned shift of a day, then it would be possible to formulate and solve just one selection and sequencing problem for both personned shifts together;

- *The importance of the information system.* An important condition for the implementation of the methods presented in Section 4 is the presence of a well-working information system. In order to avoid human mistakes, it is desirable to automate the information flow between MAPICS (the MRP-based system used by the company), the planner of the manufacturing department, the operators of the FMC, and the FMC itself. The current information system of the firm is an important design limitation with respect to the design of a new production control system for the FMC. The batch-wise processing of production control information by MAPICS limits the possibilities for on-line control in this particular case. The batch-wise processing determines the moment at which new information is available.

Furthermore, the case study demonstrates a systematic way of dealing with the production control problems of flexible manufacturing equipment: Firstly, the actual production situation and its production control problems are described. Secondly, a production control hierarchy is designed in order to address the problems. Finally, algorithms and decision support tools are designed to support the decisions that have to be taken at the various levels of the production control hierarchy. Slomp (1993) has illustrated this systematic way more extensively by means of three case studies.

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REFERENCES

Crama, Y., Kolen, A.W.J., Oerlemans, A.G., and Spieksma, F.C.R. (1994), "Minimizing the number of tool switches on a flexible machine", *International Journal of Flexible Manufacturing Systems*, 6 (1), 33-54.

Gray, A.E., Seidmann, A., and Stecke, K.E. (1993), "A synthesis of decision models for tool management in automated manufacturing", *Management Science*, 39 (5), 549-567.

Houten, F.J.A.M. van (1991), *PART: a computer-aided process planning system*, Ph.D. Thesis, Department of Mechanical Engineering, University of Twente, Enschede.

Karreman, T. (1992), *Naar POP in de praktijk*, Technical Report, Department of Mechanical Engineering, University of Twente, Enschede (in Dutch).

Meester, G.J., and Zijm, W.H.M. (1993), "Multi-resource scheduling in an FMS based job shop", Working Paper, Department of Mechanical Engineering, University of Twente, Enschede.

Nahmias, S. (1993), *Production and Operations Analysis*, Homewood, Illinois: Irwin.

Rajagopalan, S. (1986), "Formulation and heuristic solutions for parts grouping and tool loading in flexible manufacturing systems", In: *Proceedings of the Second ORSA/TIMS Conference on Flexible Manufacturing Systems: Operations Research Models and Applications*, Ann Arbor MI, Elsevier Science Publishers B.V., Amsterdam, 311-320.

Sharit, J., and Elhence, S. (1990), "Allocation of tool-replacement decision-making responsibility in flexible manufacturing systems", *International Journal of Industrial Ergonomics*, 5, 29-46.

Slomp J. (1993), *"Production control for flexible manufacturing systems, an application-oriented approach"*, Ph.D. Thesis, Department of Mechanical Engineering, University of Twente, Enschede.

Stecke, K.E., and Kim, I. (1988), "A study of FMS part type selection approaches for short-term production planning", *International Journal of Flexible Manufacturing Systems*, 1 (1), 7-29.

Tang, C.S., and Denardo, E.V. (1988^a), "Models arising from a flexible manufacturing machine, Part I: minimization of the number of tool switches", *Operations Research*, 36 (5), 767-777.

Tang, C.S., and Denardo, E.V. (1988^b), "Models arising from a flexible manufacturing machine, Part II: minimization of the number of switching instants", *Operations Research*, 36 (5), 778-784.

Van Staaveren, L., and Van der Veen, M. (1991), *Door planning beter bezet*, Technical Report, Faculty of Mechanical Engineering, University of Twente, Enschede (in Dutch).

Vollmann, T., Berry, W., and Whybark, D. (1992), *Manufacturing Planning and Control Systems*, Homewood, Illinois: Irwin.

APPENDIX A

Methods for Selecting and Sequencing Operations

This appendix describes heuristic algorithms for selecting and sequencing operations on a machining center. The various algorithms together attempt to maximize the cumulative processing time assigned to the unpersonned night shift, while minimizing the number of tool changes required in the personned shifts and performing all orders in time. The methods presented in this appendix will be illustrated by means of an example. In these algorithms, it is assumed that the operators always have enough time to perform their tasks; the machining center is the bottleneck of the FMC, which is actually the case with Stork Plastics Machinery B.V.

Section A.1 briefly places the selecting and sequencing problems in a general context. Section A.2 presents the example and the notation used. Sections A.3 to A.6 refer to the decision steps shown in Figure 7. Several algorithms are presented for first selecting appropriate operations for each shift and then sequencing them. Sections A.3, A.4, and A.5 refer to the selection problems. Section A.6 concerns the sequencing problems. The impact of the selection and sequencing of operations on the tasks of the operators will be mentioned in section A.7.

A.1 GENERAL CONTEXT

Several researchers have dealt with the problems concerning tool management. Gray et al. (1993) mention that industry data suggest that tooling accounts for 25% to 30% of both the fixed costs and variable costs of production in an automated machining environment. They present a hierarchical framework in which tool management issues can be addressed systematically. They distinguish tool-specific issues, machine-level issues, and system management tooling issues. Tool-specific issues concern the economic determination of tool types, feed rates, and machining speeds for any given part operation. Other tool-specific issues involve the standardization of tool types, the real-time data monitoring, and the adaptive process planning. Tool-specific issues are not dealt with in this Appendix. Machine-level issues relate to the tooling of a single automated machine. The sequencing problems in this Appendix relate to these issues. System management tooling issues deal with the impact of tool allocations among several machines and the interactions between machining conditions and the overall system productivity. The selection problems of this

Appendix belong to the 'System Management Tooling Issues', and more specifically to the Part-Type Selection problems. See Gray et al. (1993) and Stecke and Kim (1988).

The system management tooling, the machine-level, and the tool-specific issues are all related and should, ideally, be solved simultaneously. Because of the complexity of each of the issues, it is assumed in most articles that the system management tooling, the machine-level, and tool-specific issues are solved sequentially. This may not be optimal (see, e.g., Van Houten 1992). However, it is in conformity with current practice in most firms.

A.2 EXAMPLE AND NOTATION

The methods are illustrated by means of the simplified example of Table A.1, which presents the data available for the human scheduler at the beginning of the second personned shift of day X. The operations of Table A.1 are the operations from the daily MAPICS list of orders (see Figure 4) minus the operations that have been performed in the first personned shift of day X. The tool magazine of the machining center, in this simplified example, has a capacity of 6 slots. In reality, the tool magazine has a capacity of 110 slots. However, in the case of Stork Plastics Machinery, a significant part of the tool magazine capacity is reserved for standard tools and, therefore, the real tool magazine capacity available for tool changes is considerably smaller than 110 slots. Suppose furthermore that the firm possesses two fixtures of each type (A, B, and C) and that the pallet storage of the cell has a capacity of five pallets. The notation used in this Appendix is given in Table A.2.

A.3 THE SELECTION OF OPERATIONS FOR THE UNPERSONNED NIGHT SHIFT

Several aspects play a role in the selection of operations for the unpersonned night shift. The number of operations that can be selected is limited by the capacity of the pallet storage and the capacity of the tool magazine. Furthermore, some complex operations may require human monitoring and cannot be considered for the unpersonned night shift. (This aspect is no longer pursued in this paper. It has no impact on the principles of the proposed selection method. It is considered extraneous to the proposed algorithms.) The total operating time of the FMC in the unpersonned shift depends on the processing times of the selected operations.

Table A.1 Tool/order matrix.

Tools Order/ Operation	1	2	3	4	5 *	6 *	7 *	8 *	9	10	11	12	13	14	Require-ments	Due Day	Machining Time	Fixture Type
1 / 1							3		1			1			2	X	1.0	A
2												1	1				0.5	B
2 / 1							3								3	X+1	1.5	A
2						1							1				0.5	C
3 / 1		1	1												1	X+1	1.0	B
2			1							1							0.5	C
3										1	1						1.0	A
4 / 1				1								1	1		2	X+1	2.0	C
5 / 1	1						3								2	X+1	0.5	B
6 / 1			1					1				1			1	X+1	2.0	A
7 / 1						1					1			3	1	X+1	1.0	B
2											1			3			0.5	C
3						1											1.5	B
8 / 1					1			1	1						1	X+2	0.5	A
2				1				1									1.5	B
9 / 1						1								3	2	X+2	2.0	C
2						1				1							0.5	B
10 / 1													1	3	3	X+2	1.0	A
11 / 1		1							1	1					3	X+2	2.0	A
2										1	1						0.5	B

The *'s indicate the resident tool set at the beginning of the second personned shift (day X).
The figures in the matrix show the number of slots needed for each of the cutting tools.

Suppose that the main objective of the selection problem is to maximize the operating time of the FMC in the unpersonned night shift. This objective is only relevant if it is hard to fill up the eight hours of the unpersonned shift. The objective only causes a complex selection problem if the capacity of the tool magazine limits the number of operations that can be selected. If the capacity of the pallet storage is the only limitation, one would simply select the operations with the longest processing times. The method presented in this section assumes that the capacity of the tool magazine is the limiting restriction.

Suppose that operations <4,1,1> and <6,1,1> of Table A.1 are selected beforehand for the night shift because of their long processing times. This is in conformity with the decision framework in Figure 7. The selection means that cutting tools 3, 4, 8, 12, and 13 and fixtures of

Table A.2 Notation.

i	order index	$i=1,\ldots,I$
O_i	the number of operations needed for each part of order i	
o	operation index	$o=1,\ldots,O_i$
S_i	the production requirements of order i	
s	part number index	$s=1,\ldots,S_i$
c	cutting tool index	$c=1,\ldots,C$
b_{ioc}	$\begin{cases} 1, & \text{if operation o of order i requires tool c;} \\ 0, & \text{otherwise.} \end{cases}$	
d_c	the number of slots required in the tool magazine for holding cutting tool c;	
$<i,o,s>$	operation o of part s of order i	
y_c	$\begin{cases} 1, & \text{if tool c is needed in the tool magazine;} \\ 0, & \text{otherwise.} \end{cases}$	
$\{y_c\}$	the set of cutting tools needed for the already selected operations;	
$\{y_c^*\}$	the set of cutting tools resident at the beginning of the second personned shift of day X;	
$\{y_c^{**}\}$	the set of cutting tools needed for the unpersonned night shift;	
PS_A	partial schedule of operations of the set A;	
S_A	all operations which may be scheduled immediately after the partial schedule PS_A;	
u	the average use of the slots required by the selected operations, expressed in the number of times a tool (from that slot) is needed.	

types A and C are minimally needed in the night shift. The previously selected operations have to be feasible with respect to the capacity of the tool magazine and the use of fixtures. The following heuristic algorithm is suggested to select extra operations:

NIGHT SHIFT ALGORITHM

1. *Create the set of acceptable extra operations for the night shift. Choices are subject to the tool magazine constraint (maximal 6 slots available in the illustrative example), the limited availability of fixtures, and to constraints concerning precedence relationships. Also the operations with due date X have to be excluded from the list of acceptable extra operations, since these operations have to be performed in the second personned shift of day X.*

   Stop if the set of acceptable extra operations is empty.

2. *Select that operation (from the operations that can be selected) which gives the maximum average use (u) of the required slots in the tool magazine of the machining center. Here, the average use is defined as the ratio of the total number of tool slot requirements for all selected operations (expressed in the number of times a tool from a tool slot is needed) to the total number of tool slots required for these operations.*

   (The average use of required slots, $u = \Sigma_c \Sigma_{\text{all i and o selected}} (b_{ioc}\, d_c) \,/\, \Sigma_c (y_c\, d_c)$ *is calculated, where* $y_c = \max (b_{ioc})$ *over all i and o selected.*1)*)*

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1) See Rajagopalan (1986), which presents somewhat similar heuristic rules for the loading problem of FMSs.

3. *Go to Step 1.*

Important in Step 1 are the precedence relationships which reduce the number of acceptable extra operations. Each iteration may add new precedence relationships. For instance, operation <9,2,1> cannot be selected if operation <9,1,1> is selected earlier for the night shift (operations on the same part have to be performed sequentially). In the example here, the following operations belong to the set of acceptable extra operations: <2,2,1>, <2,2,2>, <2,2,3>, <3,1,1>, <3,2,1>, <7,3,1>, and <8,2,1>. Operation <4,1,2> cannot be selected because operation <4,1,1> is already selected and there is only one pallet/fixture available for an operation that has to be performed on all parts of an order. This assumption conforms to the reality at Stork Plastics Machinery B.V. Step 2 implicitly assumes that a more intensive use of the available tool slots will have a positive impact on the total processing time of the operations assigned to the machining center. In Step 2, the first operation that will be selected is operation <8,2,1> (u=1.6). If there are other operations which also lead to the same use of tool slots (u), one should select the operation with the longest processing time. Following this heuristic algorithm, the next and last operation to be selected for the night shift is operation <3,1,1>. The selected operations correspond with a productive period of 6.5 hours in the unpersonned shift. More operations cannot be selected because of physical limitations.

A.4 THE SELECTION OF OPERATIONS FOR THE SECOND PERSONNED SHIFT OF DAY X

The operations that will be selected for the second personned shift of day X should take less than eight hours production time, since the operator is only present between 14.00 p.m. and 22.00 p.m. (see Figure 2) for changing cutting tools, clamping/unclamping parts on/from pallets, and doing the necessary preparations for the unpersonned night shift. Furthermore, it is likely that one operation, which is started in the first personned shift of day X, is still running in the second personned shift of day X. This further limits the time available for operations in the second personned shift of day X. Suppose that in the example of this Appendix, 7.5 hours are maximally available for performing operations in the second shift (in other words: one operation from the previous shift may be running until about 14.30 p.m.). The objective of the method is to fill up the second personned shift of day X with operations in such a way so as to minimize the number of tools that has to be handled during the shift, while performing the orders with due date X in time.

Several operations have of necessity to be performed in the second personned shift of day X. In this example, the operations of order 1 (<1,1,1>, <1,2,1>, <1,1,2>, and <1,2,1>) have to be performed then because of the due date of the order. Operation <8,1,1> has to be performed in the second personned shift because the next operation (<8,2,1>) on the same part is assigned to the unpersonned night shift. In total, the necessary operations correspond with 3.5 hours production time. (It is assumed that the total operation time required for the necessary operations is usually smaller than the available time in the second personned shift of day X.) Extra operations can be found by applying the following heuristic algorithm:

SECOND PERSONNED SHIFT ALGORITHM

1. *Create the set of acceptable extra operations for the second personned shift of day X. Here, only those operations are selected which do not require also the selection of a previous operation (in other words, all operations with no technological predecessors). Furthermore, the processing time of each of the operations should be less than the 'remaining time' in the second personned shift. (The remaining time is defined as the time available for performing extra operations.)*

   Stop if the set of acceptable extra operations is empty.

2. *Select that operation (from the operations that can be selected) which requires the fewest number of extra tools to be handled during the second shift. In other words, that operation is selected which needs the fewest number of extra cutting tools on top of those tools in sets* $\{y_c^*\}$, $\{y_c^{**}\}$, *and* $\{y_c\}$. $\{y_c\}$ *is the set of tools needed for the operations previously selected for the second personned shift of day X. An extra selection criterion, if needed in case of a tie, may be to select that operation which requires the fewest cutting tools of* $\{y_c^{**}\}$ *(= night shift).*

3. *Go to Step 1.*

Initially, the remaining time in this example is 7.5-3.5=4 hours and the following operations belong to the set of acceptable extra operations: <2,1,1>, <3,2,1>, <4,1,2>[1], <5,1,1>, <7,1,1>, <9,1,1>, <10,1,1>, and <11,1,1>. At the start of the second personned shift of day X, cutting tools 5, 6, 7, and 8 (=$\{y_c^*\}$) are loaded in the tool magazine. In the night shift, cutting tools 2, 3, 4, 8, 12, and 13 (=$\{y_c^{**}\}$) are needed to perform the operations selected. In the

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1) Operation <4,1,1> is already assigned to the night shift.

second personned shift of day X, at least cutting tools 5, 7, 8, 9, 12, and 13 (=$\{y_c\}$) will be used for the operations selected beforehand. Step 2 of the selection method is based on the fact that if the number of different tools in $\{y_c^*\} \cup \{y_c^{**}\} \cup \{y_c\}$ increases, that also the number of tools that has to be handled during the shift will increase. The extra criterion, which is needed if more than one operation needs the same number of extra cutting tools above $\{y_c^*\} \cup \{y_c^{**}\} \cup \{y_c\}$, comes from the thought that the operation which requires the most cutting tools of the set $\{y_c^{**}\}$ (=night shift) can be processed easily in the first personned shift of day X+1, immediately after the unpersonned night shift. In step 2, the operations <2,1,1> and <4,1,2> are selected initially from the set of acceptable operations. The extra criterion leads to the selection of operation <2,1,1> for the second personned shift of day X.

Following the heuristic algorithm, operations <2,1,1>, <2,1,2>, and <2,2,1> are selected in the example of this Appendix as the extra operations for the second personned shift of day X. The total processing time of operations assigned to the second personned shift is 7.5 hours (7 hours from the selected operations and 0.5 hour from an overlapping operation from the first shift of day X).

A.5 THE SELECTION OF OPERATIONS FOR THE FIRST PERSONNED SHIFT OF DAY X+1

The operations that will be selected for the first personned shift of day X+1 should correspond with a total processing time of more than eight hours. This is because it is likely that one operation will be performed partly in the first and the second personned shifts of day X+1. The preparations for this operation, clamping/unclamping and tool changes, have to be performed in the first personned shift. Besides a minimization of the required tool handling, it is important to select the operations for the first personned shift of day X+1 in such a way as to enable the processing of all orders with due date X+1 in time. In the illustrative example, the remaining operations with due date X+1 require a cumulative processing time of 10 hours. This means that at least 10-8=2 hours of processing time[1] in the first shift of day X+1 should be used for

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1) The more operations (processing hours) with due date X+1 that are assigned to the first personned shift of day X+1, the larger the flexibility with respect to the future assignment of operations to the second shift of day X+1.

operations with due date X+1. A maximum of 6 hours may be used for operations with due date X+2. The following heuristic algorithm is proposed:

FIRST PERSONNED SHIFT ALGORITHM

1. *Create the set of acceptable operations for the first personned shift of day X+1. Here, only those operations are selected which do not also require the selection of a previous operation (in other words, all operations with no technological predecessors). Furthermore, none of the operations should frustrate the realization of due dates; only a limited number of hours is available in the first personned shift of day X+1 for operations with due date X+2.*
2. *Select that operation (from the operations that can be selected) which requires the fewest number of extra tools to be handled during the second shift. In other words, that operation is selected which needs the fewest number of extra cutting tools on top of* $\{y_c^{**}\}$ *and* $\{y_c\}$. $\{y_c\}$ *is the set of tools needed for the operations previously selected for the first personned shift of day X+1 and is empty at the start of this heuristic algorithm. If several operations require a minimum of extra cutting tools, then select from these operations the one which belongs to an order that in the first place has a due date of X+1 and secondly has the most previously unselected operations.*
3. *Stop, if the total processing time that is needed for the selected operations is more than the available time in the first personned shift of day X+1 (= 8 hours). Otherwise, go to Step 1.*

In the illustrative example, the following operations belong initially to the set of acceptable operations: <2,1,3>, <2,2,2>, <3,2,1>, <4,1,2>, <5,1,1>, <7,1,1>, <9,1,1>, <10,1,1>, and <11,1,1>. At the start of the first personned shift of day X+1, cutting tools 2, 3, 4, 8, 12, and 13 ($=\{y_c^{**}\}$) are loaded in the tool magazine. These tools are needed in the night shift. Step 2 of the selection method is based on the fact that if the number of different tools in $\{y_c^{**}\} \cup \{y_c\}$ increases, then also the number of tools that has to be handled during the shift will increase. The extra criterion departs from the typical consideration that it may be wise to minimize the number of necessary operations and precedence relations in the second personned shift of day X+1. Following Step 2 of the heuristic algorithm, operation <4,1,2> is selected first out of the set of acceptable operations. The following operations are additionally selected for the first personned shift of day X+1: <4,1,2>, <2,1,3>, <2,2,2>, <2,2,3>, <3,2,1>, <3,3,1>, <5,1,1>, <5,1,2>, <7,1,1>, and <7,2,1>. The total processing time of operations assigned to this shift is 8.5 hours.

The results of the three heuristic algorithms used for selecting operations of orders are summarized in Table A.3.

Table A.3 Operations selected for the three shifts.

The second personned shift of day X	<1,1,1>, <1,2,1>, <1,1,2>, <1,2,2>, <2,1,1>, <2,1,2>, <2,2,1> and <8,1,1> = 7.5 hours
The unpersonned night shift	<8,2,1>, <4,1,1>, <6,1,1> and <3,1,1> = 6.5 hours
The first personned shift of day X+1	<4,1,2>, <2,1,3>, <2,2,2>, <2,2,3>, <3,2,1>, <3,3,1>, <5,1,1>, <5,1,2>, <7,1,1> and <7,2,1> = 8.5 hours

A.6 THE SEQUENCING OF OPERATIONS

Within each shift, the operations have to be sequenced in such a way so as to minimize in the first place the machine idle time caused by precedence relations between operations and secondly the number of cutting tool changes required. In the night shift all sequences are acceptable since there are no precedence relations between operations and no cutting tool changes are needed. In the example, eight and ten operations have to be sequenced in the second personned shift of day X and the first personned shift of day X+1, respectively. In reality, the number of operations per shift is of the same order (6 to 10 operations per shift) since the processing times per pallet vary between 0.5 and 1.5 hours. Each operation, therefore, only has a limited number of possible successors.

This number is further reduced by possible precedence constraints between operations. Important precedence constraints are: (i) operations on the same part have to be performed in a prescribed technological order, (ii) operations on the same part should not be scheduled in succession, (iii) operations which need the same pallet/fixture should not be scheduled in succession. Precedence constraint (i) is a technological constraint. Precedence constraints (ii) and (iii) are desirable in order to avoid idle time on the machining center because of the times needed for clamping/unclamping and transportation. It is assumed here that solutions which satisfy the precedence constraints exist for the sequencing problems. This can be checked by a simple tree-search method.

The following heuristic can be applied in order to solve the sequencing problem of the second personned shift of day X:

SEQUENCING ALGORITHM

1. *Let* $A := \emptyset$. *Start with* PS_A *as an empty schedule;*

2. *Create* S_A, *which contains all operations that may be scheduled in addition to the partial schedule* PS_A *in conformity with the precedence constraints, and without causing future problems with respect to the precedence constraints. Consider the night shift as the situation in which all other operations which have to be performed in the second personned shift of day X are predecessors;*

3. *Create a new partial schedule* $PS_{A+<i,o,s>}$ ($<i,o,s> \in S_A$) *in such a way that the addition of operation* <i,o,s> *maximizes the number of cutting tools in the tool magazine which are no longer needed for the remaining operations to be scheduled by this algorithm. This rule is attempting to minimize the number of future cutting tool switches. If more than one operation can be selected by this criterion, select the one which has the maximum number of precedence relations with remaining operations;*

4. *If operation* $<i,o,s> \neq$ *night shift, then let* $A := A + <i,o,s>$. *Apply the KTNS (Keep Tool Needed Soonest) rule for calculating the minimum number of required tool changes and for finding the load of the tool magazine (at the end of the partial schedule). The remaining operations which have to be scheduled by this algorithm (including the nightshift) have to be seen as one final operation in the KTNS rule.*

   Return to Step 2. If operation <i,o,s> = night shift, then stop.

Step 2 in the heuristic algorithm is an important step. In the creation of set S_A, both a local and a global constraint are of importance. The local constraint concerns the precedence relations of the last scheduled operation and can easily be dealt with by means of a little computer support. The global constraint refers to the operations that are not yet scheduled and demands that these operations can be sequenced without causing precedence problems. It is possible to deal with this constraint by means of a simple tree-search method; it is sufficient to find just one sequence for the remaining operations, starting with $<i,o,s> \in S_A$, which satisfies the precedence constraints. Another way to deal with the global constraint is to allow some human interaction. Sharit and Elhence (1990) have shown that human involvement in the decision making process may be effective, especially in those situations where global and local information play a role.

The *solution* obtained by this heuristic algorithm is: [1] - <8,1,1>- [1] - <1,1,1> - [0] - <2,1,1> - [0] - <1,1,2> - [0] -<2,1,2> - [1] - <1,2,1> - [1] - <2,2,1> - [0] - <1,2,2> - [3] - night shift. The *number of tool changes* needed are given in the square brackets. It must be noted that all tool changes can be performed earlier than suggested in the given sequence; tool changes can be done during the processing of the parts. Table A.4 shows the final results by means of a tool/operation matrix.

Table A.4 Tool/operation matrix and operation sequence for the second personned shift of day X

Tools Order/ Operation	1	2 n	3 n	4 n	5 *	6 *	7 *	8 n *	9	10	11	12 n	13 n	14	**Part Number**	**Due Day**	**Machining Time**	**Fixture Type**
8 / 1					1			1	1						1	X+2	0.5	A
1 / 1							3		1			1			1	X	1.0	A
2 / 1							3								1	X+1	1.5	A
1 / 1							3		1			1			2	X	1.0	A
2 / 1							3								2	X+1	1.5	A
1 / 2												1	1		1	X	0.5	B
2 / 2						1							1		1	X+1	0.5	C
1 / 2												1	1		2	X	0.5	B

The n's indicate the tool set needed in the unpersonned night shift
The *'s indicate the resident tool set at the beginning of the second personned shift (day X).
The figures in the matrix show the number of slots needed for each of the cutting tools.

A similar algorithm to the one used for the sequencing of operations for the second personned shift of day X can be applied for the sequencing of the operations of the first personned shift of day X+1. The only difference concerns the absence of the night shift.

The solution obtained by applying the Sequencing Algorithm is: [0] - <4,1,1> - [1] - <3,2,1> - [1] - <2,2,2> - [3] - <2,1,3> - [1] -<3,3,1> - [1] - <2,2,3> - [1] - <5,1,1> - [1] - <7,1,1> - [1] - <5,1,2> - [1] - <7,2,1>. The number of tool changes needed are given in the square brackets. Table A.5 shows the final schedule with a tool/operation matrix.

Table A.5 Tool/operation matrix and sequence of operations for the first personned shift in day X+1

Tools Order/ Operation	1	2 n	3 n	4 n	5	6	7	8 n	9	10	11	12 n	13 n	14	**Part Number**	**Due Day**	**Machining Time**	**Fixture Type**
4 / 1				1								1	1		2	X+1	2.0	C
3 / 2			1							1					1	X+1	0.5	C
2 / 2						1							1		2	X+1	0.5	C
2 / 1							3								3	X+1	1.5	A
3 / 3										1	1				1	X+1	1.0	A
2 / 2						1							1		3	X+1	0.5	C
5 / 1	1						3								1	X+1	0.5	B
7 / 1						1					1			3	1	X+1	1.0	B
5 / 1	1						3								2	X+1	0.5	B
7 / 2											1			3	1	X+1	0.5	C

The n's indicate the tool set needed in the unpersonned night shift
The figures in the matrix show the number of slots needed for each of the cutting tools.

A.7 CONSEQUENCES OF THE METHODS/SOLUTIONS FOR THE TASKS OF THE OPERATORS

Tables A.6 and A.7 describe the tasks of the operators during both personned shifts in detail. It must be noted that several of these tasks can be performed earlier than noted (e.g., several tool changing tasks and clamping tasks). Clamping, for instance, can be done as soon as the fixture/pallet and the raw material is available. Tool changes can be performed as soon as a cutting tool can be removed from the tool magazine.

Not all of the operator tasks are mentioned in Tables A.6 and A.7. It is obvious that the operators have to unclamp and unload a pallet/fixture before it can be loaded with a new part. The operators also have to instruct the supervisory control computer of the FMC of their completed tasks. They are further responsible for some small maintenance tasks and for the quality of the parts produced.

Another operator task, not mentioned before, concerns the inspection and replacement of cutting tools due to tool wear. In current practice, tools are replaced if the sum of the tool's actual life-to-date and the forthcoming processing times required from that tool by the part(s) on the pallet exceeds the tool's expected life. Cutting tools which are frequently needed are usually doubled in the tool magazine of the machining center. Refurbishing of these cutting tools does not cause idle time of the machining center. In practice at Stork Plastics Machinery, a significant part of the tool magazine capacity is reserved for frequently used tools. This part of the tool magazine is not considered for the tool changes due to product variety. Therefore, tool changes due to tool wear, relate especially to the cutting tools in the reserved part of the tool magazine. The cutting tools in the other part of the tool magazine have to be changed frequently because of the product variety. Refurbishing of these cutting tools can be done while these tools are not present in the tool magazine.

Table A.6 Tasks of the operators in the *second* personned shift of day X for the considered example.

Time (+ Machining Center Activity)	Tasks of the Operator
14.00 p.m. {Start second personned shift of day x. An operation from the previous shift is still running.}	Selection of operations for the unpersonned night shift; Selection of operations for the second personned shift of day X; Sequencing the operations for the second personned shift of day X; Clamping a part of order 8 on a pallet in order to enable the processing of <8,1,1>; Removing tool 6 from the tool magazine and inserting tool 12;
14.30 p.m. {Processing of <8,1,1>}	Clamping a part of order 1 on a pallet in order to enable the processing of <1,1,1>;
15.00 p.m.	Removing tool 5 from the tool magazine and inserting tool 12; {This has to be done during the pallet change at the machining center. Regrettably, it was not possible to do it earlier. One may suggest changing operations <1,1,1> and <1,1,2> with <2,2,1> and <2,1,2>, however, this is not in conformity with the heuristic algorithm.}
{Processing of <1,1,1>}	Clamping a part of order 2 on a pallet in order to enable the processing of <2,1,1>;
16.00 p.m. {Processing of <2,1,1>}	Clamping a part of order 1 on a pallet in order to enable the processing of <1,1,2>;
17.30 p.m {Processing of <1,1,2>}	Clamping a part of order 2 on a pallet in order to enable the processing of <2,1,2>;
18.30 p.m {Processing of <2,1,2>}	Clamping a part of order 1 on a pallet in order to enable the processing of <1,2,1>; Removing tool 9 from the tool magazine and inserting tool 13;
20.00 p.m {Processing of <1,2,1>}	Clamping a part of order 2 on a pallet in order to enable the processing of <2,2,1>; Removing tool 7 from the tool magazine and inserting tool 6;
20.30 p.m {Processing of <2,2,1>}	Clamping a part of order 1 on a pallet in order to enable the processing of <1,2,2>;
21.00 p.m {Processing of <1,2,2>}	Removing tool 6 and inserting tools 2, 3, and 4 in order to serve the unpersonned night shift (two slots in the tool magazine are available because of the removal of tool 7 earlier; Clamping parts of orders 8, 4, and 6 on pallets in order to enable the processing in the night shift of <8,2,1>, <4,1,1>, <6,1,1>;
21.30 p.m {Processing of <8,2,1>, <4,1,1>, <6,1,1> and <3,1,1> in the night shift}	Clamping of a part of order 3 on a pallet of type B in order to enable the processing of operation <3,1,1> in the unpersonned night shift (a pallet of type B was not available earlier).
End of the shift = 22.00 p.m. End of the processing in the night shift = 6.00 a.m.	

Table A.7 Tasks of the operators in the *first* personned shift of day X+1.

Time (+ Machining Center Activity)	Tasks of the Operator
6.00 a.m.	Selection of operations for the first personned shift of day X+1; Sequencing the operations for the first personned shift of day X+1; Clamping a part of order 4 on a pallet in order to enable the processing of <4,1,2>;
{Processing of <4,1,2>}	Clamping a part of order 3 on a pallet in order to enable the processing of <3,2,1>; Removing tool 2 from the tool magazine and inserting tool 10;
8.00 a.m. {Processing of <3,2,1>}	Clamping a part of order 2 on a pallet in order to enable the processing of <2,2,2>; Removing tool 8 from the tool magazine and inserting tool 6;
8.30 a.m. {Processing of <2,2,2>}	Clamping a part of order 2 on a pallet in order to enable the processing of <2,1,3>; Removing tools 3, 4, and 12 from the tool magazine and inserting cutting tool 7, which needs three slots.
9.00 a.m. {Processing of <2,1,3>}	Clamping a part of order 3 on a pallet in order to enable the processing of <3,3,1>; Removing tool 6 from the tool magazine and inserting tool 11.
10.30 a.m. {Processing of <3,3,1>}	Clamping a part of order 2 on a pallet in order to enable the processing of <2,2,3>;
11.30 a.m.	Removing tool 10 from the tool magazine and inserting tool 6; {This has to be done during the pallet change at the machining center. Regrettably, it was not possible to do it earlier because tool 10 is needed for the previous operation <3,3,1>}
{Processing of <2,2,3>}	Clamping a part of order 5 on a pallet in order to enable the processing of <5,1,1>; Removing tool 13 from the tool magazine and inserting tool 1;
12.00 a.m. {Processing of <5,1,1>}	Clamping a part of order 7 on a pallet in order to enable the processing of <7,1,1>;
12.30 p.m.	Removing tool 7 from the tool magazine and inserting tool 14; {This has to be done during the pallet change at the machining center. It was not possible to do it earlier because tool 7 is needed for the previous operation <5,1,1>}
{Processing of <7,1,1>}	Clamping a part of order 5 on a pallet in order to enable the processing of <5,1,2>;
13.30 p.m.	Removing tool 14 from the tool magazine and inserting tool 7; {This has to be done during the pallet change at the machining center. It was not possible to do it earlier because tool 14 is needed for the previous operation <7,1,1>}
{Processing of <5,1,2>}	Clamping a part of order 7 on a pallet in order to enable the processing of <7,2,1>;
14.00 p.m.	Removing tool 7 from the tool magazine and inserting tool 14; {This has to be done during the pallet change at the machining center. It was not possible to do it earlier because tool 7 is needed for the previous operation <5,1,2>}
{Processing of <3,2,1>}	
End of the shift = 14.00 p.m. End of the last prepared operation in the first shift of day X+1 = 14.30 p.m.	

As can be seen in Tables A.6 and A.7, a few tool changes have to be done during the pallet change on the machining center. It is possible that this will cause a little additional idle time on the machining center.

Appendix B
Comparison of Two Methods for Selecting and Sequencing Operations

Initially, some masters students were allocated to Stork Plastics Machinery B.V. in order to perform small research projects (200 hours each) in which they were asked to outline a production control system for the FMC. Van Staaveren and Van der Veen (1991) have described the production control complexity and subsequently, have suggested a production control system. They did not consider a future unpersonned night shift. Part of their suggestion was an interactive scheduling tool in which a human scheduler can decide on a sequence of operations. Karreman (1992) programmed the interactive scheduling tool in a user-friendly software package (in DBase III, Clipper). The interactive scheduling tool works as follows:

INTERACTIVE SCHEDULING TOOL

1. *The starting situation is an empty schedule and a set of operations to be scheduled.*
2. *An operation that can be scheduled next is suggested by considering the due date of orders and several precedence constraints. The number of tool changes required is not considered.*
3. *The human scheduler may reject or accept this suggestion. One reason for rejection may be that the number of tool changes required seems to be too large.*
4. *Proceed with the suggested operations of Step 2, until the human scheduler decides to finish the interactive session.*

The proposed scheduling mechanism is different from the one suggested in Appendix A. Considerations concerning tool changes and the use of the unpersonned night shift had not yet been considered above and so are not explicitly integrated in the interactive scheduling mechanism.

In the current practice of Stork Plastics Machinery B.V., the major considerations while sequencing the operations on the FMC are the due dates of the orders and the precedence constraints between operations. The operators decide on a sequence of operations without extensive computer support.

Suppose that the operators use the interactive scheduling tool of Van Staaveren and Van der Veen (1991) and Karreman (1992) and they also apply the Keep Tool Needed Soonest (KTNS) rule for minimizing the number of tool changes. Suppose further that they select executable operations for the unpersonned night shift according to decreasing processing times, until the tool magazine constraint is violated or no other executable operation can be found. This situation will certainly improve current practice. The final scheduling results are given in Table B.1.

Table B.1 Tool/operation matrix and sequence operations during the shifts.

Tools Order/ Operation	1	2	3	4	5 *	6 *	7 *	8 *	9	10	11	12	13	14	Part Number	Due Day	Machining Time	Fixture Type	Min. # Tool Changes
Second Personned Shift of Day X																			
1 / 1							3		1			1			1	X	1.0	A	2
2 / 1							3								1	X+1	1.5	A	0
1 / 1							3		1			1			2	X	1.0	A	0
1 / 2												1	1		1	X	0.5	B	1
2 / 1							3								2	X+1	1.5	A	0
1 / 2												1	1		2	X	0.5	B	0
2 / 1							3								3	X+1	1.5	A	0
(7.5 hours are available in the second shift of day X and, fortunately, the cumulative processing time of all sequenced orders is 7.5 hours. The operator has to change cutting tools at the end of the shift in order to support the unpersonned shift.)																			
Unpersonned Night Shift																			
4 / 1				1								1	1		2	X+1	2.0	C	4
6 / 1			1					1				1			1	X+1	2.0	A	0
3 / 1		1	1												1	X+1	1.0	B	0
(Only three operations can be assigned to the night shift, due to the limited tool magazine of the machining center.)																			
First Personned Shift of Day X+1																			
2 / 2						1							1		1	X+1	0.5	C	1
3 / 2			1							1					1	X+1	0.5	C	1
2 / 2						1							1		2	X+1	0.5	C	0
3 / 3										1	1				1	X+1	1.0	A	1
2 / 2						1							1		3	X+1	0.5	C	0
4 / 1				1								1	1		2	X+1	2.0	C	1
5 / 1	1						3								1	X+1	0.5	B	4
7 / 1						1					1			3	1	X+1	1.0	B	1
8 / 1					1			1	1						1	X+1	0.5	A	3
7 / 2											1			3	1	X+1	0.5	C	1
8 / 2				1				1							1	X+1	1.5	B	1
(The last operation will run 1 hour in the second shift of day X+1)																			
The *'s indicate the resident tool set at the beginning of the second personned shift (day X). The figures in the matrix show the number of slots needed for each of the cutting tools.																			

Comparing Table B.1 with the scheduling results from the algorithms of Appendix A leads to the following observations:

- The total number of tool changes required when executing the schedule of Table B.1 is at least 21 (while also using the KTNS rule). The final schedule of Appendix 6.A requires 18 tool changes;
- The schedule of Table B.1 leads to 5 hours of running time of the machining center in the unpersonned night shift. With the final schedule of Appendix A, the machining center is running for 6 hours in the unpersonned shift.

Therefore, one may conclude that the heuristic algorithms proposed in Appendix A perform significantly better than the methods currently used and also better than earlier suggested methods to plan and schedule the FMC. More system realities are also considered.