Engineering Costs and Production Economics, 12 (1987) 107-115
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

TOOL SHARING IN AN FMS – A FEASIBILITY STUDY*

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ABSTRACT

In a flexible manufacturing system, cylinder blocks and heads are processed in batches by four machines in line. Each part is fully processed on one machine only. During batch production the tool magazines contain the same set of tools. This paper reports on a simulation study to investigate the possibility of reducing the investment in tools by sharing the tools among the machines by means of an automated tool transporting vehicle.

The performance of the system is measured by the fraction of time that machines must wait for a tool required for the next imminent operation. These waiting (i.e. idle) times, which characterize the productivity loss, will depend on the selected tool mix, that is the number of tools (< 4) per tool type.

The input to the simulation program consists of the process plan, tool lives, tool transport and handling times and the tool mix. Machines may break down due to tool breakages. The transport device carries one tool at a time.

Special attention is given to the allocation policy of tools, which plays a central role during real-time operations. Since the process plans are fixed, the times when specific tools are required are known in advance. However, these "events" must be updated continually, due to waiting and breakdown periods. Since the lengths of these periods are not known in advance, updating takes place at the end of such periods. A "look-ahead" policy is defined based on the events.

Results show that the system can be operated with considerable less investment in tools while maintaining a small fraction of machine idle times. The reduction in the tool investment outweighs the extra investment in the tool transport device.

INTRODUCTION

The Dutch truck manufacturer DAF produces in its engine plant three types of engines; referred herein as A, B and C. The plant consists of a mechanical department and an assembly department. In the mechanical department cylinder blocks and cylinder heads of the engine types are processed. Typical operations here are milling and drilling. In addition there are tapping, boring, reaming, washing and some assembly operations. Beside "standard" milling and boring machines there are special-purpose machines, such as multiple

*Presented at the Fourth International Working Seminar on Production Economics, Igls, Austria, Feb. 17-21, 1986.

0167-188X/87/$03.50

spindle drilling centres with head exchange facilities.

The blocks and heads are produced on three production lines, independently operating of each other. Line I processes blocks of type A and B and consists of about 40 stations. On line II the heads of type A and B are produced and this line contains about 25 stations. Line III partly consists of two parallel lines, one processes heads C and the other produces blocks C. In the other part of this line both heads and blocks of type C are processed. Line III contains about 50 stations. The parts (blocks and heads) are transported on roller conveyors. Transportation between stations is carried out by the operator of the station.

There are several reasons to change the (current) manufacturing system in the mechanical department. Among these are: (1) several machines are worn and should be replaced by new ones; (2) the development of a new generation of engines, that could not be produced on the current lines without high set-up costs; (3) the relative inflexibility of the lines to cope with small changes in the processing of parts. The manufacturer has therefore decided to partly dismantle the lines and to assign the drilling and tapping operations to a new flexible manufacturing system (FMS) consisting of 2×4 horizontal C.N.C. machining centres and a part transportation system with one cart running on a straight track (see Fig. 1).

PROBLEM FORMULATION

Due to set-up times in other sections of the mechanical department, batches of 100 to 200 identical part types are formed. In order to balance the capacity of the stations in the department, four machining centres of the FMS should be used to produce a batch. In principle, four machines of the FMS are performing operations on heads and the other four machines are used for blocks. Moreover, a batch is processed by a group of four machines. There exist several production policies for each group of machines. That is to say, the set of operations of a part can be partitioned and assigned to the machines of the group in several ways. The truck manufacturer has decided to process all the operations of a part on the same machine.

This decision has important consequences on the investment of tools for this FMS. The operations on a block need about 45 different tools, while for a head about 29 different tools are needed. The tool set of one part type has a small overlap with the tool set of another part

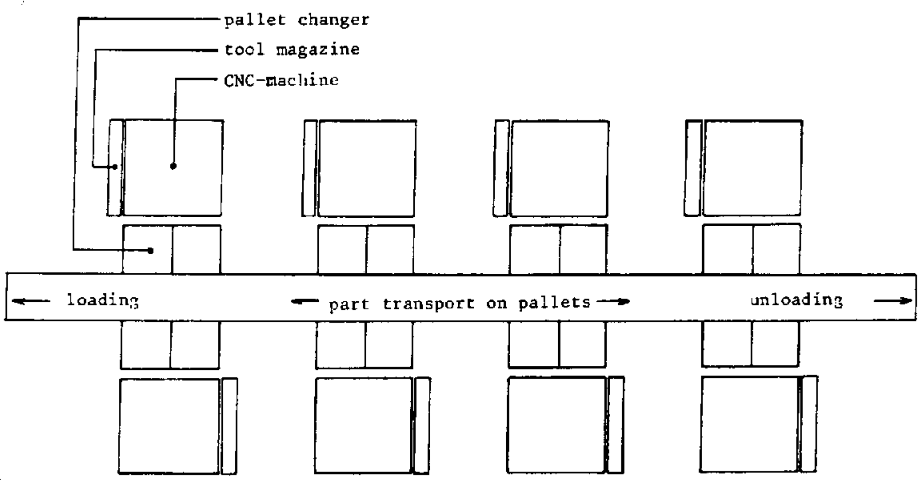

Fig. 1. Layout of the Flexible Manufacturing System (F.M.S.).

type. So, at least, 2×3 tool sets are necessary. However, due to the described production policy $2 \times 3 \times 4$ tool sets are needed. Moreover, 2 or 3 reserve tool sets seems reasonable. The costs of a tool set are about Dfl. 46000 for heads and Dfl. 90000 for blocks. There are relatively few expensive tools; 20% of the most expensive tools for a head form 51% of the total costs. For blocks 20% of the tools comprises 68% of the total costs. The complete investment in tool sets is about Dfl. 2.4×10^6 (taking into account some reduction due to overlap in tools) to compare with an investment in the FMS of about Dfl. 10^7.

These figures raise the question whether it is possible to reduce the tool costs. Some possible answers might be:

(1) Rationalization of the process plans of the part types such that:
   (a) less expensive tools are necessary;
   (b) more common tools among the part types are used.

(2) Partition a tool set in four subsets and assign these subsets to the four machines of a group, so the group acts as a transfer line. This policy, however, enlarges the load of the part transportation system.

(3) Develop a tool transportation system for a group of machines by which it is possible to share tools. In this case it is not necessary to use four tools per type within the group. Depending on a selected tool mix savings in tool costs are obtained, however, at the expense of an investment in the tool transportation system and a possible loss of machining capacity due to waiting for tools.

In this paper we report on a feasibility study of the tool sharing solution. With respect to the choice of a suitable tool transport system the following starting points are formulated: (a) simplicity, because of low costs and high reliability; (b) fast speed, because of the number of expected tool transportations; (c) exchange possibility of worn tools by new ones from an ancillary tool magazine; (d) no buffer place on the tool transport vehicle because in the machine magazines there is sufficient buffer capacity available.

The proposed layout of such a system is given in Fig. 2. Figure 3 shows an impression of a possible transport vehicle. Additional FMS tool sharing solutions are described in refs. [1–4].

In order to study the performance of the system (i.e. machine idle times) for a selected tool mix of the various part types, a detailed simulation model is developed. This model is discussed in the next section.

THE SIMULATION MODEL

We subsequently discuss the assumptions regarding the machines, the tool transport vehicle (refered to as ATT) and the operational control governing the flow of tools.

Machines

There are four identical machines processing the palletized parts in an identical way, according to a known and fixed process plan. A pallet is fully processed by one machine. It is assumed that a machine is never idle due to lack of parts, i.e. after processing a pallet the machine always finds a new pallet and processing starts immediately after pallet changing. During the simulation, only one batch of a particular part type is being processed. A process plan contains the processing times and the tool types needed for the various operations in the processing cycle.

Machines may break down due to tool breakage. Breakdowns of a machine are generated by a Poisson process, defined over the machining time. The operation during which the breakdown occurs will be finished later outside the FMS, so that after the breakdown period the machine starts with the next operation. The broken tool is removed and replaced by a new one manually. The length of the breakdown period is assumed to be constant.

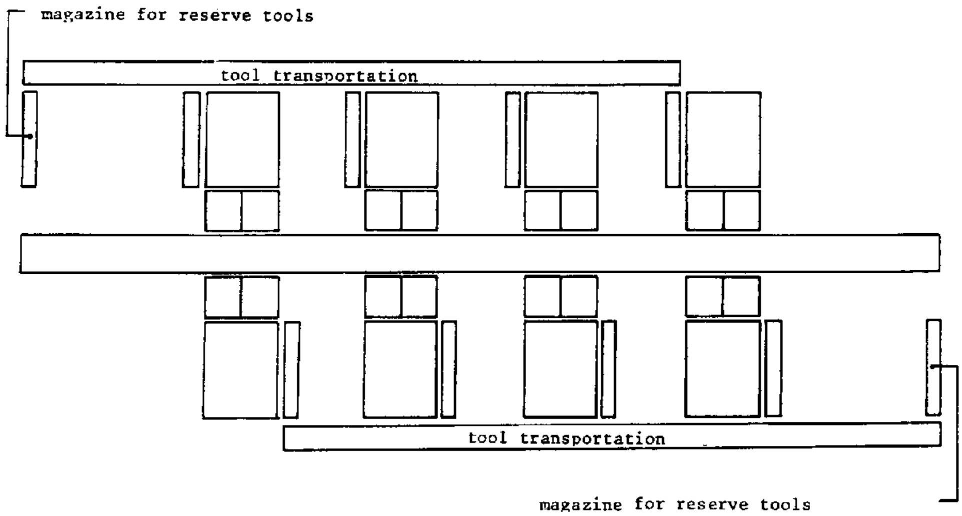

Fig. 2. Layout of the F.M.S. using tool sharing.

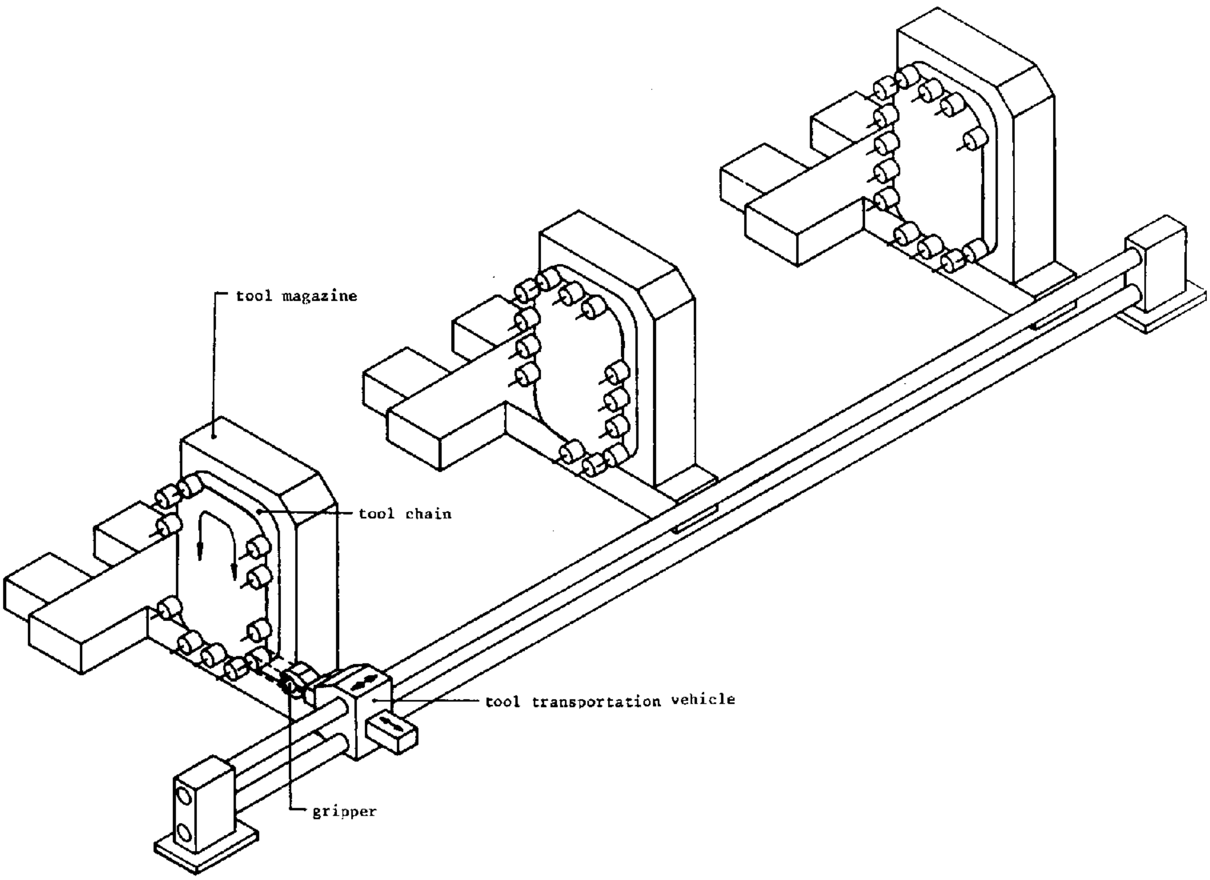

Fig. 3. A possible tool transportation system.

The automated tool transporter

The ATT carries only one tool at a time. When the ATT starts to move, it accelerates with a constant acceleration until its maximum velocity has been reached. After moving with constant velocity it decelerates with a constant deceleration until it stops in front of the exchange position at a particular tool magazine.

The indexing time of a tool in a magazine to or from the exchange position is set equal to the indexing time between the exchange position and the tool changing position near the spindle.

It is assumed that the ATT will never break down.

The operational control

To control the flow of tools shared by the four machines a number of operational rules are required. Although highly sophisticated rules can be imagined, these rules should be chosen so that they are able to be implemented in practice.

The tool availability strategy used in the model is based on a look-ahead principle. Since the processing cycle of a part is known, the moments when specific tools are needed on a machine are known in advance. We will refer to these moments as tooling events. As long as there are no breakdowns or machines having to wait for a tool, the tooling events of the various machines occur periodically, cycle after cycle. However, when a machine has to wait for a tool, or when a breakdown occurs, the tooling events are shifted. Since, in practice, the length of a breakdown period is not known in advance, the tooling events are updated (i.e. rescheduled) at the end of the breakdown period. Also, when a machine has to wait for a tool, tooling events are updated once the tool has arrived in the tool magazine. The flow of tools through the system is governed by the following rules:

(1) Upon completion of an operation, a tool is immediately assigned to the machine which needs this tool first (excluding any machines which have already a tool of the same type in its magazine or spindle, or to which such a tool is already under way, or machines which are experiencing a breakdown).

(2) Having determined the above assignment, the transport starts as soon as possible.

(3) Transports are executed in order of increasing tooling event times.

(4) A machine will not be visited during its breakdown period for security reasons, since breakdowns are remedied manually. However, when the ATT is already underway to this machine at the start of the breakdown period, this transport will be finished.

(5) When, after completing a transport to a machine, there are no subsequent transport assignments available the ATT waits on the spot until its next assignment.

As a consequence of these rules, identical tools can never be on the same machine. It should also be noted that, as a consequence of the rules (1) and (2), certain transport assignments must be cancelled and tools must be reallocated at the end of a breakdown or waiting period once the tooling events have been updated. In other words our policy gives rise to a number of transports, either scheduled or already executed, which should be readjusted in the course of time. We will return to this issue later on when discussing some alternative policy rules.

THE SIMULATION PROGRAM

The program is written in PASCAL and can be run on an IBM-XT or compatible PC with 256 Kb memory.

Input data of the program consists of:
- the process cycle (processing times, tool types);
- tool lives (in machining hours);
- tool mix (number of available tools per type);

- transport data (velocity, acceleration, deceleration, tool changing time between ATT and tool magazine);
- distances between machines and ancillary tool magazine;
- machine data (tool changing time, pallet changing time, tool indexing time in magazine);
- failure data (failure rate per cycle, length of breakdown period);
- simulation run length (in number of cycles)
- seed of random generator.

The three main system characteristics comprised in the *output* are:

- total machine idle time per machine (the idle time refers only to the idleness caused by the non-availability of tools);
- total idle time caused by a particular tool type, in order to assess the tool mix;
- the utilization factor of the ATT.

In the simulation program, the event scheduling approach is used. There are four essential system events:

(1) operation ready;
(2) transport ready;
(3) start breakdown;
(4) breakdown terminated.

Sub 1. Operation ready

At this event the following statements are executed:

(a) generate next tooling event for this type of tool (one cycle ahead on this machine);
(b) update residual lifetime of the tool;
(c) determine tool destination according to control rule (1);
(d) if tool destination refers to the same machine and residual tool life > 0, then the tool remains on this machine;
(e) if residual tool life < 0, the transport assignment incorporates a trip via the ancillary tool magazine where the tool is replaced by a new one;
(f) place transport assignment in transport list (if necessary);
(g) if next tool is present then calculate next event ("operation ready" or "start breakdown"), otherwise start waiting period for this type of tool.

Sub 2. Transport ready

At this event the ATT always arrives at a particular machine; the statements executed are:

(a) update position ATT;
(b) place tool into magazine;
(c) if machine was waiting for this tool, then
  (1) update waiting time,
  (2) calculate next event ("operation ready" or "start breakdown"),
  (3) eliminate all planned transport assignments to or from this machine from the transport list,
  (4) reallocate tools and generate new transport assignments;
(d) if the transport list is empty the ATT becomes idle, otherwise put the next event "transport ready" from transport list into event list.

Sub 3. Start breakdown

At this event the following statements are executed:

(a) machine status becomes "down";
(b) calculate event "breakdown terminated";
(c) sample start of new breakdown of this machine;
(d) update tooling events for this machine;
(e) delete planned transport assignments to and from this machine from the transport list.

Sub 4. Breakdown terminated

The following statements are executed

(a) generate next tooling event for the broken tool type on this machine (one cycle ahead);

(b) set residual lifetime of tool to full lifetime;
(c) machine status becomes "up";
(d) delete all planned transport assignments from transport list;
(e) reallocate tools and generate new transport assignments;

The statements following (e) are identical to the statements (c), (d), ..., (g) listed under the event "Operation ready" (Sub 1).

When executing the events "Transport ready" (Sub 2), see (c) (2) and (3) and (4), "Breakdown terminated" (Sub 4), see (d) and (e), planned transport assignment should be eliminated and, subsequently, tools should be reallocated and new transport assignment generated, for reasons we already pointed out. To understand the elimination, let the transport list contain the following transport assignment, ordered chronologically.

transport	tool type	from	to (machine)
1	A1	1	4
2	B	4	2
3	A2	2	1
4	A3	3	2

(Note that the system contains three identical tools of type A and one of type B). Suppose that transports to and from machine 4 should be cancelled, e.g. in case machine 4 breaks down. Obviously, transports 1 and 2 are eliminated from the list. However, since transport 1 is cancelled, tool A1 remains on machine 1. Hence, according to policy rule (1) transport 3 is forbidden and should also be cancelled. Subsequently, by the same reasoning, we conclude that transport 4 must also be eliminated. The example shows that the elimination of transports to and from a particular machine may lead to a chain of eliminations of logically connected transports induced by the transport policy rules.

In the reallocation procedure, it is checked whether all tools are on the machine that needs them first, according to the most recent tooling events. If this is not the case, a reallocation is made and appropriate transport assignment are generated and placed in the transport list.

TABLE 1

Simulation input

Number of machines	: 4
Run length:	
Cylinder head	: 200 parts
Cylinder block	: 100 parts
Transport vehicle:	
Velocity	: 1 m/s
Acceleration/deceleration	: 3 m/s^2
Tool changing time	: 5 sec
Machines:	
Distance	: 7 m
Tool indexing time	: 5 sec
Tool changing time	: 10 sec
Pallet changing time	: 168 sec
Failure rate cycle per part:	
Cylinder head	: 0.1
Cylinder block	: 0.2
Length of breakdown period	: 600 sec

INITIALISATION

The simulation starts at time zero. At that time all tools reside in the tool magazines. As many tools as necessary are allocated to the first machine, then to the second and so on. Consequently, if for example only two tools are available to process the first operation in the cycle, the first two machines can start their machining cycle, whereas the two other machines must wait.

RESULTS

Several simulation runs are carried out in order to select a suitable tool mix for each part type (3 heads and 3 blocks). Criteria for such a selection were: (1) total machine idle time not greater than 2%; (2) utilization factor of the ATT less than 75% and preferably about 50%. Besides the specific tool data (processing

TABLE 2

Simulation output for cylinder heads

Type A	
Tool savings	: Dfl. 82,638.-
Total machine idle time: $\bar{s}$	: 1.7%
Confidence interval*	: $0.7\% < s < 2.7\%$
Utilization factor of the ATT: $\bar{b}$	: 54%
Confidence interval	: $52\% < b < 56\%$
Type B	
Tool savings	: 48% Dfl. 87,849.-
Total machine idle time: $\bar{s}$	: 1.5%
Confidence interval	: $1.0\% < s < 2.0\%$
Utilization factor of the ATT: $\bar{b}$	: 53%
Confidence interval	: $51\% < b < 55\%$
Type C	
Tool savings	: 53% Dfl. 110,558.-
Total machine idle time: $\bar{s}$	: 1.1%
Confidence interval	: $0.1\% < s < 2.1\%$
Utilization factor of the ATT: $\bar{b}$	: 44%
Confidence interval	: $42\% < b < 46\%$

*95% confidence intervals

TABLE 3

Simulation output for cylinder blocks

Type A	
Tool savings	: 59% Dfl. 189,548.-
Total machine idle time: $\bar{s}$	: 0.7%
Confidence interval	: $0.4\% < s < 1.0\%$
Utilization factor of the ATT: $\bar{b}$	: 36%
Confidence interval	: $34\% < b < 38\%$
Type B	
Tool savings	: 57% Dfl. 226,278.-
Total machine idle time: $\bar{s}$	: 1.0%
Confidence interval	: $0.2\% < s < 1.8\%$
Utilization factor of the ATT: $\bar{b}$	: 36%
Confidence interval	: $34\% < b < 38\%$
Type C	
Tool savings	: 48% Dfl. 109,513.-
Total machine idle time: $\bar{s}$	: 1.7%
Confidence interval	: $1.2\% < s < 2.2\%$
Utilization factor of the ATT: $\bar{b}$	: 51%
Confidence interval	: $46\% < b < 56\%$

TABLE 4

The number of reserve tools as a function of the tools per type in the system

Number of tools per type	In system	Reserve	Total
Without tool sharing	4	3	7
With tool sharing	1	2	3
	2	2	4
	3	3	6
	4	3	7

time, tool life, tool price), the data of Table 1 are used as input for these simulation runs.

The output, averaged over five simulation runs per part type, are given in Tables 2 and 3, using different seeds for the random generator. In these tables the obtained tool savings are also given. These savings are calculated from the difference in costs between a complete quadruplicate tool set and the selected tool mix for a type. The savings could be obtained, for the most part, by sharing the expensive tools. Additional savings result from the necessary reserve tool set. If, for example one tool of a particular type appears to be sufficient for the production of a batch then it seems reasonable that no more than two reserve tools of this type are necessary. If the investment policy of Table 4 is followed than the total tool savings are about Dfl. 985000. In both cases correction has been made for the overlap of tools between the part types. Although the savings are considerable, one should remember the additional investment in the tool transport system and in the two extra reserve tool magazines. The total costs of this investment are about Dfl. 640000.

ALTERNATIVE POLICIES

In the operational control considered here, tools are transported as soon as possible, based on the current knowledge of future tooling events. Consequently, the tool allocation must sometimes be adjusted in view of unforeseen disturbances, leading to additional transportations. To overcome this drawback one might use a policy based on the following rule: a machine calls for a tool as late as possible. Here one should at least take into account the transportation time for a selected tool from its current position to the calling machine and, moreover, one should have a criterion to select such a tool. Although such a policy might be better with respect to the number of transportations, it may possibly lead to unnecessary idle time of machines due to non-controllable overload of the ATT. An additional transportation slack time can be introduced to cope with this problem, which could be determined by simulation. However, in this case readjustments are still necessary. Which of these policies is the better one is a subject for further investigation.

A point of serious concern regarding our present policy is the seemingly unnecessary tool transportations. When, under the present policy for instance, three tools of a certain type are present in the system, recirculating of all three tools takes place. Thus a tool might be transported from its current machine to another machine although the current machine needs this type of tool only slightly later. If, however, two tools will be assigned exclusively to two particular machines, only the third will be migrating between the two other machines. In doing so, the number of transportations will be reduced and the utilization of the ATT will be lowered. The effect on the machine idle times is also a topic of future research.

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