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EXPANDED SIMULATION STUDIES TO EVALUATE TOOL DELIVERY SYSTEMS IN AN FMC

Lisa Marie Dullum

Cummins Engine Company
Mail Code 41401
Box 3005
Columbus, IN 47201

Wayne J. Davis

Department of General Engineering
University of Illinois
104 S. Mathews
Urbana, IL 61801

ABSTRACT

A previously developed simulation model of a proposed flexible manufacturing cell (FMC) was modified to further determine the effects of operating fewer machines, considering machine maintenance and breakdowns, and installing larger tool magazines upon the system performance. In particular, these simulation studies attempted to quantify the performance constraints arising from the inclusion of an automated tool transporter to deliver tools to the included milling machines within an FMC.

Key Words

Flexible systems, breakdowns, maintenance, tooling.

1 INTRODUCTION

The goal of flexible automation is to produce a wide variety of parts without a major restructuring of the manufacturing facilities. This capability reduces manufacturing costs and shortens lead times. Just-in-time manufacturing becomes possible which reduces work-in-progress inventory. Because of the large amount of capital invested in flexible manufacturing systems, high utilization of equipment represents another performance consideration.

This paper will discuss an expanded simulation study using a previously developed simulation model for a flexible manufacturing cell (FMC) at the Rock Island Arsenal in Rock Island, IL (see Hedlund, Davis and Webster 1990). Because the FMC machines hardened steel, small tool lives are expected, increasing the number of tool transfers. In addition, the parts to be manufactured are very complex. The number of tools required for each fixturing step is variable, and this number can actually exceed the number of positions available for storing tools at the machine. The mean number of tools required for processing each fixture was between 10 and 20 in this study, but this mean is obviously dependent upon the mix of parts considered.

There are also no common tools that can be shared in the processing of more than one part type which again significantly increases both the number of tools that must be considered and the number of tool transfers. Finally, the number of parts of a given part type that could be mounted upon a fixture is also variable with up to eight parts being mounted upon a given fixture. Therefore, the tool life required of each tool to process the parts upon a given fixture represents a variable quantity dependent upon the number of parts actually mounted upon the fixture.

An assessment of the ability of two different proposed tool transporter systems to adequately deliver tools was desired. While the previous work (Hedlund, Davis and Webster 1990) examined the effects of speeds and the different tool delivery systems, this paper will expand the study to assess the performance dependence upon the number of operating machines, the inclusion of machine maintenance and breakdowns considerations, and an increase in the tool magazine size.

2 SYSTEM DESCRIPTION

The proposed FMC illustrated in Figure 1 is used to machine a large variety of hardened steel parts and assemblies. The major components of the FMC considered in this study are:

- The Kearney and Trecker 800 Milwaukee Matic milling machines, referred to as the "front" machines,
- The Kearney and Trecker Orion 2300 milling machines, referred to as the "back" machines,
- A tool storage carousel, and
- A tool delivery system.

Smaller parts are machined on the front machines. These parts are often then welded into larger assemblies that are next returned to the FMC at the back machines for further machining. Other large parts are also machined on the back machines. In every case, the parts are fixtured, and each fixture requires processing on only one machine of a given type.

Part scheduling is designed to reduce tool movement. The basic scheduling logic is as follows. A new part is first scheduled to a machine where the same part type has already been assigned and the required tools are available. If this is not possible, the part is then scheduled at a machine with the lowest amount of processing time currently assigned

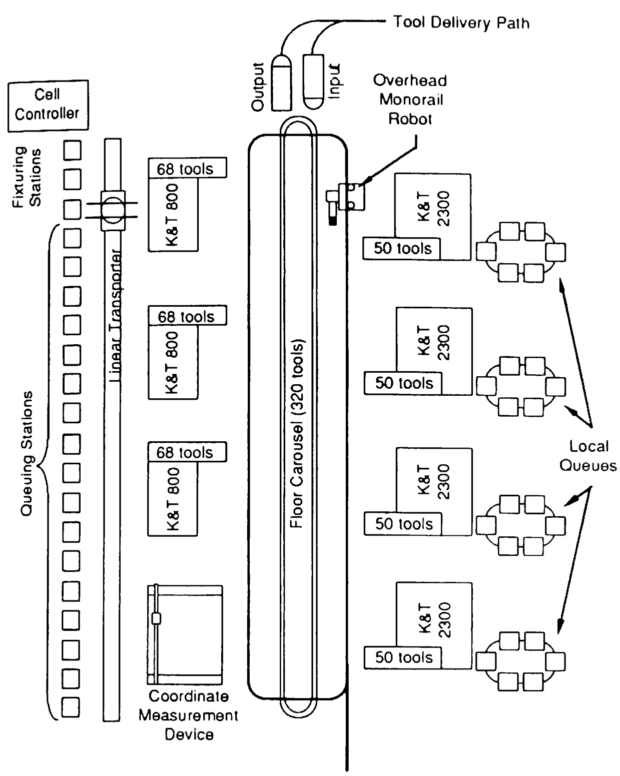

Figure 1: Layout for the Proposed FMC at the Rock Island Arsenal Using a Monorail Robot

to it. If during production, a machine becomes idle, parts can be rescheduled to it provided that no processing upon the part has taken place. The desire of the included assignment job policy is to minimize tool movement, while simultaneously maximizing machine utilization.

Parts scheduled for production at a front machine are fixtured at a common load/unload station. A linear transporter then moves them to either the assigned machine or to a common queue. There is no local space for the storage of jobs at each of the front machines. However, a common queue for the front machines can hold a maximum of sixteen pallets. Therefore, only the job that is in-process can reside at a front machine. After processing, the linear transporter brings the parts back to the load/unload station. There they are removed from the fixtures and either refixtured or exit the system. Up to three fixturing steps may be required for a given part type, but this number is again part dependent. Parts scheduled for one of the back machines are fixtured at an individual fixturing station for each machine. The local storage queues for each of the back machines can hold a maximum of five pallets

Each machine has its own tool magazine for storage of tools with either 68 pockets for the front machines, or 50 pockets for the back machines. In addition, the auxiliary tool carousel, located between the front and back machines, and a remote tool crib, where the tools are assembled and inventoried, also store tools. Tools are currently transported manually between the tool carousel and the tool crib although an automated guided vehicle system has been proposed for this task as indicated in Figure 1.

A tool handling robot will transport tools within the cell between each machine's tool magazine and the tool storage carousel located between the machines. Two types of tool transport configurations are considered: an overhead monorail robot and an overhead gantry robot. The overhead monorail robot would run on an oval track around the tool carousel, see Figure 1. The overhead gantry robot would run along two parallel tracks and also be capable of movement from side to side.

Since short tool lives and other machining constraints require many tool transfers, evaluating the ability of the tool handling system to adequately supply the machines with the necessary tools is the main focus of this study.

2.1 Previous Research

Previous studies (see Hedlund 1990 and Hedlund, Davis and Webster 1990) determined that although the original focus of the study was on the effectiveness of the tool transporter system, modeling of the tool handling system alone would not have allowed its interaction with the other parts of the FMC to be properly investigated. Since the tool transporter usage is heavily dependent on the scheduling of part production within the system, the model had to include this dependency. The FMC was determined to be too complex to employ mathematical modeling. Therefore, the simulation language SIMAN (Pegden, Shannon and Sadowski 1990) was chosen to model the system. FORTRAN-based subroutines are used to model the more complex logic associated with part scheduling and tool transport.

The simulation includes tool movement due to:

- Tool wear and replacement,
- Changes in part types, and
- Machine tool magazines nearing capacity.

In addition, tool arrivals and removals from the system are considered by the modeling of the remote tool crib. Tool wear rates are derived from data obtained in a separate study at the Rock Island Arsenal.

The developed simulation model is extremely detailed. An inventory of the included controllers in the proposed system exceeds sixty in number. The detailed interactions among these controllers are included within the simulation model to insure that a realistic portrayal of the system operation would be achieved. For example, to unload a tool from a machine's magazine, there must be a coordinated interaction among the machine magazine and tool exchanger controllers, the tool storage carousel controller and the overhead tool robot controller. The modeling of the machining of the parts details the loading and unloading of the essential tool for each processing step as well as carefully accounting for the remaining tool life for each tool employed in the processing. Detailing these interactions as well as the control logic being executed by each included controller is certainly beyond the scope of this paper. Nevertheless these definitions were essential to executing the more global scheduling and resource allocation strategies.

To keep the system operating smoothly and increase machine utilization, tool movements between the machine tool magazines and the tool storage carousel were assigned priorities. Tools being removed from a nearly full magazine received the highest priority to prevent dead-lock. The next priority was given to tools immediately needed for processing at a machine. The lowest priority was assigned to all other tool movements, such as the removal of worn or unneeded tools. The model is also designed to permit tool sharing between machines which allowed the same fixture type to be processed simultaneously on two machines using one ensemble of tools. In some cases, as noted earlier, the essential tooling to complete the processing for a fixture could not be entirely stored in the machine carousel. In this situation, tools that are no longer needed for processing the fixtured parts are removed and replaced with tools required later in the processing. Therefore, the developed priorities for scheduling tool transfers had several requirements to satisfy. Although global priority schemes were developed, these strategies are actually implemented with the logic of individual controllers and the modeled interactions among the controllers.

Because the data were not available, part order arrivals to both the front and back machines are assumed to obey exponential distributions. This choice also maximizes the variability in the job arrival stream. However, this choice of the arrival distribution likely had little effect on the final results since the arrival rate for each experimental configuration was individually increased until the system was saturated. In this manner, the maximum throughput for each experimental configuration was sought.

The three experimental factors studied to determine their effects on the FMC's performance were: the tool transporter speed, the tool carousel speed, and the type of tool transporter. Since three tool transporter speeds, two tool carousel speeds, and two tool transporter types were considered and two independent replications were generated for each possible set of parameters, a total of 24 experiments were performed. Each simulation trial considered approximately two month's production beyond a warm-up period to minimize the initial transient effects.

Results showed that throughput increased as the transporter and the carousel speeds increased, and in most cases, the gantry robot outperformed the monorail robot. Average machine utilization ranged from just over 30% in the worst scenario to 60% under the best scenario. In no case was the desired machine utilization of greater than 75% achieved. This suggested that the considered tool transport systems were inadequate. Recommendations to further study the system will be given in the conclusion. We will now discuss the results of the expanded simulation study.

3 EXPERIMENTAL RESULTS

3.1 Changing the Number of Machines

Although previous experiments suggested that the tool transporter system would not adequately supply tools to the machines, further experiments were needed to fully explore the proposed system's capabilities. New information on the system indicated there would be two front machines instead of three. The study was then generalized to analyze the production constraints arising from the tool handling system as a function of the number of operating machines. In particular, the number of both front and back machines were varied and the initial experiments were repeated.

Machine configurations of one front and three back, two front and three back, two front and four back, as well as the original three front and four back, are compared. The speeds of the floor carousel and tool transporter are varied for both the proposed alternatives of a monorail or a gantry tool delivery system. A total of 48 different parameter sets were run, each replicated twice, giving a total of 96 simulation experiments. As in the previous experiments, the system was saturated with parts to determine its upper production limit.

The results of these new experiments, summarized in Figures 2-9, concur with the previous analysis' conclusion

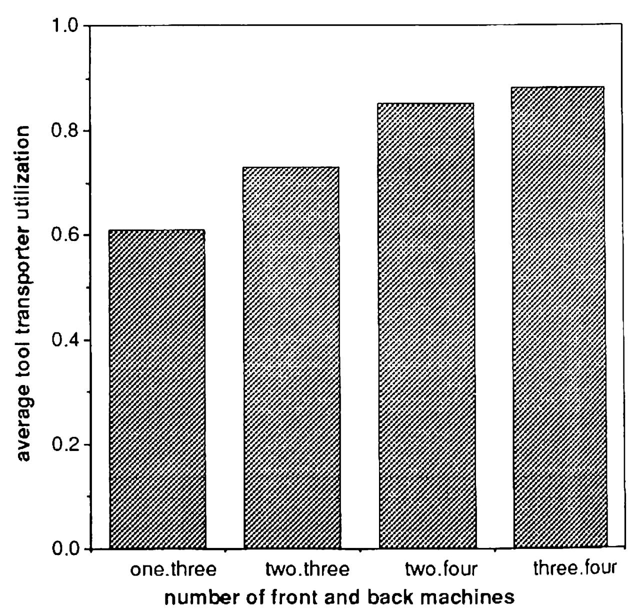

Figure 2: Average Tool Transporter Utilization for Each Machine Configuration

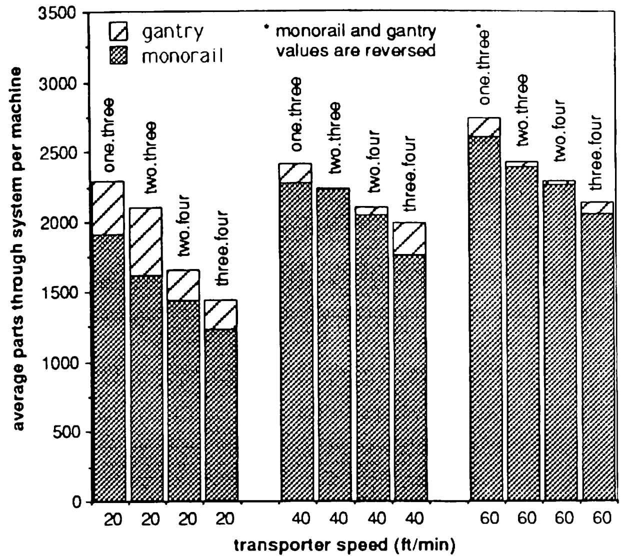

Figure 3: Average Parts through the System per Machine vs. Tool Transporter Speed for Each Machine Configuration

that the tool transporter is limiting the number of parts that are produced by the system. As the total number of machines decrease from seven to four, the average tool transporter utility decreases from 88% to 61% as shown in Figure 2. Concurrently, machine utilizations increase.

Figure 3 compares the mean number of parts through the system per machine for both monorail and gantry tool transporter systems versus transporter speeds for each of the four different machine configurations. The effects of the different flour carousel speeds are not shown in this figure and have been averaged in the throughput data. In all situations, the gantry outperforms the monorail system, except a one front and three back machine configuration with a tool transporter speed of 60. However, higher tool transporter speeds show less difference between the two types of systems as more parts per machine are processed, given the same tool transporter speed. The higher amount of parts per machine helps offset the lost production from using fewer machines. This observation suggests tool handling is less constraining on the system at higher tool transporter speeds.

More detailed information on the average number of parts through the system per machine versus transporter speeds can be seen in Figures 4-7. Figures 4 and 5 show the average number of parts through the system per machine versus tool transporter speed for a one front and a three back, and a two front and a three back machine configuration, respectively. For a tool transporter speed of 20, there is a small difference in average parts per machine for each of the different floor carousel speeds (indicated as being either 25 or 40 feet per minute beside the word "carousel" in the legend) and tool transporter types, while for tool transporter speeds of 40 and 60 little discernible difference is apparent. Thus, no marked increase in throughput occurs as the tool transporter speeds increases. This situation arises from the tool transfer constraints being less binding when fewer machines are to be serviced. This fact is further evidenced in that the greater marginal throughput is gained when the transporter speed is increased from 20 to 40 versus from 40 to 60.

Figures 6 and 7 also show the average number of parts through the system versus two transporter speeds for two front and four back and three front and four back, respectively. However, these graphs show that average part

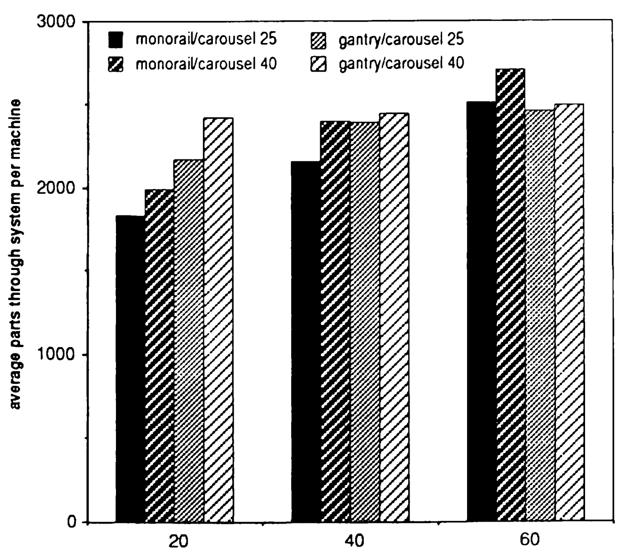

Figure 4: Average Parts through System vs. Tool Transporter Speed for One Front and Three Back Machines

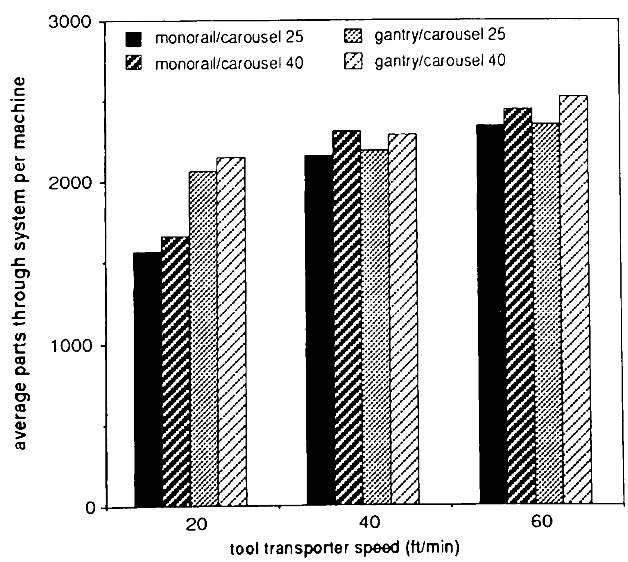

Figure 5: Average Parts through System vs. Tool Transporter Speed for Two Front and Three Back Machines

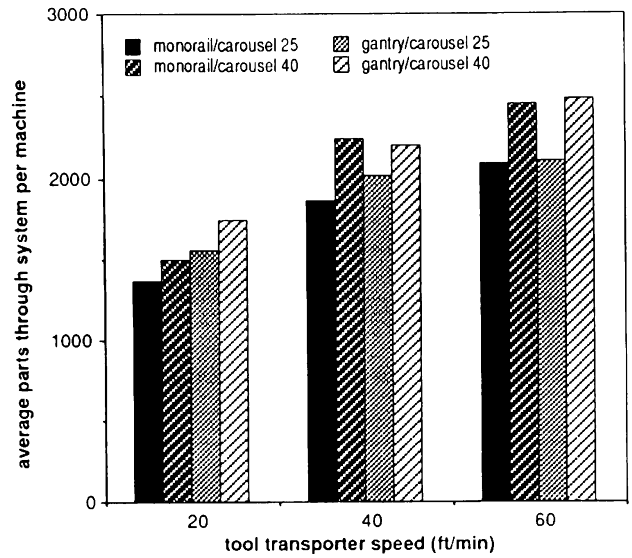

Figure 6: Average Parts through System vs. Tool Transporter Speed for Two Front and Four Back Machines

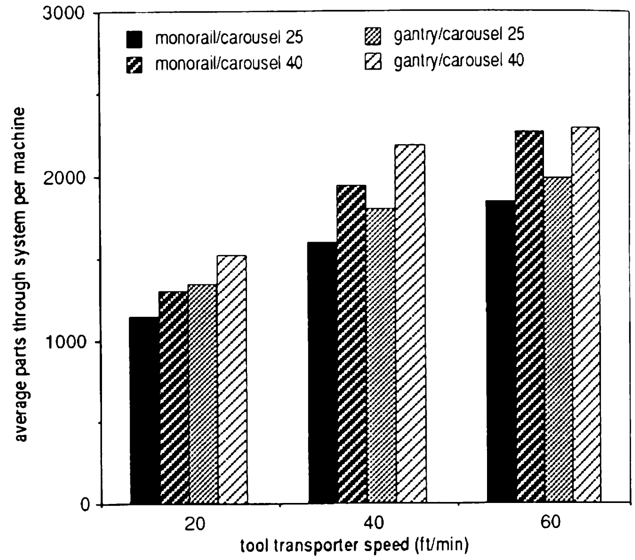

Figure 7: Average Parts through System vs. Tool Transporter Speed for Three Front and Four Back Machines

throughput per machine is highly dependent on the type of tool transporter, the tool transporter speed, and the floor carousel speed. More throughput was obtained with higher speeds and a gantry configuration. Because the marginal increase in part throughput in going from 20 to 40 is similar to that of going from 40 to 60 (especially for the three front and four back machine configuration), the tool transfer constraints are significant. Thus, as the number of machines increases, the type and the speed of the tool transporter become more important in affecting the number of parts through the system per machine. Similar results were found for floor carousel speeds.

It is also important to observe how each of the machines is employed during the simulation runs. In Table 1, the 12 parameter specifications are provided for the simulation runs performed in this phase of the analysis. In Figures 8 and 9, the spindle status is broken into four classifications that were observed over the duration of the simulation run for the one front and three back machines and three front and four back machine configuration, respectively. The four status configurations that were considered are no parts scheduled (idle), part or tool being transferred, waiting for a tool to arrive at the machine, and the spindle-up (cutting) time. For the one front and three back configuration depicted in Figure 8, the spindle-up time averages well over 50% across all 12 parameter settings that were considered. In the same figure, the percentage of time that the spindle is waiting for a tool to be delivered to the machine is significantly less than 10% across the 12 parameter settings.

For the three front and four back configuration depicted in Figure 9, the average spindle-up percentage has significantly decreased. Furthermore, the spindle-up percentage is certainly more dependent upon which parameter set is considered. Similarly, in Figure 9, percentage of the time that the spindle is waiting for a tool to be delivered has significantly increased. It is clear, in Figure 9, that the tool delivery constraints are critical to the performance of the system.

These analyses show that the investigated tool delivery

Tool Transporter	Parameter Settings (two replications each)
Monorail (parameters 1-6)	1,7: Carousel = 25 Transporter = 20
	2,8: Carousel = 40 Transporter = 20
	3,9: Carousel = 25 Transporter = 40
Gantry (parameters 7-12)	4,10: Carousel = 40 Transporter = 40
	5,11: Carousel = 25 Transporter = 60
	6,12: Carousel = 40 Transporter = 60

Table 1: Parameter Settings for Machine Configuration Experiments

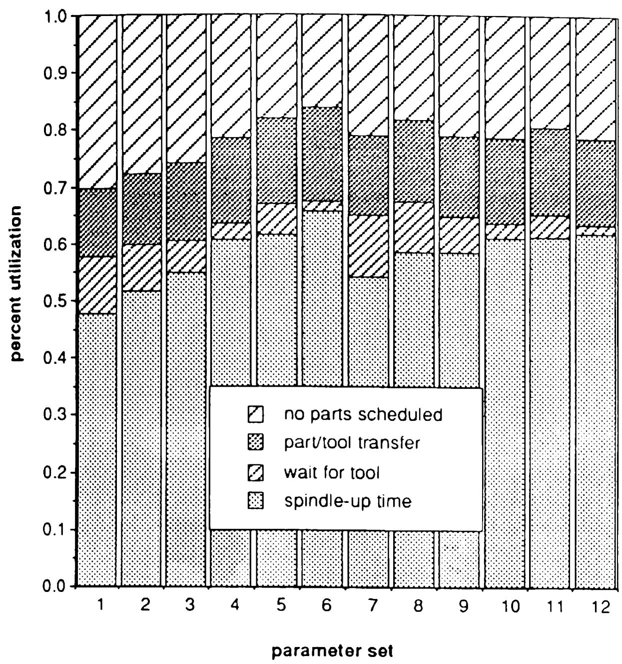

Figure 8: Breakdown of Machine Utilization for One Front and Three Back Machines

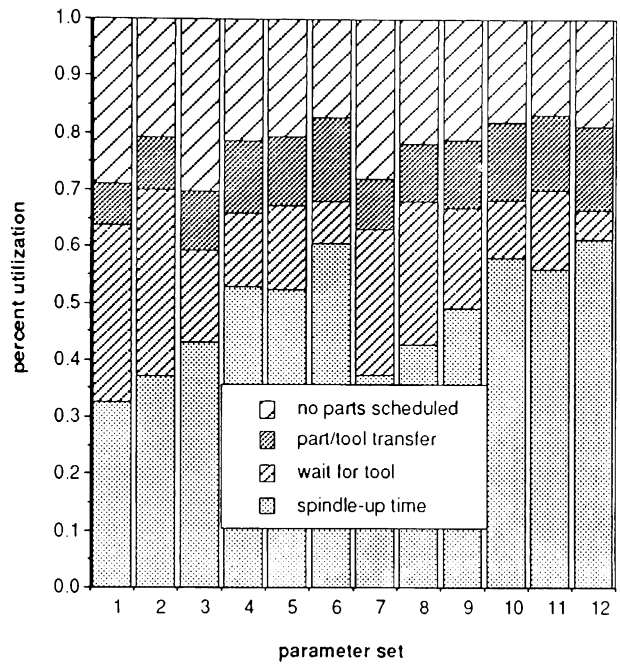

Figure 9: Breakdown of Machine Utilization for Three Front and Four Back Machines

systems are inadequate for the originally proposed machine configuration as depicted in Figure 1. However, as the number of machines decreases, the type of tool delivery system becomes less critical, as does the tool transporter and floor carousel speeds. Certainly, additional tool delivery systems must be investigated to sufficiently supply tools to the machines. One potential system might employ two monorail robots. The consequences of considering other alternatives are discussed in Section 4.

3.2 Machine Maintenance and Breakdowns

Rock Island Arsenal currently performs four levels of scheduled machine maintenance. Each level of scheduled maintenance is more rigorous and requires more time than the previous level. The type and duration are shown in Table 2. Since the simulation experiments considered only a two month period because of the length of time required to complete a simulation trial, only monthly maintenance was modeled.

Level of Maintenance	**Duration (Hours)**
Monthly	2
Quarterly	25-30
Semi-Annual	30-40
Annual	60

Table 2: Levels of Maintenance and Their Durations

The modeled maintenance cycle begins every thirty days with one of the front machines and proceeds with the remaining machines in two-hour intervals, until all machines have been serviced. If the machine is currently idle, maintenance begins immediately, otherwise the maintenance begins after the current fixture in processing has been removed from the machine. During maintenance, tools or jobs cannot be taken to or removed from the machine's tool magazine or queues, respectively.

Interviews with Rock Island Arsenal staff revealed that machine breakdowns on currently installed machines routinely occur on an average of once a week for each machine. Most of these breakdowns are minor. Downtimes are usually short, averaging two hours. The two common reasons given for a machine breakdown are lost power and switch failures. Although more serious mechanical failures cause much longer downtimes, these events are rare and were not considered in this study.

If historical data on machine breakdowns in the system is unavailable, Law suggests using a Gamma distribution to generate the occurrence of a machine breakdown and its resulting downtime (Law 1990). This procedure was adopted in our study.

Results from these experiments were inconclusive in assessing the effect of scheduled machine maintenance and machine breakdown on the system and will not be discussed in detail. In general, if the system was already being constrained by the tool transporter system which is the usual case, then the minor reduction of machining capacity arising from the consideration maintenance and break-

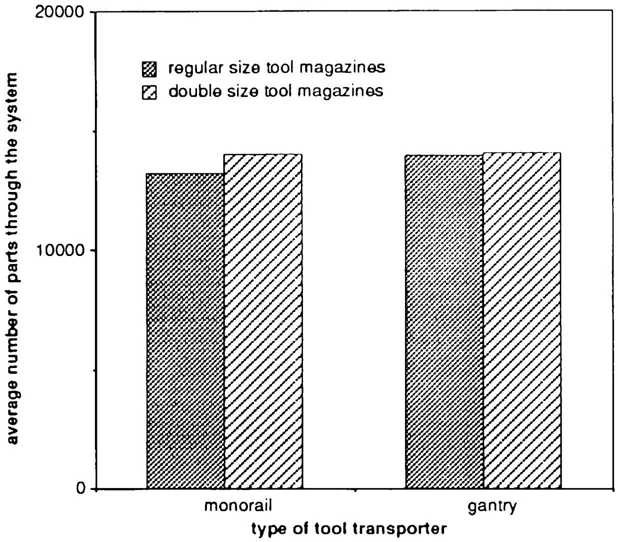

Figure 10: Average Number of Parts through the System for Each Tool Transporter Type

down resulted in similar throughputs realized in the studies where maintenance and breakdowns were not considered. The experimental results of this study again substantiated the fact that the tool transport system, not the machining capacity, was the critical resource to the production throughput.

3.3 Modifying Machine Tool Magazine Size

In an attempt to reduce the criticality of the tool transporter system, the tool magazine sizes were next doubled permitting more tools to be stored at each machine. Through this modification, it was conjectured that there would be a reduced need to offload tools from a given machine when a new fixture type was scheduled for production, and thus, the number of tool transfers would be reduced.

The machine tool magazine capacities for the front and back machines were thus increased to 136 and 100 tools, respectively. Because the larger magazines would result in longer tool search times at the machine, the modeled search times were also increased. Experiments were run for only one tool transporter speed and one floor carousel speed. Both the monorail and gantry configurations were considered. Each experiment was replicated twice with different random number streams. A total of 8 experiments were run.

Few conclusions could be drawn from the experiments with the larger tool magazines. Figure 10 shows the average number of jobs through the system for both tool transporter systems using both the original magazines and the larger magazines. The larger magazines appear to process slightly more jobs, but the difference is not significant. This is especially true for the results employing the

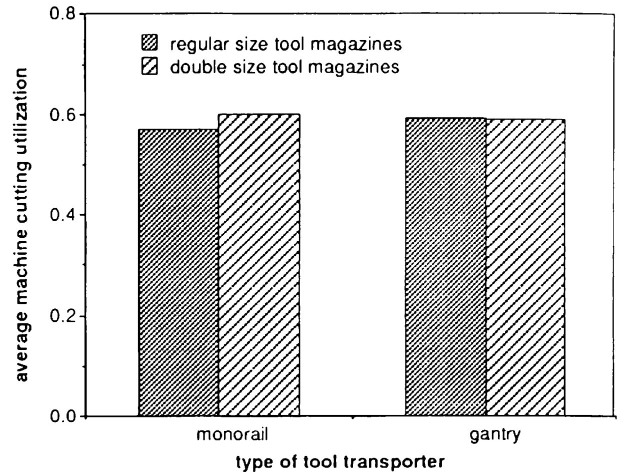

Figure 11: Average Machine Utilizations for Each Tool Transporter Type

gantry tool transporter.

Machine cutting utilizations do not significantly change for the larger tool magazines. From Figure 11, average machine cutting utilizations are higher for the larger magazines with a monorail tool transporter and slightly lower with a gantry tool transporter. Thus, the larger magazines appear to have no overall effect on machine cutting utilization.

The number of tools moved per job processed decreases with larger tool magazines. Figure 12 shows that by increasing the magazine size, fewer tool movements are needed on average to process a job. The larger tool storage at each machine evidently reduces the amount of tool movements due to overcrowding.

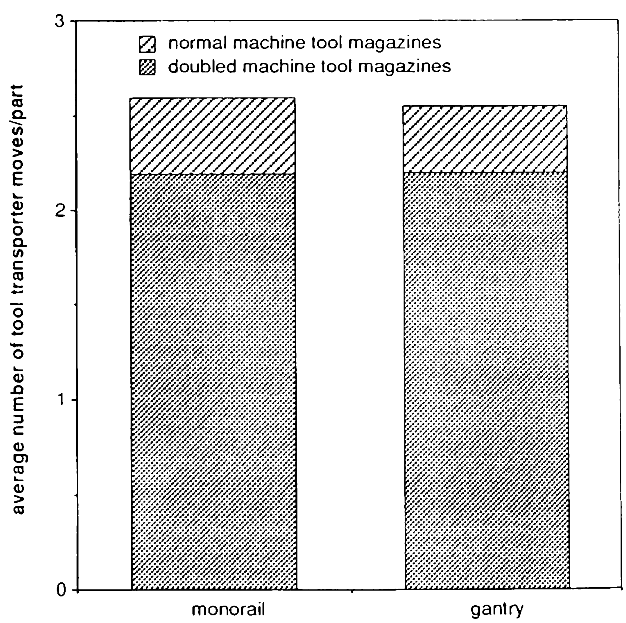

Figure 12: Average Number of Tool Transporter Moves per Part for Each Tool Transporter Type

While the larger tool magazines do provide more storage at each machine, this capacity has little or no effect on machine cutting utilization and job throughput. This result may occur because most tool movement in the system is due to job processing and tool wear rather than overcrowding at machine tool magazines. In addition, assignment of jobs to the machines does not currently consider if the tools needed for processing are currently at a machine. Rather, the simulation only checks if a similar part type has currently been scheduled to a machine. If this is not the case, the machine with the smallest scheduled production backlog is selected. This fact may reduce some of the potential advantages that can be derived from larger tool magazines. Modifying the controller codes to compare the current tooling at each machine against the tooling required to process the fixture represents a major modeling and programming effort and was not addressed. Nevertheless, because of the larger tool magazine capacity, tool movements per part produced did decrease slightly.

4. CONCLUSION

The large capital investment required for FMCs make a thorough analysis of the cell a must before any design is finalized. Because these cells are often complex, simulation modeling is an excellent tool to help predict cell performance. Criteria such as output, throughput time, and machine utilization can be obtained through simulation and used to measure cell performance.

A simulation study of a proposed FMC at the Rock Island Arsenal showed it to be incapable of meeting expectations. Specifically, the proposed tool transporter system was unable to adequately provide the tools for the machines, resulting in low machine cutting utilizations. The proposed automated tool transporter was rejected and the current manual delivery system has been retained.

There are, however, other configurations for the tool transport system that remain to be considered. In particular, it was desired to investigate the use of two overhead monorail robots instead of one to transfer tools between the machine magazines and the tool storage carousel. If this option was to be considered, it was felt that two storage carousels would be advisable. The present configuration of the FMC depicted in Figure 1, however, is also not ideal, particularly if two storage carousels were adopted. The ideal situation, would have the K&T 800's at one end and the K&T 2300's at the other. In this manner, one storage carousel could be dedicated to the K&T 800's and the other to the 2300's. The size of the carousels could also be reduced with an associated reduced time to spin the carousel to the appropriate position for exchanging a tool. Since the machines are in place, it is totally infeasible to consider repositioning of the machines.

Although several other potential alternatives for the tool handling system have been defined, none have yet been investigated through simulation studies. To modify the current simulation models to incorporate the suggested modifications in the tool delivery system would require nearly a complete rewrite of the existing simulation code, requiring several man years of effort to analyze each alternative. This situation arises from the fact that the control logic for each controller is distributed throughout the model. Current simulation tools are not designed to effectively model the interactions of the controllers, rather they are designed to model the flow of entities. In this case, the modeling is further complicated by the fact that there are two major classes of entities that need to be characterized, jobs and tools. Thus, two distinct definitions of entities were used throughout the SIMAN (Pegden, Shannon and Sadowski 1990) model.

Perhaps the major observation made in this study is the inadequacy of current simulation tools. The modeling of the flow of entities is no longer a viable approach to modeling automated manufacturing systems. In these systems, the flow of entities is being orchestrated through the interaction of controllers rather than the flow of entities controlling the controllers. New generations of simulation tools are absolutely essential to model the interaction of the controllers. To make accurate performance projections for automated systems, we must detail the consequences for all relevant constraints associated with the operation of the system. Presently, we are neglecting many of these constraints because the simulation tools do not exist to expedite their consideration. As a consequence of neglecting constraints, we are likely overestimating the expected performance of these systems.

As an example, the prime contractor for the FMC pictured in Figure 1 provided simulation studies which projected machine utilization in excess of 70%. These projected utilizations have not been achieved in practice, and the detailed simulations performed in this study appear to state that they cannot be achieved. The authors do not believe that this situation represents an isolated instance. In our discussions with other manufacturers, a nearly universal complaint is that the realized performance has not achieved the projected performance made in the planning simulation studies. Certainly, more detailed simulation models are required to provide improved estimates.

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AUTHOR BIOGRAPHIES

LISA M. DULLUM received her B.S. and M.S. degrees from the Department of General Engineering at the University of Illinois at Urbana-Champaign. Before her graduation, interned with the Automated Manufacturing Research Facility at the National Institute of Standards and Technology. She is currently employed as a manufacturing systems analyst by Cummins Engine Company in Columbus, Indiana.

WAYNE J. DAVIS is a professor of General Engineering at the University of Illinois at Urbana-Champaign. His research interests include computer-integrated manufacturing, real-time decision making and control of discrete-event systems, and simulation. He currently collaborates with the Electronics Manufacturing Productivity Facility in Indianapolis, Indiana and the Automated Manufacturing Research Facility at the National Institute of Standards and Technology.