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Osman Balci, Randall P. Sadowski, Richard E. Nance (eds.)

USING COMPUTER SIMULATION TO COMPARE TOOL DELIVERY SYSTEMS IN AN FMC

Eric P. Hedlund

Ingersoll-Rand Company
942 Memorial Parkway
Phillipsburg, New Jersey 08865

Wayne J. Davis

Department of General Engineering
University of Illinois
104 South Mathews
Urbana, Illinois 61801

Peter L. Webster

Automation Associates, Inc.
512 Via De La Valle
Solana Beach, California 92075

ABSTRACT

In the implementation of a flexible manufacturing cell (FMC), it is uncertain whether the proposed tool delivery system will be able to perform adequately. In order to determine the system's adequacy, along with the resulting efficiency of shop floor operations, a simulation has been performed. Tool transfer and job scheduling strategies were developed to aid in improving the flow of parts and tools on the shop floor. In addition, a series of output screens were developed for use during the simulation runs to verify the simulation and control strategies being used.

1. INTRODUCTION

For automated manufacturing to be efficient, well designed system layouts, cell controllers and material handling systems are required to facilitate the flow of work pieces and associated manufacturing resources on the production floor. Detailed knowledge of the manufacturing process must be ascertained, and the strategies used by the cell controller to coordinate the movement of parts and tools must be well established and proven to work. The separate components of the system must individually work in an effective manner and, when operating together, must be capable of coordinated interaction. One of the best methods for analyzing manufacturing systems and evaluating proposed system layouts is computer simulation. This paper describes the use of simulation to model the complex manufacturing operations and controlling algorithms of an FMC.

A fully automated FMC is in the process of being installed. When fully operational, the FMC is expected to process a large variety of parts, whose machining programs will each require a large number of different tools. In addition, the parts to be machined will be hardened steel, causing tool lives to be as short as 5 minutes. Therefore, a large number of tool transfers are foreseen and it is of extreme importance that a tool delivery system be installed which is able to keep the machines supplied with the essential tools.

2. DESCRIPTION OF THE FMC

The FMC being investigated is shown in Figure 1. It consists of seven CNC milling machines arranged in two rows and separated by a central tool delivery system. The rows of three and four machines will be referred to as the *front* and *back* machines respectively. Parts, mounted on fixture units, will be delivered to the *front* machines via a linear transporter. In the event that the machine required for processing is busy processing another job, fixtures of parts will await processing in a queueing area opposite the linear transporter from the three machines. Fixtures of parts to be processed on one of the *back* machines will be manually delivered to each machine. Each of these *back* machines will have a local queue for parts awaiting processing.

Tools, the main focus of this investigation, will be assembled in a remote tool room upon being ordered by a cell controller. Once assembled, multiple tools will be placed on a rack which will be manually brought to the shop floor. The tools will then be placed in two rotating floor carousels, each capable of holding 140 tools. They will be stored there until they are required at a machine for processing. Additional tools will be stored at each of the machines in machine tool magazines. These tool magazines will have a capacity of either 50 or 68 tools.

3. ALTERNATIVE TOOL DELIVERY OPTIONS

Three tool delivery options are being considered for installation in the FMC. The first system uses an overhead monorail robot to transfer tools between the machines and floor carousels. This monorail robot, if installed, will travel on a single-rail loop as shown in Figure 1. The other alternatives differ from this system by having either 1) two monorail robots which would travel on the same monorail loop shown, or 2) a gantry-mounted robot which would travel on two parallel rails and be capable of both lateral and longitudinal movement. An additional variation to the system, a single floor tool carousel, was also modeled. Its capacity was subsequently varied and the effects of this change investigated.

4. MODELING APPROACH

The simulation was performed on a PC compatible computer using the all-purpose simulation language SIMAN. Most of the logic used to control the cell is located in FORTRAN event subroutines. A system aspect contributing to its uniqueness is the large number of tools being tracked at any given moment. The considerable storage requirements forced the simulation to be conducted within the OS/2 system operating environment.

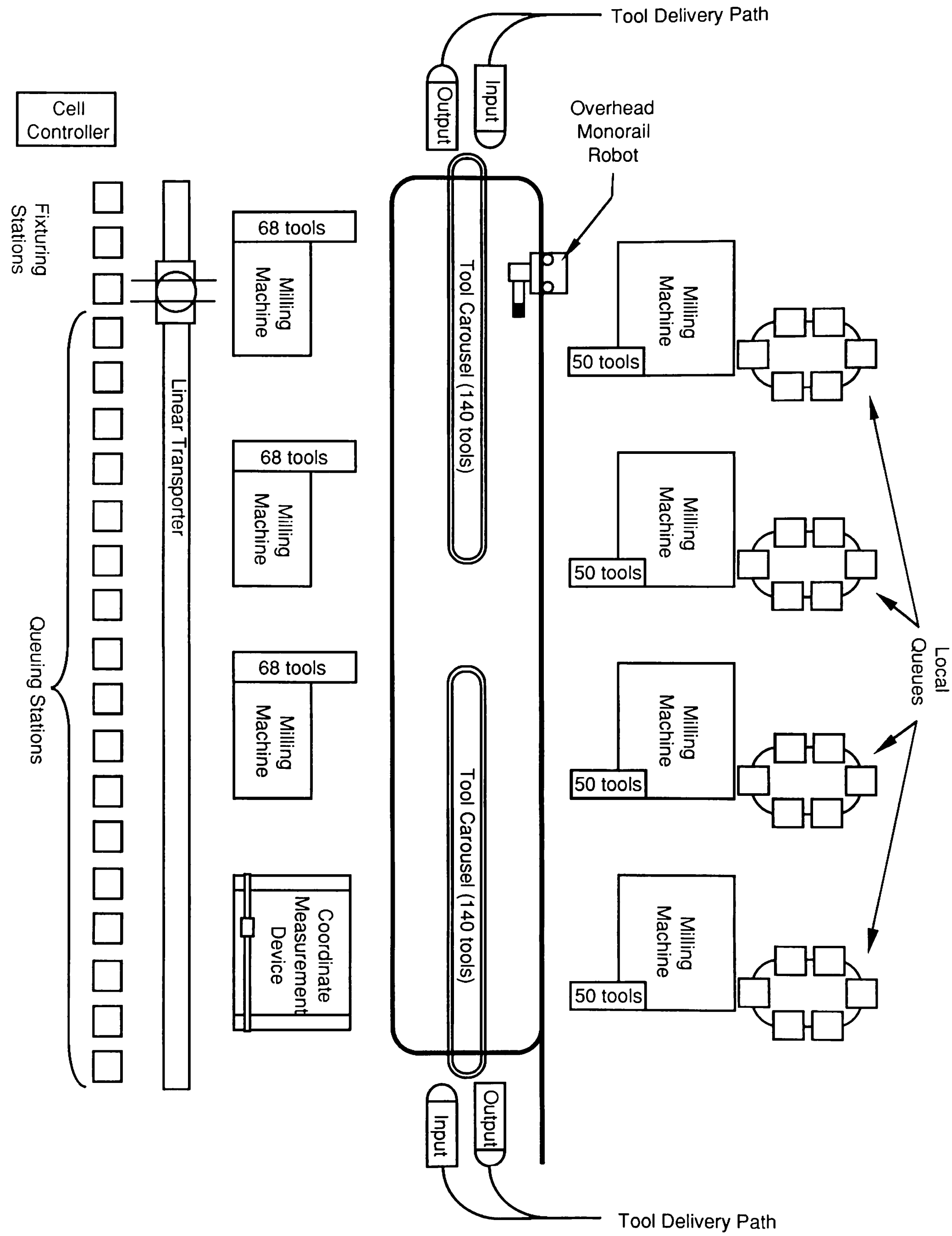
The simulation model incorporates a level of detail that extends well beyond the tool delivery system. It was felt that simply modeling each of the proposed tool delivery systems would aid only in comparing the relative efficiencies of the different systems. More importantly, it was desired to know whether the chosen tool delivery system would be able to adequately supply the system of machines being installed. Without the detailed modeling of the system as a whole, this result could not be realized. Thus, by using as much information as possible about the jobs, tools and machines to be used, an accurate assessment of the system's behavior was found. Using this information, cell control logic was developed to assure that the entire system performs in a way to expedite part manufacturing.

5. TOOL DELIVERY SYSTEM

As previously mentioned, the focus of this study was to assess the capabilities of the proposed tool delivery (TD) systems. In order to best assess the capabilities of the TD systems, control logic has been developed to best adjust for situations anticipated in the FMC. As different situations were encountered in the simulation, control strategies were progressively developed to perform a number of functions. In particular, the effects of two types of control strategies were investigated: tool transfer and job scheduling. Tool transfer logic was developed for immediate control over the tool delivery system, and job scheduling strategies were selected to help reduce the amount of tool transfer within the cell.

5.1 Job Scheduling

When investigating job scheduling strategies, it was decided to use a push strategy as opposed to a pull strategy. In this manner jobs are scheduled to a machine in advance, enabling the method in which tool-storage decisions are made to be implemented. The types of parts in the machines' queues are then taken into consideration, limiting unnecessary amounts of tool transfer between machines at peak production times when machines have the greatest need for tools. In



Note: Paths for part delivery not indicated.

Figure 1. Layout for the Flexible Manufacturing Cell at the Rock Island Arsenal using Two Floor Carousels and a Single Monorail Robot

most cases, a part entering the system is scheduled to a machine where a part of the same type is either being processed at the machine or scheduled to be processed. In the event that no jobs of that part type are currently scheduled for processing, the arriving parts are scheduled to the machine with the least processing time currently scheduled to it.

By attempting to repeatedly process the same part types at a particular machine, the number of tools transferred between machines is limited. Then, when a machine completes a job, the machine's queue is checked for parts of the same part type awaiting processing. If parts of the same type are found, the tools needed to process this part type are usually kept in the machine's tool magazine. Naturally, any space restrictions in the machine's tool magazine compel tools to be transferred to the floor tool carousel for storage.

Each time a machine goes idle, a check is made into the other machines' queues for parts awaiting processing. If parts are found that are not scheduled for immediate processing, the fixture of parts with the least number of tools in its machining program is located and rescheduled to the idle machine. Likewise, any of the tools needed for processing that part type are also transferred. Rescheduling in this manner supports an overall job scheduling goal of keeping the machines from going idle, while maintaining a balanced production loading.

5.2 Tool Transfer

The tool transfer logic centers around the transporter robot used to transfer tools between the machines and floor tool carousels. When tools need to be transferred, they are assigned a different priority based on how important it is to bring them to or remove them from a machine. Instead of processing tools in the order their transfer was requested, they are processed in order of transfer importance. The order can be simplified to the following priorities, listed high priority first:

1) Tools being removed from a 'full' tool magazine
2) Tools needed for processing at a machine
3) Tools transferred from a machine when a job in the machine's queue is rescheduled to another machine
4) Completely worn tools being removed from a machine, and
5) Tools not scheduled for processing being removed from a machine

This strategy attempts to limit the unnecessary transfer of tools within the cell, beyond the transfer of new tools to machines and used tools off machines. When none of these 'essential' tool changes are occurring, the tool delivery system is used to remove tools from a machine for storage in the floor tool carousels, thus reducing tool transfer requests when a machine tool magazine nears capacity at a peak transporter-request time.

In advance of parts being brought to a machine for processing, the locations of the first five tools needed for processing are checked. If the tools are not present in the proper machine tool magazine, their transfer from either the floor carousel or another machine is requested. Likewise, during processing, the status of the fifth tool ahead is checked. This helps assure the tools necessary for processing are at the machine when needed.

When the processing of a fixture of parts has been completed, a decision must be made whether or not to transfer the tools that were used in processing from the machine's tool magazine to the floor tool carousel for storage. If a job of the same part type is scheduled to the machine, the tools will not be removed. Any transfer here would be unnecessary since the withdrawn tools will be needed again 'shortly'. In the event that no jobs of the part type just completed are in the machine's queue, the tools are removed only if the number of tools required for the next machining program will cause the tool magazine to reach a level near capacity. This reduces the likelihood of machine tool magazines reaching capacity and requiring the tool transporter to remove tools when essential tools must be loaded. In addition, these tools are removed when the tool robot is not needed to make an 'essential' tool transfer, because these transfers are requested with the lowest priority. This strategy, as compared to others tested, helps to minimize the number of tool transfer delays at critical times, minimize the number of unnecessary tool transfers and keep the number of tools in the machines' tool magazines at a desired level. Since information concerning commonly used tools is not yet available, the modeling of resident tools at the machines was not included.

Whenever a tool arrives into a machine tool magazine that is near capacity, a search is performed of the tools in the magazine for a tool to remove. If tools are already in the queue to be removed, their priority for removal is increased, forcing them to be removed immediately. Otherwise, a search is made to find a tool not needed in the current part type or not needed soon by the current part type.

6. MODELING ASSUMPTIONS

In performing the simulation, several modeling assumptions were made. One of the assumptions made is that there are no breakdowns of machines or transporter resources. This is a valid assumption for our purposes because nominal system performance is the desired goal. Machine breakdowns will only serve to lessen the load on the tool delivery system during peak times of robot request. Another assumption made is that tools do not break. Since tool breakage would have the same effect on each of the tool delivery systems being investigated, it was left out of the model. Also, the extent of damage that could be caused by the breakage of a tool and how tool breakage would be handled by the operator of the FMC have not yet been prescribed. An extensive study of tool management study is being performed at the Rock Island Arsenal in an effort to aid in monitoring tools and removing them before breakage.

The last relevant assumption is that tools are unique to each machining program (i.e. a .375 inch drill used in one machining program has a different tool number than a .375 inch drill used in another machining program). This was assumed because available data for the machining programs to be run in the FMC did not differentiate between different lengths of the same diameter drills. In these programs, certain drills that can only be used in particular programs were not designated. Therefore, it was assumed that for all tools, no interchangeability was possible between different machining programs. One drawback to this assumption is the larger number of tools needed to be stored on the floor as a result of the need for repeated tools due to non-interchangeability. On the positive side, it made it easier to track particular tools needed for different jobs, since the same tool number can never be requested by different jobs simultaneously.

7. MODEL OUTPUT

Standard output for most simulation packages is only available in the form of a page of output statistics at the end of a simulation run. In performing this simulation, it was deemed necessary to collectively monitor the system statistics during the simulation. A method was also needed to monitor the information being used to make tool and part controlling decisions, and then to verify whether the model was handling normal and exceptional situations correctly. To accomplish this, a set of continually updated summary statistics screens were developed through the addition of FORTRAN subroutines. Three types of screens were developed to show different levels of system detail: one to show an overall summary of the system; one type to show the status of each of the machines, and a third to monitor the tool delivery system. Samples of all three screens are shown in Figures 2, 3 and 4.

To provide additional realism as to the behavior of the system, the simulation is tied to the internal computer clock. Since running the simulations at 'real-time' could be very slow for someone to watch, the simulations are run at 10 times 'real-time', with the output screen being refreshed every second. To display each of the different screens when the user wants to see them, one of the features of OS/2 has been utilized to continually sample the keyboard buffer. Thus if the person running the simulation wants to view the *System summary*, he or she can press 'S' to do so. Likewise, 'T' can be pressed to view the *Tool transfer overview* and '1' through '7' can be pressed to view the *machine status* for a particular machine.

An added benefit of these system monitoring screens, is that

DAY 3 TIME 20:54:10

NO. OF PARTS IN SYSTEM 95
NO. OF PARTS COMPLETED 57 PART TIME IN SYSTEM 10.9 Hours

MACH	CUTTING UTIL	MACH STATUS	PART TYPE	PROC STEP	CURRENT TOOL	NEXT TOOL	NXT TL STATUS	# IN MCAR
1	.92	busy	13	5	158	PROBE	----	26
2	.61	WAIT/TOOL	3	3	72	73	MACH	39
3	.55	busy	9	18	122	123	MACH	28
4	.87	busy	29	11	341	PROBE	----	46
5	.93	busy	25	23	307	308	FLOOR	41
6	.87	PART FINISH	22	58	INSP	--	----	19
7	.84	busy	19	15	PROBE	232	MACH	33

TRANSPORTERS UTILITIES

Linear Transporter	7.1%	Monorail Robot	61.7%
Material AGV	12.5%	Tool Cart	11.2%

FLOOR CAROUSEL : 221 Tools Capacity = 320 Tools

Figure 2. Sample Output Screen – SYSTEM SUMMARY

DAY 3 TIME 20:54:10

TOOL TRANSFER OVERVIEW

Monorail Robot Status: Traveling from Floor Carousel to Machine 2

7 Tools in queue to request monorail robot

Tool #	Priority	Status	Location	Time Entered Queue
115	4	worn	Mach 4	11416.5
27	5	worn	Mach 2	11417.2
108	2	worn	Mach 3	11500.1
216	3	usable	Floor	11487.3
64	6	usable	Mach 1	11420.7
76	5	worn	Mach 1	11432.4
315	4	usable	Mach 7	11462.9

221 Tools in Floor Carousel Monorail Robot Utilization: 61.7%

Tools at each machine:
1-26 2-39 3-28 4-46 5-41 6-19 7-33

Figure 3. Sample Output Screen – TOOL TRANSFER OVERVIEW

DAY 3 TIME 20:54:10

MACHINE 2

Machine Status: IDLE / WAITING FOR TOOL FROM FLOOR
Part Type at Machine: 3 Processing part 2 of 4 on fixture

4 fixtures of parts in queuing area:

Tool Information

Current tool 72 (In transport)
Next tool 73 (At machine)

PART #	# PARTS ON FIXTURE
34	3
22	4
22	3
27	4

39 Tools in machine tool magazine: 0 ==>no tool, # ==>tool number

114	111	89	90	92	94	95	92	101	104	73	23	45	65	89	33	93
76	87	46	0	65	89	0	74	5	2	78	90	7	76	43	48	49
67	0	0	0	83	92	0	29	0	0	95	0	110	0	112	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Machine Utilization: 82.3% Time Waiting for Tool: 1.8%
Cutting Utilization: 70.4%

Figure 4. Sample Output Screen – MACHINE STATUS

they give anyone watching the simulation the ability to get a feel for how the system is operating. Though this can also be done through use of an animation package such as CINEMA, an animation can not differentiate between the different tools and parts it shows on the shop floor. In addition, an animation does not have the capability to show how the cell control logic is behaving.

Once the model was verified, the information displayed during the simulation was less important than the statistical output gathered at the termination of a simulation run. Since many replications of the simulation were needed to compare both the performance of different tool delivery systems and the output resulting from different input parameters, the output screens were bypassed to allow for quicker simulation run times. The output screens were subsequently displayed only when unusual situations needed to be investigated.

8. SIMULATION ANALYSIS

After modeling the FMC with each of the single monorail and gantry configurations, a formal analysis was needed to determine the sensitivity of each proposed tool transfer configuration to different control parameters. Since the FMC has not been installed, the model cannot be truly validated. This made determining the sensitivity of the model's output to the questionable parameters more important. Through a series of initial runs, the factors most affecting the performance of the FMC were identified as being the type of transporter, the transporter speed, and the floor carousel speed. Other factors were determined to be less important, including transporters with low utilizations (whose functions were not critical to any of the scheduling algorithms), factors associated with the tool room, and factors that are not adjustable such as load/unload times for parts. Since a representative number of actual machining programs were used in the model, comparisons of different types of machining programs were not included in the sensitivity analysis.

A variation of classical experimental design was used to determine the effects of altering the model's parameters. Three settings for the tool transporter speed were compared, along with two settings for the floor carousel speed. Each simulation, already run for an extreme length of time and a warm-up period, was replicated once using different random number streams for part arrivals. This resulted in 24 different runs needing to be made. A variety of information was analyzed to determine the maximum possible loading of the FMC under each set of parameters without causing any system saturation.

The large amount of output collected during the simulation runs was reduced to a few factors which best characterize the performance of the FMC. These were: machine utilizations, part throughput, processing delays caused by missing tools, the time parts spend in the FMC, and the time spent waiting for the floor carousel versus waiting for the tool transporter for a tool transfer to occur. This information was then used to compare the performance of the FMC under the different parameter settings and then to determine the desired levels of each setting. But, the primary measure of performance used to compare the different sets of output was the overall throughput of parts.

After observing the relative performance of the FMC operating under different combinations of parameters, a number of conclusions were drawn concerning the effects of the proposed tool delivery systems on the FMC. First, the machine cutting utilizations or spindle-up times, without accounting for machine or transporter breakdowns, were found to be at or below 60% during each of the simulation runs. This is significantly short of the desired level of 75%. As important, tool transporter utilizations between 85 and 90% were evidenced, an indication that the tool delivery systems were operating at their capacity. The full utilization of the tool delivery systems caused the number of parts allowed into the system to be restricted, which in turn caused the machines to spend a considerable amount of idle time with no parts loaded for processing. Thus, each of two tool delivery options investigated have proved insufficient.

In particular, the speeds of the transporters were shown to be less than the required level. Careful comparisons were made of a variety of output statistics concerning the delays and frequencies of delays associated with machines waiting for tools. Though the floor carousel speed was shown to have an effect on system performance, its setting was deemed to be less critical than that of the tool transporter.

The two types of tool delivery systems were affected by changes in the parameters in a similar way. Naturally, since the gantry-mounted robot is able to travel between opposite (*front* and *back*) machines more directly, it performed better than the single monorail robot traveling at the same speed. Though the gantry-mounted robot and single monorail robot alternatives were found to be insufficient when operating under the specified parameters, the two monorail system, though not modeled, will likely be sufficient. The addition of a second tool transporter will have an effect similar to that of raising the speed of the single transporter.

Since the results indicate that neither of the modeled tool delivery systems will be capable of serving the FMC adequately, further analysis is being performed on the system that utilizes two monorail robots to service the FMC. In addition, alternate configurations for two floor carousels have been proposed for further study. As the FMC nears operational status, more data concerning machining programs and expected part arrival rates will also become available. This data will improve the accuracy of the results of continued parametric analysis being performed on the model. Given that a two-monorail tool delivery system proves to be adequate, the process of selecting specific equipment for installation will likely be reduced to comparing other factors with performance such as cost, reliability and flexibility.

9. CONCLUSION

Most simulation models of flexible manufacturing cells treat tool delivery as a non-critical activity. But, in the case of the FMC being investigated, the opposite is true. Here, the tool delivery system is the concentration of effort to optimize system performance. Computer simulation has been used to predict system behavior, develop cell controlling algorithms, and compare alternate proposals for a tool delivery system. To help in analyzing the behavior of the system, multiple output statistic screens have been developed to monitor the system during the simulation process.

Performing the simulation has resulted in an improved awareness of the many factors having an effect on system performance. It also aided in the understanding of many complex inter-relationships which characterize the proposed FMC. Though the tool delivery systems investigated have been tentatively shown to be insufficient, continued steps are being taken to develop a system capable of meeting the FMC's tool delivery requirements. These efforts will ensure that an efficient tool delivery system will be installed capable of delivering the essential tools to the proper machines when they are needed, allowing the machines in the FMC to be sufficiently utilized.

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