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SCHEDULING OF A MANUFACTURING CELL WITH SIMULATION

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ABSTRACT

Overcoming the difficult problem of effectively scheduling batch production in individual machine cells may be paramount to the success of a group technology/machine cell application. Simulation of the cell can incorporate the constraints and characteristics of the system, without making restrictive assumptions, in order to evaluate system performance for any particular sequence of parts. The resulting output for decision criterion variables for several different sequences may be evaluated to yield an advantageous part sequence. This paper describes the development and successful use of a generalized simulation model for the shop floor scheduling of many similar cells.

1. INTRODUCTION

Group technology (GT) is a manufacturing strategy for medium batch size production which seeks to improve productivity by exploiting the manufacturing similarities of different parts (1). Similar parts, grouped into a family, may be processed in a single machine cell instead of being transported throughout the shop, from one machine to the next, as required by the functional machine shop layout. The benefits garnered through the implementation of GT in the areas of product design, tooling and setups, materials handling, process planning, part quality, and overall cost reduction are well-documented (1, 2) and will not be explored further here. However, these benefits can only be realized in an effectively scheduled work cell.

Poor scheduling can cause blocking and poor utilization, and can generate the kinds of excessive, and costly, work-in-process that GT and the cell structure seek to reduce or eliminate. The frequency of part changes in a work cell draws special attention to scheduling considerations. Proper machine cell scheduling must take into consideration the availability of machine operators and material handling equipment, the impact of sequence-dependent setup times, the availability of intermediate storage (queue) space, and any other considerations unique to the particular cell being scheduled. Unfortunately, most sequencing algorithms exist only for special cases and are forced to make restrictive assumptions in the solution of the scheduling problem.

While there have been extensive efforts to develop algorithms which consider the extreme cases of infinite intermediate queues (3,4,5,6) and no intermediate queues (7,8), less effort has been devoted to the problem of finite intermediate queue space (9). Additionally, the solution of the difficult problem of sequence-dependent setup times has not been satisfactorily resolved (10). Unfortunately, most existing algorithms for batch scheduling do not consider more than one of these factors simultaneously, nor, in most cases, are more than two machines considered for scheduling (11). Consequently, the employment of (traditional) scheduling algorithms is often infeasible in work cell scheduling, where, typically, more than two machines require scheduling and more than one scheduling constraint exist. But the scheduling problem persists, and overcoming it is paramount to the success of a GT/machine cell application.

As an alternative to algorithms, simulation models may be utilized to determine advantageous batch sequences, while considering the particular machine cell constraints that are often disregarded in more rigid scheduling practices. While simulation will not necessarily provide an optimal sequence, system performance measures based on the tested sequences are at least an accurate representation of the cell performance and provide a sound basis for scheduling decisions. Use of simulation for part sequencing requires a solid understanding of the parts to be sequenced and their influence on each other. The foreman or scheduler must be able to produce several feasible part sequences, which are then compared using simulation.

2. SPECIFIC APPLICATION

The difficulty of scheduling a cellular manufacturing system was encountered at a medium batch-size production facility where a major effort is being undertaken to form work cells, which take advantage of GT ideologies, from a traditional functional plant layout. The company's objective is to make their commitment to cellular manufacturing profitable by making the most effective use of their work cells through proper individual cell scheduling and control. The manufacturer identified tardiness and labor costs (operator utilization) as the primary considerations in the scheduling of the machine cells. The use of simulation, which can reflect statistics for both of these criterion, was found to be a feasible and cost-effective means of overcoming the scheduling and control problem.

In order to accommodate each of the different machine cells, the model that was subsequently developed is a generalized flowline model which can be used for the simulation of any similarly configured cell. (A typical cell is shown in Figure 1.) The machine sequence, number of operators, and part database are specific to the particular cell of interest. In this way, the manufacturer is able to use only one model to simulate the operation of all of their machine cells. Additionally, a complete, menu-driven software package, that includes the simulation model, was developed, allowing the entire scheduling system to be operated by someone with an intimate knowledge of the machine cell but no knowledge of simulation software and languages.

3. CELL CONSTRAINTS

The model was developed around four constraints specified by the manufacturer which would be common to all of the existing and planned machine cells.

1) All intermediate queues have a constant limited capacity; if the queue following a machine is full,the machine is blocked and stops production until the queue is empty.
2) Setup times between parts for each machine are dependent on the sequence of parts processed on a particular machine.
3) Each cell operates as a flowline with fixed routing for all parts, so that a part batch which does not require processing on a particular machine will block that machine until there is room in the queue of the following machine.
4) Each batch of parts is completed as a discrete batch, with no product mix.

In addition to the above constraints, each cell may have any combination of the following conditions:

1) One operator may be required to operate more than one machine, so that the operator may not always be available for each machine.
2) Machines may be configured in parallel with only one operator and one

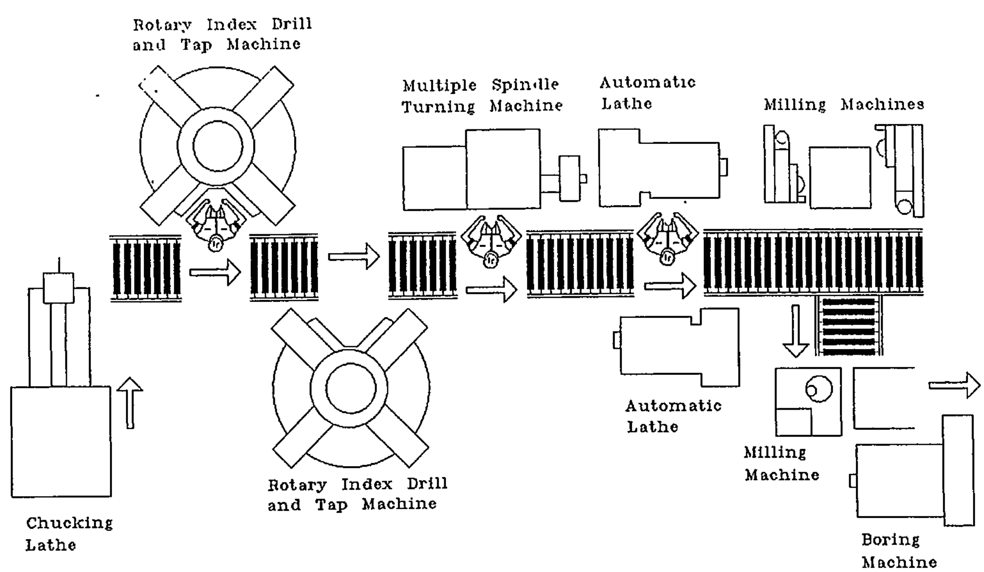

Figure 1 : Typical Manufacturing Cell Layout

queue for both machines.

3) Machines may be configured in series with no queue between machines and only one operator for both machines; the operator must be available to transfer parts between machines as well as to load the first and unload the last.

4) Each cell may have up to nineteen operators and consequently up to twenty-four machines, (14 single-machine operators, 5 two-machine operators.)

The objectives used in deciding which of a set of feasible sequences is the best are as follows:

1) The entire part schedule must be completed within a production month.

2) The sequence with the minimum direct labor requirements, in the form of man-hour requirements for production and setup, is deemed the best, provided that criterion 1) is met.

What is significant about the model is not that it can incorporate all these *particular* considerations, but that a generalized model can be developed which reflects the conditions in many individual, but similar, cells.

4. DEVELOPMENT AND FEATURES OF THE SCHEDULING PACKAGE

The reduction of direct labor costs was identified as a major control parameter and thus the simulation model and the statistics generated from the execution of the simulation model were tailored accordingly. A method used to reduce direct labor costs is the reassignment of idle machine cell operators to tasks elswhere in the plant. Consequently, the simulation model is designed to predict the status of the machine cell at any given time during the month. Using simulation to predict the system status is in many ways different from the more traditional use of simulation, which is one of capacity planning and design. To be able to predict the status of the machine cell at any given time, the simulation model needs to be deterministic and random events, such as breakdowns, cannot be included in the model. (It should be noted that while breakdowns are not simulated, when a breakdown occurs the system is simulated again to reflect this change in system status.)

The output from the simulation model identifies two conditions which cause a great deal of worker idle time. These are when a machine is blocked and when a machine waits for parts to arrive after a setup has been completed. When both the time at which these idle periods will occur and the duration of the idle periods are predicted adequately, the shop foreman can then reassign the affected workers to other tasks, for the duration of the predicted idle period, with some degree of confidence.

The actual simulation model represents only a portion of the scheduling software package. The simulation function is controlled by sequential menus, which also control the options to specify the machine cell, define a part sequence for evaluation, change the part number or machine sequence databases, change the password protecting the databases and defined schedules, delete or copy defined schedules, and print schedules, databases and simulation output. The menus were generated using the IBM Hard Disk File Manager; for each menu operation there is a corresponding DOS command to run the appropriate programs. All the programs run by picking one of the menu items are part of the entire software package which was developed

The general model, written using the SIMAN simulation language, becomes a specific model for an individual cell when the machine database is specified for the cell. The part number database is developed using the information in the machine database. When a particular sequence is to be simulated, the information in both the machine and part databases is used to enter default values for all the prompts and as a check for information which is entered by the user. All the database management and schedule definition software is written in Microsoft FORTRAN and Assembler.

When the scheduling session is initiated, the user is presented with a menu for options regarding choice of machine cell, vacation day specifications, or floppy back-up of the scheduling software (Figure 2). Plant-wide vacation days are specified at this level because they are common to all of the machine cells, so their inclusion here eliminates redundancy. Vacation days are specified so that they can be included in the prediction of the status of the machine cells. Figure 3 shows the layout of the vacation days specification screen. The vacations days are highlighted for easy identification. To change a vacation day, the cursor is moved to the appropriate day, using the cursor keys, and the "enter" key is pressed to toggle between vacation day and normal day specification.

Once the machine cell to be scheduled has been chosen, the user is prompted with the menu shown in Figure 4. (Once an option has been chosen from this menu, all prompts and menus which appear were coded in

Manufacturing Cell Scheduling Software

Date: 07-23-1986 Page 1 of 1
Time: 14:12:14 Version 1.00

1. Cell AA
2. Cell AA
3. Cell CC
4. Change the Monthly Vacation Day Specifications
5. Change the Password for the Vacation Day Specifications
6. Backup of the Scheduling Software on Floppies

Figure 2 : Primary Scheduling Software Menu

Month of: July, 1986

SUN	MON	TUE	WED	THR	FRI	SAT
		01	02	03	**04**	05
06	07	08	09	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30	31		

Press ARROW Keys to move, ENTER to set holiday, ESC to end

Figure 3 : Monthly Vacation Day Specification

FORTRAN and Assembler, rather than using the Hard Disk File Manager.) Option 1, Run a Currently Defined Schedule, activates the simulation of a given sequence of parts. When this option is chosen, the user is prompted with the menu shown in Figure 5 to specify month to simulate, and production and setup efficiencies. Additionally, the user must specify the type of output he desires: a month-long summary of decision variables or a day-by-day (intermediate) statement of system status in addition to the summary. (The day-by-day status report also includes the summary report for the entire month.)

In the latter case, the user is presented with the menu shown in Figure 6. The information about the number of shifts, shift length, meal times, amount of preventative maintenance and clean-up time, the starting time for each shift, and the vacation days, mentioned earlier, is necessary to compile the day-by-day status reports, which are shown in Figure 7. These detailed reports are used by Wagner to identify times when idle workers can be put to work elsewhere, thereby reducing the labor costs of the cell. The worker idle times are due to a machine being blocked because the queue following the machine is full, or because setup has been completed but the queue is empty so production cannot begin. A summary of the man-hour requirements and the machine idle times are always supplied to the operator. Particular examples of the man-hour and machine idle time summary reports are given in Figures 8 and 9 respectively.

The average efficiencies with which the cell will be set up and operated must always be specified by the scheduler. The shop foreman can use the efficiencies to account for small amounts of down-time and for variations in the effectiveness of the various machine operators. Summary reports are generated which indicate make-span for a particular batch and the individual pallets within a batch (Figure 10), average machine and operator utilization, work-in-progress and queue length at a machine, and total work-in-progress (Figure 11) at the levels of efficiency specified by the shop foreman. The queue lengths are reported as the number of pallets in the queue rather than the number of parts in a queue. In the case where there is one part per pallet, then the work-in-progress and queue length statistics will be the same. Additionally, the man-hours required for both setup and machining, as well as the the machine-idle times caused by blocking and waiting for parts, for each machine, are reported. The output reports described above have been tailored to the needs of this specific application, but can be generated to reflect other decision criterion as well.

Cell AA Simulation Menu

Date: 07-23-1986 Page 1 of 1
Time: 14:12:30 Version 1.00

1. Run a Currently Defined Schedule
2. Change the Machine Sequence Database
3. Change the Part Number Database
4. Change the Current Password
5. Define and Run a Schedule
6. Delete a Previous Schedule
7. Copy from one Schedule to Another Schedule
8. Printing of the Schedules, Databases, and Simulation Output

Figure 4 : Secondary Scheduling Menu

...What month's schedule do you want to simulate ?	[SEPTEMBER]
...Do you want a part schedule summary ?	[N]
...Do you want intermediate system status reports ?	[N]
...What is the production efficiency ?	[100]
...What is the setup efficiency ?	[100]

Figure 5 : Primary Menu for Sequence Simulation

[9/ 1/86]	...Date on which the schedule begins
[5]	...Working days in a calender week
[2]	...Shifts per day
[8.30]	...Hours per shift
[.10]	...Hours of clean-up per shift
[.30]	...Hours set aside for meals per shift
[11.30 AM]	...Time of FIRST shift meal break
[7.30 PM]	...Time of SECOND shift meal break
	...Time of THIRD shift meal break
[.00]	...Hours of preventive maintainance per shift
[7.00 AM]	...Time the first shift begins

Figure 6 : Secondary menu for Sequence Simulation

		09:46pm
	CELL AA	08/13/86
WSC	SEPTEMBER	Page 9

TUESDAY 9/ 2/1986
Begin FIRST shift of DAY 2
15hrs 40min of production completed

7:07am...	FINISHED processing part PART NUMB 01 on the MACHINE 09 SETUP of 3hrs 7min BEGINS for part PART NUMB 02
8:17am...	The QUEUE after the MACHINE 01 is FULL Processing of part PART NUMB 02 is HALTED
8:22am...	Setup COMPLETED for part PART NUMB 02 on the MACHINE 05
8:53am...	Setup COMPLETED for part PART NUMB 02 on the MACHINE 02
8:53am...	BEGIN processing part PART NUMB 02 on the MACHINE 02 Parts are AVAILABLE immediately for the MACHINE 02
9:18am...	Setup COMPLETED for part PART NUMB 02 on the MACHINE 04
10:14am...	Setup COMPLETED for part PART NUMB 02 on the MACHINE 09
11:10am...	The QUEUE after the MACHINE 01 is EMPTY The MACHINE 01 was blocked for 2hrs 52min + + + + + + Processing of part PART NUMB 02 is RESUMED
11:28am...	The QUEUE after the MACHINE 02 is FULL Processing of part PART NUMB 02 is HALTED
11:30am...	A MEAL break of0hrs 30min begins
12:00pm...	Setup COMPLETED for part PART NUMB 02 on the MACHINE 03
12:00pm...	BEGIN processing part PART NUMB 02 on the MACHINE 03 Parts are AVAILABLE immediately for the MACHINE 03
12:39pm...	BEGIN processing part PART NUMB 02 on the MACHINE 04 The MACHINE 04 WAITED 2hrs 50min for parts to arrive * * *
12:59pm...	BEGIN processing part PART NUMB 02 on the MACHINE 05 The MACHINE 05 WAITED 4hrs 7min for parts to arrive * * *
3:20pm...	A CLEAN-UP break of 0hrs 10min begins

Figure 7 : Typical Intermediate System Status Report

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Man-hour Requirements

Machine		Hours	
	Production	Setup	Total
MACHINE 01	70.15	23.55	94.11
MACHINE 02	97.53	52.17	150.11
MACHINE 03	111.40	51.52	163.33
MACHINE 04	99.55	28.55	128.50
MACHINE 05	103. 1	17.12	120.14
MACHINE 06 \MACHINE 07	68.41	2.12	70.53
MACHINE 08 \MACHINE 09	96.43	28. 7	124.51
Totals	648.12	204.34	852.46

Figure 8 : Man-Hour Requirements Output

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Machine Idle Times

Machine		Hours	
	Blocked	Waiting	Total
MACHINE 01	45.45	2.31	48.16
MACHINE 02	22.26	0.18	22.44
MACHINE 03	9.47	0.50	10.38
MACHINE 04	9. 3	21. 6	30.10
MACHINE 05	7.37	30.22	38. 0
MACHINE 06 \MACHINE 07	0. 0	13.20	13.20
		78. 2	78. 2
MACHINE 08 \MACHINE 09	0. 0	78.41	78.41
		17.11	17.11
Totals	94.40	242.27	337. 7

Figure 9 : Machine Idle Time Output

Options 2 and 3, Change Machine Sequence Database and Change Part Number Database, are only invoked when the cell configuration changes or a part processed by the cell is added or deleted or when the processing sequence or times change. Information in the machine sequence database includes the number and type of each machine, the machine's position in the flowline, and the default setup time for that machine. The default setup time can be overridden when the schedule to be simulated is defined. Each machine cell has a corresponding part number database. This database includes the machining time on each part number for each machine in the cell. If no machining is required by a part on a particular machine, a processing time of zero is entered. Like the setup time, the default batch size may be overridden when the schedule is defined.

Option 4, Change the Current Password, gives the user the option to change the password which protects the databases and defined schedules. These are protected in this way to prevent accidental change of these files.

Option 5, Define and Run a Schedule, allows the user to specify the type, sequence, batch sizes and setup times for the parts to be processed for the month. Based on the sequence he has selected, the scheduler can determine setup times which reflect the effects of available tooling and the setup of the preceding part. In this way, sequence-dependent setup times can be incorporated into the scheduling decision. Once the schedule has been defined, the simulation is run and the schedule may be saved for future use.

Option 7, Copy from one Schedule to Another, was incorporated into the package so that when minor changes to a schedule need to be made, the schedule can

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Identifier	Average	Standard Deviation	Minimum Value	Maximum Value	Number of Obs.
TIS PART NUMB 01	6.15167	2.21618	2.66250	9.53500	21
IN PART NUMB 01	.00000	.00000	.00000	.00000	1
OUT PART NUMB 01	15.78500	.00000	15.78500	15.78500	1
TIS PART NUMB 02	7.53267	1.61415	4.53749	10.12875	21
IN PART NUMB 02	11.64375	.00000	11.64375	11.64375	1
OUT PART NUMB 02	34.93749	.00000	34.93749	34.93749	1
TIS PART NUMB 03	5.39712	3.16037	2.18748	13.64124	50
IN PART NUMB 03	29.15375	.00000	29.15375	29.15375	1
OUT PART NUMB 03	58.21995	.00000	58.21995	58.21995	1
TIS PART NUMB 04	4.27946	2.31404	2.08749	9.63750	28
IN PART NUMB 04	54.98253	.00000	54.98253	54.98253	1
OUT PART NUMB 04	72.66999	.00000	72.66999	72.66999	1
TIS PART NUMB 05	7.82793	1.85700	4.61501	10.98502	38
IN PART NUMB 05	69.70748	.00000	69.70748	69.70748	1
OUT PART NUMB 05	103.33500	.00000	103.33500	103.33500	1
TIS PART NUMB 06	6.84972	2.42310	3.01251	13.97876	72
IN PART NUMB 06	92.74377	.00000	92.74377	92.74377	1
OUT PART NUMB 06	135.92130	.00000	135.92130	135.92130	1
TIS PART NUMB 07	7.03441	3.15963	3.55879	13.90492	14
IN PART NUMB 07	127.34370	.00000	127.34370	127.34370	1
OUT PART NUMB 07	148.05120	.00000	148.05120	148.05120	1
TIS PART NUMB 08	3.37718	1.43373	2.20631	8.13562	30
IN PART NUMB 08	144.33930	.00000	144.33930	144.33930	1
OUT PART NUMB 08	162.47760	.00000	162.47760	162.47760	1
TIS PART NUMB 09	8.41992	.00000	8.41992	8.41992	1
IN PART NUMB 09	.00000	.00000	.00000	.00000	0
OUT PART NUMB 09	168.23860	.00000	168.23860	168.23860	1
TIS PART NUMB 10	6.61088	2.92158	2.17505	10.79868	11
IN PART NUMB 10	163.28740	.00000	163.28740	163.28740	1
OUT PART NUMB 10	177.37110	.00000	177.37110	177.37110	1

Figure 10 : Make-Span and Average Sojourn Time Output

be copied, adjusted, and saved without losing the original schedule and without generating a completely new schedule. Once the schedule is copied, the user enters the edit mode, and then the newly-defined schedule is run.

The final menu item will bring up a further menu on which there are options to print the machine and part number databases, a predefined sequence of parts, and the output from a simulation of a particular sequence.

5. ADVANTAGES AND LIMITATIONS OF THE GENERAL MODEL

The primary advantages of the machine cell model are the cost savings and the ease of use. Savings are realized by reducing both direct and indirect labor costs while maintaining on-time production. Direct labor costs are reduced by choosing that sequence which has the least direct labor requirements. Indirect labor costs are reduced by being able to reassign workers to other tasks when a machine is blocked or is waiting for parts to arrive. Additional savings are achieved through the use of a single model for many cells, rather than having to develop, and train users for, a model for each cell. The short time required to use the model also contributes to the profitability of the system. The sequencing of parts through a cell for an entire month, including the simulation of about five part sequences and the required analysis, can be performed within a few hours by an individual without simulation expertise. Since the software is completely menu-driven, minimal training is required and can be accomplished by a shop foreman or technician within a day. The software runs on an IBM AT (or compatible), which can be used on the shop floor, making it easily-accessed by the technicians who use it, and for other applications as well.

An added bonus of the scheduling software package is that the general model can be used to aid in the development of future cells. With the planned cell's configuration and specifications in place in the general flowline model, determination of queue lengths, operator and machine requirements, and overall layout can be enhanced by manipulating system parameters. However, this application of the software requires a greater understanding of simulation analysis than does the scheduling function.

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Discrete Change Variables

Identifier	Average	Standard Deviation	Minimum Value	Maximum Value	Time Period
UTL MACHINE 01	.53103	.49904	.00000	1.00000	177.37
UTL MACHINE 02	.84677	.36021	.00000	1.00000	177.37
UTL MACHINE 03	.92213	.26796	.00000	1.00000	177.37
UTL MACHINE 04	.72643	.44579	.00000	1.00000	177.37
UTL MACHINE 05	1.35575	.93458	.00000	2.00000	177.37
UTL MACHINE 06	.39970	.48984	.00000	1.00000	177.37
UTL MACHINE 07	.14038	.34738	.00000	1.00000	177.37
UTL MACHINE 08	.13088	.33726	.00000	1.00000	177.37
UTL MACHINE 09	.70356	.45669	.00000	1.00000	177.37
WRK MACHINE 01	.53103	.49904	.00000	1.00000	177.37
WRK MACHINE 02	.84677	.36021	.00000	1.00000	177.37
WRK MACHINE 03	.92213	.26796	.00000	1.00000	177.37
WRK MACHINE 04	.72643	.44579	.00000	1.00000	177.37
WRK MACHINE 05	.67787	.46729	.00000	1.00000	177.37
WRK MACH6\MACH7	.39970	.48984	.00000	1.00000	177.37
WRK MACH8\MACH9	.70391	.45653	.00000	1.00000	177.37
STP MACHINE 01	.13492	.34163	.00000	1.00000	177.37
STP MACHINE 02	.29483	.45597	.00000	1.00000	177.37
STP MACHINE 03	.29249	.45491	.00000	1.00000	177.37
STP MACHINE 04	.16308	.36944	.00000	1.00000	177.37
STP MACHINE 05	.09701	.29598	.00000	1.00000	177.37
STP MACH6\MACH7	.01245	.11086	.00000	1.00000	177.37
STP MACH8\MACH9	.15857	.36527	.00000	1.00000	177.37
NQ MACHINE 01	.00000	.00000	.00000	.00000	177.37
NQ MACHINE 02	.98841	.10701	.00000	1.00000	177.37
NQ MACHINE 03	3.18882	2.40710	.00000	7.00000	177.37
NQ MACHINE 04	1.84296	2.09866	.00000	7.00000	177.37
NQ MACHINE 05	1.08476	1.49211	.00000	7.00000	177.37
NQ MACH6\MACH7	.00000	.00000	.00000	.00000	177.37
NQ MACH8\MACH9	1.09819	1.69510	.00000	7.00000	177.37
WIP MACHINE 01	105.25060	17.33327	.00000	130.00000	177.37
WIP MACHINE 02	331.57780	251.60740	.00000	910.00000	177.37
WIP MACHINE 03	187.14140	208.56940	.00000	700.00000	177.37
WIP MACHINE 04	117.69550	171.77660	.00000	910.00000	177.37
WIP MACHINE 05	119.85470	165.17040	.00000	910.00000	177.37
WIP MACH6\MACH7	124.80810	197.33520	.00000	910.00000	177.37
WIP MACH8\MACH9	58.89331	54.71346	.00000	200.00000	177.37
WIP SYSTEM	1045.22	459.99	.00	2310.00	177.37

Figure 11 : Utilization and Work-in-Progress Output

The primary disadvantage of the simulation scheduling package is that the technician using the software must provide the part sequences to be compared. In order to do this, he must have an acute familiarity with the cell and an understanding of the dependent nature of the setup times. This level of understanding is typically gained only through experience. The software does not provide the logic to develop the part sequences nor to evaluate the differences in setup time between particular parts. Because of these limitations, the sequence chosen using simulation can be no better than the best of the limited number of sequences that are tested. Similarly, the performance of the model is constrained by the reliability of the historical data which provides the input setup and processing times.

Use of a generalized model also limits the set of cells which can be captured in the same model. The system to be modeled must exhibit traits similar to the other models accommodated by the general model. .In this case, that implies that only flowline cells, without product mix, adhering to the criteria previously mentioned, can be scheduled using the general model. However, generalized models can be developed for different design criteria and operating constraints.

6. CONCLUSION

When special characteristics of a machine cell, or any manufacturing system, preclude the use algorithmic scheduling, simulation presents itself as a viable tool to aid in the scheduling of the cell. The specific configuration and conditions of the cell can be reflected in the model of the cell so that simulation results provide an accurate representation of system performance. By using a generalized flowline cell model, with corresponding part databases and machine specifications for individual cells, the manufacturer for which the software was developed has found a convenient and cost-effective means to schedule their machine cells.

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