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ANALYZING SYSTEM EFFICIENCIES/CAPACITIES IN A CLOSED-LOOP MANUFACTURING CELL

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ABSTRACT

This paper describes a simulation project performed of a closed-loop manufacturing cell. Analysis was done for an existing cell and for an enhanced version of the existing cell. This paper explores how different desired throughput rates, equipment configurations, part mixes, and fixture options affect system performance.

1 INTRODUCTION

Determining the best options for maximizing the throughput in a complex, highly integrated manufacturing cell can be a costly and time-consuming endeavor. Even a simple change may cause component interactions that degrade rather than improve system performance.

This paper describes a simulation project performed to explore options for increasing throughput in an existing cell and for improving flexibility and production capacity in an enhanced version of the cell. A SIMAN simulation model [1] was developed to perform the desired analysis. This model could be configured to represent various equipment configurations and operating logistics.

Section 2 describes the existing manufacturing cell and discusses some characteristics of closed-loop systems. Section 3 presents the objectives defined at the beginning of the project. Section 4 describes the production data files used to drive the simulation model. Section 5 discusses steady state issues and describes the procedures used to ensure statistically valid simulation results. Section 6 describes the steps taken to validate the model. Section 7 discusses concepts associated with cycle time in the manufacturing cell. Sections 8, 9 and 10 present the results of various sets of analyses performed during this project. Section 11 summarizes this project.

In order to not disclose confidential information, the numbers presented in this paper do not represent actual system parameters or simulation outputs, but rather are artificial and have been included to help illustrate system logistics and simulation findings.

2 EXISTING SYSTEM DESCRIPTION

The existing manufacturing cell produces a large variety of parts in relatively small production quantities. The cell has seven types of machines each performing a unique manufacturing operation. This paper refers to the seven machines and corresponding operations as A, B, C, D, E, F and G. All part types visit every machine and always in the same order. The system also contains staging positions that act as queues prior to operations A and B.

Parts are handled on fixtures in the system. Each part type requires a unique fixture. Prior to beginning processing, a part is placed onto a corresponding fixture at A. The part is then moved through the system to B, C, D, E, F and G while remaining on the fixture. The finished part is removed from the fixture at G after processing has been completed. Fixtures are moved between G and A without a part.

This system is closed-loop in that the number of fixtures in the system is limited, and each fixture in the system continually cycles through the seven operations. When the desired quantity of a particular part has been produced, the fixture used to produce that part is removed from the system and another fixture is brought into the system.

Once in the system, a given fixture can visit any of the machines performing operations A, B, D, E, F or G. However, the machines performing operation C are set up for a particular fixture type, and therefore a fixture can only visit operation C machines set up for that fixture type. There may or may not be more than one fixture of a particular type in the system at a given time. If there is, identical fixtures can share the same operation C machine. However, there must always be at least one operation C machine set up for each type of fixture currently in the system.

Material handling within the cell is performed via a single resource. This resource moves fixtures between all machines and staging positions. In addition, the resource services a fixture-exchange area used to bring new fixtures into the system and to remove fixtures for parts that have completed production. Material handling operates in both automatic and semi-automatic modes. In automatic mode, the computer controlling the cell determines what move to perform next. The computer also tracks projected operation completion times and will pre-position the material handling resource at the starting location of the next move. In semi-automatic mode, an operator tells the computer which move to perform next.

A simplistic explanation of the automatic material handling logic includes four rules as shown in Figure 1.

Rule 1. If a fixture is in danger of being late moving from C to D and D is available, move the fixture to D.
Rule 2. If a fixture is in danger of being late moving from C to D and all D's are occupied but at least one has finished processing, move the finished fixture from D to E if E is available.
Rule 3. If a fixture is waiting to go to A and at least one A is available, move the fixture to A.
Rule 4. Perform all other moves on a first-in, first-out (FIFO) basis.

Figure 1: Material Handling Logic

For product quality reasons, the maximum time between completion of C and start of D cannot exceed a pre-specified threshold. Rules 1 and 2 attempt to prevent fixtures from being late moving between C and D. Rule 3 ensures that fixtures are always available at A, the bottleneck resource.

In general, operation A machines and the material handling resource are highly utilized and utilization of other machines is lower. However, given that processing times at most operations are part dependent, relative machine utilizations change based on the part mix being produced.

3 PROJECT OBJECTIVES

General project objectives were as follows:

- Increase production throughput.
- Improve flexibility for handling a wider range of part types.

More specific objectives included the following:

- Determine equipment requirements for various part mixes.
- Determine the impact of enhancing the cell controller to reduce material handling move times.
- Determine the impact of connecting two cells and permitting the bottleneck machines to process parts assigned to both cells.

4 PRODUCTION DATA FILES

Three data files were used to drive the simulation. The first file contained part information including processing information specific to each part and what fixture was required. The second file contained fixture information, processing information specific to each fixture and the number of fixtures by type. The third file contained the schedule of parts to be produced in the system. The schedule specified the part number, the quantity to be produced, and the number of fixtures that the scheduler wanted in the system to produce each part. The more fixtures in the system for a given part, the quicker that part's scheduled quantity could be produced.

5 STATISTICAL VALIDITY OF SIMULATION RESULTS

This system is non-terminating, and therefore we were interested in the steady-state behavior of the system. Non-terminating systems have an initial transient phase, or warm up period, due to the significance of the starting conditions. Also, simulation outputs in a non-terminating system tend to be highly correlated, and this output bias must be taken into account when determining how simulation statistics are to be collected. This section discusses the techniques used to determine the simulation run parameters required to achieve steady-state behavior.

The simulation always begins with the system empty and idle. To estimate the warm up period, cycle time observations for each fixture were collected and graphed using moving average plots. These plots indicated that the effects of the transient phase were no longer apparent after six shifts, and therefore simulation statistics were cleared after six shifts.

Correlograms were used to determine how many shifts of data were required for the simulation output to be statistically unbiased. Correlograms plot the correlation between data points a given number of observations apart. For example, a correlogram might indicate that the correlation between every 10 observations is significant, but the correlation between every 50 observations is not. The correlogram indicated that each shift of production could provide one point estimate and the decision was made to collect 30 observations (or shifts) of data.

6 MODEL VALIDATION

Two primary means were used to validate the model. First, an animation of the cell was observed to ensure that the model's material handling logic replicated the actual system. Initial observations of the animation indicated that the model's material handling logic was making incorrect decisions in certain situations. Basically, the model was selecting a fixture's next destination at the time the material handling resource started to move to pick up the fixture. By the time it was in position to pick up the fixture, the decision on where to move the fixture might have changed. The model's material handling logic was updated to include reassessment of a fixture's destination at the point in time that the fixture was picked up.

The second means of validation involved comparing simulation results with actual production results for a given configuration and part mix. Once the material handling logic was corrected, the simulation results closely matched those of the actual system and the model was declared valid.

7 CYCLE TIME

In this closed-loop manufacturing cell, cycle time is defined as the time it takes a fixture to make a complete loop of the system (i.e., to cycle back to operation A). The number of fixtures in the system determines how often a fixture must cycle back to A for a given production throughput rate. For example, in order to produce 30 parts per hour and assuming there are 20 fixtures in the system, each fixture must cycle back to A on average every 40 minutes (20 fixtures / 30 fixtures per 60 minutes). This is referred to as the theoretical cycle time. Assuming that the desired throughput is 30 parts per hour, Table 1 illustrates the theoretical cycle times required for various numbers of fixtures in the system.

Desired Throughput	Number of Fixtures	Theoretical Cycle Time
30	24	48
30	22	44
30	20	40
30	18	36
30	16	32

Table 1: Cycle Times

During analysis, many conclusions were made regarding how theoretical and actual cycle times play a part in understanding system throughput. Therefore, prior to presenting analysis results, this section explores concepts related to theoretical and actual cycle time.

Cycle time is made up of processing time, move time and queue time. Processing times vary by operation and part type, but for a given operation and part type there is little or no variance. Therefore, for a given part type, the sum of the processing times contributes a relatively fixed quantity to the cycle time. Based on a cycle time of 40 minutes and assuming that the sum of the processing times at the seven operations is 25 minutes, 15 minutes remain for move and queue time.

The portion of cycle time required for material handling moves can be accurately estimated based on average move times between particular types of machines and the number of moves per cycle. For example, historical data might indicate that the average time to move a fixture from A to B is 1.1 minutes, from B to C is 0.9 minutes, from C to D is 1.2 minutes, from D to E is 0.8 minutes, from E to F is 1.3 minutes, from F to G is 0.7 minutes, and from G to A is 1.0 minutes. Therefore, on average, move time would contribute seven minutes to cycle time. Note that these move times do not include queue time waiting for the material handling resource to become available.

Ideally, fixtures are moved directly from one operation to the next, and no fixture is ever moved to or from a staging position. In this perfect scenario, each fixture is moved seven times per cycle. However, the nature of this particular cell makes it possible for the system to gridlock in certain situations, thereby not permitting any fixture to be moved. To prevent gridlock, the cell contains temporary staging positions, and fixtures may be moved to these staging positions both prior to and after operation A. The automatic material handling logic determines when it is necessary to move a fixture temporarily to a staging position. Whether or not a fixture visits a staging position during its cycle is very important in that the time required for an additional move is added to the fixture's cycle time.

As the number of moves increases, cycle times increase. As cycle times increase, more fixtures are required in the system to achieve the same throughput. As the number of fixtures in the system increases, the greater the likelihood of additional moves. Obviously, any situation requiring additional moves will start this cycle. Therefore, the number of fixtures allowed in the system must be chosen carefully so as to minimize the number of additional moves required, while maximizing the allowed cycle time permitted to achieve the desired throughput for a given equipment configuration.

Conceptually, there are two contributors to move time, the move time associated with performing the minimum number of moves (which is relatively fixed), and the move time associated with performing any additional moves (which is variable). Assuming that the average number of moves per cycle is very close to the minimum (i.e., the variable portion is close to zero), processing time and move time both contribute relatively fixed quantities to the cycle time.

Like move time, there are also two contributors to queue time--the queue time waiting for a machine (which turns out to be relatively fixed) and the queue time waiting for the material handling resource (which turns out to be relatively variable). Queuing theory tells us that machine queue times are relatively predictable for a given production throughput because the number of arrivals at each machine is constant (since desired throughput is fixed) and machine service times are constant (since processing times have little or no variance). However, queue times for material handling are dependent on utilization, which is dependent on the average number of moves per cycle. If the average number of moves per cycle is very close to the minimum, then material handling queue time, like machine queue time, is relatively fixed. However, if the average number of moves per cycle increases, material handling utilization increases. If material handling utilization increases, material handling queue times increase. If material handling queue times increase, cycle time increases. If cycle time increases, more fixtures are required in the system to achieve the same throughput. As the number of fixtures in the system increases, the greater is the likelihood of additional moves. Again, this initiates a cycle that cannot be stopped.

Basically, analyzing the cell for a given configuration involved applying the following logic:

1. Start by initializing the maximum number of fixtures in the system equal to the number of operation C machines. If the maximum number of fixtures exactly equals the number of operation C machines, additional moves are never required.
2. Exercise the simulation to determine the actual cycle time (and therefore actual throughput).
3. If throughput increases as compared to the previous iteration, add another fixture to the cell and go to step 2. If throughput decreases, stop.

Processing time's contribution to cycle time is always constant, and initially move time's contribution to cycle time is constant (because there are no additional material handling moves). Therefore, the question is whether or not queue time for a given configuration causes actual cycle time to exceed theoretical cycle time.

If actual cycle time exceeds theoretical cycle time, incrementing the number of fixtures in the system increases the theoretical cycle time (assuming the same desired throughput). However, while increasing the number of fixtures will not increase processing time's contribution to cycle time, it may increase move time's contribution (due to additional moves), or queue time's contribution (again due to additional moves that increase material handling utilization).

If actual cycle time is less than or equal to theoretical cycle time, the desired throughput may not be aggressive enough. Therefore, incrementing the number of fixtures in the system while conceptually keeping the same theoretical cycle time increases the desired throughput.

Understanding the relationship of theoretical cycle time to actual cycle time was the first step in performing the following analyses.

8 PART MIX AND FAILURE SENSITIVITY ANALYSES

The cell's current configuration and part mix was analyzed to determine how equipment failures and different part mixes affected system throughput. These sensitivity tests were done prior to other analyses because analysis time was limited. Also the number of possible perturbations, considering all the options being modeled, was very large. Therefore, the decision was made to assess the relative impact of these factors on the current cell configuration and to assume for the moment that a similar impact would be felt on a cell with a different configuration.

Analysis of different part mixes indicated that the system throughput varied significantly for different part mixes. This result was anticipated because processing times for different part types also vary significantly. However, preliminary results emphasized the importance of optimizing the number of each type of machine for a given part mix.

Analysis of failures indicated that failures had a relatively small, though measurable, impact on system throughput. Given these results, failures were ignored for the majority of the analyses performed. Rather, emphasis was placed on understanding the relative differences in throughput between competing options, not on the absolute system throughput for a given option.

9 TWO-CELL SYSTEM ANALYSIS

The two-cell system contains two relatively independent, mirror-image cells, each with their own material handling. However, these material handling systems were permitted to both service the operation A machines, the highest utilized machines. In this option, parts from one cell could be processed at operation A machines in either cell. For all subsequent operations, parts had to be processed at machines in their home cell.

The advantages and disadvantages of this option were relatively obvious going into the analysis. On the positive side, flexibility was added to the system in that parts could be processed at operation A machines in either cell. On the negative side, intermixing material handling systems made it possible for the two material handling systems to interfere with one another. The purpose of the simulation was to determine if either of these advantages or disadvantages had a significant impact on system throughput.

For this analysis, both cells were identical in that they produced the same part mix and had the same number of machines and fixtures. In regard to adding flexibility, the simulation showed there was no significant benefit derived from the ability to share operation A machines. This result turned out to be relatively intuitive in that both cells were doing the same things; therefore, operation A machine utilizations in both cells were the same. Also, there was very little material handling interference because there was no reason for a fixture from one cell to be processed at a machine in the other cell since utilizations were the same. Basically, having an integrated two-cell system was identical to having two independent one-cell systems.

10 ENHANCED CELL ANALYSIS

The enhanced cell had the following modifications. First, the number of operation A machines was increased. Second, the speed of the material handling resource was increased thereby reducing move times. Third, operations F and G were combined and performed at one machine, thereby reducing by one the number of required material handling moves per cycle. Finally, the number of operation B machines was increased.

10.1 Adding Dedicated Buffering at Operation A Machines

Prior to starting a complete analysis of the enhanced cell, an analysis was done to compare the performance of the enhanced cell with and without shuttle devices at A. With shuttle devices, each machine has an input position and an output position. The material handling resource deposits a new fixture at the input position, and a shuttle device moves the fixture to the machine. Upon completion of processing, the fixture is shuttled away from the machine and the material handling resource moves the fixture to its next operation.

The primary reason for considering adding a shuttle device was to add input and output buffering at operation A. Input buffering helps ensure that a machine always has more work to do while output buffering helps ensure that a machine is never blocked. Adding buffering at A also reduces the need to move a fixture to a staging position, thereby potentially reducing the number of moves per cycle.

Simulation analysis showed that adding shuttles at A causes system throughput to decrease. With the added capacity, the operation A machines were no longer bottleneck resources, and therefore buffering was not needed. Also, the average number of moves per cycle decreased only slightly because the lower machine utilizations minimized the need to use the staging positions.

Performance decreased when the shuttle was added because two shuttle moves were added to each cycle. The time required to perform these moves caused actual cycle times to exceed theoretical cycle times. Based on these results, the remainder of the enhanced system analysis was done without the shuttle.

10.2 Enhanced Cell Sensitivity Analysis

A series of simulation runs were performed to determine the system throughput associated with various part mixes, numbers of operation C machines, and numbers of fixtures.

Part mix affects throughput because different parts require different processing times. Analysis showed that selecting the appropriate number of operation C machines and fixtures for a given part mix had a significant effect on system throughput. However, if a particular configuration caused the material handling device to become fully utilized, then changing the part mix had little effect on system throughput because material handling was the limiting factor, not the processing times of the different parts.

Analysis showed that increasing the number of operation C machines and/or fixtures increased system throughput up to the point that material handling becomes fully utilized. When material handling is fully utilized, too many fixtures in the system greatly increases the number of moves to and from staging positions. Additional moves in turn cause material handling utilizations to increase further, thereby causing system throughput to drop dramatically.

Analysis also showed that increasing the number of operation C machines is more beneficial than adding duplicate fixtures. Operation C machines can be added without increasing the likelihood of moves to and from staging positions. Adding duplicate fixtures increases the likelihood of additional moves, thereby increasing material handling utilization.

For the assumptions associated with the enhanced cell, the simulation was able to indicate the optimal number of operation C machines and fixtures for a given part mix. The simulation also ruled out those part mix/configuration scenarios that caused parts to be late moving between C and D.

10.3 Sensitivity Analysis of Move Times

The "baseline" enhanced cell assumed that move times could be decreased by 20 percent, which directly corresponds to a 20 percent reduction in the portion of cycle time attributed to material handling moves. The objective in this analysis was to determine the effect on system performance if move times could only be reduced by 15 percent or 10 percent. Simulation analysis showed that move cycle times significantly impacted system throughput if the part mix and system configuration were such that the material handling resource was close to fully utilized.

10.4 Including Failures

Failures were initially only considered as part of a preliminary analysis to determine the effect of failures on throughput in the existing cell. Given that the simulation had selected the optimal configurations for different part mixes in the enhanced cell, analysis was done to determine the impact of failures in these scenarios. The simulation showed that the loss in system throughput in the new scenarios was approximately the same as that indicated in the preliminary analysis.

11 SUMMARY

Analysis indicated that the cell was well balanced in regard to part mix, material handling capacity, and number of machines and fixtures in the system. However, analysis also showed that if part mix changes, it is important to change the system configuration accordingly. The simulation model can be used to determine the best configuration for a given part mix.

Analysis indicated that a two-cell system would not increase production throughput. Production throughput could be increased in an enhanced cell, but it was important to choose the proper system configuration given the part mix.

REFERENCES

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