Impact of Machine Reliability on Key Lean Performance Measures: The Case of a Flexible Manufacturing System (FMS)

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Abstract: Uncertainty in production systems may arise from different sources including machines, parts, tools or material handling failures. For this reason the need for the production system to be flexible enough to respond to unanticipated breakdowns or failures become highly recognized. This paper considers a flexible manufacturing system (FMS) and analyzes the effect of a combination of various design and operational parameters on the overall system performance under different machine failures/breakdowns patterns. Three performance criteria including throughput rate (TR), mean flow time (MFT), work-in-process (WIP), are analyzed for various machine and AGV scheduling rule combinations over a range of AGV fleet size. These key Lean indicators are selected because they are tenants of Little's Law considered as the backbone equation in Lean Six Sigma methodologies as it advocates the reduction of waste, variability and work in process around the process in order to reduce the cycle time while increasing quality. Comparison is made with the performance profile of a system operating in a failure-free mode. The results reveal that machine and material handling scheduling rule combinations together with the maintenance policy in use may affect significantly the performance of a production system. The results also show that there is an acceptable level of machine breakdown (reliability) for which the system performance is similar to a failure free system.

1 INTRODUCTION

Manufacturers and service providers usually need to deal with a certain number of uncontrollable factors including variations in input part arrival rate, probability distribution of the input part type, failure rate of machines, and rework rate of parts after inspection, etc. (Tshibangu 2006). Because a characteristic of demand in a modern economy is small quantity and high variety of products and or services, the effects of variations due to these uncontrollable factors can be drastic. In order to face increasing global competition manufacturing and production systems operate with small batches and high variability of products and or services in conditions similar to that of a flexible manufacturing system (FMS). During the operation of such highly integrated and automation driven facilities (e.g., FMS) various components can fail due to different reasons. The failure of a single component may force a very expensive machine to idle, and, because there is limited work-in-process (WIP) within the system boundary, the entire system can be brought to starvation or stoppage. Therefore, in these potentially disruptive environments reliability-related issues become important because of their possible negative effect on the overall system performance. It has been demonstrated that for an FMS with a given performance reliability, operating policies for the scheduling decisions also affect the performance of the system (Sridharan, 2000).

Many analytical tools exist to address these issues with simulation being one of the most powerful and extensively used, particularly for design (Ball and Love, 2009). This is the reason why this study uses simulation experiments on a flexible manufacturing system (FMS) to study the effect of machine reliability on the overall performance of the system. The research investigates the effect of scheduling decisions on FMS performances under various machine failure scenarios. The scheduling decisions studied in this research include the number of automated guided vehicles AGVs, the queue discipline, and the AGV dispatching rules.

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2 MOTIVATION

At present, there is little research available on the effect of FMS reliability on the overall performance of the system. It has been shown that for an FMS with a given performance reliability, operating policies for the scheduling decisions also affect the performance of the system (Sridharan, 2000). However, during the FMS operation, some disturbances, such as machine and/or AGV breakdowns, maintenance operations, poor tool management, may drastically affect the FMS performance. Depending on the breakdowns occurrence (frequency) and the length of the repair (criticality), the system performances such as throughput time of parts, completion time of parts, machines and AGVs utilization may deteriorate significantly. Thus, it is necessary to include the breakdown aspect of disturbances for a realistic evaluation of FMS performances.

This research particularly deals with machine breakdowns and repair in an FMS. Although AGV system is considered as the backbone component of an FMS, AGV breakdown is not considered because the author believes that an AGV is such a critical component to an FMS that a wise management decision may consist in investing in redundancy than incurring loss because of unpredicted unavailability of the equipment.

3 RESEARCH PROBLEM

The research problem addressed in this study is to analyze the effect of combination of a pairwise machine and AGV dispatching rules with a design problem such as number of vehicles on the performances of an FMS operating under various patterns of machine breakdowns. The results are compared to the same FMS configuration under a failure-free operating mode.

4 DECISION LEVELS IN FMS

Decision making problems in FMSs are made at three levels, namely: i) the *design* level, which deals with long-term decisions, such as the selection and layout of machine tools and the material handling system; ii) the *planning* level which addresses medium-term resource allocation decisions, such as assigning operations and cutting tools to machines, and iii) the *scheduling* level, which considers the execution of orders in the short term, and includes determining the sequence for processing various parts on each machine.

4.1 Design-related Problems

Design related problems encompass many aspects including: i) part types to be produced; ii) process plan including tooling and tool magazine; iii) type and capacity of material handling systems; iv) fleet size (number of vehicles needed); v) speed of material handling devices; vi) inter-arrival time; vii) type and size of buffers. Buffers provide queuing spaces for in-process inventory (In this paper, the buffer size is considered fixed with a capacity of 10 parts).

4.2 Operational Control Related Problems

The ability of a manufacturing system to operate in accordance with the promised potentials depends heavily on the operational control in force. The dispatching mechanism controls the flow of material in the manufacturing system and determines the release and transfer of jobs (parts) between workstations. Dispatching rules are either machine- or material handling-related. Tshibangu (2012) shows that there is a two-way interaction between machines and AGVs, and indicates that due to this two-way interaction, a realistic analysis of AGV-served manufacturing systems needs to coordinate both machine and AGV operations.

Therefore, during shop operation, a good dispatching policy should be integrated to the design state to maximize the overall system performance. It is important to note that these scheduling decisions may be jeopardized by the failure of machines. In this research the number of vehicles is varied in order to determine whether or not the increase of fleet size may be a remedial solution to prolonged breakdowns.

5 UNCERTAINTY: ASSUMPTIONS AND CHARACTERIZATION

This research considers and analyzes the type of uncertainty related to machine breakdown rates. A flexible manufacturing system (FMS) is analyzed in order to evaluate the nature, form and extent of different machine breakdown rates. Uncertainty in this research is characterized by machine mean time to failure (MTBF). The breakdowns and the maintenance operations are highly machine dependent. Therefore, individual machines would normally have their own reliability and maintenance requirements.

Although a production environment in reality contains a variety of general-purpose and dedicated machines capable of performing various operations, this study assumes the same reliability for all equipment, that is, all machines have the same MTBF. Machine downtime, characterized by the mean time to repair (MTTR) is a measure of the severity of the breakdown. This characteristic is integrated in this research though not fully investigated. For reasons of simplicity, machine downtimes are assumed to be constant for all the machining centers, that is, the MTTR for all processing centers is identical and has the same value for all breakdown occurrences.

The FMS studied operates for 3 consecutive shifts of 8 hours. Machine mean time between failures (MTTBF) are assumed to be exponentially distributed with means varying from 150 minutes to 30 minutes, and the MTTR is also considered to be exponentially distributed with a constant mean of 10 minutes for all failure occurrences. It is assumed that the reliability function $R(t)$, defined as the probability of no failure for the machine during the time interval $(0,t)$, is given by:

$$R(t) = \exp[-\lambda t] \tag{1}$$

where λ is a constant hazard rate, and t the time.

The results of a system prone to failure are compared with the same FMS configuration with no machine failures for operation time of 30 minutes. The time range of 30 minutes has been considered this research to include the highest probable processing time.

6 LITERATURE REVIEW

Sridharan and Babu (1998) use a detailed simulation study on a typical FMS under two situations: (1) the FMS is failure free; (2) the FMS is prone to failures. They develop metamodels for the two types of FMSs. The metamodels have been found to be useful for simulating the studied FMSs and for evaluating various multi-level scheduling decisions in the FMS. Sridharan *et al.* (2000) extend their work and investigate the effects of a multi-level decisions in a failure prone FMS. Six failure-repair situations are considered, characterized by the severity of failure frequency and the length of repair time for machines and AGVs in an FMS Renna, P. and Ambrico, M. (2011) examine cycle time and WIP in a cellular manufacturing subject to dynamic changes. Wassi Sorro *et al.* (2012) examine a system in any of three states: nominal operating state, degraded state or failure state. The system state is known only after inspection. A maintenance action is undertaken when at a predetermined instant an inspection reveals that the system is in degraded or failure state. The maintenance action restores the system to its nominal operating mode with a certain probability. A periodic type inspection strategy is used and proposed. In all the studies mentioned above design and operational categories were pursued separately. As an innovation this research study integrates issues from both groups and investigates the effects of machine failure rate (or machine reliability) and AGV dispatching rules as operational variables while considering AGV fleet size as the design variable in studying FMS performances.

7 RESEARCH APPROACH

Two heuristics for vehicle-initiated dispatching have been selected in this study: i) the first come first serve (FCFS) dispatching rule assigns vehicle to demands sequentially as requests for AGVs are received from different machines; ii) the shortest traveling distance (STD) rule minimizes the time vehicle travels empty. This rule dispatches the released vehicle to the machine which is closest to the idle vehicle. The machine dispatching rules (queue discipline) considered in this study include: (1) the short processing time (SPT) rule that dispatches the job with the smallest processing time and the first in first out (FIFO) rule that dispatches jobs sequentially on the machine as the previous part in the queue has been completed. This leads to 2^2 sets of dispatching rules combinations to be analyzed, i.e., FIFO/SDT, FIFO/FCFS, SPT/SDT, SPT/FCFS. The first acronym stands for the queue discipline (machine scheduling) rule in use, while the second design the AGV dispatching rule.

For each of these machine and AGV dispatching rule combination, 5 failure-repair configurations are examined to evaluate the FMS performance under 5 situations, each one involving a different number of vehicles. This combination results into a total of 100 simulation experiments to be performed under various machine breakdowns.

In addition, for each number of vehicles studied in this research, simulation runs are also carried out on the same FMS configuration under no failures. This implies 20 additional simulation runs for the failure-free situation leading to a total of 120 of simulation experiments. The results from the failure free situation are subsequently compared with those from the FMS prone to failure in the analysis.

8 THE SHOP MODEL

The hypothetical FMS layout used in this paper is similar to the one used by Tshibangu (2003, 2012). The job shop model is composed of nine workstations, including a loading or receiving station (workstation 1) and an unloading or shipping station (workstation 9).

8.1 Job Descriptions

All jobs enter the system through the receiving department and leave the shop through the shipping department. It is assumed that raw materials are always available at the loading station and parts that arrive at the unloading station depart the system immediately after being unloaded. Each job consists of only one unit load and is processed and moved between work stations as a single unit load. AGV carts move parts between the workstations along a predetermined mixture of uni- and bi-directional paths.

8.2 Simulation Model

Jobs are simulated to arrive at random times for the entire operational period following a Poisson model because this distribution provides a good approximation for the job arrival when generating sources are assumed to be independent. For each experimental condition the simulation is run with three independently-seeded replications of 600 minutes each. The first 120 minutes of each run are truncated to eliminate the initial bias. The remaining 480 minutes representing an operational shift of 8 hours are replicated three times to represent each daily shift, and the outputs from the three replications are collected and averaged out across replications. To simulate a fairy busy system, the arrival rate of jobs is assumed to be equal to the ratio of the capacity of the job shop to the average amount of work required. The arrival rate, denoted by δ , is then given as:

$$\delta = \frac{M * \eta}{\overline{n} * \overline{p}} \tag{2}$$

where

M = number of machines

η= machine load capacity

$\overline{n}$ = average number of operations

$\overline{p}$ = average operation times

Following this model, various arrival patterns can be obtained by adjusting the machine load capacity factor η. Changing the arrival rate gives the experimenter the flexibility to control the degree of congestion in the shop. In this research, a machine load capacity of 90% $(\eta = 0.90)$ was assumed in generating the job arrival process. The jobs were simulated to have one to 7 different types of operations, the number being assigned randomly using a uniform distribution $U(1,7)$. The average number of operations is $\overline{n} = 4$. The average operation time of 15 minutes is also extracted from a uniform distribution model $U(5,25)$. Using Eqn. (2), a value of the arrival rate $\delta = 0.135$ has been used.

8.3 FMS Configuration

The FMS configuration studied is summarized in Table 1. There are 15 parts types in total, and all the processing times are assumed to be known deterministically, since all the machining operations are computer numerically controlled. Besides, all the raw materials are assumed to arrive at time zero. Two different simulation models have been developed, one for failures free machines failures, and another for machines prone to failures. The simulation experiments have been carried out for 4 different combinations of machine and AGV dispatching rules as operational control input parameters, with various numbers of vehicles as a design input parameter. Three performance measures are evaluated for each configuration and later compared for further insights and conclusions.

Table 1: Shop Configuration.

Part Types considered for production	15
Machines	9 (including one loading and one unloading stations)
Material Handling Systems (AGVs)	Variable from 3 to 15
Buffer Capacity	10 for workstations 2 to 8
	Infinite for workstation 1
Loading/Receiving stations	1 (workstation 1)
Unloading/Shipping stations	1 (workstation 9)

8.4 Shop Conditions and Assumptions

A number of simplifying assumptions have been used for the simulation model, e.g., an AGV transfers only one unit load at a time; pickup and drop-off times of a part are set at a constant of 0.25 minutes each; machine failures are time-based failures; the failure of resource (i.e., machine) will occur at different rates taken from an exponential distribution with a certain mean, e.g., EXPO (150); breakdowns of vehicles (AGVs) are not considered, etc. The reader is referred to Tshibangu 2006 for a complete list of all the assumptions used in this study.

8.5 Performance Evaluation

Three performance measures are used in this study including i) system throughput per shift (TR); ii) flow time (cycle time) MFT and iii) number of parts in the system or work in process (WIP). These key indicators are consistent with Little's Law known the governing equation of Lean Six Sigma methodology as it evaluates the MFT as the ratio of WIP to TR. The definitions and formulas of these measures are provided in the equations below. All quantities are mean values averaged across the three replications.

(1) Mean Throughput Rate (MTR), here defined as the total number of parts (all types confounded) during a shift. If $p_i = 1,2,\ldots p$ is the number of type i parts produced during a shift, then:

$$\mathrm{MTR} = \sum_{i=1}^{p=15} p_i \qquad \text{parts/min} \qquad (3)$$

(2) Mean Flow time (MFT), also known as cycle time for a part p_i is defined as the time F_i elapsed between its arrival and its departure. Thus, it is the sum of part's delay in queues and its service time. When there are more than one entity (part) in the model, the total flow time will include the sum of all flow times ($\sum_{i=1}^{p} F_i$).

The mean Flow Time in this study is computed as follows:

$$MFT = \sum_{i=1}^{15} \frac{F_i}{p_i} \qquad (4)$$

(3) Average number of parts in shop, also called work-in-process (WIP) is a time-persistent measure and represents the total number of all part types present in the system in average during the simulation time. In this research study, WIP is computed as follows:

$$WIP = \sum_{i=1}^{p=15} \left(\frac{p_i}{480} * F_i\right) \qquad (5)$$

9 RESULTS AND ANALYSIS

For each set of machine and AGV dispatching rules, 3 operational shifts of 480 minutes were simulated with different material handling fleet size and under different machine reliabilities (or different failure rates). The simulation results are presented in separate groups according to the machine/AGV rule combination used or each performance measure.

Results of the simulation experiments for all combinations of machine and AGV rules and number of vehicles are not displayed in this paper but they may be available upon request.

To answer the research question on whether or not the combination of sets of machine/AGV dispatching policies with number of AGVs in a manufacturing or production environment with machines prone to various failure rates has an impact on the performance measures such throughput rate, mean flow time, and work-in-process, graphs are plotted and ANOVA models developed. The data analysis section of this paper is broken into three sections, one for each dependent variable (performance measure), and for each performance measure the effect of fleet size and machine reliability will be analyzed.

9.1 Throughput Rate

The results of data analysis confirm the author's prior knowledge about the impact of number of vehicles present in a system. Tshibangu (2006) reported that the throughput behaves in a concave manner with respect to the AGV fleet size. The objective in determining the optimal fleet size is to have the smallest number of vehicles in the system, but still capable to achieve the performance requirements. For illustration purpose Figure 1 depicts just the throughput rate TR for SPT/SDT machine /AGV combination rules.

As the number of vehicles increases in the system the throughput rate increases due to material flow capacity. However, beyond a certain number of vehicles, an addition of more vehicles results in increasing traffic congestion and blocking of vehicles leading to a decrease in the throughput rate as a result of the delay caused to AGVs in completing their tasks. As noted in Tshibangu (2006) this is both economical and operational waste. The highest throughput rate for all rule combinations is observed with the configuration free of failures, i.e., machine reliability =100%.

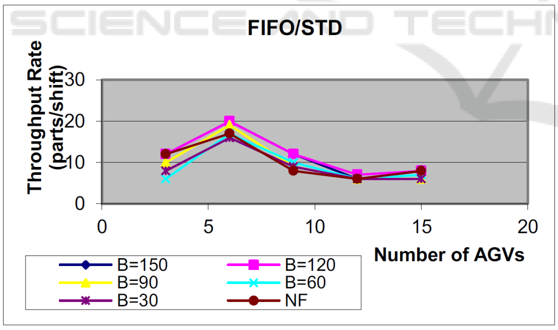

Figure 1: Average (WIP) under Machine SPT and AGV FCFS.

For a value of MTBF = EXPO (150) minutes or a machine failure rate λ = 0.0067 per minute equivalent to a half hour reliability of 82 %, the system behaves exactly like the zero-failure configuration.

The reliability is calculated on a 30 minutes time frame in order to be as close as possible to the longest possible processing time used in this research as they are generated from a uniform distribution $U(5,25)$. It can be noticed that the system TR performance starts to degrade when failure rates reach values higher than 0.0067 min^{-1}, i.e., for MTBF values less than 150.

In other words, the company production management board can ensure a good performance of the system by implementing maintenance policies that can keep the reliability of the resources (machines) at a level that will allow the FMS to behave as a failure-free system. A failure rate of 0.0067 min^{-1} or less (i.e., half-hour machine reliability of 82% or more) may be considered as good enough to keep the throughput rate at almost the same level as in a system free of failures.

A widely adopted philosophy in determining the optimum AGV fleet size recommends the optimum number of vehicles to be the one that maximizes the throughput TR of the system. Analysis of the various output graphs along with pilot simulation runs revealed that the maximum number of vehicles needed in the system under study in this research is equal to six (6) for all set of machine and AGV scheduling rule combinations.

To test the relative performance of different set of combinations of machine and AGV rules with respect to the throughput rates TR, a one-way ANOVA has been developed but the results are not presented in this paper for space compliance. However, the associated boxplots represented in Figure 2 reveal a significant difference between the performances of the 4 sets of combined machine/AGV rules tested.

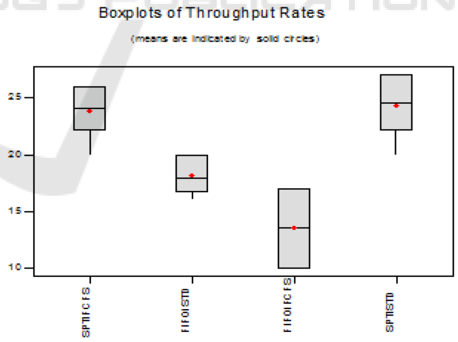

Figure 2: Relative Performance of Sets of Rules on TR.

The highest throughput is achieved by both SPT/STD and SPT/FCFS, with a slight difference in favor of SPT/STD. This means that the best queue discipline is SPT, regardless the AGV dispatching rule associated with. Results also suggest that FIFO is the worst queue discipline rule, independently of the AGV rule used along with. Poor performance of FIFO/FCFS is not a surprise because these two rules give respectively priority to the first part in the queue, or the first AGV available, without any considerations about the part attributes (e.g. processing time) or distance to be traveled to satisfy a transportation request.

9.2 Mean Flow Time

The mean flow time performances of various configurations of the system under study for different levels of machine reliabilities have been analyzed. Figure 3 depicts the MFT for STP/FCFS for illustration purposes while the rest of the graphs at other machine/AGV combination rules can be obtained upon request. Observation of the various graphs and plots produced with the study leads to the conclusion that the mean flow times of a system prone to machine failure follows the same almost convex ascendant shape with regard to the fleet size.

When considering the variances on flow times, it can be observed from the results that mean and variances of the flow times are correlated, that is a scheduling combination rules with larger mean flow time value, also depict a lager variance, with the only exception for the SPT/SDT.

The mean flow time is moderate when the number of vehicles in the system is low, and decreases to a minimum as this number is increased because of the additional material flow capacity. However, the addition of more vehicles results in an increased congestion a higher mean flow time.

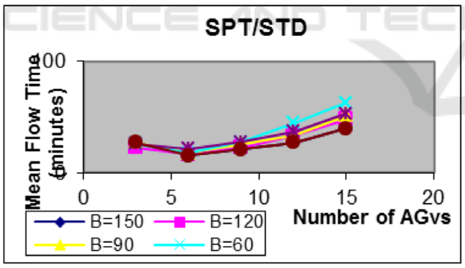

Figure 3: Average MFT under Machine SPT and AGV FCFS.

Therefore, too many vehicles in the system results in an increase of the mean flow time. The number of AGVs that minimizes the system's mean flow time is also found to be equal to six.

To answer the research question with regard to the relative performance of machine and AGV scheduling rule combinations with respect to the mean flow time ANOVA model and associated boxplots were developed. The ANOVA results are not displayed in this paper but can be obtained upon request. However, analysis of boxplots displayed in Figure 4 reveals a significant difference between the performances of various combinations of operational rules.

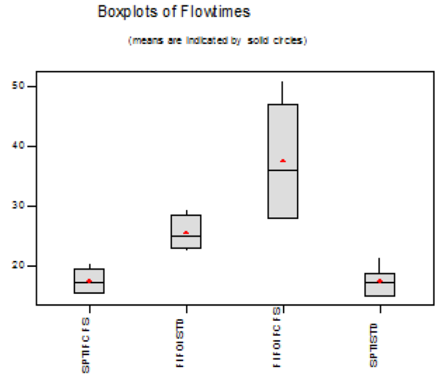

Figure 4: Relative Performance of Sets of Rules (WIP).

SPT/STD and SPT/FCFS are the best achievers with a slight difference in favor of the SPT/STD. But SPT/FCFS has the least variance. A glance on different mean flow time charts (not displayed in this paper) reveals that in all situations, the zero-failure configuration performs better than a system subject to breakdowns. The effect of breakdowns is proportional to the failure rate, i.e., the higher the machine failure rate (or the lower the machine reliability), the higher the system the mean flow time, and the lower the machine failure rate (high reliability), the lower the system mean flow time. Also, when the mean flow time of the system is used as performance measure, information from the part is more important than the distance of the requesting part from the available transportation device. FIFO/FCFS and FIFO/STD did not perform well, with FIFO/FCFS being the worst case. This again suggests that FIFO is not the best machine scheduling rule when a system is assessed with regard to the mean flow time.

9.3 Average Number of Parts in the System (WIP)

The average number of parts in the system also known as the work-in-process (WIP) behaves as illustrated in Figure 5. The simulation results (not displayed in this paper) along with the associated graphs reveal that the fleet size has no effect on the work-in-process. This almost agrees with Little Law's also known as the first law of manufacturing systems. This law, which is perhaps the most recognized working principle of production and manufacturing systems and also used extensively today in Lean Six Sigma states that: Work-in-process equals to the production rate times the throughput time.

As pointed out earlier in this paper, the production rate (also known as throughput rate) first increases with the number of vehicles in the system until an optimum fleet size is reached, and then starts to decrease as more vehicles are added in the system.

WIP = Production Rate x Throughput Time (6)

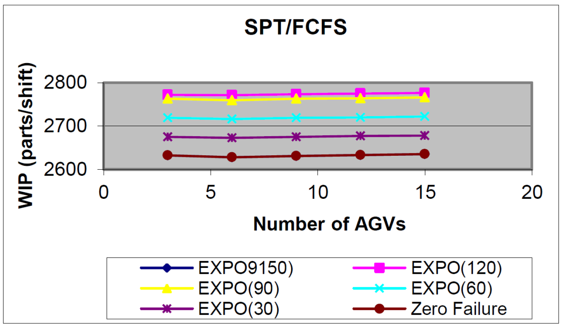

Figure 5: Average (WIP) under SPT and FCFS Rules.

The throughput time (represented by the flow time) behaves in the opposite way, i.e., first, an early decrease is observed when the number of vehicles is augmented, second, a minimum value is reached, and third an increase is observed as more vehicles are added. The two terms in Equation (6) acting in opposition, their product might tend to be constant. This would explain why WIP is not sensitive to the fleet size.

However, the effect of failure rates (or machine reliability) affects the system as expected. The lowest WIP values are observed for the zero-failure configuration for all machine and AGV scheduling rule combinations. Then, as the failure rate of the machines increases (reliability decreases), the WIP increases. To determine the relative performance and the significance of different machine and AGV dispatching rule combinations on the work-in-process (WIP) performance, a one-way ANOVA model is developed and the different data plotted in boxplots as shown in Figure 6.

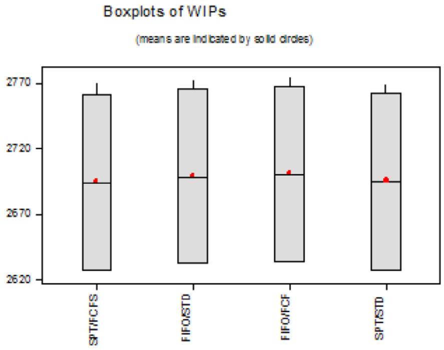

Figure 6: Relative Performance of Sets of Rules on WIP.

The difference between the highest and lowest WIPs observed for all machine and AGV scheduling combinations are not really significant, and represent less than 5% of the average number of parts in the system. The comparison is conducted under a configuration system with 6 AGVs, previously identified as the optimum fleet size.

Detailed analysis of ANOVA results associated plots of means reveals that statistically there is no significant difference between the work-in-process performances of all machine/AGV scheduling rule combinations tested. The variances for different set of rules were also found to be identical, suggesting that the machine and AGV scheduling policy combination does not seem to have significant effects on system performance in terms of work-in-process under the conditions of the present study. However, this performance measure seems to be more sensitive to part arrival rates and buffer size as revealed by earlier pilot simulation runs.

10 CONCLUSIONS AND FURTHER RESEARCH

This paper has extended the machine reliability problem into machine and AGV scheduling issues in flexible manufacturing settings.. System parameters including the number of vehicles in the system, machine and AGV scheduling rule combinations were varied in simulation runs to allow a logical and fair assessment of system performance measures. Three performance criteria including throughput rate (TR), mean flow time (MFT) and average work-in-process (WIP) are tested in this research to determine the effect of machine reliability (through failure rate), fleet size (through the number of vehicles in the system), and scheduling rules (through machine and AGV scheduling rule combinations). The results are then compared to the same system configuration when operating failure-free mode. The relative performance of a particular set of operational rules is determined through ANOVA procedures, pairwise tests on means, boxplots, and scattered charts. A system free of failures has been identified as the configuration that gives the best results as compared to a system prone to machine failures. Machine breakdowns have been found to have a significant impact on the FMS performances for failure rates larger than 18%, i.e., a good preventive maintenance policy that can keep the machine half-hour reliability of machines beyond 82% is a guaranty for good performance of the system.

Results reveal that throughput rate and mean flow time can be described as a concave, and a convex function respectively, i.e., each reaches its optimum (max for throughput, and min for mean flow time) subject to both trends, the additional flow capacity and the reduction in flow due to congestion. This suggests that for both economical and operational interests best results will be obtained by operating the FMS with only the maximum number of vehicles needed in the system. The average work-in-process seems to be only slightly affected by the fleet size. With the throughput and the flow time behaving in opposite directions over the variation of the fleet size, this result seems to comply with Little's law. Selection of particular operational plan, i.e., machine and AGV scheduling rule combination has been found to have a significant impact on all the FMS performances studied in this research with the exception of the work-in-process that seems to be insensitive to operational rules in use. However, pilot simulation runs have revealed that although the combination of machine and AGV scheduling policies did not seem to have significant effects of the average number of parts in the system (WIP), this performance value is highly affected part arrival rate and buffer size, i.e., WIP is more sensitive to part-related attributes than to the operational and control issues in force. Simulation results have shown that machine and AGV operational rules combinations that outperformed with respect to system throughput rate and mean flow time are SPT/FCFS and SPT/STD, suggesting that a combination of operational rules that includes part information as queue discipline might be the better achievers. The conclusions drawn in this research may be completed by further investigation that may include scheduling rules that consider other attributes, such as part waiting time, length of queue in front of a machine, severity of breakdowns (various MTTR), and the number of part types.

REFERENCES

Ball, P.and Love, D., 2009. Instructions in Certainty, *Institute of Industrial Technology, 29-33.*

Renna, P. and Ambrico, M. 2011. Evaluation of Cellular Manufacturing Configurations in Dynamic Conditions using simulation: *International Journal Advanced Manufacturing. Technology (2011) 56:1235–1251.*

Sridharan, R. and Babu, A.S., 1998, Multi-level scheduling decisions in a class of FMS using simulation based metamodels, *Journal of the Operational Research Society*, 49, 591-602.

Sridharan, R., Vishnu, A.S., and Babu, A. S., 2000, Effects of multi-level scheduling policies in a failure prone FMS: A simulation study. *Journal of the Operational Research Society*.

Tshibangu, WM Anselm, 2013. A Two-Step Empirical-Analytical Optimization Scheme, A DOE-Simulation Meta-Modeling Approach, *10th International Conference on Informatics in Controls, Automation and Robotics.*

Tshibangu, WM. Anselm, 2006 Robust Design of a Flexible Manufacturing Systems: A Simulation Metamodeling Approach, *Proceedings of the 2006 Global Congress on Manufacturing and Management (GCMM'2006), COPEC – Council of Researches in Education and Sciences, Nov 19-22, Santos, Brazil.*

Tshibangu, WM Ans elm. 2012: Lean, Six sigma, Simulation, and DOE: An Framework to Optimal Design and Implementation of a Cellular Manufacturing, A Case Study, *Proceedings of the 9th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2012), July 27-31, 2012 Rome, Italy.*

Wassy Soro *et. al* 2010. Production Rate Maximization of a Multi-State System Under Inspection and Repair Policy, *International Journal of Performability Engineering Vol.8, No. 4, July 2012, pp. 409-416.*