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SIMULATION-BASED PLANNING OF MAINTENANCE ACTIVITIES BY A SHIFTING PRIORITY METHOD

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ABSTRACT

Machine failures are major causes of direct downtime as well as system losses (blocked and idle times) in production flows. A previous case study shows that prioritizing bottleneck machines over others has the potential to increase the throughput by about 5%. However, the bottleneck machine in a production system is not static throughout the process of production but shifts from time to time. The approach for this paper is to integrate dynamic maintenance strategies into scheduling of reactive maintenance using Discrete Event Simulation. The aim of the paper is to investigate how a shifting priority strategy could be integrated into the scheduling of reactive maintenance. The approach is applied to and evaluated in an automotive case-study, using simulation for decision support. This shows how to shift prioritization by tracking the momentary bottleneck of the system. The effect of shifting priorities for planning maintenance activities and its specific limitations is discussed.

1 INTRODUCTION

Maintenance plays an important role in efficient production systems especially in flow oriented layouts wherein equipment failures not only lead to direct downtime but also to system losses, i.e. blocked and idle states. Several studies show that these losses contribute substantially to the fact that the average Overall Equipment Effectiveness (OEE) is as low as 50-55% in manufacturing industry (Ingemansson 2004; GoodSolutions AB 2012). In addition to the obvious economic losses, poor maintenance planning has negative impact on ecological sustainability, for example by unnecessary energy consumption in down and idle machine states (Skoogh, Johansson, and Hansson 2011). Thus, doing the right priorities in maintenance planning is crucial.

However, planning of maintenance, specifically reactive activities, is often neglected in industries. Activities are mainly executed on a first-come-first-served basis and when criticality analysis is applied, companies apply static methods such as A-B-C classification. Simulation and other potent engineering tools are rare in maintenance organizations and an increased use might well access hidden potential in terms of production efficiency. Previous research studies, e.g. Ali et al (2008), Gharbi and Kenné (2005), and Langer et al (2010), report successful application of simulation in maintenance planning.

In line with prior research, the authors presented a paper at WSC'13 showing the potential of using simulation in the planning of operator maintenance (Gopalakrishnan, Skoogh, and Laroque 2013). As much as 5% increase in throughput was achieved using priorities based on static bottleneck detection following a utilization analysis approach. No investments needed, just working smarter with prioritizing activities in critical equipment. The question is whether a static bottleneck approach is sufficient or if more dynamic solutions can lead to even higher improvements?

The aim of this paper is to take the approach from WSC'13 (Gopalakrishnan, Skoogh, and Laroque 2013) one step further and compare the static approach with a dynamic bottleneck detection method for prioritization of operator maintenance. The same case study from the automotive industry is used for analysis. The results show that complete dynamic prioritization, enabling re-prioritization in real-time, is not always the best option. System constraints, i.e. bottlenecks, are continuously shifting but there should be a lag in planning of reactive maintenance activities in order to maximize systems throughput.

2 FRAME OF REFERENCES

2.1 Maintenance & Repair using Discrete Event Simulation (DES)

Maintenance and repair are integral and unavoidable occurrences in a production system. Many decision support systems for both reactive and preventive maintenance have been researched. Wang (2002) categorizes and compares various existing maintenance policies for both single-unit and multi-unit systems. He differs between age replacement policy, random age replacement policy, block replacement policy, periodic preventive maintenance policy, failure limit policy, sequential preventive maintenance policy, repair cost limit policy, repair time limit policy, repair number counting policy, reference time policy, mixed age policy, preparedness maintenance policy, group maintenance policy, opportunistic maintenance policy, etc. Existing solutions based on model-based maintenance decision support systems are used to achieve high productivity and cost effectiveness (Ni and Jin 2012). (Li and Ni 2009) e.g. develop a short-term decision support system for maintenance task prioritization based on the system operating conditions.

Discrete event simulation (DES) is widely applied to the area of maintenance, mainly due to its ability to model stochastic changes in flexible systems. The bottleneck detection methods and maintenance and repair strategies are tested upon these simulated models. There are several examples how DES has been used for improving service and maintenance operations. (Ali et al. 2008) analyzed optimized maintenance design for manufacturing performance improvement using simulation. (Altuger and Chassapis 2009) used simulation modeling for Multi Criteria Preventive Maintenance scheduling. A Multi-Stage DES approach for Scheduling of Maintenance activities in a Semi-Conductor manufacturing line was carried out by (Scholl et al. 2012).

2.2 Static and Shifting Bottleneck Detection

To improve the throughput of the system, the throughput of the bottlenecks has to be improved (Goldratt 1990). There are different traditional bottleneck detection techniques like the Machine Utilization method (Roser, Nakano, and Tanaka 2001), waiting time method (Roser, Nakano, and Tanaka 2003) and also theoretically analyze bottleneck using the utilization rate of machines. New and more effective bottleneck detection methods are developed for short-term and long-term bottleneck detection using data-driven bottleneck detection (Li, Chang, and Ni 2009). (Li et al. 2009) introduced a real time bottleneck control method in order to efficiently utilize the finite manufacturing resources and to mitigate the short-term production constraints by using two practical approaches: initial buffer adjustment and maintenance task prioritization.

(Roser, Nakano, and Tanaka 2003) apply a shifting bottleneck detection method which shows there can be multiple bottlenecks in a production system at a given point of time. (Moench 2005) investigate the influence of several order release strategies on the performance of a distributed shifting bottleneck heuristic in electronics industry. (Langer et al. 2010) present a priority-based dispatching policy, based on the analysis of real-time data. Here, the priority is assigned to the bottleneck machine after a fixed time period, and the maintenance worker will service the high-priority machine (i.e. bottleneck machine) first when multiple service requests are received. Another method using inter-departure time and failure cycle data which dynamically detects and ranks the bottleneck is developed by (Sengupta, Das, and VanTil 2008).

3 METHODOLOGY

In this paper, the evaluation of a shifting-bottleneck strategy for maintenance planning and its impact on system performance is evaluated by using a case study from automotive industry. The paper sets up on (Gopalakrishnan, Skoogh, and Laroque 2013) and introduces a new planning approach in order to compare it with the existing results. The simulation study followed the traditional steps, e.g. described in (Banks 1996) and further on updated with a more parallel work procedure as in (Rabe, Spieckermann, and Wenzel 2008).

3.1 Use-Case Description

The case study company produces engine components to cars and the sub-system under investigation is delimited to one specific manufacturing line. There are 11 serially connected operations including 15 machines. The machines mainly execute machining operations such as multi-operational rough machining, milling, drilling, and grinding. Unpacking of raw material, washing, quality control and visual inspection are examples of other steps in the production system. Some of the operations are connected with conveyor belts, acting as buffers, which totals to nine. The buffer capacities are limited, so blocked and idle states can occur at all stations including the bottleneck. Production planning follows a push principle and the overall goal is to produce as many products as possible per time unit.

Figure 1 shows the use-case layout showing the different machines, buffers, and operators. Four operators work at the production line and they are responsible for separate areas of the line. Operator 1 (O1) is responsible for machines M1 and M2(1) to M2(2), O2 handles machines M2(3) to M2(5), O3 handles machines M3 through M6 and finally O4 handles machines M7 to M11. The operator responsibilities include set-up between product variants, quality control, and most importantly for this case study, the repair of common failures. Repair activities are currently executed on a first-come-first-served basis. The operator maintenance takes care of most problems in the machines and external assistance from the maintenance department is rare for reactive maintenance.

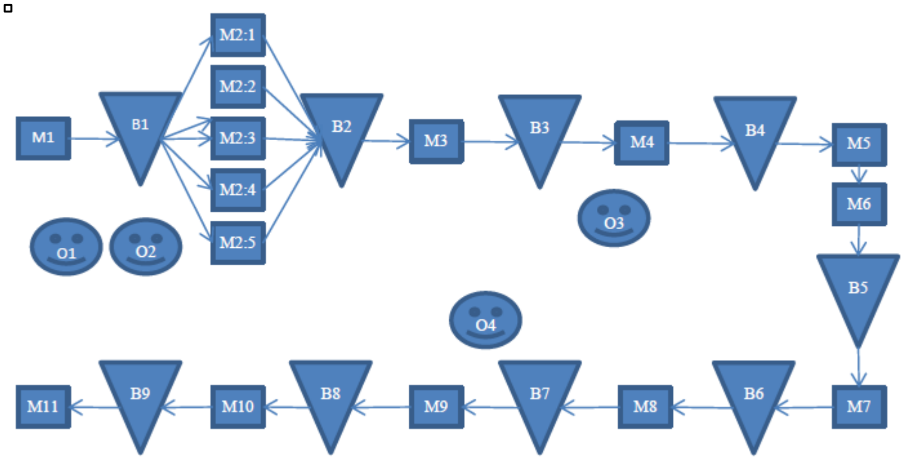

Figure 1: Use-Case Lay out showing operators (O), machines (M), and buffers (B).

3.2 Experimental Plan

The dynamic planning for repair orders was simulated and compared with existing results from authors' previous work. The experimental plan followed the steps below:

Reference Model:	This model has first-come-first-served basis planning for repair orders
Static Priority Model:	This model has static priorities for machines and the operators perform repairs based on the machine priorities
Shifting Priority Model:	This model has dynamic priorities for the machines. The priorities are set during the simulation run based on the current state of the system and the operators perform repairs based on the dynamic priorities of the machines.

The reference model and static priority model and its results are incorporated from authors' previous work. The work procedure started with the modeling of shifting priority model and the results are compared with both static priority and reference model. A warm-up period of 8 hours and one working week (168 hours) were used for all the models. The simulation was replicated 25 times for stable results.

4 SIMULATION MODEL

4.1 Model Building

The production system is modeled using Automod®. The machines and operators are individual entities and coded separately. The breakdowns are coded separately in order to have flexibility in assigning variable priorities for repair orders.

4.2 Abstraction Level

The aim of the model was not to replicate reality, but importance was given to the level of detail as pointed in the theory (Vasudevan and Devikar 2011). In order to fit the purpose of evaluating static and shifting maintenance strategies assumptions were made. Only the machine cycle times, Mean Time To Failure (MTTF), and Mean Time To Repair (MTTR) were used to build the model. Set-ups times, scrap rates, et cetera are excluded. The other assumptions were: the operators are limited to attend only repair orders, single product variant, unlimited supply of incoming raw material, material handling equipment are non-bottlenecks and no transfer times between operators for repair orders.

4.3 Verification and Validation

Animation and debugger were used to verify the base model. The code for the model were peer reviewed. The experimental scenarios were verified by comparing the utilization rates of resources to the newly created model state. The main validation was a face validation (Sargent 2005), done on the system throughput by comparing it to the real production system. Face validation was done by a system expert.

4.4 Maintenance Prioritization by Static Bottleneck Analysis

Prioritization of bottleneck machines in a production system over others yields increased throughput in comparison with first-come-first-served basis for repair orders. The reference model which resembles the current state was used to compare the results of the static priority model. A long-term bottleneck analysis (utilization method) was used to determine the bottleneck machines. Also the machines were ranked according to the utilization percentages i.e., machine with highest utilization (primary bottleneck machine) is priority 1 machine and the machine having the least utilization percentage carried the least priority. Figure 2 shows the 11 machines in the selected production system and its utilization, down time and idle & blocked percentages stacked up from the base model statistics. The reason behind prioritizing is to exploit the bottleneck of the system and improve the throughput without changing the time to repair and time to failure but by changing only the idle & blocked time of the critical machines. In the prioritized scenario the machines carry static priorities throughout the simulation run time and the repairs are done on the machines according to the priorities on them. Under this scenario, the throughput of the system increased by about 5% in comparison to the base model (Gopalakrishnan, Skoogh and Laroque 2013).

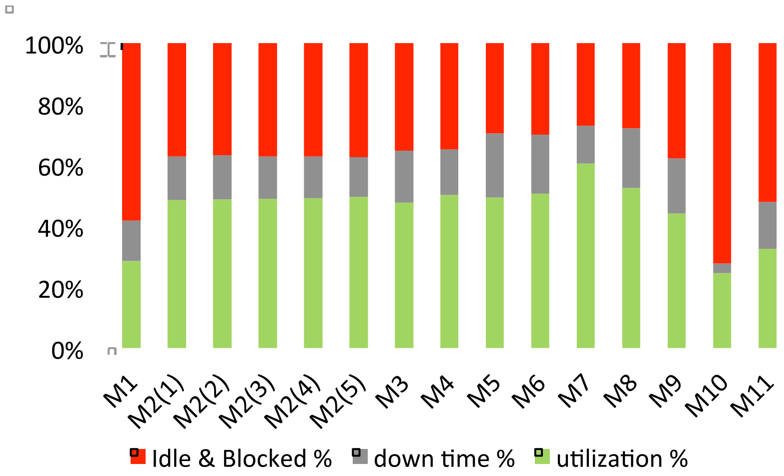

Figure 2: Utilization % of resources in the base model.

4.5 Shifting priority method implementation

The static priorities for repair orders are changed to dynamic priorities in this shifting priority method. The bottleneck analysis is made using current utilization of machines, that being dynamic instead of static. The priorities are shifted real-time for repair orders using some concepts from the bottleneck detection method (Roser et al. 2002). The active period of the machine comprises of working, in repair, changing tools and services. The priorities of the machines change during the simulation run depending upon the length of the active period. Since it is not possible to know the future state of the machines, the priorities were set only using the current active period at any moment. Therefore the priority always follows the momentary bottleneck (Roser et al. 2002) of the production system at any given time. During simulation run the active period for each machine is continuously monitored and the priorities are sorted each minute. The machine with the current longest uninterrupted active period claims Priority 1 and at the same time the machine having the shortest active period assumes the last priority. By the nature of production system, the active periods end and start continuously throughout the simulation time leading to change in the bottleneck machine from time to time. Since the active period of machines is concurrent there is more than one machine which has current active period. Therefore priorities changes only at the start and end of an active period for each machine. The figure 3 shows an example of the shifting priorities in the simulation model. At time T1, machine M1 starts an active period, since it started first it claims priority P1. At time T2, M2 claims P2 as M1 has the current longest active period. Likewise in time T3, due to current lengths the longest active length claims highest priority. At time T4, the active period of M1 ends, therefore vacating P1. Hence there is a shift in priorities at time T4. The machine M2 has the current longest active period, thereby claims P1 and similarly M3 claims P2 at time T4. The figure is extended till timeT8 for further understanding.

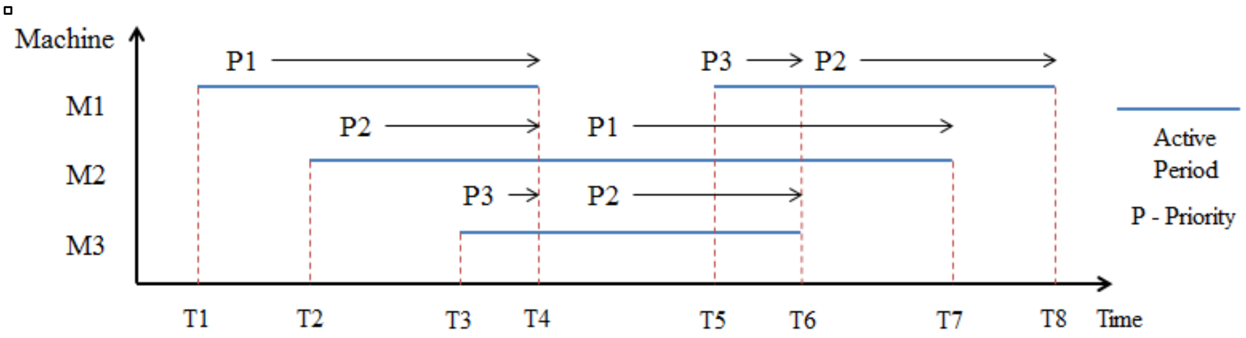

Figure 3: Shifting priorities implementation.

5 RESULTS AND ANALYSIS

From both the bottleneck analysis, it is observed that the machines M1 and M2(1) to M2(5) are not bottleneck machines, therefore they are excluded from setting priorities. Operators O1 and O2 work on these machines for repair orders. The other machines are shared by operators O3 (from M3 to M6) and O4 (from M7 to M11) (see Figure 1). For easier understanding and explanation, the figures and graphs are split into two for each operator from now on in this paper.

5.1 Shifting and static priorities comparison

The simulation experiment was run with 25 replications with shifting bottleneck priorities for repair orders in the production system. The results are produced with 95% confidence interval. The result comparison between the scenarios of reference model, static priority model and shifting priority model is tabulated in table 1.

Table 1: Throughput Comparison between different methods.

Scenarios	Mean Throughput (with deviation)	% Increase
Reference Model	24681 (+/- 481.26)	-
Static Priority Model	25940 (+/- 482.62)	5.10
Shifting Priority Model	25005 (+/- 573.72)	1.31

An improvement of about 5.1% for static priorities model was observed. The shifting priority method which is more dynamic than the static priorities method was expected to produce even higher improvement. But the shifting priorities method yields lesser throughput of only about 1.31% improvement than that of the static priorities when compared to the base model. These results let the authors go deeper to reason the reduction in throughput. The rational is described below.

5.2 Reasons for shifting priority method throughput reduction

Since the active periods are continuously ending and starting, there are a lot of active periods for each machine. This leads to continuous and quick shifting of priorities every time. The amount of time each machine occupied priority 1 is showed in figure 4 and figure 5. This means that the primary bottleneck of the machine according to this method has shifted between all the machines. Due to sharing of priority 1 between all the machines, the repair orders have been prioritized to all the machines at unnecessary times. From figure 5 it could be seen, the actual bottleneck of the system, machine M7 has been priority 1 for only about 33% of the entire time. Priority 1 has also been to machine M6 for about 48% of the time, which is clearly not a long-term primary bottleneck machine. These wide shifts in priorities collectively affect the total throughput of the system.

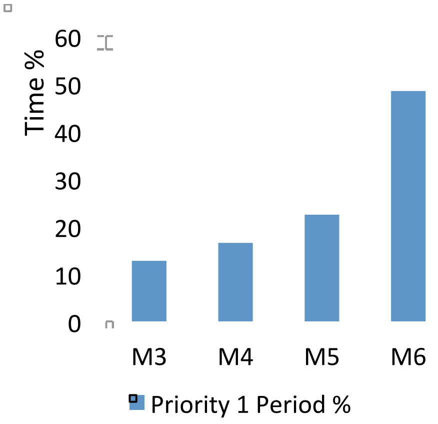

Figure 4: Priority 1 period for O3's machines. (Shifting Priority Method).

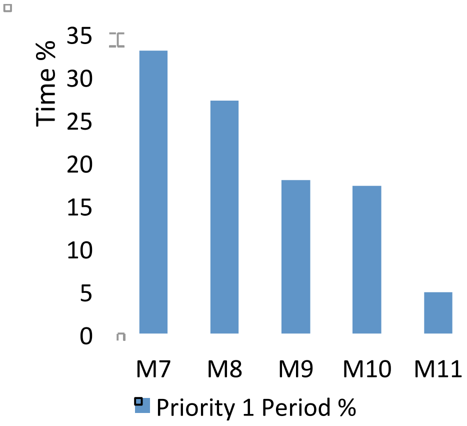

Figure 5: Priority 1 period for O4's machines. (Shifting Priority Method).

The problem of shifting period obviously does not lead to optimal prioritization of machines using this method. Due to concurrent machines having active periods, there is a high chance of shifting periods occurring between two bottleneck machines. By the definition, the current longest active period claims the priorities. Therefore the priority changes only at the end of an active period. But it is questionable at what point of the shifting period, the primary bottleneck change from one machine to the other. This also leads to wrong priorities and therefore reduction in throughput of the system.

The low percentages of priority 1 for the long term critical machines of the system means that the machines have to wait for the majority of the time for the operator to claim the machine for their repair orders. The figure 6 and figure 7 shows the split between utilization, repair, waiting, and blocked/idle percentage periods separately for the two sets of machines for both the operators who handles them.

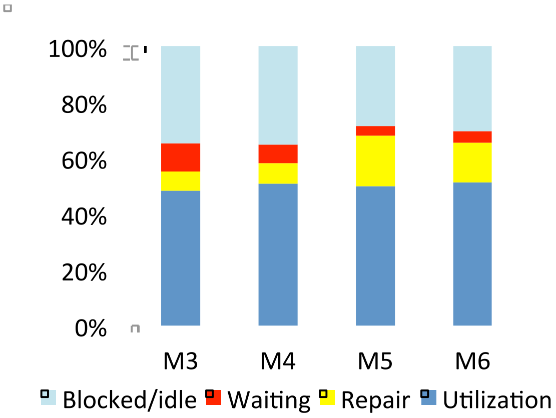

Figure 6: Utilization % for O3's machines. (Shifting Priority Method).

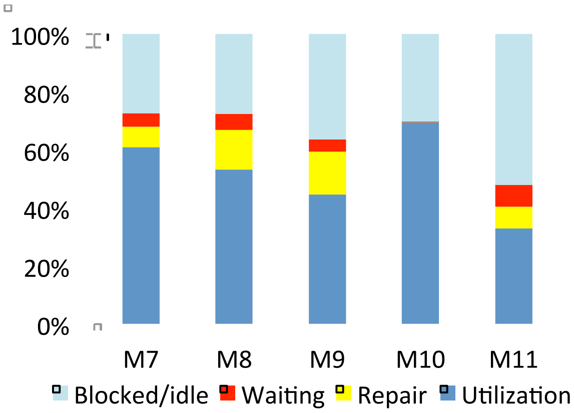

Figure 7: Utilization % for O4's machines. (Shifting Priority Method).

The repair and waiting time in the figure together contributes to the downtime of induvidual machines. It is observed that almost all the machines have waiting times before the repair orders have been executed. This could only happen because the machines were not priority 1 when there was a repair required. It is quite logical to have waiting times for machines before repair but not for the most critical machine of the system. The priorities are set for the purpose of exploiting the bottleneck machine. But the bottleneck machine of the system M7 and bottleneck of first set of machines, M5 have considerable waiting times as well along with other machines. Similar results are shown in figure 8 and figure 9, which are from simulation results of static priority method which shows zero waiting time for the long-term primary bottleneck machines and negligible waiting times for secondary bottlenecks.

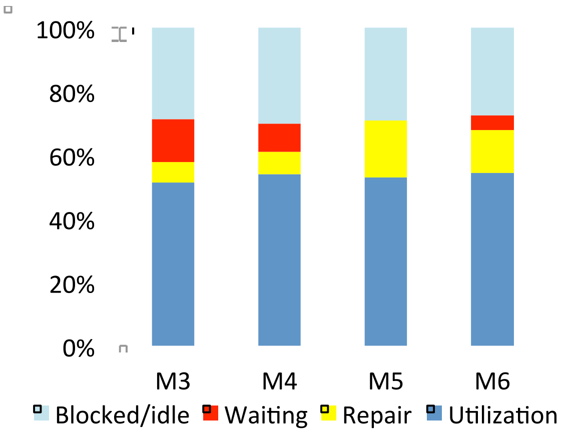

Figure 8: Utilization % for O3's machines.
(Static Priority Method).

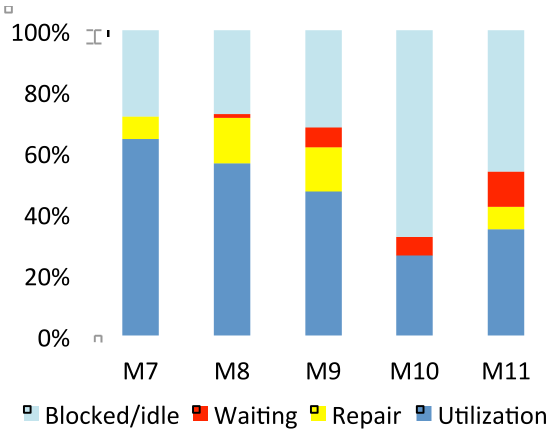

Figure 9: Utilization % for O4's machines.
(Static Priority Method)

It is understood from the shifting bottleneck method (Roser et al. 2002) that the primary bottleneck of the system changes from one machine to another. The idea was to exploit it by chasing the bottleneck machine. Thereby all machines should have waiting times before their repair orders. This momentary bottleneck does not fully represent the long-term bottleneck of the system and therefore the waiting times for the bottleneck machines of the system in this current model is not justified. Comparing the set of figures from static priorities method and shifting priorities method, it is evident that the waiting period percentage of the crital machines is too high and directly reflects in the reduction of throughput of the system in shifting priority method when compared to the base model.

5.3 High capacity machine problem

It can also be observed from the figure 7 (shifting priority method), that machine M10 has really high utilization in comparison to the utilization of M10 in figure 9. It is as close to the primary bottleneck of the system machine M7. The machine M10 is a high capacity machine (capacity 100). It is considered to be working as soon as the first part enters the machine and works as long as the last part moves out of the system. This leads to very less blocked/idle time and therefore this machine has a longer active period compared to single capacity machines and thus the high utilization percentage. Due to this longer active period this machine claims priority 1 for about 23% period of time. But this is definitely not a bottleneck of the system but it is being prioritized based on its active period percentage. This is a drawback of this shifting bottleneck detection method, as it does not consider the machine capacity. This untrue prioritizing of machine M10 leads to prioritizing repair orders for this machine despite of it producing a large number of parts due to its capacity. This grabs priority 1 from other critical machines of the system and contributes highly towards reduction of the overall throughput of the system.

6 DISCUSSION AND FUTURE STEPS

From this study it is clear that prioritizing the momentary bottleneck for the priority-based approach for planning reactive maintenance activities is not the best strategy. For example, the static priority method proved to have much higher improvement relative to the reference model. In this case-study the shifting priority method yielded 1.31% improved throughput and the static priority method yielded 5.1% improved throughput. By nature, the production system is dynamic. The bottleneck of the production system cannot continue to be the same throughout the entire period. Different machines in the production system will cause constraint to the system at different times. In this shifting priorities method, the shift in priorities happens too quickly and too many times, in reality the constraint changes but not as quickly as this method suggests. This is the highest level of dynamic shifting of priorities and the static shifting described is a highest level in static priorities. From the results described in this paper, momentary bottleneck despite representing the system constraint momentarily at any given time does not exactly represent the overall system constrain. The maintenance planning needs to be more strategic than just prioritizing the momentary bottleneck. Knowledge about the long-term bottleneck of the system and its exact period is important in exploiting it. That is the reason the authors think the highest throughput solution lies somewhere between complete static and complete dynamic methods. The current hypothesis is that there is a distribution of improvement in throughput between highest levels of static and dynamic. The figure 10 explains the idea. There is a possibility to find the right amount of dynamics to apply shifting priority to find the highest improvement of throughput. Few scenarios for further research are described and discussed below for the shifting priority method which could lead to better results than the shifting priority method.

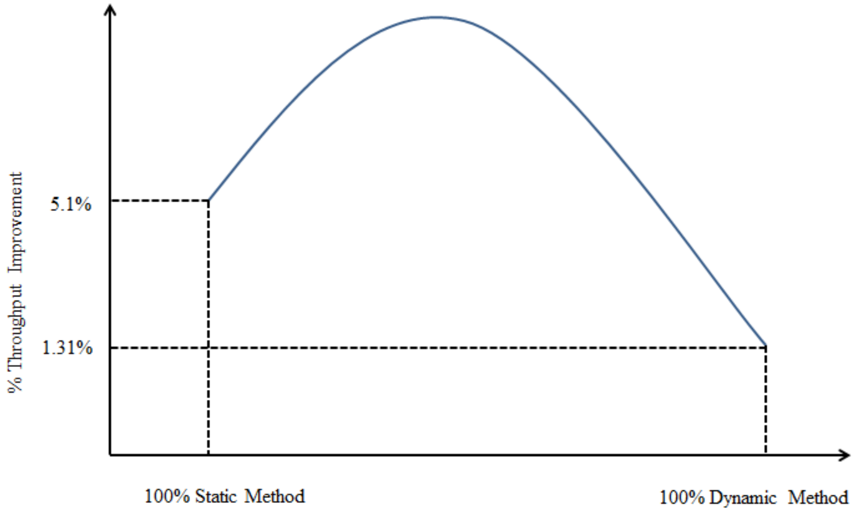

Figure 10: The assumed throughput distribution between static and dynamic methods.

6.1 Scenario 1: Shifting bottleneck method

The shifting bottleneck method described in (Roser et al. 2002) was tried to implement in this paper, but it was not possible to know the future at any given time in order to determine the longest active period during the simulation run. But it could be implemented with identifying some sort of smart forecasting technique to find longest active period during the simulation run. Another method is to consider the longest active period in the history of simulation run till the current point for comparison between machines instead of comparing just the current active period lengths of machines.

6.2 Scenario 2: Combined static and dynamic method

Instead of continuous updates of priorities, priorities could be set for intervals of time. Therefore there will be shift in priorities only once for machines at the end of every period (example: 1 day period). Therefore the bottleneck is static for each period of time and new bottleneck assessment is done to shift priorities at the end of each period of time, makes it dynamic as well.

6.3 Scenario 3: Buffer capacity method

Another method is to find the bottleneck of the system using the current level of buffer capacity of the machines. The machine before the buffer which has the current least capacity will need to produce higher than the other. This machine will constrain the system as this could lead other machines to starve. Therefore it will be the bottleneck and claims priority 1. Similarly the machine before the buffer which has maximum current capacity could lead the machine go blocked, therefore it could have the last priority.

By smart way of working around the production system, it is possible to improve the system throughput without investment on the personnel or equipment, and also without changing the current repair times and failure times using a thorough bottleneck analysis. What would be necessary is a decision support tool to trace the current bottleneck, alert the operators and assign the priorities.

7 CONCLUSION

This paper discusses the approach for improvement of productivity by comparing different maintenance planning strategies for manufacturing industries. A dynamic method of shifting priorities for repair orders is compared with a static method and a current state (reference) model. The case is validated using an automotive case study and the productivity improvement is 1.3% on average for the dynamic method. This is compared with the static priority method which showed 5.1% productivity improvement. The rationing of the differences between the two methods is presented. With accordance to these results the future studies using simulation-based approach could be based on finding the right amount of dynamics to attain the highest productivity improvement without any additional efforts.

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