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MULTI CRITERIA PREVENTIVE MAINTENANCE SCHEDULING THROUGH ARENA BASED SIMULATION MODELING

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ABSTRACT

Line performance and equipment utilization have been major points of interest for many companies due to their direct impact on productivity. Achieving the highest possible utilization while maximizing throughput will improve the line performance; will also show significant increase on the line productivity. There are many variables that affect the line utilization and performance and preventive maintenance schedule is one of them. In this paper a multi criteria decision making approach will be implemented to select the preventive maintenance schedule that gives the best utility and performance values. To demonstrate the selection process a bread packaging line is used as a case study. Environmental conditions and line behavior are developed and simulated by using an Arena-based simulation model. The Arena model is to be used as a support tool for the multi criteria decision making process.

1 INTRODUCTION

The importance of line performance and utilization was increased as competitiveness of the global market place is forcing companies to look for ways to more efficiently utilize their existing production lines especially when considering new product introduction. Even though increasing line utilization and performance can be done through various costly ways such as; replacing the existing machines and stations with new ones, it is not always financially feasible to replace the whole line.
Instead companies have started to look into improving the reliability of the existing line so that the downtimes are minimum and the machine reliability levels are under control. One way to do that is to focus on the preventive maintenance scheduling. Dekker (1996) summarized the maintenance objectives under four headings as: ensuring system function (availability, efficiency and production quality), ensuring system life (asset management), ensuring safety and ensuring human well-being; and suggested that for production equipment, ensuring the system function should be the prime objective where the prime maintenance objective is to provide the right reliability, availability, efficiency and capability. Among those objectives, providing the right system reliability gained more importance, the first Reliability Centered Maintenance (RCM) approach was developed and published by Matteson, Nowlan, Heap and several other United Airlines engineers with a goal of achieving the optimum maintenance needs for an aircraft. Production scheduling and preventive maintenance (PM) planning decisions and activities are inter-dependent, even though most of the time they are performed independently (Cassady and Kutanoglu 2003, 2005). With the goal of obtaining optimum preventive maintenance (PM) scheduling researchers have utilized queuing theory approaches when determining the order of maintenance in a manufacturing line, such as; first in first out (FIFO), last in first out (LIFO), serve in random order (SIRO), and priority queuing (PQ). Priority queuing lead engineers to develop priority based maintenance schedules. A system value based method (SVB) was proposed by (Yang et al. 2007) where value of the system is being measured by the shortest time to finish for each station, and the “value” of the stations close to the end of the line are higher than the ones in the beginning of the line. With this approach, they assigned preventive maintenance priorities to each station and machine. The station with the highest value was the first machine to get preventive maintenance.

Setting up a schedule for a production line is not always easy. Predicting the outcome of the scheduling without running the line creates a certain level of uncertainty for the design engineers. Newer technological developments have enabled the use of simulation models to test the performance of the manufacturing lines even before they exist, and define and implement the scheduling. Various researchers have reported significant benefits from the use of simulation based models for process improvement, scheduling, and scenario comparisons. In a recent study (Adams et al. 1999) two case studies are examined to show how simulation supports the continuous process improvement. A real world semiconductor example was discussed to highlight the extra benefits received from implementing simulation at a semiconductor manufacturing plant (Hickie and Fowler 1999). In Harrell and Gladwin (2007) an application was presented in which simulation was used to identify the bottleneck of a dishwasher tub manufacturing line, where the engineers were then able to determine and verify a solution to the bottleneck which resulted in an annual savings of $275,000. There are different ways of building and performing simulations. A recent study (Al-Aomar 2000) stated that with the aid of discrete-event simulations, companies were able to design efficient production and business systems, validate and tradeoff proposed design solution alternatives, troubleshoot potential problems, improve system performance metrics, and, consequently, cut cost, meet targets, and boost sales and profits. An outline was provided in their study by Knoll and Heim (2000) for the companies to determine if or when they need to adapt discrete-event simulation in their manufacturing environments. In a discrete event simulation model (Sharda and Bury 2008) which was developed to identify and understand the impact of different failures on the overall production capabilities in a chemical plant, concluded that the present work shows the potential of discrete event simulation for such applications. In Chong, Sivakumar, and Gay (2003) a simulation-based real-time manufacturing mechanism for dynamic discrete manufacturing was presented, where the basic idea of the mechanism is to engage discrete event simulation to combine different scheduling approaches based on the past performance. A real-world application of the iterative use of simulation results as an input to scheduling was presented by (Vasudevan et al. 2008), where the schedules generated used as a simulation input parameter, where iterative use of simulation and scheduling presented a powerful technique for making all-round productivity improvement recommendations. Johansson and Kaiser (2002) examined that to what extent discrete event simulation can be applied to the evaluation of resetting performance in manufacturing systems, where a discrete event simulation model of a factory unit in Sweden is used as a case study; their outcomes suggested that there is a large potential to increase the productivity in the manufacturing model by implementing the findings from the discrete event simulation model into the manufacturing system. Seppanen (2005) described an Arena-based operator-paced assembly line simulation model, where the model presented demonstrated the feasibility of including intermittent operator duties in addition to the standard assembly line paced duties. In Kelton, Sadowski and Sadowski (2002) several case studies provided for discrete event simulation processes in their book along with techniques and tutorials on building Arena models. Production engineers and managers benefit from the simulation applications as they mimic the line behavior, to perform extended analyses and to compare different scenarios. This is clearly illustrated by McLean and Shao (2003), where they stated that manufacturing managers commission simulation case studies to support their decision-making processes.

The objective of the study presented in this paper is to benefit from discrete event simulations to assess different preventive maintenance scheduling techniques, and to incorporate simulations as a decision-making support tool to the decision process. In this paper, the authors consider the outcomes of three different preventive maintenance techniques for a packaging line. Arena simulation software is used throughout the study to define the packaging line machines' characteristic and to mimic the line behavior under different preventive maintenance schedules given different reliability constraints. The outcome results from all three preventive maintenance techniques are then compared with respect to system criteria to obtain the most suitable preventive maintenance technique for the case study.

2 SIMULATION BASED PREVENTIVE MAINTENANCE SCHEDULE DEVELOPMENT

The purpose of this case study is to provide a decision-making method when selecting the preventive maintenance schedule and to demonstrate how the Arena software's packaging module can be used to simulate and analyze an existing packaging line, including how the simulation model is prepared and run and how the outcomes of the simulation process can be used as an input data for preventive maintenance schedule selection. A bread manufacturing facility is used as a demonstrative example. The performance of the equipment will be individually examined as their reliability levels are individually set for each of the different preventive maintenance schedules. The line is made up of series and parallel connected packaging machines as shown in Figure 1. The bread loaves arrive to the packaging line, and go to the slicer station (station one). After they are sliced, they move to the shrink wrap (station two) station. Shrink wrapping is a crucial process in keeping the freshness of the bread for longer periods. The shrink wrap machine uses a food grade film, takes the sliced bread loaves in and discharges a fully wrapped package. Once the shrink wrap process is completed, the sliced and wrapped bread loaves arrive to the weighting stations (stations three and four). In this packaging facility there are two weighting stations connected in parallel to each other. The incoming parts either go to station three or four based on availability. The weighting station weights each loaf and marks the weight values on the shrink wrap as well as records the data for future statistical analysis and results. Once the loaves are weighted then they are transferred to the vertical filling station (station five), where they are vertically inserted into the plastic bags. Once the loaves are inserted into the plastic bags, they leave the vertical filling station and arrive to the sealing stations (station six and seven). Like the weighting stations, sealing machines are also parallel connected. Once the plastic bags are sealed, they are moved to the last station in the line, the labeling and boxing station (station eight). In the labeling station, nutritional information, expiration date, barcode, company name and brand name along with the facts and standards are printed on the packages. Once the loaves got labeled, they are placed in cartoons that held 12 bags each, and once they are boxed, they leave the packaging line for shipment.

In this packaging process, due to machine failures and preventive maintenance stoppages, lines can form in between the stations. In any case when a line forms, the parts follow the first in first out (FIFO) queuing theory principle. There are also two buffers located in this system, with a fixed buffer capacity.

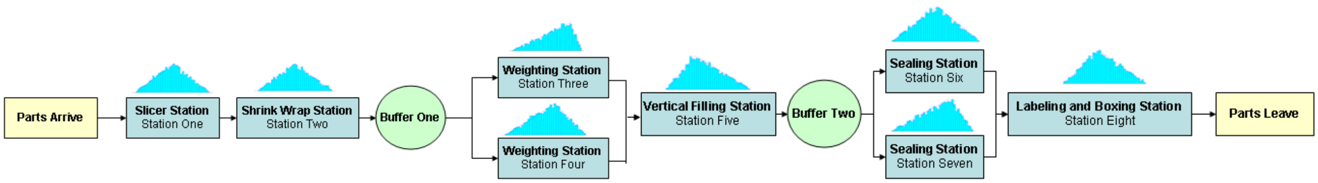

Figure 1: Bread packaging line layout

2.1 Problem Definition

Proper preventive maintenance schedules in production lines require high attention as they have major impacts on line performance, reliability and utilization. There are different approaches of setting a preventive maintenance schedules leading to different performance, reliability and utilization levels. For this example case, three different preventive maintenance scheduling and ordering methods are being considered: Global Maintenance Order (GMO), Reliability Maintenance Order (RMO) and Value-Based Maintenance Order (VMO). To quantify the outcomes of each approach, and to observe the line behavior an Arena-based simulation model will be built and run for each preventive maintenance scheduling technique. The outcomes (performance, utilization, time and cost) of the three techniques will then be compared and a multi criteria decision making analysis to facilitate the selection of the most desirable preventive maintenance (PM) scheduling technique. Each PM techniques will be run for three different minimum allowable reliability levels; 85%, 90% and 95%. These are the reliability levels required for each individual station to reach before undergoing a scheduled PM. Difference in reliability levels will lead to differences in the time needed between PMs, which ,in turn, change the overall line reliability, line performance, utilization, cost and time parameters. Considering different reliability levels will provide an insight on how the line responds to that particular PM technique and will provide more broader data when performing a multi criteria decision making process to select which PM technique should be used for the considered packaging line.

Global Maintenance Order (GMO): The basic assumption of the GMO is to stop the packaging line altogether and perform preventive maintenance on each station whenever scheduling dictates such an action. Once preventive maintenance is completed at all the stations, then the line starts again and runs until the next scheduled preventive maintenance stoppage. The order of the maintenance does not matter, since none of the machines start working until the PM is over.

Reliability-Based Maintenance Order (RMO): Reliability-Based Maintenance Order (RMO) assigns preventive maintenance schedules and order depending on the station reliability levels. The method assumes that all station carry 100% (or any other value) reliability when the line first starts and decreases over time with a probabilistic distribution (which could be specified separately for each station). The design engineer sets the minimum acceptable reliability level for all stations individually, and stations go under preventive maintenance as they reach their minimum allowable reliability level. Since stations in a production line may have different probabilistic distributions attached to them, and since processing time for each station may be different, the line doesn't get stopped all at once. The order of maintenance is dependent on the machine reliability and time to perform PM. Machine reliabilities for any given time will be calculated using Equation 1, where R(t) denotes the reliability of a station at time t, where λ is the distribution parameter and can be obtained from station's lifetime as shown in Equation 2. Mean Time to Fail (MTTF) denotes the mean time before a station fails and based on machine's life time distributions and time between failures. Once the individual station reliabilities are obtained, the overall system reliability can be calculated by using Equation 3.

$$R(t) = e^{-\int_0^t \lambda dt} \quad (1)$$

$$R(t) = e^{-\lambda t}$$

$$MTTF = \frac{1}{\lambda} \quad (2)$$

$$R_{line} = R_1 * R_2 * (1-(1-R_3)*(1-R_4)) * R_5 * (1-(1-R_6)*(1-R_7)) * R_8 \quad (3)$$

Value-Based Maintenance Order (VMO): Value-Based Maintenance Order (VMO) is built based on the value method, where each station carries a value. The station values can be defined and calculated differently for different applications, such as; time to finish, processing time, good units produced, etc.... Generally the station close to the end of line is assumed to carry higher values then the stations close to the beginning of the line. Final station value (V_i) is calculated by subtracting the product of Total Parts Lost (TPL) in that station and the penalty value for each lost product from the product of Total Parts Processed (TPP) in that station and the value of each part reach that station, as shown in Equation 4.

$$V_i = (TPP\_in\_Station)_i * (Value\_of\_Station)_i - (TPL\_in\_Station)_i * (Penalty\_Value\_of\_Station)_i \quad (4)$$

2.2 Building the Model

In order to generate results for the different maintenance approaches, a computer based simulation model is used. Even though there are various software available to carry the needed simulation, the Arena simulation software package provided (Arena's Factory Analyzer module offers the Packaging template) the most suitable templates for the case study at hand. The Arena model, shown in Figure 2, is built based on the facility layout provided in Figure 1. All packaging stations are built using the machine module (line start, process and line stop), where the "Parts Arrive" and "Parts Leave" signify the beginning of the line and end of the line, respectively. By using the machine module, each station's reliability along with failure distributions, repair times, number of units lost after failures as well as scheduled stops (time before stop and stop duration) for preventive maintenance can be defined, as shown in Figure 3. Machine links are used to link any two machines together in the layout, they do not carry any properties, and they do not affect the outcome result. The model, involves two buffers, both of which are defined via the Conveyor module. Since the Arena Packaging Template does not offer buffer modules, a conveyor module is employed to mimic the behavior of a buffer by appropriately adjusting its size and speed as shown in Figure 4 (Regions A&B of Figure 2). The material handling portions of the line are modeled using the conveyor module, where the run speed and conveyor properties are defined accordingly. Before each of the parallel connected station sets, a split module is used to divide the incoming parts into two. An adjustable splitting option is selected to maximize the system performance and utilization for both split stations. Once the parts leave the parallel connected stations, they are combined together with the Merge module. Finally a separate simulation module is placed in the model, to trigger the simulation for the packaging line simulation. This module helps the design engineer to determine which statistics will be measured, for this case study machines and conveyors statistics will be collected. Prior to running the simulation, run parameters are defined; no warm up period is defined for any of the machines, and the replication length is set to 3840 hours, which equals to one year's processing times for the machines, 20 days/monthly, 2 shifts/daily, and 8 hours/shift. To be able to properly observe the change in the equipment reliabilities and line behavior, instead of using replications, a single run has been used. The main benefit from doing so is that it avoids any simulation interruption due to replication length and also enables the user to define the simulation as a single process as it would be in the real packaging line, rather than replication. Once the simulation run is completed and the results are obtained, Arena provides a report (Run Overview Report) that enables the user to see how the line performance, line utilization, input/output ratio along with the reliability and cost have changed.

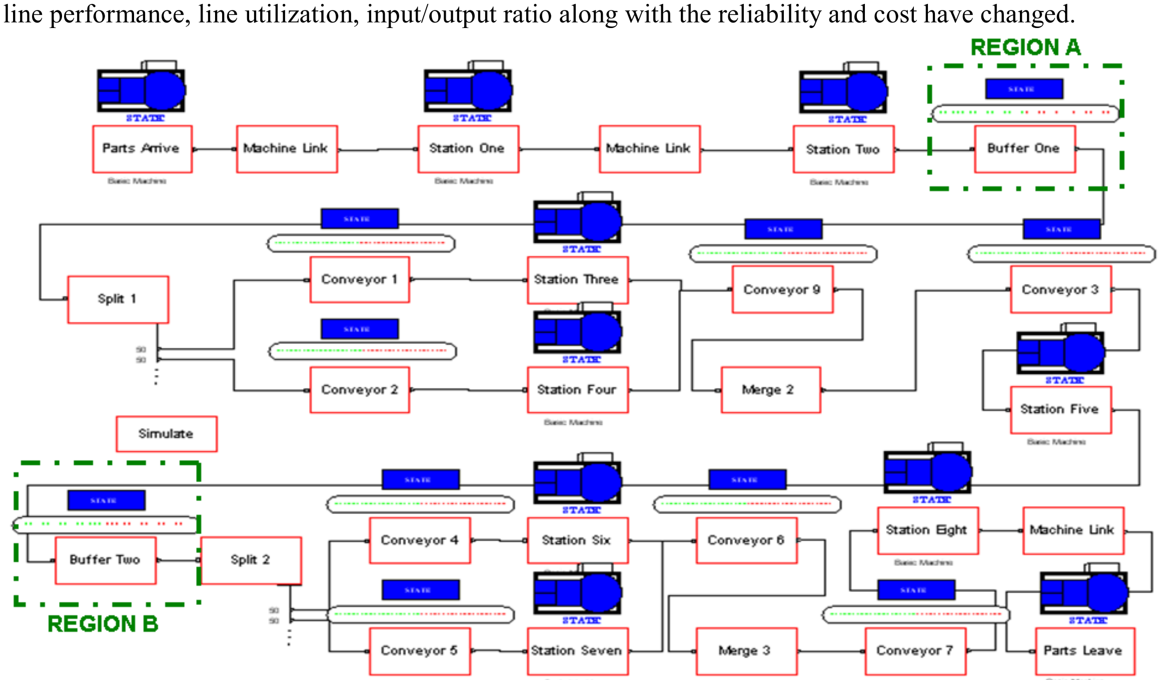

Figure 2: Arena-based model of the bread packaging facility

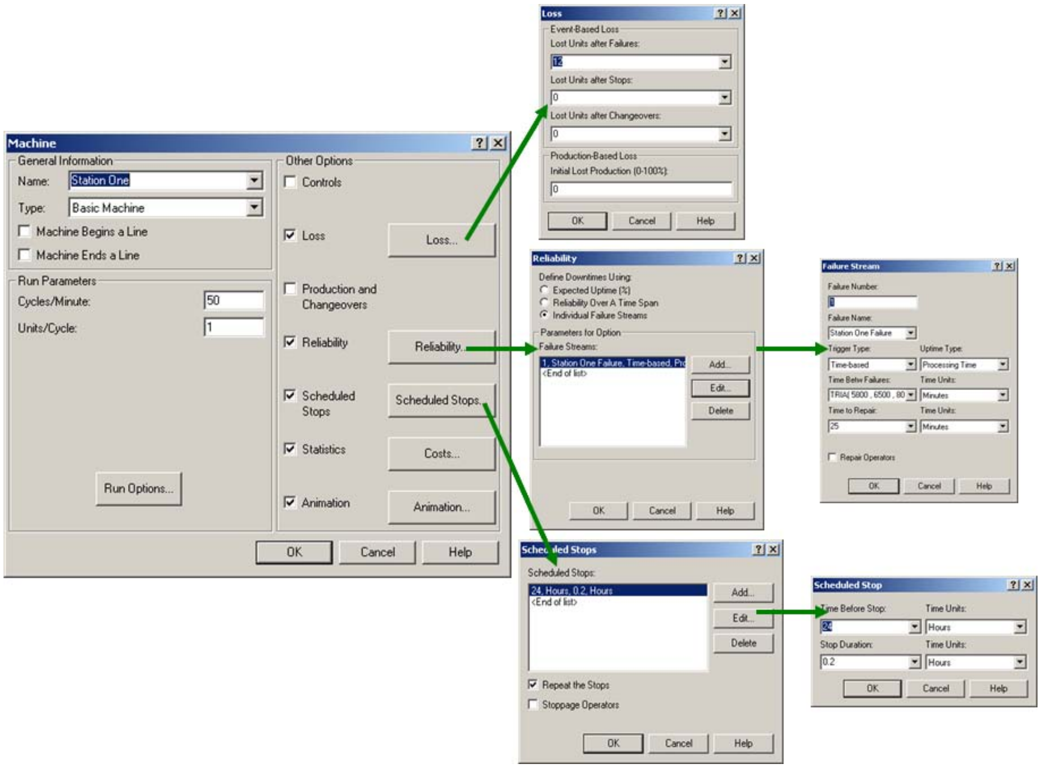

Figure 3: Building the station modules in Arena

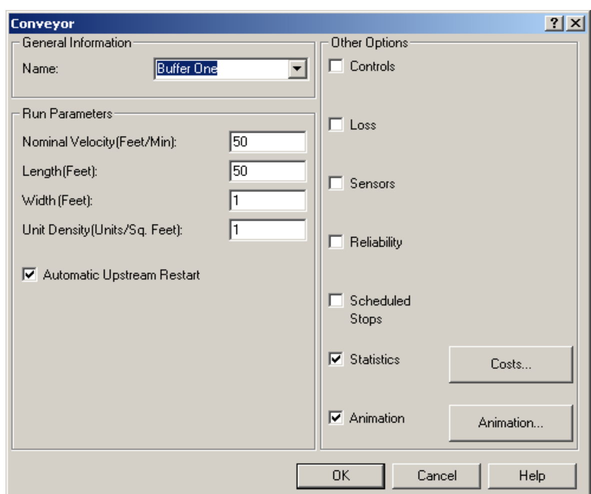

Figure 4: Building the Buffer Using a Conveyor Module

Data Generation: Recalling that the operating principle of GMO is to stop the packaging line all at once for a certain period of time and perform preventive maintenance, the imposed constraint for this example is that no station should fall below the 85%, 90% and 95% reliability levels, for the three consecutive scenarios that were conducted. The line's stoppage times for each reliability level is different and shown in Table 1. The maintenance schedule row of Table 1 indicates that Station 4 is the first station to reach the imposed reliability constraints, therefore all the other stations follow the time pattern and go under PM when station 4 reaches 85%, 90% and 95% reliability levels at 5th, 10th, and 16th hours respectively.

Table 1: System and run parameters of the GMO for the Arena model

		Parts Arrive	Station One	Station Two	Buffe r One	Station Three	Station Four	Station Five	Buffer Two	Station Six	Station Seven	Station Eight	Parts Leave
Run Parameters	Cycles/Minute	50	50	50	N/A	50	50	50	N/A	50	50	50	50
	Units/Cycle	1	1	1		1	1	1		1	1	1	1
	Trigger Type	Processing Time											
Reliability Failure and Maintenance Parameters	Time Between Failures (minutes)	N/A	TRIA(5800,6500,8000)	TRIA(8000,9000,10000)	N/A	TRIA(7450,8150,8300)	TRIA(5000,6200,7000)	TRIA(11000,12000,14000)	N/A	TRIA(9000,9100,9200)	TRIA(8760,11000,11900)	TRIA(6850,9000,12000)	N/A
	Time To Repair for CM	N/A	0.42h	0.82h	N/A	0.48h	0.65h	0.63h	N/A	0.75h	1.00h	0.37h	N/A
	Maintenance Schedule	N/A	16h (85%) 10h (90%) 5h (95%)	16h (85%) 10h (90%) 5h (95%)	N/A	16h (85%) 10h (90%) 5h (95%)	16h (85%) 10h (90%) 5h (95%)	16h (85%) 10h (90%) 5h (95%)	N/A	16h (85%) 10h (90%) 5h (95%)	16h (85%) 10h (90%) 5h (95%)	16h (85%) 10h (90%) 5h (95%)	N/A
	Scheduled Stop for PM	N/A	2h	2h	N/A	2h	2h	2h	N/A	2h	2h	2h	N/A
Unit Loss Parameters	Loss Units After Failures	N/A	12	14	N/A	17	10	9	N/A	12	12	18	N/A
	Lost Units After Stops		0	0		0	0	0		0	0	0	
Buffer Parameters	Buffer Capacity	N/A	N/A	N/A	50	N/A	N/A	N/A	50	N/A	N/A	N/A	N/A

Under the RMO preventive maintenance scheme every time a station's reliability hits the 85%, 90% and 95% mark for the three scenarios under consideration, the station will be stopped and a preventive maintenance will be performed. Once the preventive maintenance for that station is completed, the station will resume operation with a 100% reliability. The maintenance row of Table 2 provides a listing of when each station reaches the constraint reliability level, and how long it will be stopped for PM.

Table 2: System and run parameters of the RMO for the Arena model

		Parts Arrive	Station One	Station Two	Buffe r One	Station Three	Station Four	Station Five	Buffer Two	Station Six	Station Seven	Station Eight	Parts Leave
Run Parameters	Cycles/Minute	50	50	50	N/A	50	50	50	N/A	50	50	50	50
	Units/Cycle	1	1	1		1	1	1		1	1	1	1
	Trigger Type	Processing Time											
Reliability Failure and Maintenance Parameters	Time Between Failures (minutes)	N/A	TRIA(5800,6500,8000)	TRIA(8000,9000,10000)	N/A	TRIA(7450,8150,8300)	TRIA(5000,6200,7000)	TRIA(11000,12000,14000)	N/A	TRIA(9000,9100,9200)	TRIA(8760,11000,11900)	TRIA(6850,9000,12000)	N/A
	Time To Repair for CM	N/A	0.42h	0.82h	N/A	0.48h	0.65h	0.63h	N/A	0.75h	1.00h	0.37h	N/A
	Maintenance Schedule	N/A	17h (85%) 11h (90%) 5h (95%)	24h (85%) 15h (90%) 7h (95%)	N/A	22h (85%) 14h (90%) 6h (95%)	16h (85%) 10h (90%) 5h (95%)	32h (85%) 21h (90%) 10h (95%)	N/A	24h (85%) 15h (90%) 7h (95%)	29h (85%) 19h (90%) 9h (95%)	24h (85%) 15h (90%) 7h (95%)	N/A
	Scheduled Stop for PM	N/A	0.2h	0.27h	N/A	0.16h	0.13h	0.24h	N/A	0.18h	0.22h	0.18h	N/A
Unit Loss Parameters	Loss Units After Failures	N/A	12	14	N/A	17	10	9	N/A	12	12	18	N/A
	Lost Units After Stops		0	0		0	0	0		0	0	0	
Buffer Parameters	Buffer Capacity	N/A	N/A	N/A	50	N/A	N/A	N/A	50	N/A	N/A	N/A	N/A

Recalling that in the VMO scheme the closer the part to the end of the line when it is damaged, the higher penalty value will be associated with that lost, preference to maintenance is given to stations that are closest to the end of the line as their reliability approaches the minimum acceptable level. Running the simulation without any PM schedule and applying Equation 4 on the results will provide an order in which the PM should be performed. For the bread packaging line at hand, the order of maintenance is calculated from first through last as: S8, S7, S5, S4, S2, S1, S6, and S3. Once the order of maintenance is obtained then the VMO preventive maintenance schedule can be set as shown in Table 3, for all three reliability constraint scenarios (85%, 90%, 95%).

Table 3: System and run parameters of the VMO for the Arena model

		Parts Arrive	Station One	Station Two	Buffer One	Station Three	Station Four	Station Five	Buffer Two	Station Six	Station Seven	Station Eight	Parts Leave
Run Parameters	Cycles/Minute	50	50	50	N/A	50	50	50	N/A	50	50	50	50
	Units/Cycle	1	1	1		1	1	1		1	1	1	1
	Trigger Type	Processing Time											
Reliability Failure and Maintenance Parameters	Time Between Failures (minutes)	N/A	TRIA(5800,6500,8000)	TRIA(8000,9000,10000)	N/A	TRIA(7450,8150,8300)	TRIA(5000,6200,7000)	TRIA(11000,12000,14000)	N/A	TRIA(9000,9100,9200)	TRIA(8760,11000,11900)	TRIA(6850,9000,12000)	N/A
	Time To Repair for CM	N/A	0.42h	0.82h	N/A	0.48h	0.65h	0.63h	N/A	0.75h	1.00h	0.37h	N/A
	Maintenance Schedule	N/A	25.04h (85%) 16.04h (90%) 8.04h (95%)	24.77h (85%) 15.77h (90%) 7.77h (95%)	N/A	25.42h (85%) 16.42h (90%) 8.42h (95%)	24.64h (85%) 15.64h (90%) 7.64h (95%)	24.4h (85%) 15.4h (90%) 7.4h (95%)	N/A	25.24h (85%) 16.27h (90%) 8.24h (95%)	24.18h (85%) 15.18h (90%) 7.18h (95%)	24h (85%) 15h (90%) 7h (95%)	N/A
	Scheduled Stop for PM	N/A	0.2h	0.27h	N/A	0.16h	0.13h	0.24h	N/A	0.18h	0.22h	0.18h	N/A
Unit Loss Parameters	Loss Units After Failures	N/A	12	14	N/A	17	10	9	N/A	12	12	18	N/A
	Lost Units After Stops		0	0		0	0	0		0	0	0	
Buffer Parameters	Buffer Capacity	N/A	N/A	N/A	50	N/A	N/A	N/A	50	N/A	N/A	N/A	N/A

Once the input tables are built for all three scenarios (85%, 90% and 95%) for the three preventive maintenance schedule orders under consideration simulations can be run. Simulation results will be examined under several comparison criteria. For this case study, Table 4 lists the calculation and formulation for the four major criteria namely: performance (performance index, average output factor, and average output rate), usage (utilization), time (total time blocked and total time starved) and cost (equipment operating cost, cost of good product, and cost of lost product) that will be used to determine the most appropriate preventive maintenance scheduling scheme.

Table 4: Evaluation Criteria for the Three Scenarios (85%, 90%, 95%) under consideration

Performance Index (PI)	$PI = \frac{(Yield)*(Utilization)*(Average\_Output\_Factor)}{100}$
Average Output Factor (AOF)	The ratio of the Average Output Rate greater than zero statistic to the nominal run speed of the machine
Average Output Rate (AOR)	The average output rate of the machine when the output rate was greater than zero
Utilization (U)	$Utilization = \frac{(Total\_Time\_Output\_Rate\_Greater\_Than\_0)}{(Simulation\_Run\_Length - Total\_Time\_Stopped)}$
Total Time Blocked (TTB)	The total time the machine was in the *Blocked* state
Total Time Starved (TTS)	The total time the machine was in the *Fast*, *Working*, or *Slow* state but was starved
Equipment Operating Cost (EOC)	$EOC = ((Simulation\_Run\_Length) - (Total\_Time\_Stopped)) * (Cost / Hour)$
Cost of Good Product (CGP)	$CGP = (Total\_Good\_Units\_Produced) * (Cost / Good\_Unit)$
Cost of Lost Product (CLP)	$CLP = (Total\_Units\_Lost) * (Cost / Lost\_Unit)$

2.3 Simulation Results

Once the simulation runs are completed, the overall line behavior can be monitored through the output values (evaluation criteria) and overall line reliability which can be calculated using Equation 3. The simulation outcomes of the three scenarios are collected in four different evaluation criteria categories as: performance (performance index, average output factor and average output rate), usage (utilization), time (total time blocked and total time starved) and cost (equipment operating cost, cost of good product and cost of lost product). Sample criteria outcomes from each category are provided in Tables 5, 6, 7, and 8 as an example to demonstrate the data collection from simulation outputs. Table 5 provides the outcomes for the Performance Index (PI) criterion, which measures and evaluates system performance, Table 6 provides the outcomes for the Utilization (U) value for every station, which denotes system efficiency. Table 7 provides the outcomes for Total Time Blocked (TTB), which measures the down times for each station, and Table 8 provides Cost of Good Product (CGP), showing the financial value of the good units produced during the simulation period. The remainder of the criteria are examined in the same fashion, and included in the calculations. A total of nine simulation runs have been performed for three different scenarios (85%, 90% and 95% reliability constraints) for three preventive maintenance techniques.

Table 5: Simulation outcomes for GMO (85%, 90%, 95%), RMO (85%, 90%, 95%) and VMO (85%, 90%, 95%) – PI

Evaluation Criteria	Station Name	GMO - 85%	RMO - 85%	VMO - 85%	Evaluation Criteria	Station Name	GMO - 90%	RMO - 90%	VMO - 90%	Evaluation Criteria	Station Name	GMO - 95%	RMO - 95%	VMO - 95%
	Parts Arrive	44.5831	92.4812	92.7562		Parts Arrive	20.4365	89.7223	90.1118		Parts Arrive	6.134	81.6272	82.8470
	Station One	50.1151	93.5847	93.4932		Station One	24.5076	91.3535	91.2301		Station One	8.5775	84.8735	84.8959
	Station Two	50.1136	93.5143	93.7590		Station Two	24.507	91.3357	91.6463		Station Two	8.5773	84.7629	85.7107
	Station Three	1.7505	0.4115	0.3158		Station Three	1.7571	0.2699	0.1986		Station Three	1.7742	0.1235	0.0944
Performance Index (PI)	Station Four	48.1758	92.8084	92.9188	Performance Index (PI)	Station Four	22.4127	90.6101	90.6501	Performance Index (PI)	Station Four	6.132	83.6129	84.1495
	Station Five	48.1984	92.7525	93.3337		Station Five	22.4305	90.4700	91.3007		Station Five	6.1568	83.4450	85.4172
	Station Six	0.8804	0.4116	0.1559		Station Six	0.8842	0.4350	0.0973		Station Six	0.8942	0.1114	0.0450
	Station Seven	47.2093	92.3402	93.1069		Station Seven	21.3742	90.0397	91.1009		Station Seven	4.9199	83.3660	85.2229
	Station Eight	47.2073	92.3286	92.9542		Station Eight	21.3848	90.0749	90.8717		Station Eight	4.9189	83.4665	84.8137
	Parts Leave	41.9702	91.6447	92.2658		Parts Leave	17.8219	89.0107	89.7983		Parts Leave	3.515	81.3772	82.6907

Table 6: Simulation outcomes for GMO (85%, 90%, 95%), RMO (85%, 90%, 95%) and VMO (85%, 90%, 95%) – U

Evaluation Criteria	Station Name	GMO - 85%	RMO - 85%	VMO - 85%	Evaluation Criteria	Station Name	GMO - 90%	RMO - 90%	VMO - 90%	Evaluation Criteria	Station Name	GMO - 95%	RMO - 95%	VMO - 95%
	Parts Arrive	44.5831	92.4812	92.7562		Parts Arrive	20.4365	89.7293	90.1118		Parts Arrive	6.1340	81.6272	82.8470
	Station One	50.1169	93.5680	93.4964		Station One	24.5085	91.3566	91.2332		Station One	8.5778	84.8763	84.8987
	Station Two	50.1156	93.5178	93.7627		Station Two	24.5078	91.3392	91.6498		Station Two	8.5776	84.7662	85.7138
	Station Three	3.4842	0.8196	0.6316		Station Three	3.4973	0.5331	0.3972		Station Three	3.5314	0.2466	0.1889
Utilization (U)	Station Four	50.1194	93.2237	93.2401	Utilization (U)	Station Four	24.4863	90.8804	90.8540	Utilization (U)	Station Four	8.5572	83.7425	84.2485
	Station Five	50.1372	93.1641	93.6530		Station Five	24.4981	90.7366	91.5028		Station Five	8.5718	83.5712	85.5149
	Station Six	3.4826	1.2255	0.6238		Station Six	3.4918	1.1199	0.3894		Station Six	3.5157	0.3400	0.1811
	Station Seven	50.1283	93.1631	93.5818		Station Seven	24.4858	90.7371	91.3999		Station Seven	8.5504	83.6030	85.3651
	Station Eight	50.1261	93.1532	93.4300		Station Eight	24.4969	90.7725	91.1711		Station Eight	8.5461	83.7052	84.9568
	Parts Leave	44.5637	92.4597	92.7345		Parts Leave	20.4149	89.6968	90.0911		Parts Leave	6.1068	81.6069	82.8272

Table 7: Simulation outcomes for GMO (85%, 90%, 95%), RMO (85%, 90%, 95%) and VMO (85%, 90%, 95%) – TTB

Evaluation Criteria	Station Name	GMO - 85%	RMO - 85%	VMO - 85%	Evaluation Criteria	Station Name	GMO - 90%	RMO - 90%	VMO - 90%	Evaluation Criteria	Station Name	GMO - 95%	RMO - 95%	VMO - 95%
	Parts Arrive	2128.01	288.72	278.16		Parts Arrive	3055.24	394.39	379.71		Parts Arrive	3604.45	705.52	658.68
	Station One	1697.76	231.20	234.84		Station One	2414.32	313.49	320.01		Station One	2509.62	547.26	554.62
	Station Two	1286.76	170.18	174.89		Station Two	1894.23	228.65	236.97		Station Two	1490.80	388.72	410.21
	Station Three	3689.84	3807.88	3815.73		Station Three	3679.69	3818.88	3824.73		Station Three	3653.30	3829.88	3832.73
Total Time Blocked (TTB)	Station Four	869.27	106.28	121.52	Total Time Blocked (TTB)	Station Four	1372.13	143.08	168.66	Total Time Blocked (TTB)	Station Four	462.20	249.40	299.27
	Station Five	470.87	86.81	94.60		Station Five	918.77	119.10	129.93		Station Five	3.25	213.46	236.89
	Station Six	3690.09	3791.64	3815.98		Station Six	3679.94	3794.46	3824.98		Station Six	3653.55	3825.64	3832.98
	Station Seven	57.42	33.84	35.93		Station Seven	447.74	51.09	50.47		Station Seven	0.37	97.50	95.51
	Station Eight	0.00	0.00	0.00		Station Eight	0.00	0.00	0.00		Station Eight	0.00	0.00	0.00
	Parts Leave	0.00	0.00	0.00		Parts Leave	0.00	0.00	0.00		Parts Leave	0.00	0.00	0.00

Table 8: Simulation outcomes for GMO (85%, 90%, 95%), RMO (85%, 90%, 95%)and VMO (85%, 90%, 95%) – CGP

Evaluation Criteria	Station Name	GMO - 85%	RMO - 85%	VMO - 85%	Evaluation Criteria	Station Name	GMO - 90%	RMO - 90%	VMO - 90%	Evaluation Criteria	Station Name	GMO - 95%	RMO - 95%	VMO - 95%
	Parts Arrive	0	0	0		Parts Arrive	0	0	0		Parts Arrive	0.00	0	0
	Station One	20543192	42613856	42740612		Station One	9416804	41345876	41522108		Station One	2826464	37612544	38174632
	Station Two	30813858	63919020	64109070		Station Two	14124864	62017050	62281398		Station Two	4239606	56417136	57260436
	Station Three	1807326	426609	327420		Station Three	1809405	279855	205920		Station Three	1814598	128079	97920
Cost of Good Product (CGP)	Station Four	44411391	95448492	95832657	Cost of Good Product (CGP)	Station Four	19376640	92742372	93212829	Cost of Good Product (CGP)	Station Four	4544001	84494637	85790007
	Station Five	54301302	116661809	117126328		Station Five	23701458	113353900	113924646		Station Five	5575086	103269804	104851417
	Station Six	1818036	853488	323352		Station Six	1821168	901944	201852		Station Six	1829106	230976	93852
	Station Seven	87033096	190039464	191329830		Station Seven	36957672	184577634	186211890		Station Seven	7290162	168747786	171473652
	Station Eight	116039328	253379376	255096456		Station Eight	49274232	246097272	248274264		Station Eight	9718200	224991744	228623280
	Parts Leave	0	0	0		Parts Leave	0	0	0		Parts Leave	0	0	0

As one proceeds with the PM selection process, it is crucial to examine the individual station reliabilities along with overall line reliability for each case. Figure 5 provides the reliability graphics for the "85% station reliability" constraint simulation. When GMO preventive maintenance technique is applied, the line reliability level drops to the 64% mark just prior to maintenance. When RMO preventive maintenance technique is applied, the line reliability level fluctuates between 56% and 95%, As expected, since the line is never stopped all together, the overall line reliability never reaches to 100% as it did in GMO. When VMO preventive maintenance technique is applied, the line reliability level changes between 54% and 98%.

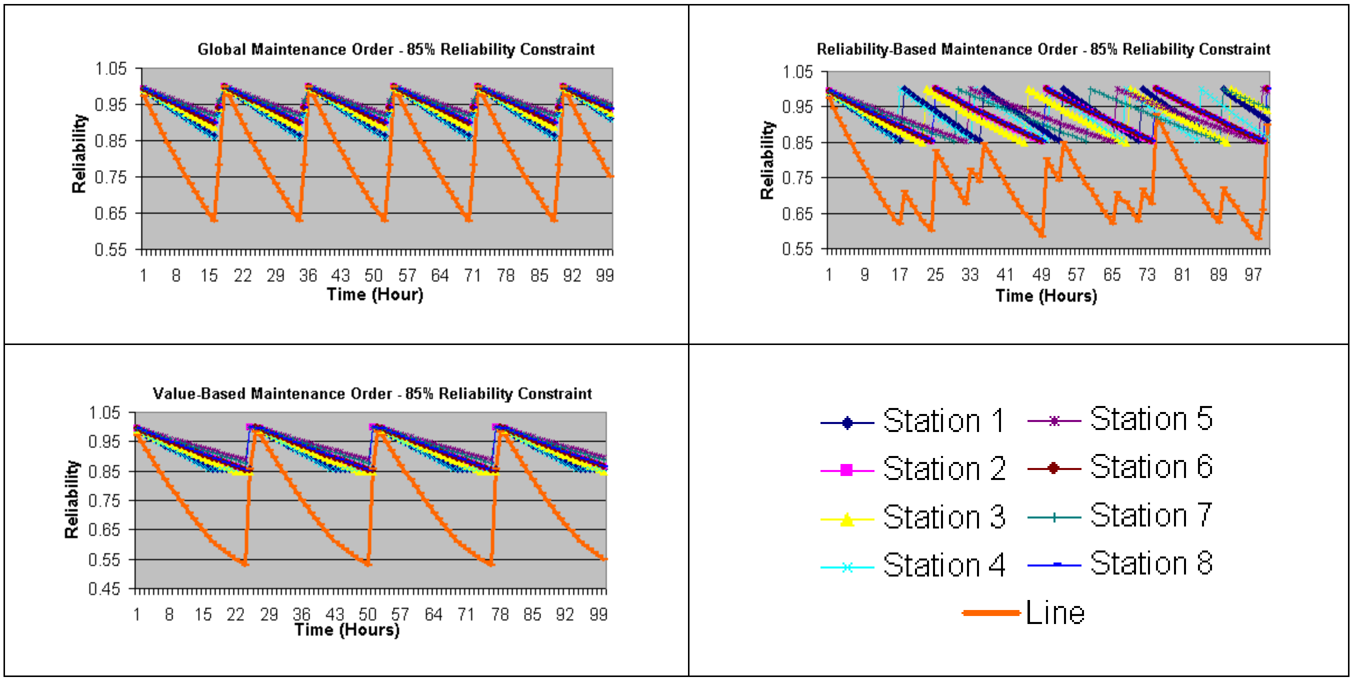

Figure 5: Machine and Line Reliability Results under GMO, RMO, and VMO for 85% Station Reliability Constraint

Figure 6 provides the reliability graphics for the "90% station reliability" constraint simulation. When GMO preventive maintenance technique is applied, the line reliability level is reduced to 75% just prior to maintenance. When RMO preventive maintenance technique is applied, the line reliability level fluctuates between 73% - 97%, not counting the starting point of 100%. When VMO preventive maintenance technique is applied, the line reliability level changes between 69% - 98%.

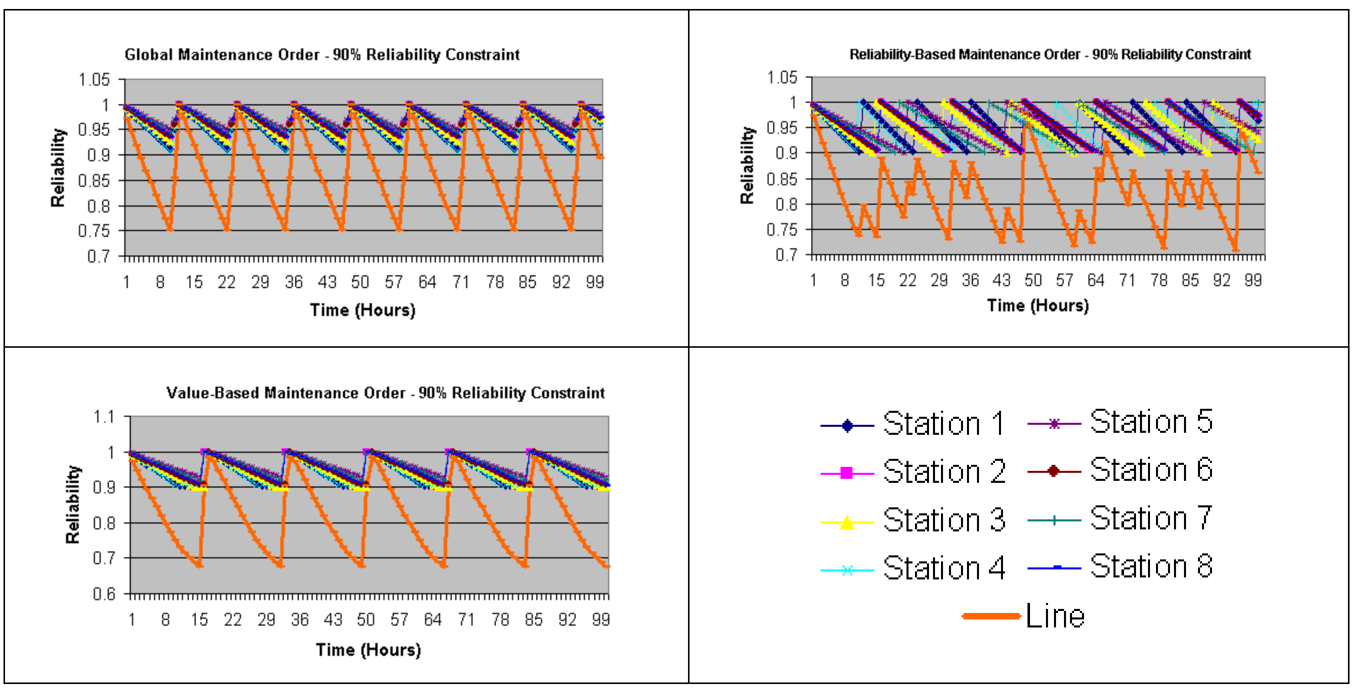

Figure 6: Machine and Line Reliability Results under GMO, RMO, and VMO for 90% Station Reliability Constraint

Figure 7 provides the reliability graphics for the "95% station reliability" constraint simulation. When GMO preventive maintenance technique is applied, the line reliability level changes between 100% and 87%. When RMO preventive maintenance technique is applied, the line reliability level fluctuates between 84% and 97%, not counting the starting point of 100%. When VMO preventive maintenance technique is applied, the line reliability level changes between 84% and 99%.

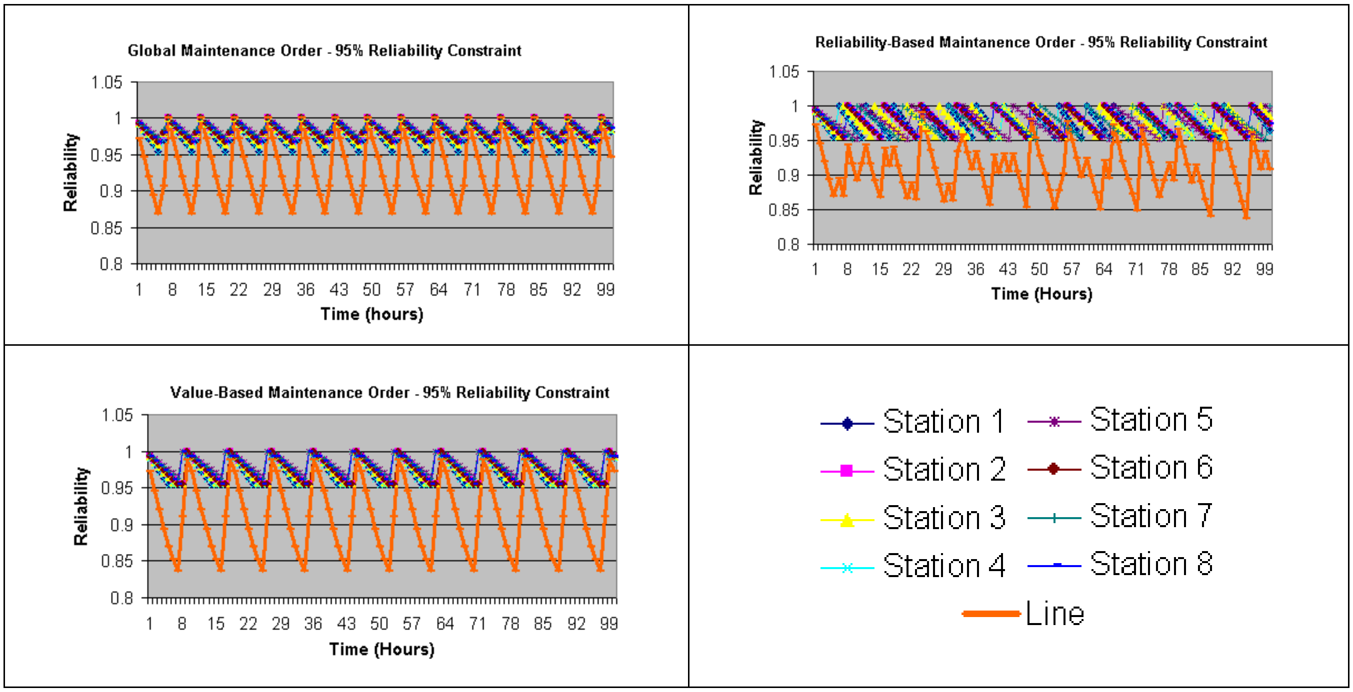

Figure 7: Machine and Line Reliability Results under GMO, RMO, and VMO for 95% Station Reliability Constraint

Performing a selection in between the preventive maintenance techniques solely based on reliability does not provide any insights on the line's performance, utilization or line lead times and bottlenecks. Therefore it is always desirable to consider multiple evaluation criteria when deciding which preventive maintenance method should be used when setting up the PM schedule for a production line. A utility theory based approach (equation 5) will be used for the selection process: where U_i denotes the utility of the i^{th} item, μ_i denotes the weight value of the i^{th} item, and u_i denotes the numerical value of the i^{th} item. The number of evaluation criteria and the extensiveness of said criteria is case specific and changes based on requirements and expectations from that line. The challenge here is to decide the relative importance of each criterion over the others. To overcome that challenge design engineers either define hierarchical rankings or employ rank assessment methods such as: rank sum, rank exponent, rank reciprocal, etc… to calculate weight values. Change in rankings or weight values may result in change in the outcome of the selection process. Once the weight assessment is completed, the preferences for each criterion should be defined. Preference indicates if higher or lower values of a certain criterion is preferred over the others. For the bread packaging case study: for performance index (PI), average output rate (AOR), average output factor (AOF), utilization (U) and cost of good product (CGP) higher values are preferred, where as for total time blocked (TTB), total time starved (TTS) and cost of lost product (CLP) lower values are preferred.

$$U_i = \mu_i * u_i \tag{5}$$

To be able to accurately comment on the selection process, and to be able to see the effects of different hierarchical rankings and different weight values, in this case study four different hierarchical rankings along with different sets of weight values have been considered. These four rankings and their utility outputs are shown in Table 9 as A, B, C and D. Once the utility values for individual stations are obtained, than the overall line utilities can be calculated by simply summing up all stations' utility values. For all four cases (A, B, C, and D), and for all minimum reliability scenarios (85%, 90%, and 95%); it can be seen from Table 9 that, RMO provided the highest overall utility values, suggesting that for the case study at hand and for the scenarios considered using RMO to set up PM schedule will provide higher line performance, higher line utilization, as well as low starvation and blockage times, along with higher number of good products.

Table 9: MCDM Final Utility Values for GMO (85%, 90%, 95%), RMO (85%, 90%, 95%) and VMO (85%, 90%, 95%)

A

Evaluation Criteria	Weight
PI	0.2
AOF	0.15
AOR	0.15
U	0.15
TTB	0.1
TTS	0.1
EOC	0.05
CGP	0.05
CLP	0.05

Station		85%			90%			95%	
No	GMO	RMO	VMO	GMO	RMO	VMO	GMO	RMO	VMO
1	0.20	0.40	0.40	0.21	0.41	0.38	0.20	0.40	0.40
2	0.16	0.42	0.42	0.16	0.42	0.42	0.16	0.42	0.42
3	0.62	0.26	0.12	0.55	0.32	0.13	0.72	0.15	0.13
4	0.03	0.48	0.49	0.02	0.49	0.49	0.03	0.49	0.48
5	0.03	0.48	0.49	0.03	0.48	0.49	0.09	0.45	0.46
6	0.48	0.40	0.12	0.48	0.40	0.12	0.50	0.36	0.14
7	0.03	0.48	0.49	0.03	0.48	0.49	0.09	0.45	0.46
8	0.08	0.45	0.47	0.07	0.46	0.47	0.08	0.46	0.46
SUM U	1.63	3.37	3.00	1.55	3.46	2.99	1.87	3.18	2.95

B

Evaluation Criteria	Weight
PI	0.3
AOF	0.18
AOR	0.18
U	0.13
TTB	0.08
TTS	0.05
EOC	0.04
CGP	0.03
CLP	0.01

Station		85%			90%			95%	
No	GMO	RMO	VMO	GMO	RMO	VMO	GMO	RMO	VMO
1	0.18	0.41	0.41	0.19	0.42	0.39	0.18	0.41	0.41
2	0.16	0.42	0.42	0.16	0.42	0.42	0.16	0.42	0.42
3	0.69	0.34	0.07	0.60	0.34	0.06	0.81	0.14	0.05
4	0.01	0.49	0.50	0.01	0.49	0.50	0.01	0.50	0.49
5	0.01	0.49	0.50	0.01	0.49	0.50	0.05	0.47	0.48
6	0.49	0.46	0.05	0.49	0.46	0.05	0.54	0.40	0.06
7	0.01	0.49	0.50	0.01	0.49	0.50	0.05	0.47	0.48
8	0.05	0.47	0.48	0.05	0.47	0.48	0.05	0.47	0.48
SUM U	1.60	3.57	2.93	1.52	3.58	2.90	1.85	3.28	2.87

C

Evaluation Criteria	Weight
PI	0.4
AOF	0.05
AOR	0.05
U	0.3
TTB	0.08
TTS	0.02
EOC	0.01
CGP	0.01
CLP	0.08

Station		85%			90%			95%	
No	GMO	RMO	VMO	GMO	RMO	VMO	GMO	RMO	VMO
1	0.10	0.45	0.45	0.11	0.48	0.41	0.10	0.45	0.45
2	0.09	0.46	0.45	0.09	0.45	0.46	0.09	0.45	0.46
3	0.74	0.18	0.08	0.73	0.19	0.08	0.80	0.12	0.08
4	0.04	0.48	0.48	0.04	0.48	0.48	0.04	0.48	0.48
5	0.04	0.48	0.48	0.04	0.48	0.48	0.09	0.45	0.46
6	0.64	0.29	0.07	0.62	0.31	0.07	0.72	0.19	0.09
7	0.04	0.48	0.48	0.05	0.47	0.48	0.08	0.45	0.47
8	0.08	0.45	0.47	0.09	0.45	0.46	0.08	0.46	0.46
SUM U	1.77	3.27	2.96	1.77	3.31	2.92	2.00	3.05	2.95

D

Evaluation Criteria	Weight
PI	0.1
AOF	0.05
AOR	0.05
U	0.5
TTB	0.1
TTS	0.05
EOC	0.05
CGP	0.05
CLP	0.05

Station		85%			90%			95%	
No	GMO	RMO	VMO	GMO	RMO	VMO	GMO	RMO	VMO
1	0.10	0.45	0.45	0.11	0.51	0.38	0.10	0.45	0.45
2	0.08	0.46	0.46	0.08	0.46	0.46	0.07	0.46	0.47
3	0.75	0.16	0.09	0.74	0.17	0.09	0.81	0.09	0.10
4	0.02	0.49	0.49	0.02	0.49	0.49	0.03	0.49	0.48
5	0.03	0.48	0.49	0.03	0.48	0.49	0.09	0.45	0.46
6	0.66	0.26	0.08	0.65	0.28	0.07	0.73	0.18	0.09
7	0.02	0.49	0.49	0.03	0.48	0.49	0.09	0.45	0.46
8	0.08	0.45	0.47	0.08	0.46	0.46	0.08	0.46	0.46
SUM U	1.74	3.24	3.02	1.74	3.33	2.93	2.00	3.03	2.97

3 CONCLUSIONS AND FUTURE WORK

The objective of the study presented in this paper is to benefit from discrete event simulations to assess different preventive maintenance scheduling techniques (GMO, RMO and VMO), and to incorporate simulations as a decision-making support tool to the evaluation and decision process when selecting a preventive maintenance technique. A bread packaging line is examined as a case study, where the line behavior and outcomes are obtained by using an Arena-based simulation model. The case study involved three parts, where the minimum allowable reliability level for each station is set to 85%, 90% and 95% respectively. A multi criteria decision making approach based on utility theory is employed for the preventive maintenance technique selection process to select the PM schedule that gives the best utility, performance and reliability values Production line utilization, performance and reliability are very tightly connected to the preventive maintenance scheduling, making preventive maintenance scheduling a major point of interest. Implementing the right preventive maintenance schedule can be challenging considering that different production lines carry different parameters, specifications, layout and complexity. The method outlined in this paper aims to provide an overall roadmap on how to incorporate simulation tools and benefit form their outcomes in a multi criteria decision making problem.

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