Int J Syst Assur Eng Manag (Apr-June 2015) 6(2):183–190
DOI 10.1007/s13198-014-0268-8

ORIGINAL ARTICLE

Analyzing the effect of maintenance strategies on throughput of a typical FMC (3-M, 1-R)

Ashok Kumar Gaula · Rajiv Kumar Sharma

Received: 13 March 2014 / Revised: 5 May 2014 / Published online: 6 June 2014

Abstract In rapidly changing product structures and customer demands flexible manufacturing cells (FMC's) are most widely used for meeting mid-volume, mid-variety production needs. They can process a variety of products in the same system and thus helps to achieve higher productivity. At the same time the components in FMC are more prone to failure because of their high operating rate. Further, it becomes more complex when components follow different failure distributions and it is difficult to plan suitable maintenance interventions. To this effect, in the present paper the authors present a hybrid framework by contemporaneous adoption of qualitative and quantitative techniques to model and analyze the failure aspects in FMC. On qualitative part potential failure modes w.r.t. various robot components are identified and risk priority number is obtained using failure mode and effect analysis. On quantitative analysis, use of Generalized Stochastic Petri Net is made and simulation experiments were carried out to model and analyze the performance of FMC (3 Machines 1 Robot). Cases of both reliable and unreliable FMC are investigated.

Keywords Flexible manufacturing cell · Petri nets · FMEA · Throughput

A. K. Gaula (✉) · R. K. Sharma
National Institute of Technology, Hamirpur, HP, India
e-mail: ashokkumargaula@gmail.com

R. K. Sharma
e-mail: rksnith@gmail.com

1 Introduction

According to Vineyard and Meredith (1999) flexible manufacturing cell operate at 70–80 % utilization as compared to traditional machines which operates at as low as 20 % utilization. Thus, the components in FMC are more susceptible to wear and tear than the traditional machines operating over the same period of time. Over the last few decades, various researchers have investigated the reliability and maintenance aspects related to FMC's. Lin et al. (2001) have presented sequential imperfect PM models incorporating adjustment/improvement factors in a hazard rate and effective age. Savsar (2000) developed mathematical models to study and compare the operations of a fully reliable and an unreliable flexible manufacturing cell (FMC), each with a flexible machine, a loading/unloading robot and a pallet handling system wherein the operation times, loading/unloading times and material handling times were assumed to be random. Sheu and Griffith (2001) have considered a generalized age replacement policy with age dependent minimal repair and random lead time. Bloch-Mercier (2002) has considered a repairable system subject to continuous time Markovian deterioration while running, that leads to failure. Gurler and Kaya (2002) have proposed a maintenance and replacement policy for a multi component, multi-state system, in which both the system and the components can be described through a range of performance levels varying from perfect functioning to complete failure. Wang (2002) surveyed, summarized and compared the various existing maintenance policies for both single and multi-unit systems. Chen et al. (2003) have proposed a combined state and time-dependent maintenance policy for a Markovian deteriorating multi-state system with inspection equipment connected. A PM policy for a degradation system with an acceptable reliability level has been proposed by Zhao (2003). Rupe and Kuo (2003) used Markov models to study the effect of equipment failures to the effectiveness of the FMS from the view point of the customer. Tsai et al. (2004) have applied PM in simultaneously considering three actions, viz. mechanical service, repair and replacement for a multi-component system based on availability. Optimal preventive maintenance policies are developed by Wu and Croome (2005) for a critical system that operates periodically, and is maintained with higher cost at the up state than at the down state. Wu and Croome (2005) have investigated the optimization problem of PM policies for situations where the quality of PM is a random variable with a certain probability distribution. Sheu et al. (2005) have described a general PM model that incorporates perfect and imperfect types of PM. Sheu et al. (2006) have proposed periodic PM policies, which maximize the availability of a repairable system with major repair at failure. The three types of PM considered are, imperfect PM, perfect PM and failed PM. Savsar (2005) has analyzed the performance measures of an FMS with different maintenance policies and different mean time to failure. Savsar and Aldaihani (2008) developed a stochastic model to analyze the performance of a two machine FMC served by a robot. Sharma and Kumar (2008) used Markovian approach to model failure and repair rates for critical engineering systems. Boschian et al. (2009) have presented a maintenance strategy for two machines working in parallel. Halim and Tang (2009) proposed a graphical method for determining the confidence interval for the optimal replacement interval of a deteriorating system, under age replacement and block replacement models, in which the inter-failure times follow a two-parameter Weibull distribution. Maheshwari et al. (2010) used birth death process to derive the differential difference equations governing the underlying Markov model for an unreliable FMC and the equations were solved by using Runge–Kutta method to find the probabilities for different system states. Philip and Sharma (2013) had used a stochastic reward net approach for reliability analysis of a flexible manufacturing module. Based upon the extent review of literature authors found that much effort has been made by various researchers to develop system models to solve the reliability and maintainability issues related with FMC's. Being analytical and complex these models are not only difficult to understand but also difficult to practice. To this effect, in the present paper authors propose a contemporaneous adoption of two different methodologies such as Failure Mode and Effect Analysis (FMEA) and Petri Nets (PNs) to build an integrated and helpful framework that could prove beneficial to analyze the FMC in both qualitative and quantitative manner. In the qualitative approach detailed FMEA analysis of Robot is carried out by listing the potential failure modes w.r.t various components and their effect on system performance. The numerical values of parameters failure occurrence probability (O_f), severity (S) and detectability (O_d) are obtained from expert elicitation and data book (MIL-HDK 217F and RADC TR-85-194) to compute risk priority number (RPN) score. In quantitative analysis, use of Generalized Stochastic Petri Nets (GSPN) is made to model the FMC. Further simulation experiments were carried out to study the performance of FMC. A case of fully reliable cell and unreliable cell with five maintenance policies is investigated. The organization of the remaining part of the paper is as follows. In Sect. 2, the illustrative cases are discussed that are to be investigated during the development and simulation of the throughput of an FMC.

2 Illustrative case

The Robot failures are analyzed by performing Failure Mode and Effect Analysis as shown in Table 1. The numerical values of parameters failure occurrence probability (O_f), Severity (S), detectability (Od). It is observed from the table that for Actuators RPN Score is highest i.e. 216.

As the Robot is used to transport the parts among the machines and is shared by all the parts of the system. Thus investigating the failure aspects of robot becomes important. So GSPN model is developed and simulation experiments are designed to study the failure aspects. The key assumptions made are as follows:

1. The failure considered is due to robot and not by machines.
2. The failure and repair distributions are deterministic in nature.
3. Weibull, Gamma and Uniform failure rate distribution are considered.

Considered in the study is flexible manufacturing cell (FMC) shown in Fig. 1. It comprises of Load/Unload (LU) station (used to mount raw parts on pallets and unload finished parts from them) and three machines (M1, M2, M3) that are used to process two different kinds of parts i.e. Part A and Part B. there are various alternative working schedules (i.e. machine processing sequences) for each part type, that are summarized in Table 2. Parts of each type have to be loaded onto pallets of corresponding type and there is a limited number of pallets of each type.

Type "A" parts have two possible working schedules that involve the movements from LU to M1, from M1 to either M2 or M3 and from M2/M3 to LU.

Type "B" parts have two possible working schedules involving the movements from LU to either M2 or M3and from M2/M3 to LU.

Table 1 FMEA analysis of different components of robot in an FMC

S No.	Components	Functions	Modes	Effects	RPN Score
1	Unload valve	To keep pressure below allowable value	Failure	Excessive pressure in the system	31
			Continuous return to the reservoir	System pressure low, slow robot movement	
2	Check valve	To control the fluid flow	Failure to open	No fluid flow	10
			Failure to close	Fluctuations in pressure	
3	Pressure gauge	To investigate fluid pressure	Incorrect reading	More or less robot movement	11
4	Relief valve	To control the fluid pressure	Failure to open	Damage to drive transmission	8
			Failure to close	Drop in driving power for joints	
5	Accumulator	To assist the pump	Ruptured	No accumulator operation	33
6	Dump valves	To release the fluid pressure	Leakage	Slight drop in pressure	7
7	Servo valves	Control the movements of actuators	Failure in closed mode	Robot joint will not drive	158
			Failure in closed mode	Unwanted drive of actuator	
8	Actuators	Convert fluid energy into mechanical energy	Housing leakage	Robot arm creeps	216
			Housing or seal rupture	Unwanted robot movement	
9	Piping and seals	To transmit fluid pressure	Leakage	Can cause fall of pressure	3
			Rupture	Unwanted robot movement	
10	Motors	To generate fluid pressure	Short circuiting	No operation	10
			Failure in bearing	No operation	
			Damage to shaft coupling	No operation of motor	
11	Bearings	Allow machine parts to move without wear or friction	Rupture	No rotational movement of robot	2
			Wear	Leads to failure of bearing and ultimately stops movement of robot	
			Corrosion	Leads to improper working of robot	
12	Sensors	To interact with environment	Information overload	Wrong detection and collision	93
			Proper current supply	Short circuiting of Sensor	
			Self-heating	Damage to the sensor	
13	Brakes	To stop the robot before collision	Wear	Collision of robot due to no means to stop	209
14	Pump	To supply fluid at pressure	Vane wheel breakage	Pump casing may be ruptured	15
15	Filter	To check for contamination	Blockage	No fluid flow to the system	6

Since, the parts have alternative working schedules (both types of parts can choose between M2 and M3), a policy is needed to select the machine to be used. The policy modelled is simple: if both machines are free, the part chooses the fastest one, while if two types of parts are waiting for the same machine, the part with shortest processing time is selected to be processed on that machine. This is represented in the Petri Net model (Figs. 2, 3) by means of the four inhibitor arcs connected to transitions t5 and t6. The transition/weight rates of transition is shown in Table 3.

In the GSPN model, the circles represent places while transitions are represented by squares. The Robot is connected by arcs with the transitions and machines (circles). The arc towards the transition represent the loading of part to the machine while the arc away from the transition represent the unloading of the finished part. Only one component at a time is considered to be under maintenance. The pallet contains 5 parts that are to be finished. The finished products are to be processed by two schedules as shown in Table 2. The arc represents the movement of parts from one place to another.

3 Experiment 1

Several simulation experiments are carried out to study the performance of FMC operations under different maintenance policies i.e. (a) a fully reliable cell (FRC); (b) a cell with Corrective Maintenance policy; (c) a cell with block based preventive policy: (d) a cell with Age

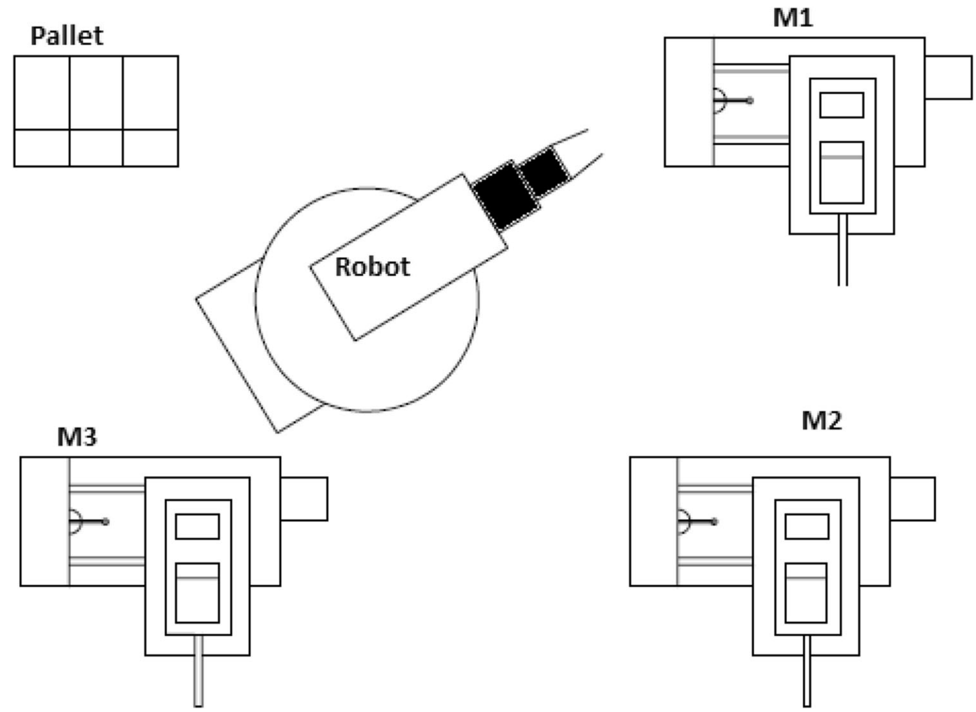

Fig. 1 Schematization of FMC with robot as transportation system

Table 2 Working schedules

Part type	Part mix (%)	Process number	Processing times (min)				
			M1	M2	M3	ROBOT	LU
A	20	1	10	15		2	4
		2	10	–	10	2	4
B	80	1	–	20	–	2	4
		2	–	–	30	2	4

based preventive policy; (e) a cell with Opportunity triggered policy. Opportunity triggered maintenance policy triggers when the failure occurs and along with corrective maintenance of the Robot component, preventive maintenance triggers which leads to lesser time for maintenance as the Robot is in idle state i.e. in the corrective maintenance mode. The performance measure considered was the throughput during the simulation period.

Each simulation experiment was carried out for the operation of the production cell over a period of 1 month (20 working days and 8 h. per day or a period of 160 h). In the case of PM introduction, it was assumed that PM time of 30 min (or 15 min when combined with CM) is added to 8 h at the end of each shift. Ten simulation replicates are made and the performance measure, the throughput during the month, was obtained for each case. Other simulation related parameters are given for each experiment. The repair rate is considered to be uniform for all the reliable and unreliable FMC.

Table 4 shows the comparison between throughput of reliable FMC and FMC with failure and Fig. 4 can easily shows the comparison between reliable and unreliable FMC considering failure only due to robot.

Different failure maintenance policies were used during the simulation which shows the variation of production rates with different MTBFs and different maintenance policies as shown in Table 5 and can be seen in Fig. 5.

The Fig. 4 shows steep increase in the production rate between 500 and 1,000 h. Rapid change in the value of throughput at TBF 500–1,000 is observed because components in Robot may fail in the initial stage i.e. stage 1 of bath tub curve. The failures might be because of improper design, or selection of operating parameters etc. As the time progresses the failure rate becomes uniform. Thus, at the subsequent intervals i.e. 1,000, 1,500, 2,000, 2,500, 3,000, 3,500, 4,000, uniform change in throughput is observed. The robot failure in Fig. 4 consider CM policy only.

Figure 5 and Table 5 shows the comparison of different maintenance policies for the failure in Robot. In Fig. 5, OT found out to be the best maintenance policy for the robot failure. Irrespective of the maintenance policies the pattern of the increase in production rate w.r.t TBF is nearly same except CM in which no preventive maintenance is considered.

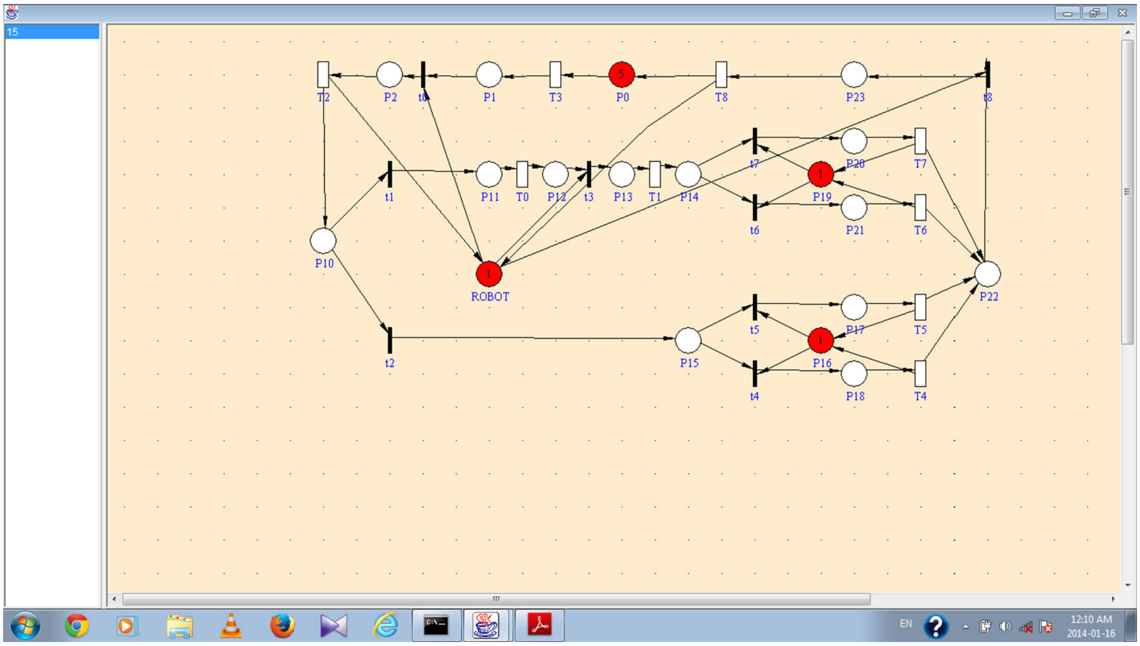

Fig. 2 GSPN model without failure

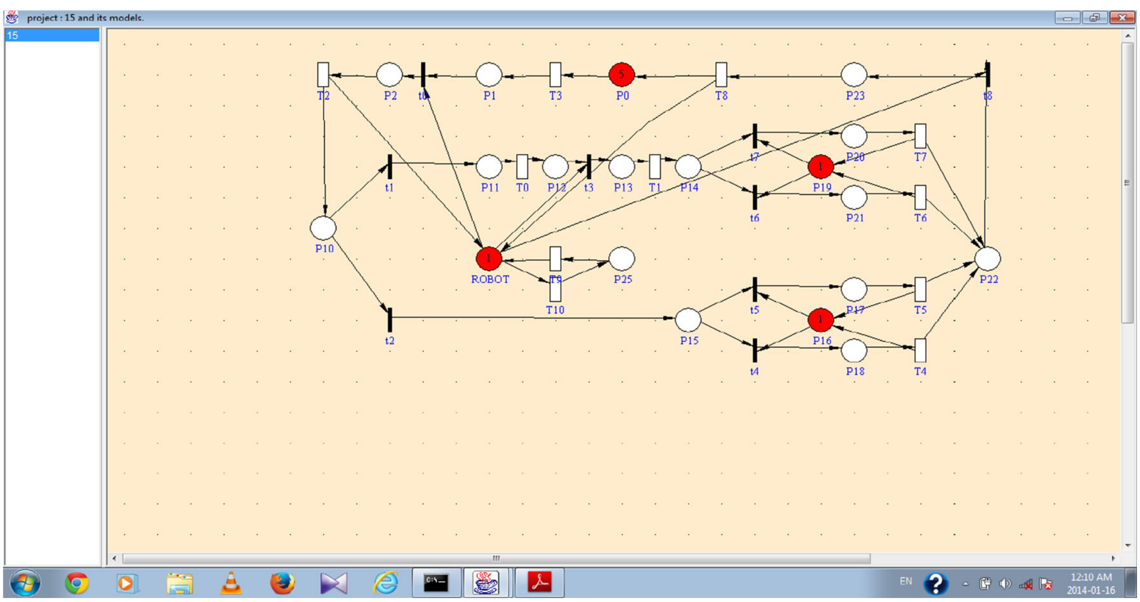

Fig. 3 GSPN model with failure

4 Experiment 2

The next experiment compares the effect of various time to failure distributions, including uniform, gamma, weibull distributions, on the FMC performance under the CM policy only. All of the FMC parameters related to operation times, repair times, and PM times are kept the same as given in the first experiment. Only time to failure distributions and the related parameters were changed such that TBF was varied between 500 and 4,000.

In the case of the gamma distribution, E (T) $= \alpha\beta$. Thus by changing the values of α and β, time between failures could be changed as required. For example, $\alpha = 250$ and $\beta = 2$ resulted in a TBF of 500; $\alpha = 750$ and $\beta = 2$ resulted in a TBF $=$ 1,500; $\alpha =$ 1,250 and $\beta = 2$ resulted in a TBF $=$ 2,500; and $\alpha =$ 2,000 and $\beta = 2$ resulted in a

Table 3 Transition rate/weight for GSPN model

Timed transition	Rate	Immediate transition	Weight
T0	6	t0	1
T1	30	t1	20
T2	30	t2	80
T3	15	t3	1
T4	3	t4	1
T5	4	t5	1
T6	2	t6	1
T7	6	t7	1
T8	30	t8	1
T9	Failure rate		
T10	Repair rate		

Table 4 Throughput of FMC of different time between failure for reliable and unreliable cell

S.No.	Time between failures (TBF)	Throughput (Unreliable)	Throughput (Reliable)
1	500	404.2	760
2	1,000	552.24	760
3	1,500	606.5	760
4	2,000	618.91	760
5	2,500	629.86	760
6	3,000	638.22	760
7	3,500	645.86	760
8	4,000	652.26	760

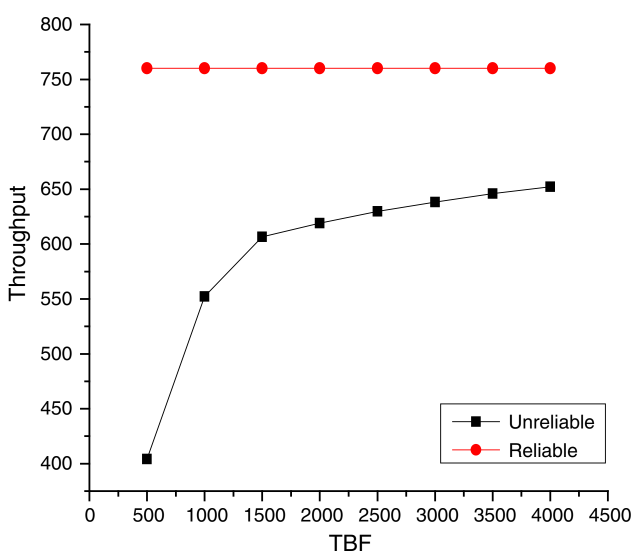

Fig. 4 Comparison of reliable and unreliable FMC when the failure rate distribution is uniform

Table 5 Production rates of an FMC under different maintenance policies and different MTBFs

S.no.	MTBF	Throughput			
		CM	BB	AB	OT
1	500	404.52	542.36	551.24	555.37
2	1,000	552.24	612.24	624.32	629.43
3	1,500	606.5	634.38	641.58	652.57
4	2,000	618.91	648.27	653.63	665.34
5	2,500	629.86	654.67	661.34	676.21
6	3,000	638.22	661.31	669.46	682.97
7	3,500	645.86	668.82	674.54	692.45
8	4,000	652.26	673.23	681.32	700.54

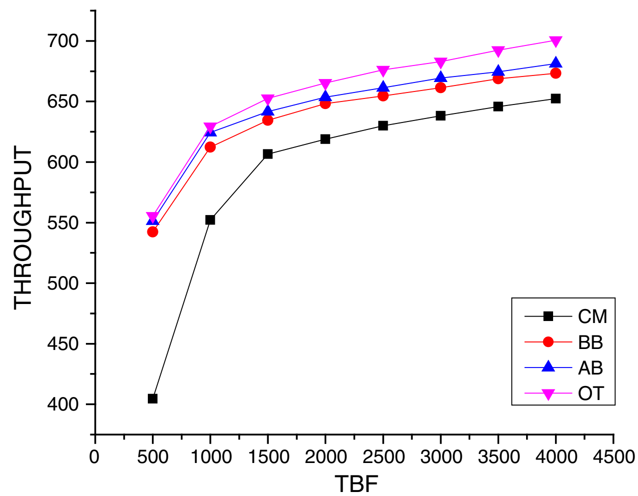

Fig. 5 Throughput for different TBF's and different maintenance policies. *CM* corrective maintenance, BB block based PM, AB age based PM, *OT* opportunity triggered

Table 6 Parameters of the distributions used in simulation

Distribution	TBF	Parameters that result in the specified TBF	
		α	Β
Gamma	500	250	2
	1,500	750	2
	2,500	1,250	2
	4,000	2,000	2
Weibull	500	2	564.2
	1,500	2	1,692.2
	2,500	2	2,820.95
	4,000	2	4,513.5

Table 7 Comparisons of FMC production rate under various distributions for the CM policy

TBF	Uniform	Gamma	Weibull
500	404.42	514.88	515.36
1,500	606.5	622.30	625.86
2,500	629.86	645.53	656.12
4,000	652.26	673.81	678.67

TBF = 4,000, which are the same values specified in the previous experiment for the uniform distribution.

For the Weibull distribution which has $TBF = E(T) = \beta\,\Gamma(1/\alpha)/\alpha$, two parameters α(shape parameter) and β(scale parameter) have to be defined. For example, if TBF = 500 and $\alpha = 2$, then on substituting the values $\beta = 564.2$. Similarly for TBF = 1,500, $\alpha = 2$ and $\beta = 1{,}692.2$, for TBF = 2,500, $\alpha = 2$ and $\beta = 2{,}820.95$, and for TBF = 4,000, $\alpha = 2$ and $\beta = 4{,}513.5$ are used.

Comparisons of the three distributions, uniform, gamma and weibull, with respect to the CM policy are presented in Table 6 for FMC production rate. All the distributions show the same trend with respect to increasing production rates at increasing TBF values (Table 7).

As it is seen in Fig. 6, uniformly distributed time between failures resulted in significantly different FMC production rate as compared to other distributions. This is because in a uniform distribution, which is structurally different from the other distributions, probability of failure is likely at all the possible values that the random variable can take, while in other distribution cases, probability concentration is around the central value. The FMC performance was almost the same under the other distributions investigated. This indicates that the type of distribution has no critical effects on FMC performance under CM policy if the distribution shapes are same. But of all three distributions Weibull distribution was found out to be the best for maximum throughput.

5 Conclusion

In the present study, authors successfully presented simultaneous adoption of both qualitative and quantitative approach to model and analyze a FMC. The qualitative analysis using Failure mode effect analysis helps to list the potential failure modes w.r.t. various components and their effect on system performance. The numerical values of parameters failure occurrence probability (O_f), severity (S) and detectability (O_d) are obtained from expert elicitation and data book (MIL- HDK 217F and RADC) to compute RPN score. The effect of various maintenance strategies on the production rate of FMC under various time to failure distributions is investigated by performing simulation experiments.

Four maintenance policies i.e. (a) a fully reliable cell (FRC); (b) a cell with Corrective Maintenance policy (CM); (c) a cell with block based preventive policy (BB): (d) a cell with Age based preventive policy (AB); (e) a cell with Opportunity triggered policy (OT) are identified and their effects on FMC performance, are analyzed by using Generalized Stochastic Petri Net model. The results of the analysis of various cases show that maintenance of any form has significant effect on the throughput of the FMC. However, the type of maintenance applied is important and should be carefully studied before implementation. In the particular example studied, the best policy in all cases was the opportunity-triggered maintenance policy and worst policy was the corrective maintenance policy.

Future studies can be carried out on analyzing failure aspects of other FMC components such as machines, pallets with robot/AGVs. Apart from the maintenance policies

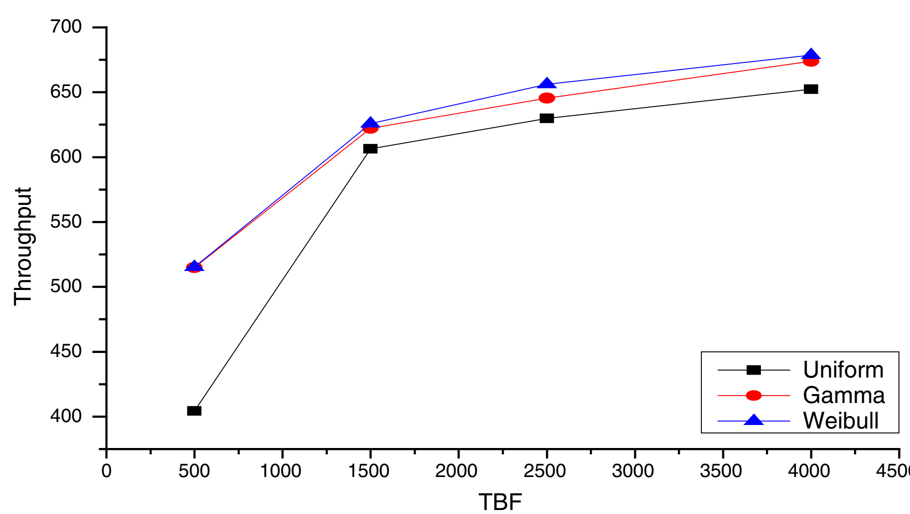

Fig. 6 Throughput for different failure distributions

considered in the study the effect of other maintenance policies can be investigated. Further, the cost of maintenance can be taken in consideration to investigate the impact of maintenance strategies in an unreliable FMC.

References

Bloch-Mercier S (2002) A preventive maintenance policy with sequential checking procedure for a Markov deteriorating system. Eur J Oper Res 147:548–576

Boschian V, Rezg N, Chelbi A (2009) Contribution of simulation to the optimization of maintenance strategies for a randomly failing production system. Eur J Oper Res 197:1142–1149

Chen CT, Chen YW, Yuan J (2003) On a dynamic preventive maintenance policy for a system under inspection. Reliab Eng Syst Saf 80:41–47

Gurler U, Kaya A (2002) A maintenance policy for a system with multi-state components: an approximate solution. Reliab Eng Saf 6(2):117–127

Halim T, Tang L (2009) Confidence interval for optimal preventive maintenance interval and its applications in maintenance planning. Int J Adv Manuf Technol 40:203–213

Lin D, Zuo MJ, Yam RC (2001) Sequential imperfect preventive maintenance models with two categories of failure modes. Naval Res Logist (NRL) 48(2):172–183

Maheshwari S, Sharma P, Jain M (2010) Unreliable flexible manufacturing cell with common cause failure. Int J Eng Sci Technol 2(9):4701–4716

Military Handbook Reliability prediction for electronic equipment, MIL-HDK 217F, Department of Defense USA

Philip A, Sharma RK (2013) A stochastic reward net approach for reliability analysis of a flexible manufacturing module. Int J Syst Assur Eng Manag 4(3):293–302. doi:10.1007/s13198-013-0175-4

RADC Non electronic reliability notebook, RADC-TR-85-94

Rupe J, Kuo W (2003) An assessment framework for optimal FMS effectiveness. Int J Flex Manuf Syst 15:151–165

Savsar M (2000) Reliability analysis of a flexible manufacturing cell. Reliab Eng Syst Saf 67:147–152

Savsar M (2005) Performance analysis of an FMS operating under different failure rate and maintenance policies. Int J Flex Manuf Syst 16:229–249

Savsar M, Aldaihani M (2008) Modeling of machine failures in a flexible manufacturing cell with two machines served by a robot. Reliab Eng Syst Safety 93:1551–1562

Sharma RK, Kumar S (2008) Performance modeling in critical engineering systems using RAM analysis. Reliab Eng Syst Saf 93(2008):891–897

Sheu SH, Griffith WS (2001) Optimal age-replacement policy with age-dependent minimal-repair and random-leadtime. IEEE Trans Reliab 5(3):302–309

Sheu SH, Lin YB, Liao GL (2005) Optimal policies with decreasing probability of imperfect maintenance. IEEE Trans Reliab 54(2):347–357

Sheu SH, Lin YB, Liao GL (2006) Optimum policies for a system with general imperfect maintenance. Reliab Eng Syst Saf 91: 362–369

Tsai YT , Wangb KS, Tsai LC (2004) A study of availability-centered preventive maintenance for multi-component systems. Reliab Eng Syst Saf 84:261–270

Vineyard M, Meredith JR, Amoako-Gyampah K (1999) Failure rate distributions for flexible manufacturing systems: an empirical study. Eur J Oper Res 116:139–155

Wang H (2002) A survey of maintenance policies of deteriorating systems. Eur J Oper Res 139:469–489

Wu S, Croome DC (2005) Optimal maintenance policies under different operational schedules. IEEE Trans Reliab 54(2):338–346

Zhao YX (2003) On preventive maintenance policy of a critical reliability level for system subject to degradation. Reliab Eng Saf 79:301–308