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Performance Evaluation of a Flexible Manufacturing Cell with Two Machines and One Robot

Kamyar Sabri-Laghaie[a,*]

[a,*] *Urmia University of Technology (sabri@uut.ac.ir)*

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ABSTRACT

This study aims to investigate performance of a Flexible Manufacturing Cell (FMC) using stochastic processes approach. The cell under study here is comprised of one robot, two machines and a pallet. The robot working in this cell and also the machines might experience some random failures. As a result, the operations of loading and unloading as well as machining will be delayed until repairing the robots and/or machines. Processing and loading/unloading times have stochastic nature due to existence of different parts and also system operation characteristics. Meanwhile, times between failures of robots and machines are considered stochastic in addition to their repairing times. It has been assumed here that processing times, loading/unloading times, times between two successive failures of robots and machines, and required time for their repair obey an exponential distribution. Performance of the cell and optimal capacity of the pallet as well as optimal speed of the cell in terms of cell costs minimization are evaluated.

1. Introduction

Survival within current manufacturing and competitive context entails that companies respond towards market changes quickly and meet great demands of requests through flexibility and adaptability. Flexible manufacturing systems are able to deal with these changes because of their flexibility in planning processes and machines. These capabilities must be utilized effectively to yield the maximum income at the minimum costs [1]. Recent advancements in the manufacturing processes, such as inexpensive and powerful computers, have made merger of previously distinct manufacturing concepts possible. Today, Flexible Manufacturing System (FMS) is the highest hierarchical level of industrial units which is controlled by computers. FMS is a manufacturing unit which can produce a vast variety of products with minimum human involvement [2]. An FMS can be classified based on volume and variation extent of its manufactured parts. Another classification is proposed based on the arrangement of equipment and scheduling techniques. All these types include configurations of FMS from the most simple to the most complicated arrangements [3].

One type of FMS is known as Flexible Machining Cell (FMC) which is the most simple and the most flexible system. It is generally consisted of a multipurpose CNC machine, in which loading, unloading, handling and storage are done automatically. Although FMC has just one machining tool, it can be used as an automatic manufacturing system since it has all the required specifications [3].

Issues put forward in justification of a manufacturing system might be associated with economy, manufacturing, product quality and flexibility. For example, the minimum investment and operational costs, the maximum yield per time, improvement of product quality and flexibility [2].

There are usually complicated and extensive general objectives for a given system which depend on special requirements. Some criteria like performance, reliability, utilization or costs are not adequate alone. There are often some other factors which are considered i.e. time schedule, maintainability and expected life. According to applications and requirements, some systems may emphasize on performance, while some others could focus on reliability or time schedule, costs and etc. Performance, time schedule, costs, maintainability and expected life of the system are all dependent on each other. System performance can be usually enhanced by increasing costs and scheduling factors. On the other hand, system cost can be reduced via adoption of rather poor performance and reliability costs. In fact, performance is the most critical factor which must be regarded for evaluation of a system. Typical performance criteria of a system are availability, yield and response time, production rate, utilization of components and system efficiency. Based on studies conducted by Rahman [2] typical performance criteria are defined as below in performance evaluation of FMS: (1) Availability, which is the probability of being operational within an scheduled period of time; (2) yield and response time, which represent the working rate of a system; (3) Extent of utilization, which is identified as the fraction of time a part or component is engaged in the scheduled period; (4) production rate, which provides the number of final parts per unit time; (5) System efficiency, which determines the probability of being successful in meeting total operational demand within specific time interval and under special operational conditions.

High performance of modern manufacturing systems has challenged analysts at various levels. Due to complicated nature of the modern industrial systems, design and operation of these systems must be modeled and analyzed in order to choose the optimal operational policy and strategy. Therefore, modeling and analysis of these systems must be particularly attended at various levels [4]. The following will look on some of the most common modeling methods of FMS which has used these techniques. The mostly used methods in the literature for modeling FMS to obtain the optimal policies and strategies are categorized as below: (1) analytic techniques, (2) simulation techniques, and (3) Petri nets. Advantages and disadvantages of the mentioned methods have been summarized in Table 1.

Analytic techniques including heuristics and operations research methods such as linear programming, queuing networks, branch and bound, and dynamic programming were utilized to find optimal solutions. Queuing networks are used to describe, optimize and control FMS. They have also attracted the most interest among analytic models.

The rest of this section will review the related articles briefly. FMS provides the necessary potential to reach higher levels of productivity in large scale production of discrete and complex parts. However, important and crucial decisions must be properly made to reach such achievements. For this purpose, Devise and Pierreval [5] introduced some new indexes for performance evaluation which contribute to find an appropriate solution for selection of material handling systems in FMSs. Talluri et al. [6] developed a creative framework based on combinational application of data envelopment analysis and nonparametric statistical procedures to choose FMSs. Karsak and Tolga [7] introduced a fuzzy decision making algorithm to select the most appropriate advanced manufacturing system from a set of separate alternatives. After that, Matsui et al. [8] assessed performance of FMSs with limited local buffers and dynamic/static routing rules. They addressed design and configuration of the system to maximize the yield. An appropriate stable decision making procedure for FMS evaluation must take into account both strategic and economic criteria. Karsak [9] proposed a distance-based and fuzzy multi-criteria decision making framework for choosing FMS from a set of mutually exclusive alternatives. Bigand et al. [10] developed an informational system to merge various viewpoints about design and control of an FMS. Aldaihani and Savsar [11] suggested a probabilistic model to determine performance of an FMC in variable operational conditions like random machining times, random loading/unloading times, and random pallet handling times. Callahan et al. [12] built a decision making framework for planning and development of an FMS. Moreover, a systematic weighting theory was made for development of decisions in the system in order to evaluate different design choices. Aldaihani and Savsar [11] suggested a probabilistic model to explore performance of an FMC. Thereby, optimal capacity of the pallet and optimal speed of the cell are determined such that total cost of the flexible cell will be minimized per unit. Li and Huang [13] studied the effect of flexible lines on product quality. Li and Huang [14] also investigated the effect of flexible lines. They presented a quantitative model based on Markov chain to evaluate qualitative performance of an FMS. Savsar and Aldaihani [15] offered a probabilistic model for performance analysis of a flexible cell, in which machines experience failures and are repaired. They introduced exact relations for steady state probabilities of the system which are utilized to calculate performance criteria of the system i.e. yield rate and utilization extent of system components. Savsar [16] offered exact relations to calculate production rate of a flexible manufacturing module which works under stochastic conditions like random machining times, random loading/unloading times, and random pallet handling times. Rao and Parnichkun [17] presented a decision making method based on combinational mathematics to evaluate various FMSs. Chuu [18] developed a group decision making model using fuzzy multiple analysis to assess fitness of a manufacturing technology.

Wang et al. [19] applied a simple analytical method to evaluate qualitative performance of FMSs with group operations. They used Markov chain to obtain relations for probabilities of manufacturing sound parts. However, Wang et al. [20] utilized a Markov chain to study quality of products in flexible manufacturing systems. Van [21] presented a queuing model for a manufacturing cell including a machining center and several parallel manufacturing stations. A precise solution has been made for steady state probabilities of the system. Savsar [22] explored operational performance of an FMC under three possible scenarios, namely: completely reliable equipment, unreliable equipment and under corrective repair, and unreliable and deteriorative equipment under corrective repairs. Al-Ahmari and Li [23] developed a generalized stochastic Petri net model to analyze the performance of a multi-machine flexible manufacturing cell. They analyzed a flexible manufacturing cell which consists of one or more machine(s), a single conveyor and a single robot. Jain and Raj [24] analyzed the performance variables of a flexible manufacturing system using different approaches including interpretive structural modelling (ISM); Structural equation modelling (SEM); Graph Theory and Matrix Approach (GTMA). Mahmood et al. [25] evaluated the performance of a FMS by using the IDEF0 modelling technique and the manufacturing simulation. They defined a criteria based on requirements regarding system reliability.

In this paper performance of a FMS is studied. Therefore, current paper aims to investigate performance of an FMC with two machines and one robot using queuing theory. In this regard steady state characteristics of the FMS are derived and then a cost model is constructed. The performance of the mentioned FMS is evaluated according to the developed models. There are few papers in the literature that have analytically studied performance of a flexible manufacturing cell in which machines or robots may fail. The main contribution of this paper is extending the previous researches on performance of flexible manufacturing cells to the case when machines and robots are unreliable.

The rest of the paper is as the following. In section 2, assumptions of the FMS are stated and the problem is formulated. In section 3 a cost model is provided. A numerical example is given in section 4. Finally, conclusions and recommendations are indicated in section 5.

2. Problem formulation

The FMS under study is depicted in Fig. 1. It can be observed that the desired cell is composed of a robot, two machines and one pallet. Meanwhile, it can be seen that an automatic pallet handling system delivers “n” parts to the cell. The robot reaches the pallet and picks a part to load it into the first machine. Once the first machine performs operation on the part, the robot will move toward the pallet and load a second part into the second machine. Afterwards, the robot approaches to the machine which has accomplished its operations first and unloads the finished part from the machine in order to load a new part on it. Loading and unloading operations are resumed with the higher priorities assigned to the machine which carries out its operation earlier. Having implemented the machining operation on all parts of it, the pallet with “n” machined parts will leave the cell to let a new pallet of “n” raw parts enter the cell automatically. The robot working in this cell might experience some random failures. So, the operations of loading and unloading will be delayed until repairing the robot. Processing and loading/unloading times have stochastic nature due to existence of different parts and also system operation characteristics. Furthermore, times between failures of robots and machines are considered stochastic in addition to their repairing times. It has been assumed in this contribution that processing times, loading/unloading times, times between two consecutive failures of the robot, and required time for their repair show an exponential distribution. In addition to the robot, it has been assumed that the machines 1 and 2 may experience random failures. Times between failures and repair time of the machines follow an exponential distribution, too. Current work tries to determine optimal capacity of the pallet as well as optimal speed of the cell such that costs of the cell will be minimized per unit production.

A probabilistic model is developed in order to evaluate performance of this cell. Nomenclature of which has been listed below:

Indexes	
i	number of raw parts on pallet
j	state of machine 1

k	state of machine 2
r	state of robot
Parameters	
l_1	loading rate on machine 1 (parts/unit time)
l_2	loading rate on machine 2 (parts/unit time)
u_1	unloading rate from machine 1 (parts/unit time)
u_2	unloading rate from machine 2 (parts/unit time)
z_1	combinatorial loading/unloading rate for machine 1 (parts/unit time)
z_2	combinatorial loading/unloading rate for machine 2 (parts/unit time)
w	pallet handling rate (pallet/unit time)
v_1	machining rate of machine 1 (parts/time unit)
v_2	machining rate of machine 2 (parts/unit time)
λ	failure rate of robot
μ	repair rate of robot
λ_1	failure rate of machine 1
μ_1	repair rate of machine 1
λ_2	failure rate of machine 2
μ_2	repair rate of machine 2
S_{ijkr}	State of the cell for indices i, j, k, and r
π_{ijkr}	probability of being at state S_{ijkr}
Variables	
n	capacity of pallet (parts/pallet)
Qc	production rate of cell (pallet/time unit)

The states of machines and robots are defined as follows:

j=	0	machine 1 is idle
	1	machine 1 is working on a part
	2	machine 1 is waiting for robot
	3	machine 1 is down
k=	0	machine 2 is idle
	1	machine 2 is working on a part
	2	machine 2 is waiting for robot
	3	machine 2 is down
r=	0	robot is idle
	1	robot is loading/unloading machine 1
	2	robot is loading/unloading machine 2
	3	robot is down

Handling times of robot are calculated based on loading/unloading times. Since demonstration of the state transition diagram is rather difficult due to the existence of numerous relations between nodes and also the relatively great number of system steady state equations, this paper has just concentrated on presentation of system state transition diagram for the case when robot is down (Fig. 2).

System steady state equations must be extracted to find the desired system steady state probabilities in both above mentioned and general cases. Probabilities of system steady state are found by solving the system steady state equations:

$$\begin{cases} \Pi \times Q = 0 \\ \sum_{i=0}^{n}\sum_{j=0}^{2}\sum_{k=0}^{2}\sum_{r=0}^{3}\pi_{ijkr} = 1 \end{cases} \quad (1)$$

Where, Q and Π are transition and steady state probabilities matrices, respectively. For example, for *n=3*, system performance criteria can be calculated as below:

1. Probability of being busy for machine 1:

$$M_1\,Busy = \pi_{0100} + \pi_{0102} + \pi_{0103} + \pi_{0110} + \pi_{0130} + \pi_{1102} + \pi_{1103} + \pi_{1110} + \pi_{1130} + \pi_{2102} + \pi_{2103} + \pi_{2110} + \pi_{2130} \quad (2)$$

2. Probability of being idle for machine 1:

$$M_1\,Idle = \pi_{0000} + \pi_{0001} + \pi_{0002} + \pi_{0003} + \pi_{0010} + \pi_{0011} + \pi_{0013} + \pi_{0021} + \pi_{0023} + \pi_{0030} + \pi_{0031} + \pi_{0033} + \pi_{1001} + \pi_{1002} + \pi_{1003} + \pi_{1011} + \pi_{1013} + \pi_{1021} + \pi_{1023} + \pi_{1031} + \pi_{1033} + \pi_{2001} + \pi_{2002} + \pi_{2003} + \pi_{2011} + \pi_{2013} + \pi_{2021} + \pi_{2023} + \pi_{2031} + \pi_{2033} + \pi_{3001} + \pi_{3003} \quad (3)$$

3. Probability of being busy for machine 2:

$$M_2\,Busy = \pi_{2110} + \pi_{2011} + \pi_{1110} + \pi_{1011} + \pi_{0110} + \pi_{0011} + \pi_{0010} + \pi_{2013} + \pi_{1013} + \pi_{0013} \quad (4)$$

4. Probability of being idle for machine 2:

$$M_2\ Idle = \pi_{0000} + \pi_{0001} + \pi_{0002} + \pi_{0003} + \pi_{0100} + \pi_{0102} + \pi_{0103} + \pi_{0202} + \pi_{0203} + \pi_{0300} + \pi_{0302} + \pi_{0303} + \pi_{1001} + \pi_{1002} + \pi_{1003} + \pi_{1102} + \pi_{1103} + \pi_{1202} + \pi_{1203} + \pi_{1302} + \pi_{1303} + \pi_{2001} + \pi_{2002} + \pi_{2003} + \pi_{2102} + \pi_{2103} + \pi_{2202} + \pi_{2203} + \pi_{2302} + \pi_{2303} + \pi_{3001} + \pi_{3003} \tag{5}$$

5. Probability of being busy for robot:

$$Robot\ Busy = \pi_{0001} + \pi_{0002} + \pi_{0003} + \pi_{0011} + \pi_{0021} + \pi_{0031} + \pi_{0102} + \pi_{0202} + \pi_{0302} + \pi_{1001} + \pi_{1002} + \pi_{1011} + \pi_{1021} +_{1031} + \pi_{1102} + \pi_{1202} + \pi_{1302} + \pi_{2001} + \pi_{2002} + \pi_{2011} + \pi_{2021} + \pi_{2031} + \pi_{2102} + \pi_{2202} + \pi_{2302} + \pi_{3001} \tag{6}$$

6. Probability of being idle for robot:

$$Robot\ Idle = \pi_{0000} + \pi_{0010} + \pi_{0030} + \pi_{0100} + \pi_{0110} + \pi_{0130} + \pi_{0300} + \pi_{0310} + \pi_{0330} + \pi_{1110} + \pi_{1130} + \pi_{1310} + \pi_{1330} + \pi_{2110} + \pi_{2130} + \pi_{2310} + \pi_{2330} \tag{7}$$

7. Probability of being down for robot:

$$Robot\ Down = \pi_{0003} + \pi_{0013} + \pi_{0023} + \pi_{0033} + \pi_{0103} + \pi_{0203} + \pi_{0303} + \pi_{1003} + \pi_{1013} + \pi_{1023} + \pi_{1033} + \pi_{1103} + \pi_{1203} +_{1303} + \pi_{2003} + \pi_{2013} + \pi_{2023} + \pi_{2033} + \pi_{2103} + \pi_{2203} + \pi_{2303} + \pi_{3003} \tag{8}$$

8. Probability of being busy for pallet:

$$Pallet\ Busy = \pi_{0000} \tag{9}$$

9. Probability of being waiting for machine 1:

$$M_1 Waiting = \pi_{0202} + \pi_{0203} + \pi_{1202} + \pi_{1203} + \pi_{2202} + \pi_{2203} \tag{10}$$

10. Probability of being waiting for machine 2:

$$M_2 Waiting = \pi_{0021} + \pi_{0023} + \pi_{1021} + \pi_{1023} + \pi_{2021} + \pi_{2023} \tag{11}$$

11. Probability of being down for machine 1:

$$M_1\ Repair = \pi_{0300} + \pi_{0302} + \pi_{0303} + \pi_{0310} + \pi_{0330} + \pi_{1302} + \pi_{1303} + \pi_{1310} + \pi_{1330} + \pi_{2302} + \pi_{2303} + \pi_{2310} + \pi_{2330} \tag{12}$$

12. Probability of being down for machine 2:

$$M_2\ Repair = \pi_{0030} + \pi_{0031} + \pi_{0033} + \pi_{0130} + \pi_{0330} + \pi_{1031} + \pi_{1033} + \pi_{1130} + \pi_{1330} + \pi_{2031} + \pi_{2033} + \pi_{2130} + \pi_{2330} \quad (13)$$

Taking into consideration the steady state probabilities, one can calculate production rate of the manufacturing cell. For this purpose, the following probabilities must be extracted for a special case where 3 raw parts exist in the pallet. The results below are simply extendable to general case which includes *n* raw parts in the pallet:

Only machine 1 is busy	$BM1 = \pi_{0100} + \pi_{0102} + \pi_{0103} + \pi_{0130} + \pi_{1102} + \pi_{1103} + \pi_{1130} + \pi_{2102} + \pi_{2103} + \pi_{2130}$
Only machine 2 is busy	$BM2 = \pi_{2011} + \pi_{1011} + \pi_{0011} + \pi_{0010} + \pi_{2013} + \pi_{1013} + \pi_{0013}$
Both machines are busy	$BM12 = \pi_{2110} + \pi_{1110} + \pi_{0110}$

Using the above mentioned probabilities which indicate the percent of busy time for the machines separately and together, production rate of the flexible cell would be calculated as below:

$$\text{Production Rate} = \upsilon_1 \times BM1 + \upsilon_2 \times BM2 + (\upsilon_1 + \upsilon_2) \times BM12$$

3. System Costs

This section aims to investigate the performance of FMC under study using a cost model. Having presented the cost model, it will be tried to optimize this model. Consider general case for allocation of "m" machines to one operator. The general cost model developed for this problem is given below based on Solberg [26]:

$$TC(m) = (C_o + mC_m) \times \frac{T}{m} \quad (14)$$

Where, *TC(m)* is the cost of allocating *m* machines to one operator per unit production, C_0 and C_m represent the costs of operator/robot and machine per time unit, *m* stands for the number of machines allocated to operator, and *T* gives the cycle time in which *m* parts are produced. This paper will launch to develop a cost model similar to the work conducted by Aldaihani and Savsar [11]. In this model, the cycle period is no longer considered as a constant and is provided for probabilistic case with variable cycle time. Terms used in the cost function are defined below:

C_1	Total cost of machine 1 per time unit
C_{f1}	Constant cost of machine 1 per time unit

C_{v1}	Variable cost of machine 1 per time unit
C_2	Total cost of machine 2 per time unit
C_{f2}	Constant cost of machine 2 per time unit
C_{v2}	Variable cost of machine 2 per time unit
C_r	Total cost of robot per time unit
C_{rf}	Constant cost of robot per time unit
C_{rv}	Variable cost of robot per time unit
C_p	Total cost of pallet per time unit
C_{pf}	Constant cost of pallet per time unit
C_{pv}	Variable cost of pallet per time unit

With respect to the above mentioned terms, costs are calculated separately as follows:

$$C_1 = C_{1f} + C_{1v} \times \upsilon_1 \quad (15)$$

$$C_2 = C_{2f} + C_{2v} \times \upsilon_2 \quad (16)$$

$$C_r = C_{rf} + C_{rv} \times (z_1 + z_2) \quad (17)$$

$$C_p = C_{pf} + C_{pv} \times n \quad (18)$$

Finally, total cost of the flexible cell is defined per time unit as follows:

$$TC = (C_1 + C_2 + C_r + C_p) / \text{Prpduction Rate} \quad (19)$$

In order to demonstrate cost behavior of the system, system cost is examined at various values of "n" and different working speeds of cell. In this regard, full enumeration is used for optimizing objective function (19). For this purpose, the value of *n* is increased so that the optimal value of objective function is found. Furthermore, the optimum speed of the cell is numerically evaluated by applying a steepest decent algorithm and finding optimum values of machining and robot loading/unloading rates.

4. Numerical Results

Model of the problem under study was introduced in the previous section along with needed theories to calculate performance criteria and also cost function. This section will apply theories shown before to solve some examples for investigating performance of the cell. Meanwhile, optimization process of the objective function will be addressed by these examples. In order to explain the implementation process of the proposed methods, an example with maximum capacity of 3 is studied for the pallet. Parameters used in model for this example imply that: machining rate for machines 1 and 2 is considered 0.5 parts/time unit; loading, unloading and combinatorial loading/unloading rate by robot are taken 4, 4, and 2 parts/time unit, respectively; handling rate of pallet is assumed as 1 per time unit; while failure rate and repair rate of robot are considered 0.1. Also, failure and repair rates of machines are equal to 0.01 and 0.1, respectively. Steady state Probabilities of the system are calculated in this case, which are summarized in Table 2.

Having calculated the steady state probabilities, the system performance criteria can be extracted. System performance criteria for this special case have been shown in Table 3.

According to the data in Table 3, production rate of flexible cell in this case (*n=3*) is calculated as follows:

$$\begin{aligned}\text{Production Rate} &= \upsilon_1 \times BM1 + \upsilon_2 \times BM2 + (\upsilon_1 + \upsilon_2) \times BM12 \\ &= 0.5 \times 0.2210 + 0.5 \times 0.1877 + 1 \times 0.2476 \\ &= 0.4519\end{aligned} \quad (20)$$

Therefore, production rate of the cell per time unit is equal to 0.4519 parts. In the following, costs of the flexible cell are examined and optimal cost for different values of parameters are calculated. For this purpose, system costs are first measured for the example mentioned in the previous section. Then, the minimum cost is found.

Cost parameters for this example are defined as listed in Table 4. Total costs of machines 1 and 2 are obtained by adding their constant costs with the products of variable costs in machining rates. Similarly, total cost of robot is found by adding its constant cost with the product of variable cost in total loading and unloading rates. At last, total cost of pallet is calculated by adding its constant cost with the product of pallet capacity in its variable cost.

As seen in the previous section, production rate of the cell for *n=3* with above mentioned parameters was obtained 0.4519. Thus, total cost of the cell can be written as below considering the production rate and Table 4 data:

$$\begin{aligned}TC &= (C_1 + C_2 + C_r + C_p) / \text{Prpduction Rate} \\ &= (12.5 + 12.5 + 3.6 + 1.75) / 0.4519 \\ &= 67.1608\end{aligned} \quad (21)$$

In the following, the cost will be calculated for different values of some parameters to explore the minimum cost per various problem parameters. The value of total cost is depicted in Fig. 2 for different machining rates. In this analysis the machining rate is increased from 0.1 to 10 parts/time unit. Based on a steepest descent algorithm and using MATLAB software, the minimum cost approximately occurs at machining rate of 19 parts/time unit and cost of 44.6405. At lower machining rates, the production rate of cell is small which can cause the total cost to be raised. Instead, at higher machining rates, increased variable cost would lead to raised total cost.

Fig. 4 shows variations of total cost versus combinatorial loading/unloading rate which has been taken equal for both machines. Based on a steepest descent algorithm and using MATLAB software, the minimum cost for different values of this rate is obtained 67.1522 at approximately 2.1 parts/time unit rate. Same as the reason argued for the previous case, the increased cost at lower combinatorial loading/unloading rates is attributed to small production rate of the cell.

The small production rate of the cell which appears in denominator of the total cost function would lead to increase in total cost. On the other hand, the variable cost of robot raises by increasing the combinatorial loading/unloading rate which can increase total cost of the system.

Fig. 5 shows variations of total cost versus combined failure and repair rate for machine 1. It is expected that total costs of the system are increased by raising the failure rate due to smaller production rate of the cell. As can be observed in Fig. 5, increasing λ_1 will raise total cost of the system. On the other hand, it is expected that total cost of the system would be decreased at greater repair rate of the robot. It is evident that total cost of the system is decreased by raising μ_1 due to greater production rate of the cell. It seems that the minimum cost is reported at low failure and high repair rates, which is confirmed by Fig.5. Decreasing the failure rate and increasing the repair rate of machine 1 would lead to gradually increased production rate for the cell. By setting the failure rate to zero, production rate of the cell will become equal to production rate of the case in which failure is not considered for machine 1. Therefore, reduction of the failure rate seems to approach system costs to the case when failure is not considered for machine 1. It can be observed that the system costs tend to approach to the same value when $\lambda_1=0$ which is the same system cost for which machine 1 is down. However, the values of λ_1 and μ_1 are initialized from 0.1 in Fig. 5.

Another issue to study is variations of cost versus simultaneous change in λ_1 and λ_2. Fig. 6 illustrates the variations of cost versus these two parameters. It can be seen that total cost of the system reveals an almost linear correlation with changing these parameters. Thereby, keeping one of these two parameters constant and increasing the other one will linearly raise the cost.

In fact, increasing the failure rates will reach the cost to its maximum value within the range of these two parameters. Similarly, reducing these two parameters will minimize the cost at λ_1 and λ_2 equal to zero. Minimum cost means a case where no failure occurs for the machines. Variations of the cost versus these two parameters are attributed to changing production rate of the cell.

At the end, variations of the total cost versus pallet capacity are investigated and it will be tried to find the optimal value of pallet capacity for the mentioned special case. Fig. 7 shows the trend of cost change versus pallet capacity. Cost values have been summarized in Table 5 for different *n* values. It can be observed that the minimum cost occurs at capacity 13 of the pallet.

5. Conclusion

It has been tried in this research to investigate performance of an FMC using queuing theory. The cell under study is comprised of a robot, two machines and one pallet. Since machines and robots might experience random failures, some system performance criteria were calculated i.e. time percentage of being busy and idle for both the machines and the robot. Later, production rate of the cell as well as total cost of the manufacturing system including constant and variable costs of machines and robot were obtained. Finally, performance criteria, production rate and total cost of the system were calculated for a typical example. Then, variations of total cost versus various parameters were assessed to verify optimality of the system in terms of cost. For future works, one can examine combinations of different number of machines and robots. Application of other approaches such as simulation techniques and/or Petri nets for more complicated cells can also be studied.

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Tables

Table1. Comparison of modeling approaches in Flexible Manufacturing Systems (FMSs) [4]

Approaches	Advantages	Disadvantages
queuing theory	providing optimal solutions providing information about system in long-term defining main aspects of the system during design using for performance evaluation of systems	limitation in complicated systems providing approximate solution in complicated systems
simulation	ability to model complicated real-world systems ability to show most details of manufacturing systems working as a tool for supporting decision making	possibly long and costly run of each simulation sensitivity to number of parameters time-consuming validation and development uncertainty in conforming to reality
Petri nets	considering prerequisite between events using powerful mathematical basis compatibility with systems having numerous states	inability to be used in performance evaluation, ability to be used only in qualitative analyses

Table2. Steady state probabilities of the syst

State	Probability	State	Probability	State	Probability	State	Probabi
0000	0.15063	0130	0.0042	1033	6.1285×10^{-5}	2021	0
0001	0.0193	0202	0.0021	1102	0.0261	2023	3.362×1
0002	0.084	0203	0.0016	1103	0.00044	2031	2.067×1
0003	0.0019	0300	0.037352	1110	0.01312	2033	3.818×1
0010	0.1309	0302	0.00059	1130	0.00219	2102	0.033
0011	0.0158	0303	4.347×10^{-5}	1202	0.00663	2103	0.0005
0013	0.00027	0310	0.0045	1203	0.00285	2110	2.62×10
0021	0.00201	0330	0.00044	1302	0.000773	2130	5.059×1
0023	0.0015	1001	0	1303	6.0533×10^{-5}	2202	0.004
0030	0.03512	1002	7.666×10^{-5}	1310	0.0027	2203	0.0031
0031	0.0005	1003	8.818×10^{-5}	1330	0.00025	2302	8.1892×
0033	4.0829×10^{-5}	1011	0.0328	2001	2.4839×10^{-17}	2303	8.1683×
0100	0.1373	1013	0.00055	2002	0	2310	4.4913× 17
0102	0.01658	1021	0.0083	2003	1.1855×10^{-16}	2330	2.2965× 18
0103	0.00028	1023	0.0036	2011	6.0376×10^{-17}	3001	0.037
0110	0.00163	1031	0.00068	2013	$4.0434\times10^{-}$	3003	0.0037

					17		

Table 3. System performance criteria

Performance Criterion	Probability
Machine 1 being busy	0.4686
Machine 1 being idle	0.4639
Machine 1 being down	0.0469
Machine 2 being busy	0.4352
Machine 2 being idle	0.5058
Machine 2 being down	0.0435
Robot being busy	0.2260
Robot being idle	0.7533
Robot being down	0.0207
Only machine 1 being busy	0.2210
Only machine 2 being busy	0.1877

Both machines being busy	0.2476
Pallet being busy	0.1506
Machine 1 waiting	0.0206
Machine 2 waiting	0.0155

Table4. System costs

Cost	Machine 1	Machine 2	Robot	Pallet
Constant	11	11	2	1
Variable	3	3	0.4	0.25
Total	1+0.25×3=1.75	2+0.4×4=3.6	11+3×0.5=12.5	11+3×0.5=12.5

Table5. Total cost of the system versus different values of *n*

n	*TC*	*n*	*TC*	*n*	*TC*	*N*	*TC*
1	101.6743	6	51.9326	11	49.0425	16	48.9914
2	69.5104	7	50.8508	12	48.9143	17	49.1080
3	60.5203	8	50.1119	13	48.8581	18	49.2509

4	56.01134	9	49.6051	14	48.8591	19	49.4163
5	53.5556	10	49.2630	15	48.9063	20	49.6008

Figures

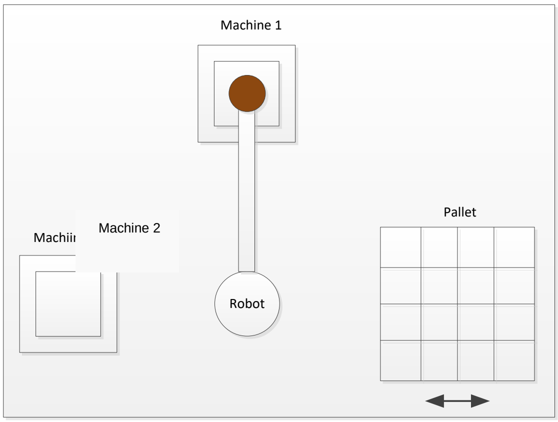

Fig.1. Flexible Manufacturing Cell with two machines, one robot and one pallet

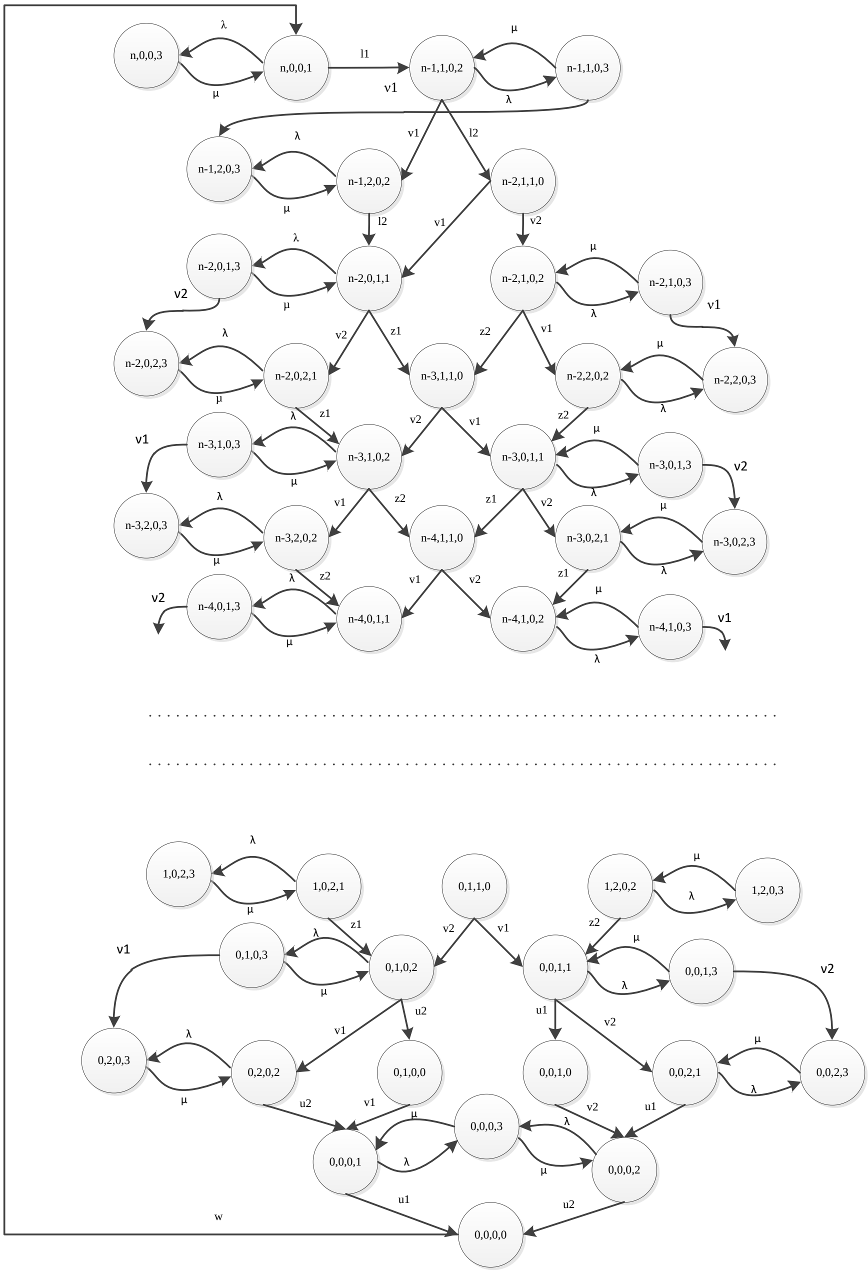

Fig.2. State transition diagram for operations of flexible cell when just the robot is down

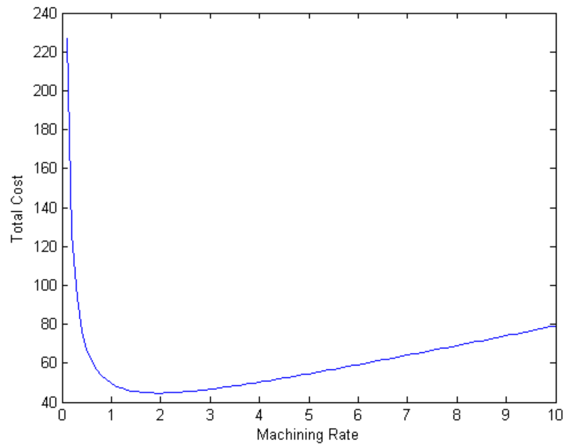

Fig.3. Variations of total cost versus machining rate

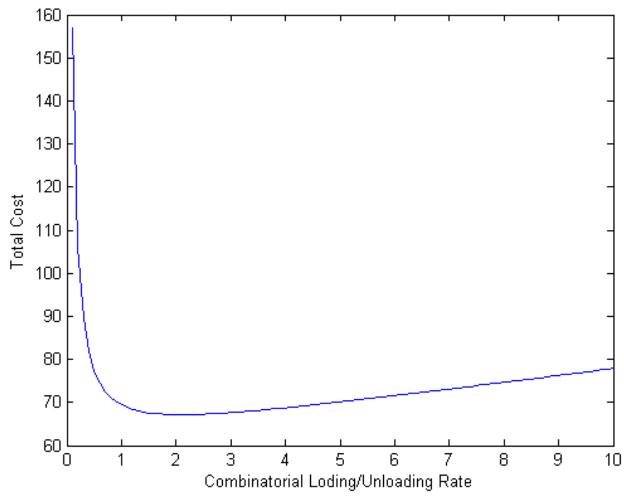

Fig.4. Variations of total cost versus combinatorial loading/unloading rate

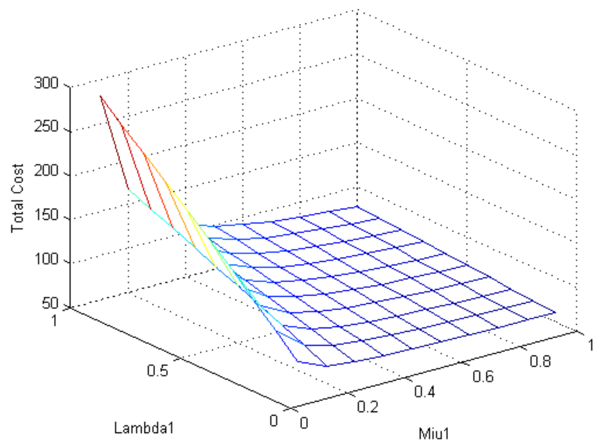

Fig.5. Variations of total cost versus combined failure and repair rates of machine 1

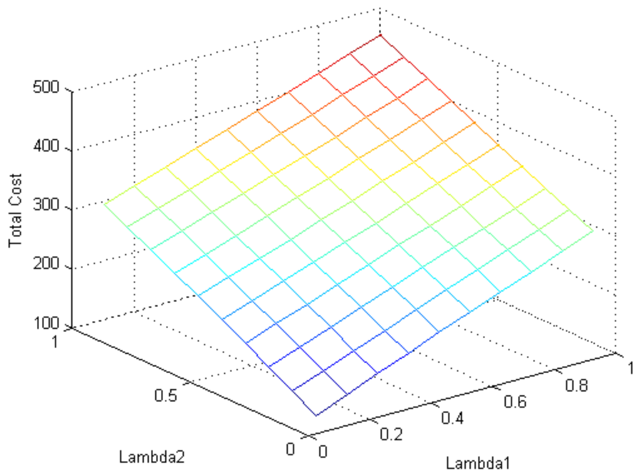

Fig.6. Variations of total cost versus simultaneous change in λ_1 and λ_2

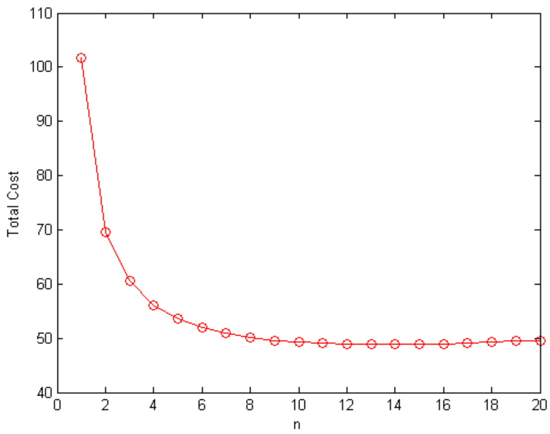

Fig.7. Variations of total cost versus pallet capacity