# PERFORMANCE PREDICTION OF A FLEXIBLE MANUFACTURING SYSTEM

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**(Received: December 8, 2001 - Accepted in Revised Form: July 28, 2002)**

**Abstract** The present investigation presents a stochastic model for a flexible manufacturing system consisting of flexible machine, loading/unloading robot and an automated pallet-handling device. We consider unreliable flexible manufacturing cell (FMC) wherein machine and robot operate under individual as well as common cause random failures. The pallet-handling system is completely reliable. The pallet operation times, loading/unloading times and material handling times are considered to be random and exponentially distributed. By constructing governing equations for various system states at equilibrium, the steady-state probabilities are obtained. Some system characteristics namely utilization rate of the handling system, utilization rate of the production machine and utilization rate of the robot etc. are obtained. Some special cases are also discussed for reliable and unreliable cells. Sensitivity analysis is facilitated to examine the effect of parameters on system performance by taking numerical illustration.

**Key Words** Flexible Manufacturing Cell (FMC), Pallet-Handling Device, Reliability, Common Cause Failure, Robot, Loading/Unloading

**چکیده** در این تحقیق، به یک مدل آماری محتمل برای سیستمهای تولید انعطاف پذیر دارای ماشین انعطاف پذیر، ربات بارگذار / باربردار و یک وسیله اتوماتیک جابجایی پالت پرداخته می شود. یک واحد ساخت از نوع انعطاف پذیر غیر مطمئن تحت شرایطی که ماشین و ربات تحت خرابی اتفاقی مختص خود یا خرابی عمومی عمل می کند را در نظر گرفته ایم. زمانهای عملیات بارگذاری / باربرداری و حمل و نقل مواد را اتفاقی با توزیع اکسپونانسیل در نظر گرفته ایم. با بنای معادلات حاکم برای حالتهای مختلف تعادل، احتمالات حالات ثبات بدست آمده اند. پاره ای از مشخصات سیستم مانند سرعت استفاده از وسیله حمل و نقل، سرعت کاربرد ماشین تولید و سرعت بکارگیری ربات بدست آمده اند. برخی حالات ویژه برای سلولهای مطمئن و غیر مطمئن بحث شده است. بررسیهای عددی، آنالیز حساسیت برای آزمایش تاثیر عوامل بر رفتار سیستم را نیز تسهیل کرده است.

## 1. INTRODUCTION

At various stages of design, planning and operation, system engineer is involved in many manufacturing cells. To address manufacturing cell design and flexibility issues, a wide range of modeling techniques are available. A variety of products can be manufactured on the one and same outfit because of new techniques and production concepts in industry by introducing flexibility into the production machines in order to obtain desired demand for customized products. Thus to achieve this flexibility, even with limited investment flexible manufacturing cells (FMC's) consisting of one or more flexible machines, material handling system and robot etc. have been used which may have the facility to be subsequent integration into a flexible manufacturing system (FMS) for larger volume of production.

Several authors have contributed their research work in this direction. Solberg [1] investigated a mathematical model of computerized manufacturing systems. Buzacott and Shanthikumar [2] studied models for understanding manufacturing flexible systems. Kimeria [3] discussed hierarchical control of production in flexible manufacturing systems. Buzacott and Mandelbaum [4] described flexibility and productivity in manufacturing systems. Mandelbaum and Brill [5] suggested measures of flexibility for production systems. Siedmann [6] provided on-line scheduling of a robotic manufacturing cell with stochastic sequence dependent processing rates in his paper.

Mandelbaum and Brill [7] also gave examples of measurement of flexibility and adaptivity in manufacturing systems. Chan and Bedworth [8] gave design of a scheduling system for flexible manufacturing cells. Hutchinson et al. [9] developed scheduling approaches for random job shop flexible manufacturing systems. Askin and Standrige [10] considered the analysis of manufacturing systems using analytical and experimental models. Dallery [11] studied the failure and repair times in stochastic models of manufacturing systems using generalized exponential distributions. Choi and Lee [12] offered a heuristic approach for machine loading problem in non-preemptive flexible manufacturing systems. Savsar [13] made the reliability analysis of a flexible manufacturing system. Recently, a dynamic scheduling for a flexible processing system was studied by Nam [14] by considering an open processing network model with discretionary routing. Choi and Lee [15] discussed computational algorithms for modeling unreliable manufacturing systems based on Markovian property.

The common cause failures (CCF) have been receiving increasing attention because of realization that the assumption of independent unit failures maybe violated in the real life environment of manufacturing system, so is the case with flexible manufacturing cell (FMC) wherein both robot and machine may fail simultaneously. Hughes [16] considered a new approach to common cause failure. Dhillon and Anude [17] gave a comprehensive review of the common cause failures in engineering systems. Littlewood [18] gave the impact of diversity upon common mode of failures. Jain and Ghimire [19] analyzed the reliability of k-r-out of N: G system subject to random and common cause failure. Jain [20] described the reliability analysis of two-unit system with common cause shock failure. A detail description of common cause failure can be found in Dhillon [21]. In this paper, we study a stochastic model to determine the characteristics of a flexible manufacturing cell under random operational conditions which include random failure of cell components, random processing times, random machine loading/unloading times and random pallet transfer times. The machine and robot both fail individually as well as due to common cause whereas material-handling device is assumed to be completely reliable.

## 2. A STOCHASTIC MODEL

We consider a flexible manufacturing cell (FMC) consisting of machine and robot, which may be fail individually and also due to common cause failure. There is also a provision of fully reliable and automated part-transfer device called pallet, which is capable of delivering n free blanks consisting of different parts into the cell. The robot goes to the pallet, grips a blank, takes it to the machine and loads the same. On the completion of the machining operation, the robot moves to the machine, grips the part, reaches to the pallet and fills the part in its proper spot. After this, robot takes up another blank, goes to the machine and loads the blank to the machine. This operation is kept on till the completion of all n blanks. After completion of the operation, the parts are moved out of the cell by the pallet and a new pallet with a set of n blanks is delivered to the cell automatically. The processing times, robot's loading/unloading times, pallet transfer times and the machine's operational and failure times are assumed to be random and exponentially distributed. The system states, in order to model the FMC operation, are defined as follows:

$S_{i,j,k}$ Steady-state of the flexible manufacturing cell

$P_{i,j,k}$ Steady-state probability of system being in state $S_{i,j,k}$

$i$ The number of blanks on the pallet and on the machine or on the robot gripper in the flexible manufacturing cell.

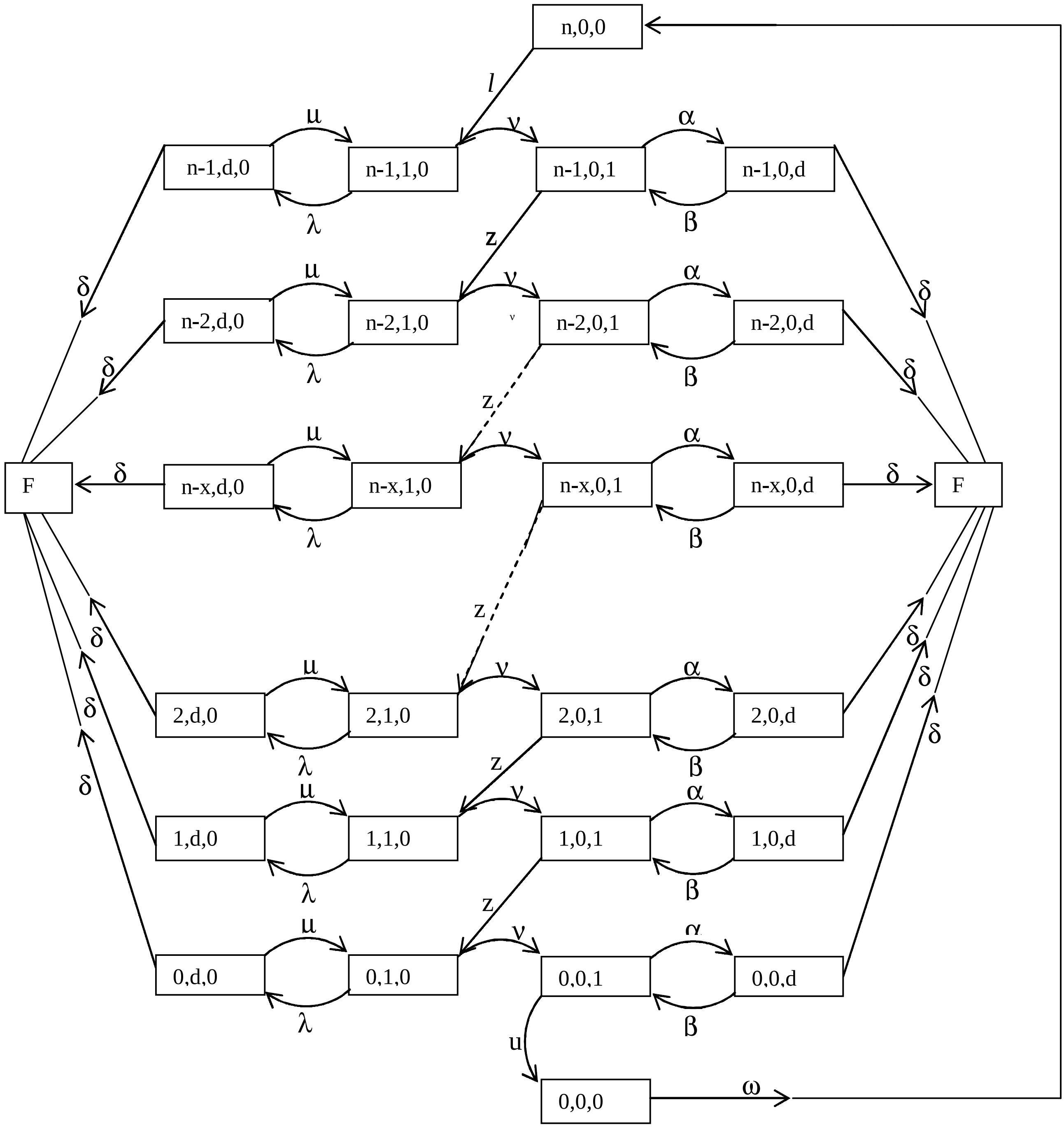


**Figure 1**. Transition rate diagram of the FMC.

j The state of the production machine (j=0 when the machine/cell is idle, j=1 if machine is operating on a part and j=d in the sense when machine is down and under repair

k The state of the robot (k = 0 if the robot is not busy in loading/unloading the machine, k = 1 when the robot is loading/unloading the machine and k = d in case of the robot is down and under repair)

The notations used for modelling purpose are given as below:

- $\omega$ Pallet transfer rate i.e. pallets/unit time
- u Unloading rate (parts/unit time) of the robot
- l Loading rate (parts/unit time) of the robot
- z Combined loading/unloading rate (i.e. parts/unit time) of the robot
- $\lambda$ Failure rate of the production machine
- $\alpha$ Failure rate of the robot
- $\delta$ Common cause failure rate of the robot and machine
- $\mu$ Repair rate of the production machine
- $\beta$ Repair rate of the robot
- $\nu$ Production rate of the machine
- n The number of parts/pallets

## 3. STEADY-STATE EQUATIONS AND ANALYSIS

In order to analyze, the stochastic model discussed in previous section, we construct the difference equation by considering the inflow and outflow rate at various system states as shown in Figure 1. Now the steady-state equations governing the model are given by

$$l\,P_{n,0,0} = wP_{0,0,0} \tag{1}$$

$$uP0,0,1 = \omega P0,0,0 \tag{2}$$

$$\nu P_{0,1,0} + \beta P_{0,0,d} = (\alpha + u) P_{0,0,1} \tag{3}$$

$$\alpha P_{n-x,0,1} = (\beta + \delta) P_{n-x,0,d}\ ,\ x = 1,2,\ldots, n \tag{4}$$

$$\nu P_{n-x,1,0} + \beta P_{n-x,0,d} = (\alpha + z) P_{n-x,0,1},\ x=1,2,\ldots,n-1 \tag{5}$$

$$\lambda P_{n-x,1,0} = (\mu + \delta) P_{n-x,d,0},\ x = 1,2\ldots n \tag{6}$$

$$\mu P_{n-x,d,0} + z\,P_{n-x+1,0,1} = (\lambda + \nu) P_{n-x,1,0},\ x = 1,2\ldots,n \tag{7}$$

On solving the Equations 1-7 recursively, we get

$$P_{n,0,0} = \frac{\omega}{l} P_{0,0,0} \tag{8}$$

$$P_{0,0,1} = \frac{\omega}{u} P_{0,0,0} \tag{9}$$

$$P_{i,0,1} = \frac{\omega\xi\eta^{i}\rho^{i-1}}{\nu^{i}\,u\,z^{i}\,(\mu+\delta)^{i}(\beta+\delta)^{i}} P_{0,0,0},\ i = 1,2,\ldots,n-1 \tag{10}$$

where $\xi = \alpha\delta + (\beta+\delta)u$ , $\eta = \lambda\delta + (\mu+\delta)\nu$ and $\rho = \alpha\delta + (\beta+\delta)z$

$$P_{i,1,0} = \frac{\omega\xi\eta^{i}\rho^{i}}{\nu^{i+1}\,u\,z^{i}\,(\mu+\delta)^{i}(\beta+\delta)^{i+1}} P_{0,0,0},\ i = 0,1,2,\ldots,n-1 \tag{11}$$

$$P_{i,d,0} = \frac{\lambda\omega\xi\eta^{i}\rho^{i}}{\nu^{i+1}\,u\,z^{i}\,(\mu+\delta)^{i+1}(\beta+\delta)^{i+1}} P_{0,0,0},\ i = 0,1,2,\ldots,n-1 \tag{12}$$

$$P_{0,0,d} = \frac{\alpha\,\omega}{(\beta+\delta)u} P_{0,0,0} \tag{13}$$

$$P_{i,0,d} = \frac{\alpha\,\omega\xi\eta^{i}\rho^{i-1}}{\nu^{i}\,u\,z^{i}\,(\mu+\delta)^{i}(\beta+\delta)^{i+1}} P_{0,0,0},\ i=1,2,\ldots,n-1 \tag{14}$$

To obtain the value of $P_{0,0,0}$, we apply the following normalizing condition:

$$\sum_{i=0}^{n}\sum_{j=0}^{d}\sum_{k=0}^{d} P_{i,j,k} = 1 \tag{15}$$

so that we have

$$P_{0,0,0} = \left[1 + \frac{\omega}{l} + \frac{\omega}{u} + \frac{\omega\xi\eta}{\nu u z(\mu+\delta)(\beta+\delta)}\left(\frac{1-\phi^{n-1}}{1-\phi}\right)\right]^{-1} \times \left[\left(1 - \frac{\alpha}{(\beta+\delta)}\right) + \frac{\omega\xi}{\nu u(\beta+\delta)}\left(\frac{1-\phi^{n}}{1-\phi}\right)\left(1 - \frac{\lambda}{\mu+\delta}\right)\right]^{-1} \tag{16}$$

where $\phi = \dfrac{\eta\rho}{\nu z(\mu+\delta)(\beta+\delta)}$

## 4. SOME SYSTEM CHARACTERISTICS

In this section, various measures of performance such as utilization rate of the pallet ($S_p$), utilization rate of production machine ($S_m$) and utilization rate of the robot ($S_r$) are obtained by using the system state probabilities, which have already been determined in previous section.

- The utilization rate of pallet i.e. the fraction of the time during which the handling system is loading and unloading a pallet at a rate of $\omega$ pallets / per unit time (or $n\omega$ parts per unit time), given as:

$$S_p = P_{0,0,0} \tag{17}$$

- The utilization rate of the production machine i.e. the fraction of time that the machine is operational, is given by

$$S_m = \sum_{i=0}^{n-1} P_{i,1,0} = \frac{\omega\xi}{\nu u(\beta+\delta)}\left[\frac{1-\phi^n}{1-\phi}\right]P_{0,0,0} \tag{18}$$

- The utilization rate of the robot i.e. the fraction of the time that the machine is operational is obtained as:

$$S_r = P_{n,0,0} + \sum_{i=1}^{n-1} P_{i,0,1} + P_{0,0,1} =$$

$$\left[\frac{\omega}{l} + \frac{\omega\xi\eta}{\nu uz(\mu+\delta)(\beta+\delta)}\left(\frac{1-\phi^{n-1}}{1-\phi}\right) + \frac{\omega}{u}\right]P_{0,0,0} \tag{19}$$

The performance characteristics obtained in Equations 17-19 hold for the unreliable cell with machine and robot failures. In case of reliable flexible manufacturing cell i.e. without machine and robot failures, the system states corresponding to states $S_{i,d,0}$ and $S_{i,0,d}$ (see Figure 1) wherein i varies from 0 to n-1, are not applicable. We can construct the corresponding equations and performance characteristics easily by taking other states into consideration. However results for the reliable FMC can be easily deduced by using 17-19 by putting $\lambda = 0$ and $\alpha = 0$ as obtained in special case (C).

## 5. SOME SPECIAL CASES

**FMC Model without Common Cause Failure** In this case we put $\delta = 0$ so that our model becomes same as Savsar's Model. We obtain the utilization rate of the pallet as

$$S_p = P_{0,0,0} \tag{20}$$

where

$$P_{0,0,0} = \left[\frac{n\omega}{\nu}\left(1+\frac{\lambda}{\mu}\right) + \omega\left(1+\frac{\alpha}{\beta}\right)\left(\frac{n}{z}+\frac{1}{u}-\frac{1}{z}\right) + \frac{\omega}{l} + 1\right]^{-1}$$

The utilization rate of the production machine is given by

$$S_m = \sum_{i=0}^{n-1} P_{i,1,0} = \left(\frac{n\omega}{\nu}\right)P_{0,0,0} \tag{21}$$

The utilization rate of the robot is

$$S_r = P_{n,0,0} + \sum_{i=1}^{n-1} P_{i,0,1} + P_{0,0,1}$$

$$= \left[\frac{\omega}{l} + (n-1)\frac{\omega}{z} + \frac{\omega}{u}\right]P_{0,0,0} \tag{22}$$

**Reliable FMC Model** In this case, putting $\lambda = 0$ and $\alpha = 0$, we have $\xi = (\beta+\delta)\nu$, $\eta = (\mu+\delta)\nu$ and $\rho = (\beta+\delta)z$. Now the Equations 17-19 become as

$$S_p = P_{0,0,0} \tag{23}$$

$$S_m = \sum_{i=0}^{n-1} P_{i,1,0} = \frac{\omega\xi}{\nu u(\beta+\delta)}\left[\frac{1-\phi^n}{1-\phi}\right]P_{0,0,0} \tag{24}$$

$$S_r = P_{n,0,0} + \sum_{i=1}^{n-1} P_{i,0,1} + P_{0,0,1} =$$

$$\left[\frac{\omega}{l} + \frac{\omega\xi\eta}{\nu uz(\mu+\delta)(\beta+\delta)}\left(\frac{1-\phi^{n-1}}{1-\phi}\right) + \frac{\omega}{u}\right]P_{0,0,0}$$

(25)

**TABLE 1. Performance Measures by Varying Common Cause Failure Rate (δ) of the Machine and Robot.**

| n | Pallet Utilization ($S_p$) | | Machine Utilization ($S_m$) | | Robot Utilization ($S_r$) | |
|---|---|---|---|---|---|---|
| | δ=0.002 | δ=0.006 | δ=0.002 | δ=0.006 | δ=0.002 | δ=0.006 |
| 5 | 0.1618 | 0.1595 | 0.8131 | 0.7984 | 15.14 | 5.8 |
| 10 | 0.0895 | 0.0876 | 0.9042 | 0.8840 | 8.4 | 3.2 |
| 15 | 0.0616 | 0.0600 | 0.9393 | 0.9168 | 5.8 | 2.2 |
| 20 | 0.0469 | 0.0454 | 0.9579 | 0.9341 | 4.5 | 1.7 |
| 25 | 0.0378 | 0.0364 | 0.9694 | 0.9448 | 3.6 | 1.4 |
| 30 | 0.0315 | 0.0302 | 0.9772 | 0.9521 | 3.1 | 1.2 |
| 35 | 0.0270 | 0.0258 | 0.9829 | 0.9573 | 2.6 | 1.0 |
| 40 | 0.0236 | 0.0224 | 0.9872 | 0.9613 | 2.3 | 0.9 |

**TABLE 2. Performance Measures by Varying Failure Rate (α) of the Robot.**

| n | Pallet Utilization ($S_p$) | | Machine Utilization ($S_m$) | | Robot Utilization ($S_r$) | |
|---|---|---|---|---|---|---|
| | α=0.001 | α=0.005 | α=0.001 | α=0.005 | α=0.001 | α=0.005 |
| 5 | 0.1522 | 0.1581 | 0.7620 | 0.7918 | 53.4 | 36.1 |
| 10 | 0.0832 | 0.0871 | 0.8342 | 0.8747 | 29.3 | 20.0 |
| 15 | 0.0572 | 0.0600 | 0.8614 | 0.9064 | 20.2 | 13.8 |
| 20 | 0.0435 | 0.0458 | 0.8756 | 0.9231 | 15.4 | 10.6 |
| 25 | 0.0351 | 0.0369 | 0.8844 | 0.9334 | 12.5 | 8.6 |
| 30 | 0.0294 | 0.0309 | 0.8904 | 0.9404 | 10.5 | 7.2 |
| 35 | 0.0253 | 0.0266 | 0.8947 | 0.9455 | 9.0 | 6.2 |
| 40 | 0.0222 | 0.0233 | 0.8979 | 0.9493 | 7.9 | 5.5 |

where

$$P_{0,0,0} = \left[1 + \frac{\omega}{l} + \frac{\omega}{u} + \frac{\omega\xi\eta}{\nu uz(\mu+\delta)(\beta+\delta)}\left(\frac{1-\phi^{n-1}}{1-\phi}\right) + \frac{\omega\xi}{\nu u(\beta+\delta)}\left(\frac{1-\phi^{n}}{1-\phi}\right)\right]^{-1}$$

**Reliable FMC Model with Common Cause Failure** On setting $\lambda = 0$ and $\alpha = 0$ and $\delta = 0$, the Equations 20-22 provide for the reliable FMC without common cause failure studied by Savsar [13]. Now we have

$$S_p = P_{0,0,0} \tag{26}$$

where $P_{0,0,0} = \left[1 + \frac{n\omega}{\nu} + \frac{\omega}{l} + \frac{\omega}{u} + (n-1)\frac{\omega}{z}\right]^{-1}$

$$S_m = \sum_{i=0}^{n-1} P_{i,1,0} = \left(\frac{n\omega}{\nu}\right)P_{0,0,0} \tag{27}$$

and

$$S_r = \left[\frac{\omega}{l} + (n-1)\frac{\omega}{z} + \frac{\omega}{u}\right]P_{0,0,0} \tag{28}$$

## 5. NUMERICAL ILLUSTRATION

\In this section we compute the utilization rates of the pallet, machine and robot for unreliable FMC in order to exhibit the effect of failures on the utilization for different pallet capacities. We examine the analytical results provided by taking a

**TABLE 3. Performance Measures by Varying Failure Rate (λ) of the Production Machine.**

| n | Pallet Utilization ($S_p$) | | Machine Utilization ($S_m$) | | Robot Utilization ($S_r$) | |
|---|---|---|---|---|---|---|
| | λ=0.010 | λ=0.020 | λ=0.010 | λ=0.020 | λ=0.010 | λ=0.020 |
| 5 | 0.1632 | 0.1775 | 0.8183 | 0.8906 | 29.0 | 22.0 |
| 10 | 0.0906 | 0.0994 | 0.9113 | 1.0020 | 16.2 | 12.4 |
| 15 | 0.0626 | 0.0689 | 0.9472 | 1.0456 | 11.3 | 8.7 |
| 20 | 0.0478 | 0.0526 | 0.9662 | 1.0688 | 8.6 | 6.7 |
| 25 | 0.0386 | 0.0425 | 0.9780 | 1.0832 | 7.0 | 5.4 |
| 30 | 0.0323 | 0.0356 | 0.9861 | 1.0931 | 5.9 | 4.6 |
| 35 | 0.0278 | 0.0306 | 0.9919 | 1.1002 | 5.1 | 4.0 |
| 40 | 0.0244 | 0.0268 | 0.9963 | 1.1057 | 4.5 | 3.5 |

**TABLE 4. Performance Measures by Varying Repair Rate (μ) of the Production Machine.**

| n | Pallet Utilization ($S_p$) | | Machine Utilization ($S_m$) | | Robot Utilization ($S_r$) | |
|---|---|---|---|---|---|---|
| | μ=0.2 | μ=0.6 | μ=0.2 | μ=0.6 | μ=0.2 | μ=0.6 |
| 5 | 0.1570 | 0.1530 | 0.7865 | 0.7665 | 35.6 | 42.6 |
| 10 | 0.0868 | 0.0844 | 0.8721 | 0.8475 | 19.8 | 23.6 |
| 15 | 0.0599 | 0.0582 | 0.9049 | 0.8785 | 13.7 | 16.3 |
| 20 | 0.0457 | 0.0444 | 0.9222 | 0.8948 | 10.5 | 12.5 |
| 25 | 0.0369 | 0.0359 | 0.9330 | 0.9049 | 8.5 | 10.1 |
| 30 | 0.0309 | 0.0301 | 0.9403 | 0.9118 | 7.2 | 8.5 |
| 35 | 0.0266 | 0.0259 | 0.9455 | 0.9167 | 6.2 | 7.4 |
| 40 | 0.0233 | 0.0227 | 0.9495 | 0.9205 | 5.5 | 6.5 |

numerical example for fixed parameters as follows: $v^{-1}$=5 time units, $\lambda^{-1}$=0.06 time units, $z^{-1}$=1.0 time units, $u^{-1}$=0.6 time units, $\beta^{-1}$=12 time units, $\omega^{-1}$=5 time units per pallet. Tables 1 and 2 depict the pallet, machine and robot utilization by varying common cause failure rate (δ) and failure rate (α) of the robot respectively. We observe from Table 1 that $S_p$, $S_m$ and $S_r$ decrease with increase in pallet capacity (n) and common cause failure rate (δ). From Table 2, it is observed that machine and pallet utilization increase with the increase in failure rate of robot (α). Table 3 displays pallet, machine and robot utilization for different values of failure rate of production machine (λ). We observe that pallet and machine utilization increase with the failure rate of the production machine (λ) but the robot utilization decreases with λ. From Table 4, it is found that by increasing repair rate of the production machine (μ), pallet and machine utilization decrease whereas the robot utilization increases.

Figures 2(a-d) and 3(a-d) reveal machine utilization ($S_m$) and robot utilization ($S_r$) vs. pallet capacity (n) for different values of δ, α, λ and μ respectively. Figure 2(a) depicts machine utilization ($S_m$) for different values of common cause failure of machine (δ). It is observed that $S_m$ increases with n whereas decreases with the increase in δ. Figures 2(b) and 2(c) display machine utilization ($S_m$) for different values of failure rate of robot (α) and

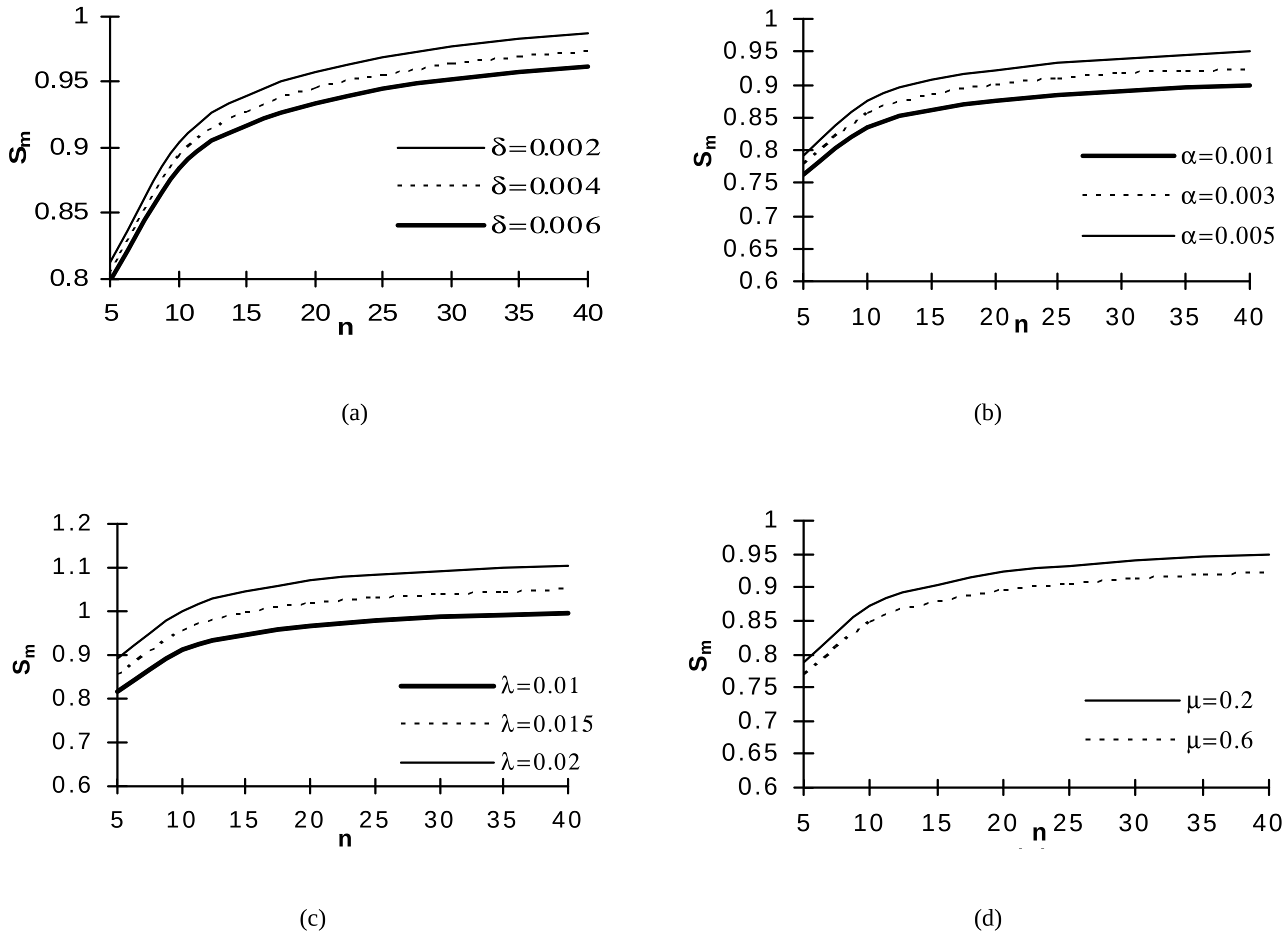


**Figure 2**. Machine Utilization vs. Pallet Capacity (a) $\delta$ (b) $\alpha$ (c) $\lambda$ and (d) $\mu$ .

failure rate of production machine ($\lambda$) respectively. We observe that machine utilization ($S_m$) increases with $\alpha$ and $\lambda$ both. Figure 2(d) demonstrates machine utilization ($S_m$) for different values of repair rate of the production machine. It is easily seen that $S_m$ decreases with the increase in $\mu$.

Figures 3(a-c) depict robot utilization ($S_r$) for different values of $\delta$, $\alpha$ and $\lambda$ respectively. We observe that robot utilization ($S_r$) decreases for increasing values of n, $\delta$, $\alpha$ and $\lambda$. Figure 3(d) displays the robot utilization ($S_r$) for $\mu$=0.2, 0.6. It is evident that robot utilization ($S_r$) increases by improving the repair rate of the production machine ($\mu$).

## 6. DISCUSSION

In this paper, we have developed a stochastic model for flexible manufacturing cell having a flexible machine, a loading/unloading robot and a pallet-handling device. The flexible manufacturing environments, where the parts of machine and robot fail individually and also due to a common cause have been analyzed. Explicit expressions obtained for various performance measures namely the utilization rate of the pallet-handling device, utilization rate of the production machine and utilization rate of the robot can be employed easily to explore the production planning and automating the system changeover in material handling system. The

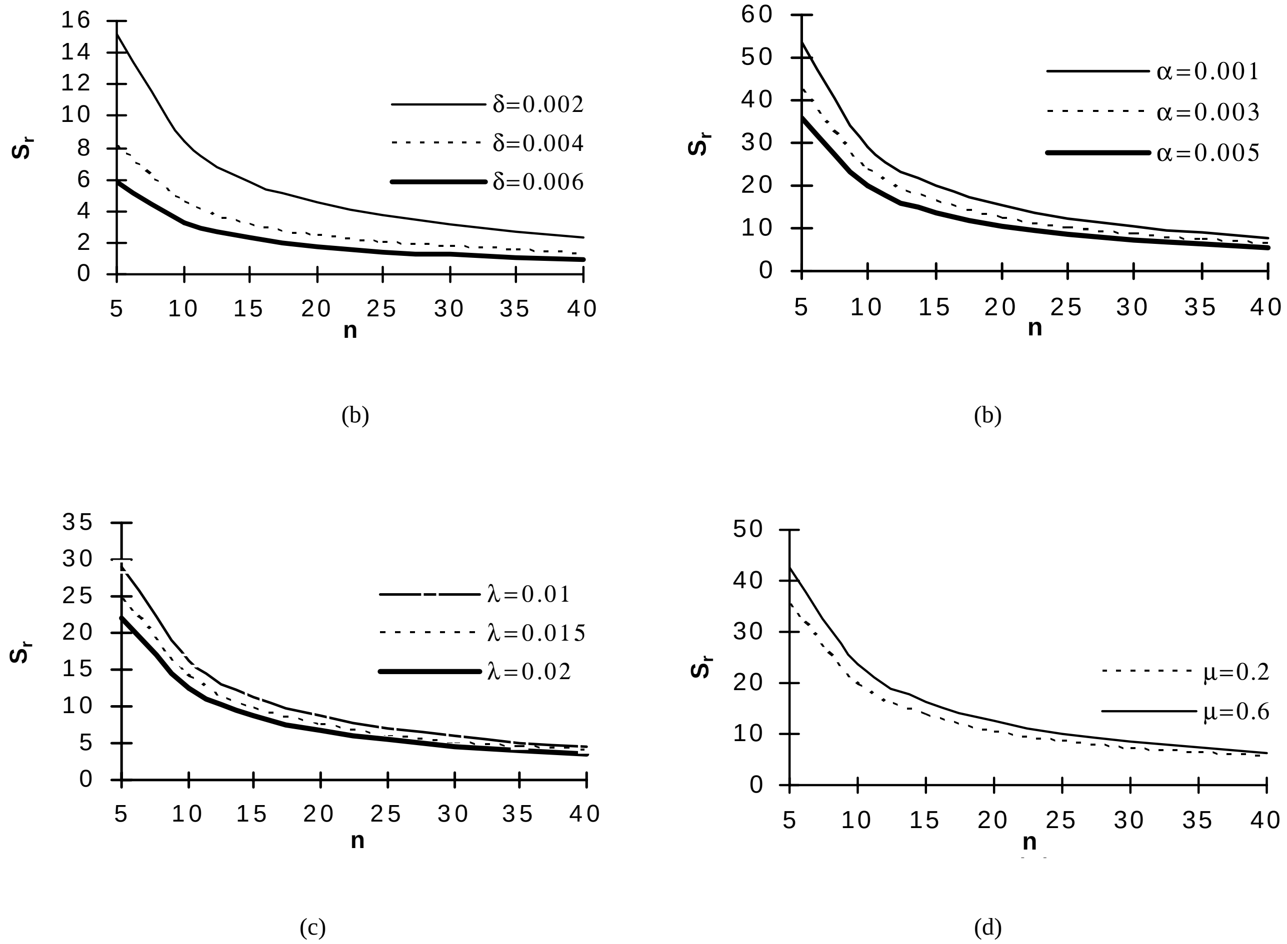


**Figure 3**. Robot Utilization vs. Pallet Capacity (a) $\delta$ (b) $\alpha$ (c) $\lambda$ and (d) $\mu$ .

special cases discussed may offer analytical insights on the benefits of our model in comparison to earlier existing results as shown in numerical simulation. A design problem in cellular manufacturing where the objective of cell formation is to streamline the material flow can be easily handled by using explicit formulae developed for FMC in real time operation.

## 7. ACKNOWLEDGEMENTS

This research has been supported by University Grants Commission, New Delhi, vide project No. F 8-5/98 (SR-I).

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