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Transient Analysis of Flexible Manufacturing Cell with Loading/Unloading Robot and Two Unreliable Machines

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ABSTRACT

This paper presents the transient analysis of a flexible manufacturing cell (FMC) consisting of two identical machines, a pallet handling system and a loading/unloading robot. After delivering the blanks by the pallet to the cell, the robot loads the first machine followed by the second. Unloading of a part starts with the machine that finishes its part first, followed by the next machine. The handling system shifts the pallet with finished parts out and carries in a new pallet with blanks, when the machining of all parts is completed. Machines are subject to failure individual as well as due to common cause failure. The failure and repair times are exponentially distributed. The pallet handing system is considered completely reliable. Robot loading/unloading times and pallet transfer times also follow exponential distributions. A computational method based on Runge-Kutta approach is developed to solve the differential difference equations governing the model in order to obtain the transient probabilities. Expressions for various performance indices have been established. The variation of different performance characteristics are displayed in graphs with respect to different parameters.

Keywords: Flexible manufacturing cell (FMC), Unreliable machines, Robot, Common cause failure, Transient analysis.

INTRODUCTION

Flexible manufacturing system (FMS) offers manufacturers a flexible and reliable system to control and monitor their manufacturing process. By using FMS, the manufacturers can produce customized products at a faster rate, making it easier for them to meet market demand. As cost and quality became bigger concerns, along with the market becoming more complex, the speed of delivery became more important to the customers. Flexibility became a great focus of attention in industry and in academic research for a number of years. Kianfar (2005) proposed a model to maximize the expected total profit over an infinite time horizon by assuming that the demand of the manufacturing product is time dependent and the failure rate of the machines was supposed to be a function of its age. Aldaihani and Savsar (2005) proposed a stochastic model to determine the performance of a flexible manufacturing cell under variable operational conditions including random machining time, random loading and unloading times and random pallet transfer times. A generalized economic manufacturing quantity model was specified by Giri and Dhohi (2005) with stochastic machine breakdown and repair in which the time to machine failure, corrective and preventive repair times are all assumed to be random variables. Kenne and Nkeungoue (2007) dealt with the control of corrective and preventive maintenance rates in the production planning of a manufacturing system with machines subject to random failures and repairs. Jain et al. (2008) investigated a queueing model for the performance prediction of flexible manufacturing system with a multiple discrete material handling devices. Turgay (2009) introduced the design of an agent based FMS control system and evaluate the performance using time placed petri nets.

Industrial robots play an important role in advanced manufacturing systems. A major application of these robots involves loading and unloading of production machines in cellular manufacturing. Since a robot in such a cell performs repeated sequences of pickup, move, load, unload and drop operations, the throughput of the cell will depend upon the sequence of the different robot activities as well as on the sequence of different parts to be produced in the cell. Gultekin et al. (2007) have investigated the productivity gain attained by the additional flexible manufacturing cell processing identical part and the loading and unloading of machines done by the robot. Gultekin et al. (2009) determined the optimal number of machines that minimize the cycle time for given cell parameters such as processing time, robot travel times and the loading unloading times of the machines.

Flexible manufacturing cells are widely used in industry to achieve high productivity in production environments with rapidly changing product structures and customer demand. Part selection and machine loading are two major production planning problems in flexible manufacturing systems. A multi-objective mixed integer programming model of cellular manufacturing system (CMS) design was presented by Das et al. (2007) which minimizes the total system costs and maximizes the machine reliabilities along the selected processing routes. Organizational and economic aspects of FMC were discussed by Kruger et al. (2009), where the interaction between human and robots improves the efficiency of cooperative assembly.

In this paper, we have given the realistic status to the model of Savsar and Aldaihani (2007) by incorporating the state dependent failure and repair rate and common cause failure. The rest of the chapter is organized as follows. Mathematical model of FMC is described in section 2. Section 3 is devoted to Runge-Kutta algorithm. Some performance characteristics are provided in section 4. Section 5 is dedicated to sensitivity analysis. Finally concluding remarks are given in last section 6.

2. MATHEMATICAL MODEL

Consider a manufacturing system with two unreliable machines, pallet handling system and a loading/unloading robot. Following basic assumptions as detailed below we proceed for the modeling of the present study.

- n blanks are delivered to the cell by an automated pallet handling system.
- The robot reaches the pallet, holds the blank and loads the blank to the first machine. At the same time as the machine starts operation on the part, the robot reaches the pallet, grips the second part and moves to the second machine and loads it. Loading rate of the robot to mth machine is considered to be l_m (m=1,2).

- The robot reaches the machine that finishes its operation first, unloads the finished parts and loads a new part with unloading rate u_m (m=1,2) at m^{th} machine. Combined loading/unloading rate of the robot is given by z_m.
- After the machining operations of all parts on the pallet are completed, the pallet with n blanks is delivered into cell automatically with pallet transfer rate w.
- Let the production rates of m^{th} machine is υ_m (m=1,2). The m^{th} machines may fail during the operations with rate λ_m and λ'_m (m=1,2). Let λ_c is the common cause failure rate. As soon as the m^{th} (m=1,2) machine fails, it is immediately sent for repair with rate μ_m and μ'_m (m=1,2). Time to failure and time to repair are assumed to be random quantities that follow exponential distribution.

System states are defined as

$S_{i,j,k,l}(t)$: State of flexible manufacturing cell at time t

$P_{i,j,k,l}(t)$: Probability that the system will be in state $S_{i,j,k,l}(t)$ at time t

i : Number of blanks on the pallet

States of the production machine 1 can be defined as

$$j = \begin{cases} 0, & machine\ is\ idle \\ 1, & machine\ is\ operating\ on\ a\ part \\ 2, & machine\ is\ waiting\ for\ the\ robot \\ 3, & machine\ is\ under\ repair \end{cases}$$

States of the production machine 2 is defined as

$$k = \begin{cases} 0, & machine\ is\ idle \\ 1, & machine\ is\ operating\ on\ a\ part \\ 2, & machine\ is\ waiting\ for\ the\ robot \\ 3, & machine\ is\ under\ repair \end{cases}$$

and state of robot are given as

$$l = \begin{cases} 0, & robot\ is\ idle \\ 1, & robot\ is\ loading/unloading machine\ 1 \\ 2, & robot\ is\ loading/unloading machine\ 2 \end{cases}$$

The differential difference equations governing the models are

$$\frac{d}{dt}P_{n,0,0,1}(t) = wP_{0,0,0,0}(t) - l_1 P_{n,0,0,1}(t) \quad (1)$$

$$\frac{d}{dt}P_{n-1,1,0,2}(t)=l_1P_{n,0,0,1}(t)+\mu_1P_{-1,3,0,2}(t)-(\nu_1+l_2+\lambda_1)P_{n-1,1,0,2}(t) \quad (2)$$

$$\frac{d}{dt}P_{n-1,3,0,2}(t)=\lambda_1P_{n-1,1,0,2}(t)-(l_2+\mu_1)P_{n-1,3,0,2}(t) \quad (3)$$

$$\frac{d}{dt}P_{n-1,2,0,2}(t)=\nu_1P_{n-1,1,0,2}(t)-l_2P_{-1,2,0,2}(t) \quad (4)$$

$$\frac{d}{dt}P_{n-2,1,3,0}(t)=\lambda_2P_{n-2,1,1,0}(t)+\mu_1^{'}P_{n-2,3,3,0}(t)-(\nu_1+\lambda_1^{'}+\mu_2)P_{n-2,1,3,0}(t) \quad (5)$$

$$\begin{aligned}\frac{d}{dt}P_{n-2,1,1,0}(t)&=l_2P_{n-1,1,0,2}(t)+\mu_1P_{n-2,3,1,0}(t)+\mu_2P_{n-2,1,3,0}(t)+\mu_cP_{n-2,3,3,0}(t)\\&-(\nu_1+\nu_2+\lambda_1+\lambda_2+\lambda_c)P_{n-2,1,1,0}(t)\end{aligned} \quad (6)$$

$$\frac{d}{dt}P_{n-2,3,1,0}(t)=l_2P_{n-1,1,0,2}(t)+\lambda_1P_{n-2,1,1,0}(t)+\mu_2^{'}P_{n-2,3,3,0}(t)-(\nu_2+\lambda_2^{'}+\mu_1)P_{n-2,3,1,0}(t) \quad (7)$$

$$\frac{d}{dt}P_{n-2,3,3,0}(t)=\lambda_1^{'}P_{n-2,1,3,0}(t)+\lambda_2^{'}P_{n-2,3,1,0}(t)+\lambda_cP_{n-2,1,1,0}(t)-(\mu_1^{'}+\mu_2^{'}+\mu_c)P_{n-2,3,3,0}(t) \quad (8)$$

$$\frac{d}{dt}P_{n-2,0,2,1}(t)=\nu_2P_{n-2,0,1,1}(t)-z_1P_{n-2,0,2,1}(t) \quad (9)$$

$$\frac{d}{dt}P_{n-2,0,1,1}(t)=\nu_1P_{n-2,1,1,0}(t)+l_2P_{n-1,2,0,2}(t)+\mu_2P_{n-2,0,3,1}(t)-(\nu_2+z_1+\lambda_2)P_{n-2,0,1,1}(t) \quad (10)$$

$$\frac{d}{dt}P_{n-2,0,3,1}(t)=\nu_1P_{n-2,1,3,0}(t)+\lambda_2P_{n-2,0,1,1}(t)-(z_1+\mu_2)P_{n-2,0,3,1}(t) \quad (11)$$

$$\frac{d}{dt}P_{n-2,3,0,2}(t)=\nu_2P_{n-2,3,1,0}(t)+\lambda_1P_{n-2,1,0,2}(t)-(z_2+\mu_1)P_{n-2,3,0,2}(t) \quad (12)$$

$$\frac{d}{dt}P_{n-2,1,0,2}(t)=\nu_2P_{n-2,1,1,0}(t)+\mu_1P_{n-2,3,0,2}(t)-(\nu_1+z_2+\lambda_1)P_{n-2,1,0,2}(t) \quad (13)$$

$$\frac{d}{dt}P_{n-2,2,0,2}(t)=\nu_1P_{n-2,1,0,2}(t)-z_2P_{n-2,2,0,2}(t) \quad (14)$$

$$\begin{aligned}\frac{d}{dt}P_{x,1,3,0}(t)&=z_1P_{x+1,0,3,1}(t)+\lambda_2P_{x,1,1,0}(t)+\mu_1^{'}P_{x,3,3,0}(t)-(\nu_1+\lambda_1^{'}+\mu_2)P_{x,1,3,0}(t),\\&x=1,2,\ldots,n-3\end{aligned} \quad (15)$$

$$\begin{aligned}\frac{d}{dt}P_{x,1,1,0}(t)&=z_1P_{x+1,0,1,1}(t)+z_2P_{x+1,1,0,2}(t)+\mu_1P_{x,3,1,0}(t)+\mu_2P_{x,1,3,0}(t)\\&-(\nu_1+\nu_2+\lambda_1+\lambda_2+\lambda_c)P_{x,1,1,0}(t)+\mu_cP_{n-3,3,3,0},\quad x=1,2,\ldots,n-3\end{aligned} \quad (16)$$

$$\frac{d}{dt}P_{x,3,1,0}(t) = z_2 P_{x+1,3,0,2} + \lambda_1 P_{x,1,1,0}(t) + \mu_2^{'} P_{x,3,3,0}(t) - (v_2 + \lambda_2^{'} + \mu_1) P_{x,3,1,0}(t), \quad x = 1,2,\ldots, n-3 \tag{17}$$

$$\frac{d}{dt}P_{x,3,3,0}(t) = \lambda_1^{'} P_{x,1,3,0}(t) + \lambda_2^{'} P_{x,3,1,0}(t) + \lambda_c P_{x,1,1,0}(t) - (\mu_1^{'} + \mu_2^{'} + \mu_c) P_{x,3,3,0}(t), \quad x = 1,2,\ldots, n-3 \tag{18}$$

$$\frac{d}{dt}P_{x,2,0,2}(t) = v_1 P_{x,1,0,2}(t) - z_2 P_{x,2,0,2}(t), \quad x = 1,2,\ldots, n-3 \tag{19}$$

$$\frac{d}{dt}P_{x,1,0,2}(t) = z_1 P_{x+1,0,2,1}(t) + v_2 P_{x,1,1,0}(t) + \mu_1 P_{x,3,0,2}(t) - (v_1 + z_2 + \lambda_1) P_{x,1,0,2}(t), \quad x = 1,2,\ldots, n-3 \tag{20}$$

$$\frac{d}{dt}P_{x,3,0,2}(t) = v_2 P_{x,3,1,0}(t) + \lambda_1 P_{x,1,0,2}(t) - (z_2 + \mu_1) P_{x,3,0,2}(t), \quad x = 1,2,\ldots, n-3 \tag{21}$$

$$\frac{d}{dt}P_{x,0,3,1}(t) = v_1 P_{x,1,3,0}(t) + \lambda_2 P_{x,0,1,1}(t) - (z_1 + \mu_2) P_{x,0,3,}(t), \quad x = 1,2,\ldots, n-3 \tag{22}$$

$$\frac{d}{dt}P_{x,0,1,1}(t) = z_2 P_{x+1,2,0,2}(t) + v_1 P_{x,1,1,0}(t) + l_2 P_{x,2,0,2}(t) + \mu_2 P_{x,0,3,1}(t) - (v_2 + z_1 + \lambda_2) P_{x,0,1,1}(t), \quad x = 1,2,\ldots, n-3 \tag{23}$$

$$\frac{d}{dt}P_{x,0,2,1}(t) = v_2 P_{x,0,1,1}(t) - z_1 P_{x,0,2,1}(t), \quad x = 1,2,\ldots, n-3 \tag{24}$$

$$\frac{d}{dt}P_{0,1,3,0}(t) = z_1 P_{1,0,3,1}(t) + \lambda_2 P_{0,1,1,0}(t) + \mu_1^{'} P_{0,3,3,0}(t) - (v_1 + \lambda_1^{'} + \mu_2) P_{0,1,3,0}(t) \tag{25}$$

$$\frac{d}{dt}P_{0,1,1,0}(t) = z_1 P_{1,0,1,1}(t) + z_2 P_{1,1,0,2}(t) + \mu_1 P_{0,3,1,0}(t) + \mu_2 P_{0,1,3,0}(t) + \mu_c P_{0,3,3,0} - (v_1 + v_2 + \lambda_1 + \lambda_2 + \lambda_c) P_{0,1,1,0}(t) \tag{26}$$

$$\frac{d}{dt}P_{0,3,1,0}(t) = z_2 P_{1,3,0,2} + \lambda_1 P_{0,1,1,0}(t) + \mu_2^{'} P_{0,3,3,0}(t) - (v_2 + \lambda_2^{'} + \mu_1) P_{0,3,1,0}(t) \tag{27}$$

$$\frac{d}{dt}P_{0,3,3,0}(t) = \lambda_1^{'} P_{0,1,3,0}(t) + \lambda_2^{'} P_{0,3,1,0}(t) + \lambda_c P_{0,1,1,0}(t) - (\mu_1^{'} + \mu_2^{'} + \mu_c) P_{0,3,3,0}(t) \tag{28}$$

$$\frac{d}{dt}P_{0,2,0,2}(t) = v_1 P_{0,1,0,2}(t) - z_2 P_{0,2,0,2}(t) \tag{29}$$

$$\frac{d}{dt}P_{0,1,0,2}(t) = z_1 P_{1,0,2,1}(t) + v_2 P_{0,1,1,0}(t) + \mu_1 P_{0,3,0,2}(t) - (v_1 + z_2 + \lambda_1) P_{0,1,0,2}(t) \tag{30}$$

$$\frac{d}{dt}P_{0,3,0,2}(t) = v_2 P_{0,3,1,0}(t) + \lambda_1 P_{0,1,0,2}(t) - (z_2 + \mu_1) P_{0,3,0,2}(t) \tag{31}$$

$$\frac{d}{dt}P_{0,0,3,1}(t)=\nu_1P_{0,1,3,0}(t)+\lambda_2P_{0,0,1,1}(t)-(z_1+\mu_2)P_{0,0,3,1}(t) \quad (32)$$

$$\frac{d}{dt}P_{0,0,1,1}(t)=z_2P_{1,2,0,2}(t)+\nu_1P_{0,1,1,0}(t)+l_2P_{0,2,0,2}(t)+\mu_2P_{0,0,3,1}(t)-(\nu_2+z_1+\lambda_2)P_{0,0,1,1}(t) \quad (33)$$

$$\frac{d}{dt}P_{0,0,2,1}(t)=\nu_2P_{0,0,1,1}(t)-u_1P_{0,0,2,1}(t) \quad (34)$$

$$\frac{d}{dt}P_{0,3,0,0}(t)=u_2P_{0,3,0,2}(t)+\lambda_1P_{0,1,0,0}(t)-\mu_1P_{0,3,0,0}(t) \quad (35)$$

$$\frac{d}{dt}P_{0,1,0,0}(t)=u_2P_{0,1,0,2}(t)+\mu_1P_{0,3,0,0}(t)-(\nu_1+\lambda_1)P_{0,1,0,0}(t) \quad (36)$$

$$\frac{d}{dt}P_{0,0,1,0}(t)=u_1P_{0,0,1,1}(t)+\mu_2P_{0,0,3,0}(t)-(\nu_2+\lambda_2)P_{0,0,1,0}(t) \quad (37)$$

$$\frac{d}{dt}P_{0,0,3,0}(t)=u_1P_{0,0,3,1}(t)+\lambda_2P_{0,0,1,0}(t)-\mu_2P_{0,0,3,0}(t) \quad (38)$$

$$\frac{d}{dt}P_{0,0,0,1}(t)=\nu_1P_{0,1,0,0}(t)+u_2P_{0,2,0,2}(t)-u_1P_{0,0,0,1}(t) \quad (39)$$

$$\frac{d}{dt}P_{0,0,0,2}(t)=\nu_2P_{0,0,1,0}(t)+u_1P_{0,0,2,1}(t)-u_2P_{0,0,0,2}(t) \quad (40)$$

$$\frac{d}{dt}P_{0,0,0,0}(t)=u_1P_{0,0,0,1}(t)+u_2P_{0,0,0,2}(t)-wP_{0,0,0,0}(t) \quad (41)$$

3. RUNGE-KUTTA ALGORITHM

Runge-Kutta algorithm is developed to determine the solution of a system of ordinary differential equations (1)-(41). It is worthwhile to discuss procedure to implement Runge-Kutta approach.

Consider a general set of differential equations that can be written as

$$X^{'}=F(t,X)\ ;\ X(a)=S \quad (42)$$

where $X=\begin{bmatrix}x\\y\end{bmatrix}$, $X'=\begin{bmatrix}x'\\y'\end{bmatrix}$ and F is the vector. We can write

$$X_i^{'}=f_n(t,X_1,X_2,.....,X_n)$$

for i=1,2,3,…,n and $X_i(a)=S_i$, i=1,2,3,…,n.

and let

$$X=[X_1,X_2,X_3,.....,X_n]^T$$

$$F=[f_1,f_2,f_3,.....,f_n]^T$$

$X' = [X_1^{'}, X_2^{'}, X_3^{'}, ..., X_n^{'}]^T$

$S = [S_1, S_2, S_3, ..., S_n]^T$

R-K method gives the algorithm to solve differential equations as

$$X(t+h) = X + \frac{h}{6}(k_1 + 2k_2 + 2k_3 + k_4)$$

where

$k_1 = F(t, X)$

$k_2 = F(t + \frac{h}{2}, X + \frac{h}{2}k_1)$

$k_3 = F(t + \frac{h}{2}, X + \frac{h}{2}k_2)$

$k_4 = F(t + \frac{h}{2}, X + hk_3)$

The Runge-Kutta algorithm is known to be very accurate and well behaved for wide range of problems if can be implemented successfully in MATLAB software. Runge-Kutta algorithm of fourth order by using the "ode 45" function of MATLAB is employed for computational purpose.

4. PERFORMANCE CAHARCTERISTICS

In this section, various performance characteristics are formulated, in terms of the transient probabilities. The following performance characteristics are constructed:

- Probability $I_1(t)$ that machine 1 is idle

$$I_1(t) = \sum_{i=0}^{n}\sum_{k=0}^{3}\sum_{l=0}^{2} P_{i,0,k,l}(t) \tag{43}$$

- Probability $B_1(t)$ that machine 1 is busy

$$B_1(t) = \sum_{i=0}^{n}\sum_{k=0}^{3}\sum_{l=0}^{2} P_{i,1,k,l}(t) \tag{44}$$

- Probability $W_1(t)$ that machine 1 is waiting for robot

$$W_1(t) = \sum_{i=0}^{n}\sum_{i=0}^{n}\sum_{k=0}^{3}\sum_{l=0}^{2} P_{i,2,k,l}(t) \tag{45}$$

- Probability $R_1(t)$ that machine 1 is under repair

$$R_1(t) = \sum_{i=0}^{n}\sum_{k=0}^{3}\sum_{l=0}^{2} P_{i,3,k,l}(t) \tag{46}$$

- Probability $I_2(t)$ that machine 2 is idle

$$I_2(t)=\sum_{i=0}^{n}\sum_{j=0}^{3}\sum_{l=0}^{2}P_{i,j,0,l}(t) \tag{47}$$

- Probability $B_2(t)$ that machine 2 is busy

$$B_2(t)=\sum_{i=0}^{n}\sum_{j=0}^{3}\sum_{l=0}^{2}P_{i,j,1,l}(t) \tag{48}$$

- Probability $W_2(t)$ that machine 2 is waiting for robot

$$W_2(t)=\sum_{i=0}^{n}\sum_{j=0}^{3}\sum_{l=0}^{2}P_{i,j,2,l}(t) \tag{49}$$

- Probability $R_2(t)$ that machine 2 is under repair

$$R_2(t)=\sum_{i=0}^{n}\sum_{j=0}^{3}\sum_{l=0}^{2}P_{i,j,3,l}(t) \tag{50}$$

- Probability $I_R(t)$ of robot being idle

$$I_R(t)=\sum_{i=0}^{n}\sum_{j=0}^{3}\sum_{k=0}^{3}P_{i,j,k,0}(t) \tag{51}$$

- Probability $B_{1R}(t)$ that robot is busy with machine 1

$$B_{1R}(t)=\sum_{i=0}^{n}\sum_{j=0}^{3}\sum_{k=0}^{3}P_{i,j,k,1}(t) \tag{52}$$

- Probability $B_{2R}(t)$ that robot is busy with machine 2

$$B_{2R}(t)=\sum_{i=0}^{n}\sum_{j=0}^{3}\sum_{k=0}^{3}P_{i,j,k,2}(t) \tag{53}$$

- Machine utilization $U_M(t)$

$$U_M(t)=\frac{B_1(t)+B_2(t)}{2} \tag{54}$$

- Robot utilization $U_R(t)$

$$U_R(t)=B_{1R}(t)+B_{2R}(t) \tag{55}$$

SENSITIVITY ANALYSIS

The Runge-Kutta method has been employed by developing a computer program in MATLAB software using routine 'ode 45' to compute the probabilities of various system states. Various performance measures for flexible manufacturing cell are computed by taking an illustration. The effect of various parameters on machine utilization and robot utilization by varying t are shown in figures 1 and 2, respectively.

For numerical results displayed in figures 1-2, we set default parameters as

$z=3$, $w=2$, $v=2$, $u_1=1$, $u_2=3$, $\mu_1=0.2$, $\mu_2=0.3$, $\mu_c=0.4$, $\lambda_1=0.02$, $\lambda_2=0.04$, $\lambda_c=0.01$, $l_1=4$, $l_2=3$.

In figures 1(a)-1(e), we display machine utilization $U_M(t)$ with the increase in time t, by varying combined loading/unloading rate of the robot, repair rate of the machine, failure rate of the machine, unloading rate of the robot, loading rate of the robot and pallet transfer rate, respectively.

From figure 1(a) it is noted that machine utilization increases sharply initially with time t then after it increase gradually for higher values of t and becomes constant almost. Utilization also increases with the increased rate of combined loading/unloading rate z. Figure 1(b) demonstrates the effect of pallet transfer rate on machine utilization $U_M(t)$. An increasing trend is seen in $U_M(t)$ as we increase the pallet transfer rate. Machine utilization increases for increased values of homogeneous and heterogeneous machine repair rates, as shown in figure 1(c). Figure 1(d) reveals that the machine failure rate deteriorates the machine utilization $U_M(t)$ highly, as it follows decreasing trend on increasing the value of machine failure rate λ for both heterogeneous and homogeneous cases. The effects of unloading and loading rates of robot are displayed in figures 1(e) and 1(f). Machine utilization rate can be increased by taking higher values of loading / unloading rates of robot.

In figures 2(a)-2(e), we plot the graphs for robot utilization by varying different parameters. The robot utilization $U_R(t)$ increases with time t, as can be seen when we plot the graphs by varying combined loading/unloading rate of the robot, repair rate of the machine, failure rate of the machine, unloading rate of the robot, loading rate of the robot and pallet transfer rate.

The increase in robot utilization can be observed initially as we increase the combined loading/unloading rate z; then it decreases for higher values of t, as depicted in figure 2 (a). The effect of pallet transfer rate on robot utilization $U_R(t)$ is depicted in figure 2(b). For increased rate of homogeneous and heterogeneous pallet transfer rates, $U_R(t)$ shows an increasing trend. The effect of homogeneous and heterogeneous machine repair rates is exhibited in figure 2 (c). Here $U_R(t)$ increases on increasing μ_1, μ_2 and μ_c. Robot utilization decreases by increasing the machine failure rates, as shown in figure 2(d). Figures 2(e) and 2(f) show how loading/unloading rates can effect the robot utilization $U_R(t)$.

Finally, we conclude that performance of a flexible manufacturing cell can be improved by providing sufficiently higher loading/unloading rates of robot, pallet transfer rates, repair rate of the machine and loading rate of robot. On the contrary, higher failure rates of the machine and unloading rate of the robot result in the reduction in machine and robot utilization.

6. CONCLUDING REMARKS

Globalization has created new demands for manufacturers to produce a wide range of products, which have to be of higher quality at lower prices, and shorten their manufacturing lead times. In this paper we have developed a transient analysis of machining system working in flexible environment and having two machines served by a robot and pallet. The inclusion of state dependent failure and repair rates make our model more versatile and robust in the perspective of FMC. The concept of common cause failure included is also a very frequent incident when machines work on a part. Machining rate, pallet capacity, robot speed and pallet speed are important system parameters affecting FMC performance; we have examined the effects of these parameters numerically by using Runge-Kutta algorithm. The model presented may be helpful to analyze and optimize the productivity and resolve techno-economic issues based on cost, quality and buffer criterion.

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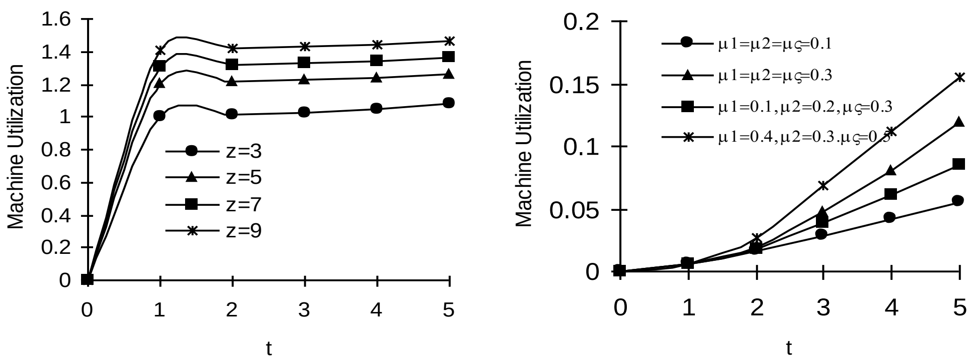
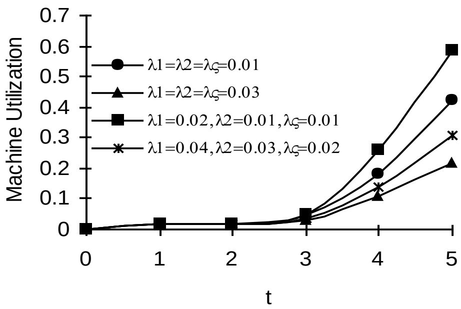


(a) (b)



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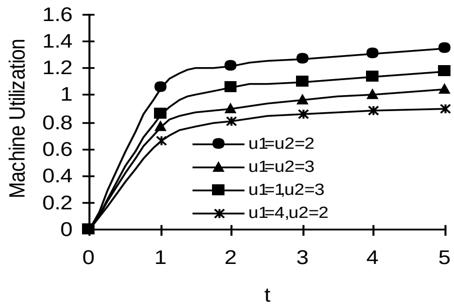

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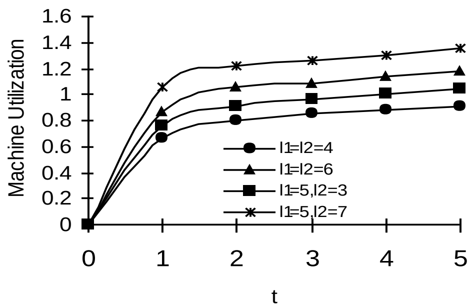

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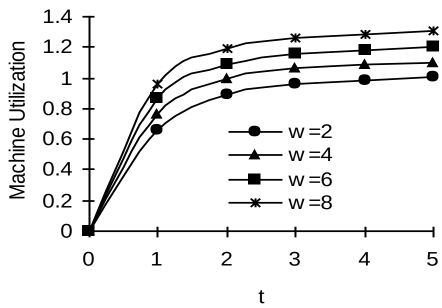
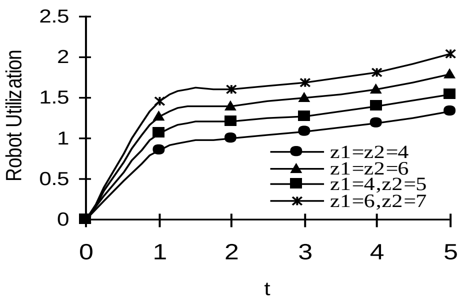
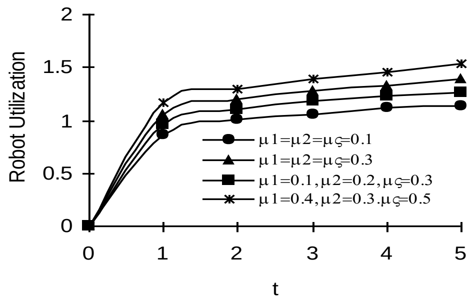


(f)

Figure 1: Machine utilization vs t by varying (a) combined loading/unloading rate of the robot (b) repair rate of the machine (c) failure rate of the machine (d) unloading rate of the robot (e) loading rate of the robot (f) pallet transfer rate.



(a)



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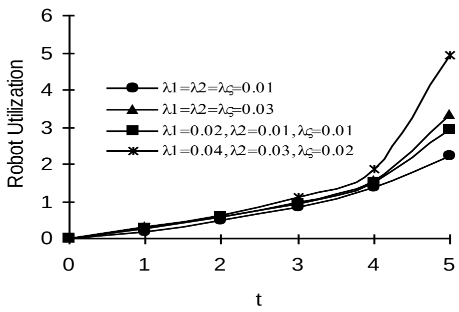

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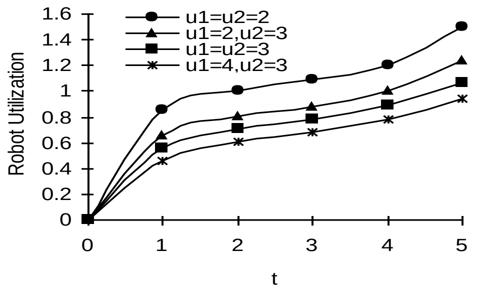

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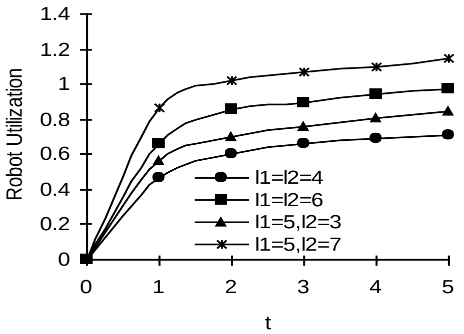

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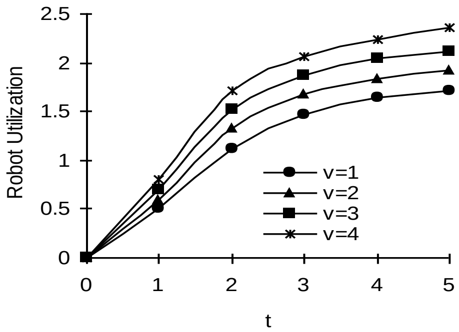

(f)

Figure 2: Robot utilization vs t by varying (a) combined loading/unloading rate of the robot (b) repair rate of the machine (c) failure rate of the machine (d) unloading rate of the robot (e) loading rate of the robot (f) production rate of the machine.