Multi-State Reliability Modeling of A Manufacturing Cell

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Abstract: A Manufacturing cell consists of a machine served by a loading and unloading robot and a pallet handling system, which moves a batch of parts into and out of the system. In this study, a stochastic model is developed to analyze performance measures of a cell, which is allowed to operate under multi-states including degraded mode. The model is used to determine state probabilities of the system, which are used to determine reliability and productivity of the cell, as well as the utilization of its components, under various operational conditions, including equipment failures and fault-tolerant states. The model and the results can be useful for design engineers and operational managers to analyze performance of a system at the design or operational stage.

Keywords: Manufacturing cells, degraded machine operation, CNC press reliability, failure analysis, stochastic modeling.

1. Introduction

A machining cell consists of one or more machines, served by a loading and unloading system, which could be a robot or an operator, and a pallet handling system to transfer a batch of parts in and out to be machined by the system. Manufacturing cells are usually designed around flexible machines to produce a high variety of products. Flexibility in manufacturing results in higher utilization of equipment than it would be in traditional manufacturing systems. Consequently, flexible systems have higher failure rates and require well planned maintenance activities. Unexpected changes in machine states can be classified as faults and failures. A fault is a tolerable malfunction rather than a total breakdown or a failure. With a tolerable malfunction, a machine can operate in a degraded performance level as opposed to its normal performance level. Thus, a machine can be in one of three states: Up-Normal, Up-Degraded, and Down states.

Machining cells are widely used in industry to process a variety of parts to achieve high productivity in production environments with rapidly changing product structures and customer demand. They offer flexibility to be adapted to the changes in operational requirements. There are various types of Flexible Manufacturing Cells (FMC) incorporated into Flexible Manufacturing Systems (FMS) with a variety of flexible machines for discrete part machining. In addition to discrete part machining systems, there are different types of
CNC punching press systems, which are also configured as flexible cell systems. A CNC press with a special loading and unloading device for handling sheet metals and a pallet handling equipment to move a batch of sheet metals into and out of the system forms a CNC press cell.

FMS and FMC performance depends on several operational and system characteristics, which may include part scheduling and system operational characteristics. In the past, most of the FMC related research has been in the areas of part scheduling and system control. Scheduling algorithms are developed to determine the best processing sequence of parts to optimize FMC performance and equipment utilization. It has also been realized that system characteristics, such as design configuration and operation of an FMC have significant effect on its performance. Machining rate, pallet capacity, robot and pallet speed, and equipment failure and repair rates are important system characteristics affecting FMC performance.

Several models have been developed for FMS and FMC in relation to the effects of different parameters on system performance. Wang and Wan [1] studied the dynamic reliability of a FMS based on fuzzy information. Yuanidis et al. [2] used a heuristic procedure called group method of data handling to assess FMS reliability with minimal data available. Han et al. [3] analyzed FMC reliability through the method of fuzzy fault tree based on triangular fuzzy membership. Khodabandehloo and Sayles [4] investigated the applicability of fault tree analysis and event tree analysis to production reliability in FMS and concluded that event tree analysis was more effective in solving this problem. Henneke and Choi [5], Savsar and Cogun [6], and Cogun and Savsar [7] have presented stochastic and simulation models for evaluating the performance of FMC and FMS with respect to system configuration and component speeds, such as machining rate, robot and pallet speeds. Koulamas [8] and Savsar [9] have looked into the reliability and maintenance aspects and presented stochastic models for the FMC, which operate under stochastic environment with tool failure and replacement consideration. They developed Markov models to study the effects of tool failures on system performance measures for a FMC with a single machine served by a robot for part loading/unloading and a pallet for part transfers.

There are several other studies related to the reliability analysis of manufacturing systems. Butler and Rao [10] use symbolic logic to analyze reliability of complex systems. Their heuristic approach is based on artificial intelligence and expert systems. Black and Mejabi [11] have used object oriented simulation modeling to study reliability of complex manufacturing equipment. They present a hierarchical approach to model complex systems. Simeu-Abazi, et. al. [12] uses decomposition and iterative analysis of Markov chains to obtain numerical solutions for the reliability and dependable of manufacturing systems. Adamyan and He [13] present a methodology to identify the sequences of failures and probability of their occurrences in an automated manufacturing system. They used Petri nets and reachability trees to develop a model for sequential failure analysis in manufacturing systems. Aldaihani and Savsar [14] and Savsar [15] presented a stochastic analytical model and numerical solutions for a reliable FMC with two machines served by a single robot. Savsar and Aldaihani [16] and Aldaihani and Savsar [17] have presented stochastic models and numerical solutions for performance analysis of a reliable FMC with two machines served by two robots and a pallet. These performance measures are compared to the previous results obtained for the FMC with a single robot. Abdulmalek, Savsar, and Aldaihani [18] presented a simulation model and analysis for tool change policies in a FMC with two machines and a robot.
Aldaihani and Savsar [19] have further extended the previous models and developed stochastic models for unreliable FMC systems with two unreliable machines served by a robot and a pallet system. Closed form analytical solutions are obtained and FMC analysis is performed for performance measures and selected cell operations. The results are also compared to reliable FMC systems. Dhillon and Li [21] presented a model to perform availability analysis of a system in which partial failures were allowed.

This paper presents a stochastic model for a FMC with a machine served by a robot or an operator for loading and unloading of parts and a pallet handling device. This study differs from all previous studies in that fault-tolerance states are incorporated into the model and the machine is allowed to operate in a degraded state. A Markovian model is developed for the FMC with fault tolerance states to determine reliability and productivity of the system under various operational conditions. The model and the results can be useful for design engineers as well as operational managers in production and maintenance planning.

2. Operation of the Cell

Operation of the FMC system is illustrated in Figure 1. An automated pallet handling system delivers n blanks consisting of different parts into the cell. Initially the robot reaches to the pallet, grips a blank, moves to the machine and loads the blank. After the operation is completed, the robot reaches the machine, unloads the completed part and places it into the pallet, picks another blank and loads it onto the machine. This sequence of operations continues until all parts on the pallet are completed, at which time the pallet with n finished parts moves out and a new pallet with n blanks is delivered into the cell automatically. Since a variety of parts, which require different operations, are introduced into the system, part processing times as well as loading/unloading times are assumed stochastic. Machines are assumed to be unreliable and fail during the operations. Time to failure and time to repair are assumed to follow exponential distribution. Due to the introduction of different parts into the FMC, failures of machines, and random characteristics of system operation, processing times as well as loading/unloading times are random, which present a complication in studying and modeling the cell performance. If there were no randomness in system parameters and the pallet exchange times were neglected, the problem could be analyzed by a man-machine assignment chart for non-identical machines, and by a symbolic formulation for identical machines. However, due to randomness, system needs to be modeled by a stochastic process.

![Figure 1: A Flexible Manufacturing Cell](image)
3. **Stochastic Modeling of Cell Operations**

In order to analyze the FMC operations with random system parameters, a stochastic model has been developed. Processing times on the machines, robot loading and unloading times, pallet transfer times, machine operation times, as well as machine failure and repair times are all assumed as random quantities that follow exponential distribution. Therefore, the stochastic model is based on continuous time Markov chains and result in Chapman-Kolmogorov equations, which are solved for steady state system probabilities. The state probabilities are then utilized to determine various system performance measures and best system operational conditions. In order to present the model and related analysis, three set of notations are introduced below:

The following notation is used for system states and parameters:

- $S_{ijkl}(t)$: State of the FMC at time $t$
- $P_{ijkl}(t)$: Probability that the system will be in state $S_{ijkl}(t)$
- $i$: Number of blanks in FMC (on the pallet, the machine, or the robot gripper)
- $j$: State of the production machine (j=0 if the machine is idle in normal mode; j=1 if the machine is operating in the normal mode; j=2 if the machine is operating in the fault-tolerant (degraded) mode; j=3 if the machine has failed and is under repair; j=4 if the machine is idle in the fault-tolerant state)
- $k$: State of the robot (l=0 if the robot is idle; l=1 if the robot is loading or unloading)
- $l$: Loading rate of the robot (parts/unit time)
- $u$: Unloading rate of the robot (parts/unit time)
- $z$: Combined loading/unloading rate of the robot
- $w$: Pallet transfer rate (pallets/unit time)
- $\lambda_1$: Failure rate of machine when in normal mode (1/$\lambda_1$ = mean time between failures)
- $\lambda_2$: Rate at which machine transfers to the degraded (fault-tolerant) mode from normal operational mode (1/$\lambda_2$ = mean time to transfer to fault-tolerant from normal mode)
- $\lambda_3$: Failure rate of the machine when in degraded mode (1/$\lambda_3$ = mean time between failures in degraded mode)
- $\mu_1$: Repair rate of the machine from failed to normal operational mode (1/$\mu_1$ = mean time to repair to move to normal mode)
- $\mu_2$: Repair rate of the machine from degraded mode to normal mode (1/$\mu_2$ = mean time to repair to move from degraded mode to normal mode)
- $\mu_3$: Repair rate of the machine from failed to degraded mode (1/$\mu_3$ = mean repair time to move from failed to degraded mode). It may occur if full repair is not possible.
- $v_i$: Machining rate (parts/unit time) (i=1 for normal mode; i=2 for degraded mode)
- $n$: Pallet capacity (number of parts/pallet)
- $M_{iu}$: Percent of time machine is in operating in normal state (Up-Normal State).
- $M_{id}$: Percent of time machine is in operating in degraded state (Up-Degraded State).
- $M_d$: Percent of time machine is not operating (Down State).
- $R_u$: Percent of time robot is being utilized in loading and unloading state.
- $P_u$: Percent of time pallet is being utilized in transferring the pallets.
- $Q_c$: System production rate (parts/unit time) based on machine production rates.
Figure 2 shows the probability transition diagram for the FMC with an unreliable machine served by a robot. Using the fact that the net flow rate at each state is equal to the difference between the rates of flow in and flow out, a set of differential equations are obtained for the stochastic FMC. For example, for the state (n,01), rate of change with respect to time $t$ is given by:

$$\frac{dP_{n01}(t)}{dt} = wP_{000}(t) - lP_{n01}(t)$$

The set of differential equations for all states are given by equations 1-19 below. Note that equations are given in three different sets since each set has a unique form. The first set represents the initial system states when a new pallet arrives with $n$ blanks; the last set represents the final system states when the last parts on the pallet are being processed; and the second set represents the intermediate state operations. In each term, $t$ has been omitted for simplification. At steady state, $t \rightarrow \infty$; $\frac{dP_{n01}(t)}{dt} \rightarrow 0$ and the differential equation changes into a difference equation as: $wP_{000} - lP_{n01} = 0$ for the state equation given above. These equations must be solved to obtain the steady state probabilities and system performance measures. The system consists of $14+5(n-2)$ equations and equal number of unknowns. For example, for $n=4$, number of system states, as well as number of equations, is $14+5(4-2) = 24$ and for $n=10$, it is $14+5(10-2) = 54$. It is possible to obtain an exact solution for this system of equations given by $PT=0$, where $P$ is the steady state probabilities vector to be determined and $T$ is the probability transition rate matrix. It is known that all of the equations in $PT=0$ are not linearly independent and thus the matrix $T$ is singular, which does not have an inverse.

$$wp_{0,0,0} - lp_{n,0,1} = 0$$  \hspace{1cm} (1)

$$wp_{0,4,0} - lp_{n,4,1} = 0$$  \hspace{1cm} (2)

$$\lambda_1 p_{n-1,1,0} + \lambda_3 p_{n-1,2,0} - (\mu_1 + \mu_3) p_{n-1,3,0} = 0$$  \hspace{1cm} (3)

$$lp_{n,0,1} + \mu_1 p_{n-1,3,0} + \mu_2 p_{n-1,2,0} - (\lambda_1 + \lambda_2 + \nu_1) p_{n-1,3,0} = 0$$  \hspace{1cm} (4)

$$\lambda_3 p_{n-1,0,1} + \mu_3 p_{n-1,3,0} + lp_{n,4,1} - (\lambda_1 + \mu_2 + \nu_2) p_{n-1,2,0} = 0$$  \hspace{1cm} (5)

$$v_1 p_{n-1,0,1} + \mu_2 p_{n-1,4,1} - z p_{n-1,0,1} = 0$$  \hspace{1cm} (6)

$$v_2 p_{n-1,2,0} - (\mu_2 + z) p_{n-1,4,1} = 0$$  \hspace{1cm} (7)

$$\lambda_1 p_{n-x,1,0} + \lambda_3 p_{n-x,2,0} - (\mu_1 + \mu_3) p_{n-x,3,0} = 0$$  \hspace{1cm} (8)

$$zp_{n-x+1,0,1} + \mu_1 p_{n-x,3,0} + \mu_2 p_{n-x,2,0} - (\lambda_1 + \lambda_2 + \nu_1) p_{n-x,1,0} = 0$$  \hspace{1cm} (9)

$$\lambda_2 p_{n-x,1,0} + \mu_3 p_{n-x,3,0} + zp_{n-x+1,4,1} - (\lambda_3 + \mu_2 + \nu_2) p_{n-x,2,0} = 0$$  \hspace{1cm} (10)

$$v_1 p_{n-x,1,0} + \mu_2 p_{n-x,4,1} - z p_{n-x,0,1} = 0$$  \hspace{1cm} (11)

$$v_2 p_{n-x,2,0} - (\mu_2 + z) p_{n-x,4,1} = 0$$  \hspace{1cm} (12)

$$\vdots$$

$$\lambda_1 p_{0,1,0} + \lambda_3 p_{0,2,0} - (\mu_1 + \mu_3) p_{0,3,0} = 0$$  \hspace{1cm} (13)
Figure 2: Transition Flow Diagram

Subscript Notation:
- $S_{0,n}$: System State
- $r$: Part on the Pallet
- $m$: Machine State ($0$, $4$)
- $k$: Robot State ($Q, I$)

Machine States:
- $0$ = Idle Normal
- $1$ = Up Normal
- $2$ = Up Degraded
- $3$ = Failed
- $4$ = Idle Degraded

Robot States:
- $0$ = Idle
- $1$ = Operating
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\[ \begin{align*}
zp_{1,0,1} + \mu_1 p_{0,3,0} + \mu_2 p_{0,2,0} - (\lambda_1 + \lambda_2 + v_1) p_{0,1,0} &= 0 \\
\lambda_2 p_{0,1,0} + \mu_3 p_{0,3,0} + zp_{1,4,1} - (\lambda_3 + \mu_2 + v_2) p_{0,2,0} &= 0 \\
v_1 p_{0,1,0} + \mu_2 p_{0,4,1} - up_{0,0,1} &= 0 \\
v_2 p_{0,2,0} - (\mu_2 + u) p_{0,4,1} &= 0 \\
up_{0,4,1} - (\mu_2 + w) p_{0,4,0} &= 0 \\
up_{0,0,1} + \mu_2 p_{0,4,0} - wp_{0,0,0} &= 0 \\
\end{align*} \]

We must add the normalizing condition given by equation (20) below, which assures that sum of all state probabilities is 1, to the sets of equations above by eliminating one of them.

\[ \sum_{i=0}^{n} \sum_{j=0}^{2} \sum_{k=0}^{2} P_{ijkl} = 1 \]

Theoretically it may be possible to manipulate the equations 1-19 in order to determine closed form solutions for state probabilities. However, because of large number of equations involved, it is difficult to obtain closed form solutions. Exact numerical solutions can be obtained for all state probabilities by solving the set of linear equations \( PT=0 \) by any method. We have solved the equations by MAPLE software for the state probabilities. Once the state probabilities, \( P_{i,j,k} \), are determined, it is then possible to determine various system and subsystem performance measures as follows.

\[ M_u = \sum_{k=0}^{kn-1} p_{1,0,0} ; M_g = \sum_{k=0}^{kn-1} p_{k,2,0} ; M_d = \sum_{k=0}^{kn-1} p_{k,3,0} ; \]

\[ M_i = \sum_{k=0}^{kn} (p_{k,0,1} + p_{k,4,1}) + p_{0,0,0} + p_{0,4,0} ; R_u = \sum_{k=0}^{kn} (p_{k,0,1} + p_{k,4,1}) ; P_u = p_{0,0,0} + p_{0,4,0} \]

\[ Q_c = v_1 M_u + v_2 M_g \]

Equation \( Q_c \) gives the FMC production rate which is sum of the production rates in normal up state \( (v_1 M_u) \) and in degraded up state \( (v_2 M_g) \).

4. Numerical Results

In this section, we present some numerical results for a case problem with different parameters for an FMC system allowed to operate under degraded mode. The parameter values, based on author's experience for the unreliable FMC system, are shown in table 1.
Values given in the table are the mean values for various parameters in the case examples. It should be noted that the mean is the inverse of the rate in each case. Figure 3 shows the production output rate as a function of pallet capacity (n) at different pallet transfer rates of \( w=0.25, w=0.125, \) and \( w=0.0833 \). As it is seen from the figure, production rate increases with increasing pallet capacity and pallet transfer rates. While the rate of increase is higher initially, it levels off at higher values of n. Figures 4 and 5 show machine utilizations with respect to pallet capacity and pallet transfer rate at normal up and degraded up states respectively. An increasing trend is observed in machine utilizations as the pallet capacity and pallet transfer rates are increased. The increase levels off at higher pallet capacities exceeding 10 units.

**Table 1: Parameter values for the unreliable FMC system**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation time per part at Normal Up state</td>
<td>( \frac{1}{v_1} = 4 ) time unit</td>
</tr>
<tr>
<td>Operation time per part at Degraded Up state</td>
<td>( \frac{1}{v_2} = 8 ) time unit</td>
</tr>
<tr>
<td>Robot loading time for the first part</td>
<td>( \frac{1}{l} = \frac{1}{6} ) time units</td>
</tr>
<tr>
<td>Robot load/unload time for subsequent parts</td>
<td>( \frac{1}{z} = \frac{1}{3} ) time units</td>
</tr>
<tr>
<td>Robot unloading time for the last part</td>
<td>( \frac{1}{u} = \frac{1}{6} ) time units</td>
</tr>
<tr>
<td>Mean time to failure of the machine at Normal Up state</td>
<td>( \frac{1}{\lambda_1} = 100 ) time units</td>
</tr>
<tr>
<td>Mean time machine transfers from Normal Up to Degraded state</td>
<td>( \frac{1}{\lambda_2} = 50 ) time units</td>
</tr>
<tr>
<td>Mean time to failure of the machine at Degraded state</td>
<td>( \frac{1}{\lambda_3} = 80 ) time units</td>
</tr>
<tr>
<td>Mean time to repair (MTTR) the machine when in failed state</td>
<td>( \frac{1}{\mu_1} = 10 ) time units</td>
</tr>
<tr>
<td>MTTR the machine to move it from Degraded to Normal Up state</td>
<td>( \frac{1}{\mu_2} = 5 ) time units</td>
</tr>
<tr>
<td>MTTR the machine to move it from failed to Degraded state</td>
<td>( \frac{1}{\mu_3} = 8 ) time units</td>
</tr>
<tr>
<td>Pallet transfer time</td>
<td>( \frac{1}{w} = 4, 8, 12 ) time units/pallet</td>
</tr>
<tr>
<td>Pallet capacity</td>
<td>( N=2, \ldots, 20 ) units</td>
</tr>
</tbody>
</table>

Figures 6 and 7 show robot and pallet utilizations respectively as functions of pallet capacity and pallet transfer rates. Robot utilization increases with increasing pallet capacity due to increased loading/unloading frequency per pallet. However, pallet utilization decreases as the pallet capacity is increased or pallet transfer rate is decreased. This is because more parts are transferred at each transfer time and thus frequency of the transfer reduces. While the trends obtained in these results and shown in the figures could be obvious, it is not so obvious and easy to determine exact production output rate of an FMC for a given set of parameters or for some operational conditions, including failure and repair information. In order to determine the exact production output rate or other performance measures related to equipment utilization of a given FMC, it is necessary to have an analytical formulation or a model that describes the FMC system behavior as presented in this paper. The usefulness of this model is obvious for such analysis.

**5. Economical Analysis**

In order to illustrate the application of the model in economical analysis, the following notation and equations are introduced. Let:

- \( C_m \) Total machine cost per unit time
- \( C_{mf} \) Fixed machine cost per unit of time
- \( C_{mn} \) Variable machine cost at normal up state per unit of production
- \( C_{mvd} \) Variable machine cost at degraded up state per unit of production
Total robot cost per unit time
Fixed robot cost per unit time
Variable robot cost per unit of production;
Total pallet cost per unit time
Fixed pallet cost per unit time
Variable pallet cost per unit of production

Then,
\[ C_m = C_{mf} + (C_{mvn} \cdot v_1) + (C_{mvd} \cdot v_2) \]  \hspace{1cm} (22)
\[ C_r = C_{rf} + C_{rv} \cdot z_i \]  \hspace{1cm} (23)
\[ C_p = C_{pf} + C_{pv} \cdot n \]  \hspace{1cm} (24)

Total FMC cost per unit of production, TC, is given by the following equation.
\[ TC = \frac{C_m + C_r + C_p}{Q_c} \]  \hspace{1cm} (25)

In order to illustrate behavior of the system with respect to various cost measures, a case problem with specified cost parameters is selected as given in Table 2. Total costs, machining and robot loading/unloading rates are also shown in the table. Other parameters are as given in Table 1. Figure 8 shows the behavior of FMC cost per unit of production as function of pallet capacity and three selected pallet transfer rates of \( w = 0.25 \), \( w = 0.125 \) and \( w = 0.0833 \) pallets per unit time. Total cost, TC1, TC2, and TC3 corresponds to these transfer rates respectively.

Table 2: Cost parameters for the case problem

<table>
<thead>
<tr>
<th>Machine</th>
<th>( C_{mf} = 1.0 )</th>
<th>( C_{mvn} = 0.2 )</th>
<th>Total Cost = 1.075</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robot</td>
<td>( C_{rf} = 0.108 )</td>
<td>( C_{rv} = 0.125 )</td>
<td>( z = 3 )</td>
</tr>
<tr>
<td>Pallet</td>
<td>Total Robot Cost = ( C_r = 0.432 )</td>
<td>( C_{pf} = 0.108 )</td>
<td>( C_{pv} = 0.108 )</td>
</tr>
</tbody>
</table>

As it can be seen from Figure 8, total costs show a decreasing pattern with increasing pallet capacity with an optimum pallet capacity ranging between 3 and 6 units depending on the pallet transfer rates the case example presented here. It is possible to include other cost related parameters related to lot sizes (pallet capacity) and develop models that could be utilized in real life applications.

6. Conclusions

In today’s dynamic manufacturing environment, manufacturing firms produce a variety of products on the same production equipment in order to reduce the costs. Flexible manufacturing equipment must be utilized to achieve this goal. A selection of flexible manufacturing machines have been developed and introduced into industry. These machines are incorporated into manufacturing cells with automated material handling equipment. Because of high utilization of these equipments, different levels of operations, including fault-
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tolerance operation modes, may be needed. It is important to be able to analyze such systems in order to gain full benefits in their implementation and subsequent operations.

While modeling and analysis of traditional machines and production systems has been subject of extensive research over the past several years, FMC systems have not been analyzed in detail. Stochastic models and solution formulas obtained in this paper are used to analyze and optimize the productivity and other performance measures of and FMC system under different machine, robot, and pallet operational characteristics. Best parameter combinations can be determined for a given system. In particular, best machining rates, machine repair rates, robot loading and unloading rates, pallet capacity, and pallet transfer rates can be determined for a given set of FMC machine characteristics. Furthermore, reliability and availability analysis of the FMC system can be determined based on different failure/repair characteristics of the machines in the system. It is possible to optimize machine repair rates, based on other system parameters, to achieve maximum production output rates and other performance measures. Models related to cost analysis and optimization of costs with respect to system characteristics are used to evaluate system performance before acquiring a system to install it or during its operation.

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References


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