Reliability Modeling of a Manufacturing Cell Operated under Degraded Mode

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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 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-tolerance 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
Degraded Machine Operation, Multi-State Reliability Modeling, Manufacturing Cells, 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 Cell (FMC) systems or Flexible Manufacturing Modules (FMM) with 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 the batch of sheet metals into and out of the system forms a CNC press cell. The most feasible approach to automate a production system with flexibility is to initially incorporate small machining cell systems into the system as indicated by Chan and Bedworth (1990). This approach requires lower investment, less risk, and also satisfies many of the benefits gained through larger and more costly structures, such as flexible manufacturing systems (FMS). While FMS are very expensive and generally require investments in millions of dollars, FMC are less costly, smaller and less complex systems. Therefore, for smaller companies with restricted capital resources, a gradual integration is initiated with limited investment in a small FMC, which facilitates subsequent integration into larger systems.

An FMC consists of a robot, one or more flexible machines including inspection, and an external material handling system such as an automated pallet for moving blanks and finished parts into and out of the cell. The robot is utilized for internal material handling which includes machine loading and unloading. The FMC is capable of doing different operations on a variety of parts, which usually form a part family with selection by a group technology approach. The cell performance depends on several operational and system characteristics, which include, part scheduling, robot speeds, machine and pallet characteristics. Most of the researches related to operational characteristics of FMC are directed to the scheduling, control, part grouping, and layout aspects. Scheduling algorithms are used to determine the sequence of parts, which are continuously introduced to the cell. Hitomi and Yoshimura (1986), Chan and Bedworth (1990) and Hutchinson et al. (1991) have developed models for static and dynamic scheduling in FMC; Farahmand (2000) developed and tested a simulation model to justify the implementation of an FMC; the model was found to be a useful tool for evaluating and assessing a manufacturing line to switch to a FMC; Sohal et al. (2001) presents a case example of a FMC and lists critical factors, such as the initial planning, cell layouts, human resources, and management inputs that affect successful FMC operations. Kim et al. (2001) presents a model for supervisory control of a FMC system. Lashkari, et al. (2002) presented a model for allocation of pallets in FMC; Agnetis, et al. (2003) considered part batching and scheduling in a flexible cell to minimize setup costs.

It has been realized that system characteristics, such as configuration, design, and operation of an FMC have significant effect on its performance. Machining rate, pallet capacity, robot speed and pallet speed 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. Henneke and Choi (1990), Savsar and Cogun (1993), and Cogun and Savsar (1996) 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 (1992) and Savsar (2000) 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 A. C. and Rao, S. S. (1993) use symbolic logic to analyze reliability of complex systems. Their heuristic approach is based on artificial intelligence and expert systems. Black and Mejabi (1995) 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. (1997) uses decomposition and iterative analysis of Markov chains to obtain numerical solutions for the reliability and dependability of manufacturing systems. Adamyan and He (2002) 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 (2005a) and Savsar (2008) presented a stochastic analytical model and numerical solutions for a reliable FMC with two machines served by a single robot. Savsar and Aldaihani (2004) and Aldaihani and Savsar (2005b) 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 (2004) presented a simulation model and analysis for tool change policies in a FMC with two machines and a robot, based on ARENA simulation software, Kelton et al (2002), which allows flexibility in modeling manufacturing systems. Aldaihani and Savsar (2008a) Savsar and Aldaihani (2008b) 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 different performance measures and selected cell operations. The results are also compared to reliable FMC system.

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, because of random operations the system needs to be modeled by a stochastic process.

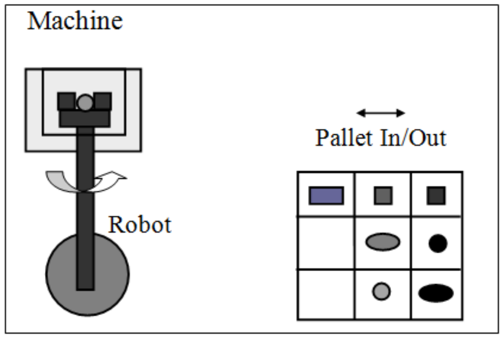

Figure 1: A Flexible Manufacturing Cell

3. Stochastic Modeling of Cell Operations

In order to analyze the FMC with stochastic operation parameters, the following model is 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. The following system states are defined:

$S_{ijk}(t)$ = state of the FMC at time t
$P_{ijk}(t)$ = probability that the system will be in state $S_{ijk}(t)$
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).

We assume that the machine fails at different rates when in normal up state and when in degraded up state. Also it is assumed that a failed machine can be repaired to bring it to normal up state, or partially repaired for temporary reasons, to bring it to the degraded up state.

k= state of the robot (l=0 if the robot is idle; l=1 if the robot is loading or unloading)

The following notation is used for the system parameters in the model.

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)
λ_1= failure rate of the machine when in normal mode ($1/\lambda_1$ = mean time between failures)
λ_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 mode from normal mode)
λ_3= failure rate of the machine when in degraded mode ($1/\lambda_3$ = mean time between failures in degraded mode)
μ_1= repair rate of the machine from failed to normal operational mode ($1/\mu_1$ = mean time to repair to move

to normal mode)

μ_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)

μ_3= repair rate of the machine from failed to degraded mode ($1/\mu_2$ = mean time to repair to move from failed mode to degraded mode)

v_i= machining rate (or production rate) of the machine (parts/unit time) (i=1 for normal mode; i=2 for degraded mode)

n = pallet capacity (number of parts/pallet)

Q_c= production output rate of the cell in terms of parts/unit time.

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, 001), rate of change with respect to time t is given by:

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

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 when a new pallet arrives with n blanks; the last set represents the system when the last parts on the pallet are being processed; and the second set represents the intermediate operations. In each term, t has been omitted for simplification. At steady state, $t \rightarrow \infty$; $dP_{n01}(t)/dt \rightarrow 0$ and the differential equation changes into a difference equation as: $wP_{000} - lP_{n01}=0$. These equations must be solved to obtain the steady state probabilities and system performance measures.

$$\frac{dp_{0,0,0}}{dt} = lp_{n-0,1} - wp_{0,0,0} \tag{1}$$

$$\frac{dp_{0,4,0}}{dt} = lp_{n,4,1} - wp_{0,4,0} \tag{2}$$

$$\frac{dp_{n-1,3,0}}{dt} = \lambda_1 p_{n-1,1,0} + \lambda_3 p_{n-1,2,0} - (\mu_1 + \mu_3) p_{n-1,3,0} \tag{3}$$

$$\frac{dp_{n-1,1,0}}{dt} = lp_{n,0,1} + \mu_1 p_{n-1,3,0} + \mu_2 p_{n-1,2,0} - (\lambda_1 + \lambda_2 + v_1) p_{n-1,3,0} \tag{4}$$

$$\frac{dp_{n-1,2,0}}{dt} = \lambda_2 p_{n-1,1,0} + \mu_3 p_{n-1,3,0} + lp_{n,4,1} - (\lambda_3 + \mu_2 + v_2) p_{n-1,2,0} \tag{5}$$

$$\frac{dp_{n-1,0,1}}{dt} = v_1 p_{n-1,1,0} + \mu_2 p_{n-1,4,1} - zp_{n-1,0,1} \tag{6}$$

$$\frac{dp_{n-1,4,1}}{dt} = v_2 p_{n-1,2,0} - (\mu_2 + z) p_{n-1,4,1} \tag{7}$$

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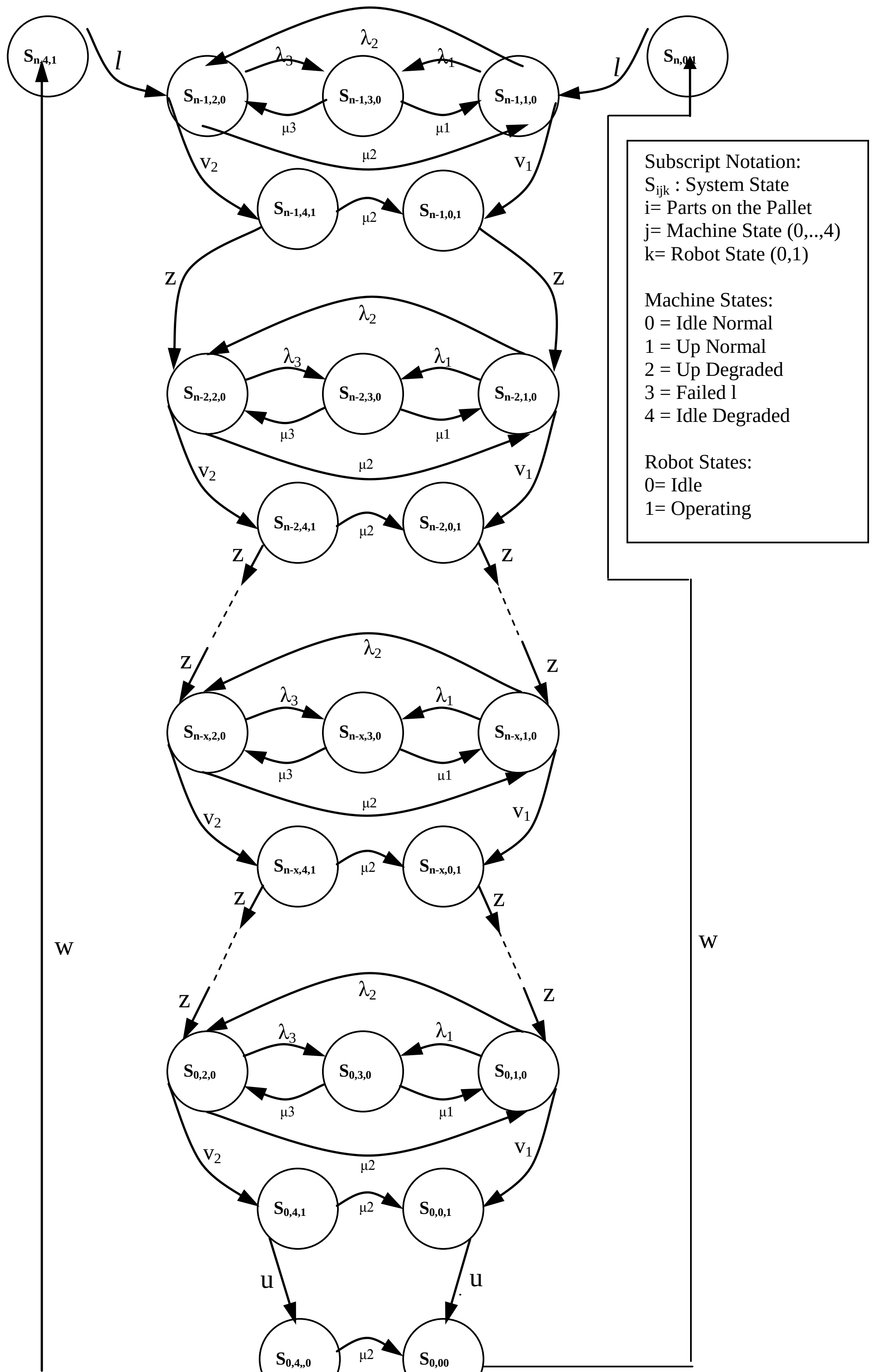

Figure 2: Transition Flow Diagram

$$\frac{dp_{n-x,3,0}}{dt} = \lambda_1 p_{n-x,1,0} + \lambda_3 p_{n-x,2,0} - (\mu_1 + \mu_3) p_{n-x,3,0} \quad (8)$$

$$\frac{dp_{n-x,1,0}}{dt} = zp_{n-x+1,0,1} + \mu_1 p_{n-x,3,0} + \mu_2 p_{n-x,2,0} - (\lambda_1 + \lambda_2 + v_1) p_{n-x,1,0} \quad (9)$$

$$\frac{dp_{n-x,2,0}}{dt} = \lambda_2 p_{n-x,1,0} + \mu_3 p_{n-x,3,0} + zp_{n-x+1,4,1} - (\lambda_3 + \mu_2 + v_2) p_{n-x,2,0} \quad (10)$$

$$\frac{dp_{n-x,0,1}}{dt} = v_1 p_{n-x,1,0} + \mu_2 p_{n-x,4,1} - zp_{n-x,0,1} \quad (11)$$

$$\frac{dp_{n-x,4,1}}{dt} = v_2 p_{n-x,2,0} - (\mu_2 + z) p_{n-x,4,1} \quad (12)$$

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$$\frac{dp_{0,3,0}}{dt} = \lambda_1 p_{0,1,0} + \lambda_3 p_{0,2,0} - (\mu_1 + \mu_3) p_{0,3,0} \quad (13)$$

$$\frac{dp_{0,1,0}}{dt} = zp_{1,0,1} + \mu_1 p_{0,3,0} + \mu_2 p_{0,2,0} - (\lambda_1 + \lambda_2 + v_1) p_{0,1,0} \quad (14)$$

$$\frac{dp_{0,2,0}}{dt} = \lambda_2 p_{0,1,0} + \mu_3 p_{0,3,0} + zp_{1,4,1} - (\lambda_3 + \mu_2 + v_2) p_{0,2,0} \quad (15)$$

$$\frac{dp_{0,0,1}}{dt} = v_1 p_{0,1,0} + \mu_2 p_{0,4,1} - up_{0,0,1} \quad (16)$$

$$\frac{dp_{0,4,1}}{dt} = v_2 p_{0,2,0} - (\mu_2 + u) p_{0,4,1} \quad (17)$$

$$\frac{dp_{0,4,0}}{dt} = up_{0,4,1} - (\mu_2 + w) p_{0,4,0} \quad (18)$$

$$\frac{dp_{0,0,0}}{dt} = up_{0,0,1} + \mu_2 p_{0,4,0} - wp_{0,0,0} \quad (19)$$

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. 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.

$$\sum_{i=0}^{n}\sum_{j=0}^{2}\sum_{k=0}^{2}\sum_{l=0}^{2} P_{ijkl} = 1 \quad (20)$$

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 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. Let:

M_u = Percent of time machine is in operating in normal state (*Up-Normal State*).
M_g = Percent of time machine is in operating in degraded state (*Up-Degraded State*).
M_d = Percent of time machine is not operating (*Down State)*.
M_i = Percent of time machine is idle waiting for loading, unloading and pallet transfers.
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 pallets in and out of the system.
Q = System production rate based on machine rates of production in different up states.

$$M_u = \sum_{k=0}^{k=n-1} P_{k,2,1} \tag{21}$$

$$M_g = \sum_{k=0}^{k=n-1} P_{k,3,1} \tag{22}$$

$$M_d = \sum_{k=0}^{k=n-1} P_{k,4,1} \tag{23}$$

$$M_i = \sum_{k=0}^{k=n} (P_{k,1,2} + P_{k,5,2}) + P_{0,1,1} + P_{0,5,1} \tag{24}$$

$$R_u = \sum_{k=0}^{k=n} (P_{k,1,2} + P_{k,5,2}) \tag{25}$$

$$P_u = P_{0,1,1} + P_{0,5,1} \tag{26}$$

$$Q_c = v_1 M_u + v_2 M_g \tag{27}$$

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 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.

Table 1. Parameter values for the unreliable FMC system

Operation time per part at Normal Up state	$1/v_1$ = 4 time unit
Operation time per part at Degraded Up state	$1/v_2$ = 8 time unit
Robot loading time for the first part	$1/\ell$ = 1/6 time units
Robot load/unload time for subsequent parts	1/z = 1/3 time units
Robot unloading time for the last part	1/u = 1/6 time units
Mean time to failure of the machine at Normal Up state	$1/\lambda_1$ = 100 time units
Mean time machine transfers from Normal Up to Degraded state	$1/\lambda_2$ = 50 time units
Mean time to failure of the machine at Degraded state	$1/\lambda_3$ = 80 time units
Mean time to repair (MTTR) the machine when in failed state	$1/\mu_1$ = 10 time units
MTTR the machine to move it from Degraded to Normal Up state	$1/\mu_2$ = 5 time units
MTTR the machine to move it from failed to Degraded state	$1/\mu_3$ = 8 time units
Pallet transfer time	1/w=4,8,12 time units/pallet
Pallet capacity	n= 2,…..,20 units

Figures 4 and 5 show machine utilizations with respect to pallet capacity and pallet transfer rate at normal up state and degraded state 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. Figure 6 shows the percent of time machine is down under repair, while figure 7 shows the percent of time machine is idle waiting for the robot loading/unloading and for the pallet transferring parts. While down time percentages increase with increasing pallet capacity due to increased utilization and failures, percent idle time decreases with increasing pallet capacities.

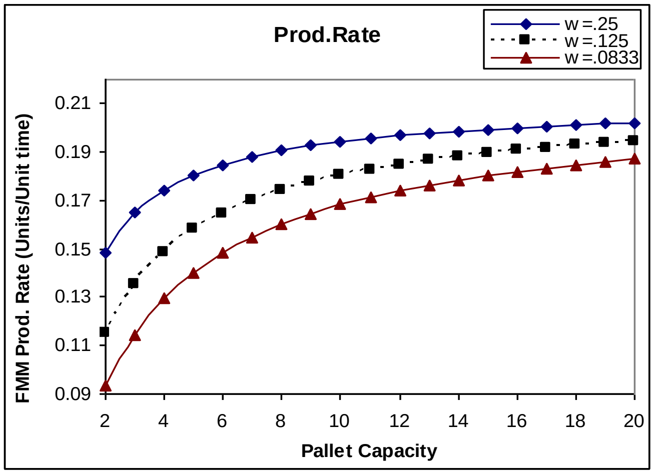

Figure 3: Production output rate as a function of pallet capacity

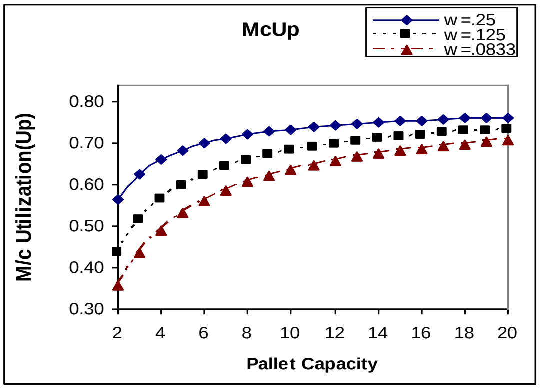

Figure 4: FMC machine utilization at normal up state as a function of pallet capacity

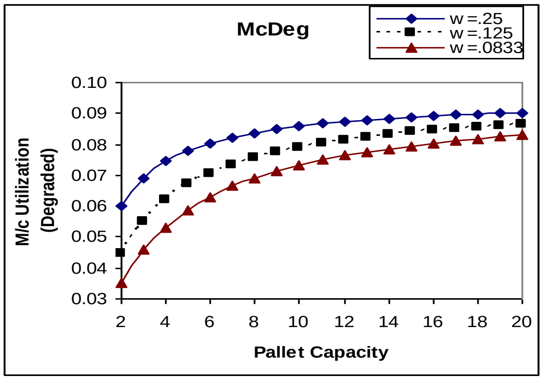

Figure 5: FMC machine utilization at degraded mode as a function of pallet capacity

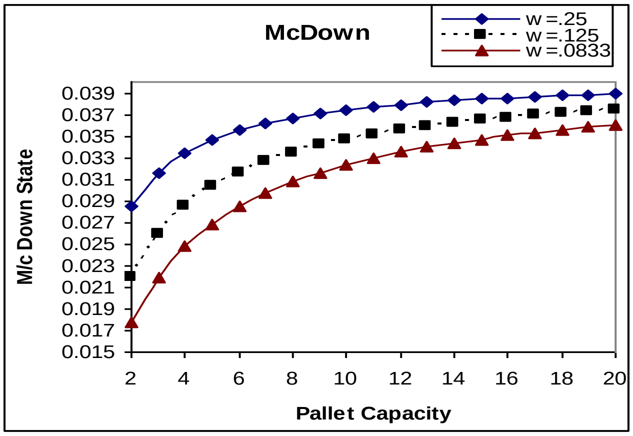

Figure 6: Percent of time machine is in down state as a function of pallet capacity

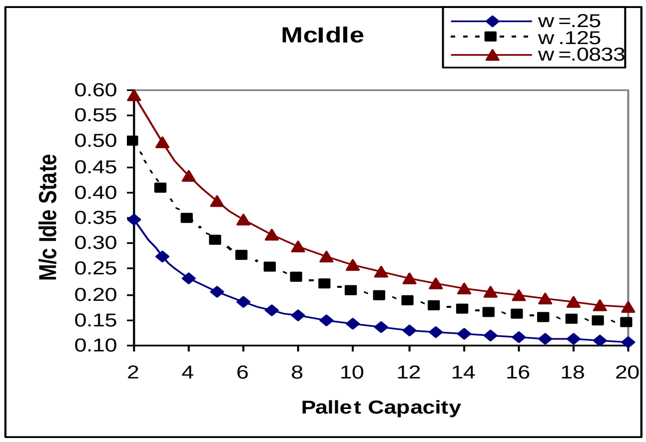

Figure 7: Percent of time machine is idle as a function of pallet capacity

Figures 8 and 9 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 frequency of transfer reduces.

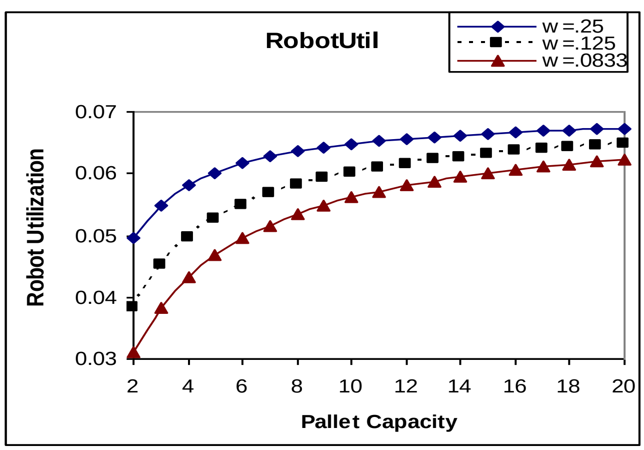

Figure 8: Robot utilization as a function of pallet capacity

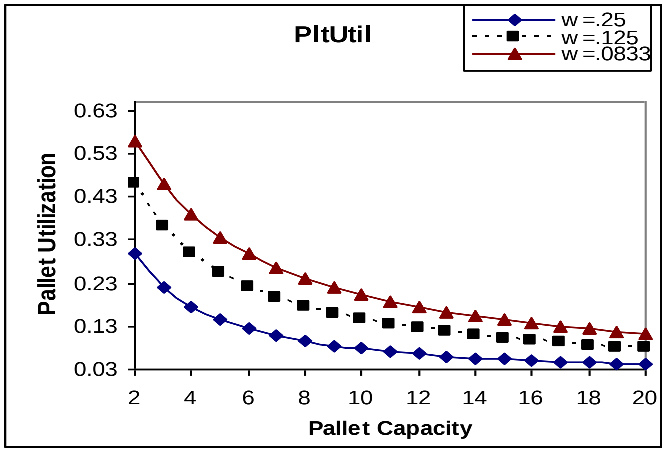

Figure 9: Pallet utilization as a function of pallet capacity

5. Economical Analysis

In order to show the use of the model in economical analysis, the following notations and models are introduced. Let:

C_m=Total machine cost per unit time
C_{mn}=Fixe machine cost per unit of time
C_{mvn}=Variable machine cost at normal up state per unit time
C_{mvd}= Variable machine cost at degraded up state per unit time
C_r= Total robot cost per unit time
C_{rn}= Fixed robot cost per unit time
C_{rvn} =Variable robot cost at normal machine up state per unit time
C_{rdn} = Variable robot cost at degraded machine up state per unit time
C_p= Total pallet cost per unit time
C_{pn}= Fixed pallet cost per unit time
C_{pvn} =Variable pallet cost at normal machine up state per unit time
C_{pdn} = Variable pallet cost at degraded machine up state per unit time

Then,

$$C_m = C_{mn}+(C_{mvn}*v_1)+(C_{mvd}*v_2) \quad (28)$$

$$C_r = C_{rn}+(C_{rvn}+C_{rvd})*z_i \quad (29)$$

$$C_p = C_{pn}+(C_{pvn}+C_{pvd})*n \quad (30)$$

Total FMC cost per unit of production, TC, is given by the following equation, where Q_c is production rate (units produced per unit time).

$$TC=(C_m+C_r+C_p)/Q_c \quad (31)$$

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 10 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 three transfer rates respectively.

Table 4: Cost parameters for the case problem

Machine	C_{mn} = 1.0		**Robot**	C_{rn} = 0.108	**Pallet**	C_{pn}= 0.108
	C_{mvn}= 0.2			C_{rvn}= 0.054		C_{rvn}= 0.054
	C_{mvd}= 0.2			C_{rvd}= 0.054		C_{rvd}= 0.054
	Total Cost = C_m =1.075	V_1= 0.25		Total Robot Cost = C_r = 0.43		
		V_2=0.125				
		z = 3				

As it can be seen from Figure 10, 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.

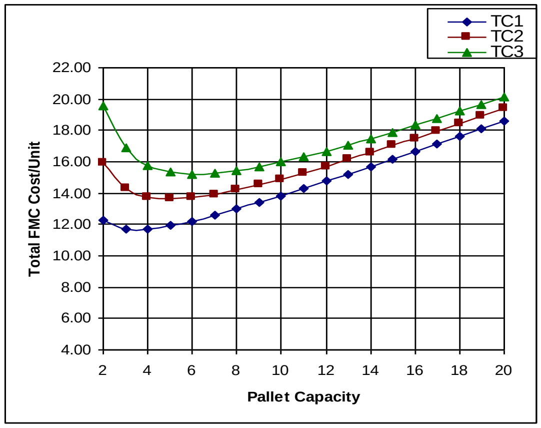

Figure 10: Production output rate as a function of pallet capacity

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-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 are 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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