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Hierarchical Control Scheme in Flexible Manufacturing Systems That have unreliable Machines and Maintenance

기계고장과 保全을 고려한 유연생산시스템의 계층적 통제계획

Wan-sup Um*

엄완섭*

Abstract

This paper describes an approach for the incorporation of maintenance times into a hierarchical scheduling for a failure prone flexible manufacturing system. The maintenance should not be performed too often because of the resulting reduction of capacity. Most manufacturing systems are large and complex. It is natural to divide the control into a hierarchy consisting of a number of different levels. Each level is characterized by the length of the planning horizon and the kind of data required for the decision making process. The goal of the analysis reported here is to calculate the production requirements while the machines fail and are repaired at random times. The machine failure and preventive maintenance are considered simultaneously.

1. Introduction

While the technology of manufacturing is improving rapidly, a basic understanding of the system's issues remains incomplete. They are production planning, scheduling, and control of work in process. They are complicated by randomness in the manufacturing environment particularly due to machine failures and other events, including setups, preventive maintenance, absences of raw materials, engineering changes, training sessions for new personnel, expedited batches, and many others.

We study systems involving many part types that are disturbed by machine failures and others. The basic idea is to keep track of the

* Department. of Industrial Engineering Kangnung National Univerisity

capacity of the system, as it varies over time as machines fail and are repaired. It is important to develop models and algorithms which allow the FMS controller to generate production schedules which satisfy demand requirements and exercise control over the system so that the output conforms to the schedule.

Rishel[8] showed that the solution of the optimization problem divides the continuous part of the state space into regions. Associated with each region is a different feedback law. He describes an abstract dynamic programming problem whose state has both a continuous and a discrete component. Olsder and Suri[7] proposed a dynamic programming model to describe the disruptive nature of machine failures. They represented machine repair states with a set of discrete variables.

Kimemia and Gershwin[5] derived a closed loop solution to the problem of dispatching parts to machines in a failure prone FMS. They found suboptimal strategies that are easy to calculate and that provide satisfactory performance. Formulation is modeled as a continuous time, mixed state dynamic programming problem. The discrete constituent of the state (α) is the vector of machine states. The other is the vector of surpluses (x), the cumulative differences between production and demand. The objective is to minimize these differences. The production rate vector (u) is constrained to be within a capacity set ($\Omega(\alpha)$) that is determined by the set of operational machines.

A feedback control law determines the current production rate as a function of current production surplus ($u(x, \alpha)$). The solution of dynamic program has two components. One is the calculation of the cost to go function $J(x, \alpha)$. Since the calculation of J is performed once, it is the longest term component of the scheduling rule. The other is the calculation of the control law, which requires J. The short term portion of the scheduling rule is the loading of parts in a way that agrees with the current production rates.

Maimon and Gershwin[6] found that the hierarchy has three levels. At the top Kimemia and Gershwin proposed a formulation which had the minimization of the surplus. They suggested an approximation in which they separated the solution of the Bellman equation into a number of subproblems. They approximated the value function J for each subproblem by a quadratic. The middle level of the hierarchy is the maximum principle of an optimal control problem. They showed that this maximum principle is a linear programming problem for the scheduling problem. The lower level developed an algorithm to choose part dispatch times to achieve flow rate u.

Akella, Gershwin, and Choong[1] led to improvements at all three levels. At the top level, the Bellman equation was replaced by a far simple procedure to generate the quadratic approximation for J. Because the behavior of a manufacturing system is highly insensitive to errors in the cost to go function. In the middle level, they found a way to make use of the quadratic approximation of J to eliminate the chattering phenomenon. For the part dispatch level, they replaced Kimemia and Gershwin's algorithm with one that was simpler and more effective.

Akella and Kumar[2], Bielecki and Kumar [3], and Sharifnia[9] obtained analytic solutions for special cases of Kimemia and Gershwin's formulation. They analyzed unreliable manufacturing systems that produce only one part type. Real manufacturing systems exhibit a much richer catalog of events, including setups, preventive maintenance, absences of raw materials, engineering changes, training sessions for new personnel, expedited batches, and many others.

This paper proposes a new modelling of FMS that have unreliable machines and preventive maintenance times. The general problems of FMS are described in section 2. Overview of hierarchical policy is explained in section 3. Section 4 contains hierarchical flow control with respect to FMS that has unreliable machines. Finally section 5 suggests a real time control model with respect to FMS that has unreliable machines and preventive maintenance times.

2. Problems of FMS

A flexible manufacturing system (FMS) is an automated, batch manufacturing system consisting of a set of numerically controlled machine tools with automatic tool interchange capabilities. Design, planning, scheduling, and control problems of FMS involve some intricate operations research problems. FMS design problems include determining the appropriate number of machine tools of each type, the capacity of the material handling system, and the size of buffers. FMS planning problems contain part type selection, machine grouping, product mix, resource allocation, and loading problem. FMS scheduling problems are concerned with running the FMS during real time once it has been set up in the planning stage. FMS control problems are those associated with monitoring the system, keeping track of production to be sure that requirements and due dates are being met as scheduled.

Operational control of an FMS is very complicated. It involves accessing large static and dynamic data sets and complex control algorithms. The control algorithms are structured hierarchically, where an upper level issues commands to a lower level and gets feedback on the achievement of these commands. In order to make good decisions under uncertainty, it is necessary to know something about the current state of the system and to use this information effectively. At the shortest time scale, this includes the conditions of the machines and the amount of material already processed. All the control functions necessary for planning and executing manufacturing activities in order to make products most efficient have been grouped into a few large areas.

3. Overview of hierarchical policy

Operating policies for manufacturing systems must repond to machine failures and other important events that occur during production such as setups, demand changes, expedited batches, preventive maintenance, etc. Each of these events takes up time at resource. Some events are controllable, others are not controllable but predictable. In this paper, we develop hierarchical scheduling and planning algorithms. The levels of the hierarchy correspond to classes of events that have distinct frequencies of occurrence.

Here, three kinds of events are considered. They are production operations on parts, failures and repairs of machines, and preventive maintenances. Operations occur much more often than failures, maintenence, and we can use the continuous representation of material flow. A dynamic programming formulation based on this representation leads to a feedback control policy. The state of the system has two parts. One is a vector of real numbers (x(t)) that represents the surplus, the cumulative difference between production and requirements, the other is a vector of integers (α(t)) that represents the set of machines that are operational. The object is to choose the production rate vector (u(t)) as a function of the state (x(t)) and (α(t)) to keep the surplus (x(t)) near 0.

The formulation of FMS control problem is as a stochastic linear programming problem. A set of constraints can be developed that say that a part cannot arrive at a station until the station has completed its previous operation. The problem can be formulated as a stochastic integer programming problem. The major difficulty with both of these formulations is the very large number of variables. Large integer programming problems are difficult and there are no standard methods for the solution of stochastic linear or integer programming problems.

The purpose of the short term FMS scheduling algorithm is to solve the following problem. When should parts be dispatched into an FMS with failure prone machines to satisfy production requirements? Kimemia and Gershwin decomposed the problem into two parts. The one is a high level continuous dynamic programming problem to determine the instantaneous production rates, the other is a combinatorial algorithm to determine the dispatch times at the bottom level.

A three level control hierarchy designed to compensate for work station failures and maintenance is proposed. The hierarchy is illustrated in Figure 1.

Assume that the production requirements are stated in the form of a demand rate vector d (t). Let the instantaneous production rate vector be denoted u(t). Define x(t) to be production surplus. It is the cumulative difference between production and demand and satisfies

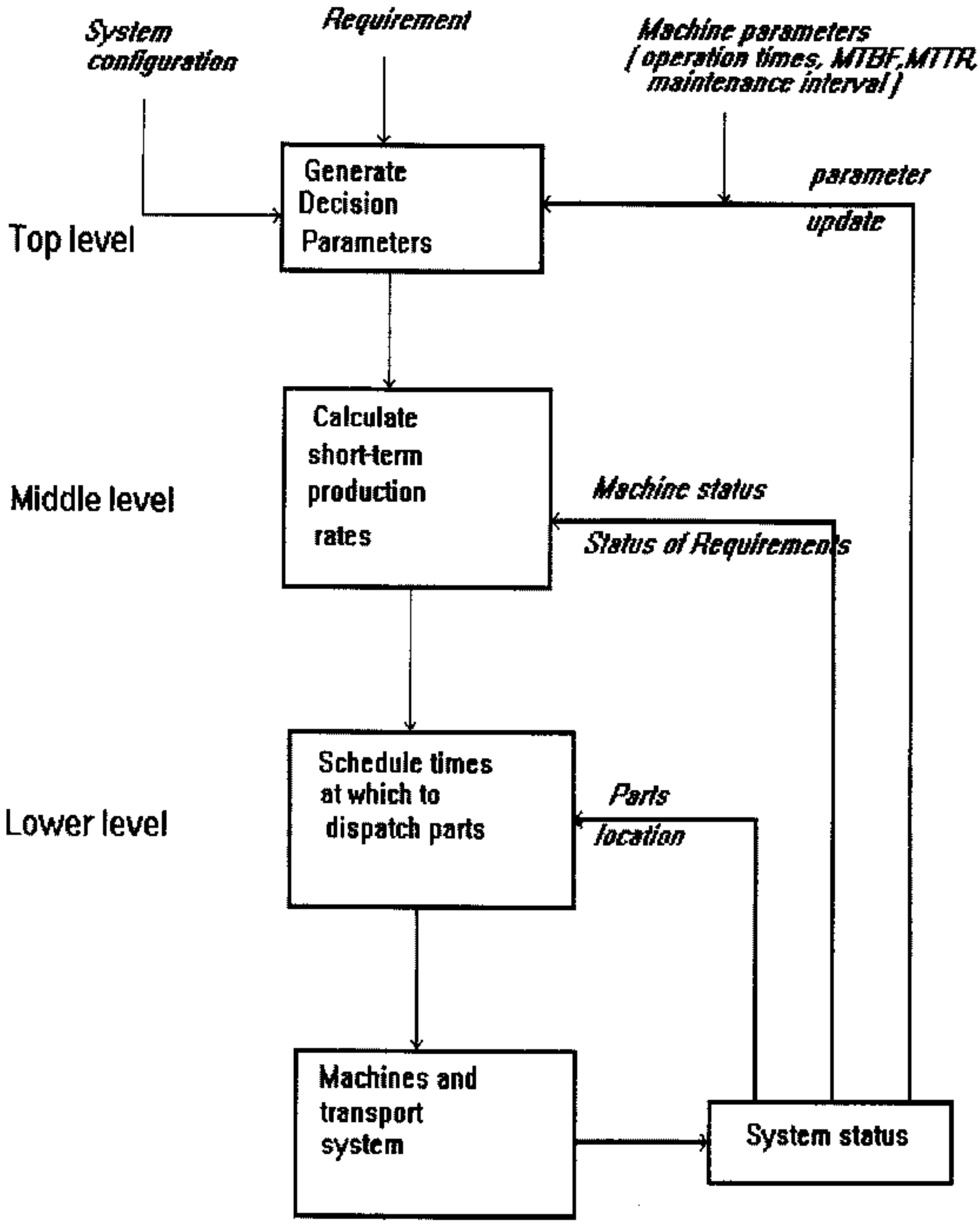


Figure 1. Three level control hierarchy

$$\frac{dx}{dt} = u(t) - d(t) \tag{3.1}$$

If x(t) is positive, there is a inventory, and if x(t) is negative, there is a backlog. A cost g(x) representing both the inventory and backlog costs can be assigned. The objective of the policy is to compute production rates to meet production targets while minimizing the total cost.

The production rate vector u(t) is limited by the capabilities of the machines. Let part type j require time τ_{ij} for all of its operations on machine i. Then

$$\sum_{j=1}^{n} \tau_{ij}\, u_j(t) \leq \alpha_i(t) \tag{3.2}$$

where $\alpha_i(t)$ is 1 if machine i is operational and 0 if it is down. If there is a set of identical type i machines, $\alpha_i(t)$ is the number of these that are operational at time t.

$$u_j(t) \geq 0. \tag{3.3}$$

Inequalities (3.2) and (3.3) can be written as

$$u(t) \in \Omega\,[\,\alpha(t)] \tag{3.4}$$

These requirements and constraints on the production rates can be expressed as a dynamic optimization problem as follows.

$$J[x(0), \alpha(0)] = \min E\left\{ \int g[x(t)]dt \,\middle|\, x(0), \alpha(0) \right\} \tag{3.5}$$

subject to

$$\frac{dx}{dt} = u(t) - d(t)$$

$$\sum_{j=1}^{n} \tau_{ij} u_j(t) \leq \alpha_i(t)$$

$$u_j(t) \geq 0. \text{ for } all\ j$$

given initial conditions x(0) and $\alpha(0)$

The scheduling policy can be decomposed into the three levels as follows

Top level: evaluation of J[x(0), $\alpha(0)$] and hedging point.

Middle level: compute the instantaneous production rates.

Lower level: determine the actual part dispatch times.

4. Hierarchical flow control with failure prone machine

Flow control problem is as follows. Given an FMS, an initial surplus state $x(t_0)$ and machine state $\alpha(t_0)$, we wish to find a production plan for the time interval $[t_0, T]$ that minimizes the performance index

$$J(x(t_0), \alpha(t_0), t_0) = E\left\{ \int_{t_0}^{T} g(x(s))ds \,\middle|\, x(t_0), \alpha(t_0) \right\} \tag{4.1}$$

subject to

$$\frac{dx}{dt} = u(t) - d(t) \tag{4.2}$$

$$P[\alpha(t+\delta t)=m \mid \alpha(t)=n]=\lambda_{nm}\delta t \text{ for } m \neq n \quad (4.3)$$

$$u(t) \in \Omega(\alpha(t)) \quad (4.4)$$

where λ_{mn} is called the generator transformation matrix.

The probability of having m resources available at time $t+\delta t$ given that there were n resources available at time t is $\lambda_{mn}\delta t$.

4.1 Cost to go function and hedging point

At the highest level of the control scheme is the off-line calculation of the parameters of the control policy to be used in the flow level. If all problem data is known, this is required only once: when a scheduling policy is established. The function g(x(t)) penalizes the controller for failing to meet demand and for getting too far ahead of demand. The performance index is thus the expected total penalty incurred by the controller in the interval[t_0, T]. The solution u(x, α, t) of (4.1) ~ (4.4) is the optimal feedback control. We develop the Bellman equation for this problem. Define the optimal cost to go or value function J as

$$J(x(t), \alpha(t), t) = \min E\left\{ \int_t^T g(x(s))ds \mid x(t), \alpha(t) \right\} \quad (4.5)$$

The cost to go is the expected total penalty incurred by the controller for the remaining time, given the buffer and machine states are x(t) and α(t) at time t. The ideal production policy would minimize the performance index by producing parts at exactly the demand rate, keeping the buffer state at zero. The hedging point is the value of x that minimizes J(x, α) for a fixed α. Hedging point is the level to which one builds up inventory to compensate for future production losses due to machine failures. In order to estimate the hedging point, consider Figure 2, which demonstrates a typical trajectory of $x_j(t)$. If $x_j(t)$ has reached $H_j(\alpha(t))$, the hedging point corresponding to the machine state before the failure, then $u_j(t)$ is chosen to be demand $d_j(t)$ and $x_j(t)$ remains constant.

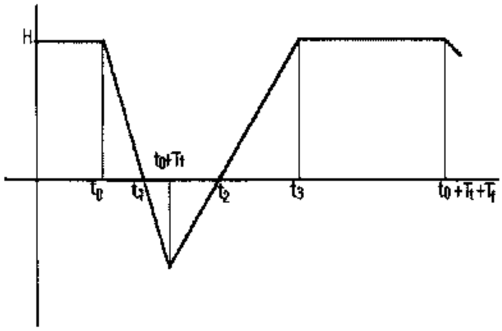


Figure 2. Production surplus

A failure occurs at time t_0 that forces $u_j(t)$ to be zero. This causes $x_j(t)$ to decrease at rate $-d_j(t)$. If failure lasts for a length of time T_r then the minimum value of $x_j(t)$ is $H_j(\alpha) - d_j(t)T_r$. And T_r, the repair time, is a random variable. Just after the repair at time $t_0 + T_r$, $u_j(t)$ is assigned the maximum production rate. Our objective is to obtain an approximation to J . We can do this by choosing H to minimize the total inventory cost in Figure 2.

The total inventory cost per cycle is

$$J(H_j) = \frac{1}{2}\{ (t_1 - t_0) + (t_3 - t_2) \} h + (t_0 + T_t + T_f - t_3)$$

$$H_j h + \frac{1}{2}(t_2 - t_1)(H_j - d_j T_t) \pi \qquad (4.6)$$

We obtain

$$H_j = \frac{T_f d_j(\pi u_j - hd_j) - T_f hd_j(u_j - d_j)}{(h + \pi)u_j} \qquad (4.7)$$

Where T_t and T_f are MTTR and MTBF. Average inventory cost and shortage cost are h and π. Maximum production rate is u_j and d_j is demand rate.

4.2 Production rate

In this level we describe a computationally effective method of computing the instantaneous production rates. The optimal production rate vector $u(x, \alpha)$ satisfies linear programming problem (4.8) at every time instant t

$$Minimize \frac{\partial J}{\partial x}(x, \alpha)u \qquad (4.8)$$

subject to

$$u \in \Omega(\alpha(t))$$

Once the surplus reaches the hedging point, the production rate is chosen to keep it there as long as possible. We derive the control law and calculate an optimal H that minimizes a cost function. Then the optimal production rate is

$$\begin{aligned} u(t) &= 0 \quad \text{if} \quad x(t) > H \\ u(t) &= d \quad \text{if} \quad x(t) = H \\ u(t) &= u \quad \text{if} \quad x(t) < H \end{aligned} \qquad (4.9)$$

where H is hedging point, and u is maximum production rate, and d is demand rate.

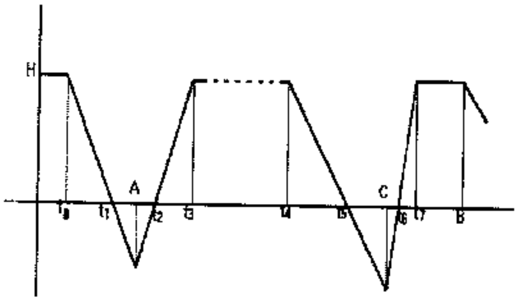
5. Real time control with failure and maintenance

Many manufacturing systems can process more than one kind of part. In most, a important cost in time or money is incurred each time a production resource is maintained for the processing of a new part type after it has been used for another type. Maintenance problem is to decide when to stop the resource from doing its current operation, and which part to making next.

5.1 Parameter calculation

At the highest level of the control scheme is the off-line calculation of the parameters of the control policy to be used in the flow level. In order to calculate the hedging point we consider Figure 3 as follows.

A maintenance begins at time t_0 that forces $u_j(t)$ to be zero. This causes $x_j(t)$ to decrease at rate $-d_j$. If maintenance continues for a length of time $A-t_0$ then the minimum value of $x_j(t)$ is $H_j(\alpha) - d_j(A-t_0)$, A failure occurs at time t_4 that forces again $u_j(t)$ to be zero. This causes $x_j(t)$ to decrease at rate $-d_j(t)$. If failure lasts for a length of time $C-t_4$ then the minimum



t_0: the starting point of maintenance

A: the ending point of maintenance

B: the next starting point of maintenance

t_4: the starting point of machine failure

C: the ending point of machine repair

Figure 3. Production surplus

value of $x_j(t)$ is $H_j(\alpha) - d_j(C-t_4)$. We can find hedging point H to minimize the total inventory cost in Figure 3. Just after the repair at time $t_4 + T_t$, $u_j(t)$ is assigned the maximum production rate. Our objective is to obtain an approximation to J. We can do this by choosing H to minimize the total inventory cost in Figure 3.

The total inventory cost per cycle is

$$J(H) = h\left\{\frac{1}{2}H\left[\frac{H}{d_j}\right] + \frac{1}{2}H\left[\frac{H}{u_j - d_j}\right] + H(T_t + T_f)\right\}$$
$$+ \pi\left\{\frac{1}{2}(H - d_jT_t)\left[T_t - \frac{H}{d_j}\right] + \frac{1}{2}\frac{(H - d_jT_t)^2}{u_f - d_j}\right\} \quad (5.1)$$

We obtains

$$H = \frac{d(s + mT_t)(\pi u + hd) - (w + mT_f)hd(u - d)}{(m+1)U(h+\pi)} \quad (5.2)$$

Where s is the mean maintenance time and w is the mean time interval between consecutive maintenances and T_t, T_f are MTTR and MTBF. Average inventory cost and shortage cost are h and π. Mean number of machine failure during w is m.

5.2 Production rate calculation

Flow control level determines the short-term production rates of each member of the part family. The mix of parts being produced is adjusted to take into account the random failure states of the machines. The production rate is such that x tends to a value H called the hedging point. The formulation of dynamic control model is as follows

5.2.1 Model notation

$u_{na}(t)$ = production rate of part n while system is in state a

d_n = demand rate of part n

$x_n(t)$ = the difference between cumulative production and cumulative demand for type n at time t

$y_{nmk}(t)$ = the rate at which work-station m performs operation k on part n

t_{nma} = the time that part n requires at machine m while system is in state a

f_{ab} = the frequency that the system state changes from a to b

λ_{ab} = the frequency that the system state changes from a to b while the system state is a

s_{ab} = the time required to change system state from a to b

w_a = the fraction of time that the system state is a

5.2.2 Model assumptions

1) Materials is sufficient to the production operation.
2) MTBF and MTTR are independent of the rate of machine utilization.
3) Machines in the work-station are all identical type and have the same operation times.
4) Changes of system state are due to machine failure and maintenance policy.

5.2.3 Flow Control Model

We wish to find the optimal production rate for each part type, the frequencies of maintenance, and the fraction of time that the system spends in each state. An optimization problem has objective function that represents the cost of surplus.

$$\textit{Minimize } J(x_0, \alpha_0, 0) = E[\int g(x(s))ds \mid x(0) = x_0, \alpha(0) = \alpha_0] \qquad (5.3)$$

subject to

$$\frac{dx_n}{dt} = u_n(t) - d_n \qquad (5.4)$$

$$P[\alpha(t+\delta t) = b \mid \alpha(t) = a] = \lambda_{ab}\delta t \qquad (5.5)$$

$$\sum_n \sum_m t_{nma} u_{na} \leq 1 \text{ for } all\ a \qquad (5.6)$$

$$d_n = \sum_a w_a u_{na} \text{ for } all\ a \qquad (5.7)$$

$$f_{ab} = \lambda_{ab} w_a \qquad (5.8)$$

$$\sum_a w_a + \sum_a \sum_b s_{ab} f_{ab} = 1 \qquad (5.9)$$

$$\sum_a \lambda_{ab} w_a = [\sum_a \lambda_{ba}] w_b \text{ for } all\ a \neq b \qquad (5.10)$$

(5.4) represents the dynamics of surplus x, and (5.6) shows capacity constraints. In order to satisfy demand, we must have (5.6). Equation (5.8) represents the relationship between frequency f_{ab} and z_{ab} . The total system time can be in any state or having its state changed, we have (5.9). And in steady state, we have (5.10)

5.2.4 Solution methodology

The solution of model is the optimal feedback control we are seeking. We develop the Bellman equation for this problem which helps to characterize this function. While we cannot solve the Bellman equation for any but the simplest of problems, we can use its properties to help derive practical policies for realistic problems. With hierarchical flow control structure and optimal control theory we can find the simple solution methodology.

The cost to go is the expected total penalty incurred by the controller for the remaining time, given that the buffer and machine states are x and α at the time t. We wish to specify a production plan for $t_0 \leq t \leq t_f$ that minimizes the performance index

$$J_u(x, \alpha, t) = E\left\{ \int_t^{t_f} g[x(s)]ds \mid x(t) = x, \alpha(t) = \alpha \right\}$$

For any δt, this satisfies a partial differential equation.

$$J_u[x(t), \alpha(t), t] = E\left\{ \int_t^{t+\delta t} g[x(s)]ds + J_u[x(t+\delta t), \alpha(t+\delta t), t+\delta t] \right\}$$

The production policies are feedback control laws that give a feasible production rate for each buffer and machine state in the interval (t_0, t_f). The "cost to go" minimization problem satisfies Hamilton-Jacobi-Bellman equation. We can consider that $\int_t^{t+\delta t} g[x(s)]ds = g[x(t)]\delta t$

We obtain the Taylor expansion.

$$J_u[x(t), \alpha(t), t] = g[x(t)]\delta t + \sum_b \lambda_{ab}\delta t J_u [x(t+\delta t), b, t+\delta t] + (1+\lambda_{a,a}\delta t)\left\{ J_u[x(t), \alpha, t] + \frac{\partial J_u[x(t), \alpha(t), t]}{\partial x}\dot{x}\delta t + \frac{\partial J_u[x(t), \alpha(t), t]}{\partial t}\delta t \right\}$$

An optimal feedback control law $u^0(x, \alpha, t)$ and the optimal cost to go J satisfy

$$Min\left\{ g[x(t)] + \frac{\partial J_u}{\partial x}(u-d) + \frac{\partial J_u}{\partial t} + \sum_b \lambda_{ab} J_u[x(t), b, t] \right\}$$

The exact solution to the flow control problem requires the solution of a coupled set of differential equations. Only after solving the continuous problem is the detailed discrete problem treated. The detailed scheduling problem is then much easier than it would be if it were treated without first solving the continuous problem.

5.2.5 Numerical Example

Consider a manufacturing system that has flexiblility with two different tools. The system can make types 1 and 3 in system state 1, and it can make types 1 and 2 in system state 2. It takes one hour on the average to do operation any part. We assume that the system makes three part types in two system state. The demands are $d_1 = 0.5$, $d_2 = 0.3$, $d_3 = 0.7$ parts per hour.

For system state 1, the capacity constraint is $u_{11} + u_{31} \leq 1$.

For system state 2, the capacity constraint is $u_{12} + u_{22} \leq 1$

If we treat the system in steady state, the demand constraints are

$w_1 u_{11} + w_2 u_{12} = 0.5$ for part type 1

$w_2 u_{22} = 0.3$ for part type 2

$w_1 u_{31} = 0.7$ for part type 3

The steady state condition is $z_{12}w_1 = z_{21}w_2$ because there are only two system states.

The normalization equation is

$$w_1 + w_2 + s_{12}f_{12} + s_{21}f_{21} = 1$$

$$w_1[1 + \frac{z_{12}}{z_{21}} + s_{12}z_{12} + s_{21}z_{12}] = 1$$

so, let $\frac{1}{z_{12}} + \frac{1}{z_{21}} + s_{12} + s_{21} = \Phi$

Then $w_1 = \frac{\frac{1}{z_{12}}}{\Phi}$ and $w_2 = \frac{\frac{1}{z_{21}}}{\Phi}$

From demand constraints we can get

$$\frac{1}{z_{12}} + \frac{1}{z_{21}} \leq 15(s_{12} + s_{21})$$

The results are as follows

$$w_1 = w_2 = 0.75$$

$$z_{12} = z_{21} = \frac{2}{15(s_{12} + s_{21})}$$

$$u_{11} = \frac{1}{15} \quad u_{31} = \frac{14}{15} \quad u_{12} = \frac{9}{15} \quad u_{22} = \frac{6}{15}$$

It is the sum of the times $s_{12} + s_{21}$ that is important. The system start in state 1 producing part type 1 and 3 at rate $\frac{1}{15}$ and $\frac{14}{15}$ pieces per hour. The hedging point is derived by equation (5.2). The system stays in state 1 for $\frac{2}{15(s_{12} + s_{21})}$ hours, and then change to state 2. The production rate calculated here are averages because we assumed that the system are under numerous failures and repairs while it is in each state. And those are requirements that the lower level must satisfy.

6. Conclusion

This paper suggests an approach to incorporating maintenance times into the hierarchical control for unreliable FMS's. The goal of the control system is to meet production requirements while the machines fail and are repaired at random times.

The control is organized in a hierarchical structure according to the various decisions at the different time scales. Here the formulation of hierarchical scheduling and maintenance problem of FMS and the simple solution methodology are suggested and the hedging point of this model is calculated.

Future work includes the development of the lower level algorithms. The widely used concept of hierarchical decomposition of scheduling algorithms should be examined.

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