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A Hierarchical Scheduling Model of Manufacturing Systems on Receding Horizon *

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Abstract: A new hierarchical optimal control production and setup scheduling model is discussed in an inflexible manufacturing system with jump Markov disturbances consisting of a single machine. The system can produce several types of products, but each time it can produce only one type of product. A setup (with setup time or cost or both) is required if production is to be switched from one type of product to another. The objective is to minimize the costs of setup, production and inventory. The decision variables are a sequence of setups and the production plan. Based on the idea of hierarchical control policy, a new hierarchical framework and hedging point control policy construct the hierarchical optimal control policy. An algorithm on receding horizon is also addressed.

Key words: hierarchical optimal control; receding horizon; manufacturing systems; scheduling; machine setup
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制造系统的递阶滚动优化调度模型

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摘要: 研究的对象是只有一台不可靠(failure-prone)机器的非完全柔性制造系统,该系统能生产多种产品,但在同一时刻只能生产一种产品,并且当机器由生产一种产品向生产另一种产品切换时,需要考虑 setup 时间及其成本.待决策变量是 setup 序列及产品生产率.本文基于非完全柔性制造系统的特点,引入递阶层控的思想,采用新的递阶结构框架和阈值控制策略,对问题进行分解,建立了考虑 setup 时间及成本的递阶流率控制最优化调度模型,并给出了递阶的滚动优化算法.仿真结果表明,这种调度策略更易于工程实现.

关键词: 递阶优化控制; 滚动时域; 制造系统; 调度; 机器 setup

1 Introduction

In the production systems in process industry, the characteristics of products and process recipe are quite different from those in workshop or job-shop. In real-time, both continuous processes and discrete events are contained in the systems, because uncertainties and stochastic perturbations can be unavoidable. Such systems own the characteristics of hybrid dynamic systems. There are few literatures on scheduling and optimal modelling of these hybrid systems due to their complexities. A review of previous researches on manufacturing systems tells us that Prof. Gershwin S. B. has made some remarkable contributions to the field. He discussed flow rate control model, hierarchical flow control, hedging point (HP) control, etc. [1] gave a hierarchical flow control framework of manufacturing systems based on the production process. The levels of the hierarchy correspond to the classes of events that occur with distinct frequencies. [2] discussed the selection of setup times via a hierarchical control policy of inflexible manufacturing systems, which involve setup. But in those literatures, the optimal solution is treated over infinite horizon, which is not feasible and computational in the engineering for dimension problems.

In this paper, discussions are extended from discrete manufacturing systems to production systems in process industry. Owing to the nature of such production systems, the setup is a vital factor and can not be ignored.

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A production planning model involving setup times is considered at length. From the viewpoint of practical applications, a two-level hierarchical framework is proposed. At the first level, setup times as typical events are determined in view of optimal inventory. At the second level, setup times and production rate are justified on real-time according to the frequency of machine failure. Part loading is considered at the lowest level by new hedging point control policy. From the viewpoint of asymptotic optimality, the production and setup scheduling model is discussed in an inflexible manufacturing system, based on the hierarchical flow control and hedging point policy. The hierarchy and hedging point are redefined in this paper according to [1], which decreases the dimensions and is computational and feasible in engineering.

In the paper, Section 2 presents the production system dynamic model and the objective function. In Section 3, the framework of the hierarchical control policy is described. The first level, where setup is treated as a typical event, is discussed in Section 4. Then in Section 5 & 6, the second level and the lowest level is described respectively. The basic advantage of the method illusrated by an example in Section 7. Finally, Section 8 concludes the paper.

2 Description of the problem

A production system is considered, which consists of a set of unreliable equipment and can produce n different types of products P_i, $i = 1, \cdots, n$. Each time only one type of product can be produced by the system. Moreover, the system is not completely flexible. A setup is required if production is to be switched from one type of product to another. This kind of system can be described as follows.

2.1 Setup time and cost

Suppose, for $i, j = 1, \cdots, n$ and $i \neq j$, $\theta_{ij} \geqslant 0$, which denotes the setup duration for switching from production of P_i to P_j, and $K_{ij} \geqslant 0$, which denotes the setup costs of switching from production of P_i to P_j. The setup duration θ_{ij} and the setup costs K_{ij} are constants. Moreover, for any $i, j, k = 1, \cdots, n$, $i \neq j$ and $j \neq k$, $\max\{\theta_{ij}, K_{ij}\} > 0$, $\theta_{ij} + \theta_{jk} - \theta_{ik} \geqslant 0$ and $K_{ij} + K_{jk} e^{-\rho\theta_{ij}} - K_{ik} > 0$. If $i = j$, then $\theta_{ij} = K_{ij} = 0$. Here $0 < \rho < 1$ denotes the discount rate.

2.2 Dynamic model of the system

For $t \geqslant 0$, let $x_i(t) \in \mathbb{R}^1 = (-\infty, \infty)$, $u_i(t) \in \mathbb{R}^+ = [0, \infty)$, and $z_i(t) \in \mathbb{R}^+ = [0, \infty)$ denote the surplus, production rate, and the rate of demand for product P_i, $i = 1, \cdots, n$, respectively. x, u and z are used to denote vectors $[x_1, \cdots, x_n]^T \in \mathbb{R}^n$, $[u_1, \cdots, u_n]^T \in \mathbb{R}^{+n}$, and $[z_1, \cdots, z_n]^T \in \mathbb{R}^{+n}$, respectively, where A^T denotes the transpose of a vector (or a matrix) A. The ordinary differential equation can be satisfied as follows

$$\dot{x}(t) = u(t) - z(t), \quad x(0) = x. \tag{2.1}$$

For $t \geqslant 0$, the production constraints are given as follows:

$$\begin{cases} 0 \leqslant u_i(t) \leqslant r_i, & i = 1, 2, \cdots, n, \\ u_j(t) = 0, & j \neq i, \end{cases} \tag{2.2}$$

r_i denotes the maximum production rate of P_i.

x, u respectively denote state variable and control variable in 2.1. Considering that the machine is subject to random failures and repairs, the machine states can be classified into i) operational, denoted by state 1; ii) under repair, denoted by state 0. When the equipment is operational, any type of the products can be produced; when it is under repair, nothing is produced. So the hybrid model of the systems is described in the following:

$$\dot{x}(t) = F(\zeta(t), t, x, u) = \begin{cases} u(t) - z(t), & \text{If } \zeta(t) = 1, \\ -z(t), & \text{If } \zeta(t) = 0, \end{cases} \tag{2.3}$$

$x(0) = x \in \mathbb{R}^n$, $\zeta(0) = \beta \in E$ (index set).

Where $F = [f_1, f_2, \cdots, f_n]^T$, because of single set of equipment, we have $f_1 = f_2 = \cdots = f_n = f$.

In Eq. (2.3), $\zeta = \{\zeta(t): t \geqslant 0\}$ is a finite state controlled Markov process with state-space $E = \{0, 1\}$. According to our notation, if there is a jump from state β to state α, then the derivatives $F(\beta, x, u)$ jumps to $F(\alpha, x, u)$.

Definition 1 $(\lambda_{\beta\alpha})$ denotes the generator matrix, and $(\lambda_{\beta\alpha}) := \begin{bmatrix} \lambda_{11} & \lambda_{10} \\ \lambda_{00} & \lambda_{01} \end{bmatrix}$, $\forall \alpha, \beta \in E, \alpha \neq \beta$, with $\lambda_{\beta\alpha} \geqslant 0$ and $\sum\limits_{\alpha} \lambda_{\beta\alpha} = 0$, $\forall \beta \in E$. α, β are exogenous Markov process with parameter λ. Here $\lambda_{10}/\lambda_{01}$ denotes the rate of transition from the operational/breakdown to the breakdown/operational state. Moreover, $\lambda_{11} = -\lambda_{10}$, $\lambda_{00} = -\lambda_{01}$.

For each $\beta \in E$, let $F(\cdot, \cdot): \mathbb{R}^n \times \mathbb{R}^{+n} \times E \rightarrow \mathbb{R}^n$ be a bounded continuously differentiable function with bounded partial derivatives in x. Let $U(\beta), \beta \in E$, (a close subset of $\mathbb{R}^{+n}$) denote the control constraints. Any measurable function $u(t)$ defined on $[0, T]$ with value in $U(\beta)$, for each $\beta \in E$, is called an admissible control, and $U = \{u(t): t \geqslant 0\}$ denotes admissible policy. The admissible control function $u(t)$ is supposed to be piecewise continuous in t and continuously differentiable with bounded partial derivatives in x.

2.3 Cost function

Over the infinite horizon, the cost function J can be defined as

$$J(i, x, s, \Xi, u(\cdot)) = \int_0^s e^{-\rho t} G(x(t), 0) dt + E\left(\int_s^{\infty} e^{-\rho t} G(x(t), u(t)) dt + \sum_{l=0}^{\infty} e^{-\rho \tau_l} K_{i_l i_{l+1}}\right), \tag{2.4}$$

where s denotes the remaining setup time, $0 \leqslant s \leqslant \theta_{ij}$. Moreover, the setup cost is assumed to be charged at the beginning of the setup. The decision variables are the rates of production $u(\cdot)$ over time and a sequence of setups denoted by $\Xi = \{(\tau_0, i_0 i_1), (\tau_1, i_1 i_2), \cdots\}$, where a setup (τ, ij) is defined by the time τ when it begins and a pair ij denoting that the equipment was already set up to produce P_i and is being switched to be able to produce P_j.

Let $G(x(t), u(t))$ denote the running cost function of surplus and production, and it is locally Lipschitz and has at the most polynomial growth. Usually $G(x(t), u(t)) = \sum_{i=1}^{n} c_i^+ x_i^+(t) + c_i^- x_i^-(t)$. Suppose a holding cost of c_i^+ per unit commodity per unit time is incurred by positive surplus, while a cost of c_i^- is incurred by negative surplus, with $c_i^+ > 0, c_i^- > 0$. And $x_i^+ := \max(x_i, 0), x_i^- := \max(-x_i, 0)$. The problem is to find an admissible decision $(\Xi, u(\cdot))$ that minimizes $J(i, x, s, \Xi, u(\cdot))$.

3 Framework of the hierarchical control policy

In this section, the framework of the hierarchical control policy is described, according to the properties of the system.

In unreliable manufacturing systems, events can be categorized into the events that may or may not be under the control of the decision-maker. For the purpose of this paper, an event is considered to be controllable if its time of occurrence may be chosen, whether or not there are constraints on that choice. An event is uncontrollable otherwise. Setup and production rate are controllable, for example, while failures are not. The structure of the hierarchy is based on events tending to occur on a discrete spectrum. Classes of events have frequency that cluster near discrete points on the spectrum. The control hierarchy is tied to the spectrum. Each level k in the hierarchy corresponds to a discrete point on the spectrum. So the events in the manufacturing system are classified into classes based on the frequency of their occurrence. It is assumed that the events in different classes occur with very different frequencies. Each level of the hierarchy responds to events in a single frequency class, schedules the controllable events of that class and sets target rates for lower levels. The least frequent events are treated at the highest level whereas more frequent events are assigned to lower levels of the hierarchy. A special case of the system with a three-level hierarchy is considered. Level 1 is the highest level where all discrete events are represented by their average rates. By the nature of the production system, the setup which is a controllable event is treated as a typical event in the level based on the optimal inventory. Level 2 corresponds to failures and repairs which are more frequent than setup changes. Part loading is the most frequent kind of event and is treated at the lowest level.

Each scheduling algorithm is carried out only to one type of product by using receding horizon scheme based on the optimal inventory. The policy is receding carried out on line not off line. The original inventory of the hierarchy is renewed by real-time detected inventory. As in many literatures receding horizon scheme is adopted, by which the adverse effects in the control policy caused by random events, random demands, model inaccuracy and the mismatch between model and the real system can be minimized.

The setup times and the duration of producing T are chosen to agree with the production rate, so the production rate affects them badly. The receding horizon scheme here is of importance. Now the framework of the hierarchical receding control policy can be given. The setup times and the expected optimal production rate are decided by Level 1. The real time production rate is kept close to the expected rate by Level 2 in view of the dynamic properties of the system by using receding horizon scheme. Part loading is carried out in the lowest level on real-time. The framework of the hierarchical control policy is described as Fig.1.

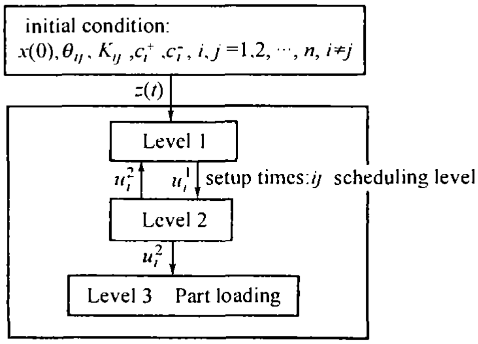

Fig. 1 Framework of the hierarchical control policy

4 Level 1—Optimization of stable state

The failure-prone of the machine is not considered, and the production process of the system is treated as a continuous process in this section. For the nature of the system, only one type of product can be produced by the system at any given time, and the objective function of stable state can be written in the following[3]:

$$JS(i,x,u(\cdot)) = \int_0^{\theta_{ij}} e^{-\rho t}G(x(t),0)\mathrm{d}t + \left(\int_{\theta_{ij}}^{T} e^{-\rho t}G(x(t),u(t))\mathrm{d}t \mid x(0)=x,\beta(0)=\beta\right)+e^{-\rho\tau_0}K_{ij}, \tag{4.1}$$

which denotes the cost function of running and setup cost in horizon $[0,T]$ not considering the dynamic property of the system, where T denotes the time when the first setup is finished and the system is already set up to produce the second type of product. And τ_0 denotes the initial time of setup, without losing generality, $\tau_0 = 0$. In Eq. (4.1), the problem is to find the following decision variables: i) which type of product P_j is to be produced according to the current producing product P_i; ii) the duration T of producing the type of product P_j; iii) the production rate $u_j(t)$ of P_j, which makes the objective function $JS(i,x,u)$ minimum. $T = T^* + \theta_{ij}$, where T^* denotes the duration over which the inventory of P_j reaches its optimal inventory at the optimal production rate $u_j^*(t)$. As to the manufacturing system with jump Markov disturbances, only one type of product can be produced and optimal production control is hedging point policy. And the optimal inventory x^* of this system is given by [4]. But new hedging point policy is given by the following paragraph.

$$x^* = \max\left\{0,\frac{1}{\lambda_-}\log\left[\frac{c^+}{c^+ + c^-}\left(1 + \frac{\rho^* z(t)}{\lambda_{10}z(t)-(\rho+\lambda_{01}+z(t)\lambda_-)(r-z(t))}\right)\right]\right\}, \tag{4.2}$$

where λ_- is the only negative eigenvalue of the matrix

$$A1 := \begin{bmatrix} \dfrac{\rho+\lambda_{10}}{r-z(t)} & \dfrac{\lambda_{11}}{r-z(t)} \\ \dfrac{\lambda_{01}}{z(t)} & \dfrac{\lambda_{00}-\rho}{z(t)} \end{bmatrix}.$$

4.1 Decision of HP T

$\int_0^{\theta_{ij}} e^{-\rho t}G(x(t),0)\mathrm{d}t$ and $e^{-\rho\tau_0}K_{ij}$ are independent of the production rate $u_j(t)$ in Eq. (4.1). As a result, the problem of 4.1 can be converted to the following problem:

$$\begin{cases} \min J(u(t)) = \min\limits_{u_j(t)\in U}\int_0^T e^{-\rho t}G(x(t),u(t))\mathrm{d}t, \\ \text{s.t. } \dot{x}(t) = u(t) - z(t),\ x(0) = x_0. \end{cases} \tag{4.3}$$

The terminal condition is: $x(T) = [x_1(T), x_2(T), \cdots, x_{i-1}(T), x_i^*, x_{i+1}(T), \cdots, x_n(T)]^{\mathrm{T}}$, where T is the duration over which the optimal production rate $u_j(t)$ drives $x_i(0)$ to x_i^*.

From $G(x(t),u(t)) = \sum_{i=1}^{n}[c_i^+x_i^+ + c_i^-x_i^-]$, the following can be gotten:

$$J(u(t)) = \int_0^T e^{-\rho t}G(x(t),u(t))\mathrm{d}t = \int_0^T e^{-\rho t}\bar{G}(x(t),0)\mathrm{d}t + \int_0^T e^{-\rho t}g(x_i(t),u_i(t))\mathrm{d}t,$$

where

$$\bar{G}(x(t),0) = \sum_{j=1,j\neq i}^{n}[c_j^+x_j^+ + c_j^-x_j^-],$$

$$g(x_i(t),u_i(t)) = c_i^+x_i^+ + c_i^-x_i^-.$$

$\bar{G}(x(t),0)$ can be rewritten as $\bar{G}(x(t),0) = c \mid x_0' - z(t)t \mid$ responding to the constant demand $z(t)$ and the definition of x_i^+ and x_i^-, where c is a constant parameter determined by c_j^+ and c_j^-.

Then the tendency of the function $L(t) = e^{-\rho t}\bar{G}(x(t),0)$ is illustrated by the solid lines in Fig. 2 ($n = 2$). Let $J_1 = \int_0^T e^{-\rho t}\bar{G}(x(t),0)dt$ then J_1 can be rewritten as $J_1 = A - e^{-\rho T}(BT + A)$, where A, B are piecewise constants according to the initial conditions. And the dash lines in Fig. 2 illustrate the tendency of function J_1. $\int_0^T e^{-\rho t}\bar{G}(x(t),0)dt$ only is a function of T and monotonously increases to T. As a result, when T decreases, $\int_0^T e^{-\rho t}\bar{G}(x(t),0)dt$ decreases too. Another shortest time objective function $J_1 = -e^{-\rho T}(BT + A)$ can be incurred, which converts the optimal problem of Eq. (4.3) into the problem of finding the optimal solution of the following objective function:

$$J(u(t)) = J_1 + \int_0^T e^{-\rho t} g(x_i(t), u_i(t))d_t = -e^{-\rho t}(BT + A) + \int_0^T e^{-\rho t} g(x_i(t), u_i(t))dt, \tag{4.4}$$

and T can be obtained by the following:

$$\dot{x}_i(t) = u_i(t) - z_i(t) \Rightarrow \int_0^T \dot{x}_i(t)dt = \int_0^T u_i^*(t)dt - \int_0^T z_i(t)dt \Rightarrow$$
$$x_i^* - x_i(0) = \int_0^T u_i^*(t)dt - z_i T.$$

Let $u_i^*(t) = \dot{U}_i^*(t)$, then

$$x_i^* - x_i(0) = \int_0^T \dot{U}_i^*(t)dt - z_i T = U_i^*(T) - U_i^*(0) - z_i \Rightarrow$$

$$T = \frac{U_i^*(T) - U_i^*(0) - x_i^* + x_i(0)}{z_i}. \tag{4.5}$$

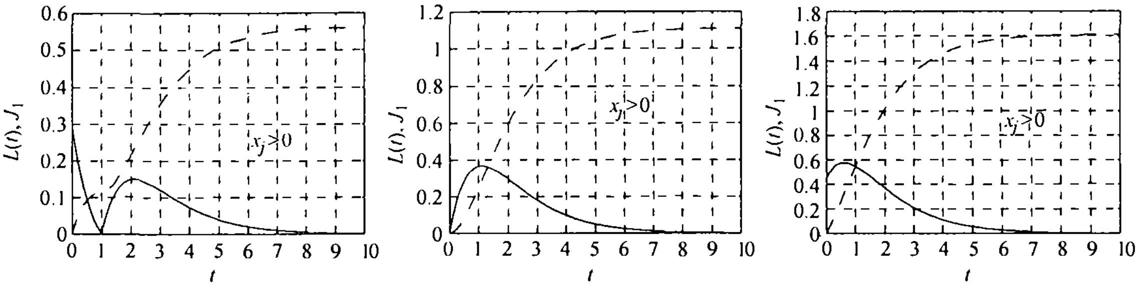

Fig. 2 Tendency of $L(t)=e^{-\rho t}\bar{G}(x(t),0)$ and $\int_0^T e^{-\rho t}\bar{G}(x(t),0)dt$

4.2 Static programming

Eq. (4.4) can be solved to get the optimal production rate $u_i^*(t)$ by static programming method. A series of $u_i^*(t)$ can be gotten, for $i = 1,2,\cdots,n$, by iterative algorithm. The setup times ij and hedging point T can be first gotten by comparing the values of objective function, for more details in [3]. And the result as a set value to Level 2 will be adjusted for more accuracy at Level 2.

5 Level 2—Machine failure involved

Definition 2 x_i^k, u_i^k denotes the production surplus and production rate of product P_i at the level k respectively.

Based on the dynamic property, i.e. failure-prone, of the system, keep u_i^2 close to u_i^1 at the level. The production surplus of Level 2 satisfies the following equation:

$$x_i^2(t) = \int_0^t u_i^2(s)ds - \int_0^t u_i^1(s)ds \text{ or } \frac{dx_i^2}{dt} = u_i^2 - u_i^1. \tag{5.1}$$

5.1 Resolve $u_i^2(t,\alpha)$

Based on the setup times ij set by Level 1, the optimal feedback variable $u_i^2(t,\alpha)$ can be found to make the following objective function minimal:

$$JS'(i,x,u(\cdot)) = \int_0^{\theta_{ij}} e^{-\rho t}G(x(t),0)dt + E[(\int_{\theta_{ij}}^T e^{-\rho t}G(x(t),u(t))dt \mid x(0)=x, \beta(0)=\beta) + e^{-\rho\tau_0}K_{ij}],$$

the initial conditions are $x^2(0) = x, \alpha^2(0) = \alpha$. Kimemai and Gershwin[5] derived a Bellman's equation for this problem

$$\min\{G(x_i^2) + \frac{\partial JS'}{\partial x_i}(u_i^2 - \text{Proj}(u_i^1,2)) + \frac{\partial J}{\partial t} +$$

$$\sum_{\beta}\lambda_{\alpha\beta} JS'[x_i^2,\beta,t]\} = 0, \qquad (5.2)$$

where $\mathrm{Proj}(u^1,2) = E_1(u^2) = u^1$. $\mathrm{Proj}(u,k)$ is the projection of the vector u into the space of u_k. As to the production process without setup changes, since the function JS' is given, Eq. (5.1) can reduced to solve

$$\min_u \frac{\partial JS'(x,\alpha)}{\partial x_i} u_i^2,\ u_i \in U(\alpha). \qquad (5.3)$$

For the system, the constrain set of u_i is a linear function, which makes 5.3 a linear programming problem. [4] and [7] have obtained analytic solution for the versions of this problem. The optimal production rate $u_i^2(t,\alpha)$ can also be gotten by using a numerical method for the finite horizon $[0,T]$ deducing the dimension.

5.2 Update setup times

The real-time setup times are carried out in practice and updated by using the optimal production rate gotten by Eq. (5.3) via iterative method. The algorithm to update setup times is similar to that in Level 1.

6 Level 3—Part loading

The new hedging point policy is to check the hedging point T and the system will produce another type of product P_j as soon as T comes. The definition of hedging point policy is different from that in [1]. T as the hedging point is reasonable according to the analysis in Section 4. At T, the objective function J reaches its minimum over horizon $[0,T]$. T is also the time when the next setup begins and part loading is carried out at Level 3, by which it is convenient to get setup times. Since the hedging point policy is based on the optimal inventory, the time when one type of product reaches its optimal inventory is definite. T is employed to judge whether the part loading can be carried out or not. This method provides a particular welcome additional feature that the hedging point can be gotten analytically, and can be feasibly used in practice.

According to Eq. (4.5), the terminate time is $T = \dfrac{U_i^*(T) - U_i^*(0) - x_i^* + x_i(0)}{z_i}$ at which the process of producing P_i is over. The type of product P_i is being produced until $t = T$. When the time T is reached, the system is switched to produce the type of product P_j. The optimization of the system is renewed.

7 Simulation

The performance of the hierarchical receding control policy is shown with an example with the following specifications: $n=2, \rho=0.9$. The demand rate is $z_1 = z_2 = 0.4$ and the initial conditions are $x_1(0) = -2.0, x_2(0) = 0.0, \alpha \in E = \{0,1\}$, $(\lambda_{\beta\alpha}) = \begin{bmatrix}\lambda_{11} & \lambda_{10}\\ \lambda_{00} & \lambda_{01}\end{bmatrix}$. The other parameters are shown in Table 1. Figs. 3, 4 are the simulation results. According to the results, the setup times of producing the products P_1, P_2 will reach a dynamic balance after a finite horizon, which agrees with the fact based on the optimal inventory. Moreover, when $z > r$, as time goes by, T will be infinite, which also agrees with the fact. The later condition $(z > r)$ is not illustrated here.

Table 1 Parameters of the system

C_1^+	C_2^+	C_1^-	C_2^-	θ_{12}	θ_{21}	K_{12}	K_{21}	λ_{10}	λ_{01}
1.0	1.0	3.0	3.0	0.4	0.5	0.95	0.85	0.1	0.2

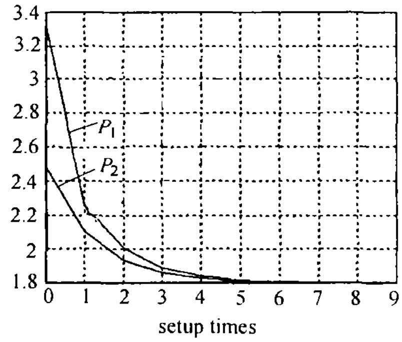

Fig. 3 Production duration tendency of P_1, P_2

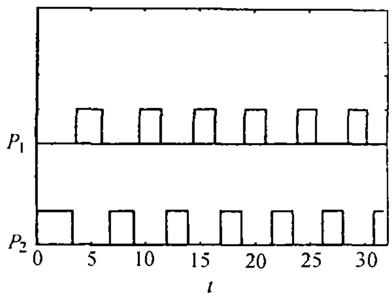

Fig. 4 The Gantt graph of receding scheduling

8 Conclusions

Hierarchical control policy is presented based on the hierarchical flow control policy in [1]. But the hierarchy is redefined. In the paper, the setup, a controllable event, is treated in Level 1 as a typical event without considering the dynamic property of the system. A new objective function is discussed in Level 1 and the solution of the problem is submitted. The hedging point policy based on the optimal inventory is carried out. At the lowest level, part loading is set up at the new hedging point. By decomposition and simplification, the original problem is turned into the problem on one dimension, which is computational and tractable. And the policy makes the control law more accurate and be carried out in time. The method of simplification and definition of the new hedging point is reasonable and have strong application background. The fault of the policy is that the solution to this problem is not globally optimal but asymptotical optimal. However, the receding control policy can decrease the drawback to some extent.

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