Research Article

The Application of Time-Delay Dependent H_∞ Control Model in Manufacturing Decision Optimization

Haifeng Guo,¹ Bo Wang,² Jianhua Zhang,^{1,3} Song Chen,¹ and Yi Qiu¹

¹School of Management, Harbin Institute of Technology, Harbin 150001, China

²School of Humanities and Social Sciences, Harbin Institute of Technology, Harbin 150001, China

³Northeast Petroleum University, Daqing 163318, China

Correspondence should be addressed to Bo Wang; wangbo@hit.edu.cn

Received 30 July 2015; Accepted 3 November 2015

Academic Editor: Francesco Franco

Copyright © 2015 Haifeng Guo et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

This paper uses a time-delay dependent H_∞ control model to analyze the effect of manufacturing decisions on the process of transmission from resources to capability. We establish a theoretical framework of manufacturing management process based on three terms: resource, manufacturing decision, and capability. Then we build a time-delay H_∞ robust control model to analyze the robustness of manufacturing management. With the state feedback controller between manufacturing resources and decision, we find that there is an optimal decision to adjust the process of transmission from resources to capability under uncertain environment. Finally, we provide an example to prove the robustness of this model.

1. Introduction

The resource-based view (RBV) has been employed in many research fields since it indicates that the internal key resources should be accompanied with strong organization-related, nontransferable, and nonduplicated characteristics, such as McKone-Sweet and Lee's study [1] in supply chain. Therefore, according to RBV, the key resources are not those which are directly purchased in the market, but are the decision methods and information in which an enterprise is allocating and consuming the materials and the capability which is accumulated in the manufacturing process.

It is very important for an enterprise to establish manufacturing capability and keep the capability nonduplicated. Park and Tran [2] build an Intelligent Manufacturing System based on Cognitive Agent technology to improve the manufacturing capability. Jain et al. [3] construct four instruments to assess the manufacturing capability with questionnaires.

Therefore, we discuss the transformation process from resources to manufacturing capability. Then we propose a competitive strategy model and indicate that the manufacturing

capability can be established by combining the resources and manufacturing decisions. It is argued that there exists a cross influence between resources and manufacturing decisions; that is, manufacturing decisions are based on current resources and actions on how resources are allocated and used, which further affects the results of manufacturing capability. This process makes purchased resources nontransferable and organization-reliable.

The manufacturing system is complex and uncertain when the resources are put into production. Pei [4] once tried to use fuzzy multiattribute decision making models to make rational decision. However, he ignores the manufacturing process, especially the manufacturing capability which is the ultimate goal. So it is of significant importance to make the manufacturing system stable and then make the capability not disturbed by uncertain factors. There is lack of studies in this area; that is, it is not addressed how to optimize the manufacturing capability when the firms allocate and use the resources after the decision. In order to solve this problem, we propose H_∞ control model to find an optimal feedback control method. Because the decision should be made and

then resource can be allocated and put into production, there exists a time delay between decision and resource. Further, the manufacturing capability might be produced after a while, and thus there exists a time delay between capability and resources. So we expand our model into a time-delay H_∞ control model.

As we all known, robust control model is widely used in the field of control. It starts by Zames using H_∞ functional to optimize index [5] and now the application of robust control spread to every field, like aerospace, mechanical engineering, economic, manufacturing, and so on. Karimi [6] considers the problem of stability analysis with an H -infinity performance for a class of production networks of autonomous work systems with delays in the capacity changes. Hu et al. [7] make an event-triggered H -infinity stabilization (in the mean square sense) for networked stochastic system with multiplicative noise and network-induced delays. Others like Nazarian and Ko [8] and Yu and Wang [9] also study the robust control in manufacturing, but few pays attention to the management of manufacturing. This paper would study how to design optimal manufacturing decisions in the process of transformation from resources to capability.

This paper makes contributions in two ways. We construct a model of resource, manufacturing decision, and manufacturing capability based on resource-based view (RBV). This model explains how an enterprise transfers resources into manufacturing capability using the manufacturing decision. The second contribution is that we employ time-delay H_∞ control model in the manufacturing management to find an optimal feedback control method. This paper constructs a new H_∞ control model to reflect the relationship between manufacturing resources and decision, which is a first try in manufacturing management by adopting the H_∞ control theory. Meanwhile, after detecting that there is a delay effect of manufacturing resources on the capability construction, this paper introducing time delay in the model, which is a contribution in methodology in manufacturing management area. With the state feedback controller between manufacturing resources and decision, we find that there is an optimal decision to adjust the process of transmission from resources to capability under uncertain environment. This paper makes the combination of control theory with manufacturing management. This paper could be used by manufacturing managers. They could take this paper into account when they make decision in allocating resources.

The remainder of our paper is arranged as follows. Section 2 explains the theory and framework of the manufacturing capability based on RBV. Section 3 gives the basic model to solve the instability of the manufacturing system. Section 4 proposes the time-delay dependent H_∞ control model and Section 5 makes a design model to explain how to control the manufacturing process. The conclusion is in Section 6.

2. The Theory and Framework

2.1. Resource-Based Views (RBV). The resource-based view (RBV) can be traced back to Wernerfelt [10] who proposed that resource is key to a firm. However, RBV is not focused

until Barney et al. presented it in the Firm Resource-Based View (RBV) Management Forum [11]. Then the theory is widely applied to the field of strategic management, human resource management, sales management, and related empirical research.

The RBV indicates that firms are different because of unique resources aggregation. Firms exhibit heterogeneity due to the different resource endowment and could obtain competitive advantage and excess profits derived from the heterogeneity resources which are valuable, rare, imperfectly imitating, and nonsubstitutable.

2.2. Manufacturing Capability. Skinner [12] suggests that manufacturing capability is one of the most important elements of competitive priorities and therefore critical to gain competitive advantage. Manufacturing capability is realized manufacturing strategy. Roth and Van Der Velde [13] view manufacturing capacity as a strategic capability which is achieved in the manufacturing process and the conversion of enterprise strategy. We define manufacturing capability as a method and process by which an organization integrates and utilizes resources. Manufacturing capability includes skills, technology, knowledge, and ability which are accumulated in the process. It is the main source of firms' sustainable competitive advantage in manufacturing field.

Although manufacturing capacity covers lots of elements, at present, the most widely accepted manufacturing capability elements are as follows.

(1) *Quality*. Product quality is the aggregate of product characteristics which meets customer needs. Quality is the degree of production system behavior and results conform to customer requirement and technical specification. The quality assurance aspects constitute the most basic standard of manufacturing capacity. Quality is the foundation for the development of manufacturing capabilities [14].

(2) *Cost Efficiency*. Cost is the aggregate expenditure of both material and labor in production process. Cost is the value which compensates capital consumption. It also sets the minimum product price. Product price is an important order winner for manufacturing firms when the marginal profit declines [15]. Therefore, cost efficiency is regarded as the ultimate manufacturing capability.

(3) *Flexibility*. Flexibility is the ability that enables firms to adapt to the market change. Due to the rapid change in customer needs, flexibility has become a key element of manufacturing capability [16].

(4) *Delivery*. Delivery is the ability by which firms can rapidly, effectively, and accurately deliver products to the specified location within prescribed time. Delivery mainly includes the delivery reliability and speed. Delivery is a corporate manifestation to customer service and has become one of the dimensions of manufacturing capability.

(5) *Innovation*. Innovation refers to the ability by which firms can develop new product to meet market requirement. Innovation is a comprehensive ability; it includes fit processing

FIGURE 1: The theoretical framework of resource, manufacturing decision, and manufacturing capability.

technology to produce new products, developing and using new product and process, facing new technology and competitors, and so on. For manufacturing firms, product innovation is the innovation focus and starting point [17].

2.3. Manufacturing Decision. Manufacturing decision is presented by Wheelwright in 1978 [18]. He proposed that the company strategy can be realized by decision-making activities in manufacturing field. Then, he pointed out that decision is the key factor to realize the company strategy and manufacturing performance with manufacturing; however, most studies neglected the influence of decision activities in manufacturing process. Roth and Van Der Velde [13] defined manufacturing decision as a series of manufacturing decision to achieve business objectives in forms of operations in the patterns of choices. We define the manufacturing decision as the following three parts.

(1) *Structure Decision.* Structure decision is firms' choice of "hard" or "brick-and-mortar" and refers to decision and strategic choice associating with rigid resource in production process, and it includes the design of production line, process technology selection, factory site planning, product plan, facility decision, standard rules, and the vertical integration of organization.

(2) *Infrastructure Decision.* Infrastructure decision refers to the management policy and system related to the production process, especially those policy and system related to structure decision factors. Infrastructure decision is the decision and management activities which combine firms' facilities, equipment, and staff into an organic whole. Infrastructure decision is more related to labor policies, production management, and control policies.

(3) *Integration Decision.* Integration decision refers to interaction, communication decision activities among production functions, other internal functions, and external organizations.

2.4. The Relationships among Resource, Manufacturing Capability, and Manufacturing Decision

(1) *The Relationship between Manufacturing Decision and Resource.* It is widely accepted that manufacturing decisions played an important role in which resource transforms into manufacturing capabilities. Hayes and Pisano [19] pointed out that the strategy implementation was closely related to the labor. The degree of strategy implementation depends on the development manufacturing capability of employee. Therefore, all firms' decision is key strategy factor in which resource transforms into manufacturing capabilities. The uniqueness of the ability derived from the resource and impacted by manufacturing decision in the using process is not easy to be imitated. Therefore, we assume that there are relationships between resources and manufacturing decisions.

(2) *The Relationship between Manufacturing Decision and Manufacturing Capability.* Many researchers have proposed that decision making can directly enhance manufacturing capacity in practice. Schroeder et al. [20] claimed that early participation of employees in design process can directly improve quality and flexibility. Hayes and Pisano [19] suggested that manufacturing capabilities come from structure decision, such as the human resources management method and policy. Therefore, manufacturing capability could be improved from resources and manufacturing decision processes.

Based on the above discussion and derivation, this paper puts forward the theoretical model manufacturing capacity resource based on RBV in Figure 1. This model is the theoretical framework for our analysis.

3. Basic Model

In this section, we will build a mathematical model with the theoretical framework above. The key idea is to build a continuous H_∞ control, as

$$\begin{aligned}\dot{X}(t) &= AX(t) + Bu(t) + B_1\omega(t), \\ Y(t) &= CX(t) + Du(t) + D_1\omega(t),\end{aligned}\tag{1}$$

where $u(t)$ is the control input; $X(t)$ is the state variable; $Y(t)$ is the output which is the goal [21]. So we can get

$$\begin{aligned}
 \begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \\ \dot{x}_3(t) \end{bmatrix} &= \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \end{bmatrix} \\
 &+ \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} u_1(t) \\ u_2(t) \\ u_3(t) \end{bmatrix} \\
 &+ \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} \omega(t), \\
 \begin{bmatrix} Y_1(t) \\ Y_2(t) \\ Y_3(t) \\ Y_4(t) \\ Y_5(t) \end{bmatrix} &= \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \\ c_{41} & c_{42} & c_{43} \\ c_{51} & c_{52} & c_{53} \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \end{bmatrix} \\
 &+ \begin{bmatrix} d_{11} & d_{12} & d_{13} \\ d_{21} & d_{22} & d_{23} \\ d_{31} & d_{32} & d_{33} \\ d_{41} & d_{42} & d_{43} \\ d_{51} & d_{52} & d_{53} \end{bmatrix} \begin{bmatrix} u_1(t) \\ u_2(t) \\ u_3(t) \end{bmatrix} \\
 &+ \begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \\ d_5 \end{bmatrix} \omega(t),
 \end{aligned} \tag{2}$$

where x_1 means the material resource, x_2 means the capital resource, x_3 means the human resource, u_1 means the decision of company's structure, u_2 means the decision of manufacturing process, u_3 means the decision of manufacturing integration, Y_1 means the quality, Y_2 means the cost, Y_3 means the flexibility, Y_4 means the delivery, Y_5 means the innovation, ω means the disturbance term, and the others are the undetermined coefficients.

Because the decisions are made firstly and then resource will be allocated and used, there exists a time delay between decision and resource; that is, the decision is made before resources allocation. The resource used in time t is related to the decision which is made in previous time $t - h$.

Further, the manufacturing capability might be produced after a while, and thus there exists a time delay between capability and resource allocation. If we assume that the time

lag is ξ , the capability of time $t + \xi$ is the result of the resource allocation in time t . So, we can get

$$\begin{aligned}
 \begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \\ \dot{x}_3(t) \end{bmatrix} &= \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \end{bmatrix} \\
 &+ \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} u_1(t-h) \\ u_2(t-h) \\ u_3(t-h) \end{bmatrix} \\
 &+ \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} \omega(t), \\
 \begin{bmatrix} Y_1(t+\xi) \\ Y_2(t+\xi) \\ Y_3(t+\xi) \\ Y_4(t+\xi) \\ Y_5(t+\xi) \end{bmatrix} &= \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \\ c_{41} & c_{42} & c_{43} \\ c_{51} & c_{52} & c_{53} \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \end{bmatrix} \\
 &+ \begin{bmatrix} d_{11} & d_{12} & d_{13} \\ d_{21} & d_{22} & d_{23} \\ d_{31} & d_{32} & d_{33} \\ d_{41} & d_{42} & d_{43} \\ d_{51} & d_{52} & d_{53} \end{bmatrix} \begin{bmatrix} u_1(t-h) \\ u_2(t-h) \\ u_3(t-h) \end{bmatrix} \\
 &+ \begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \\ d_5 \end{bmatrix} \omega(t).
 \end{aligned} \tag{3}$$

If we replace the matrices as

$$X(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \end{bmatrix};$$

$$u(t-h) = \begin{bmatrix} u_1(t-h) \\ u_2(t-h) \\ u_3(t-h) \end{bmatrix};$$

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix};$$

$$\begin{aligned}
B &= \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix}; \\
B_1 &= \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}; \\
Y(t + \xi) &= \begin{bmatrix} Y_1(t + \xi) \\ Y_2(t + \xi) \\ Y_3(t + \xi) \\ Y_4(t + \xi) \\ Y_5(t + \xi) \end{bmatrix}; \\
C &= \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \\ c_{41} & c_{42} & c_{43} \\ c_{51} & c_{52} & c_{53} \end{bmatrix}; \\
D &= \begin{bmatrix} d_{11} & d_{12} & d_{13} \\ d_{21} & d_{22} & d_{23} \\ d_{31} & d_{32} & d_{33} \\ d_{41} & d_{42} & d_{43} \\ d_{51} & d_{52} & d_{53} \end{bmatrix}; \\
D_1 &= \begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \\ d_5 \end{bmatrix},
\end{aligned} \tag{4}$$

we can get

$$\begin{aligned}
\dot{X}(t) &= AX(t) + Bu(t - h) + B_1\omega(t), \\
Y(t + \xi) &= CX(t) + Du(t - h) + D_1\omega(t).
\end{aligned} \tag{5}$$

While being in the uncertain environment, the system would be affected by asymmetric information, credit risk, error, and many other unknown factors. To avoid these disturbances, we use the continuous H_∞ control to make optimal manufacturing decisions at the “worst case,” which means

$$\|Y(t + \xi)\|_2 < \gamma^2 \|\omega(t)\|_2 \tag{6}$$

with the smallest possible γ^2 .

To design H_∞ control, what first we should do is to find the state feedback gain coefficient, such as K . Then we can build a state feedback controller as

$$u(t) = KX(t). \tag{7}$$

Thus, the closed-loop system is given by

$$\begin{aligned}
\dot{X}(t) &= AX(t) + BKX(t - h) + B_1\omega(t), \\
Y(t + \xi) &= CX(t) + DKX(t - h) + D_1\omega(t).
\end{aligned} \tag{8}$$

If we get the appropriate K , the closed-loop system would be asymptotically stable. And we can prove that, under the zero initial condition, for all nonzero $\omega \in L_2[0, \infty)$, $\|Y(t + \xi)\|_2 < \gamma^2 \|\omega(t)\|_2$ is feasible, where $\gamma > 0$ is a prescribed constant which is as small as possible. The process of proof is given in Section 4.

4. Time-Delay Dependent H_∞ Control Model

In this section, we will give the sufficient conditions to present the existence of delay-dependent H_∞ state feedback control.

Theorem 1. Consider delay-dependent system (5) and the designed state feedback controller to be system (7). Given scalars $\gamma > 0$ and $h > 0$, if there exist matrices $P = P^T > 0$, $Q = Q^T > 0$, and S_p , satisfying

$$\begin{bmatrix} A^T P + PA + S_1 + S_1^T & PBK - S_1 + S_2^T & PB_1 + S_3^T & \sqrt{h}S_1 & \sqrt{h}A^T & C^T \\ * & -S_2 - S_2^T & -S_3^T & \sqrt{h}S_2 & \sqrt{h}K^T B^T & K^T D^T \\ * & * & -\gamma^2 & \sqrt{h}S_3 & \sqrt{h}B_1^T & D_1^T \\ * & * & * & -Q & 0 & 0 \\ * & * & * & * & -Q^{-1} & 0 \\ * & * & * & * & * & -I \end{bmatrix} < 0, \tag{9}$$

then the matrix inequality (6) is possible.

Proof. With the basic model build in Section 3, firstly, we choose two symmetric matrices P and Q ($P > 0$; $Q > 0$),

to make a Lyapunov functional candidate:

$$V(t) = X^T(t)PX(t) + \int_{-h}^0 \int_{t+\beta}^t \dot{X}^T(\alpha)Q\dot{X}(\alpha)d\alpha d\beta. \tag{10}$$

The derivative of $V(t)$ satisfies

$$\begin{aligned} \dot{V}(t) = & \dot{X}^T(t)PX(t) + X^T(t)P\dot{X}(t) \\ & + h\dot{X}^T(t)Q\dot{X}(t) - \int_{t-h}^t \dot{X}^T(\alpha)Q\dot{X}(\alpha)d\alpha. \end{aligned} \quad (11)$$

Also, we can easily find that $V(0) = 0$ and $V(\infty) \geq 0$, with zero initial condition.

If we establish Z with

$$Z(t) = \dot{V}(t) + Y^T(t+\xi)Y(t+\xi) - \gamma^2\omega^T(t)\omega(t), \quad (12)$$

then

$$\begin{aligned} Z(t) = & \dot{V}(t) + Y^T(t+\xi)Y(t+\xi) - \gamma^2\omega^T(t)\omega(t) \\ = & (AX + BKX_1 + B_1\omega)^T PX \\ & + X^T P (AX + BKX_1 + B_1\omega) \\ & + (CX + DKX_1 + D_1\omega)^T (CX + DKX_1 + D_1\omega) \\ & + h(AX + BKX_1 + B_1\omega)^T Q (AX + BKX_1 + B_1\omega) \\ & - \int_{t-h}^t \dot{X}^T(\alpha)Q\dot{X}(\alpha)d\alpha - \gamma^2\omega^T\omega \\ = & X^T (A^T P + PA + hA^T Q A + C^T C) X \\ & + X^T (PBK + C^T DK + hA^T Q BK) X_1 \\ & + X^T (PB_1 + hA^T Q B_1 + C^T D_1) \omega \\ & + X_1^T (K^T B^T P + K^T D^T C + hK^T B^T Q A) X \\ & + X_1^T (hK^T B^T Q BK + K^T D^T DK) X_1 \\ & + X_1^T (hK^T B^T Q B_1 + K^T D^T D_1) \omega \\ & + \omega^T (B_1^T P + hB_1^T Q A + D_1^T C) X \\ & + \omega^T (hB_1^T Q BK + D_1^T DK) X_1 \\ & + \omega^T (hB_1 Q B_1 + D_1^T D_1 - \gamma^2 I) \omega \\ & - \int_{t-h}^t \dot{X}^T(\alpha)Q\dot{X}(\alpha)d\alpha, \end{aligned} \quad (13)$$

where $X = X(t)$, $X_1 = X(t-h)$, and $\omega = \omega(t)$.

For simplification, we define

$$\begin{aligned} \lambda(t) = & \begin{bmatrix} X^T(t) & X^T(t-h) & \omega^T(t) \end{bmatrix}^T, \\ \theta_1 = & [C \quad DK \quad D_1]^T * [C \quad DK \quad D_1], \\ \theta_3 = & h[A \quad BK \quad B_1]^T Q [A \quad BK \quad B_1], \\ \theta_2 = & \begin{bmatrix} A^T P + PA & PBK & PB_1 \\ K^T B^T P & 0 & 0 \\ B_1^T P & 0 & -\gamma^2 I \end{bmatrix}. \end{aligned} \quad (14)$$

Then, the first part of Z can be converted into a quadratic form:

$$Z = \lambda^T (\theta_1 + \theta_2 + \theta_3) \lambda - \int_{t-h}^t \dot{X}^T(\alpha)Q\dot{X}(\alpha)d\alpha. \quad (15)$$

As we all know the Leibniz-Newton formula, for any appropriately matrices $S = [S_1^T \quad S_2^T \quad S_3^T]^T$, we have

$$\lambda^T(t)S \left[X(t) - X(t-h) - \int_{t-h}^t \dot{X}(\alpha)d\alpha \right] = 0, \quad (16)$$

$$h\lambda^T(t)SQ^{-1}S^T\lambda(t) - \int_{t-h}^t \lambda^T(t)SQ^{-1}S^T\lambda(t)d\alpha = 0.$$

So we can get that

$$\begin{aligned} Z = & \lambda^T(t)(\theta_1 + \theta_2 + \theta_3)\lambda(t) - \int_{t-h}^t \dot{X}^T(\alpha) \\ & \cdot Q\dot{X}(\alpha)d\alpha + \lambda^T(t)S \left[X(t) - X(t-h) \right. \\ & \left. - \int_{t-h}^t \dot{X}(\alpha)d\alpha \right] + \left[X(t) - X(t-h) \right. \\ & \left. - \int_{t-h}^t \dot{X}(\alpha)d\alpha \right]^T S^T\lambda(t) + h\lambda^T(t)SQ^{-1}S^T\lambda(t) \\ & - \int_{t-h}^t \lambda^T(t)SQ^{-1}S^T\lambda(t)d\alpha = \lambda^T(t)(\theta_1 + \theta_2 \end{aligned}$$

$$\begin{aligned}
& + \theta_3) \lambda(t) + \lambda^T(t) S(X - X_1) + (X^T - X_1^T) S^T \lambda(t) \\
& + h \lambda^T(t) S Q^{-1} S^T \lambda(t) - \int_{t-h}^t [\dot{X}^T(\alpha) Q \dot{X}(\alpha) \\
& + \lambda^T(t) S \dot{X}(\alpha) + \dot{X}^T(\alpha) S^T \lambda(t) \\
& + \lambda^T(t) S Q^{-1} S^T \lambda(t)] d\alpha = \lambda^T(t) \left(\theta_1 + \theta_2 \right. \\
& \left. + \theta_3 + h S Q^{-1} S^T + [S \quad -S \quad 0] + \begin{bmatrix} S^T \\ -S^T \\ 0 \end{bmatrix} \right) \lambda(t) \\
& - \int_{t-h}^t [\dot{X}^T(\alpha) Q + \lambda^T(t) S] Q^{-1} [Q \dot{X}(\alpha) \\
& + S^T \lambda(t)] d\alpha.
\end{aligned} \tag{17}$$

With the addition of $\theta_4 = [S \quad -S \quad 0]$, then we can get that

$$\begin{aligned}
Z &= \lambda^T(t) (\theta_1 + \theta_2 + \theta_3 + \theta_4 + \theta_4^T + h S Q^{-1} S^T) \lambda(t) \\
&- \int_{t-h}^t [Q \dot{X}(\alpha) + S^T \lambda(t)]^T \\
&\cdot Q^{-1} [Q \dot{X}(\alpha) + S^T \lambda(t)] d\alpha.
\end{aligned} \tag{18}$$

While $Q > 0$, $\int_{t-h}^t [Q \dot{X}(\alpha) + S^T \lambda(t)]^T Q^{-1} [Q \dot{X}(\alpha) + S^T \lambda(t)] d\alpha$ is positive. Then we can get that

$$\begin{aligned}
Z(t) & < \lambda^T(t) (\theta_1 + \theta_2 + \theta_3 + \theta_4 + \theta_4^T + h S Q^{-1} S^T) \lambda(t).
\end{aligned} \tag{19}$$

By Schur complement, inequality (9) guarantees

$$\theta_1 + \theta_2 + \theta_3 + \theta_4 + \theta_4^T + h S Q^{-1} S^T < 0. \tag{20}$$

Therefore, we can get that

$$\begin{aligned}
Z(t) &= \dot{V}(t) + Y^T(t + \xi) Y(t + \xi) - \gamma^2 \omega^T(t) \omega(t) \\
&< 0
\end{aligned} \tag{21}$$

for all nonzero $\omega \in L_2[0, \infty)$, and the asymptotic stability of system (8) is established.

Under zero initial condition, we have $V(0) = 0$ and $V(\infty) \geq 0$. Integrating both sides of inequality (21), we obtain

$$0 < V(\infty) - V(0) < \gamma^2 \|\omega\|_2 - \|Y(t + \xi)\|_2. \tag{22}$$

So, the inequality above means that $\|Y(t + \xi)\|_2 < \gamma^2 \|\omega\|_2$, and H_∞ performance is established. The proof is completed. $\square$

Define $J = \text{diag}\{P^{-1}, P^{-1}, I, P^{-1}, I, I\}$. By pre- and post-multiplying inequality (9) by J and with the change of matrix variables defined by $\bar{P} = P^{-1}$, $\bar{K} = K P^{-1}$, $\bar{Q} = P^{-1} Q P^{-1}$, $\bar{S}_1 = P^{-1} S_1 P^{-1}$, $\bar{S}_2 = P^{-1} S_2 P^{-1}$, and $\bar{S}_3 = S_3 P^{-1}$, we can further get the following result by noting that $-Q^{-1} \leq P^{-1} Q P^{-1} - 2P^{-1} = \bar{Q} - 2\bar{P}$:

$$\begin{bmatrix}
\bar{P} A^T + A \bar{P} + \bar{S}_1 + \bar{S}_1^T & B \bar{K} - \bar{S}_1 + \bar{S}_2^T & B_1 + \bar{S}_3^T & \sqrt{h} \bar{S}_1 & \sqrt{h} \bar{P} A^T & \bar{P} C^T \\
* & -\bar{S}_2 - \bar{S}_2^T & -\bar{S}_3^T & \sqrt{h} \bar{S}_2 & \sqrt{h} \bar{K}^T B^T & \bar{K}^T D^T \\
* & * & -\gamma^2 & \sqrt{h} \bar{S}_3 & \sqrt{h} B_1^T & D_1^T \\
* & * & * & -\bar{Q} & 0 & 0 \\
* & * & * & * & \bar{Q} - 2\bar{P} & 0 \\
* & * & * & * & * & -I
\end{bmatrix} < 0, \tag{23}$$

where $\bar{P} = \bar{P}^T > 0$, $\bar{Q} = \bar{Q}^T > 0$, with given scalars $\gamma > 0$, and $h > 0$.

Moreover, if inequality (23) has a feasible solution, then a stabilizing state feedback controller in system (7) exists. Also, the closed-loop system is asymptotically stable. And under

the zero initial condition, $\|Y(t + \xi)\|_2 < \gamma^2 \|\omega(t)\|_2$ is feasible for all nonzero $\omega \in L_2[0, \infty)$. Further, the controller K in (7) can be solved by

$$K = \bar{K} \bar{P}^{-1}. \tag{24}$$

5. A Design Example

In this section, we will provide an example to illustrate the effectiveness of the proposed continuous system delay-dependent state feedback H_∞ control based on the theories above. In order to reflect our model's application, we use simulation method to test how the model works in manufacturing management.

We set the initial parameters as the following values which are based on the manufacturing management results of on Guo's study [22] (25). Guo's study (2009) uses the data based on International Manufacturing Strategy Survey (IMSS) which is conducted by IMSS members and has been conducted for more than five times in more than 10 countries. This survey hands out questionnaires to managers in manufacturing corporations and asks the true situation of manufacturing experiences including resources, capabilities, and decisions. There are a bunch of publications based on IMSS survey. Therefore, this paper sets the initial parameters in simulation process based on the results of Guo's study:

$$A = \begin{bmatrix} 3.414 & 1 & -1 \\ -39.813 & 1 & 1.021 \\ 344.514 & 8.831 & -8.942 \end{bmatrix};$$

$$B = \begin{bmatrix} 1 & 0.04 & 0.02 \\ 0.009 & -15.4435 & 0.0009 \\ 0.003 & 0.0004 & -0.0081 \end{bmatrix};$$

$$B_1 = \begin{bmatrix} 1 \\ 0.003 \\ 0.1177 \end{bmatrix};$$

$$C = \begin{bmatrix} 0.4014 & 2.5041 & 0.0004 \\ -3.3684 & 2.0431 & 0.002 \\ 0.002 & 0.0021 & 0.9147 \\ -0.2838 & 0.005 & 2.1022 \\ 0.3319 & -11.8272 & 10.8089 \end{bmatrix};$$

$$D = \begin{bmatrix} 0.517 & 0.305 & 0.108 \\ -0.377 & 0.408 & 0.247 \\ 0.306 & 0.487 & 0.262 \\ 0.248 & 0.339 & 0.482 \\ 0.685 & 0.411 & 0.571 \end{bmatrix};$$

FIGURE 2: The disturbance.

$$D_1 = \begin{bmatrix} 1 \\ 2 \\ -3 \\ 0 \\ 1 \end{bmatrix}.$$

(25)

In addition, we set the lag phase (h) to be 0.01. On the basis of Sections 3 and 4, to design a continuous delay-dependent H_∞ control, we should find K which satisfies the matrices inequality (9), while there exist matrices $P = P^T > 0$, $Q = Q^T > 0$, and S with a given scalar $\gamma > 0$. Solving the matrices inequality (9) by MATLAB, we can find that when the smallest $\gamma = 4.3163$, the state feedback coefficient K is as follows:

$$K = \begin{bmatrix} -59.6779 & -0.6514 & -1.4909 \\ -9.7907 & 4.0638 & -2.1948 \\ 32.8308 & 2.4184 & -6.5633 \end{bmatrix}. \quad (26)$$

So, we can find that if system (4) meets the parameters in (25), we can design a state feedback controller as system (7) with the coefficient of (26). Then due to matrix inequality system (9), we can prove that $\|Y(t + \xi)\|_2 < \gamma^2 \|\omega\|_2$. In other words, we get the robustness of manufacturing system. Assume that the close-loop system is stable. With the uncertainty of system, there is some disturbance deviate the manufacturing capability from the forecast. To adjust, we need design new decisions which are optimal. So, we build a state feedback controller (7). Then, with the time-delay robust control, manufacturing capabilities are asymptotically stable.

Further, if the new disturbing single is as in Figure 2, under the condition of the initial zero, we can get the system

FIGURE 3: The quality.

FIGURE 5: The flexibility.

FIGURE 4: The cost.

FIGURE 6: The delivery.

control output trajectory with simulation as in Figures 3–7, which means that, with the designed optimal decisions, the capabilities are asymptotically stable.

6. Conclusion

This paper uses a time-delay dependent H_∞ control model to analyze the influences of manufacturing decisions on the process of transformation from resources to capabilities and finds the result which meets the optimal feedback requirement. We test the robustness of the model with an example

and prove that this model has a good ability to be employed. Based on the simulation test, we find that, under an uncertain circumstance, when the disturbance deviate the capability from the expected, we can design an optimal decision with the feedback of resource to make the capability asymptotic stable. So, the model can give an optimal result to fulfill the goal of controlling the risk and improve the decisions' effectiveness. In the manufacturing, the decisions can have a good effect on the process of transformation from resources to capabilities, when the decisions are well combined based on the simulation test.

FIGURE 7: The innovation.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This study was sponsored by the NSFC (nos. 71303069 and 71103049), the New Century Talents of Ministry of Education (NCET-13-0167), the Chinese Distinguished Postdoctoral Fund (2012T50369), Humanities and Social Science Foundation of Ministry of Education (nos. 10YJC790070, 13YJC630158, and 12YJC790262), the Natural Science Foundation of Heilongjiang Province of China (no. F201209), the Heilongjiang Postdoctoral Special Fund (LBH-TZ0508), the Research Fund for the Doctoral Program of Higher Education (20112302120038) of MoE, and the Fundamental Research Funds for the Central Universities (HIT.BRETHIII.201408).

References

- [1] K. McKone-Sweet and Y.-T. Lee, "Development and analysis of a supply chain strategy taxonomy," *Journal of Supply Chain Management*, vol. 45, no. 3, pp. 3–24, 2009.
- [2] H.-S. Park and N.-H. Tran, "A cognitive agent based manufacturing system adapting to disturbances," *International Journal of Control, Automation and Systems*, vol. 10, no. 4, pp. 806–816, 2012.
- [3] B. Jain, G. K. Adil, and U. Ananthakumar, "Development of questionnaire to assess manufacturing capability along different decision areas," *International Journal of Advanced Manufacturing Technology*, vol. 71, no. 9–12, pp. 2091–2105, 2014.
- [4] Z. Pei, "Rational decision making models with incomplete weight information for production line assessment," *Information Sciences*, vol. 222, pp. 696–716, 2013.
- [5] G. Zames, "Feedback and optimal sensitivity: model reference transformations, multiplicative seminorms, and approximate inverses," *IEEE Transactions on Automatic Control*, vol. 26, no. 2, pp. 301–320, 1981.
- [6] H. R. Karimi, "Stability analysis with H_∞ performance of production networks with autonomous work systems and time-varying delays," in *Proceedings of the 30th Chinese Control Conference (CCC '11)*, pp. 5170–5174, July 2011.
- [7] S. L. Hu, D. Yue, H. P. Xie, and Z. P. Du, "Event-triggered H_∞ stabilization for networked stochastic systems with multiplicative noise and network-induced delays," *Information Sciences*, vol. 299, pp. 178–197, 2015.
- [8] E. Nazarian and J. Ko, "Robust manufacturing line design with controlled moderate robustness in bottleneck buffer time to manage stochastic inter-task times," *Journal of Manufacturing Systems*, vol. 32, no. 2, pp. 382–391, 2013.
- [9] Y. Yu and W. Wang, "H-infinity controller for networked non-linear manufacturing process interconnected systems based on T-S fuzzy model," in *Proceedings of the International Conference on Materials and Manufacturing*, vol. 299, pp. 844–850, 2011.
- [10] B. Wernerfelt, "A resource-based view of the firm," *Strategic Management Journal*, vol. 5, no. 2, pp. 171–180, 1984.
- [11] J. Barney, M. Wright, and D. J. Ketchen Jr., "The resource-based view of the firm: ten years after 1991," *Journal of Management*, vol. 27, no. 6, pp. 625–641, 2001.
- [12] W. Skinner, "Manufacturing—missing link in corporate strategy," *Harvard Business Review*, vol. 47, no. 3, pp. 176–215, 1969.
- [13] A. V. Roth and M. Van Der Velde, "Operations as marketing: a competitive service strategy," *Journal of Operations Management*, vol. 10, no. 3, pp. 303–328, 1991.
- [14] H. Bae, S. Kim, K.-B. Woo, G. S. May, and D.-K. Lee, "Fault detection, diagnosis, and optimization of wafer manufacturing processes utilizing knowledge creation," *International Journal of Control, Automation and Systems*, vol. 4, no. 3, pp. 372–381, 2006.
- [15] L. J. LeBlanc, J. A. Hill, J. Harder, and G. W. Greenwell, "Modeling uncertain forecast accuracy in supply chains with postponement," *Journal of Business Logistics*, vol. 30, no. 1, pp. 19–31, 2009.
- [16] H. Wang, G. Y. Li, and G. Li, "Research on quality control technology in manufacturing process based on flexibility of production capability," in *Proceedings of the International Conference on Wireless Communications, Networking and Mobile Computing*, pp. 5115–5118, IEEE, Shanghai, China, September 2007.
- [17] J. Tidd, J. Bessant, and K. Pavitt, *Innovation Management—Technological Change, Market Change and the Integration of Organizational Change*, Tsinghua University Press, 2004.
- [18] S. C. Wheelwright, "Reflecting corporate strategy in manufacturing decisions," *Business Horizons*, vol. 21, no. 1, pp. 57–66, 1978.
- [19] R. H. Hayes and G. P. Pisano, "Beyond world-class: the new manufacturing strategy," *Harvard Business Review*, vol. 72, no. 1, pp. 77–86, 1994.
- [20] R. G. Schroeder, K. A. Bates, and M. A. Junttila, "A resource-based view of manufacturing strategy and the relationship to manufacturing performance," *Strategic Management Journal*, vol. 23, no. 2, pp. 105–117, 2002.

- [21] C. M. Yang, Q. Zhou, H. R. Karimi, and H. Q. Wang, "State-feedback sampled-data control design for nonlinear systems via passive theory," *Mathematical Problems in Engineering*, vol. 2013, Article ID 230413, 12 pages, 2013.
- [22] H. F. Guo, *Study on manufacturing capability from resource-based view [Ph.D. thesis]*, Harbin Institute of Technology, 2009.