A fuzzy robust control approach to closed-loop supply chain network design under uncertainty

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Abstract In this paper, we construct a type of dynamic closed-loop supply chain network (CLSCN) model with dual-channel (the traditional channel and the Internet channel), time-delays and uncertainties of cost parameters, gratuitous return rate, remanufacturing/recycling/disposal rates, customer preference rate and customer demand. Furthermore, in order to improve the robustness of CLSCN, we propose a relative strategy with the fuzzy robust control method, present a sufficient condition for the quadratic asymptotic stability of the CLSCN, and obtain a steady cost of the CLSCN operation. Finally, an example is provided to illustrate the effectiveness of the proposed method.

Key words: Closed-loop supply chain network, Fuzzy robust control, Uncertainty

Introduction

Due to outsourcing, global sourcing and environmental turbulence, supply chain risks have recently gained much attention from practitioners and supply chain risk management has evolved into one of the most active fields within supply chain management research (Hofmann et al. 2013). Essentially, in a supply chain context, if there are some sources of uncertainty such as demand uncertainty and supply uncertainty, the performance of the supply chain will also be affected and become uncertain (Chiu and Choi 2013). As a result, risk emerges and supply chain agents need to make decisions under risk (Zsidisin and Ritchie 2008). In supply chain systems, two sources of supply chain risk are commonly present, namely the supply chain disruption risk (SCDR) (Sodhi et al. 2012) and the supply chain operational risk (SCOR) (Choi and Chiu 2012). SCDR comes from some kinds of disruptions which affect the normal operations of the supply chain systems. For example, both natural and man-made problems such as wars, earthquakes and hurricanes, terrorist attacks, diseases, typhoons are called disruptions which directly lead to SCDR. SCOR refers to the some “expected” variations which commonly and normally exist. For instance, fluctuation of exchange rate (under normal situation), and demand uncertainty are all
factors which create SCOR. The unpredictability of the business environment, variable consumer demands, along with market dynamics and continuous improvement initiatives within organisations imply that the supply chain never actually reaches a stable steady state. Meanwhile, the CLSC is concerned with the integration of material flows, financial flows, and information flows throughout both the forward chain and the reverse chain, and reflects a generalization and extension of traditional supply chain concepts. Therefore, there are more operations and more uncertain factors in the CLSC because of the complexity and the difficulty to control reverse logistics activities compared with the traditional supply chains. These parameters of uncertainty can propagate through a closed-loop supply chain network (CLSCN). Therefore, it is important to establish an analytical framework for conducting systematic risk analysis and control of the CLSCN.

On the one hand, as noted by Sabri and Beamon (2000), uncertainty is one of the most challenging and significant problems in CLSCN. Various sources of uncertainty can be found in the related literature, namely customer demands, production costs, return rates, supply lead times and exchange rates. However, the literature integrating multiple uncertainties in the CLSCN areas remains scare. Moreover, with the development of the electronic commerce, there are more and more people shopping online. Thus products can be obtained through dual-channel (i.e. the traditional channel and the Internet channel). Meanwhile, there are consumer returns, which are products that have experienced little or no use by consumers—they are a result of liberal return policies by retailers and are mostly not defective (Ferguson et al. 2006, Ferguson et al. 2009). Sellers on the Internet should accept consumers' claims for refunds, which are clearly stipulated in China's "Law of Protection of Consumers' Rights" enforced at March 15, 2014. And few studies have accounted for the capacity levels as decision variables in the CLSCN (Georgiadis and Athanasiou 2010).

On the another hand, remanufacturing planning has the peculiar characteristic of non-uniformity of inputs (returns), which has several implications: the firm needs to separate returns into different quality categories (grading); this leads to an uncertain mix of inputs in each period, as quantity, quality, and timing of returns are typically uncertain. More importantly, different quality grades may have different cost and processing requirements (with capacity implications), and graded returns can be salvaged or disposed of at potentially different salvage values depending on their quality. Some returns are unfit for remanufacturing, and need to be disposed of.

Moreover, fuzzy control which is a kind of intelligent control is good at handling ill-defined and complex systems with uncertainties because it has simple properties and is easy to be implemented. In the CLSCN system, the different product strategies (or the order strategies) will be adopted according to the different inventory levels of the raw materials, the manufacturer, the distributor and the retailer, therefore, the fuzzy robust control approach is particularly suitable for the accurate control of the CLSCN system. Therefore, during the past two decades, it has been widely accepted and researched in the academic and industrial societies (Gong and Su 2009).

The main contributions in this paper are as follows: To begin with, a model for the discrete-time CLSCN system with the dual-channel is constructed in this paper. In this model, the reverse logistics includes the recovery part and the gratuitous return. One of the most important points is that the problems of controller design for the discrete-time CLSCN system with uncertainties are studied by using T-S fuzzy model. Another important point is that the time-delay in remanufacturing, production capacity and more uncertainties which are rarely seen
in the related literature are considered: the uncertainties of system cost parameters, the uncertainties of customer’s demand disturbances, the uncertainties of remanufacturing/disposal rate, the uncertainty of gratuitous return rate, the uncertainty of preference rate of the customer to the Internet channel. Following the point mentioned above, a dynamic discrete-time CLSCN model is dynamically established and analyzed in order to investigate how to restrain the impacts of the uncertain environment on the closed-loop system performance by using fuzzy control theories. Furthermore, we study the controller design approach for the fuzzy system. Lastly, the dual-channel, the production capacity, the safety stock and the expected inventory of the manufacturer are considered in the research on the CLSCN system. Moreover, this controller design approach can be applied to cases when all individual systems are unstable. Hence, it has good application foreground.

The system under study

A Stock and Flow Diagram (Morecroft 2007) of a CLSCN system for recycling and remanufacturing employed for our study is presented in Figure 1.

The forward supply chain comprises four echelons: the producers’ inventory of raw materials, the serviceable inventory, the distributor’s inventory and the customers’ virtual inventory (Nakashima et al. 2004). The producers’ demand for raw materials is satisfied with a mix of natural materials, provided by external suppliers, and recycled materials deriving from the firm’s recycling operations (recycling rate). White goods (like refrigerators), tires and photofilms (Vlachos et al. 2007), vehicles (Gupta 1995), bumpers, batteries, sand (Barros et al. 1998) and household waste (Chang and Wei 2000) are representative examples of products that fit the above description. The reverse channel starts at the end of the products' usage period and comprises three echelons: gratuitous returned products, remanufactured products, and recyclable products.
The gratuitous returned products, which are products that have experienced little or no use by consumers, are returned to distributors or manufacturers either through the traditional channel or through the Internet channel. The collected products are inspected, and they are either accepted for remanufacturing (remanufactured products) or recycling (recyclable products), or rejected for remanufacturing or recycling (disposed products). The recyclable products turn into recycled materials after recycling. For simplification, the reverse logistics considered in here is only in the end consumer (group) part, which includes the collection part and the gratuitous return. The return part is defined as the gratuitous return of goods that manufacturer and distributor promise the consumer, which may be sold as new products (Guo and Sun 2010).

System modeling of the CLSCN system

A number of assumptions are made throughout this analysis in order to simplify the system and facilitate the modeling process by helping focus on the most important factors. The assumptions are summarized as follows: (i) The remanufactured products are defined as-good-as-new; (ii) Capacity of collection and inspection activities is considered to be infinite.

(1) Situation 1.

In this situation, we consider that market share of products which are produced by the manufacturer is low, that is to say, the virtual inventory level of customers ($x_{4,k}$) is less than a specific value ($D_0$). Meanwhile, the actual inventory of the manufacturer ($x_{2,k}$) is less than the safety inventory ($S_0$), so the manufacturer not only produces the new products but also recovers the wasted products for remanufacturing.

The dynamic model of the CLSCN with the dual-channel is established in this situation at period $k$ as follows.

\[
\begin{align*}
    x_{1,k+1} &= x_{1,k} + u_{1,k} + \sum_{r=1}^{5} x_r \sigma_r \left( \kappa_1 + \Delta \kappa_1 \right) x_{5,(k-d)} - \rho u_{2,k} - \rho \left( \kappa_2 + \Delta \kappa_2 \right) x_{5,(k-d)} \\
    x_{2,k+1} &= x_{2,k} + u_{2,k} + \left( \kappa_2 + \Delta \kappa_2 \right) x_{5,(k-d)} + \left( \mu_1 + \Delta \mu_1 \right) x_{4,k} - u_{3,k} - \left( \lambda + \Delta \lambda \right) w_{1,k} \\
    x_{3,k+1} &= x_{3,k} + u_{3,k} + \left( \mu_2 + \Delta \mu_2 \right) x_{4,k} - \left( 1 - \lambda - \Delta \lambda \right) w_{1,k} \\
    x_{4,k+1} &= x_{4,k} + w_{1,k} - \left( \zeta_1 + \Delta \zeta_1 \right) x_{4,k} - u_{4,k} - \left( \mu_1 + \Delta \mu_1 + \mu_2 + \Delta \mu_2 \right) x_{4,k} \\
    x_{5,k+1} &= x_{5,k} + u_{4,k} - \left( \kappa_1 + \Delta \kappa_1 \right) x_{5,(k-d)} - \left( \kappa_2 + \Delta \kappa_2 \right) x_{5,(k-d)} - u_{5,k}
\end{align*}
\]

where $x_{1,k}$, $x_{2,k}$, $x_{3,k}$, $x_{4,k}$ and $x_{5,k}$ are actual inventory level of raw materials resources, actual inventory level of the manufacturer, actual inventory level of the distributor, virtual inventory of the customers(Nakashima et al. 2004) and actual inventory level of collected products at period $k$ respectively, which are the state variables. $x_{5,(k-d)}$ is the actual inventory with the time delay $d$, in which $d$ is an independent time delay parameter and $0 \leq d < \infty$. $u_1(k)$, $u_2(k)$, $u_3(k)$, $u_4(k)$ and $u_5(k)$ are the control variables of the procurement of natural resources, production of the manufacturer, the order quantity of the distributor, the quantity of recycle for the waste products and the disposal of the recycled products, respectively. $w_{1,k}$ is the customer’s demand at period $k$, which is an uncertain and disturbance variable. When sold,
products are returned at the gratuitous return rate \( \mu_1 \) and \( \mu_2 \) from the customer to the manufacturer and the distributor. \( \lambda \) is the preference rate of the customer to the Internet channel. \( \kappa_1 \) and \( \kappa_2 \) are the proportion of recycled products used for the recovery of raw materials and the proportion of the recycled products used for the remanufacturing, respectively, under the condition that the manufacturer not only produces the new products but also recovers the wasted products for remanufacturing. \( \rho \) is the number of units of raw materials to produce a new product. \( \chi_i \) are the proportion of different quality levels of collected products in the inventory of the collector. \( \sigma_i \) are the number of raw materials which can be obtained from different quality levels of collected products. \( \zeta_1 \) is the uncontrollable disposal rate of the used products in the situation 1. \( \Delta \kappa_1 \), \( \Delta \kappa_2 \), \( \Delta \mu_1 \), \( \Delta \mu_2 \), \( \Delta \lambda \) and \( \Delta \zeta_1 \) are relative uncertain parameters. Similarly for rationality, suppose \( 0 \leq \mu_1 + \Delta \mu_1 \leq 1 \), \( 0 \leq \mu_2 + \Delta \mu_2 \leq 1 \), \( 0 \leq \mu_1 + \Delta \mu_1 + \mu_2 + \Delta \mu_2 \leq 1 \), \( 0 \leq \lambda + \Delta \lambda \leq 1 \), \( 0 \leq \kappa_1 + \Delta \kappa_1 \leq 1 \), \( 0 \leq \kappa_2 + \Delta \kappa_2 \leq 1 \), \( 0 \leq \kappa_1 + \kappa_2 + \Delta \kappa_1 + \Delta \kappa_2 \leq 1 \), \( 0 \leq \chi_i \leq 1 \), \( 0 \leq \kappa_1 + \Delta \kappa_1 < 1 \).

Similarly, the deviation operational cost of the whole supply chain system at period \( k \) would be

\[
C_k = \left( c_d + \Delta c_d \right) x_{1,k} + \left( c_g + \Delta c_g \right) x_{2,k} + \left( c_r + \Delta c_r \right) x_{3,k} + \left( c_r + \Delta c_r + c_p + \Delta c_p \right) x_{5,k} +
\]

\[
\sum_{i=1}^{5} c_{nt} \kappa_i \sigma_i \left( \kappa_1 + \Delta \kappa_1 \right) x_{5,(k-i)} + \left( c_d + \Delta c_d \right) u_{1,k} + \left( c_f + \Delta c_f \right) u_{2,k} + \left( c_q + \Delta c_q \right) u_{4,k} +
\]

\[
\left( c_r + \Delta c_r \right) u_{5,k} + c_h \left( \kappa_2 + \Delta \kappa_2 \right) x_{5,(k-i)} + c_n \left( \mu_i + \Delta \mu_i \right) x_{4,k} + c_i \left( \mu_2 + \Delta \mu_2 \right) x_{4,k} +
\]

\[
c_i \left[ \rho \left( \kappa_1 + \Delta \kappa_1 \right) x_{5,(k-i)} - \sum_{i=1}^{5} \chi_i \sigma_i \left( \kappa_2 + \Delta \kappa_2 \right) x_{5,(k-i)} \right].
\]

where \( C_k \) is an output variable of the total operation cost of the whole CLSCN system, which is the output variable. \( c_a \), \( c_g \), \( c_r \) and \( c_r \) are the unit inventory costs of the raw materials resources, the new products, the distributor and the collector, respectively. \( c_p \) is the unit inspection cost of the collector. \( c_{na} \) is the sum of the unit inspection cost and the unit disassembly cost of the collected products used for recycling material resources. \( \tau \) \( \left( \tau = 1, 2, \cdots, 5 \right) \) are the quality levels of collected products. \( c_d \) is the unit purchasing cost of natural resources. \( c_f \) is the unit manufacturing cost for the new product. \( c_q \) is the unit collect cost of the collector. \( c_s \) is the unit disposal cost after the first screening. \( c_h \) is the unit remanufacturing cost of the manufacturer. \( c_u \) and \( c_l \) are the unit gratuitous return costs of the manufacturer and the distributor, respectively. \( c_i \) is the unit disposal cost after the second screening. \( \Delta c_d \), \( \Delta c_g \), \( \Delta c_r \), \( \Delta c_f \), \( \Delta c_p \), \( \Delta c_q \) and \( \Delta c_s \) are the relative uncertain costs. Similarly for rationality, suppose \( c_p + \Delta c_p + c_h \leq c_f + \Delta c_f \), \( c_q + \Delta c_q + c_n + c_r + \Delta c_r + c_s + \Delta c_s + c_i \leq c_f + \Delta c_f \).

(2) Situation 2.
In this situation, we consider that market share of products which are produced by the manufacturer is low, too. Meanwhile, the actual inventory of the manufacturer ($x_{2,k}$) is more than the safety inventory ($S_0$) and less than the expected inventory ($S_1$) of the manufacturer, so the manufacturer only produces the new products instead of recovering the wasted products for remanufacturing.

(3) Situation 3.
In this situation, we consider that market share of products which are produced by the manufacturer is ascending to a certain degree, that is to say, the virtual inventory level of customers ($x_{4,k}$) is more than a specific value ($D_0$). Meanwhile, the actual inventory of the manufacturer ($x_{2,k}$) is less than the safety inventory ($S_0$), so the manufacturer not only produces the new products but also recovers the wasted products for remanufacturing.

(4) Situation 4.
In this situation, we consider that market share of products which are produced by the manufacturer is ascending to the same certain degree as that in Situation 3. However, the actual inventory of the manufacturer ($x_{3,k}$) is more than the safety inventory ($S_0$) and less than the expected inventory ($S_1$) of the manufacturer, so the manufacturer only recovers the wasted products for remanufacturing instead of producing the new products.

Remark 1: We used the same method as it in the Situation 1 to establish the dynamic models of the CLSCN in other situations.

In order to construct the nonlinear CLSCN system and restrain the large fluctuations by utilizing the uncertain Takagi-Sugeno fuzzy system with time delay, the $i$th fuzzy model of the dynamic CLSCN system is established based on from Situation 1 to Situation 4 as follows.

Plant Rule $i$: if

$$
\begin{align*}
&x_{4}(k) \text{ is } M_4^i \text{ and } x_{2}(k) \text{ is } M_2^i,
\end{align*}
$$

then

$$
\begin{align*}
\dot{x}(k+1) &= (A_i + \Delta A_i) x(k) + (B_i + \Delta B_i) u(k) + (B_{wi} + \Delta B_{wi}) w(k) \\
z(k) &= (C_i + \Delta C_i) x(k) + (D_i + \Delta D_i) u(k) + (D_{wi} + \Delta D_{wi}) w(k)
\end{align*}
$$

(8)

where $x^T(k) = [x_{1}(k) \ x_{2}(k) \ x_{4}(k) \ x_{5}(k) \ x_{6}(k) \ x_{7}(k)]$ denotes the inventory levels at period $k$; $\Delta x(k) = [x_{1}(k) \ x_{2}(k) \ x_{4}(k) \ x_{5}(k) \ x_{6}(k) \ x_{7}(k)]$ denotes the inventory levels with the time delay $d (0 < d < \infty)$; $u^T(k) = [u_{1}(k) \ u_{2}(k) \ u_{3}(k) \ u_{4}(k) \ u_{5}(k)]$ denotes the control vector at period $k$; $w(k)$ denotes the customers’ demand at period $k$, which is an external input vector; $z^T(k) = [C_i]$ can also denote the deviation operational cost of the whole supply chain system at period $k$; $M_4^i$ and $M_2^i$ are the membership functions of the customers’ virtual inventory level; $M_4^i$ and $M_2^i$ are the membership functions of the service inventory level of the manufacturer; $r$ is the number of inference rules; $A_i$, $A_{di}$, $B_i$, $B_{wi}$, $C_i$, $C_{di}$, $D_i$ and $D_{wi}$ are the parameter matrices with the appropriate dimensions; $\Delta A_i$, $\Delta A_{di}$, $\Delta B_i$, $\Delta B_{wi}$, $\Delta C_i$, $\Delta C_{di}$, $\Delta D_i$ and $\Delta D_{wi}$ are real-valued matrix functions representing norm-bounded parameter uncertainties; $\phi(k)$ is a discrete initial vector function.

Remark 2: Equation (3) is described with the deviation values. The nominal operation value is a designed operation value which the designers hope the actual operation value is equal
to. The deviation value is the difference between the actual operation value and the nominal operation value which is resulted from the customers’ demand, and so on.

Fuzzy robust control of the CLSCN system with time delays

1. Robust operation of the CLSCN system

The parameter \( \gamma \) is used to describe the inhibition degree of \( u(k) \), i.e. \( \| z(k) \| / \| w(k) \| \leq \gamma \), where \( \| \cdot \| \) is \( \ell_2 \) norm and \( \gamma > 0 \) is a prescribed scalar. \( \| z(k) \| / \| w(k) \| \) describes the CLSCN system gain caused from \( w(k) \) to \( z(k) \).

2. Fuzzy robust control method

Theorem 1 (Zhao and Zhang 2014). For a given scalar \( \gamma > 0 \), if there exist positive definite matrices \( P_l, Q_l \) and \( Q_{2j} \), nonsingular matrix \( U_i \), and the matrices \( N_{li}, N_{l2}, N_{l3}, N_{l4}, M_{l1}, M_{l2}, M_{l3}, M_{l4} \) and \( Y_{jl} \), scalars \( \varepsilon_{lj} > 0 \) (\( i, j = 1, 2, \cdots, r \)) satisfying the following LMIs with the appropriate dimensions such that

\[
\Omega_{ij} < 0, i \in I_1, \quad \Omega_{ij} + \Omega_{ji} < 0, i < j, \quad i, j \in I_1,
\]

where

\[
\begin{bmatrix}
-U_l - U_l^T + A_{dij} \Pi_{12} \Pi_{13} \Pi_{14} \Pi_{15} & 0 & 0 & 0 & 0 \\
* & D_{l1} & D_{l2} & D_{l3} & D_{l4} & N_{l1} & \Pi_{27} & \Pi_{28} & \Pi_{29} \\
* & * & D_{l4} & D_{l6} & D_{l7} & N_{l1} & \Pi_{37} & \Pi_{38} & \Pi_{39} \\
* & * & * & D_{l8} & D_{l9} & N_{l3} & 0 & 0 & 0 \\
* & * & * & * & -d^{-1}Q_{2l} & 0 & 0 & 0 & 0 \\
* & * & * & * & * & * & * & * & \varepsilon_{lj} I + A_{dij} \\
* & * & * & * & * & * & * & * & * \\
\end{bmatrix} < 0
\]

\( \varepsilon_{lj} \) is the set of the rule numbers included in \( G_l \), \( G_l \) denotes the number of the fuzzy partitions of the \( j \)th input variable, then the discrete T-S fuzzy time-delay system (3) is asymptotically stable by using the fuzzy controller, and the \( H_\infty \) norm is less than a given bound \( \gamma \). The controller gain in Theorem 1 can be expressed as \( K_{jl} = Y_{jl} U_l^{-1} \).
Simulation analysis

Our analysis focused on the total system cost. A similar total system cost (Kenne et al. 2012, Pishvaee et al. 2011) were previously used by several authors. The membership functions of $x_{2,k}$ and $x_{4,k}$ can be seen in Figure 2 ($\bar{S}_0$ and $\bar{S}_1$ denote the deviation of the manufacturer’s safety inventory and the deviation of the manufacturer’s expected inventory, respectively. $\bar{D}_0$ and $\bar{D}_1$ denote two specific values, respectively).

By utilizing Takagi-Sugeno fuzzy model, Situation 1~ Situation 4 can be transformed into the matrix format. The uncertain CLSCN system with time delays in recycling and remanufacturing can be expressed as Equation (3) ($i = 1, 2, 3, 4$).

The simulation analysis involved the use of several assumptions related to the values of the model parameters. However, in line with the purpose of this simulation analysis to evaluate strategies aimed at improving the performance of the system, we believe that the exact value of the parameters is not as important as an understanding of the changes in the behavior of the system under different scenarios. Based on the practices, all parameters are set as: $\lambda = 70\%$, $\mu_1 = 3\%$, $\mu_2 = 2\%$, $\zeta_1 = 20\%$, $\zeta_2 = 21\%$, $\zeta_3 = 31\%$, $\zeta_4 = 41\%$, $\chi_1 = 30\%$, $\chi_2 = 21\%$, $\chi_3 = 20\%$, $\chi_4 = 19\%$, $\chi_5 = 10\%$, $\sigma_1 = 2.5$, $\sigma_2 = 2$, $\sigma_3 = 1.5$, $\sigma_4 = 1$, $\sigma_5 = 0.5$, $\kappa_1 = 65\%$, $\kappa_2 = 30\%$, $\kappa_3 = 70\%$, $\kappa_4 = 15\%$, $\kappa_5 = 65\%$, $\rho = 27$, $c_u = 0.055$, $c_o = 0.1$, $c_{e1} = 1.2$, $c_{e2} = 1.4$, $c_{e3} = 1.6$, $c_{e4} = 1.8$, $c_{e5} = 2.0$ (unit: $\times 10^2$ Yuan/Unit); $c_g = 1.2$, $c_f = 8$, $c_h = 4.87$, $c_u = 1.8$, $c_v = 1.22$, $c_i = 1.2$, $c_{a1} = 0.3$, $c_{a2} = 0.4$, $c_{a3} = 0.5$, $c_{a4} = 0.6$, $c_{a5} = 0.7$, $c_p = 0.5$, $c_q = 1.2$, $c_r = 0.9$, $c_s = 1.4$, $c_t = 1.8$, (unit: $\times 10^3$ Yuan/Unit); $d = 7$ (unit: Day); $\bar{D}_0 = 0$, $\bar{D}_1 = 2$, $\bar{S}_0 = 0$ and $\bar{S}_1 = 1$ (unit: $\times 10^5$ Unit). It is need to be pointed out that uncertain parameters will range from 1 percent to 23 percent. By using the feasp solver in LMI Toolbox of
MATLAB, the inhibition rate is \( \gamma = 0.45 \).

**Case 1:** Suppose the customer’s demand follows the wide pulse distribution disturbance (e.g. Disaster demand), i.e. 
\[
\begin{cases} 
    3 & 5 \leq k \leq 10 \\
    0.5 & \text{others} 
\end{cases}
\]. The simulation results are depicted in Figure 3.

**Case 2:** Suppose the customer’s demand follows the normal distribution disturbance, i.e. 
\[
w_2(k) = \frac{10}{\sqrt{2\pi}} e^{-\frac{(k-5)^2}{2}}.
\] The simulation results are depicted in Figure 4.

From the above simulation results, it is clear that using the fuzzy robust control strategy proposed above can restrain uncertainties and the demand disturbance no matter what kind of distribution form it follows. So the operational costs of the CLSCN (controlled output) can be asymptotically stable. Consequently it may be helpful for operation managers to deal with these uncertain factors in the operation.

**Conclusions**

A model for the uncertain dual-channel CLSCN system is constructed. How to deal with some kinds of uncertainties in the CLSCN are focused on in this paper. The time-delay in
remanufacturing and more uncertain parameters are considered, such as cost parameters, gratuitous return rate, remanufacturing/disposal rate, preference rate of the customer to the Internet channel and customer’s demand under the Internet. Through the fuzzy robust control strategy, a firm cost of the CLSCN operation is obtained. Finally, an example illustrates the validity of the stability analysis of the CLSCN and the controller design for the T-S fuzzy discrete-time system in this paper.

References


