An optimization approach to cycle quality network chain based on improved SCOR model

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Abstract

Based on the improved supply chain operations reference (SCOR) model, a network-topology structure of cycle quality chain operations reference (CQCOR) model is built up, which realizes the cycle operation by an added quality process of reverse manufacturing. The concept of cycle quality chain management is defined, and its cost structure is analyzed according to positive and reverse quality processes. If the quality level is controlled by the positive quality cost, then the reverse quality cost is a nonlinear function of quality level. All the quality processes are connected by acceptable probability, so the optimized objective function is described as a fuzzy multi-objective function comprising maximum of the total profit of quality chain, maximum of the recycling efficiency and maximum of environment protection and source saving. The effects of different quality policies on fuzzy rules are compared by a simplified example. When the policy of recycling efficiency dominates, the total quality profit will be less than that of maximum profit policy.

Keywords: Quality chain; Cycle operation; Quality cost; SCOR

1. Introduction

Modern quality management passed three main ages, from early statistical process control (SPC) [1], total quality management (TQM) [2], to quality chain management (QCM).

The early SPC applied the engineering mathematics to quality management, but its development was not plain sailing. Because of its absence of quality cost control, it has not received enough attention.

After the appearance of TQM, the modern quality management system came into being. In its early period, the mainstream was single cooperation quality management. With the development of supply chain and logistics, cooperation began to pay attention to not only the quality management of itself, but also those of its upstream and downstream enterprises. Because of its advantages over SPC, TQM has gained more attention from modern enterprises since its origination [2].

At the late period of TQM, modern quality management began to combine with supply chain management, resulting in the supply chain quality management, which can decrease the cost of supply chain as well as improve its security [3]. Now supply chain quality management is very popular in all kinds of manufacturing supply chain and is becoming an absolute system [4]. A novel quality chain management mode has been developed [5]. Robinson defined a supply chain quality management (SCQM) [6]; and Lin further studied the basic structure and organization of supply chain quality management [7].

After entering the 21st century, the demand of international society for strategic sustainable development,
industrial ecology and environment protection [8] has become stronger and stronger so green GDP appeared [9] and enterprises no longer focus on mercantilism only. Based on this background, recycling and its quality management appeared [10]. As a result traditional supply chain turned into closed-loop operation with a reverse process, and a closed-loop supply chain (CLSC) came forth [11]. Additionally several researchers proposed environment protection requirement to all processes of supply chain and treated it as a substantial part in performance evaluation of supply chain [12]. The novel supply chain is often called “green supply chain” [13] or “lean and green supply chain” [14].

As we all know, a uniform design model and management tool is helpful for supply chain cooperation to compare horizontally and integrate vertically. Recently, many researchers proposed different modeling methods, such as supply chain quality management structure model [7], a production-recycling model [10], CLSC model [11], green supply chain management [13], and fuzzy supply chain modeling [15]. In 1996, the international supply chain council (SCC) proposed a supply chain operations reference (SCOR) model, which gained much popularity in the world [16] and turned into SCOR 9.0 in 2008 [17]. The SCOR model provides a unique framework that links business process, metrics, best practices and technology features into a unified structure to support communication among supply chain partners and to improve the effectiveness of supply chain management as well as related supply chain improvement activities [17], but it is not a network model. A network model was put forward for global supply chain and demonstrated that the network structure was closer to supply chain practice [18].

This paper defines the cycle quality chain and builds a network structure model of cycle quality chain operation. The quality cost structure is analyzed on both positive and reverse processes. Based on the differences between nodes and quality processes, the effects of quality investment on acceptable probability and reverse quality cost are analyzed. The performance function of quality chain management is built to include not only quality management profit but also recycling efficiency, environment protection and resource saving. The model is solved by fuzzy multi-object evaluation and the effects of different quality policies on fuzzy rules are compared.

2. Cycle quality network chain model and quality cost analysis

2.1. Fundamental concept

Based on definitions of supply chain quality management [6], CLSC [11], and green supply chain [12–14], the definition of cycle quality chain management can be made, which is produced in cycle supply chain management. Imitating the natural ecology circulation, cycle supply chain realizes cycle operation by added recycling processes.

Cycle quality chain management is defined as follows:

**Definition 1.** Cycle quality chain management (CQCM) is to plan and control the quality activities, ecology protection, resource and energy saving, etc. of all the cooperation in the cycle supply chain from raw materials markets to end customers, including positive quality chain management (PQCM) and reverse quality chain management (RQCM). PQCM focuses on providing product/service to customer demand and sustainable development while RQCM intends to meet the need of reverse product/service or recycling product/service.

Some characteristics may be found from the definition mentioned above.

1. Cycle quality chain is the combination of bidirectional quality chains. Not only is the reverse quality chain included to reflect reverse or recycling supply chain/logistics, but also the quality management of positive quality chain, comprising of ecology protection, resource and energy saving, etc., is more complex than traditional quality chain.

2. The element of cycle quality chain is the total quality management system and environment management system of cooperation nodes in cycle supply chain from raw material sources to end customers. Therefore, this is a systematic view to cycle quality chain management where only if the joint efforts of all nodes are explored can the best performance of the whole chain be obtained.

3. Cycle quality chain is always a complex network structure, in which all network nodes connect with each other by positive and reverse processes. Therefore, the traditional TQM model and SCOR model that are often used for single cooperation or series-wound chain become a sub-system of cycle quality chain network.

Hence some comparisons between cycle operation and closed-loop operation can be made as follows.

First, both closed-loop operation and cycle operation comprise two processes, namely positive and reverse operations. Therefore their basic topology structures are similar, especially their positive operations.

Second, the reverse operation in cycle supply chain/quality chain consists of two kinds of reverse processes. One is operation return including defective return and excess return, and the other is recycling process including used product recycle, packaging recycle, and manufacturing-induced wastes recycle. Apparently the former is a traditional closed-loop operation while the latter is a new recycle requirement of strategic sustainable development.

Third, it is necessary to protect environment and manage recycle resources, energy, etc. and to improve the operational performance of the whole cycle operation. Traditional closed-loop operation, however, focuses on
the profit or cost of operation and environment protection and resource saving do not play important roles in its operation.

In conclusions, cycle supply chain/quality chain operation is more complex than closed-loop supply chain/quality chain operation, and is a higher development level of the latter.

2.2. Cycle quality network model

The proposed cycle quality chain model is based on supply chain operations reference (SCOR) model [14,19], which has gained great popularity in supply chain operating and modeling. SCOR model is a process-based quality management whose processes can be regulated according to quality cost control [20] and therefore is well suited for quality chain management modeling.

In SCOR model, there are six main processes in a supply chain node, including plan (P), source (S), make (M), deliver (D), source return (SR) and deliver return (DR). In cycle supply chain management (CQCM), there is another process, namely reverse make (MR) for repairing, separating, wastes recycling, etc. Now the number of processes in SCOR model increases from six to seven and all these processes constitute a cycle operation. Such an improved model is called cycle quality chain operations reference (CQCOR) model.

A cycle quality chain network model based on CQCOR model is shown in Fig. 1. In this model, all quality management systems (QMS) connect in network topology, including m stages of supply chain corporation nodes, which construct a cycle quality chain, a stage of raw material nodes and a stage of end customer nodes.

In Fig. 1, the quality process (QP) is built based on the process viewpoint of SCOR model. The quality management system of corporation is represented by dashed rectangles with round angles, the positive quality process by solid arrow lines and reverse process by dashed arrow lines. In fact, there are two processes in reverse process SR (reverse return), MR (reverse make) and DR (reverse deliver), namely operating return process and recycling return process, which are different from those of source return (SR) and deliver return (DR) in SCOR with only defective return, excess return, etc.

It can be seen macroscopically that the raw material market nodes are the origination of positive quality chain and the termination of reverse quality chain, however the end customer nodes are the origination of reverse quality chain and termination of positive quality chain. In microcosmic nodes, the nodes in the front stage are the origination of positive quality chain and termination of reverse quality chain of these nodes, and the nodes in the next stage are the origination of reverse quality chain and termination of positive quality chain of these nodes.

In each corporation node \( N_{ij} \) (\( i = 1, 2, \ldots, m; \ j = 1, 2, \ldots, n \)), there are three positive quality processes, namely quality process of source (QPS), quality process of make (QPM), and quality process of deliver (QPD); three reverse quality processes, namely quality process of reverse source (QrPS), quality process of reverse make (QrPM), and quality process of reverse deliver (QrPD), and a bidirectional process namely quality plan process (QPP). To differentiate the operating return processes in SCOR model and reverse quality processes in cycle quality chain network model based on QCOR model, the reverse quality processes (QrP) are defined to include operating return processes and recycling return processes. Apparently all these quality processes are consistent with their counterparts in SCOR model, but the QrPM is derived from the added reverse make process.

Assume that the quality in \( N_{ij} \) (\( i = 1, 2, \ldots, m; \ j = 1, 2, \ldots, n \)) is defined as \( QN_{ij} \).
There are three kinds of nodes, raw material source nodes, quality chain corporation nodes and end customer nodes. As such, there are $m$ stages of corporation nodes in cycle quality chain, and $n$ maximum nodes in each stage. If there are less than $n$ nodes in a stage, the network $QC(m, n)$ can be expressed as a deformation matrix.

\[ QC(m, n) = \begin{bmatrix}
QN_{11} & QN_{12} & \ldots & QN_{1j} & \cdots & QN_{1n} \\
QN_{21} & QN_{22} & \ldots & QN_{2j} & \cdots & QN_{2n} \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
QN_{m1} & QN_{m2} & \ldots & QN_{mj} & \cdots & QN_{mn}
\end{bmatrix} \]  

\[ QN_{ij} = QPP_{ij}, QPS_{ij}, QPM_{ij}, QPD_{ij}, QPrS_{ij}, QPrM_{ij}, QPrD_{ij} \]  

Then the whole quality of cycle quality chain network can be expressed as $QC(m, n)$.

\[ QC(m, n) = \begin{bmatrix}
QN_{11} & QN_{12} & \ldots & QN_{1j} & \cdots & QN_{1n} \\
QN_{21} & QN_{22} & \ldots & QN_{2j} & \cdots & QN_{2n} \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
QN_{m1} & QN_{m2} & \ldots & QN_{mj} & \cdots & QN_{mn}
\end{bmatrix} \]

2.3. Cost analysis of cycle quality chain

To popularize cycle supply chain management, the cost of the proposed model should be controlled and managed as that of TQM [3]. Sharma verified that the quality cost can be controlled by regulating quality processes [21]. Most researches focus on three kinds of objective functions: namely the minimum of cost [22], the maximum of revenue and the maximum of profit [19]. However till now there exists no uniform quality cost scope [20]. Zhu et al. considered that supply chain quality costs comprise inventory-related cost, quality cost, quality improvement investment, etc. [4]. Apparently these quality cost management methods are rough and unhelpful to manage and integrate quality cost of the whole chain [23].

To manage quality cost effectively, systematic definition of quality cost structure and variables is therefore necessary. One important reason for the difficulty to set up these quality cost structures is the uncertainties of quality level and quality cost [24]. Here the uncertainty optimization problems are modeled and solved by fuzzy quality [25].

According to Definition 1, the quality cost of cycle quality chain can be defined as follows.

Definition 2. The quality cost of cycle quality chain comprises all the quality management-operation costs of corporation nodes in the whole quality chain.

This cost counts in all the items and subjects that can be counted in quality cost and should be comparable for different corporation nodes and easy for cost integration. According to Fig. 1, the quality cost can be set up by quality processes.

For node $N_{ij}(i = 1, 2, \ldots, n; j = 1, 2, \ldots, n)$, the variable set of quality processes can be expressed as

\[ X_{ij} = \{x_{ij1}, x_{ij2}, x_{ij3}, x_{ij4}, x_{ij5}, x_{ij6}, x_{ij7}\} \]

where $x_{ij1} = QPP$, $x_{ij2} = QPS$, $x_{ij3} = QPM$, $x_{ij4} = QPD$, $x_{ij5} = QPrS$, $x_{ij6} = QPrM$, $x_{ij7} = QPrD$.

Now three classes of quality cost subjects can be analyzed as shown in Table 1.

Hence, quality cost items comprise two directions of subjects. First, positive quality cost used for assuring the positive quality operation and management to the end customers. Second, reverse quality cost resulted from reverse quality chain for operating and recycling resources.

From Table 1, it can be noticed that we can get all the cost variables as follows.

\[ C_{ij1} = CH_{ij1} + CE_{ij1} + CM_{ij1} + CO_{ij1} + CT_{ij1} \]  

\[ C_{ij2} = CH_{ij2} + CE_{ij2} + CM_{ij2} + CO_{ij2} + CT_{ij2} \]  

\[ C_{ij3} = CH_{ij3} + CE_{ij3} + CM_{ij3} + CO_{ij3} + CT_{ij3} \]  

\[ C_{ij4} = CH_{ij4} + CE_{ij4} + CM_{ij4} + CO_{ij4} + CT_{ij4} \]  

\[ C_{ij5} = CH_{ij5} + CE_{ij5} + CM_{ij5} + CO_{ij5} + CT_{ij5} \]  

\[ C_{ij6} = CH_{ij6} + CE_{ij6} + CM_{ij6} + CO_{ij6} + CT_{ij6} \]  

\[ C_{ij7} = CH_{ij7} + CE_{ij7} + CM_{ij7} + CO_{ij7} + CT_{ij7} \]

For node $N_{ij}(i = 1, 2, \ldots, n; j = 1, 2, \ldots, n)$, positive quality cost is defined as $C_{Pij}$.

\[ C_{Pij} = C_{ij2} + C_{ij3} + C_{ij4} \]

Correspondingly, reverse quality cost is defined as $C_{Rij}$

\[ C_{Rij} = C_{ij5} + C_{ij6} + C_{ij7} \]

where, reverse quality cost involves operating return cost $C_{Rij}$ and recycling return cost $C_{Rij}''$, then the total quality cost of node $N_{ij}(i = 1, 2, \ldots, n; j = 1, 2, \ldots, n)$ can be written as

\[ C_{ij} = C_{ij1} + C_{Pij} + C_{Rij} + C_{Rij}'' \]

Because the reclaiming activity in reverse quality cost aims at resource reuse and ecological cycle, the object of quality chain management cannot be expressed as the minimum of positive and reverse cost or the maximum of profit. Only including these measures will mislead corporation to seek economic profit, and overlook resources saving, cycle reclaiming and environment protection which are not included in quality cost subjects.

Here two variables are introduced for evaluating cycle quality chain performance, one is the total profit of quality management activity, written as $\xi_{ij}$, and the other is recycling efficiency, written as $\eta_{ij}$. Assume that $\xi_{ij}$ results from the revenue of $N_{ij}(i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)$ written as $R_{ij}$ and subtracts quality cost $C_{ij}$. We can get

\[ \xi_{ij} = R_{ij} - C_{ij} \]  

The variable $\xi_{ij}$ is described as the ratio of recycling product number of $N_{ij}(i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)$ written as $r_{ij}$ to recycling cost $C_{Rij}''$, reflecting the recycling capability of unit cost to encourage more recycling with less cost. The variable $\eta_{ij}$ can be expressed as

\[ \eta_{ij} = r_{ij} C_{Rij}'' \]
Table 1
Quality cost subjects and variable definitions.

<table>
<thead>
<tr>
<th>Second class subject</th>
<th>Third class subject</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manpower cost</td>
<td>$C_{ij}$</td>
</tr>
<tr>
<td>Equipment cost</td>
<td>$CE_{ij}$</td>
</tr>
<tr>
<td>Material cost</td>
<td>$CM_{ij}$</td>
</tr>
<tr>
<td>Official cost</td>
<td>$CO_{ij}$</td>
</tr>
<tr>
<td>Others</td>
<td>$CT_{ij}$</td>
</tr>
</tbody>
</table>

For environment protection and resource saving, we can define another variable $\tau_{ij}$ for evaluation. It is apparent that the performance of environment protection and resource saving is better, and the variable $\tau_{ij}$ is larger.

3. An optimization model of cycle quality network chain

3.1. Objective function of cycle quality chain

To facilitate the model optimizing, some assumptions are specified below.

1. Only the single-product condition is considered.
2. There are enough and eligible suppliers delivering raw materials with stable prices over time.
3. Standard cost and variance analysis are overlooked, together with indirect costs.
4. The satisfying degree and quality demand of the end customers to product/service can be acquired without distortion, and the quality chain can be adopted just in time.
5. The cooperation in the next stage proposes quality requirement to those in the front stage by industrial standards.
6. Quality cost management in all nodes is scientific without wasting.
7. The return ratio of product in end customers relies on product quality, instead of customer usage.

For node $N_{ij}(i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)$, quality level is $\lambda_{ij}$, qualified ratio is $\gamma_{ij}$, so $\gamma_{ij}$ is a monotony function of $\lambda_{ij}$. Assume that the qualified product is accepted by $N_{ij}(i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)$ in the next stage with a probability of $\alpha_{ij}(i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)$ and unqualified product is accepted by $N_{ij}(i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)$ in the next stage with a probability of $\beta_{ij}(i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)$ so all products in $N_{ij}$ are accepted by the next stage with a probability of $PA_{ij}$.

$$PA_{ij} = \sum_{k=1}^{n} \gamma_{ij} \alpha_{ij}(i+1)k + \sum_{k=1}^{n} (1 - \gamma_{ij}) \beta_{ij}(i+1)k$$

As we all know that the accepted product can bring revenue to its corporation. Assume that the price of accepted product is defined as $p_{ij}$, and the number of positive product is $pD_{ij}$, and the revenue $R_{ij}$ is written as

$$R_{ij} = PA_{ij} \times pD_{ij} \times p_{ij}$$

Additionally, unaccepted product is transferred to relevant reverse quality process with a probability of $PA_{ij}$.

$$PA_{ij} = 1 - PA_{ij}$$

For node $N_{ij}(i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)$, the unit quality cost of operating return per product is $c_{r_{ij}}$, that is

$$c_{r_{ij}} = PA_{ij} \times pD_{ij} \times c_{r_{ij}}$$

Based on assumption 6, if the positive quality cost $c_{p_{ij}}$ increases, the quality level $\lambda_{ij}$ and the qualified probability $\gamma_{ij}$ of node $N_{ij}$ will be improved.

$$\lambda_{ij} = \Phi_{l}(c_{p_{ij}})$$

$$\gamma_{ij} = \Phi_{l}(c_{p_{ij}})$$

where $\Phi_{l}(c_{p_{ij}})$, $\Phi_{l}(c_{p_{ij}})$ are increasing monotony functions of $c_{p_{ij}}$.

The acceptable probability $\alpha_{ij}(i+1)k$ of qualified product by next stage, lies in the quality level $\lambda_{ij}$ of $N_{ij}$ and quality level $\lambda_{ij+k}$ of $N_{ij+k}$. It is similar to the acceptable probability $\beta_{ij}(i+1)k$ of unqualified product.

$$\alpha_{ij}(i+1)k = \Phi_{l}(\lambda_{ij}, \lambda_{ij+k})$$

$$\beta_{ij}(i+1)k = \Phi_{l}(\lambda_{ij}, \lambda_{ij+k})$$

where $\Phi_{l}(\lambda_{ij}, \lambda_{ij+k})$, $\Phi_{l}(\lambda_{ij}, \lambda_{ij+k})$ are all two-dimensional functions of $\lambda_{ij}$ and $\lambda_{ij+k}$.

In reverse quality process, there is another recycling process. Based on the assumption 7, the recycling ratio is defined as $\mu_{ij}(i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)$.

$$\mu_{ij} = rD_{ij}/pD_{ij} = \Phi_{l}(\lambda_{ij})$$

where $\Phi_{l}(\lambda_{ij})$ is a nonlinear function of $\lambda_{ij}$.

Recycled product will be transferred to the front stage for repairing, separating, recycling, and so on, resulting
in recycling cost \( C^r_{ij} \). The recycling cost per product is defined as \( cr^r_{ij} \).

\[
 cr^r_{ij} = \Phi_r(\lambda_{ij})
\]

where \( \Phi_r(\lambda_{ij}) \) is an increasing monotony function of \( \lambda_{ij} \), namely, the better the quality level is, the higher the recycling cost will be needed.

Consequently, the recycling quality cost \( C^r_{ij} \) can be expressed as

\[
 C^r_{ij} = \mu_{ij} \times Pd_{ij} \times cr^r_{ij}
\]

The total quality cost \( C^t_{ij}(c_{pij}) \) is

\[
 C^t_{ij}(c_{pij}) = c_{pij} \times Pd_{ij} + PA_{ij} \times Pd_{ij} \times cr^r_{ij} + u_{ij} \times Pd_{ij} \times cr^r_{ij}
\]

The main quality variables of node \( N_{ij} \) \((i = 1, 2, ..., m; j = 1, 2, ..., n)\) are shown in Fig. 2. The \( x \)-axis denotes positive quality cost per product that can be counted by statistical data, and the \( y \)-axis shows the level of related variables. Hence the reverse quality cost and total quality cost are also expressed as unit quality cost level in the interval of \([0, 1]\).

We can see from Fig. 2 that at node \( N_{ij} \) \((i = 1, 2, ..., m; j = 1, 2, ..., n)\), because of the constraint of its technology and management capacity, when the positive quality investment reaches a point \( b_{ij} \), the quality level \( \lambda_{ij} \) \((i = 1, 2, ..., m; j = 1, 2, ..., n)\) not reach the ideal station, restricted by the highest quality level \( \Omega_{ij} \leq 1 \). Similarly, when the quality investment is lower than a level \( a_{ij} \), the quality level will drop to a low level \( \lambda_{ij} \) in \( [a_{ij}, b_{ij}] \). Only in the interval of \([a_{ij}, b_{ij}]\), the quality level \( \lambda_{ij} \) will increase linearly with the positive quality cost \( c_{pij} \). Thereby, quality level can be approximately expressed as

\[
\lambda_{ij} = \begin{cases} 
\lambda_{ij,m} & c_{pij} < a_{ij} \\
\frac{a_{ij} - b_{ij}}{a_{ij} - c_{pij}}(c_{pij} - a_{ij}) + b_{ij} & a_{ij} \leq c_{pij} \leq b_{ij} \\
\Omega_{ij} & c_{pij} > b_{ij}
\end{cases}
\]

Similarly, for raw material suppliers, the highest quality level is \( \Omega_{ij} \leq 1 \), and \( \Omega_{ij} > 1 \) for end customers. Now the optimized objective function of the whole chain can be given as follows.

\[
\text{Obj : } \theta = \left\{ \max \left[ \sum_{i=1}^{m} \sum_{j=1}^{n} \zeta_{ij}(c_{pij}) \right] \right.
\]

\[
\left. \max \left[ \sum_{i=1}^{m} \sum_{j=1}^{n} \zeta_{ij}(c_{pij}) \right] \right) \quad (i = 1, 2, ..., m; j = 1, 2, ..., n)
\]

This is a multi-objective fuzzy optimal function with three criteria, namely the maximum of profit, the maximum of recycling efficiency, and the maximum of environment protection and resource saving.

The constraint conditions can be written as follows.

\[
s.t. 0 \leq \lambda_{ij} \leq \Omega_{ij} \leq 1
\]

\[
0 \leq p_{ij} \leq 1
\]

3.2 Solving approach to objective function

Because of the uncertainty of quality and unknown quality cost, the optimization of quality cost is fuzzy. For a cycle quality network chain with \( m \) stages and \( n \) nodes, the optimization of quality cost in a problem of multi-criteria searching process, in which genetic algorithm (GA) is very popular [26].

To evaluate the objective function, a fuzzy multi-criteria evaluation is introduced. Then the objective function is transferred into traditional multi-criteria optimization problem by max–min fuzzy rule. Genetic algorithm can solve the problem effectively in an evolutionary approach.

The main solving steps are as follows.

3.2.1 Encoding/decoding

Encoding process turns the cost variables into binary string, and its length lies in precision requirement of quality cost variables. On the contrary, decoding process changes the binary strings to decimal variables. It is assumed that the positive quality investment level per product is \( c_{pij} \in [0, 1] \), precision is \( \delta \) bits after decimal, coding length is \( K \), then we can get

\[
2^{K-1} < 10^\delta < 2^K - 1
\]

Consequently the coding distance is given as

\[
\Delta = \frac{1}{2^K - 1}
\]

There are \( 2^K \) chromosomes.

3.2.2 Constraint conditions

Here penalty functions are used for constraint feasibility. Assume that \( k_d(i = 0, 1, ..., m + 1; j = 1, 2, ..., n) \) are large enough positive number, the penalty function \( P \) can be defined as
\[ P = \sum_{i=0}^{m+1} \sum_{j=1}^{n} k_{ij} \cdot \max(\lambda_{ij} - \Omega_{ij}, 0) \]  \hspace{1cm} (34)

Correspondingly, the objective function is changed to
\[ \theta = \left\{ \max \left( \sum_{i=1}^{m} \sum_{j=1}^{n} \zeta_{ij} - \sum_{i=0}^{m+1} \sum_{j=1}^{n} k_{ij} \cdot \max(\lambda_{ij} - \Omega_{ij}, 0) \right) \right\} \]
\[ \max \left( \sum_{i=1}^{m} \sum_{j=1}^{n} \zeta_{ij} \right), \ \max \left( \sum_{i=1}^{m} \sum_{j=1}^{n} \tau_{ij} \right) \]  \hspace{1cm} (35)

3.2.3. Fuzzy evaluation

The capacity of each individual to survive natural selection is evaluated through the objective function.

3.2.3.1. Data dictionary definition. At first, all objective variables are fuzzy, and fuzzy linguistic variables are
\{Ler, Low, Med, Hig, Her\}  \hspace{1cm} (36)

where each variable denotes lower, low, medium, high and higher, respectively.

The domains of \( \xi(c_{ij}), \zeta(c_{ij}), \tau(c_{ij}), \theta \) are given below
\{0, f_s, 2f_s, 3f_s, 4f_s\}  \hspace{1cm} (37)

where \( s = \xi(c_{ij}), \zeta(c_{ij}), \tau(c_{ij}), \theta \).

Therefore the variables are quantified to five ranks, where \( f_s \) is the quantifying gene of \( \xi(c_{ij}), \zeta(c_{ij}) \) and \( \theta \) modified by different quality network chains. Based on fuzzy statistical results and professional experience, the domains and fuzzy set memberships can be used and the membership functions of all fuzzy variables can be gotten. Usual membership functions are triangle and normal distribution.

3.2.3.2. Definition of fuzzy rules. According to the idea of experts, look-up tables can be constructed by multi-fuzzy condition (if–then) sentences, and the resulted fuzzy rules are
\[ R(\xi(c_{ij}), \zeta(c_{ij})) = \bigcup_{i=1}^{m} \bigcup_{j=1}^{n} \left\{ \left[ \xi(c_{ij}) \times \zeta(c_{ij}) \right] \times \tau(c_{ij}) \right\} \]  \hspace{1cm} (38)

For example: if \( \xi(c_{ij}) = \text{Her} \) and \( \zeta(c_{ij}) = \text{Her} \), and \( \tau(c_{ij}) = \text{Hig} \) then \( \theta = \text{Her} \).

3.2.3.3. Defuzzy. Output crisp values by defuzzy method on fuzzy consequence, usually max/min method. The defuzzy results of every chromosome can be produced.

3.2.4. Reproduction

3.2.4.1. Natural selection. Natural selection is performed on the population by keeping the most promising individuals based on their fitness value. In GA, the minimum operation is often used. If a positive constant is defined as \( C \), then the fitness function can be gotten from objective function Eq. (35).

3.2.4.2. Crossover. The operations of cross and mutation are the most important characters of the genetic algorithm different from other algorithms and the global searching performance of GA rests with its coding method. The two algorithms are primary ways to produce a new generation of candidate solutions, and the best individual is reproduced based on their ability to survive natural selection. Symbol coding usually uses single point crossover, two points crossover, multi points crossover, equality crossover, etc., whereas serial number coding usually uses sequence crossover and cycle crossover.

3.2.4.3. Mutation. Mutation makes it possible to diversify to a completely different solution and determines the local searching performance of GA. Symbol coding often use standard bit mutation, available bit mutation, etc. However real coding often use equality mutation and non-equality mutation.

3.2.5. Termination condition

Termination condition is set up by fitness results. Repeating the steps mentioned above, the GA will finish when the average fitness results is smaller than an error scope. It is possible that predefined maximum number of generation or time limit is reached. The size of population lies in the space of feasible solutions, usually smaller than 15% of feasible solutions.

4. An example

4.1. Problem description

A simplified numerical study was conducted for illustrating the applicability of the proposed model. A product quality chain comprises 4 nodes in stage 0, 2 nodes in stage 1, 2 nodes in stage 2, 2 nodes in stage 3, and 5 nodes in stage 4. The goal of problem is the optimum of objective function \( \theta \) with all nodes optimizing. To simplify solving process, the requirement of environment protection and resource saving is only to meet the basic need, so the variable \( \tau_{ij} \) can be overlooked here. The main computing information on quality chain is provided in Table 2 by statistical quality cost data of corporation.

Assume that the reverse price per product is half of positive price \( p_{ij} \) and the unit of price is ten thousand yuan (RMB). The problem model can be described as in Fig. 1, and distributor \( N_{31} \) only provides product to and recycle used-product from \( N_{41} \) and \( N_{42} \), whereas \( N_{32} \) for users \( N_{43}, N_{44} \) and \( N_{45} \).

4.2. Solving steps

4.2.1. Encoding/Decoding

Assume that the precision of quality cost level is 4 bits after the decimal, then the coding distance is \( d = 0.0001 \), and coding length is 10 bits. Therefore there are
2^{10} = 1028 combinations, and we can define 10 chromosomes with 6 dimensions.

The main variables in simulating program are as follows: number of individuals is 40, maximum number of generation MAXGEN = 200, dimension of variables NVAR = 6, precision of every variable bit PRECI = 10, generation gap GGAP = 0.9.

4.2.2. Constraint conditions
Assume that $k_j (j = 0, 1, \ldots, 4; \; j = 1, 2)$ equals to 100, then a penalty function $P$ for constraint conditions is

$$P = \sum_{i=0}^{4} \sum_{j=1}^{2} \{100 \cdot \max(\{\hat{\lambda}_{ij} - \Omega_{ij}\}, 0)\}$$

Assume a positive constant $C = 400$, then the fitness function with constraint conditions is turned into

$$\theta = \left\{ \max \left\{ \frac{1}{C} \left[ \sum_{i=0}^{4} \sum_{j=1}^{2} \hat{\lambda}_{ij} - \sum_{i=0}^{4} \sum_{j=1}^{2} 100 \cdot \max(\{\hat{\lambda}_{ij} - \Omega_{ij}\}, 0) \right] \right\}, \right.$$ \left. \max \left( \sum_{i=0}^{4} \sum_{j=1}^{2} \hat{\xi}_{ij} \right) \right\}$$

4.2.3. Fuzzy evaluation
4.2.3.1. Data dictionary definition. Fuzzy linguistic variables set is Eq. (36).

The domains of $\hat{\xi}_{ij}(cp_{ij})$, $\hat{\lambda}_{ij}(cp_{ij})$, $\theta$ are ($f_5 = 0.25$): [0.0, 0.25, 0.5, 0.75, 1.0].

The usual triangle membership functions are shown in Fig. 3.

4.2.3.2. Fuzzy rule definition. A look-up table can be constructed by multi-fuzzy condition (if-then) sentences, and can be regulated by different quality chain requirements. For comparison, two kinds of fuzzy rules are defined here based on the maximum of profit and maximum of recycling efficiency, respectively.

If the quality management profit is stressed upon, and if the maximum profit or the minimum cost is preferred to be won, we can strengthen $\hat{\xi}_{ij}(cp_{ij})$, and the corresponding look-up table is shown in Table 3.

On the contrary, if the recycling efficiency is stressed upon, and if improving the recycling efficiency is preferred, we can strengthen $\hat{\xi}_{ij}(cp_{ij})$, and the corresponding look-up table is shown in Table 4.
According to fuzzy consequence, the evaluation results can be gotten by max/min defuzzy method.

4.2.4. Reproduction

Here only single point crossover and equality mutation are employed. Two parents are chosen randomly from the population, and two children are produced by crossover and mutation operation. The two parents and subsequence are evaluated by fitness function. We can select the excellent chromosome based on its ability. If children are superior to their parents, then they substitute their parents, otherwise the parents are kept down.

4.2.5. Termination condition

For comparison, the algorithm finished until 200 generations. The maximum population number is 300.

4.3. Discussion

Matlab is employed for simulating experiment, and fuzzy rule surface plots of rule Table 1 and rule Table 2 are shown in Figs. 4 and 5, respectively.

As we can see, there are 25 rules in both rule Table 1 and rule Table 2, and $\theta$ increases with $\xi_{ij}(cp_{ij})$ and $\xi_{ij}(cp_{ij})$. In rule Table 1, quality cost management is stressed. For example, if $\xi_{ij}(cp_{ij}) = 0$ (Ler) and $\xi_{ij}(cp_{ij}) = 0\sim1$, then $\theta = 0$ (Ler). Namely if the recycling quality management is bad, the objective function cannot get high score whether the quality cost management is good or not. In conclusions, the fuzzy rules can be adjusted according to different requirements of quality management.

In both rule Table 1 and rule Table 2, the change of solutions and the average value of populations are shown in Fig. 6.

Comparing curves in Fig. 6, we can find that the objective profit of rule Table 1 is higher than that of rule Table 2 when objective functions reach their optimum. After 100 simulation runs, the average values of $\theta$ are $\bar{\theta} = 0.3061$ in rule Table 1 and $\bar{\theta} = 0.2532$ in rule Table 2. The higher part in quality cost results from recycling quality management, which gain less profit.

The average values of solutions in 100 times simulation are shown in Table 5.

Because constant $C$ equals to 400, it is apparent that the profit of rule Table 1 is about 50% higher than those of rule Table 2 according to the construction of fitness function, but the former maximum quality level (0.8063) is lower than that of the latter (0.9131).

In rule Table 1, cycle quality chain stresses maximizing the profit of quality management, reflecting the idea of mercantilism and overlooking the cycle utilizing of resources. However in rule Table 2, cycle quality chain stresses maximizing the recycling efficiency, reflecting the idea of utilizing resources as more as possible. Therefore the latter is aimed at environment protection and sustainable development.

As we can see, in different cycle quality chain managements, the optimal quality profit differentiates from each other by management objectives. In the early days of cycle quality chain, rules preferring to quality cost management are appropriate, such as rule Table 1, since total cost of corporation quality management can be limited and good profit can make a foundation for further development of corporation. In the later development of cycle quality chain management, more stress should be shifted to recycling quality management step by step. In this way the corporation can transfer its main objective from mercantilism to
recycle and sustainable development. When cycle quality chain management is mature, the rules should focus on recycling efficiency as rule Table 2, which make corporation really recognize recycling and strategic sustainable development. Because the recycling process is cost-expensive with inconspicuous profit, even to the bad, the government regulations might be necessary to set up policies including allowance and penalty to encourage recycling.

5. Conclusions

The study tries to provide a simple and useful tool to promote strategic sustainable development and recycle operation, thus a network-topology structure of cycle quality chain operations reference model is built up based on improved SCOR model. Three classes of quality cost structure are studied which are easy for practice, suitable for cost comparison between corporations and integrated optimization of entire chain. The optimization model with multi objectives can avoid the traditional mercantilism idea. Fuzzy evaluation decreases the distortion of un-rigorous factors in modeling and improves searching efficiency in the optimizing of cycle quality chain. The proposed model helps to map out a rough framework for supply chain manager to put the sustainable development strategy and resources recycle into practice.

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