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Research Article

Critical Quality Source Diagnosis for Dam Concrete Construction Based on Quality Gain-loss Function

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Abstract

In dam concrete construction process, it not only has quality loss arising from quality fluctuation, but also gains quality compensation effect due to the mutual cooperation and adaptation coupling between working procedures (WPs). The calculation and transmission complexity of the quality loss and quality compensation affect the quality management of dam concrete construction. As the quality compensation effect existing in the production practice cannot be described by Taguchi quality loss function, the concept of quality gain-loss function was presented in this paper, which was based on endowing the constant term in the expansion of Taylor series with physical meaning—quality compensation. Based on quality gain-loss function theory, a new quality gain-loss transmission model of dam concrete construction based on GERT network was constructed and its effective algorithm was designed. WP quality gain-loss and its impact on the final product were reasonably measured, and the critical quality routes and critical quality WPs were detected and diagnosed in dam concrete construction network. Summer temperature-controlled concrete construction in the third phase of Three Gorges Project (TGP) was taken as an example to carry out the study, and the calculation results showed the validity and practicability of the presented model and algorithm.

Keywords: Quality Gain-loss Function, GERT, Dam Concrete Construction, Critical Quality Source, Three Gorges Project

1. Introduction

Dam concrete construction is a giant and complex project with huge engineering work, long duration, high strength of the peak, numerous WPs, many construction disturbance factors and high construction technical requirements. For example, in the TGP, the total concrete pouring amount is 28,000,000 m^3, annual pouring amount in the hinge project peak can be reached to 5,480,000 m^3, and the maximum monthly pouring amount is 553,500 m^3. For another example, during the first phase of TGP, for the concrete construction below 90 meter elevation of the longitudinal cofferdam dam section, there are more than 50 concrete pouring warehouses in total and 2 group WP cycles; each warehouse requires to go though more than 200 WPs, and over 10 production departments and more than 100 construction teams will be involved at the same time once pouring. Dam concrete construction quality mainly depends on the overall quality level of construction network composed of WP units, therefore, detecting and diagnosing the critical quality source, implementing strict monitoring and improvement are effective methods of quality management.

Existing researches believe that the quality loss is constantly accumulated and amplified in the transmission process of complex product, which will greatly affect the product quality level in the end. Dam concrete construction, for such a giant and complex project composed of tens of thousands of WPs, even if each WP produces small quality loss (loss amount within the quality standard requirements), ultimately it would be difficult to meet the product quality requirements through the accumulation and amplification, which is inconsistent with the actual high quality concrete dam. Therefore, the new quality variation and quality transmission theory need to be explored and researched to solve the quality management issues in complex product.

In the industrial production, due to various influence factors arising from raw material quality, production environment, equipment level, manipulation and so on, quality fluctuation is incurred. In the 1970s, in order to estimate the loss produced by quality characteristic deviating from the target value, and unify the concepts of quality category and economic category, quadratic quality loss function was presented by Dr. Taguchi [1] for quantitative description of product quality. However, a large number of production practices have shown that it is not the case. In fact, not only quality loss, but the quality gain effect brought from quality compensation sometimes also exists in the production process. Take the production process of temperature-controlled concrete during the concrete dam construction in summer for an example, assuming that the design target value of concrete mixture machine-outlet

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temperature is 7℃, due to the errors or interferences, quality loss can be produced by machine-outlet temperature deviating from the target value. However, the loss can be compensated by the latter WPs, such as through covering the heat preservation quilt on concrete mixture belt conveyor, building awnings for transport vehicles or spraying in warehouse surface to reduce loss or gain quality compensation.

Since quality loss function is presented by Taguchi, scholars have made a large number of researches around quality loss modeling. In order to solve the unboundedness of Taguchi quality loss function, upside-down normal distribution quality loss function was proposed by Spring [2] and Naghizadeh [3]. In view of the asymmetry problem, asymmetric quality loss function models were proposed by Spring [4] and Wu [5]. Using fuzzy theory, the concept of fuzzy quality loss was presented and the corresponding fuzzy quality loss model was established by Cao [6]. As most studies have focused on the quality loss function with single characteristic, the total quality loss model with multiple correlated quality characteristics and its tolerance design method were presented by Lee and Tang [7]. A robust optimum method was presented to directly determine the process tolerances from multiple correlated critical tolerances in an assembly by Huang [8]. The above-mentioned Taguchi quality loss function and its corresponding expansion studies are based on the assumption that the quality characteristic at target value has the minimum quality loss and the loss equals to 0. However, a large number of production practices indicate that the formation process of product quality is not the case. On one hand, quality loss can be produced due to the deviation of products' characteristics from their target values, and the greater the volatility, the greater the quality loss. On the other hand, it is also a mutual cooperation and adaptation coupling processes between WPs, i.e., the former WPs can get quality compensation from the latter WPs or through the mutual collaboration and adaptation coupling between the parallel WPs, so as to reduce WP quality loss or achieve quality gain. In view of the quality compensation effect existing in production practice that cannot be described by Taguchi's quality loss function, the concept of quality gain-loss function is presented in this paper.

A generalized network technology with "decision box" on which the next step of routes can be determined by different probabilities proposed by E. Eisner in 1962 was the preliminary form of Graphical evaluation and review technique (GERT). After that GERT was gradually improved and formed by S.S.Elmaghraby and A.A.B. Pritsker [9] [10]. In recent years, GERT network is widely used in water conservancy and hydropower construction, project management, time and cost analysis, transportation and route selection, etc. As in aspect of water resources and hydropower construction, the GERT network model of longitudinal concrete cofferdam construction in TGP was established by Zhou Hougui [11], and the stochastic problems existing in the project was successfully solved. In terms of project risk management, risk element transmission analytical model was constructed by Li Cunbin [12] based on GERT network to avoid and reduce risk in the actual projects. In terms of cost analysis, the method of stochastic budget simulation, combining the conventional calculation method stochastic simulation with basic facets of the successive principle, was presented by Martin, and it is a new way to analyze and evaluate the economic consequences of large-scale projects by quantifying intervals for cost items and using simulation as a tool to represent distributions of the possible costs [13]. In transportation field, a network model was proposed by Paletta to solve the dynamic traveling salesman problem [14], and network technology was further used to study the random delay problem in priority service by Afeche [15]. In terms of methods, GERT network model with grey information was proposed, and the construction of moment generating function in GERT network with grey variables was studied by Yang [16]. In addition, multi-parameter GERT network model was constructed by Guo based on energy transfer relationship, so as to revel the various sectors of energy efficiency realization mechanism [17].

GERT network model is actually a semi-Markov process model, and its theoretical bases are signal flow graph theory and moment generating function theory. In addition to being compatible with the role of CPM/PERT, GERT could also be used to make scheme decisions, reasonably allocate resources, simulate production process, solve random and cycle operation problems, etc. It is a powerful tool for solving complex manufacturing problems. GERT network technology has obtained widespread application in many fields, but throughout related studies in recent years, we can find little literature applying GERT to the quality gain-loss transmission. On one hand, quality gain-loss transmission has the general characteristics of quality loss transmission. On the other hand, GERT network transmission characteristics are especially suitable for the resolution ideas of quality gain-loss transmission. Therefore, quality gain-loss transmission analytical model is established based on GERT network. Quality gain-loss of WP and the degree of its influence on the final product quality are reasonably measured. The critical quality routes and critical quality WPs in dam concrete construction network are detected and diagnosed, and a new analytical method and theoretical support for quality management of dam concrete construction is presented in this paper.

2. Quality Gain-loss Function

2.1 Definition of quality loss function

Let product quality characteristic value be y and target value be m. When $y \neq m$, quality loss can be produced, and the greater the $|y-m|$, the greater the loss. Let the corresponding loss of quality characteristic value y be $L(y)$. If $L(y)$ has the second derivative at $y=m$, it can be expanded by Taylor series:

$$L(y) = L(m) + \frac{L'(m)}{1!}(y-m) + \frac{L''(m)}{2!}(y-m)^2 + o[(y-m)^2] \quad (1)$$

It is assumed that when $y=m$, $L(y)=L(m)=0$, and it has the minimum loss, i.e. $L'(m)=0$. Omit the high order terms which are more than second order, there:

$$L(y) = k_1(y-m)^2 \quad (2)$$

$$k_1 = A_0 / \Delta_0^2 = A / \zeta^2 \quad (3)$$

Where k_1 is a coefficient independent of y. Quality loss function is expressed as Eq. (2), where $L(y)$ represents the corresponding loss when quality characteristic value is y. Generally k_1 can be determined based on functional boundaries Δ_0 and the loss of no function A_0, or the tolerance ζ and unqualified loss A, expressed as Eq. (3).

2.2 Definition of quality gain-loss function

Let product quality characteristic value be y and target value be m. Let the corresponding gain-loss of quality characteristic value y be $G(y)$. If $G(y)$ has the second derivative at $y=m$, it can be expanded by Taylor series:

$$G(y) = G(m) + \frac{G^{'}(m)}{1!}(y-m) + \frac{G^{''}(m)}{2!}(y-m)^2 + o[(y-m)^2] \quad (4)$$

It is assumed that the minimum loss is produced when $y=m$, i.e., $G'(m)=0$. Because quality compensation exists, so $G(m)\in R$. Omit the high order terms which are more than second order, there:

$$G(y)=G(m)+k_2(y-m)^2 \quad (5)$$

$$k_2 = [A_0 - G(m)]/\Delta_0^2 = [A - G(m)]/\zeta^2 \quad (6)$$

Where k_2 is a coefficient independent of y, and $G(m)$ is a real number R. Quality loss function has the minimum loss 0 when $y=m$, so the maximum quality gain can be expressed as $G(m)$, called quality compensation. Quality gain-loss function is expressed as Eq. (5), in which, $G(y)$ represents the corresponding quality gain-loss when quality characteristic value is y. When $G(y)>0$, the total quality loss is generated, i.e., quality loss produced by fluctuation is greater than quality compensation. When $G(y)=0$, the quality loss and quality gain do not occur or the loss produced by fluctuation is equal to quality compensation, i.e., quality gain-loss equal to 0. When $G(y)<0$, the total quality gain is generated, i.e., quality loss produced by fluctuation is less than quality compensation. Generally k_2 can be expressed as Eq. (6).

From Eq (5), we can get that quality gain-loss function consists of two parts: quality loss term and quality compensation term. In quality loss term, the loss produced by fluctuation is proportional to the square of the deviation deviating from the target value m, and the greater the deviation, the greater the loss. The complexity of the actual production cannot be expressed sufficiently when quality compensation term is a constant. Therefore, it is assumed that the quality compensation is a function of quality characteristic value y, expressed as:

$$g(y)=h(y) \quad (7)$$

Eq. (7) is called quality compensation function. So quality gain-loss function can be expressed as:

$$G(y)=g(y)+k_2(y-m)^2 \quad (8)$$

Similarly, the quality gain-loss function with larger-the-better characteristics $G_L(y)$ and with smaller-the-better characteristics $G_M(y)$ can be expressed as:

$$G_L(y)=g_l(y)+k_l/y^2 \qquad y>0 \quad (9)$$

$$G_M(y)=g_m(y)+k_m y^2 \qquad y\geq 0 \quad (10)$$

Since the concepts of quality category and economic category are unified by quality gain-loss function, it eliminates the measuring unit influence of quality characteristic which is unified by the price. This characterization is conducive to carry out transmission and analogy of quality gain-loss amount between WPs.

3. Construction of Quality Gain-loss Transmission Model Based on GERT Network

Definition: Quality gain-loss transmission model based on GERT network consists of three elements—the node, the arrow line and the quality gain-loss flow. Nodes represent WPs, arrow lines represent quality gain-loss transmission activities between WPs, and flows reflect the quantitative mutual constraint relationship of quality gain-loss transmission activities between WPs in network.

Assumption 1: In construction process of WPs, on one hand, quality loss can be produced by the deviation between WP quality characteristic value and its target value, and on the other hand, WP can produce quality compensation effect to its internal WPs.

Assumption 2: Quality compensation circuit cannot occur, and quality compensation only can be generated for its internal WPs.

Assumption 3: Quality compensation amount from the initial WP to its internal WPs is 0.

WP quality compensation is conducted in the construction process, i.e. quality compensation generating from WP j to its internal WP i is transmitted to the next WP after the completion of WP j. If j is the terminal WP, it still produces quality loss and quality compensation. In order to express quality loss of the terminal WP, illustrate quality gain-loss transmission process conveniently and calculate easily, assume a virtual terminal WP not existing in the actual construction, i.e., add a WP after terminal WP. Quality gain-loss transmission process is shown in Fig. 1.

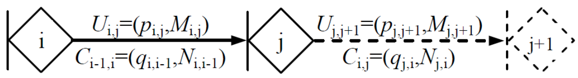

Fig. 1. Quality gain-loss transmission process

In Fig. 1, quality loss flow from WP i to its external WP j is expressed as $U_{i,j}$, the occurrence probability of quality loss flow is expressed as $p_{i,j}$, and the conditional probability function of quality loss transmission between WP i and WP j is expressed as $M_{i,j}$. Quality compensation flow from WP j to its internal WP i is expressed as $C_{i,j}$, the occurrence probability of quality compensation flow is expressed as $q_{j,i}$, and the conditional probability function of quality compensation transmission between WP i and WP j is expressed as $N_{j,i}$. If i is the initial WP, according to assumption 3 we can get the quality compensation amount from WP i to its internal WP is 0, i.e., $C_{i,0}=0$. In order to calculate conveniently, label the quality compensation from WP j to its internal WP i on the bottom of arrow line from WP i to WP j, only expressing the quality compensation from WP j to WP i but not meaning quality compensation transmit from WP i to WP j. The basic composition unit of quality gain-loss transmission model based on GERT network is shown in Fig. 2.

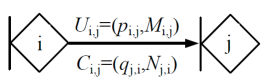

Fig. 2. The basic composition unit of quality gain-loss transmission model based on GERT network

In quality gain-loss transmission GERT network, based on the logical relationship between WPs, the basic composition units can be divided into series, parallel and hybrid forms. The structural schematic diagram of quality gain-loss transmission GERT network is shown in Fig. 3.

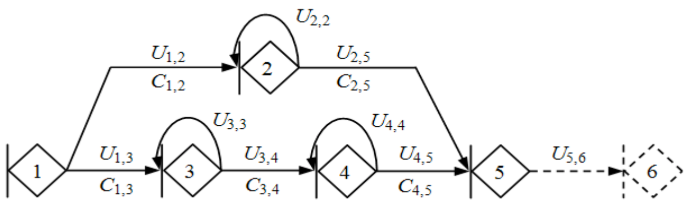

Fig. 3. The structural schematic diagram of quality gain-loss transmission GERT network

In particular, for quality loss flow $U_{i,j}$, if $i≠j$, it indicates the quality of WP i can meet the design requirements, and the external WP j can be carried out construction on the basis of WP i. If $i=j$, a loop at the node will be formed, indicating the quality of WP i cannot meet the design requirements and need to rework or re-construct, which can be considered as a quality compensation to WP i.

4. The Critical Quality Source Diagnosis and Its Detection Algorithms Study of Quality Gain-loss Transmission Network in Dam Concrete Construction

4.1 The moment generating functions design for quality loss and quality compensation transmission process

In quality gain-loss transmission model based on GERT network, if the quality loss $L_{i,j}(x)$ transmitted from WP i to its external WP j obeys a certain probability distribution $f_{i,j}(x)$, then the moment generating function of quality loss directed arc (i, j) can be expressed as:

$$M_{i,j}(s) = \int_{-\infty}^{+\infty} e^{sX} f(x)dx \tag{11}$$

If the quality compensation $G_{i,j}(x)$ generated from WP j to its internal WP i obeys a certain probability distribution $g_{i,j}(x)$, then the moment generating function of quality compensation directed arc (i, j) can be expressed as:

$$N_{j,i}(s) = \int_{-\infty}^{+\infty} e^{sX} g(x)dx \tag{12}$$

In engineering practice, parameter distribution $f(x)$ and $g(x)$ can be obtained from the following two ways: (a) under the condition of engineering quality data being complete, it can be obtained by mathematical statistics method; (b) under the condition of engineering quality data being incomplete, it can be obtained by estimating the expected number of WP quality loss and quality compensation according to experts experience and the maximum entropy model.

4.2 Equivalent parameter calculation of quality gain-loss transmission based on GERT network

In quality gain-loss transmission based on GERT network, if quality loss equivalent transmission function between WP i and its external WP j is $W_{i,j}^{1}(s)$, then the quality loss equivalent transmission probability from WP i to WP j $p_{i,j}=W_{i,j}^{1}(s)\mid_{s=0}$ and its equivalent moment generating function $M_{i,j}(s) = W_{i,j}^{1}(s) / p_{i,j}$. If quality compensation equivalent transmission function from WP j to its internal WP i is $W_{i,j}^{c}(s)$, then the quality compensation equivalent transmission probability from WP j to WP i $q_{j,i}= W_{i,j}^{c}(s)\mid_{s=0}$ and its equivalent moment generating function $N_{j,i}(s) = W_{i,j}^{c}(s)/q_{j,i}$. Based on the logical relationship between WPs, quality gain-loss transmission GERT network can be divided into three basic structures—series, parallel and hybrid, and equivalent transmission parameters with different structures in network are different.

4.2.1 Equivalent parameter calculation of serial structure in quality gain-loss transmission GERT network

The structure that multiple WPs were continuously stringed together is called serial structure. Because of the linear features, serial structure can always be replaced by a single arrow equivalent network contacting all inclusive WP nodes. Equivalent parameter calculation schematic diagram of serial structure is shown in Fig. 4.

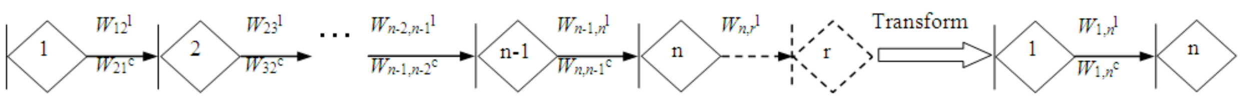

Fig. 4. Equivalent parameter calculation schematic diagram of serial structure

Theorem 1: Serial structure equivalent parameter in quality gain-loss transmission GERT network can be expressed as: firstly multiply the quality loss and quality compensation equivalent transmission function between adjacent nodes respectively, and then sum the results, i.e.

$$W_{1,n}(s) = \prod_{i=1}^{n} W_{i,i+1}^{1}(s) + \prod_{i=1}^{n-1} W_{i,i+1}^{c}(s) \tag{13}$$

Demonstration:

Since $W_{i,j}(s)=p_{i,j}M_{i,j}(s)$, so

$$W_{1,n}{}^{1}(s) = p_{1,n}M_{1,n}(s) = \prod_{i=1}^{n} p_{i,i+1} \prod_{i=1}^{n} M_{i,i+1}(s)$$

$$= \prod_{i=1}^{n} p_{i,i+1} M_{i,i+1}(s) = \prod_{i=1}^{n} W_{i,i+1}{}^{1}(s)$$

For the same reason, we can get:

$$W_{1,n}{}^{c}(s) = \prod_{i=1}^{n-1} W_{i,i+1}^{c}(s) \cdot$$

Since quality loss and quality compensation of each WP eliminate the measuring unit influence of quality characteristic which is unified by the price, theorem 1 can be proved.

4.2.2 Equivalent parameter calculation of parallel structure in quality gain-loss transmission GERT network

Similar to the parallel structure of circuit theory, assuming that there are k routes from WP node i to WP node n, the corresponding quality gain-loss transmission function of the t_{th} route is $W_{i,n}^{\text{t}}$, in which quality loss transmission function is $W_{i,n}^{\text{lt}}$ and quality compensation transmission function is $W_{i,n}^{\text{ct}}$. Equivalent parameter calculation schematic diagram of parallel structure is shown in Fig. 5.

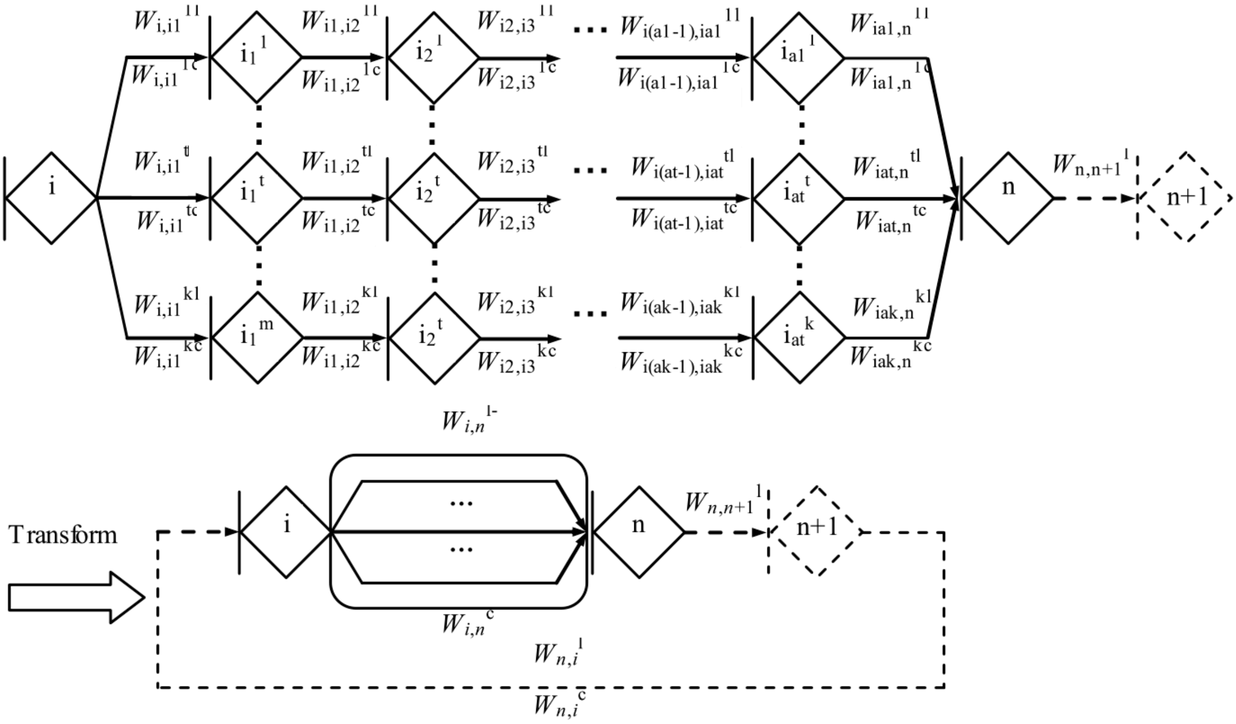

Fig. 5. Equivalent parameter calculation schematic diagram of parallel structure

Theorem 2: Equivalent parameter calculation of parallel structure in quality gain-loss transmission GERT network can be expressed as: sum the quality gain-loss equivalent transmission function of each route, i.e.

$$W_{i,n}(s) = \sum_{t=1}^{\text{k}} W_{i,n}^{t}(s) = W_{n,n+1}^{1} \sum_{t=1}^{\text{k}} W_{i,n}^{t\text{l-}}(s) + \sum_{t=1}^{\text{k}} W_{i,n}^{t\text{c}}(s) \quad (14)$$

Where, a_t represents the number of WP nodes on the t_{th} route in parallel structure.

$$W_{i,n}^{t\text{l-}}(s) = W_{i,i_1^t}^{1}(s) W_{i_1^t,i_2^t}^{1}(s) \cdots W_{i_{a_t-1}^t,a_t}^{1}(s) W_{i_{a_t}^t,n}^{1}(s)$$

$$W_{i,n}^{t\text{c}}(s) = W_{i,i_1^t}^{\text{c}}(s) W_{i_1^t,i_2^t}^{\text{c}}(s) \cdots W_{i_{a_t-1}^t,a_t}^{\text{c}}(s) W_{i_{a_t}^t,n}^{\text{c}}(s)$$

Demonstration: As shown in figure 5, encapsulate all arrow lines between WP node i and WP node j, and replace with an arrow line. Transmission function of its quality loss and quality compensation can be respectively expressed as $W_{i,n}^{\text{l-}}(s)$ and $W_{i,n}^{\text{c}}(s)$. In addition, the auxiliary arrow line (dotted line) can be constructed regarding WP node n as the initial node and WP node i as the terminal node, and the transmission function of its quality loss and quality compensation can be respectively expressed as $W_{n,i}^{\text{l}}(s)$ and $W_{n,i}^{\text{c}}(s)$. So the original parallel structure model can be transformed into a loop model, and there are k closed loops in this loop model. According to mason formula, the network characteristic values can be expressed as:

$$\begin{aligned} H_1 &= 1 - W_{i,n}^{\text{1l-}}(s) W_{n,n+1}^{1}(s) W_{n,i}^{1}(s) - W_{i,n}^{\text{2l-}}(s) W_{n,n+1}^{1}(s) W_{n,i}^{1}(s) \\ &\quad - \cdots - W_{i,n}^{t\text{l-}}(s) W_{n,n+1}^{1}(s) W_{n,i}^{1}(s) \\ &\quad - \cdots - W_{i,n}^{\text{kl-}}(s) W_{n,n+1}^{1}(s) W_{n,i}^{1}(s) \\ &= 1 - \sum_{t=1}^{\text{k}} W_{i,n}^{t\text{l-}}(s) W_{n,n+1}^{1}(s) \frac{1}{W_{i,n}^{1}(s)} = 0 \end{aligned} \quad (15)$$

$$\begin{aligned} H_2 &= 1 - W_{i,n}^{\text{1c}}(s) W_{n,i}^{\text{c}}(s) - W_{i,n}^{\text{2c}}(s) W_{n,i}^{\text{c}}(s) \\ &\quad - \cdots - W_{i,n}^{t\text{c}}(s) W_{n,i}^{\text{c}}(s) - \cdots - W_{i,n}^{\text{kc}}(s) W_{n,i}^{\text{c}}(s) \\ &= 1 - \sum_{t=1}^{\text{k}} W_{i,n}^{t\text{c}}(s) \frac{1}{W_{i,n}^{\text{c}}(s)} = 0 \end{aligned} \quad (16)$$

So, we can get:

$$W_{i,n}^{1}(s) = W_{n,n+1}^{1} \sum_{t=1}^{\text{k}} W_{i,n}^{t\text{l-}}(s)$$

$$W_{i,n}^{\text{c}}(s) = \sum_{t=1}^{\text{k}} W_{i,n}^{t\text{c}}(s)$$

Since $W_{i,n}(s)=W_{i,n}^{1}(s)+W_{i,n}^{\text{c}}(s)$, theorem 2 can be proved.

4.2.3 Equivalent parameter calculation of hybrid structure in quality gain-loss transmission GERT network

Equivalent parameter calculation schematic diagram of hybrid structure is shown in Fig. 6.

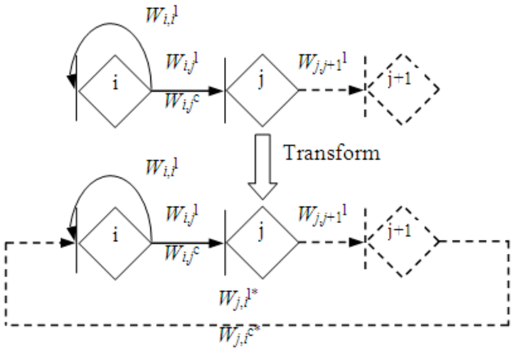

Fig. 6. Equivalent parameter calculation schematic diagram of hybrid structure

Theorem 3: In actual GERT network, the network structure existing of loop can be called hybrid structure, and equivalent parameter calculation formula of hybrid structure in quality gain-loss transmission GERT network is:

$$W_{i,j}(s) = \frac{W^{1}_{i,j}(s)W^{1}_{j,j+1}(s)}{1-W^{1}_{i,i}(s)} + W^{c}_{i,j}(s) \tag{17}$$

Demonstration: the auxiliary arrow line (dotted line) can be constructed regarding WP node j as the initial node and WP node i as the terminal node, and the transmission function of its quality loss and quality compensation can be respectively expressed as $W_{i,i}^{1}(s)$ and $W_{i,i}^{c}(s)$. So the original hybrid structure model can be transformed into a loop model. According to mason formula, the network characteristic values can be expressed as:

$$\begin{aligned} H_3 &= 1 - W^{1}_{i,i}(s) - W^{1}_{i,j}(s)W^{1}_{j,j+1}(s)W^{1*}_{j,i}(s) \\ &= 1 - W^{1}_{i,i}(s) - \frac{W^{1}_{i,j}(s)W^{1}_{j,j+1}(s)}{W^{1*}_{i,j}(s)} = 0 \end{aligned} \tag{18}$$

$$H_4 = 1 - W^{c}_{i,j}(s)W^{c*}_{j,i}(s) = 1 - \frac{W^{c}_{i,j}(s)}{W^{c*}_{j,i}(s)} = 0 \tag{19}$$

So, we get the following results:

$$W^{1*}_{i,j}(s) = \frac{W^{1}_{i,j}(s)W^{1}_{j,j+1}(s)}{1-W^{1}_{i,i}(s)}$$

$$W^{c*}_{i,j}(s) = W^{c}_{i,j}(s)$$

Since $W_{i,j}(s)=W_{i,j}^{1*}(s)+W_{i,j}^{c*}(s)$, theorem 3 can be proved.

4.3 Quality gain-loss transmission parameter calculation of dam concrete construction

Theorem 4: If quality gain-loss equivalent transmission function from WP i to WP j is $W_{i,j}(s)$, the first moment of quality gain-loss parameter $x_{i,j}$ transmitted from WP i to WP j is:

$$E(x_{i,j}) = \frac{\partial}{\partial s}\left[\frac{W_{i,j}(s)}{W_{i,j}(0)}\right]\Bigg|_{s=0} = \frac{\partial}{\partial s}\left[\frac{W^{1}_{i,j}(s)}{W^{1}_{i,j}(0)}\right]\Bigg|_{s=0} + \frac{\partial}{\partial s}\left[\frac{W^{c}_{i,j}(s)}{W^{c}_{i,j}(0)}\right]\Bigg|_{s=0} \tag{20}$$

Demonstration: since $M_{i,j}(s)=W_{i,j}^{1}(s)/p_{i,j}=W_{i,j}^{1}(s)/W_{i,j}^{1}(0)$, $N_{j,i}(s)=W_{i,j}^{c}(s)/q_{j,i}=W_{i,j}^{c}(s)/W_{i,j}^{c}(0)$, the first moment of quality gain-loss parameter $x_{i,j}$ transmitted from WP node i to WP node j, that is the average quality gain-loss, can be expressed as:

$$\begin{aligned} E(x_{i,j}) &= \int_{-\infty}^{+\infty} x_{i,j} f(x_{i,j})dx_{i,j} + \int_{-\infty}^{+\infty} x_{i,j} g(x_{i,j})dx_{i,j} \\ &= \frac{\partial}{\partial s}\left[\int_{-\infty}^{+\infty} e^{sx_{i,j}} f(x_{i,j})dx_{i,j}\right]\Bigg|_{s=0} \\ &+ \frac{\partial}{\partial s}\left[\int_{-\infty}^{+\infty} e^{sx_{i,j}} g(x_{i,j})dx_{i,j}\right]\Bigg|_{s=0} \\ &= \frac{\partial}{\partial s}\left[\frac{W^{1}_{i,j}(s)}{W^{1}_{i,j}(0)}\right]\Bigg|_{s=0} + \frac{\partial}{\partial s}\left[\frac{W^{c}_{i,j}(s)}{W^{c}_{i,j}(0)}\right]\Bigg|_{s=0} \end{aligned} \tag{21}$$

Theorem 4 can be proved.

Corollary 1: If quality gain-loss equivalent transmission function from WP i to WP j is $W_{i,j}(s)$, the n order moments of quality gain-loss parameter $x_{i,j}$ transmitted from WP i to WP j is:

$$E[(x_{i,j})^{n}] = \frac{\partial^{n}}{\partial s^{n}}\left[\frac{W_{i,j}(s)}{W_{i,j}(0)}\right]\Bigg|_{s=0} = \frac{\partial^{n}}{\partial s^{n}}\left[\frac{W^{1}_{i,j}(s)}{W^{1}_{i,j}(0)}\right]\Bigg|_{s=0} + \frac{\partial^{n}}{\partial s^{n}}\left[\frac{W^{c}_{i,j}(s)}{W^{c}_{i,j}(0)}\right]\Bigg|_{s=0} \tag{22}$$

Theorem 5: If quality gain-loss equivalent transmission function from WP i to WP j is $W_{i,j}(s)$, the quality gain-loss fluctuation variance of quality gain-loss parameter $x_{i,j}$ transmitted from WP i to WP j is:

$$V[x_{i,j}] = \frac{\partial^2}{\partial s^2}\left[\frac{W_{i,j}(s)}{W_{i,j}(0)}\right]\Bigg|_{s=0} - \left\{\frac{\partial}{\partial s}\left[\frac{W_{i,j}(s)}{W_{i,j}(0)}\right]\Bigg|_{s=0}\right\}^2 \tag{23}$$

Demonstration: the second moment of quality gain-loss parameter $x_{i,j}$ transferred from WP node i to WP node j can be calculated as follows:

$$\begin{aligned} E(x^2_{i,j}) &= \int_{-\infty}^{+\infty} x^2_{i,j} f(x_{i,j})dx_{i,j} + \int_{-\infty}^{+\infty} x^2_{i,j} g(x_{i,j})dx_{i,j} \\ &= \int_{-\infty}^{+\infty} x^2_{i,j} e^{sx_{i,j}} f(x_{i,j})dx_{i,j} + \int_{-\infty}^{+\infty} e^{sx_{i,j}} x^2_{i,j} g(x_{i,j})dx_{i,j} \\ &= \frac{\partial^2}{\partial s^2}\left[\int_{-\infty}^{+\infty} e^{sx_{i,j}} f(x_{i,j})dx_{i,j}\right]\Bigg|_{s=0} \\ &+ \frac{\partial^2}{\partial s^2}\left[\int_{-\infty}^{+\infty} e^{sx_{i,j}} g(x_{i,j})dx_{i,j}\right]\Bigg|_{s=0} \\ &= \frac{\partial^2}{\partial s^2}\left[\frac{W^{1}_{i,j}(s)}{W^{1}_{i,j}(0)}\right]\Bigg|_{s=0} + \frac{\partial^2}{\partial s^2}\left[\frac{W^{c}_{i,j}(s)}{W^{c}_{i,j}(0)}\right]\Bigg|_{s=0} \\ &= \frac{\partial^2}{\partial s^2}\left[\frac{W_{i,j}(s)}{W_{i,j}(0)}\right]\Bigg|_{s=0} \end{aligned} \tag{24}$$

So the fluctuation variance of quality gain-loss parameter $x_{i,j}$ transferred from WP node i to WP node j can be expressed as:

$$\begin{aligned} V[x_{i,j}] &= E(x^2_{i,j}) - E(x_{i,j})^2 \\ &= \frac{\partial^2}{\partial s^2}\left[\frac{W_{i,j}(s)}{W_{i,j}(0)}\right]\Bigg|_{s=0} - \left\{\frac{\partial}{\partial s}\left[\frac{W_{i,j}(s)}{W_{i,j}(0)}\right]\Bigg|_{s=0}\right\}^2 \end{aligned}$$

Theorem 5 can be proved.

4.4 Critical quality routes diagnosis and detection of dam concrete construction

In dam concrete construction gain-loss network, the minimum quality gain-loss is required on one hand, and the steady quality fluctuation is required on the other hand. $\theta_{ti\to tn}$ is selected in this paper as a indicator measuring the influence degree of project (separated item project, sub-project, unit project, etc.) quality from the route t. $\theta_{ti\to tn}$ is an integrated utility of average quality gain-loss $E(ti\to tn)$ and fluctuation variance $V(ti\to tn)$ from initial WP ti to the terminal WP tn in route t. $\theta_{ti\to tn}$ is composed of quality loss impact indicator $\theta^l_{ti\to tn}$ and quality gain-loss impact indicator $\theta^c_{ti\to tn}$ from the route t to the project, and it can be expressed as:

$$\theta_{ti\to tn} = \theta^l_{ti\to tn} + \theta^c_{ti\to tn} \tag{25}$$

The greater the route $\theta_{ti\to tn}$, the greater the impact on dam concrete construction quality, and the stronger its critical quality characteristic. In order to unify the measuring unit, the route critical quality indicator form is designed as below:

$$\begin{aligned}\theta_t = \theta_{ti\to tn} &= \alpha_l E_l(ti\to tn) + \beta_l\sqrt{V_l(ti\to tn)} \\ &+ \alpha_c E_c(ti\to tn) + \beta_c\sqrt{V_c(ti\to tn)}\end{aligned} \tag{26}$$

Where, α_l, β_l, α_c, $\beta_c>0$, $\alpha_l+\beta_l=1$, $\alpha_c+\beta_c=1$.

4.5 Critical quality WPs diagnosis and detection of dam concrete construction

Because quality gain-loss of dam concrete construction is an integrated effect of all WPs quality gain-loss in the construction network, quality gain-loss of each WP to the engineering can be calculated based on the route reverse derivation in network. Assuming the nodes $i\to j\to\cdots\to n$ are in turn connected WPs and n is the engineering terminal WP, the critical quality indicator ω_i of WP i to the engineering is expressed as:

$$\omega_i = \theta^l_{i\to n} - \sum_{v=1}^{d} p_{i,jv}\theta^l_{jv\to n} + \theta^c_{i\to n} - \sum_{v=1}^{d} q_{jv,i}\theta^c_{jv\to n} \tag{27}$$

Where, d is the number of branches between WP i and WP j, WP j is the external WP of i, $p_{i,j}$ is the quality loss transmission probability from WP i to WP j, and $q_{j,i}$ is the quality compensation transmission probability from WP j to WP i.

Demonstration: the quality loss from WP i to WP n is

$$\theta^l_{i\to n} = \omega^l_i + \omega^l_j + \text{L} \ + \omega^l_{n-1} + \omega^l_n = \omega^l_i + \sum_{v=1}^{d} p_{i,jv}\theta^l_{jv\to n}$$

so $\omega^l_i = \theta^l_{i\to n} - \sum_{v=1}^{d} p_{i,jv}\theta^l_{jv\to n}$.

For the same reason, we can get:

$$\omega^c_i = \theta^c_{i\to n} - \sum_{v=1}^{d} q_{jv,i}\theta^c_{jv\to n}$$

So, $\omega_i = \theta^l_{i\to n} - \sum_{v=1}^{d} p_{i,jv}\theta^l_{jv\to n} + \theta^c_{i\to n} - \sum_{v=1}^{d} q_{jv,i}\theta^c_{jv\to n}$

5. The Empirical Analysis

Summer dam concrete construction in the third phase of TGP is taken as an example to carry out empirical research. Dam concrete construction in summer mainly includes some WPs such as raw materials transportation, temperature-controlled concrete production, concrete conveying (tower-belt-crane, dump truck, cable crane, etc.), measurement and lofting, warehouse preparation, wind, water and electricity preparation, concrete pouring, warehouse closure, concrete curing and so on. Quality gain-loss transmission GERT network model of dam concrete construction in summer is shown in Fig. 7.

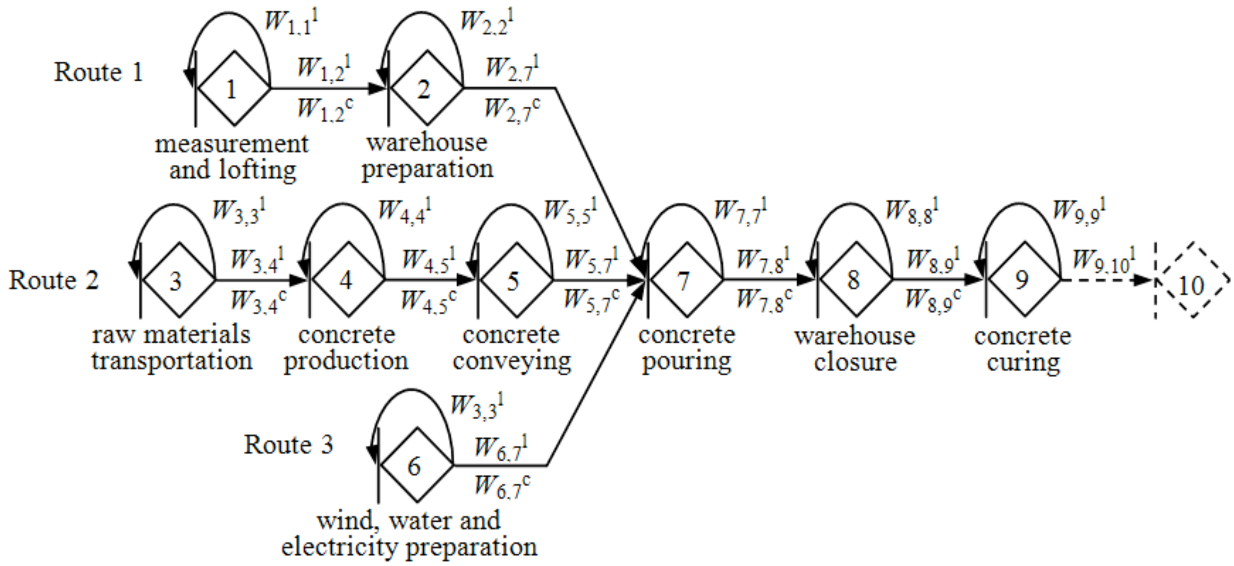

Fig. 7. Quality gain-loss transmission GERT network model of dam concrete construction in summer

According to the quality statistic tested by contractor, supervisor and the owner, each WP quality gain-loss value can be calculated by Eq. (8), (9) and (10). Parameter types can be estimated by curve fitting method and distribution parameters can be obtained by applying statistical analysis methods. Activity parameters table of quality gain-loss transmission GERT network is shown in Tab. 1.

Tab.1. Activity parameters table of quality gain-loss transmission GERT network

WP (i, j)	Probability $p_{i,j}$	Distribution $f(x)$/T RMB	Probability $q_{i,j}$	Distribution $g(x)$/T RMB
(1, 2)	0.9	N(0.1, 0.01)	1	N(-0.1, 0.01)
(1, 1)	0.1	-0.1	-	-
(2, 7)	0.8	N(0.15, 0.02)	0.4	N(-0.1, 0.01)
(2, 2)	0.2	-0.1	-	-
(3, 4)	0.7	N(0.2, 0.01)	1	N(-0.1, 0.05)
(3, 3)	0.3	-0.15	-	-
(4, 5)	0.8	N(1.2, 0.05)	1	N(-0.6, 0.01)
(4, 4)	0.2	-0.8	-	-
(5, 7)	0.8	N(1.2, 0.04)	0.5	N(-0.8, 0.02）
(5, 5)	0.2	-0.6	-	-
(6, 7)	0.9	N(0.5, 0.01)	0.1	N(-1.0, 0.02)
(6, 6)	0.1	-0.2	-	-
(7, 8)	0.95	N(1, 0.05)	1	N(-0.5, 0.02)
(7, 7)	0.05	-0.4	-	-
(8, 9)	0.9	N(0.1, 0.01)	1	N(-0.1, 0.01)
(8, 8)	0.1	-0.1	-	-
(9, 9)	0.1	-0.1	-	-
(9, 10)	0.9	N(0.2, 0.02)	-	-

5.1 Critical quality routes diagnosis and detection

Taking route 1 as an example, as per the above analysis, the equivalent transmission function between initial WP node 1 to terminal WP node 9 of route 1 is expressed as:

$$\begin{aligned} W_{1\to9}(s) &= W^{1}_{1\to9}(s) + W^{c}_{1\to9}(s) \\ &= \frac{W^{1}_{1,2}(s)W^{1}_{2,7}(s)W^{1}_{7,8}(s)W^{1}_{8,9}(s)W^{1}_{9,10}(s)}{(1-W^{1}_{1,1}(s))(1-W^{1}_{2,2}(s))(1-W^{1}_{7,7}(s))(1-W^{1}_{8,8}(s))(1-W^{1}_{9,9}(s))} \\ &\quad + W^{c}_{1,2}(s)W^{c}_{2,7}(s)W^{c}_{7,8}(s)W^{c}_{8,9}(s) \\ &= \frac{0.554\exp(1.55s+0.055s^2)}{(1-0.1\exp(-0.1s))^3(1-0.2\exp(-0.1s))(1-0.05\exp(-0.4s))} \\ &\quad + 0.4\exp(-1.1s+0.025s^2) \end{aligned} \tag{28}$$

Its moment generating function is:

$$\begin{aligned} M_{1\to9}(s) &= \frac{W_{1\to9}(s)}{W_{1\to9}(0)} = \frac{W^{1}_{1\to9}(s)}{W^{1}_{1\to9}(0)} + \frac{W^{c}_{1\to9}(s)}{W^{c}_{1\to9}(0)} \\ &= \frac{0.554\exp(1.55s+0.055s^2)}{(1-0.1\exp(-0.1s))^3(1-0.2\exp(-0.1s))(1-0.05\exp(-0.4s))} \\ &\quad + \exp(-0.8s+0.025s^2) \end{aligned} \tag{29}$$

Using Maple computing software, the parameters calculation of route 1 are as follows:

Average quality loss:

$$E_l(1\to9) = \frac{\partial M^{l}_{1\to9}(s)}{\partial s}\Big|_{s=0} = 1.471 \tag{30}$$

Quality loss fluctuation variance:

$$\mathrm{V}_1(1\to9) = \frac{\partial^2 M^{1}_{1\to9}(s)}{\partial s^2}\Big|_{s=0} - \{\frac{\partial M^{1}_{1\to9}(s)}{\partial s}\Big|_{s=0}\}^2 = 0.124 \tag{31}$$

Average quality compensation:

$$E_c(1\to9) = \frac{\partial M^{c}_{1\to9}(s)}{\partial s}\Big|_{s=0} = -0.800 \tag{32}$$

Quality compensation fluctuation variance:

$$V_c(1\to9) = \frac{\partial^2 M^{c}_{1\to9}(s)}{\partial s^2}\Big|_{s=0} - \{\frac{\partial M^{c}_{1\to9}(s)}{\partial s}\Big|_{s=0}\}^2 = 0.050 \tag{33}$$

In Eq. (33), it expresses the quality compensation caused by quality compensation fluctuation is -0.05. According to Eq. (26), the critical quality indicator of route 1 is: $\theta_1 = \alpha_l E_l(1\to9)+\beta_l V_l(1\to9)^{0.5}+\alpha_c E_c(1\to9)+\beta_c V_c(3\to9)^{0.5}=0.298$, where, $\alpha_l = \beta_l = 0.5$, $\alpha_c = 0.6$, $\beta_c = 0.4$. For the same reason, we can get $\theta_2 = 0.639$ and $\theta_3 = -0.06$. Since max $\{\theta_1, \theta_2, \theta_3\}=\theta_2$, so route 2 is the critical quality route with the maximum influence degree to the overall quality of concrete construction. Therefore, the contractor, supervisor and the owner must strictly control and actively improve the quality of route 2.

5.2 Critical quality WPs diagnosis and detection

Taking WP node 3—raw materials transportation as an example, the calculation process of the critical quality indicator ω_3 is as follows:

The quality loss influence degree indicator of route 3→9: $\theta^{l}_{(3\to9)} = \alpha_1 E_l(3\to9)+\beta_1 V_l(3\to9)^{0.5}=0.5\times3.445+0.5\times0.44=1.943$, quality compensation influence degree indicator of route 3→9: $\theta^{c}_{(3\to9)} = \alpha_2 E_c(3\to9)+\beta_2 V_c(3\to9)^{0.5} = -0.6\times2.1-0.4\times0.11 = -1.304$, the quality loss influence degree indicator of route 4→9: $\theta^{l}_{(4\to9)} = 1.903$, and quality compensation influence degree indicator of route 4→9: $\theta^{c}_{(4\to9)} = -1.224$. According to Eq. (27) we can get $\omega_3 = \theta^{l}_{(3\to9)} - p_{3,4}\theta^{l}_{(4\to9)} + \theta^{c}_{(3\to9)} - q_{4,3}\theta^{c}_{(4\to9)} = -0.04$. For the same reason, we can get $\omega_4=0.264$, $\omega_5=0.113$, $\omega_7=0.21$, $\omega_8=-0.013$ and $\omega_9=0.105$. Since max $\{\omega_3, \omega_4, \omega_5, \omega_7, \omega_8, \omega_9\}=\omega_4$, so the critical quality WP in route 2 is concrete production. Therefore, the contractor, supervisor and the owner must strictly control and actively improve the concrete production quality.

6. Conclusions

Dam concrete construction is a giant and complex project with huge engineering work, numerous WPs and high construction technical requirements. The construction process not only has the quality loss arising from quality fluctuation, but also gains quality compensation effect due to mutual cooperation and adaptation coupling between WPs. In view of that the quality compensation effect existing in production practice cannot be described by Taguchi's quality loss function, the concept of quality gain-loss function is presented in this paper. The calculation and transmission complexity of quality gain-loss affects to quality management of dam concrete construction. Based on the quality gain-loss function theory, a new quality gain-loss transmission model based on GERT network is constructed, and its corresponding algorithm is designed to diagnose and detect the critical routes and critical WPs in dam concrete construction network. A new quality management method for dam concrete construction is provided.

Quality gain-loss function with single characteristic and its transmission model are only presented in this paper, and quality gain-loss function with multivariate characteristics and its transmission model are valuable directions to further study. On the other side, the critical quality source diagnosis discussed in this paper is carried out on the basis of homology, and the critical quality routes and critical quality WPs diagnosis under the condition of different sources are also potential research directions to be conducted interestingly in the future.

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