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Quantitative Model of Multi-Subject Quality Responsibility in General Contracting Projects Based on Sailed Fish Optimizer

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Abstract: In order to address the issue of the quantitative allocation of quality responsibility among different subjects in engineering general contracting projects, this paper proposed a quantitative model (M-ResQu) for multi-subject quality responsibility allocation based on quality behavior classification criteria. Firstly, utility theory and game theory were used to establish a behavioral choice model for construction units and general contractors, investigating the quality behavioral choice mechanisms in the general contracting mode. Secondly, the sailed fish optimizer (SFO) was used to screen potential laws across 84 practical judicial cases and obtain the type coefficients of three types of quality risk behaviors: technical defects, non-compliance management and non-standard behaviors. Thirdly, a fuzzy mathematics theory was employed to establish the M-ResQu model for multi-subject quality responsibility allocation in general contracting mode. Finally, a simulation analysis was conducted to demonstrate the applicability of the M-ResQu model, and results suggested that it can provide a valuable quantitative tool for quality dispute resolution in the general contracting mode.

Keywords: project general contracting; subject of quality responsibility; quality responsibility; quality risk behavior; dispute settlement

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1. Introduction

Different organizations, both domestic and international, have offered varying interpretations of the definition of engineering general contracting. However, they do agree that it is characterized by the integration of design and construction. The definition provided by the Chinese government in the *Management Measures for Engineering General Contracting of Construction and Municipal Infrastructure Projects* defines engineering general contracting as a construction organization and implementation that is responsible for the overall process of engineering design, procurement, construction or design and construction, based on a contract signed with the construction unit, which bears all the responsibility for the quality, safety, construction period, and cost of the project. This definition of engineering general contracting includes not only the two mainstream modes of design–build (DB) and design–procurement–construction (EPC), but also other related derivative models. Scholars domestically and abroad have conducted a series of investigations and research on the theory and practice of the general contracting mode. Specifically, Takim et al. [1] conducted an empirical study on six public and private projects in Malaysia to investigate the concept of integrating development projects, establish the integral elements of the projects (social and technical), and propose a conceptual framework for improving the integration process of design–build (DB) projects. Apte and Bali [2] comprehensively analyzed risks in an industrial project contract through empirical research and identified a crucial tool for identifying and evaluating project risks—the Work Breakdown Structure (WBS). Liu et al. [3] studied the causal relationships between partnership relationships, design management, design capability, and EPC hydropower project performance, using a validated conceptual model based on data collected from a large-scale EPC hydropower project. The path analysis yielded insights that enhancing design management directly fosters the improvement in design management and design capability, which affects the quality of design and outcomes of hydropower projects. Zheng et al. [4] examined the impact of digitization on EPC construction projects using a combination of descriptive statistics and Survey-Based Exploratory Factor Analysis (SEFA). The SEFA results demonstrated the potential for digitization to improve both the cost and time performances of EPC projects. Peng [5] discussed risk control measures for highway EPC projects, proposing that risk boundaries and reasonable risk-sharing should be defined between the construction unit and the general contractor.

In recent years, there has been an increasing amount of research on engineering quality control in the general contracting mode, providing effective measures and suggestions for quality control under this mode. For example, Anon [6] suggested that the construction unit and contractor should establish an efficient quality management organization, formulate strict quality control and testing standards, and implement quality control in accordance with the requirements of the EPC contract. He [7] pointed out many types of quality problems in project quality management in practice and proposed the main measures to improve project quality management. In addition, Yang and Li [8] studied the relationship between interface and project quality in general contracting projects, and explored the causes of project interface and the significance of implementing project interface management. Wang [9], Pongpeng and Liston [10], and Yang and Ren [11] believed that a sound credit mechanism should be established as soon as possible in the construction industry to solve quality problems caused by the non-standard and dishonest behavior of contractors during project implementation. Based on the definition of the quality chain and the regularity of project quality formation, Xu and Ren [12] established the project quality chain under the general contracting system. Pang et al. [13] proposed a quality-cost linkage control implementation path to solve the linkage control challenges in the design and construction of residential construction projects under the general contracting model. Shen et al. [14] explored the core elements and operating mechanism of the EPC engineering quality supervision mechanism from the perspective of government engineering quality supervision through field research and in-depth interviews, and used constructionism grounded theory to encode interview data substantively. Luo [15], Yang [16], and Lu [17] analyzed the changes in the quality status and responsibility of the general contractor and the changes in its quality behavior, studied the unique laws and characteristics of contractor quality behavior under the general contracting system, and proposed the engineering quality supervision system and its operating mechanism under the general contracting system.

In the construction industry, the majority of accidents, around 80–90%, are caused by unsafe behavior [18]. This statistic suggests that inadequate quality behavior is the primary cause of quality-related issues and is also the major factor in determining the responsibilities of the different subjects. Hence, studying subject quality risk behavior is crucial to resolving quality disputes. Positive quality behavior refers to legal and lawful conduct by construction market players in adherence with national regulations, while negative quality behavior refers to instances where entities prioritize self-interests, making use of fragmented information and information asymmetry, resulting in harm to other subjects and even compromising project quality [19]. Quality risk conduct, in the case of quality responsibility subjects, suggests counter-organizational behavior, which means that such behavior hinders the achievement of engineering quality objectives [20]. Chen et al. [21] systematically categorized quality risk behavior into three types—technical defect, illegal and non-compliant, and non-standard risks. Existing scholars have studied the relationship between quality risk behavior and quality defects, and proposed a quality responsibility division model dependent on such behavior [22].

In order to solve the quality dispute better, the quantitative responsibility method is the focus of domestic and foreign experts. Hu et al. [23] and Xie et al. [24] have made a great deal of discussion on the relevant factors of responsibility capability and made a preliminary exploration on quantitative evaluation. Hu et al. [25] exploited an Expert System for Assessment of Legal Capacity (ESALC) for professionals to use as AIDS in forensic expertise. Zeng et al. [26] used the scale to demonstrate the identification process of the causative force of the liability for medical damage and quantify the causative force of the liability for medical damage. Wang et al. [27] proposed a quantitative model applicable to the division of legal liability for ship collisions based on AHP. Zhang et al. [26] adopted the expert scoring method (Delphi method) to determine the influence degree of each influencing factor based on the analysis of the accident causes so as to calculate the cumulative impact degree of the responsible person to measure the responsibility. Chen et al. [28] proposed the quantification model of multi-agent responsibility for project quality under the traditional design–bid–build (DBB) based on the fuzzy mathematics theory. Available studies on the quantification of quality responsibility mainly focus on the traditional design–bid–build (DBB). However, the quality behavior choice for engineering construction entities and the quantification-sharing mechanism of quality responsibility will be different under different construction modes; therefore, available quantitative analysis research mainly revolving around the traditional design-bid-build (DBB) mode cannot be well apt to satisfy the general contracting mode requirements. Moreover, in practice, many problems are subject to various constraints, so solving a problem often requires solving it to its optimal solution. For the risk liability quantification model proposed in this paper, it needs to obtain the optimal parameters of the quantification model, so as to achieve the quantified liability of different responsible subjects according to the input of the actual case. Recently, there have been many optimization methods, such as particle swarm optimization, colony optimization algorithm, and genetic algorithms [29]. However, because numerous algorithms have their application ranges, researchers have attempted to propose some new optimization methods for solving wide range areas because the existing methods are only beneficial for some specific problems. As for new optimization methods, sailfish optimizer (SFO) [29] is very representative because SFO can achieve high exploration, exploitation and convergence speed on the majority of actual problems, and it can be utilized in this paper. Based on the problems of current research, the contributions of this paper can be itemized as follows:

(1) Investigating the model of quality behavior choice for engineering construction entities under the general contracting mode, as well as analyzing the mechanism of quality behavior choice for such entities.
(2) Utilizing the sailed fish optimizer (SFO) to extract the coefficient values of the three types of quality risks for engineering construction subjects under the general contracting mode.
(3) Employing the fuzzy mathematics theory to establish the M-ResQu mathematical model, providing a scientifically and reasonably sound method for quantitatively dividing multi-subject quality responsibilities under the general contracting mode, which has been proven to be beneficial in the resolution of multi-subject quality disputes in engineering projects.

2. Classification and Choice of the Quality Behavior of Project Construction Subjects under the General Contracting Mode

Engineering quality behavior refers to an organizational behavior that can be divided into positive and negative forms, depending on their contribution to the attainment of quality objectives [30]. In particular, quality risk behavior from the party responsible for quality management in an engineering project represents a type of negative organizational behavior which impedes the achievement of engineering quality objectives. When implementing the general contracting mode, the participating parties become the most influential and dynamic factors that shape the quality of the construction project. These parties primarily include construction units, general contractors, and supervisory units. Thus, their quality risk behaviors are the direct influencing factor of the project quality problems.

2.1. Quality Risk Behavior Classification of the Project Construction Subject under the General Contracting Mode

Quality issues in completed construction projects can be caused either by one quality responsibility subject's implementation of one or more quality risk behaviors or by multiple quality responsibility subjects' joint implementation of a series of quality risk behaviors. Different forms of quality risks have significant impacts on engineering quality. Under the general contracting mode, the construction unit and supervisory unit primarily undertake the project's construction management and supervision duties. Their main behaviors implemented in the name of management may exhibit more violations of management or non-standard quality risk behaviors when reversed. The general contractor provides integrated delivery services of design, procurement, and construction to offer not only technical but also management responsibilities. Therefore, its risk behaviors of reverse demonstration include not only technical-defect quality risk behaviors, but also violations of management and non-standard management behaviors.

This study classified the quality risk behaviors of three subjects, namely the construction unit, the general contractor, and the supervisory unit, under the general contracting mode, based on the performance and behavioral characteristics of quality risk behaviors displayed by the project participants. The classification was made according to the classification research results of quality risk behaviors in references [20–22]. These quality risk behaviors were grouped into three categories: technical-defect-type quality risk behaviors, non-compliance management quality risk behaviors, and non-standard quality risk behaviors. For more details, refer to Table 1.

Table 1. Classification of quality risk behaviors of project construction subjects under the general contracting mode.

Classification Type of Quality Risk Behaviors	Code of Type	Construction Unit	General Contractor	Supervisory Unit
Technical-defect-type quality risk behavior	β_S	×	√	×
Non-compliance management quality risk behaviors	β_B	√	√	√
Non-standard quality risk behaviors	β_P	√	√	√

2.2. Quality Behavior Choice of Project Construction Subject under General Contracting Mode

Each participant in the general contracting mode has a strong inherent driving force for high returns and low costs (e.g., reducing investment/cutting costs), low risks (avoiding quality responsibility), and high standards (high-quality standards under low investment), from the perspective of rational agents. Therefore, these participants naturally choose behavioral methods that favor their interests in achieving goals. To some extent, the participants' motivation for choosing quality risk behaviors is a significant obstacle to improving construction project quality. Therefore, exploring the behavior choice mechanism and motivation of participants under the general contracting mode is vital to evaluating the quality risk behavior choice of participants. However, it should be noted that the discussion on quality behavior choice mainly focuses on the construction unit and the general contractor since the supervisory unit assists the construction unit to fulfill relevant supervision and management responsibilities and performs a similar supervisory role with the construction unit.

2.2.1. Quality Behavior Choice of Construction Unit under the General Contracting Mode

"Positive quality behavior" and "quality risk behavior" are terms to express the construction unit's choice of behaviors that either facilitate or pose a threat to the accomplishment of quality objectives during the construction management process. Administrative supervisory agencies prioritize cost effectiveness and quality safety in regulating construction projects. They seek to minimize supervision intensity and cost while maximizing the supervision effect. Similarly, construction units prioritize maximizing the economic benefit of engineering investment while choosing favorable quality behaviors. A game theory model that is based on supervision can establish a mathematical model to assess the correlation between administrative supervisory regulation intensity and the construction unit's quality behavior. The supervisory agency and construction unit's payment matrix can be observed in Table 2, while Table 3 lists and details parameter explanations.

Table 2. Payment matrix of the administrative supervisory unit and construction unit.

Payment Matrix		Construction Unit	
		Quality Risk Behavior (*r*)	**Positive Quality Behavior (1-*r*)**
Administrative supervisory unit	Inspection (s)	$-b + f(m)$, $-f(m)$	$-b$, 0
	Non-inspection ($1 - s$)	$-a$, a	0, 0

Table 3. Parameter description of the game model between the administrative supervisory unit and construction unit.

Code	Descriptions
a	Benefit from the quality risk behavior of construction units
b	Inspection cost of the administrative supervisory unit
$f(m)$	Penalties incurred by the construction unit in carrying out quality acts
s	The probability of a random inspection by the administrative supervisory unit
r	The probability of the construction unit choosing quality risk behavior

It should be noted that when $-b + f(m) \leq -a$, it is not necessary for the supervisory unit to conduct an inspection because the benefit of inspection for the administrative supervisory unit is less than the benefit of non-inspection. Assuming $b > a + f(m)$, $s = 0$, a supervisory game model can be established to determine the construction unit's expected utility function E. This results in Equation (1).

$$E = r[(-f(m)s + a(1-s)] + (1-r)[0 \cdot s + 0 \cdot (1-s)] = -ars - f(m)rs + ar \quad (1)$$

Taking the partial derivative of r results in the stationary point: $s^* = a/[f(m) + a]$. Based on this, further analysis can be conducted on the construction unit's expected utility function.

E_2 shows a monotonic increase when $s^* < a/[f(m) + a]$ and $\partial E_2/\partial r > 0$; at $r = 1$, it reaches a maximum point of $-as - f(m)s + a$ for the construction unit. Under these circumstances, choosing a quality risk behavior could be an optimal strategy for the construction unit, and $f(m) < a(1-s)/s$ should be present when the expected utility of the construction unit is >0. These factors highlight the correlation between punishment for quality risk behavior and the expected utility of construction units. Upon choosing quality risk behaviors, construction units may experience a higher expected utility. When it comes to $a(1/s - 1)$, the reduction in supervisory inspections as a deterrence for quality risk behaviors could only be effective if $f(m)$, the cost of punishment, is increased. In practical applications, supervisory inspections should be matched with the standards of penalties prescribed by supervision authorities. Alternatively, E_2 decreases monotonically at $s^* > a/[f(m)+a]$, $\partial E_2/\partial r < 0$, and at r = 0, the expected utility function (E_2) of the construction unit maximizes at 0, indicating that the construction unit would not choose quality risk behaviors under these conditions.

2.2.2. Quality Behavior Choice of the General Contractor under the General Contracting Mode

The primary objective of a project general contractor is to maximize their own interests, prioritizing positive and quality risk behaviors that result in long-term benefits. The positive quality behaviors involve practices that enhance the engineering quality during the construction process, while the quality risk behaviors refer to practices that negatively impact the engineering quality. The choice of these behaviors depends on several factors, including the contractor's pursuit of high returns, low risk, and a good market reputation. These factors also influence their behavior choice to decrease the penalties imposed by supervisory authorities and to evade quality responsibilities. To achieve their goal of maximizing profits, the project's general contractor measures future profits as present equivalent benefits using a discount rate that suits them. The profitability function of the contractor is established, where the necessary parameters are defined, as shown in Table 4.

Table 4. Description of related parameters of the income function of the general contractor of the project.

Code	Descriptions
R	The normal income that the general contractor can get according to the general contract
a	The effort degree of the general contractor to choose positive quality behaviors (greater than 0)
b	Cost function of the general contractor (greater than 0)
p_1	The probability that the general contractor obtains project quality reward for implementing positive quality behaviors
p_2	The probability of detecting the quality risk behavior implemented by the project general contractor, i. e. the level of supervision exercised by the construction unit or supervisory unit.
$I(m)$	The severity of quality risk behavior implemented by the general contractor of the project
C_1	The cost to be paid by the general contractor to choose the positive quality behavior, $C_1 = ba^2/2$
C_2	The cost paid by the general contractor to choose quality risk behavior, $C_2 = bI^2(m)/2$
π	The factor that the general contractor obtains extra income (greater than 0)
M	Additional benefits obtained by the general contractor of the project, $M = \pi I(m)$
v	The reward equally distributed to the general contractor of the project in the current and future projects
w	Penalty received by the general contractor for implementing quality risk behavior
η	The benchmark discount rate applicable to the general contractor of the project
T	Income period of the general contractor of the project
Q	The conversion coefficient of equivalent earnings converted by the discount rate of the general contractor in the T income period, $Q = \frac{1-\eta^T}{1-\eta}$
L_1	The income of the general contractor's choice of positive quality behavior
L_2	The income of the general contractor's choice of quality risk behavior
$\triangle L$	The utility difference between positive behavior and quality risk behavior of the general contractor

Based on utility theory, the income function of the general contractor's positive quality behavior can be constructed as follows:

$$L_1 = R - C_1 + ap_1vQ \tag{2}$$

Similarly, the income function of the general contractor's choice of quality risk behavior is:

$$L_2 = R + M - C_2 + I(m)p_2wQ \tag{3}$$

Utility difference between positive behavior and quality risk behavior of the general contractor is:

$$\triangle L = C_2 - C_1 - M + [ap_1v - I(m)p_2w]Q \tag{4}$$

By taking the first-order derivative of (2) with respect to a, the optimal effort level for the construction general contractor to select positive behavior, maximizing their profits, can be obtained as $a^* = p_1vQ/b$. Similarly, by taking the first-order derivative of (3) with respect to $I(m)$, the optimal level of quality risk behavior choice by the construction general contractor can be calculated as $I^*(m) = (\pi + p_2wQ)/b$. Substituting values for a^* and $I^*(m)$, we can derive:

$$L_1(a^*) = R + \frac{(p_1vQ)^2}{2b} \tag{5}$$

$$L_2(I^*(m)) = R + \frac{(\pi + p_2wQ)^2}{2b} \tag{6}$$

$$\triangle L(a^*, I^*(m)) = \frac{(p_1vQ)^2 - (\pi + p_2wQ)^2}{2b} \tag{7}$$

(1) When $\triangle L(a^*, I^*(m)) = 0$, it represents the boundary value where the project general contractor will select zero quality risk behavior and zero positive quality behavior. Based on Equation (8), we can derive Equation (9):

$$p_1vQ = \pi + p_2wQ \tag{8}$$

For the convenience of discussion, the equivalent benefits obtained through discounting are not considered, so we set $Q = 1$. Consequently, Equation (9) can be simplified as:

$$p_1v = \pi + p_2w \tag{9}$$

(2) When $\triangle L(a^*, I^*(m)) > 0$, a rational project general contractor will inevitably opt for positive quality behavior, and this requires that:

$$v > \frac{\pi + p_2w}{p_1}, p_2 < \frac{p_1v - \pi}{w}, w < \frac{p_1v - \pi}{p_2} \tag{10}$$

(3) When $\triangle L(a^*, I^*(m)) < 0$, a rational project general contractor will inevitably opt for quality risk behavior, and this requires that:

$$v < \frac{\pi + p_2w}{p_1}, p_2 > \frac{p_1v - \pi}{w}, w > \frac{p_1v - \pi}{p_2} \tag{11}$$

The following conclusions can be drawn through a model construction and results discussion:

(1) When $\triangle L(a^*, I^*(m)) = 0$, it represents the boundary value where the project general contractor will select zero quality risk behavior and zero positive quality behavior. To ensure that the project general contractor makes behavior choices that are favorable to engineering quality, it is necessary to ensure $\triangle L(a^*, I^*(m)) > 0$.

(2) The behavior of project general contractors in terms of quality is strongly influenced by several factors: the level of supervision provided by the construction unit, the

incentives offered by the construction unit for achieving good engineering quality, and the severity of penalties for engaging in quality risk behavior. Insufficient supervision, inadequate rewards for good engineering quality, and lenient penalties for quality risk behavior can create a situation where project general contractors may decide to engage in risks that compromise the quality of their work.

(3) The level of supervision by the construction unit, the severity of penalties for quality risk behavior, and the additional benefits for engaging in such behavior (represented by π) are positively correlated. In other words, the greater the additional benefits for quality risk behavior, the stronger the tendency for project general contractors to engage in such behavior. In such cases, the construction unit may adopt strategies such as intensifying supervision or increasing penalties for the general contractor's quality risk behavior.

(4) In order to effectively control the quality behavior of project general contractors, the supervision, incentives for quality performance, and penalties for quality risks imposed by the construction unit should be reasonably balanced and coordinated. Solely elevating the level of supervision, incentives, and penalties may prompt project general contractors to enhance their quality performance; however, this approach entails a huge cost that is not economically viable.

3. Optimization of the Quality-Risk-Behavior-Type Coefficient under the General Contracting Mode

3.1. Theory of Sailed Fish Optimizer

The sailed fish optimizer (SFO) is a heuristic swarm intelligence algorithm proposed by Shadravan et al. [23] in 2019. It has been inspired by a group of hunting sailed fish, and mimics the process of these fish during their hunting activities. In nature, sailed fish hunt in groups, and their hunting process can be mathematically modeled as follows:

(1) Alternate attack

Sailed fish do not attack from top to bottom or from right to left. Instead, they can attack in all directions within a reduced circle. Therefore, in the search for the best solution in a spherical space, sailed fish update their position. The position update of the sailed fish is represented by the following Equation (12):

$$X^i_{\text{newSF}} = X^i_{\text{elitesF}} - \lambda_i \times \left(\text{rand}(0,1) \times \left(\frac{X^i_{\text{elitesF}} + X^i_{\text{injuredS}}}{2}\right) - X^i_{\text{oldSF}}\right) \quad (12)$$

where X^i_{elitesF} represents the best position of the sailed fish at the current iteration i, X^i_{injuredS} represents the best position of the sardines at the current iteration i, and X^i_{oldSF} represents the current position of the sailed fish at the current iteration i. The position coefficient λ_i is defined as follows:

$$\lambda_i = 2 \times \text{rand}(0,1) \times PD - PD \quad (13)$$

where PD stands for the density of prey group, expressed by the following expression:

$$PD = 1 - (N_{SF}/(N_{SF} + N_S)) \quad (14)$$

where N_{SF} and N_S represent the numbers of swordfish and sardines, respectively.

(2) Prey capture

During the hunting process, the attacking power of sailed fish weakens as time elapses. The reduction in the energy stored in the prey's body due to frequent and intense attacks leads to a loss in their ability to escape, culminating in its capture. Consequently, the position updating method for the sardines during this stage is as follows:

$$X^i_{\text{newS}} = r \times \left(X^i_{\text{elitesF}} - X^i_{\text{oldS}} + AP\right) \quad (15)$$

where X^i_{elitesF} represents the best position of the sailed fish at the current iteration i, X^i_{oldS} represents the current position of the sardines at the current iteration i. r is a random number in [0, 1]. AP is the attack capability of sailed fish under the current iteration number:

$$AP = A \times (1 - (2 \times I_{\text{tr}} \times \varepsilon)) \tag{16}$$

In this Equation, A represents the attacking intensity and ε represents the intensity control coefficient, where A is linearly reduced to 0 by default. To balance the exploration and exploitation capabilities of the algorithm, the algorithm updates all sardines using Equation (4) when $AP > 0.5$, and selectively updates some sardines' positions when $AP < 0.5$. The number of individuals and dimensions for updating are determined using α and β.

$$\alpha = N_S \times AP \tag{17}$$

$$\beta = d_i \times AP \tag{18}$$

where α represents the number of sardines to be updated and β represents the number of dimensions to be updated.

(3) Position replacement

If the fitness value of the optimal sardine is better than that of the sailed fish, a replacement is generated and the sardine individual is deleted.

$$X^i_{SF} = X^i_s \qquad \text{if } f(S_i) < f(SF_i) \tag{19}$$

3.2. Type Coefficient Optimization Method

The coefficients of the quality risk behavior types required for Table 1 were obtained by using the sailed fish optimizer to optimize and extract the coefficients based on case sources from previous research results [22]. The construction of an appropriate fitness function is the key factor in applying the sailed fish optimizer. This paper employed the absolute error for this purpose, with the expression shown in Equation (20):

$$F = \sum_{j=1}^{J} \sum_{u=1}^{B} \left| W^L_{ju} - W^l_{ju} \right| \tag{20}$$

where u represents the number of the subject involved, B represents the maximum value of the subject involved, W^L_{ju} represents the true responsibility ratio of the u-th unit of the j-th sample, and W^l_{ju} represents the estimated responsibility ratio of the u-th unit of the j-th sample.

After establishing the fitness function, the specific process for optimizing the type coefficients is comprised of the following steps:

(1) Collecting samples of subjects involved in the case and obtaining the actual responsibility ratios of each unit in the samples.
(2) Constructing the target search space of the optimization algorithm by utilizing the sailed fish optimizer through the use of the type coefficients.
(3) Initializing the sailed fish population, position coefficients, and density of prey group.
(4) Calculating the fitness values of the sailed fish and sardines, and recording the optimal fitness value and its position. The optimal fitness value represents the minimum value in the fitness.
(5) Updating the positions of the sailed fish and sardines, calculating the values of α and β if the AP is less than 0.5, and updating the positions of some sardines. If not, updating the positions of all sardines.
(6) Replacing the positions of the sardines and sailed fish, calculating the value of Equation (20), and recording the minimum fitness value and corresponding position.
(7) Evaluating whether the iterative stop condition is met. If the condition is met, then the optimization results are produced; otherwise, the process repeats from step (4).

3.3. Analysis of the Type Coefficient Optimization Results

As reported in the existing literature [31], it is observed that different values of the parameter might yield different results. Hence, according to the theoretical foundations of sailed fish optimizer (SFO), various factors, including the size of the sailed fish population, the magnitude of attack intensity, density control coefficients, density of prey group, and the number of iterations significantly influence SFO performance. The population size stands as the most vital variable since the increased population size raises the chances of achieving optimal outcomes and may determine the higher probability of the global optima [32]. However, a large population size can slow down the algorithm's computational speed. Consequently, this study initiated an experiment to identify the optimal population size.

Experiment 1: By sequentially changing the particle population size to 10, 100, 500, 1000, 1500, and 2000, with a maximum iteration of 200, an attack intensity of 4, a density control system of 0.00001, and a density of prey group of 0.7, we obtained the iterative graph of the algorithm for different population sizes, as presented in Figure 1.

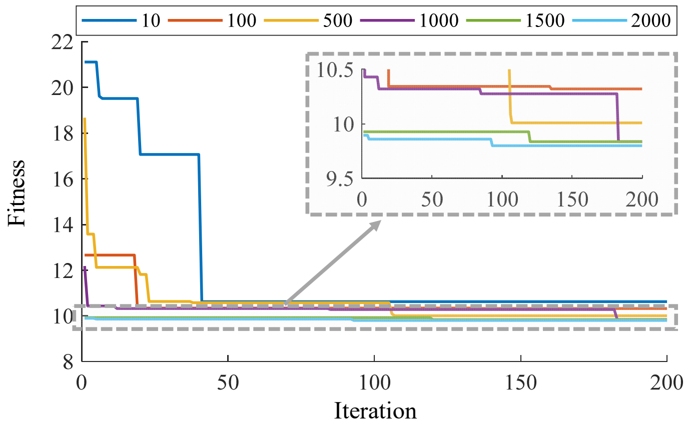

Figure 1. SFO iterations in different populations.

Based on Figure 1, it is evident that higher population sizes decrease the fitness value, particularly during the initial iteration period while the rate of decline of fitness value lessens with an increase in the population size. However, increasing the population size indiscriminately does not further lower the fitness value. For example, comparing the iterative curves for population sizes of 1500 and 2000, the difference between the minimum values is minimal. For this reason, a population size of 1500 was chosen in this paper.

Figure 1 indicates a decrease in the fitness value of the function with an increase in the iteration count. Hence, to examine the effect of the iteration count on algorithm performance, we conducted Experiment 2.

Experiment 2: The population size was 1500, the attack intensity was set at 4, and the intensity control coefficient was 0.00001. We sequentially tested the maximum iteration counts of 20, 200, 600, and 800, as shown in Figure 2, with a density of prey group of 0.7. Figure 2 demonstrates that as the iteration count increases, the fitness value decreases.

Nevertheless, no significant decrease was observed in the fitness value when the iteration count was increased from 600 to 800. Therefore, we set the maximum iteration number to 600 in this study.

Experiment 3 examined the influence of different attack intensities on algorithm performance after the population size and maximum iteration count were determined.

In Experiment 3, the population size remained at 1500, maximum iteration count at 600, intensity control coefficient at 0.00001, and the density of prey group at 0.7. Attack intensities of 1, 2, 4, and 6 were considered, and the algorithm's iteration graph under different circumstances is presented in Figure 3.

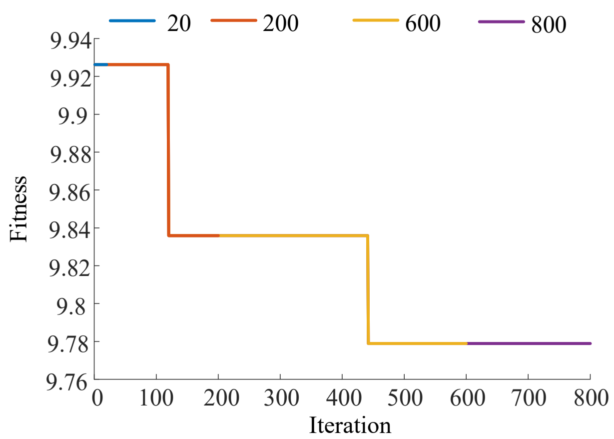

Figure 2. SFO iteration in different iterations.

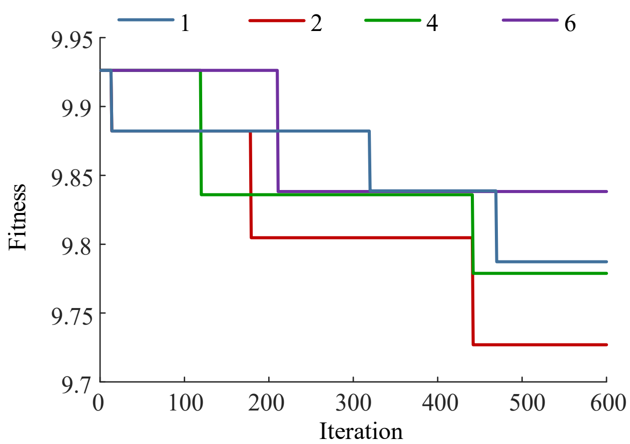

Figure 3. SFO iterations in different attack intensities.

The depicted figure shows that the fitness value fails to decrease as the attack intensity increases. Excessively high attack intensities may increase the fitness value. Therefore, 2 was chosen as the optimal attack intensity in this paper.

Experiment 4 was conducted with a population size of 1500, a maximum iteration count of 600, an attack intensity of 2, an intensity control coefficient of 0.00001, and densities of prey groups of 0.1, 0.3, 0.5, and 0.7. Figure 4 illustrates the algorithm's iteration graph under different attack intensities.

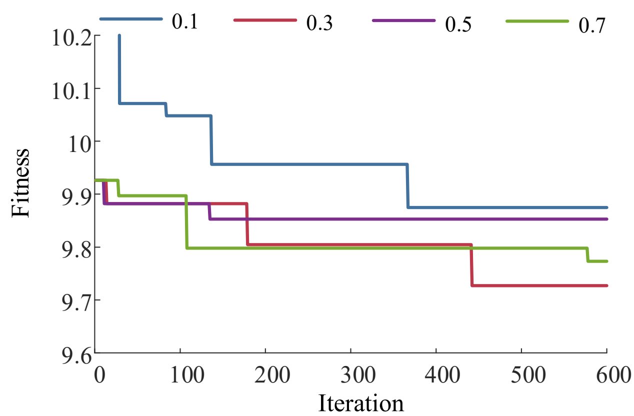

Figure 4. SFO iterations in different densities of prey groups.

Figure 4 indicates that there is no linear relationship between density of prey group and fitness value, and excessively high or low prey densities do not result in lower fitness values. Therefore, a density of prey group of 0.3 was selected in this study.

Experiment 5 was conducted with a population size of 1500, a maximum iteration count of 600, an attack intensity of 2, and a density of prey group of 0.3. The intensity control coefficient varied between 0.00001, 0.001, and 0.1, resulting in different iteration graphs for each attack intensity, as shown in Figure 5.

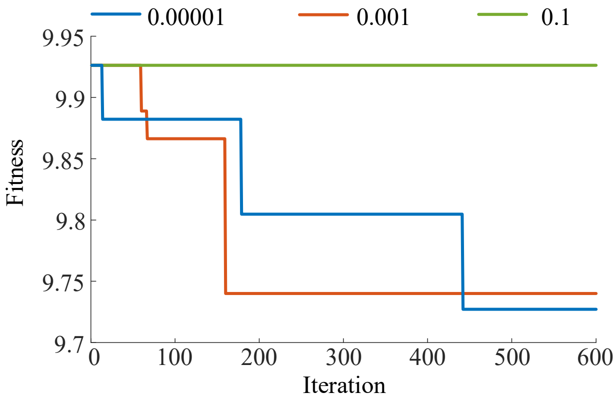

Figure 5. SFO iterations in different intensity control parameters.

The results indicate that decreasing the intensity control coefficient leads to lower fitness values. Therefore, an intensity control coefficient of 0.00001 was selected for this study.

Based on the samples and experiments using the proposed sailed fish optimizer, it is observed that the algorithm is capable of optimizing the target function as intended. At convergence, the optimal variables, represented by Equation (21), correspond to the coefficient values of technical-defect-type quality risk behaviors, non-compliance management quality risk behaviors, and non-standard quality risk behaviors, respectively.

$$(\mathrm{M}_{\ \mathrm{SFO}})^{\mathrm{T}} = (0.6003,\ 0.3120,\ 0.0877)^{\mathrm{T}} \tag{21}$$

4. The Quantitative Responsibility Model (M-ResQu) of the Project Construction Subject under the General Contracting Mode

Various types of risky behavior have different levels of causal impact on engineering quality deviations. These impacts can serve as evaluation indicators for the causal force domain. Additionally, the severity of quality risk behavior can be used to assess the behavior subject's degree of fault. Based on previous research [28], Equations (22) and (23) can be formulated, respectively, to quantify the engineering quality responsibility framework and calculate the quality responsibility ratio.

$$\left(\left\{S_{\mathrm{g}}^{1}, S_{\mathrm{g}}^{2}, \cdots, S_{\mathrm{g}}^{K}\right\}, \left\{B_{\mathrm{g}}^{1}, B_{\mathrm{g}}^{2}, \cdots, B_{\mathrm{g}}^{K}\right\}, \left\{P_{\mathrm{g}}^{1}, P_{\mathrm{g}}^{2}, \cdots, P_{\mathrm{g}}^{K}\right\}\right)\begin{pmatrix}\beta_S \\ \beta_B \\ \beta_P\end{pmatrix} = k_{\mathrm{g}} \tag{22}$$

$$Z_{\mathrm{g}} = \frac{k_{\mathrm{g}}}{\sum_{\mathrm{g}=1}^{N} k_{\mathrm{g}}} \tag{23}$$

Equations (22) and (23) above satisfy $S_{\mathrm{g}}^{K} \in [0,1]$, $B_{\mathrm{g}}^{K} \in [0,1]$, $P_{\mathrm{g}}^{K} \in [0,1]$, and $\sum_{\mathrm{g}=1,K=1}^{\mathrm{g}=N,K=M} S_{\mathrm{g}}^{K} + B_{\mathrm{g}}^{K} + P_{\mathrm{g}}^{K} = 1$; and quality-risk-type sets $\beta_S \in [0,1]$, $\beta_B \in [0,1]$, $\beta_P \in [0,1]$, $\beta_S + \beta_B + \beta_P = 1$, and $\beta_S > \beta_B > \beta_P$.

In the project general contracting mode, the subjects involved are the construction unit, project general contractor, and supervisory unit. By utilizing Equations (22) and (23), a responsibility analysis model for each of these entities can be developed. Specifically, we denote the construction unit as j, project general contractor as g, and supervisory unit as m.

Since the construction unit/supervisory unit does not exhibit the technical-defect-type quality risk behavior, $\left\{S_j^1, S_j^2, \cdots, S_j^K\right\} = 0$. Their accountability is expressed by Equations (24) and (25), respectively.

$$\left(0, \left\{B_j^1, B_j^2, \cdots, B_j^K\right\}, \left\{P_j^1, P_j^2, \cdots, P_j^K\right\}\right)\begin{pmatrix} 0 \\ \beta_B \\ \beta_P \end{pmatrix} = k_j \tag{24}$$

$$\left(0, \left\{B_m^1, B_m^2, \cdots, B_m^K\right\}, \left\{P_m^1, P_m^2, \cdots, P_m^K\right\}\right)\begin{pmatrix} 0 \\ \beta_B \\ \beta_P \end{pmatrix} = k_m \tag{25}$$

As project general contractors exhibit technical-defect-type quality risk behaviors, non-compliance management quality risk behaviors, and non-standard quality risk behaviors simultaneously, their accountability can be established using Equation (26).

$$\left(\left\{S_g^1, S_g^2, \cdots, S_g^K\right\}, \left\{B_g^1, B_g^2, \cdots, B_g^K\right\}, \left\{P_g^1, P_g^2, \cdots, P_g^K\right\}\right)\begin{pmatrix} \beta_S \\ \beta_B \\ \beta_P \end{pmatrix} = k_g \tag{26}$$

When the construction unit (j), project general contractor (g), and supervisory unit (m) each perform a series of quality risk behaviors that result in deviations from engineering quality standards, a multi-subject quality responsibility allocation model for the project general contracting mode, denoted as M-ResQu, can be constructed using Equation (27). The formula used to calculate the responsibility ratio of each participating entity in the project general contracting mode is presented in Equation (28).

$$M - ResQu = \begin{cases} \left(0, \left\{B_j^1, B_j^2, \cdots, B_j^K\right\}, \left\{P_j^1, P_j^2, \cdots, P_j^K\right\}\right)\begin{pmatrix} 0 \\ \beta_B \\ \beta_P \end{pmatrix} \\ \left(\{S_g^1, S_g^2, \cdots, S_g^K\}, \{B_g^1, B_g^2, \cdots, B_g^K\}, \{P_g^1, P_g^2, \cdots, P_g^K\}\right)\begin{pmatrix} \beta_S \\ \beta_B \\ \beta_P \end{pmatrix} \\ \left(0, \{B_m^1, B_m^2, \cdots, B_m^K\}, \{P_m^1, P_m^2, \cdots, P_m^K\}\right)\begin{pmatrix} 0 \\ \beta_B \\ \beta_P \end{pmatrix} \end{cases} \tag{27}$$

$$\begin{pmatrix} \text{Construction unit } j \\ \text{General contractor g} \\ \text{Supervisory unit } m \end{pmatrix} = \begin{pmatrix} \frac{k_j}{k_j + k_g + k_m} \\ \frac{k_g}{k_j + k_g + k_m} \\ \frac{k_m}{k_j + k_g + k_m} \end{pmatrix} \tag{28}$$

5. Simulation Calculation and Verification of the M-ResQu Model

5.1. Modeling and Calculation

In the project general contracting mode, the subjects involved are the construction unit, the general contractor, and the supervisory unit. Quality disputes arising from quality problems mainly pertain to the interactions between the construction unit (A), the general contractor (C), and the supervisory unit (B). Consequently, two real-world engineering quality dispute cases consisting of two-party (AC) and three-party (ABC) responsible parties were chosen as the model validation cases, denominated as EPC-Subject II and EPC-Subject III, correspondingly. The T-value of (M_{SFO}) represents the coefficient for the three types of quality risk behaviors: technical defect, non-compliance management, and non-standard behavior. In cases where one type of quality risk behavior is not involved or only two types of quality risk behavior exist, the two types of risk behaviors should undergo normalization. The outcomes are detailed in Table 5.

Table 5. Type coefficient values of different groups.

Normalized Group I		Normalized Group II		Normalized Group III	
Technical-Defect Type	**Non-Compliance Management Type**	**Technical-Defect Type**	**Non-Standard Type**	**Non-Compliance Management Type**	**Non-Standard Type**
0.6580	0.3420	0.8725	0.1275	0.7806	0.2194

For instance, in the validation case EPC-Subject III, all subjects involved in the project, namely the construction unit, supervisory unit, and general contractor, executed one or more types of quality risk behaviors, leading to notable quality deficiencies in the basement flooring of the relevant case. Table 6 presents an exhaustive catalogue of the quality risk behaviors of the aforementioned subjects, as well as their respective categories of risk behaviors.

Table 6. Summary of quality risk behaviors of each responsible subject in EPC-Subject III.

Types	Specific Quality Risk Behaviors Occurred	Responsible Subject
Technical-defect type	Failing to design according to the mandatory standards for engineering construction	General contractor
	Construction not according to design drawings	General contractor
Non-compliance management type	Illegal subcontracting	General contractor
	Failing to perform supervision duties in accordance with laws and regulations, relevant technical standards, design documents and construction contract	Supervisory unit
	The construction unit forces the general contractor to bid below cost	Construction unit

Simulation analysis results show that the severity of the general contractor's (C) quality risk behaviors for violation management is significantly more severe than that of the supervisory unit (B), while the severity of quality risk behaviors of the construction unit (A) falls between "very severe" and "somewhat severe". The general contractor's (C) quality risk behaviors are labelled as "somewhat severe" in comparison to those of the construction unit (A). Referring to the method presented in reference [21] to determine the judgment matrix and calculate the judgment coefficient of the non-compliance management quality risk behavior set using simulation analysis, the results are tabulated in Table 7.

Table 7. Judgment matrix of non-compliance management evaluation criteria.

Non-Compliance Management Type	Construction Unit A	Supervisory Unit B	General Contractor C
Construction unit A	1	8	1/3
Supervisory unit B	1/8	1	1/9
General contractor C	3	9	1
Judgment coefficient	0.300	0.052	0.648

According to Equation (26), derived based on fuzzy mathematics theory, the corresponding parameters were assigned; the simulation results are shown in detail in Table 8.

Table 8. Simulation values of Subject IV cases.

Responsible Subject	Technical-Defect Type	Non-Compliance Management Type	Simulation Calculation Values
	0.6580	**0.3420**	
Construction unit A	0	0.3000	10.26%
Supervisory unit B	0	0.0520	1.78%
General contractor C	1.0	0.6480	87.96%

5.2. Comparison of Model Calculation Results and Litigation Practice Results

The simulation calculation results for EPC-Subject II can be obtained based on the case modeling and calculation process of EPC-Subject III. Subsequently, the simulated results of EPC-Subject II and EPC-Subject III were compared and analyzed with practical judgment values, as illustrated in Figure 6. The examination of Figure 6 indicates that for the general contracting mode, the simulated results of the construction unit, supervisory unit, and the general contractor in the case are consistent with the practical judgment values. The simplicity in risky behavior types for the construction unit and supervisory unit results in less biased actual identification. On the other hand, the quality risk behavior of the general contractor, with its diverse and complex performance, is integrated with the responsibilities and obligations of the original construction unit and design unit under the general contracting mode. Therefore, the subject is more unified, and the actual identification is less prone to deviate. Furthermore, a decrease in deviation degree was observed between the simulation results of EPC-Subject III and practical judgment values compared to that of EPC-Subject II. This outcome is mainly due to the increase in the number of subjects and types and quantities of risk behaviors, leading to a better correction of the initial value of the type coefficient $(M_{SFO})^T$ and ultimately reducing the discreteness problem. Collectively, the simulation findings obtained from the M-ResQu model proposed in this study demonstrated a high degree of resemblance to the practical judgment values.

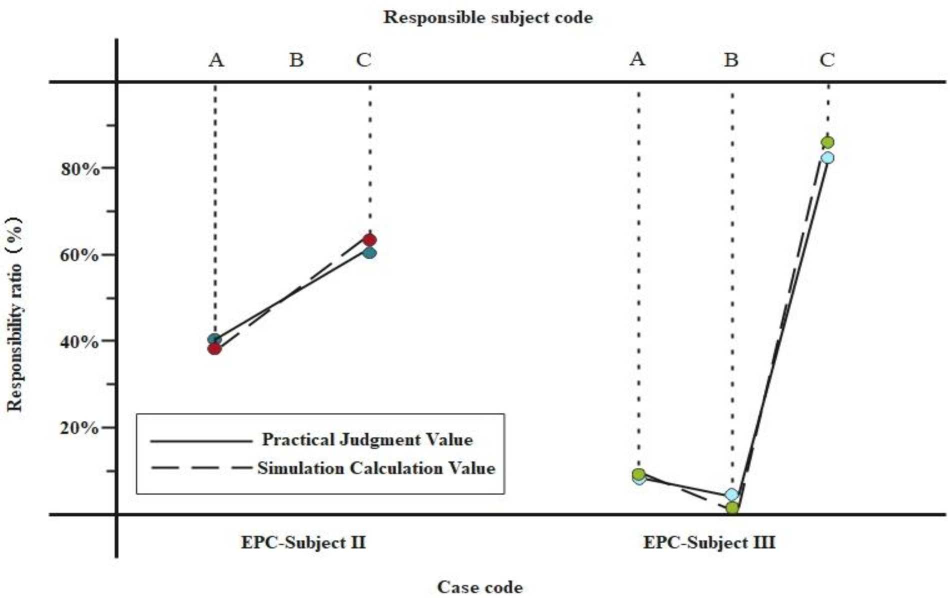

Figure 6. Comparison of simulation and practice decision values in the general contracting mode.

6. Discussion

This paper proposes a quantitative model of quality responsibility in general contracting projects. The M-ResQu model can quickly calculate the proportion of responsibility of each responsible party and provide a quantitative basis for multi-subject quality responsibility disputes. Different from the existing liability quantification methods [23–27], this paper selects the liability judgment value of real judicial cases as the data source of the optimization extraction of the quality-risk-behavior-type coefficient, so the simulation results of the M-ResQu model are closer to the practical values. Some limitations of the proposed method are as follows:

(1) Although the current number of cases can prove the effectiveness of the proposed method, a further increase in the number of sample cases is needed to allow for the proposed method to be adapted to a larger range of situations.
(2) The number of subjects considered in this paper is obtained based on limited cases. In the future, with the emergence of more complex dispute situations, the number of subjects will be further increased, and the M-ResQu model may need to be further adjusted.
(3) The influencing factors of quality responsibility allocation need to be further explored, such as the natural environment or the intervention of the third party, which will affect the results. The above factors are not taken into account at this stage.

Based on the above limitations and improvement needs, we will focus on the following aspects of work in the future:

(1) The number of subjects considered in the model should be further increased.
(2) More representative cases should be considered, and the number and diversity of case samples should be increased.
(3) The influences of external factors such as natural environment change and natural disaster on quality responsibility sharing are considered.

7. Conclusions

This paper presents a detailed analysis of the choice mechanism for subject quality behaviors, the categorization of quality risk behaviors and their associated optimization of the type coefficients, as well as the construction of a quantitative model to account for quality responsibility in general contracting projects. The following conclusions were drawn:

(1) Drawing on game theory and utility theory, this study delved into the quality behavior choice mechanisms adopted by construction units and general contractors under the general contracting mode. The findings expose that quality risk behavior choice by construction units is contingent on the supervisory intensity of administrative regulatory departments, and punitive measures were enforced following the identification of such behaviors. In contrast, quality risk behavior choice by general contractors is reliant on factors such as the degree of supervision by construction units, the level of engineering quality incentives, and the punishment intensity associated with quality risk behaviors.
(2) The SFO was employed to optimize the type coefficients of quality risk behaviors for participating subjects under the general contracting mode. After conducting simulation tests, the value of the type coefficient $(M_{SFO})^T$ was deemed suitable for quality dispute resolution in general contracting projects.
(3) In utilizing the general contracting mode, this study consolidated the responsibilities and obligations of original construction units and design units into the duties of the general contractors, successfully reducing the number of responsible subjects. The resulting decline in the identification bias associated with the complexity of distinguishing multiple quality risk behaviors of multiple subjects increased the precision of practical applications of the M-ResQu model. As the number of responsible subjects or the types and quantities of risk behaviors that were enforced continue to increase, the problem of discreteness initiated by the initial value of the type coefficient $(M_{SFO})^T$ could be effectively mitigated, thus improving simulation performance.
(4) This study presented the M-ResQu model, which quantitatively calculated the proportion of multiple-subject quality responsibility division under the general contracting mode, providing users with a quantitative model for quality dispute resolution in

general contracting projects. In practical applications, the M-ResQu model calculation results are available to adjudication bodies, who can draw informed judgments based on the specifics of the case at hand.

(5) The M-ResQu model constructed in this paper can scientifically predict the assignment of engineering quality responsibility according to the specific situation, so as to reduce the litigation risk of the parties. Meanwhile, the research method and quantitative model proposed in this paper also provide a new idea and method for the legal empirical research based on algorithm and machine learning.

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