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Retraction

Retracted: Safety Investment Decision Problem without Probability Distribution: A Robust Optimization Approach

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This article has been retracted by Hindawi following an investigation undertaken by the publisher [1]. This investigation has uncovered evidence of one or more of the following indicators of systematic manipulation of the publication process:

(1) Discrepancies in scope
(2) Discrepancies in the description of the research reported
(3) Discrepancies between the availability of data and the research described
(4) Inappropriate citations
(5) Incoherent, meaningless and/or irrelevant content included in the article
(6) Peer-review manipulation

The presence of these indicators undermines our confidence in the integrity of the article's content and we cannot, therefore, vouch for its reliability. Please note that this notice is intended solely to alert readers that the content of this article is unreliable. We have not investigated whether authors were aware of or involved in the systematic manipulation of the publication process.

Wiley and Hindawi regrets that the usual quality checks did not identify these issues before publication and have since put additional measures in place to safeguard research integrity.

We wish to credit our own Research Integrity and Research Publishing teams and anonymous and named external researchers and research integrity experts for contributing to this investigation.

The corresponding author, as the representative of all authors, has been given the opportunity to register their agreement or disagreement to this retraction. We have kept a record of any response received.

References

[1] C. Xin, J. Zhang, C. Wu, and S. Tsai, "Safety Investment Decision Problem without Probability Distribution: A Robust Optimization Approach," *Mathematical Problems in Engineering*, vol. 2020, Article ID 8874057, 10 pages, 2020.

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Research Article

Safety Investment Decision Problem without Probability Distribution: A Robust Optimization Approach

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Accidents occur frequently, causing huge losses to enterprises and individuals. Safety investment is an important means to prevent accidents, but how much to invest is a dilemma. Previous studies have assumed that the demand of safety investment follows some probability distribution. In practice, the distribution information of safety investment is usually limited or difficult to obtain, i.e., it is unknown. To deal with this kind of problem without a probability distribution, we construct the measures of marginal accident loss (MAL) and marginal opportunity loss (MOL) from the perspective of demand uncertainty. Robust optimization technology is utilized to establish three robust optimization models, which are the absolute robust models (ARM), deviation robust models (DRM), and relative robust models (RRM). The results of numerical analysis show that MAL is positively correlated with safety investment and MOL is negatively correlated with the uncertainty of safety investment. The above robust optimization models in this study can be applied to different enterprise's risk scenarios. ARM, DRM, and RRM are suitable for high- and nonhigh-risk industries and other industries, respectively.

1. Introduction

Safety accidents always are a topic of concern. With the continuous and rapid growth of China's economy, the death toll of work safety accidents has decreased year by year, but there are still huge numbers of casualties, as shown in Figure 1.

The occurrence of safety accidents not only causes property losses but also often has adverse social impacts on injured personnel, their families, and society [1]. Therefore, it is still an urgent problem for enterprises to prevent casualty accidents and ensure the safety and health of workers. The direct cause of accidents is generally insufficient safety investment, and increasing safety investment can apparently reduce industrial accidents [2]. However, the effect of safety investment is not immediate. Enterprises are motivated to use potential safety investment for other purposes, which leads to production safety accidents.

Accidents are also economic activities in safety economic theory. The economic loss caused by an accident is often huge, and the prevention of an accident can bring many hidden benefits to an enterprise. Many modern managers regard accident prevention as an investment with significant returns, and when prevention activities are deemed to bring sufficient profits, investors may be willing to invest [3]. The effect of safety investment in different periods, as shown in Figure 2, indicates that safety investment of 1 point in the design phase has the safety effect of 10 points in the construction stage and 1000 points in the operation or production stage. That is, a small investment at an early stage is equivalent to a large investment at a later stage. This so-called law of the pyramid emphasizes the importance of early investment. At the same time, Figure 3 shows that when safety investment is small, once an accident occurs, it will cause huge loss. Therefore, to avoid causing great losses, safety investment ahead of time is a top priority.

Figure 1: 2012–2018 Chinese GDP growth and death toll of production safety accidents.

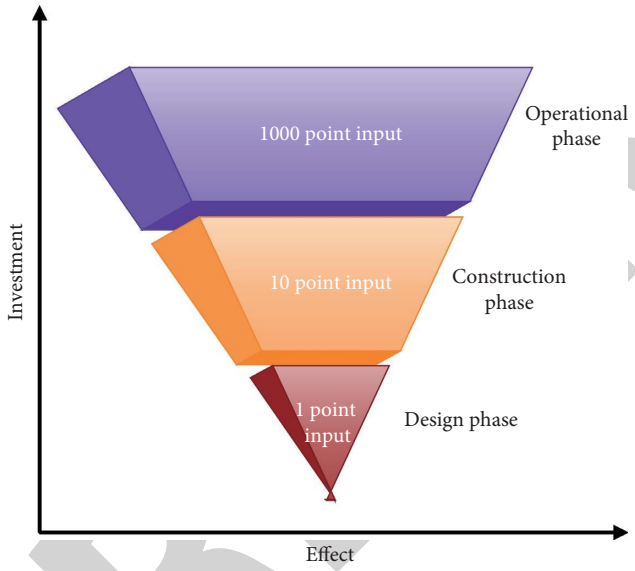

Figure 2: Effect of safety investment in different periods.

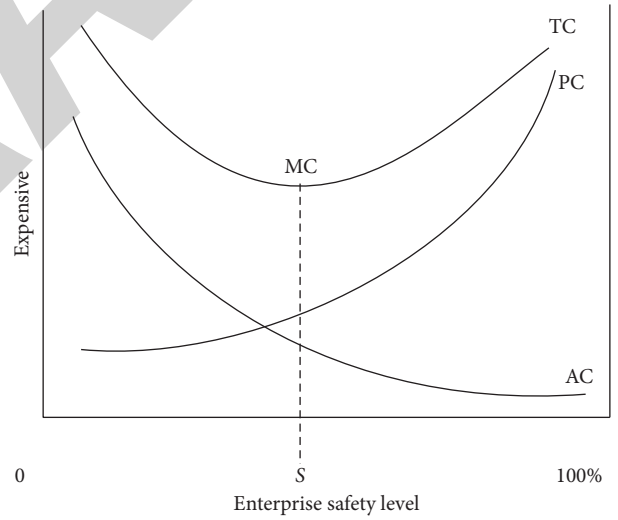

Figure 3: Labor health and safety cost model. PC, prevention cost; AC, accident cost; TC, total cost; MC, minimum cost.

The labor health and safety cost model [4] in Figure 3 reflects the relationship between prevention cost (PC), accident cost (AC), total cost (TC), and enterprise safety level (ESL). With the improvement of enterprise safety level, PC and AC are, respectively, increasing and decreasing functions of ESL. The sum of PC and AC is TC, in which prevention cost (PC) is considered a safety investment. As can be seen from Figure 3, TC will first decrease with ESL, and then, when ESL is greater than the break-even point S, TC will increase rapidly. Hence, ESL that is too low or high can lead to high TC.

It is most economical and feasible for enterprises to eliminate accidents through prior safety investment. However, it is impossible to make an unlimited safety investment. In other words, enterprises should reasonably use resources to strike a balance between safety investment and safety production [5]. Obviously, if an enterprise does not know what is a reasonable amount of safety investment, then excessive investment in safety is a waste of its resources, but insufficient safety investment may not guarantee a reasonable level of safety.

The purpose of safety investment is to reduce the possibility of accidents or to even avoid them, and therefore enterprises should invest some money in production safety every year. However, to ensure production safety, how much money should enterprises invest? In practice, it is difficult for decision makers to obtain safety investment information,

accurately determine the demand of safety investment of enterprises, and reduce the probability of accidents. That is, an enterprise's safety investment decision has strong uncertainty, and it is difficult to determine the probability distribution of safety investment. First of all, the occurrence of safety accidents has great contingency and suddenness, and then the safety investment decision to deal with safety accidents also has great contingency. Secondly, the safety accident is usually a small probability event, and the historical data cannot reflect the actual situation based on probability theory. Finally, people also expect that safety accidents will not happen and are not willing to invest in safety, which results in a failure to reflect the true demand situation. The above three reasons make it difficult to describe the safety investment demand with probability distribution.

Therefore, the study of safety investment decision in uncertain environment has become a pressing issue. On the one hand, with too little safety investment, enterprises will bear the losses caused by accidents. On the other hand, if safety investment is too high, it will waste valuable resources.

The motivation of this paper tends to address the dilemma of the amount of investment in production safety, and we establish a safety investment model in uncertainty environment from the perspective of opportunity cost. Most studies on the above uncertain problems have assumed that safety investment obeys some probability distribution and have dealt with them through stochastic optimization. Robust optimization technology is adopted to solve this uncertain safety investment model. Robust optimization is a specific and novel methodology for handling optimization problems with uncertain environment. Based on the unknown probability distribution of safety investment, we study the influence of different investment conditions on safety cost by using absolute robust optimization, deviation robust optimization, and relative robust optimization and analyze the influence of these methods on safety investment decisions.

This article studies safety cost minimization models under known and unknown safety investment probability distributions, which determine the amount of safety investment under different circumstances.

The interval scenario method describes the safety investment demand whose probability distribution is unknown, i.e., $D \in (\underline{D}, \overline{D})$. Similar to the robust definition [6], we establish absolute robust, robust deviation, and relative robust models of safety investment and obtain the optimal results. The steps of the research method are shown in Figure 4.

The remainder of this article is structured as follows. Section 2 summarizes the research of safety investment. Section 4 discusses safety investment minimization models under known and unknown probability distributions of safety investment demand. Section 5 discusses calculations and numerical analysis. Section 6 relates our conclusions.

2. Literature Review

Safety investment can promote economic growth, and studying its impact on safety performance can help decision makers to invest purposefully and improve productivity [7]. The research on safety performance mainly focuses on the relationship between safety input and safety benefits [8], as well as the influence of different risk factors on safety performance. Feng [9] proposed that cultivating a positive safety culture is necessary to obtain better safety benefits. At the same time, how to allocate resources reasonably, optimize a safety investment scheme, establish an investment direction, and evaluate the effect of safety investment are of more practical guiding significance for the safety decision-making of enterprises [10].

López-Alonso et al. [11] studied the impact of safety investment on construction companies' costs and found that the cost of accident prevention is inversely proportional to the average number of accidents. To some extent, this proves the general hypothesis that the higher the safety investment, the better the safety benefit. In fact, although safety investment helps improve safety performance, it will affect the total cost of the enterprise, whose goal is to maximize profit. Therefore, appropriate safety investment decisions are important to prevent accidents while controlling an enterprise's costs. Increasing safety investment in the early stage can reduce accident cost [12]. By studying the relationship between safety investment and accident cost, the best strategy of safety investment and a method of effective safety control cost can be found [13].

Ma et al. [14] studied the problem of safety investment from the perspective of opportunity cost by establishing a safety investment decision model of opportunity cost minimization. Two main scenarios were considered: underinvestment generates shortage costs and overinvestment generates excess costs.

Safety investment decision-making problem is a branch of the typical combinatorial optimization [15–18]. The above models assume that the decision maker knows either the exact amount or a certain probability distribution of the demand of safety investment. But in reality, it is difficult to obtain such information for the decision maker. First of all, the occurrence of safety accidents has great contingency and suddenness, and then the safety investment decision to deal with safety accidents also has great contingency. Secondly, the safety accident is usually a small probability event, and the historical data cannot reflect the actual situation based on probability theory. Finally, people also expect that safety accidents will not happen and are not willing to invest in safety, which results in a failure to reflect the true demand situation. The above three reasons make it difficult to describe the safety investment demand with probability distribution.

In order to deal with uncertain probability distribution, there are many research models, such as fuzzy technology and rough set theory [19–22]. Stochastic approach and

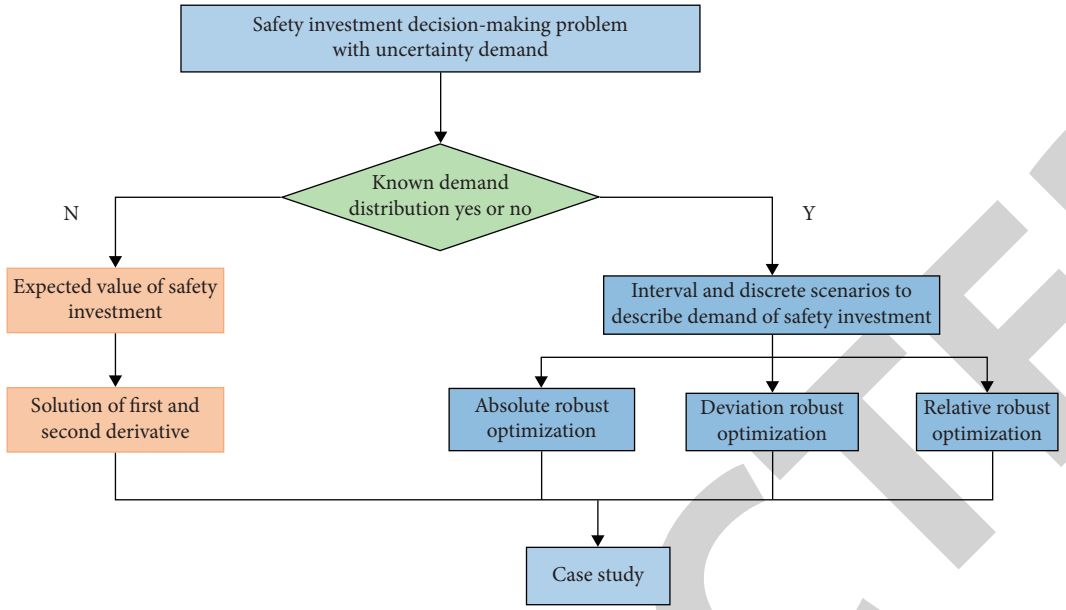

Figure 4: Diagram of the research method.

robust optimization are complementary methods for handling data uncertainty, which have their own advantages and disadvantages. Stochastic approach assumed that uncertainty is the random data, which obeys a known in advance probability distribution [23–26]. Fuzzy technology is often used to deal with cognitive uncertainty, especially when decision makers lack the knowledge, and it is difficult to obtain real parameter data. In contrast, robust optimization avoids the probability distribution hypothesis, which can avoid decision-making risks caused by data loss and empiricism. Robust optimization models have been used recently in many uncertain economic management decision problems. Unfortunately, it is rarely used in safety management. Interested readers can refer to several comprehensive guides to reformulating robust counterparts [27–30].

This study presents a robust safety investment model with uncertain investment demand. Uncertainty is traditionally described by probability density functions. This is difficult in practice because of factors such as economic development level, environmental policy, and society. We adopt a deterministic optimization model [6] that considers uncertainty using both interval and discrete scenarios. We have established absolute robust, robust deviation, and relative robust models of safety investment and obtained the optimal results. We compared these different robust models and obtained their shortages or advantages in Section 5.

Table 1 summarizes the research of safety investment decision-making from the aspects of research methods and objects.

3. Problem Formulation and Definition

Enterprises generally invest in safety to prevent production accidents. The following definitions are given.

Definition 1. Safety investment (I) is the sum of all kinds of resources in which enterprises invest in the process of production safety.

Definition 2. Demand of safety investment (D) is the safety investment required by an enterprise to prevent accidents.

Definition 3. Safety cost (SC) is the sum of the costs of preventing accidents and the losses due to insufficient safety investment.

Theoretically, people always try to improve the safety level as much as possible and to protect lives and property. However, enterprises' safety investment cannot increase without limit, and if the risk of accident is under control, most enterprises are reluctant to invest in safety.

There are three cases of safety investment from the point of view of accident prevention:

(1) Underinvestment: safety investment is insufficient, i.e., safety investment (I) is smaller than the demand (D) ($I < D$)

(2) Overinvestment: safety investment (I) is larger than the demand (D), i.e., $I > D$

(3) Exact investment: safety investment (I) is equal to the demand (D), i.e., $I = D$

According to the above situations, decision makers can adopt two strategies: investment or no investment. Five cases can be analyzed, as follows:

(i) *Strategy 1.* If decision makers make no safety investment, then there are two possible cases:

(a) Case 1: enterprises are lucky and no accidents occur; hence, the safety cost is zero.

(b) Case 2: accidents occur; hence, the enterprise must bear a series of losses due to accidents, such

Table 1: Summary of safety investment decision-making research.

Paper	Research method									Research objective	
	Empirical analysis	Questionnaire	Regression analysis	Agent-based modeling	Risk mapping	System dynamics	Cost-benefit analysis	Robust optimization	Opportunity cost	Cost	Safety performance
[7]	√										√
[11]		√								√	
[9]		√	√								√
[8]		√		√							√
[10]					√						√
[12]						√				√	
[13]							√				√
[25]							√			√	
[14]									√	√	
This paper								√	√	√	

as compensation of victims and cost of stopping production. Because the enterprise's safety investment is insufficient to prevent accidents, its safety cost is the accident loss.

(ii) *Strategy 2*. If decision makers make safety investments, there are three possible cases.

(c) Case 3: no accident occurs; hence, safety investments are sufficient to prevent accidents, and the enterprise has no accident losses, and safety costs are equal to safety investments.

(d) Case 4: although no accidents occur, safety investment is likely to exceed the demand for accident prevention, which indicates overinvestment. Every additional unit of safety investment precludes the opportunity to obtain other income. Income given up due to excess safety investment is a kind of loss for the enterprise, which is measured by opportunity cost. At this time, the safety investment cost is the sum of investment costs and opportunity losses to prevent accidents.

(e) Case 5: decision makers invest in safety, but accidents still occur, which shows that the safety investment is not enough to prevent all accidents. Accident losses are generated, similar to Case 2, where the safety costs are the sum of the safety investment costs and accident losses. Table 2 summarizes the above five cases.

Definition 4. Accident loss (AL) is the loss due to insufficient safety investment.

Definition 5. Marginal accident loss (MAL) occurs when demand for safety investment is greater than the amount invested. The enterprise's accident incremental loss increases for each unit of safety investment demand that exceeds the amount invested.

Definition 6. Opportunity loss (OL) is the opportunity cost caused by safety investment exceeding demand.

Definition 7. Marginal opportunity loss (MOL) is the amount of safety investment in excess of demand. The enterprise's incremental opportunity loss increases for every unit of safety investment that exceeds demand.

The ultimate goal of enterprise investment is profit maximization. An enterprise takes risk to gamble that an accident will not occur. Therefore, for the greater interest, decision makers tend to ignore safety investment. But, once an accident occurs, huge economic losses come to the enterprise and to the social environment, natural resources, and employees in the form of an adverse life impact. However, although safety overinvestment forfeits potential opportunity income, it reduces the probability that an accident occurs, and the investment loss is far less than that caused by an accident; hence, the marginal accident loss is much larger than the marginal opportunity loss.

The MAL and MOL are two very important parameters. The motivation of MAL and MOL is to address the balance between overinvestment and underinvestment besides the aim for problem solving. MAL and MOL are also piecewise functions. If the safety investment demand exceeds the actual investment, then $MAL > 0$, otherwise $MAL = 0$. On the contrary, if the actual investment exceeds the safety investment demand, then $MOL > 0$, otherwise $MOL = 0$.

Generally, enterprises pay more attention to the loss of accident and ignore the loss of opportunity.

Without loss of generality, we make two assumptions from the above analysis.

Assumption 1. Adequate safety investment can prevent the occurrence of accidents, and when the amount of safety investment meets the safety investment demand, accidents will not occur in the enterprise.

Assumption 2. Marginal accident loss is much larger than marginal opportunity loss, i.e., $MAL \gg MOL > 1$.

Table 3 presents parameter definitions.

From the above analysis, there are five decision-making cases, as shown in Table 4.

We obtain the following model, which aims to minimize the cost of safety investment:

Table 2: Classification of safety investment decision-making and effects.

Case	Investment		Accident		Effects		Investment result
	Yes	No	Yes	No	Loss	Opportunity cost	
1		√		√			
2		√	√		√		
3	√			√		√	Sufficient
4	√			√		√	Overinvestment
5	√		√		√		Underinvestment

Table 3: Parameter definitions.

Symbol	Name	Meaning
I	Safety investment	Resources utilized in safety, including human resources, capital, and material
D	Demand of safety investment	Amount of investment required to prevent accidents
AL	Accident loss	Losses caused when demand for safety investment exceeds the amount of investment
MAL	Marginal accident loss	Accident loss resulting from the investment of a unit when safety investment demand exceeds the actual investment
OL	Opportunity loss	Opportunity cost due to safety investment exceeding demand
MOL	Marginal opportunity loss	Opportunity loss resulting from the investment of a unit when actual safety investment exceeding demand
$C_s(I, D)$	Function of safety cost	Function of safety cost relative to input parameters I and D

Table 4: Five decision-making cases relative to input parameters I and D.

Case	Safety investment	Safety cost
1	$I = 0$	0
3	$I = D$	I/D
4	$I > D$	$D + \mathrm{OL}$
2, 5	$I < D$	$I + \mathrm{AL}$

$$\min C_s(I, D) = \begin{cases} I + \mathrm{MAL} \times (D - I), & D \geq I, \\ D + \mathrm{MOL} \times (I - D), & D \leq I. \end{cases} \tag{1}$$

4. Mathematical Model

In this section, we discussed the safety investment model with known or unknown probability distribution, respectively.

4.1. Known Probability Distribution. Assuming that safety investment demand D is known, $f(\cdot)$ is the probability density function of safety investment demand and $F(\cdot)$ is the distribution function of safety investment demand. The expected cost of safety investment can be expressed as

$$\begin{aligned} C_s(I, D) = &\int_0^I [D + \mathrm{MOL} \times (I - D)] f(D) d(D) \\ &+ \int_I^\infty [I + \mathrm{MAL} \times (D - I)] f(D) d(D). \end{aligned} \tag{2}$$

The first and second derivatives of the above functions can be obtained as

$$\begin{aligned} \frac{\partial C_s(I, D)}{\partial I} &= (\mathrm{MOL} + \mathrm{MAL} - 1) F(I) - \mathrm{MAL} + 1, \\ \frac{\partial^2 C_s(I, D)}{\partial I^2} &= (\mathrm{MOL} + \mathrm{MAL} - 1) f(I) \geq 0. \end{aligned} \tag{3}$$

Since the second derivative is greater than 0, there exists a unique solution I^* to minimize the expected cost of the safety investment.

Let the first derivatives be equal to zero:

$$\frac{\partial C_s(I, D)}{\partial I} = 0. \tag{4}$$

Then, we can obtain that

$$F(I^*) = \frac{\mathrm{MAL} - 1}{\mathrm{MOL} + \mathrm{MAL} - 1}. \tag{5}$$

That is, when the demand for safety investment is known, the safety investment I^* is the minimal safety cost.

4.2. Unknown Probability Distribution. With an unknown probability distribution, we consider the following three robust optimization models.

4.2.1. Absolute Robust Model (ARM). Absolute robust optimization is to minimize the worst-case cost of implementing all possible safety investment demand. The model can be expressed as

$$\min_{I\in[\underline{D},\overline{D}]}\max_{D\in[\underline{D},\overline{D}]} C_S(I,D)=\min_{I\in[\underline{D},\overline{D}]}\max_{D\in[\underline{D},\overline{D}]}\begin{cases} I+\mathrm{MAL}\times(D-I), & D\geq I,\\ D+\mathrm{MOL}\times(I-D), & D\leq I,\end{cases}$$
$$f^A(I)=\max_{D\in[\underline{D},\overline{D}]} C_s(I,D)=\begin{cases} I+\mathrm{MAL}\times(\overline{D}-I), & I\leq I^A\leq\overline{D},\\ \underline{D}+\mathrm{MOL}\times(I-\underline{D}), & \underline{D}\leq I^A\leq I,\end{cases} \tag{6}$$

where I^A is the solution of equation $C(I^A,\underline{D})=C(\overline{D},I^A)$, and we can obtain

$$I^A=\frac{(\mathrm{MOL}-1)\times\underline{D}+\mathrm{MAL}\times\overline{D}}{\mathrm{MOL}+\mathrm{MAL}-1}. \tag{7}$$

Apparently, I^A is the convex connection between $\underline{D}$ and $\overline{D}$, and the proportions are $((\mathrm{MOL}-1)/(\mathrm{MOL}+\mathrm{MAL}-1))$ and $(\mathrm{MAL}/(\mathrm{MOL}+\mathrm{MAL}-1))$, respectively.

4.2.2. Robust Deviation Model (RDM). Robust deviation optimization is to minimize the maximal deviation of safety cost, which is a min-max regret method, expressed as $C_S(I,D)-C_S(D,D)$. The robust deviation model of safety cost can be expressed as

$$\min_{I\in[\underline{D},\overline{D}]}\max_{D\in[\underline{D},\overline{D}]}\left(C_s(I,D)-C_s(D,D)\right)=\min_{I\in[\underline{D},\overline{D}]}\max_{D\in[\underline{D},\overline{D}]}\begin{cases}(\mathrm{MAL}-1)\times(D-I), & D\geq I,\\ \mathrm{MOL}\times(I-D), & D\leq I,\end{cases} \tag{8}$$

$$f^D(I)=\max_{D\in[\underline{D},\overline{D}]}\left(C_s(I,D)-C_s(D,D)\right)=\begin{cases}(\mathrm{MAL}-1)\times(\overline{D}-I), & I\leq I^D,\\ \mathrm{MOL}\times(I-D), & I\geq I^D.\end{cases} \tag{9}$$

To minimize function (9), the intersection of two branches can be obtained as

$$I^D=\frac{(\mathrm{MAL}-1)\times\overline{D}+\mathrm{MOL}\times\underline{D}}{\mathrm{MOL}+\mathrm{MAL}-1}, \tag{10}$$

where I^D is also a convex combination of $\underline{D}$ and $\overline{D}$, weighted by $\mathrm{MOL}/(\mathrm{MOL}+\mathrm{MOL}-1)$ and $(\mathrm{MAL}-1)/(\mathrm{MOL}+\mathrm{MAL}-1)$, respectively.

4.2.3. Relative Robust Model (RRM). Relative robust optimization is to minimize the maximal relative deviation of safety investment cost, which obtains the relative robust safety investment I^R. The model is established as

$$\min_{I\in[\underline{D},\overline{D}]}\max_{D\in[\underline{D},\overline{D}]}\frac{C_s(I,D)-C_s(D,D)}{C_s(D,D)}=\min_{I\in[\underline{D},\overline{D}]}\max_{D\in[\underline{D},\overline{D}]}\begin{cases}\dfrac{(\mathrm{MAL}-1)\times(D-I)}{D}, & D\geq I,\\ \dfrac{(1+\mathrm{MOL})\times(I-D)}{D}, & D\leq I,\end{cases}$$
$$f^R(I)=\max_{D\in[\underline{D},\overline{D}]}\frac{C_s(I,D)-C_s(D,D)}{C_s(D,D)}=\begin{cases}\dfrac{(\mathrm{MAL}-1)\times(\overline{D}-I)}{\overline{D}}, & I\leq I^R,\\ \dfrac{\mathrm{MOL}\times(I-\underline{D})}{\underline{D}}, & I\geq I^R,\end{cases} \tag{11}$$

where I^R is the solution of $(C(I,\overline{D})/C(\overline{D},\overline{D}))=(C(I,\underline{D})/C(\underline{D},\underline{D}))$. We solve it and obtain

$$I^R=\frac{\overline{D}\,\underline{D}\,(\mathrm{MOL}+\mathrm{MAL}-1)}{\mathrm{MOL}\overline{D}+(\mathrm{MAL}-1)\,\underline{D}}. \tag{12}$$

Table 5: Range of values of MAL and MOL (unit: 10,000 yuan).

Parameter	Range of parameter values (10%)										
	−50	−40	−30	−20	−10	0	10	20	30	40	50
MAL	7.5	9	10.5	12	13.5	15	16.5	18	19.5	21	22.5
MOL	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5

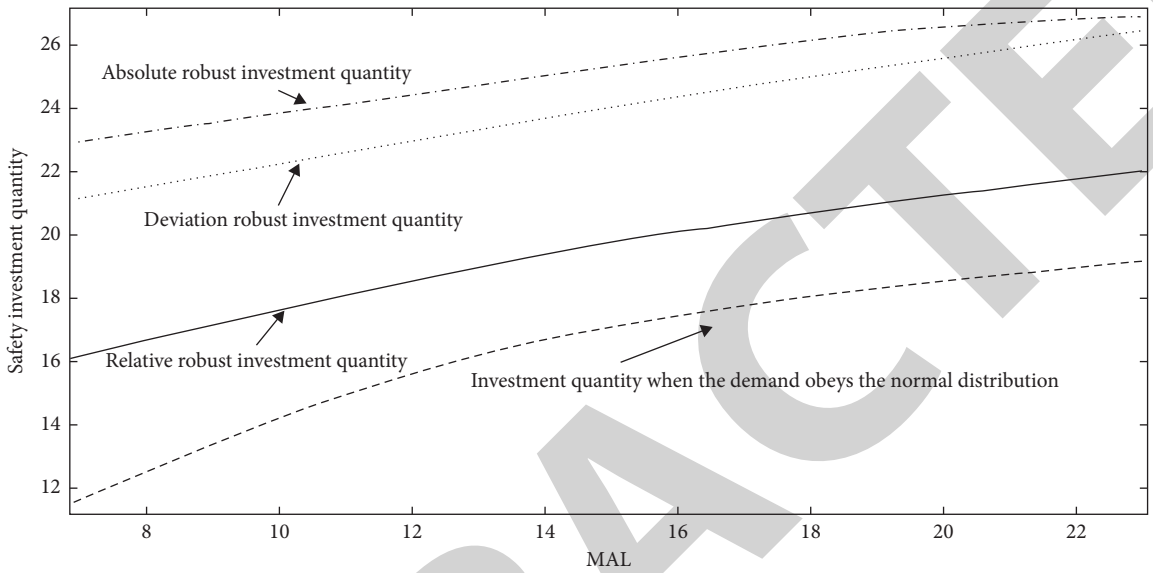

Figure 5: Relationship between MAL and I^*, I^A, I^D, and I^R.

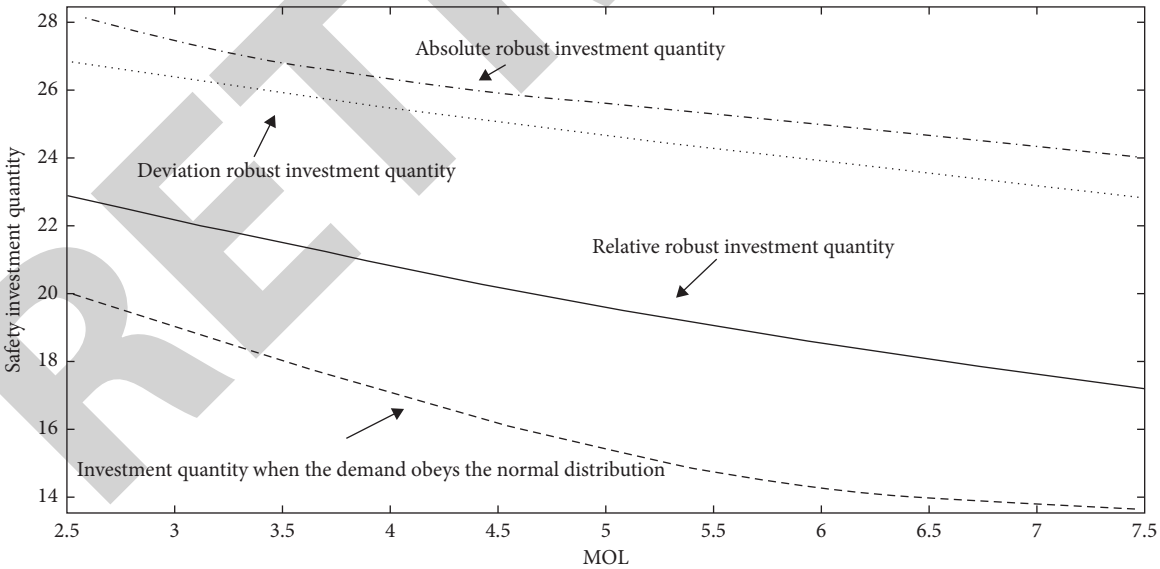

Figure 6: Relationship between MOL and I^*, I^A, I^D, and I^R.

Table 6: Safety investment models in three scenarios.

Scenario	Classification of industry	Safety investment model
1	High-risk	Absolute/deviation robust model
2	Nonhigh-risk	Relative robust model
3	General	Probability distribution model

5. Numerical Analysis

Assume that MAL = 15 and MOL = 5, with the range of values shown in Table 5.

(i) *Case 1*. The probability distribution of safety investment demand is known, and it obeys a normal distribution, i.e., $D \sim N(10, 10^2)$

(ii) *Case 2*. The probability distribution of safety investment demand is unknown, but it lies in a certain range, i.e., $D \in [10, 30]$

Solving equations (5), (7), (10), and (12), we can get the relationship between MAL, MOL, I^*, I^A, I^D, and I^R from two different cases, as described in Figures 5 and 6.

From Figures 5 and 6, we can get the following results.

(1) The safety investment is negatively correlated with the marginal opportunity loss but correlated with marginal accident loss, which is in accordance with reality.

(2) The safety investment of known probability distribution is lower than that of unknown probability distribution due to the conservatism of robust optimization.

(3) Among the three robust methods, the result of absolute robust optimization is the most conservative for pessimistic decision-making. The result of relative robust optimization is more positive than that of deviation robust optimization.

(4) The difference of value between I^D and I^A is very small, which reflects that the strategies of decision makers have the same nature of pessimism and conservatism. Similar to absolute robust optimization, the deviation of robust optimization also considers the worst cases, combined with the regret value. This can avoid risks to some extent, which is suitable for risk-sensitive decision makers. By contrast, the conservative nature of I^R is reduced greatly, which is suitable for decision makers with low risk tolerance.

6. Conclusion

Using the robust optimization approach, we researched the safety investment decision problem without the probability distribution of safety investment demand. From the perspective of accident prevention, three safety investment decision-making models were established to minimize safety investment cost.

Three robust optimization models in this study apply to different enterprise's risk scenarios. For example, according to the national standard of China's National Economic Industry Classification, national economic industries are divided into 20 categories. Among these, industries prone to safety accidents are further divided into high- and nonhigh-risk industries, and other industries, with relatively low risk coefficients, are classified as general industries.

Although high-risk industries have established a relatively perfect safety production management system, many large production safety accidents still occur, exerting a bad influence on society and bringing huge losses in lives and property. Owing to the high risk of such industries, an accident can bring economic losses to enterprises and cause irreparable harm to the public. The harm caused by accidents in nonhigh-risk industries such as textiles, tobacco, trade, and warehousing is relatively small, as is the scope of impact. We provide suggestions for safety investment decisions in different industries.

Enterprises with high risk will always be in the worst-case decision stage. Enough resources should be spent on accident prevention because the prevention effect is much greater than the stop loss after an accident, which minimizes the possibility of accidents as much as possible, to reduce costs and bring more profits. Absolute robust optimization can be used for this kind of enterprise to make decisions.

Compared with ARM and RDM, RRM not only overcomes the problem of an unknown probability of investment demand but also has better flexibility and avoids conservatism to some extent. Therefore, relative robust optimization can be used for nonhigh-risk industries, whose risk is low and whose property damage is on a smaller scale.

General industries have less possibility of safety accidents occurring than in nonhigh-risk industries. Decision makers should focus on promoting safety education, training, and knowledge, so that personnel form a deeper understanding and know their own safety risk. At the same time, a relatively perfect long-term mechanism of production safety management is constructed to improve the access in the field of production safety and form a strict control system, so as to better avoid accidents and minimize harm.

From the above analysis, three scenarios can be summarized from the classification of industries, and different safety investment models can be selected, as shown in Table 6.

We used a robust optimization method to deal with the decision problem with unknown demand distribution. The following deficiencies still exist.

First, this article chooses interval scenarios to describe demand uncertainty, but it is not the only way to describe it. For example, we can use discrete scenarios, or a mix of interval and discrete scenarios, and use Bayesian and noncooperative game theory to study information uncertainty.

Second, a case study will be more convincing than numerical analysis. Through enterprise investigation, we will apply our model to the practice of an actual enterprise.

Data Availability

All data are provided in this paper.

Conflicts of Interest

The authors have declared that no conflicts of interest exist.

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