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Cask Principle of Multi-Attribute Risk Assessment: Non-Weighted Maximal Approach for Production Accidents

LEI WANG[1], **(Member, IEEE), XIN WANG**[1], **AND ZHAOWEI DING**[2]
[1]School of Narcotics Control and Public Order Studies, Criminal Investigation Police University of China, Shenyang 110035, China
[2]School of Economics and Management, University of Science and Technology Beijing, Beijing 100083, China

Corresponding author: Xin Wang (vibiheba@163.com)

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ABSTRACT This paper proposes a non-weighted maximal approach of multi-attribute risk assessment for production accidents, which comes from the Chinese practice of risk management rather than the theoretical weighted multi-attribute approach. The existing literature for risk assessment of pipeline accidents, there is an absence of or lack of explicit consideration of some special dimensions, i.e., environmental pollution as the important derivative disaster. The non-weighted maximal approach is described the maximum function among multiple criteria, which include fatalities, serious injuries, direct economic loss, and environment pollutions. The approach comes from the Chinese government official achievement assessment system with the characteristics of "one ticket veto system for production safety", and has applied to ex ante assessing likelihood of the accident, and ex post holding the responsible for accidents. At last, applying the case of the Chinese Qingdao oil pipeline accident, the maximal approach is compared with the FN curve criterion, the ALARP principle and the ELECTRE TRI method. The results show that the maximal approach of production safety accident criterion pays more attention to the risk density or risk consequences, which follows the "cask principle" and is much more useful controlling the risk when targeting the vulnerable links of engineering systems.

INDEX TERMS Risk assessment, multi-attribute analysis, maximal approach, production accident, cask principle.

I. INTRODUCTION

Human industrial production system becomes the more and more complex, which leads to the inherently vulnerable. Especially facing the natural disasters struck, even some little contingencies, it could cause a complete systemic collapse, and then generate catastrophic consequences. For example, the human error in processes led directly to the tragic Chernobyl nuclear accident of 1986. Following the Tohoku earthquake and tsunami, the Fukushima Daiichi nuclear disaster occurred with a series of equipment failures, nuclear meltdowns, and releases of radioactive materials [1]. Both the unreasonable layout design and incorrect emergency measures together led to the 2013 Qingdao oil pipeline spill and explosion accident [2], and the appalling 2015 Tianjin container terminal explosion accident [3]. The major disasters have prompted rethinks on the vulnerabilities of engineering systems exposed in the risk management practice. In the past various types of analysis techniques have been developed to assess risk.

Historical records of accidents around the world show that the single risk dimension approach is not appropriate, if it only considers the human or financial aspects [4]. Disaster risk is not only associated with the occurrence of intense hazard events but also with the vulnerability conditions that facilitate disasters when such events occur. The new risks caused by human activities, together with the social, economic, institutional and environmental factors in the past, determine the consequences of emergencies [5]. On the other hand, the assessment results and strategy orientation will be decided

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when the assessor conceptualizing and characterizing risk [6] Taken the multiple attributes of accident damage about life, human health, property and environment into considerations, to establish a simple and practicable risk assessment approach of production accidents becomes an important strategic and tactical decision making problem.

From an academic perspective, there are mainly two approaches to deal with the multiple attribute decision-making (MADM) problems. One approach is to convert every attribute into a monetary cost, and then apply some systemic integration methods to obtain evaluation results. Commercial bank risk assessment is one of the typical applications [7]. This approach has disadvantage in production accidents that although one could add all cost components and perform a cost-benefit assessment, monetization of the value of life, human health and environment is very difficult. The other approach is to construct various weight models, such as multi-attribute utility theory (MAUT) and subjective expected utility [8], [9] analytic hierarchy process (AHP) [10], preference ranking organization method for enrichment of evaluations (PROMETHEE) [11], technique for order preference by similarity to ideal solution (TOPSIS) [12], data envelopment analysis (DEA) [13], compromise ranking method (VIKOR) [14], and so on. Besides the theoretical controversy about the weighted approaches that should be discussed in the next section, their actual applications in production accidents on-site are seriously restricted, because the overly complicated MADM approaches can hardly be applied to time-starved emergency decision-making.

Reviewing the large number of engineering practices in China, Chinese engineering practices seem to lack a body like the AIR Worldwide (AIR) to provide scientific risk assessments. Until 2012, China's new leadership has announced that it will require a social risk assessment before any major industrial project can be begun. The adoption of social risk assessment of engineering projects makes explicit what has long been a key distinction between the US and China in terms of the institutional context, the role of public oversight [15], and the risk assessment methods. As representative of the new authoritarianism with one party dominant, the Chinese government is occupying the dominant position in the course of request authorization, risk assessment, and disaster management of engineering projects. As the same time, local governmental officials bear the greatest responsibility for any production accident accordingly. This is particularly reflected in the accountability system for principle officials according with Chinese situation, i.e., the ''one ticket veto system for production safety'' [16]. Generally speaking, the related responsibility departments and principle officials would be rejected in the government performance examination system, once any index, which includes fatalities, serious injuries, direct economic loss, or environment pollutions, exceed the limited values of accident damage. This simple and easy approach of risk assessment, which is known in this paper as ''the non-weighted maximal approach'', is widely applied to ex ante assessing likelihood of the accident, and ex post holding the responsible for accidents in China.

In the multiple attributes risk assessment problem for production accident, there are three theoretical difficulties: weight, evaluation standards and indicators selection.

First, most of risk assessment models belong to the weighted models [17]–[21], which assumed that decision conflicts are solved by a compensatory process involving a trade-off of probability among weighted attributes. However, weighted models maybe face a couple of problems. First, selecting an appropriate weight is not a trivial task. Second, it is unclear whether a compensatory process is actually supported when people make a single-play risky decision [22], [23]. Researchers have argued that the stockholders' preferential choice in pipeline accident can be better described by a non-compensatory process [24] such as the ELECTRE TRI method [4], even some single-dimension models (Alonso, *et al.*, 2008). Moreover, if a risk assessment method for solving weights is too complicated, it may be difficult to be applied in practice, especially in the time-intensive emergency management. In practice, some simple and direct risk assessment methods are usually adopted by decision-makers. Especially, in China, the ''One ticket veto system for production safety'' is enforced, in order to bring the high tendency of serious accidents under control. More specifically, only if any of the attributes, in terms of the number of deaths, or serious bodily injuries, or direct economic losses [25], exceeds the critical values of risk degrees, the official would be held accountable for safety incident. Obviously, the above relationship among multiple attributes of risk assessment is a non-weighted maximum relationship.

Second, it is strikingly noticeable that there are many different risk assessment principles and criteria used in different countries. Most regulators, such as in UK and Norway, use the concept of ALARP (as low as reasonably practicable) as a basic risk evaluation principle, where risk within the ALARP area is considered acceptable (Schofield, 1998). Meanwhile, the societal risk criterion usually take a function between event cumulative frequencies F and the number of fatalities N that could be affected by each event, which are called ''FN Curves'' [26], [27]. In China, the consequence assessment method of a number of conceivable scenarios is widely used to assess the degree of accident, which includes economy loss, injuries number, death number, and marine pollution area. If any attribute exceeds the follow limit values (number of deaths ≥ 30; or number of serious injuries/wounds ≥ 100; or direct economic losses ≥ 100 million RMB; or polluted oceanic area ≥ 10 square kilometers), it can be seen as ''Particular serious accident'' that is unacceptable [25]. Thus, according to the concerned national regulations, other attributes, including economic and environmental consequences, have been equally transformed into the attribute of death number.

Third, among the most widely used indexes proposed in the existing literature for risk assessment of pipeline accidents, there is an absence of or lack of explicit consideration of some special dimensions, i.e., marine environmental pollution as the important derivative disaster, within the context of sea-land pipeline transportation. From the viewpoint of economic-social-ecological sustainable systems, it is not appropriate that only the human or property losses are considered. Considering the effects of scorched vegetation, Brito *et al.* [4] took environmental impacts into consideration by the index of the extension of vegetation destroyed (in square meters). The catastrophic marine environmental impacts have aroused wide concerns among the public [28], when a pipeline leakage accident occurs at port cities, or offshore drilling platforms. Although the pollution damage assessment of marine oil spills is a very complicated task [29], in this paper, marine environmental pollution is taken as another risk attribute of pipeline accidents.

In order to abstract risk assessment model derived from Chinese engineering project management and explain the specific risk assessment link more conveniently, we choose the more representative pipeline transportation risk assessment as the research background. With respect to the currently popular models about risk assessment of pipeline accidents, the main contributions in this paper are reflected in Table 1. The rest of the paper is organized as follows. Section 2 presents the non-weighted multi-attribute model with maximum principle of risk assessment of pipeline accident. Section 3 provides an illustrative case study of the Qingdao oil pipeline explosion accident. The conclusions drawn from the research and some open questions are presented in the final section.

II. RISK ASSESSMENT MODEL WITH MAXIMUM PRINCIPLE

The operation of (Petro)-Chemical facilities, oil and gas production and nuclear power plants are not possible without acceptance of a certain risk, especially for transportation systems of dangerous substances, such as pipeline networks. Quantitative risk analysis sets out to answer three questions: What can go wrong? What is the probability that it will go wrong? What are the consequences? To answer the first question, a Hazard Identification study has to be performed. By applying physical models, the magnitude of the undesired consequences, i.e. the potential physical effects of the undesired event and the potential damage caused by the undesired consequence, have to be calculated [30]. The objective of risk management is to prevent or reduce the deaths (D) or injuries (I), or damage to property (E) or environment (M), due to the operation of engineering facilities. According to the expected utility theory, DM makes risky decisions by balancing the values of all possible outcomes.

A. RISK ASSESSMENT FLOW DIAGRAM OF PRODUCTION ACCIDENTS

For pipeline transportation systems of dangerous substances, the risk assessment flow diagram with the non-weighted multi-attribute method is presented in Figure. 1. According to the practical risk assessment style of the "One ticket veto system for production safety" in China, the calculation of total risk of engineering system are governed by the maximum function among all of the risk assessments of subsystems. By contrast, we further make risk assessment of pipeline systems by the FN curve criterion and the ALARP principle used in some developed countries.

B. RISK IDENTIFICATION-BASED EVENT TREE ANALYSIS OF PIPELINE ACCIDENTS

The probability of oil or gas leakage depends on the degree of pipeline corrosion, soil characteristics and location [31], the stealing of crude oil by drilling holes on the pipeline [32], the ground construction, etc. Therefore, to assess the risk in pipelines, it is useful to divide the whole pipeline into smaller sections as their conditions change along their routes, such as intermediate pump station and special danger zone nearby the residential buildings or environmentally sensitive areas. Hence, a pipeline is segmented into a discrete set $S = \{s_1, s_2, s_3, \ldots, s_n\}$ of pipeline sections.

All the possible states of pipeline accidental scenarios θ derived from physical and human factors are shown in Figure. 2. Because of the human factors such as third-party interference, bad planning and construction, failed pre-accident supervision to prevent derivative events, the probability of hazard scenario $P_i(\theta)$ changes with the pipeline section s_i. These probabilities of initial and pivotal events can be obtained from two ways: one is based on historical data and data reports of accidents and leakages [32], and the other is the experts' prior knowledge or some empirical equations [20], [33], [34]. The probabilities of final events can be obtained by the ETA.

The existing literature analyzing the main factors and courses of pipeline failure mode used the Even Tree Analysis [4], [35], [36],Those researches focus on pipeline leakage risk from the viewpoint of hazard sources, where the initial event is gas or oil leakage and the final outcomes maybe detonation, flash fire or dispersion. However, the ETA of hazard sources only considers the physical mechanism of pipeline leakage accidents under the different objective scenarios, so human factors or social interference in the all-process of risk management are neglected. In a socio-technical system such as pipeline transportation, it is obvious that human factors play an important role in the initiation, mitigation, escalation and recovery phases of an accident, as long as the societal context in which the accident occurs is considered [37].

"Human factors refer to environmental, organizational and job factors, and human and individual characteristics, which influence behavior at work in a way which can affect health and safety [38]", which can be schematized in Fig. 1. From an engineering perspective, the highly complex interaction between operators, technology and organizations is a recurring subject arising from investigations involving major events [39]. Following the investigation of Qingdao oil pipeline explosion accident in 2013, it has

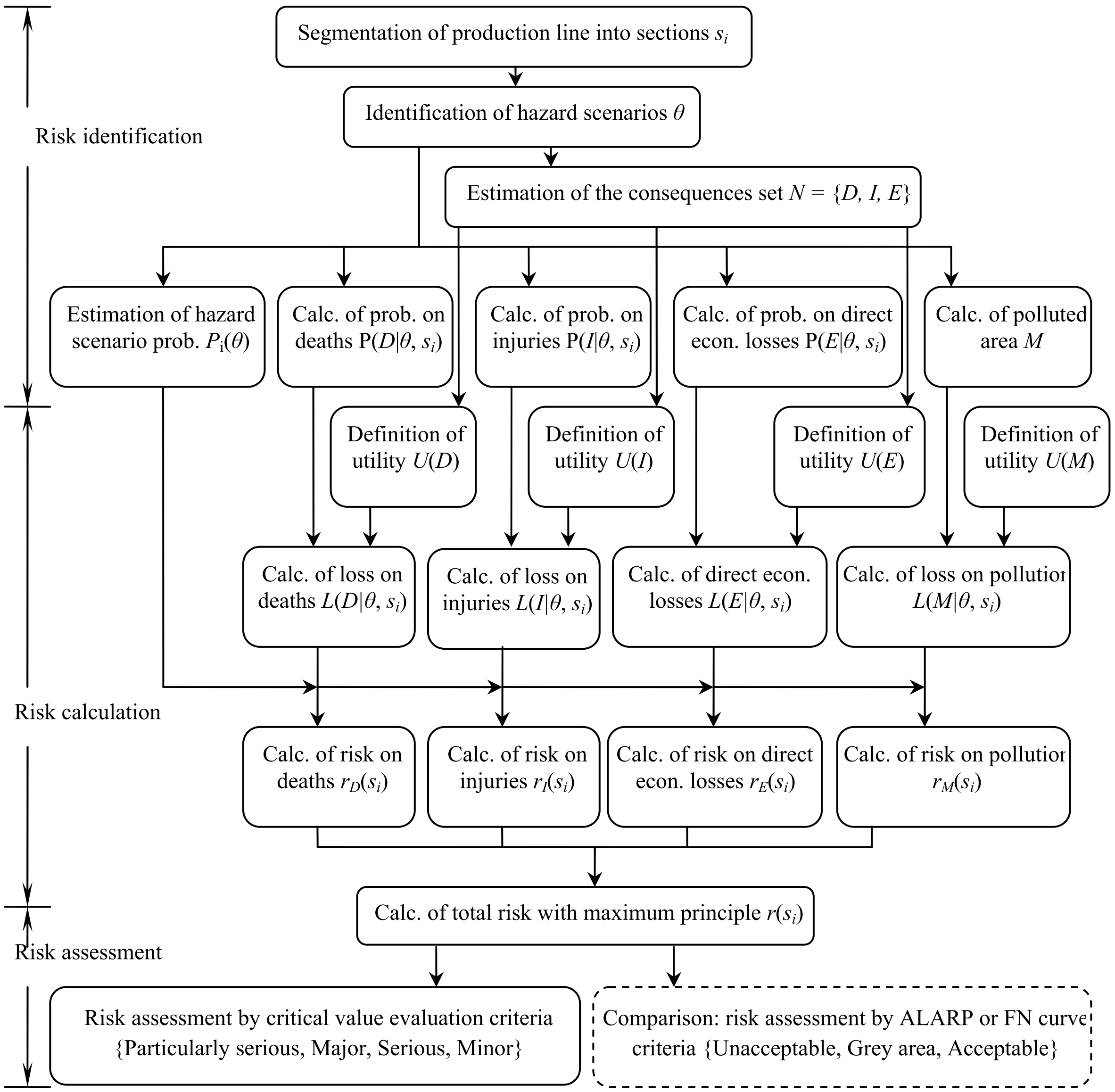

FIGURE 1. **Risk assessment flow diagram for engineering systems.**

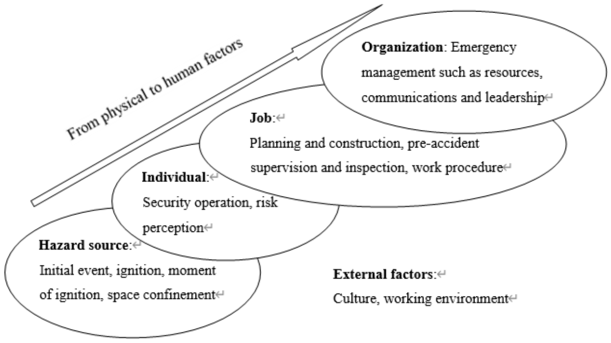

FIGURE 2. **Conceptual model of risk identification in production accidents.**

become increasingly clear that the role of management and organizational factors must be considered, rather than placing responsibility solely with the operators [40].

Because of the complex, long-term, socio-technological interaction and the secondary characteristics of the accidents, besides the hazard source, we should further consider human, organization and management system, and environment factors by building a conceptual model of risk identification in pipeline accidents. Obviously, those human factors have a significant impact on the effective and efficient risk management of pipeline accidents. It is even more important to build Disaster Recovery Plans when a pipeline accident happens.

Crisis evolution is described as having four stages of life cycle: prodromal (hints of future crisis appear), breakout (triggering events appear), chronic (crisis develops and continues), and then resolution [41]. Similarly, the main factors of oil pipeline risk assessment should be extended from the traditional physical factors to the complex human impacts, among the different evolutionary phases. In the prodromal stage, human factors include planning and construction, pre-accident supervision and inspection, etc. In the breakout stage, the hazard source contains the human factors, mainly the human-caused oil leakage. In the chronic stage, operation error caused ignition. In the resolution stage, emergency management leads to the different accident scenarios. Once referred human factors in pipeline risk assessment, the term ‘‘scenario’’ is not only related to the sense of the possible states of nature [42], but also includes the alternative strategies of DM based on the method of constructivism scenario analysis [43].

C. RISK CALCULATION BASED PROBIT EXPERIENCE FUNCTION

Based on the decision analysis approach proposed by Berger (1985), the risk for each section of the pipeline is estimated as per the following equation:

$$r(s_i) = E\left[L\left(N|\theta, s_i\right)\right] = \sum\nolimits_{\theta} P_i\left(\theta\right)\cdot L\left(N|\theta, s_i\right) \quad (1)$$

where $N = \{N, I, E, M\}$ and θ is the final accidental scenarios of pipeline accident as shown in Fig. 2, and s_i represents sections of the pipeline. $P_i(\theta)$ is the probability of each accidental scenario at section s_i, and $L(N|\theta, s_i)$ is the loss function on a consequence N, when the scenario θ and the pipeline section s_i are considered.

By developing a loss function through the utility theory construction, we have the important fact that the expected loss is the proper measure of loss in risk situations (Berger, 1985). The expected loss is given by combining the probability over some deterministic consequences N, including the injury, or loss of life, or damage to property or the environment, $N = \{D, I, E, M\}$, and the loss function (or utility function) over these consequences U(N), as shown in the following equation:

$$L\left(N|\theta, s_i\right) = -U\left(N|\theta, s_i\right) = -U\left(\int_p f\left(p|\theta, s_i\right)\cdot dp\right) \quad (2)$$

where $p \in N, N = \{D, I, E, M\}$, where $f(p|\theta, s_i)$ is the probability density function in an element p of the set of consequences N, which can be transformed by the statistical models of probit function $\Pr(p|\theta, s_i)$ [44]. Further, the probit function of consequences can be confirmed through the statistical model based on historical data [44].

In Equation (2), the expected loss is able to incorporate the DM's attitude towards risk by means of the utility elicitation. This is applied in the intra-criterion assessment process for each risk assessment attribute N such as death (D), injury (I), direct economic damage (E), or marine environment pollution (M) posed by each section of the pipeline. So the risk for each section of the pipeline is estimated as following:

$$r(s_i) = -\sum\nolimits_{\theta} P_i\left(\theta\right)\cdot U\left(\int_p f\left(p|\theta, s_i\right)dp\right) \quad (3)$$

where $p \in N, N = \{D, I, E, M\}$.

(1) Definitions of utility functions $U(D)$, $U(I)$, $U(E)$ and $U(M)$.

TABLE 1. Evaluation criterion of production safety accidents in China (PRC state council, 2007).

Categorizing of accidents	Criteria	Reporting government level
Particularly serious accident	number of deaths ≥ 30; or number of serious injuries/wounds ≥ 100; or direct economic losses ≥ 100 million RMB.	State Council
Major accident	10 ≤ number of deaths < 30; or 50 ≤ number of serious injuries /wounds < 100; or 50 ≤ direct economic losses < 100 million RMB.	State Council
Serious accident	3 ≤ number of deaths < 10; or 10 ≤ number of serious injuries /wounds < 50; or 10 ≤ direct economic losses < 50 million RMB.	Provincial level government, autonomous region government, municipalities
Accident of minor seriousness	number of deaths < 3; or number of serious injuries /wounds < 10; or direct economic losses < 10 million RMB.	City level government

The consequence about the human aspect mainly deals with the number of fatalities/deaths (D) [31], [45]. Based on the creed of ‘‘all human beings are equal’’, policymakers should not have risk preference differences among the number of deaths, which means that every life must be treated equally. This equal principle is also embodied in the right to death compensation in accordance with the provisions of law. So the utility function on the number of deaths is described as the risk neutral function $U(D) = D$.

According to the Identification Standard of Human Serious Injuries in China, when second-degree burns surface area accounts for over 30 percent of the body, it can be identified as serious injury. This evaluation index is also adopted by Brito *et al.* [4]. The Evaluation Criterion of Production Safety Accidents [25] provides the transformational relationship between the number of injuries and deaths as (10, 3), (50, 10) and (100, 30), as shown in Table 1. So the utility function on the number of injuries should be a parabolic function with risk appetite as the following:

$$U\left(I\right) = \begin{cases} 0.0025I^2 + 0.025I + 2.5 & if\ I \geq 10 \\ 0 & if\ I < 10 \end{cases} \quad (4)$$

The direct economic losses E (million RMB) refer to property losses, expenses on labor, equipment and raw material to substitute pipes, refunds to customers for interrupted production, and compensation for deaths and injuries, and so on. Unlike the human and environmental dimensions, these consequences may be the object of direct monetary estimates as shown in Table 2. Similarly, if we use million RMB as the unit of measurement, the utility function on the direct economic losses should be a parabolic function with risk appetite as following:

$$U\left(E\right) = \begin{cases} 0.0025E^2 + 0.025E + 2.5 & if\ E \geq 10 \\ 0 & if\ E < 10 \end{cases} \quad (5)$$

The assessment of damages caused by marine environment pollution is very complicated which involves many aspects such as ecological environment damages, fishery losses, restoration expenses. Some common methods, such as the Habitat Equivalency Analysis method [46]and the Natural Resource Damage Assessment process [47], are used to assess marine environment pollution impacts, which contain several indices and indicative variables. Those assessment models are suitable for ex-post assessment, but can hardly be applied to the real-time emergency management. According to the Chinese identification criterion of marine pollution accidents [48][1], we can choose some simple statistical indexes, i.e., polluted oceanic area or leakage volume, instead of the complex index of direct economic losses. Obviously, the polluted oceanic area index (M) can be equivalent to transform into direct economic losses (E), or leakage volume. So the utility function of the marine pollution is same as Equation (5).

(2) Calculation of probability functions $P(p|\theta,\ s_i)$ and losses $L(N|\theta, s_i)$.

By performing object exposure analysis, not only can danger zones, population density and fixed assets-net value be drawn up for each section of the pipeline, but also it is possible to estimate the possible environmental impacts, damage to properties, and effects on the health and safety of people exposed to fire and heat by a series of probit functions.

According to the existing literature of QRA [35], [49], the probit functions for deaths, injuries and direct economic losses can be obtained for each pair (θ, s_i) of scenario and section of pipeline. The probit function of these consequences can be confirmed through three methods: the calculation model based on the physical mechanism, the experimental determination, and the statistical model based on historical data [44]. In this paper, we adopt the relevant statistical model of probit function. The probit functions $\Pr(x)$ should transform into the probability functions $\mathrm{P}(x)$ by the conversion equation $\mathrm{P} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\mathrm{pr}-5} e^{-\frac{s^2}{2}} ds$, or on a probit transformation chart such as that provided by Finney [50].

In the open space nearby the burst point, the toxic cloud caused by pipeline explosion should be dissipated in the wind, which only pollutes the air. Thus, the number of deaths[1] due to exposure to a toxic cloud in the open space can be omitted [31]. For the exposure to heat radiation in the explosive scenarios, the vulnerability model (probit function) for death is given by [49]:

$$\Pr(D) = -36.38 + 2.56 \ln \left(Q^{4/3} t \right) \tag{6}$$

where the value of $\Pr(\cdot)$ ranges from 2.67 to 8.09 representing the probability from 1% to 99.9%, Q is heat radiation (W/m^2), $Q \leq 35$ kW/m^2, and t is exposure time (s), $t \leq 20$s, where the two variables depend on the scenario and section of pipeline (θ, s_i).

From lethality data for different magnitudes of "fires of hydrocarbons", a probit function for second-degree burns in both the explosive and the flame scenarios can be derived [44]:

$$\Pr(I) = -43.14 + 3.0186 \ln \left(Q^{4/3} t \right) \tag{7}$$

In order to calculate analytically the probability of a given degree of damage, a suitable damage criterion and a probit function should be given, we adopt the criterion of "major structural damage" [51] to describe the direct economic losses (E) caused by pipeline accidents. Because the damage of houses or apartment buildings higher than four stories seldom occurs in the explosive scenarios of pipeline accidents, so we only consider the probit function for houses or apartment buildings up to 4 stories as follows [44]:

$$\Pr(E) = 5 - 0.26 \ln \left[\left(\frac{17500}{P_s} \right)^{8.4} + \left(\frac{290}{i_s} \right)^{9.3} \right] \tag{8}$$

where P_s is side-on peak overpressure (Pa), and i_s is positive impulse of the side-on blast (Pa.s). For the blast with the shape of shock or pressure wave, $i_s = 0.5 P_s \cdot t_p$, where t_p is the positive phase duration. Those variables also depend on the scenario and section of pipeline (θ, s_i).

According to the regulations of State Environmental Protection Administration (SEPA) [52], in practice the marine environment pollution damage is assessed by the polluted oceanic area. The computation of polluted oceanic area adopts the Blocker formula:

$$D_t^3 = D_0^3 + \frac{24}{\pi} K \left(\gamma_w - \gamma_0 \right) \frac{\gamma_0}{\gamma_w} V_0 t \tag{9}$$

where D_t and D_0 are the diameters of the oil film at time 0 and t (m); γ_w and γ_0 are the specific gravity of water and oil; V_0 is the leakage volume (m^3); t is the diffusing time (min) and K is constant $K = 15000$/min. The variables of leakage volume and diffusing time depend on the scenario and section of pipeline (θ, s_i).

According to the utility functions $U(N)$ and the probability functions $\mathrm{P}(p|\theta,\ s_i)$ for the first three dimensions $N = \{D, I, E\}$, the loss $L(N|\theta, s_i)$ from an accident scenario in each section s_i of pipeline is obtained as follows:

$$L\left(N|\,\theta, s_i\right) = -U\left(P\left(p|\,\theta, s_i\right) \cdot N\right) \tag{10}$$

where $p \in N, N = \{D, I, E\}$.

For the assessment criterion of marine environment pollution, we can calculate the accurate value of polluted oceanic area M (square kilometers) and the loss $L(M|\theta, s_i)$ as follows:

$$\begin{aligned} L\left(M|\,\theta, s_i\right) &= -U\left(M\right) \\ &= \begin{cases} -0.0025M^2 - 0.025M - 2.5 & \textit{if } M \geq 10 \\ 0 & \textit{if } M < 10 \end{cases} \end{aligned} \tag{11}$$

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[1] As the first relevant regulation in China, the "Treatment method for marine environment pollution damage and fisheries area pollution accident in Fujian province" proposes that a serious marine environment pollution accident can be confirmed, when any one of the following conditions is satisfied: direct economic losses ≥ 10 million RMB; polluted oceanic area ≥ 10 square kilometers; or leakage volume ≥ 10 tons.

D. RISK ASSESSMENT APPROACH BY CHINESE PRODUCTION SAFETY ACCIDENTS ASSESSMENT CRITERION

So far, China has not established any consistent societal risk criterion [52]. However, according to the "Byelaw governing reporting, investigation and handling of production safety accidents" issued by PRC State Council [25], a production safety accident can be classified into four risk categories {particularly serious, major, serious, minor}, in terms of bodily injuries, deaths, or direct economic losses. If any case exceeds the thresholds, the relative accident level can be confirmed. Moreover, under the "One ticket veto system for production safety" in China, once any serious accident happens, the total performance evaluation can be determined to be unqualified. Thus, according to Chinese risk management practices, the consequence assessment criteria are adopted instead of the FN curve criteria and the ALARP principle that are frequently adopted in some developed countries.

To describe the maximum relationship by considering the most pessimistic consequence among multiple attributes, this paper introduces the maximum function to the QRA of pipeline accidents. Another advantage of the maximum function applied to QRA is that it is easy to calculate in practice. As the more reasonable risk assessment criterion, it needs to consider both the consequences and the probabilities, such as the FN curve. However, the Chinese assessment criteria neglect the probability of occurrence of the possible accident scenarios. In this paper, the relative probabilities among all the hazard scenarios are introduced into the existing risk consequences assessment criterion:

$$r'_N(s_i) = -\sum_{\theta}\left(\frac{P_i(\theta_j)}{\sum_j P_i(\theta_j)} \cdot U\left(\mathrm{P}\left(p|\,\theta_j, s_i\right)\cdot N\right)\right) \tag{12}$$

where $N = \{D, I, E, M\}$.

The total risk assessment of pipeline accidents based on the maximum function is shown as following:

$$r'(s_i) = \max\left\{r'_D(s_i), r'_I(s_i), r'_E(s_i), r'_M(s_i)\right\} \tag{13}$$

E. OTHER RISK ASSESSMENT APPROACHES BY THE FN CURVE CRITERION AND THE ALARP PRINCIPLE

By contrast, we further make risk assessment of pipeline accidents by the FN curve criterion and the ALARP principle used in some developed countries [53], where the risk related to a particular section of the pipeline is obtained by the event cumulative frequencies and the number of fatalities, and risk within the ALARP area is considered acceptable.

In the FN curve, for the sake of simplicity, it has often been assumed that risk criteria for major hazards should relate to the likelihood of death. In this paper, according to the national regulations [25], we further equivalently extend the death criterion in the FN curve to include four assessing attributes: injury, fatality, property damage, and environment pollution. From the viewpoint of the FN curve, the risk value with a pair of numbers $r_N(F, N|s_i)$ can be calculated as per the following equation:

$$r_N(F, N|\,s_i) = \left(\sum\nolimits_{N\neq 0} P_i\left(N|\,\theta\right), -\sum\nolimits_{N} U\left(P\left(p|\,\theta, s_i\right)\cdot N\right)\right) \tag{14}$$

where $N = \{D, I, E, M\}$.

Under the "One ticket veto system for production safety", we need to identify the maximal risk value with a pair of numbers $r_N(F, N|s_i)$ among all of risk attributes $N = \{D, I, E, M\}$ by the aid of the FN curve. Similarly, based on the FN curve, the maximum function is used to obtain the total risk assessment as following:

$$r(s_i) = \max\left\{r_D(s_i), r_I(s_i), r_E(s_i), r_M(s_i)\right\} \tag{15}$$

Comparing two risk assessment standards between the FN curve (or the ALARP) criteria and the Chinese accident criteria, the FN curve pays more attention on the event cumulative frequencies, but the Chinese accident criterion pays more attention on the accident consequences. More detailed comparison can be seen in the analysis of the following case.

III. CASE STUDY OF THE QINGDAO PIPELINE ACCIDENT

In this section, as an illustration of the use of the proposed non-weighted decision model with maximum principle for multi-attribute risk assessment, a case study of the Qingdao Pipeline Accident is presented.

A. INTRODUCTION OF QINGDAO PIPELINE ACCIDENT

Qingdao is one of China's largest crude oil import terminals, supplying at least two major refineries of the China Petroleum & Chemical Corporation (Sinopec)- the Qingdao Plant and the Qilu Petrochemical Corporation - as well as many small, independent refineries. It includes the Dong-Huang Pipeline No. 2 and the Guang-Qi oil pipeline. Since 1998, Sinopec adjusted the eastern pipe network. The Dong-Huang Pipeline No. 2 begins to adversely pipe imported oil from Huangdao oil terminal to Qilu Petrochemical Corporation, and the section of Guangrao-Dongying was shut down [54]. The structure diagram of Dong-Huang Pipeline No. 2 is shown in Figure. 3.

In the early morning of November 22, 2013, there was a crude oil leakage. When workers were cleaning up the leakage, two explosions occurred. The disaster caused at least 62 deaths and 136 injuries in urban residential areas, resulting in a direct economic loss of 750 million yuan [55]. Petroleum

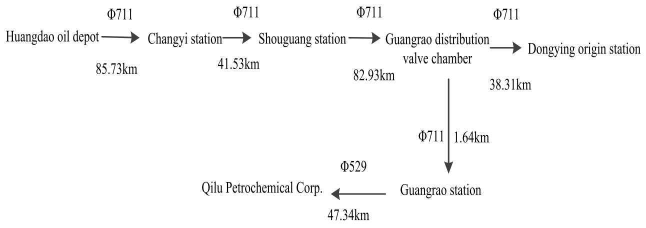

FIGURE 3. Structure diagram of the Dong-Huang Pipeline No. 2.

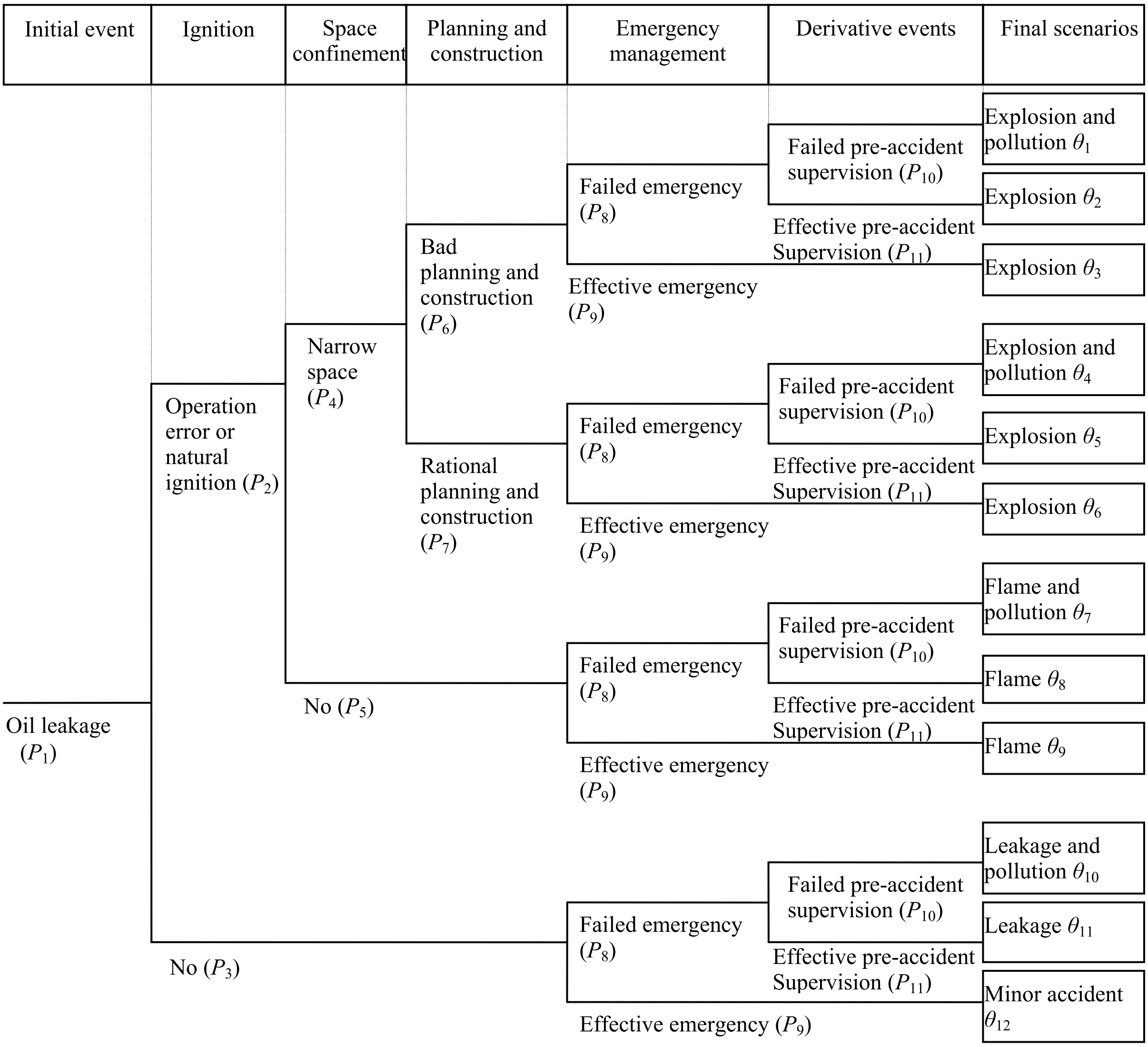

FIGURE 4. Event tree diagram of pipeline accidents with life-cycle viewpoint.

from the pipeline contaminated about 3,000 square meters of water and 18,000 people had to be evacuated, according to authorities [56]. The accident is the deadliest this year in China, and the Central government blamed the blast on human errors.

B. ACCIDENT SCENARIO ANALYSIS

From the viewpoint of life-cycle of in crisis management, a set of pipeline accidental scenarios derived from physical and human factors are shown in Figure. 4.

According to the structure diagram of the Dong-Huang Pipeline No. 2 in Figure. 3, the pipeline grid was segmented into 7 different sections. These segments were divided according to the several technical factors such as: age of the pipeline section, pipe diameter, soil characteristics, land occupation, degree of third-party interference, and demographic concentration on the surface area surrounding each section. The probabilities of the initial and pivotal events are derived from the report of EGIG [57], which are shown in Table 3. As the initial event, the primary failure frequency of oil leakage is 0.000351km/yr. Though the construction year have some effects on the failure frequency of corrosion, the cause of corrosion accounts for only 16.1% of the failure frequency of oil leakage. So the factor of construction year is omitted. Fortunately not every leakage ignites, which limits the consequences of the accidents. In the period 1970-2010, only 4.5% of the leakages recorded as accidents in the EGIG database ignited.

Due to historical reasons, the construction of buildings is without planning; the pipeline layout is unreasonable; the residential buildings are too close to the pipeline. These hidden dangers are widely found in many of the fast-developing cities in China. Once the crude oil leaks into other civil pipelines with narrow space, the mixed gas is highly explosive. Otherwise, the leaked gas is easily evaporated in the open space such as in the field [58].

TABLE 2. Probabilities estimated for the initial and pivotal events.

Probabilities	P_1	P_2	P_3	$P_4(s_{1,7})$	$P_5(s_{1,7})$	$P_5(s_{2\text{-}6})$	$P_6(s_1)$	$P_7(s_{2\text{-}7})$	P_8	P_9	P_{10}	P_{11}
Values	0.000351	0.045	0.955	0.8	0.2	1	1	1	0.538	0.462	0.984	0.016

TABLE 3. Probabilities estimated for the accidental scenarios and for each section of the pipeline.

Probability	s_1 Huangdao oil depot - Yanghe river (20.4 kms, 28 yrs)	s_2 Yanghe river - Changyi station (65.33 kms, 28 yrs)	s_3 Changyi station – Shouguang station (82.93 kms, 28 yrs)	s_4 Shouguang station - Guangrao valve chamber (41.53 kms, 28 yrs)	s_5 Guangrao valve chamber - Guangrao station (1.64 kms, 16 yrs)	s_6 Guangrao station – Jiqing highway (35.84 kms, 16 yrs)	s_7 Qilu Petrochemical Corp. (11.5 kms, 16 yrs)
$P_1(s_i)$	0.00716	0.02293	0.02911	0.01458	0.00058	0.01258	0.00404
$P_i(\theta_1)$	$136.46*10^{-6}$	0	0	0	0	0	0
$P_i(\theta_2)$	$2.22*10^{-6}$	0	0	0	0	0	0
$P_i(\theta_3)$	$119.09*10^{-6}$	0	0	0	0	0	0
$P_i(\theta_4)$	0	0	0	0	0	0	0
$P_i(\theta_5)$	0	0	0	0	0	0	$78.25*10^{-6}$
$P_i(\theta_6)$	0	0	0	0	0	0	$67.19*10^{-6}$
$P_i(\theta_7)$	$34.11*10^{-6}$	0	0	0	0	0	0
$P_i(\theta_8)$	$0.55*10^{-6}$	$555.14*10^{-6}$	$704.75*10^{-6}$	$352.98*10^{-6}$	$14.04*10^{-6}$	$304.56*10^{-6}$	$19.56*10^{-6}$
$P_i(\theta_9)$	$29.77*10^{-6}$	$476.72*10^{-6}$	$605.20*10^{-6}$	$303.12*10^{-6}$	$12.06*10^{-6}$	$261.54*10^{-6}$	$17.80*10^{-6}$
$P_i(\theta_{10})$	0.00362	0	0	0	0	0	0
$P_i(\theta_{11})$	$58.86*10^{-6}$	0.01178	0.01496	0.00749	$298.00*10^{-6}$	0.00646	0.00208
$P_i(\theta_{12})$	0.00316	0.01012	0.01284	0.00643	$255.90*10^{-6}$	0.00555	0.00178

According to "Code for design for oil transportation pipeline engineering (GB50253-2003)", the distance between crude oil pipeline and urban settlement or crowded houses should not be less than 15 meters [59]. By 2013, the continuous expansion of Huangdao district has occupied the oil pipeline about 16 kilometers, which means huge potential security problems [60].

Up to 2010, 53.8% of the accidents were detected by the public, clients, landowners and other unknown sources, which falls into the failed emergency management. The other 46.2% of the accidents were detected by the patrol, contractors, company staffs, or river police, etc., which is in the effective emergency management. The on line inspection with 1.6% of the accidents is the most common pre-accident supervision [57].

Based on the basic frequency for occurrence of a leakage [57], the probability for the initial event $P_1(s_i)$ can be estimated, taking into account the length of sections s_i of the pipeline. The total failure rate is calculated by adding each failure rate from other causes, such as security operation, space confinement, planning and construction, emergency management, pre-accident supervision, etc. Based on 12 scenarios presented in the Event Tree of Figure. 4, and the probabilities estimation for the pivotal events in Table 2, the accidental scenario probabilities $P_i(\theta)$ of the Dong-Huang Pipeline No. 2 could be estimated as shown in Table 3.

In the case of Dong-Huang Pipeline No. 2, sections $s_2 - s_6$ located in rural plain areas with open space, so the accidental scenario probabilities occurred in the narrow space $P_{2-6}(\theta_{1-6})$ are all zeros. Moreover, because sections $s_2 - s_7$ located in the inland areas away from the coast, the accidental scenario probabilities of marine pollution $P_{2-7}(\theta_{1,4,7,10})$ are zeros, too. For section s_1 in Huangdao district, because of the construction of buildings without planning, the accidental scenario probabilities with the rational planning and construction $P_1(\theta_{4,5,6})$ are all zeros. Similarly, for section s_7 in Qilu Petrochemical Corporation, because of the rigorous facilities planning, the accidental scenario probabilities with the bad planning and construction $P_7(\theta_{1,2,3})$ are zeros. So the accidental scenario θ_4 with zero probabilities of every section can be omitted.

C. PARAMETER CALIBRATIONS OF THE LOSS FUNCTIONS

To estimate the net values of the fixed assets in Huangdao district and Qilu Petrochemical Corporation, we quote from the assessed net values of the fixed assets of Tianjin Binhai New Area where the net value of the fixed assets is 292 million RMB per square kilometer in 2010 [61]. The net value of the fixed assets in rural areas can be omitted except the value of the pipeline itself. The safety distance between crude oil pipeline and urban settlement or crowded buildings should not be less than 15 meters [59]. Because of the rational planning and construction in the district of the Qilu factory, the danger zones of section s_7 are reduced to 5 meters. Population densities of the Qingdao Economic and Technological Development Zone (section s_1), Gaomi (section s_2), Changyi (section s_3), Shouguang (section s_4), Guangrao (section $s_{5,6}$) and Qilu factory's district (section s_7) are 2189, 574, 382.3, 545.5, 439.4 and 2116 people per square kilometer, respectively. So the total number of people $N(s_i)$ exposed in the danger zones of section s_i can be calculated. Parameter calibrations in different scenarios and the damage

TABLE 4. **Parameter calibrations and damage probabilities.**

Scenarios	Parameters	Source	Probit value	Damage probability
Failed emer.: 20cm from flame	Q = 14167W/m^2, t = 15s	Zhu and Chen (2000)	Pr(D) = 3.17	$P(D\|\theta_{1,2,4,5})$=0.034
Effective emer.: 30cm from flame	Q = 8530W/m^2, t = 15s	Zhu and Chen (2000)	Pr(D) = 1.44	$P(D\|\theta_{3,6})$=0.005
Failed emer.: 20cm from flame	Q = 14167W/m^2, t = 15s	Zhu and Chen (2000)	Pr(I) = 3.50	$P(I\|\theta_{1,2,4,5,7,8})$=0.066
Effective emer.: 30cm from flame	Q = 8530W/m^2, t = 15s	Zhu and Chen (2000)	Pr(I) = 1.46	$P(I\|\theta_{3,6,9})$=0.005
Explosion scenarios	P_s = 5000Pa, t_p = 0.5s	TNO (1992) (Ch.2, p.53)	Pr(E) = 5.08	$P(E\|\theta_{1\text{-}6})$=0.53
Explosion scenario: t = 10days	$_0$ = 0.86, V_0 = 44.25 t/min	Wu, et al. (2004)	D_t = 2063.9m	$M(\theta_{1,4})$ = 3.45 sq km
Flame scenario: t = 300mins	$_0$ = 0.86, V_0 = 44.25 t/min	Wu, et al. (2004)	D_t = 567.9m	$M(\theta_7)$ = 0.25 sq km
Leakage scenario: t = 60mins	$_0$ = 0.86, V_0 = 44.25 t/min	Wu, et al. (2004)	D_t = 332.1m	$M(\theta_{10})$ = 0.087 sq km

TABLE 5. **Loss values of single criterion for each section of the pipeline.**

Risk	s_1 Huangdao oil depot - Yanghe river (20.4km*15m)	s_2 Yanghe river - Changyi station (65.33km*15m)	s_3 Changyi station – Shouguang station (82.93km*15m)	s_4 Shouguang station - Guangrao valve chamber (41.53km*15m)	s_5 Guangrao valve chamber - Guangrao station (1.64km*15m)	s_6 Guangrao station – Jiqing highway (35.84km*15m)	s_7 Qilu Petrochemical Corp (11.5km*5m)
$N(s_i)$	670	562	476	340	11	236	122
$L(D\|\theta_{1,2,4,5})$	-23	0	0	0	0	0	-4
$L(D\|\theta_{3,6})$	-3	0	0	0	0	0	-1
$L(I\|\theta_{1,2,4,5,7.8})$	-9(45)	-7(37)	-6(32)	-4(23)	-0(0.7)	-4(16)	-0(8)
$L(I\|\theta_{3,6,9})$	-0(3)	-0(3)	-0(2)	-0(2)	-0(0)	-0(1)	-0(0)
$L(E\|\theta_{1\text{-}6})$	-9(47.4)	0	0	0	0	0	-0(8.9)
$L(M\|\theta_{1,4})$	-0(3.45)	0	0	0	0	0	0
$L(M\|\theta_7)$	-0(0.25)	0	0	0	0	0	0
$L(M\|\theta_{10})$	-0(0.087)	0	0	0	0	0	0

Note: Values in the parentheses are the number of second-degree burns, or the direct economic losses (million RMB), or the polluted oceanic area (sq km).

probabilities are described in Table 4, where the specific gravity of water and crude oil imported from the Middle East is about 0.86 in the Huangdao oil port [54].

D. PARAMETER CALIBRATIONS OF THE LOSS FUNCTIONS

In order to estimate the one-dimensional loss $L(N|\theta_i, s_i)$, the combination of the damage probabilities $P(N|\theta_i)$ to the relative number of hazard-bearing body in the danger zones N was undertaken. The results can be seen in Table 5. All the four types of risk attributes (damage) occurred in section s_1 located in the urban area of Huangdao district. Except for the marine pollution damage, other three types of risk criterion also applied in section s_7 located in the factory area of Qilu Petrochemical Corporation. Because other sections are located in the rural plain area, the main damage comes from serious burns which are under the failed emergency management.

Lastly, after obtained the loss values and the accident scenario probabilities, the risk assessment criteria of the Chinese accident standard $r'_N(s_i)$ [25] is compared with the FN curve $r_N(s_i)$ [44] for each section of the pipeline, as described in Table 6.

For the Chinese production safety accident criterion, only the number of people in the danger region depends on the length of a section, but the accident scenario relative probabilities are independent of the length after standardizing the scenario probabilities. So the Chinese production safety accident criterion pays more attention to the risk consequences per unit length of the pipeline. In the second row of Table 7, the results show that section s_1 in Huangdao district is assigned to the "Major" risk level. Once a pipeline accident occurs in section s_1, it should be expected to be a major accident of more than 10 fatalities. For example, the "11.22" Qingdao pipeline accident killed at least 62 people in 2013. Sections s_2 and s_3 in the rural plain areas are assigned to the "Serious" risk level, where the main damage scenario is the second-degree burns of flame because of failed emergency management. Section s_7 in Qilu factory is also assigned to the "Serious" risk level, where the main damage comes from explosion because of failed emergency management. Other remaining sections are in the "Minor" risk level. Although marine environmental pollution has been considered in this paper, the loss value of single criterion of marine pollution is very low such that it fails to meet the basic accident standard. It reflects that

TABLE 6. Risk assessments comparison between the Chinese accident standard and the FN curve.

Risk	s_1 Huangdao oil depot - Yanghe river (20.4km*15m)	s_2 Yanghe river - Changyi station (65.33km*15m)	s_3 Changyi station – Shouguang station (82.93km*15m)	s_4 Shouguang station - Guangrao valve chamber (41.53km*15m)	s_5 Guangrao valve chamber - Guangrao station (1.64km*15m)	s_6 Guangrao station – JiQing highway (35.84km*15m)	s_7 Qilu Petrochemical Corp (11.5km*5m)
$r'_D(s_\mathrm{i})$	-13.8	0	0	0	0	0	-2.6
$r'_I(s_\mathrm{i})$	-4.8	-3.8	-3.2	-2.2	0	-2.2	0
$r'_E(s_\mathrm{i})$	9	0	0	0	0	0	0
$r'_M(s_\mathrm{i})$	0	0	0	0	0	0	0
QRA(Chinese)	-13.7/Major	-3.8/Serious	-3.2/Serious	-2.2/Minor	-0.4/Minor	-2.2/Minor	-2.6/Serious
$r_D(\mathrm{F,N}\|s_\mathrm{i})$	$(258*10^{-6},-26)$	0	0	0	0	0	$(145*10^{-6},-5)$
$r_I(\mathrm{F,N}\|s_\mathrm{i})$	$(173*10^{-6},-9)$	$(555*10^{-6},-7)$	$(705*10^{-6},-6)$	$(353*10^{-6},-4)$	$(14*10^{-6},-0.7)$	$(305*10^{-6},-4)$	0
$r_E(\mathrm{F,N}\|s_\mathrm{i})$	$(258*10^{-6},-9)$	0	0	0	0	0	0
$r_M(\mathrm{F,N}\|s_\mathrm{i})$	0	0	0	0	0	0	0
QRA(F-N)	$(258*10^{-6},-26)$	$(555*10^{-6},-7)$	$(705*10^{-6},-6)$	$(353*10^{-6},-4)$	$(14*10^{-6},-0.7)$	$(305*10^{-6},-4)$	$(145*10^{-6},-5)$

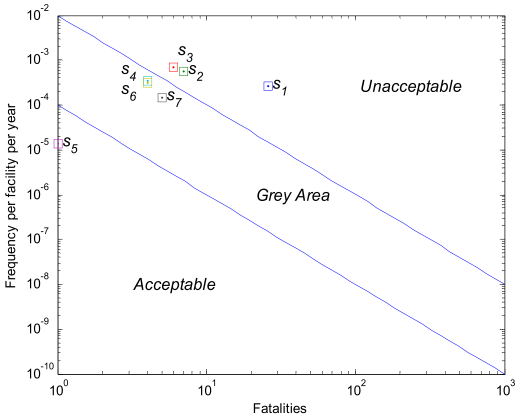

FIGURE 5. Societal risk values of pipeline accident in the log-log plot of the FN curve.

the accident standard of marine pollution maybe lags behind the actual need for marine environmental protection.

In order to make more explicit description for the risk assessment values of the FN curve, the corresponding risk values are described on the log-log plot of the FN curve in Figure. 5, where the comparison of risk values for each section of the pipeline is $s_1 > s_2 > s_3 > s_4 > s_6 > s_7 > s_5$. The result shows that the appraisals of the first three sections are "Unacceptable" level of risk. Only the risk value of the very short section s_5 is at the acceptable level, as the transition part of the valve chamber and the pump station. Other remaining sections are at risk of grey areas. Moreover, because of having longer lengths, sections s_2 and s_3 are assigned to the higher risk values despite the fact that they are in rural plain areas. Section s_7 of Qilu Petrochemical Corporation is assigned the lower risk value among all of the sections except the transition part s_5, because of its shorter length and well planning and construction. Comparing to sections s_2 and s_3, the risk value of section s_1 in Huangdao district is not very high, too. Those results of risk assessment are not consistent with common sense and historical data that pipeline sections located at the urban and factory areas are usually at higher risk, because of the higher human-population density, complex sociotechnical systems and the fragile environment. The direct and main reason is that the risk assessment standard of the FN curve has itself inherited flaws.

According to the definition, the risk assessment criteria of the FN curve provides a functional relation between event cumulative frequencies F and the number of equivalent fatalities N. Not only the event cumulative frequencies F depend on the length of a section, but the number of fatalities N depends on the length, too. Thus, risk assessment based on the FN curve experiences the "superimposed effect" on the length of pipeline. However, policymakers are more concerned with the risk intensity than the cumulative risk consequences along with the length of pipeline. Otherwise, only a subdivision of the original section can reduce the risk without any other risk control measurement.

IV. CONCLUSION

Along with the increasing complexity of socio-technical system in modern society, some human errors further aggravate the vulnerability of the system, which leads to a particularly high probability for all kinds of safety accidents with serious consequences. As the risk assessment system with Chinese characteristics, "One ticket veto system for production safety" highlights seriousness and importance of production safety management problem. From the practical point of view, how to effectively assess the risks and then to perform risk control become important challenges to policymakers.

Coming from the Chinese production safety management practice, this paper discusses a non-weighted multi-attribute approach with the maximal principle for risk assessment of oil pipelines. Its main contribution includes the following three parts. Firstly, from the viewpoint of life cycle, the paper builds an Event Tree Analysis model of pipeline accident considering the human factors after the leakage as dangerous sources occurs, such as operational errors, planning and construction, pre-accident supervision, emergency responses, etc. Secondly, besides the human or property losses, marine environmental pollution is taken as another risk attribute of pipeline accidents. According to the national regulations, the relative simple index of "polluted oceanic area" is chosen as the criterion of marine pollution accidents instead of "direct economic losses". Thirdly, the paper provides a non-weighted multi-attribute risk assessment model with the maximal principle, according to the "One ticket veto system for production safety" in practice. Moreover, the societal risk assessment criteria of the FN curve and the ALARP principle are compared with the Chinese production safety accident criterion. The results show that the Chinese production safety accident criterion pays more attention to the risk density (risk value in the unit space) or risk consequences in the intuitive sense, which is useful when targeting the measurement of risk control for the vulnerable sections.

An obvious question is whether there will be any evidence that the risk consequences assessment method, aimed at Chinese risk management scenario, is appropriate to other developed countries with well risk management systems. The European Agency for Safety and Health at Work (EASHW) and the United States Occupational Safety and Health Review Board (OSHRC) classify accidents into 3 or 4 risk categories according to their severity in order to facilitate effective risk management, which is also the common practice in many countries. The non-weighted multi-attribute risk assessment model with the maximal principle provides the more effective, practical, and maneuverable risk assessment approach. The assessment system with the characteristics of "one ticket veto system for production safety" has applied to ex ante assessing likelihood of the accident, and ex post holding the responsible for accidents.

There are also issues for future research. First of all, risk assessment is a group decision making problem that encompasses managers' preferences and value judgments in the decision-making processes [4]. Although the life cycle of pipeline accidents and some human factors are introduced in this paper, there is still an absence of conflict analysis among the different stockholders, such as nearby residents, oil and pipeline companies, local government, etc. Second, even if marine environment population is adopted as a new assessing index, the result of risk assessment of the Qingdao pipeline is not noticeable. One reason is that the simplified Blokker formula of polluted oceanic area recommended by Chinese SEPA [59] does not consider the dynamic influence of other complex factors such as waves, tides and wind directions, and the other reason is the overly loose assessment standards of marine environment pollution in China. In many developing countries, risk assessment standards need continuous improvement, especially for marine pollution.

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LEI WANG (Member, IEEE) received the Ph.D. degree from the University of Science and Technology Beijing. He is currently an Associate Professor with the School of Narcotics Control and Public Order Studies, Criminal Investigation Police University of China. His research interests include emergency management and algorithm.

XIN WANG received the Ph.D. degree from Northwest A&F University. She is currently an Assistant Professor with the School of Narcotics Control and Public Order Studies, Criminal Investigation Police University of China. Her research interests include emergency management and public security.

ZHAOWEI DING is currently pursuing the Ph.D. degree with the University of Science and Technology Beijing. His research interests include emergency management and algorithm.

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