Heliyon 10 (2024) e26471

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Decision model for binary safety management behavior in a supply chain under digital scenarios: A study based on differential game theory

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ARTICLE INFO

Keywords:
Digital context
Safety organization
Safety R&D
differential game

ABSTRACT

The purpose of this study is to expand and deepen research in the field of safety production, explore the role of enterprises as decision-making entities in safety production, analyze the role of different types of decision-making behaviors in the process of enterprise safety production, and provide certain theoretical guidance for multi-agent decision-making in safety production. By summarizing and comparing the existing dual system of supply chain safety management, this study proposes dividing supply chain safety management into the two categories of safety organization and safety research and development (safety R&D) in the context of digitalization. Differential equations are established to describe a two-level supply chain safety management problem including manufacturers and suppliers. The research results show that, compared with the Nash equilibrium, when there are strong manufacturers involved in safety management cooperation, the manufacturer's safety R&D subsidy to suppliers improves the total revenue of the supply chain. When the manufacturer's safety organization supervision efficiency is high, the Stackelberg equilibrium is lower. It is a Pareto improvement for the manufacturer to supervise the supplier's safety organization to the Nash equilibrium. In the case of dual safety cooperation in the supply chain, when there are strong manufacturers, R&D subsidies have a crowding out effect on the safety organization cooperation. Finally, based on the example analysis, relevant suggestions are put forward for supply chain safety management.

1. Introduction

Economic globalization has brought about a refinement of the division of labor in society, deepening the links between upstream and downstream enterprises and forming an intertwined supply chain network. However, the rapid development of information technology and profound changes in the external environment make it difficult for these complex and sophisticated organizational systems to resist various impacts from both internal and external sources, as well as any link containing unpredictable risks. In addition, once the risks occur, a knock-on effect will be triggered, causing an incalculable negative impact on the core reputation of the supply chain. This, in turn, will give rise to safety management problems [1].

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https://doi.org/10.1016/j.heliyon.2024.e26471
Received 4 September 2023; Received in revised form 7 February 2024; Accepted 14 February 2024
Available online 23 February 2024

Supply chain safety issues not only pose a threat to the safety of employees and consumers in the supply chain, but they also inhibit the sustainable development of enterprises in the supply chain, especially small- and medium-sized enterprises (SMEs). The technological changes brought about by Industry 4.0 bring important opportunities for process safety and environmental protection [2]. Digitization is an important component of the upgrading of chemical safety. The intelligent process planning assisted by deep learning and decision algorithms based on artificial intelligence bring important opportunities for safety management, which can significantly improve production efficiency and reduce safety risks [3–5]. For example, BASF, a pioneer in the digitization of chemical companies, has provided a model for the safe and smooth operation of chemical plants by enabling "R&D + production + supply chain building" through emerging technologies, such as 5G [6].

On June 19, 2020, BASF signed a cooperation agreement with Guangzhou Auto New Energy's smart eco factory to explore digital solutions for the automotive industry. By providing a customized digital platform and training opportunities for GAC New Energy's employees, BASF has improved the efficiency and safety of GAC New Energy's paint shop production, reduced the frequency of operators' close contact with spray paint and had a positive impact on the employees' occupational health. The partnership is also part of BASF's "1 + 3″ corporate social responsibility program. Since 2006, the company has been collaborating with Chinese suppliers on environmental protection, occupational health and safety, and production safety through technical support, safety training, and business coaching. By encouraging its suppliers to practice social responsibility, BASF has strategically reduced operational risks in the supply chain, both upstream and downstream. The reputation of the supply chain has also been improved and has thus become an important tool used by BASF to improve its global competitiveness and achieve a win-win situation [7].

Profound changes in the policy environment and the continuous development of science and technology have led to a constant change in the elements and boundaries of safety management systems. Identify different safety management concepts based on existing research, this paper summarizes two typical binary safety management systems. One system is based on the different characteristics of the supply chain's upstream and downstream, dividing the safety management area into internal supply chain safety management and external supply chain safety management [8]. The other system distinguishes between employees and managers, dividing the safety management area into employee safety management and leadership safety management [9].

Internal supply chain safety management comes down to collaboration and control within the company and is the basis upon which the safety of production and continued operation are ensured. Successful internal supply chain safety management requires cooperation and coordination between the procurement and supply chain within the company [10]. Internal supply chain safety management can be defined from a behavioral perspective as defensive and responsive, this mainly focuses on quality management and has a positive relationship with safety performance [11]. The former is a control-based approach, which regulates potential problems in a company's operations before they arise. This is mainly achieved by regulating elements such as product production standards, employee operating practices and the company's production environment, with the aim of reducing the occurrence of safety problems from an institutional perspective. The latter is an innovative means of improving the existing standardized management processes and norms, according to changes in the external institutional environment. In this way, the quality of safety management is continuously improved and can quickly adapt to changes in the external environment [12]. External supply chain safety management emphasizes vertical cooperation between the upstream and downstream of a supply chain. Studies have also shown that vertical cooperation between the upstream and downstream of a supply chain significantly improves the quality of supply chain safety [13]. In terms of degree, vertical cooperation between supply chain members can be divided into two stages, namely synergy and sharing. Safety synergy focuses on the management of processes and elements between upstream and downstream companies in the supply chain. This synergistic management deepens supply chain safety cooperation and improves the quality of safety management [14]. Supply chain information sharing refers to taking the initiative to seamlessly connect the information of all elements of upstream and downstream enterprises in the supply chain through the Internet, the Internet of Things, and other technical means. The ultimate aim is to build a three-dimensional, all-round supply chain safety management cooperation mechanism. Under the information sharing mechanism, moral hazard and adverse selection problems will be effectively curbed, providing a good foundation for the core reputation of the supply chain [15,16].

The boundaries of safety management are judged through individual behavior, while employee safety behavior in the organization presents the two dimensions of active and passive. Passive safety behavior is mainly reflected in safety compliance, i.e. consciously complying with safety rules and regulations at work and developing good safety behavior habits [17]. Active safety behavior consists of safety participation and safety communication. Safety participation refers to employees taking the initiative to improve their own safety skills and to take the initiative in the daily safety organization [18]. Safety communication refers to employees taking the initiative to communicate with each other to identify safety risks and reduce the chances of accidents through communication [19]. Leadership safety behavior is similar to employee safety behavior and can also be summarized as passive safety behavior and active safety behavior. In recent years, there has been an increase in the importance attached by business leaders to safety management in their enterprises, largely out of concern for accountability. This is a passive behavior, and managers very often do not have a deep understanding of the connotations of safety management [20]. Active safety management, on the other hand, requires managers to have a professional knowledge base and rational decision-making ability. They must also be able to identify in advance possible risk points in the production process, so as to prevent problems before they occur [21].

The rapid development of science and technology and the profound changes in the policy environment have led to new features in safety management. The traditional safety management model is mainly an experience-based management model that focuses on summing up the lessons learned from the past to formulate safety regulations. This model lacks the innovation in management thinking and safety technology needed to meet the needs of the rapid development of the modern economic situation. The traditional safety management model can be defined as a form of safety organization, brought about through operational, governance and compliance learning through experience [22]. The model mainly includes defensive measures in internal supply chain safety management, safety synergy in external supply chain safety management, safety compliance in employee safety behavior and passive safety management in leadership safety behavior. Compared to the traditional safety management model, the scientific safety management model should emphasize innovative thinking and highlight safety management in innovative digital contexts. This can be regarded as safety R&D, which refers to organizations and individuals giving full play to their initiatives and adopting new technologies and methods to promote scientific safety management and information-based safety management [23].

In practical cases, suppliers' lack of management and innovation resources often leads to a low level of safety management. Vertical cooperation is required in the supply chain to improve the efficiency of safety management. On April 24, 2013, a serious accident occurred in a garment factory premises in Bangladesh, resulting in the death of more than one thousand people. Following the accident, some of Europe's leading garment companies, trade unions and Bangladeshi factory owners signed a "Fire and Building Safety Agreement". Under this agreement, core companies in the supply chain are required to independently monitor and report safety matters to suppliers in Bangladesh. Any suppliers who breach the agreement may be shut down. After the agreement was signed, safety facilities and conditions in Bangladeshi factories have improved considerably, and the accident rate has decreased [24]. Accordingly, the first question posed by this study is, under what circumstances is it more efficient for safety organizations to work together?

Earlier, this paper talked about BASF's improved safety R&D through supply chain cooperation. However, the opposite case is emerging in the automotive industry. For example, CATL is the world's leading supplier of batteries for new energy vehicles, with a recent market capitalisation of over \$143.5 billion. Schneider Electric help CATL build an advanced green and intelligent factory to expand the lithium battery application market. In 2021, two consecutive explosions at CATL subsidiaries caused serious reputational damage to the company. The cause of the explosions was used lithium batteries catching fire in the slag stacking workshop. Based on the above cases, this study finds that cooperation does not always have a positive impact on the level of safety. Interestingly, strong alliances, such as the one between CATL and Schneider Electric, do not achieve the desired goal of cooperation. Now, a second question is asked: under what circumstances is safety R&D cooperation efficient?

Safety management practices in the supply chain are sometimes accompanied by safety organization and safety R&D cooperation. Intuitively, dual cooperation appears to be more efficient. However, transaction cost theory states that dedicated asset investment by one party in a collaboration may lead to opportunistic behavior by the other party. This belief is also supported by empirical studies [25]. Referring to studies related to R&D that is subsidized government enterprise cooperation, one can find that government R&D subsidies can have a squeezing out effect on firms' R&D investments. This dual internal and external cooperation behavior does not produce a $1 + 1 = 2$ effect [26]. Given that, in secure R&D cooperation, if a manufacturer gives R&D subsidies to a supplier, the R&D subsidies are in the form of financial or technological inputs. This R&D subsidy is clearly a dedicated asset input. A third question can therefore be asked: in the presence of dual safety cooperation in a supply chain, do R&D subsidies have a crowding-out effect on safety organization cooperation?

The remainder of this paper is structured as follows: Section 2 reviews the relevant literature. Section 3 presents the main model formulation and analyzes the state function of the level of supply chain safety. Section 4 discusses supply chain differential decision-making for supply chain Nash equilibrium, Stackelberg secure organizational cooperation, Stackelberg secure R&D cooperation, and

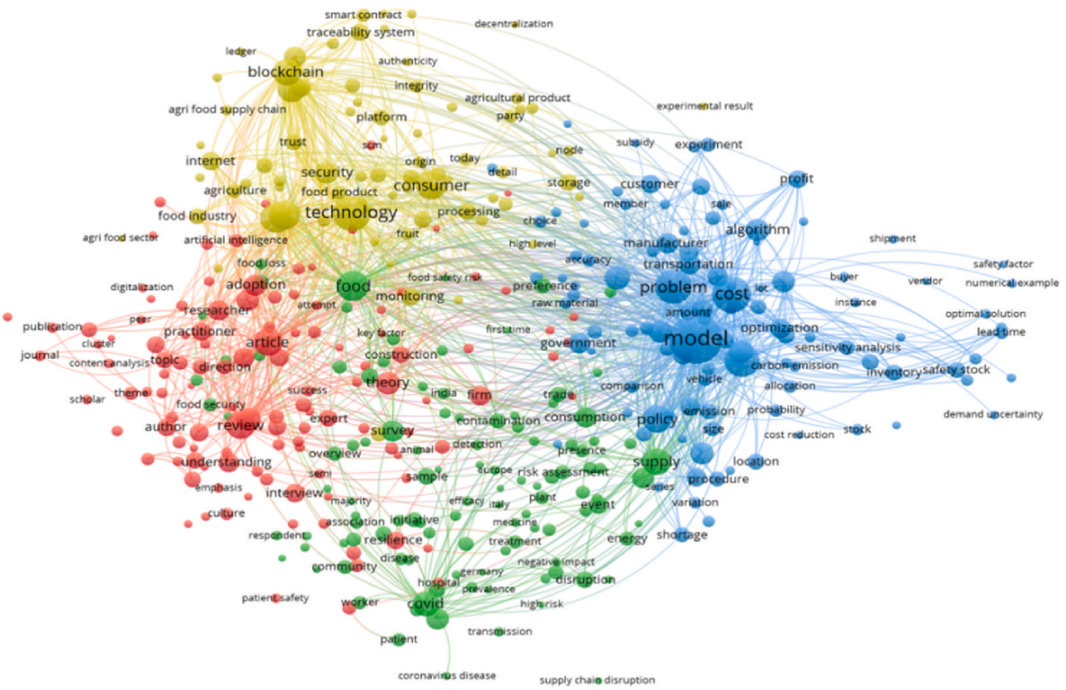

Fig. 1. VOSviewer mapping of the keywords.

Stackelberg dual cooperation, respectively. In Section 5, a numerical sensitivity analysis is conducted to explore the factors that influence supply chain safety cooperation. Finally, the study's conclusions are drawn in Section 6.

2. Literature review

We use VOSviewer to map research topic keywords and obtain Fig. 1. We focus on two major areas in our research review: supply chain safety management technology and supply chain safety management models (see Fig. 2).

In recent years, the emergence of Industry 4.0 technology in the field of supply chain management has had a positive impact on corporate social responsibility and safety. Wassink (2020) analyzed how Industry 4.0 technology promotes safety in the oil and gas industry [27]. Wu (2023) found that digital technology can effectively improve the effectiveness of employee safety management and stakeholder loyalty in the cold chain logistics industry [28]. Molero (2019) studied the hazardous goods transportation industry and found that the use of digital technology can effectively reduce safety accidents [29]. Foreman (2023) explores the application of big data in the field of occupational safety and health [30]. Kirkels (2022) discussed the fire safety issues caused by electric vehicles in the EU region, and the article suggests that safety risk standards should be established to improve battery technology [31]. Zhang (2022) found that intelligent mines can effectively meet the needs of green, safe, and automated coal mining [32]. Edirisinghe (2019) introduced how intelligent construction sites can achieve real-time safety management of construction sites [33].

According to Fig. 3. Regarding the hot topic of supply chain security management, scholars have adopted various research models to enrich the research in this field. The method of conducting in-depth interviews and conducting questionnaire surveys is an important tool for studying organizational behavior. Relevant literature has affirmed the role of safety factors in the supplier selection

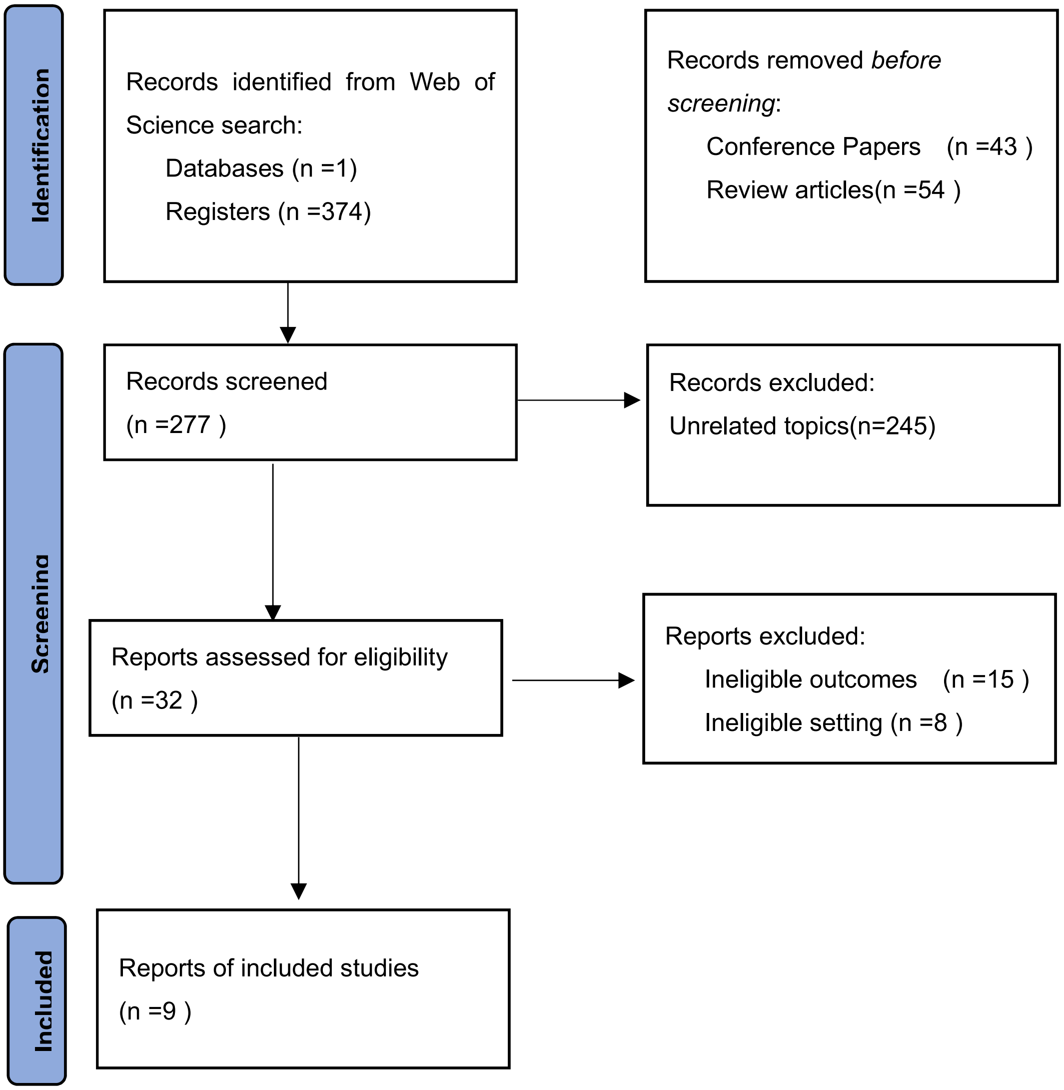

Fig. 2. PRISMA flowchart for supply chain safety management technology.

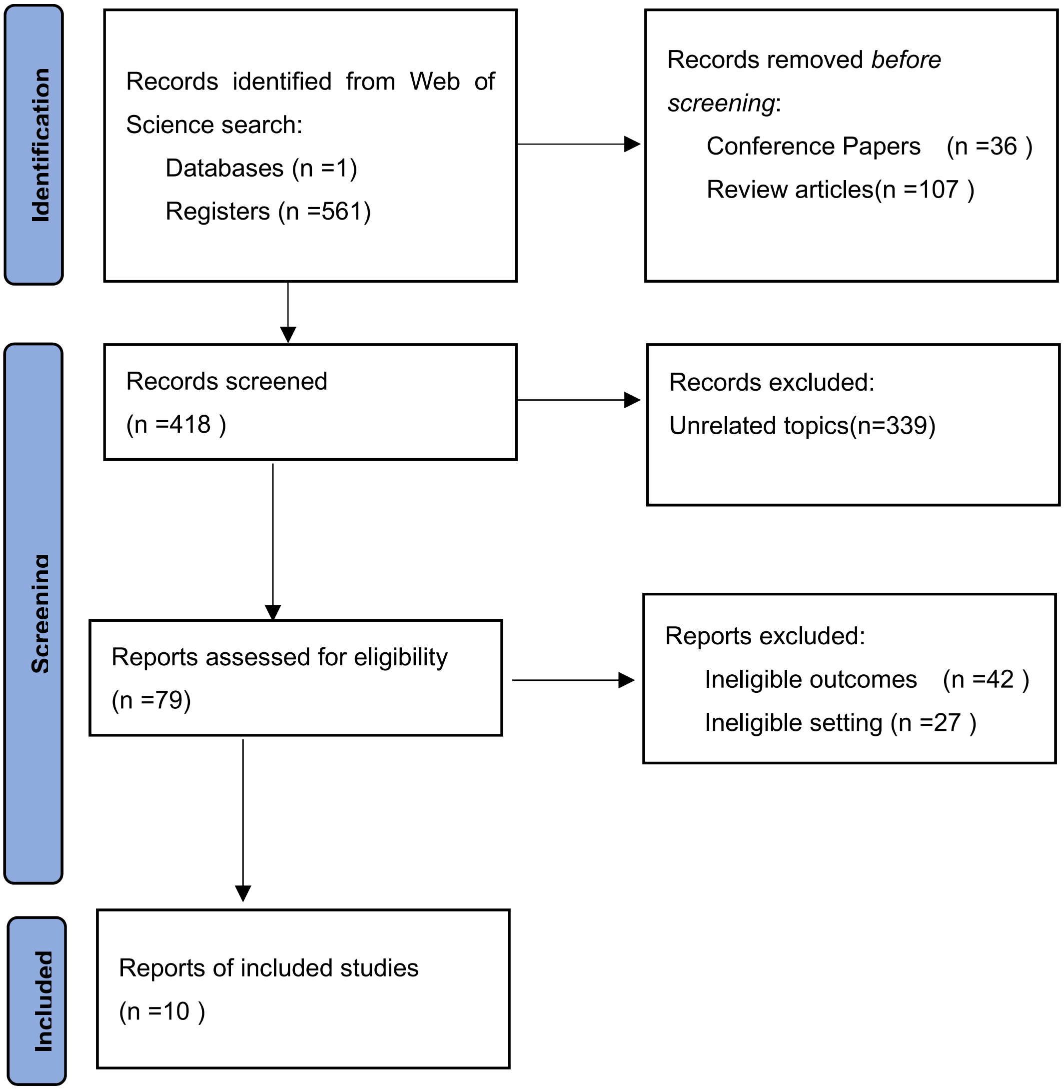

Fig. 3. PRISMA flowchart for supply chain safety management model

process of core enterprises through questionnaire surveys [34,35]. Further research has employed structural equation modeling tools to empirically analyze the relationship between safety production and sustainable development of the supply chain [36,37]. Game theory is a commonly used tool in supply chain management research. Previous studies have analyzed through game theory tools how procurement companies can exert influence on suppliers, thereby reducing the risk of suppliers violating corporate social responsibility [24,38]. Yang (2021) found that core enterprises can improve the overall security level of the supply chain through revenue and cost sharing contracts [39]. Given the many uncertainties in safety management, the levels of a firm's safety and reputation exhibit a dynamic process of change. Differential games can reveal the dynamic process of changes in firms' behavioral strategies over time; such games have also become an important research tool in the field of supply chain safety management. Some scholars have applied differential equations to carve out safety levels or brand goodwill to optimize food safety problems [40,41].

In summary, compared with existing literature on supply chain safety management, this paper has two main features. Firstly, considering the dynamic change characteristics of supply chain safety management, this paper attempts to introduce the differential game approach to study safety management decisions in the supply chain. Secondly, in order to systematically analyze the advantages and disadvantages of various supply chain safety management behaviors, this paper distinguishes and divides supply chain safety management behavior into the two categories of "safety organization" and "safety research and development". To explore how to establish an optimal coordination mechanism for supply chain safety management, various safety management strategies in the upstream and downstream of the supply chain under Nash and Stackelberg are analyzed. The goal is to achieve improvement in the effectiveness of supply chain safety management.

3. Basic model

Differential game is a commonly used continuous time dynamic optimization research tool in the field of management, suitable for studying supply chain safety production management strategies under dynamic changes. In this paper, a two-level supply chain is developed that includes manufacturers Z and suppliers G. The assumption is that there are two strategies for manufacturers and suppliers in the safety management process, with safety organization focusing on process management and safety R&D focusing on goal orientation. It is further assumed that the utility generated by the joint safety management of manufacturers and suppliers is distributed by the lead manufacturer, who gives the suppliers a share of the utility of $\delta, \delta \in (0,1)$, a constant that is predetermined, while the manufacturer receives the remaining share of 1—δ. The manufacturer's monitoring of the supplier's production process results in the manufacturer incurring monitoring costs of $C(G_z)$, at which point the supply chain safety management utility increases, proportional to the coefficient of φ with the impact of the manufacturer's safety organization monitoring on the supply chain safety management utility. The manufacturer subsidizes the supplier's safety R&D, and the subsidy reduces the supplier's safety at a rate of θ, $\theta \in (0,1)$. This article first lists the main parameters and symbols through Table 1:

Members in the supply chain manage safety through both R&D input and management process control. The costs of effort for supply chain safety organization, safety R&D and safety organization regulation are as follows (Eq. (1)):

$$C(R_g) = \frac{\mu_1}{2}R_g{}^2, C(R_z) = \frac{\mu_2}{2}R_z{}^2, C(M_g) = \frac{\mu_3}{2}M_g{}^2, C(M_z) = \frac{\mu_4}{2}M_z{}^2, C(G_z) = \frac{\mu_5}{2}G_z{}^2 \tag{1}$$

The core of safety management is safety R&D. The level of safety in a digital context is determined by the company's safety R&D efforts. According to the classical NA model on reputation, the safety level is also a dynamic change process, similar to reputation. Therefore, safety level can also be expressed as a state function (Eq. (2)) [42].

$$S(t)' = \alpha R_g(t) + \beta R_z(t) - \gamma S(t) \tag{2}$$

where S(t) denotes the safety level at time t and the initial safety level.

The total utility of safety management can be seen as a function of safety R&D and safety organization and is proportional to the safety level (Eq. (3)).

$$U(t) = \varepsilon M_g(t) + \eta M_z(t) + \chi S(t) \tag{3}$$

Assuming that the manufacturer's and the supplier's discount rates are the same and positive, both of them aim for an optimal safety management strategy that maximizes their own utility.

In this paper, based on the above assumptions, the objective functions of the supplier and the manufacturer are obtained, according to the construction method of the differential game (Eq. (4)):

$$J_g(R_g(t), M_g(t)) = \int_0^{+\infty} e^{-\rho t}\left\{\delta\left[\varepsilon M_g(t) + \eta M_z(t) + \chi S(t)\right] - \frac{\mu_1}{2}R_g{}^2 - \frac{\mu_3}{2}M_g{}^2\right\}dt$$

$$J_z(R_z(t), M_z(t)) = \int_0^{+\infty} e^{-\rho t}\left\{(1-\delta)\left[\varepsilon M_g(t) + \eta M_z(t) + \chi S(t)\right] - \frac{\mu_2}{2}R_z{}^2 - \frac{\mu_4}{2}M_z{}^2\right\}dt \tag{4}$$

Table 1
Symbol description.

R_i	Safety R&D effort, safety regulation effort and safety R&D subsidy rate
M_i	Safety organization effort
$S(t)$	Safety level
$U(t)$	Supply chain safety management utility
$C(R_i)$	Safety R&D effort cost
$C(M_i)$	Safety R&D effort cost
$C(G_z)$	Cost of safety organization supervision
μ_i	Cost of effort impact factor
ρ	Discount rate
α	Coefficient of supplier's influence
β	Impact factor of manufacturer safety R&D on safety level
γ	Degradation rate of safety level
ε	Coefficient of impact of manufacturer safety organization on the utility of supply chain safety management
η	Coefficient of influence of manufacturer safety organization regulation on the utility of supply chain safety management
φ	Coefficient of influence of manufacturer safety organization regulation on the utility of supply chain safety management
χ	Coefficient of impact of safety level on utility function
δ	Manufacturer's share of utility gained by a given supplier
π	Cost of manufacturer oversight on supplier improvement
θ	Manufacturer's rate of subsidy to suppliers for safety R&D

4. Model solving

4.1. The nash differential game scenario

In the case of the Nash game, the manufacturer and the supplier independently decide on their own safety organization and safety R&D efforts. On that basis, they each determine the strategy that maximizes their own respective utilities.

Theorem 1. In the Nash non-cooperative game case, the static feedback Nash equilibrium of the manufacturer and supplier is (Eq. (5)):

$$\left(M_g{}^1, R_g{}^1\right) = \left(\frac{\delta\varepsilon}{\mu_3}, \frac{\alpha\chi\delta}{\mu_1(\rho+\gamma)}\right)\left(M_z{}^1, R_z{}^1\right) = \left(\frac{(1-\delta)\eta}{\mu_4}, \frac{(1-\delta)\chi\beta}{\mu_2(\rho+\gamma)}\right) \tag{5}$$

Proving (Eq. (6)):

$$\begin{aligned} \rho V_g(S) &= \max_{M_g, R_g}\left\{\delta\left[\varepsilon M_g(t) + \eta M_z(t) + \chi S(t)\right] - \frac{\mu_1}{2}R_g{}^2 - \frac{\mu_3}{2}M_g{}^2 + V_g'(S)\left[\alpha R_g + \beta R_z - \gamma S(t)\right]\right\} \\ \rho V_z(S) &= \max_{M_z, R_z}\left\{(1-\delta)\left[\varepsilon M_g(t) + \eta M_z(t) + \chi S(t)\right] - \frac{\mu_2}{2}R_z{}^2 - \frac{\mu_4}{2}M_z{}^2 + V_z'(S)\left[\alpha R_g + \beta R_z - \gamma S(t)\right]\right\} \end{aligned} \tag{6}$$

Derivation of the HJB equations for safety organization and safety R&D, respectively, leads to (Eq. (7)):

$$\left(M_g, R_g\right) = \left(\frac{\delta\varepsilon}{\mu_3}, \frac{\alpha V_g'(S)}{\mu_1}\right)\left(M_z, R_z\right) = \left(\frac{(1-\delta)\eta}{\mu_4}, \frac{\beta V_z'(S)}{\mu_2}\right) \tag{7}$$

Substituting into the HJB equation, we obtain (Eq. (8)):

$$\begin{aligned} \rho V_g &= \delta\left[\frac{\delta\varepsilon^2}{\mu_3} + \frac{(1-\delta)\eta^2}{\mu_4} + \chi S\right] - \frac{\alpha^2\left(V_g'\right)^2}{2\mu_1} - \frac{\delta^2\varepsilon^2}{2\mu_3} + V_g'\left(\frac{\alpha^2 V_g'}{\mu_1} + \frac{\beta^2 V_z'}{\mu_2} - \gamma S\right) \\ \rho V_z &= (1-\delta)\left[\frac{\delta\varepsilon^2}{\mu_3} + \frac{(1-\delta)\eta^2}{\mu_4} + \chi S\right] - \frac{\beta^2\left(V_z'\right)^2}{2\mu_2} - \frac{(1-\delta)^2\eta^2}{2\mu_4} + V_z'\left(\frac{\alpha^2 V_g'}{\mu_1} + \frac{\beta^2 V_z'}{\mu_2} - \gamma S\right) \end{aligned} \tag{8}$$

From the above equation, a linear function with respect to S is a solution of the HJB equation (Eq. (9)):

$$\begin{aligned} V_g &= a_1 S + a_2 \\ V_z &= a_3 S + a_4 \end{aligned} \tag{9}$$

With substitution (Eq. (10))

$$\begin{aligned} \rho(a_1 S + a_2) &= (\delta\chi - \gamma a_1)S + \frac{\delta^2\varepsilon^2}{2\mu_3} + \frac{\delta(1-\delta)\eta^2}{\mu_4} + \frac{\alpha^2 a_1{}^2}{2\mu_1} + \frac{\beta^2 a_1 a_3}{\mu_2} \\ \rho(a_3 S + a_4) &= [(1-\delta)\chi - \gamma a_3)]S + \frac{(1-\delta)^2\eta^2}{2\mu_4} + \frac{\delta(1-\delta)\varepsilon^2}{\mu_3} + \frac{\beta^2 a_3{}^2}{2\mu_2} + \frac{\alpha^2 a_1 a_3}{\mu_1} \end{aligned} \tag{10}$$

One can obtain (from Eq. (11) and (12)):

$$a_1 = \frac{\chi\delta}{\rho+\gamma}, a_2 = \frac{\delta^2\varepsilon^2}{2\rho\mu_3} + \frac{\delta(1-\delta)\eta^2}{\rho\mu_4} + \frac{\chi^2\delta^2\alpha^2}{2\mu_1\rho(\rho+\gamma)^2} + \frac{\chi^2\delta(1-\delta)\beta^2}{\mu_2\rho(\rho+\gamma)^2}$$

$$a_3 = \frac{(1-\delta)\chi}{\rho+\gamma}, a_4 = \frac{(1-\delta)\delta\varepsilon^2}{\rho\mu_3} + \frac{(1-\delta)^2\eta^2}{2\mu_4\rho} + \frac{\alpha^2\chi^2(1-\delta)\delta}{\mu_1(\rho+\gamma)^2\rho} + \frac{(1-\delta)^2\chi^2\beta^2}{2\mu_2(\rho+\gamma)^2\rho}$$

$$V_g{}^1 = \left(\frac{\chi\delta}{\rho+\gamma}\right)S + \frac{\delta^2\varepsilon^2}{2\rho\mu_3} + \frac{\delta(1-\delta)\eta^2}{\rho\mu_4} + \frac{\chi^2\delta^2\alpha^2}{2\mu_1\rho(\rho+\gamma)^2} + \frac{\chi^2\delta(1-\delta)\beta^2}{\mu_2\rho(\rho+\gamma)^2}$$

$$V_z{}^1 = \left[\frac{(1-\delta)\chi}{\rho+\gamma}\right]S + \frac{(1-\delta)\delta\varepsilon^2}{\rho\mu_3} + \frac{(1-\delta)^2\eta^2}{2\mu_4\rho} + \frac{\alpha^2\chi^2(1-\delta)\delta}{\mu_1(\rho+\gamma)^2\rho} + \frac{(1-\delta)^2\chi^2\beta^2}{2\mu_2(\rho+\gamma)^2\rho}$$

$$V_W{}^1 = V_g{}^1 + V_Z{}^1 = \left(\frac{\chi}{\rho+\gamma}\right)S + \frac{2\delta\varepsilon^2 - \delta^2\varepsilon^2}{2\rho\mu_3} + \frac{\eta^2 - \delta^2\eta^2}{2\rho\mu_4} + \frac{2\chi^2\delta\alpha^2 - \chi^2\delta^2\alpha^2}{2\mu_1\rho(\rho+\gamma)^2} + \frac{\chi^2(1-\delta^2)\beta^2}{2\mu_2\rho(\rho+\gamma)^2} \tag{11}$$

$$\left(M_g{}^1, R_g{}^1, M_z{}^1, R_z{}^1\right) = \left(\frac{\delta\varepsilon}{\mu_3}, \frac{\alpha\chi\delta}{\mu_1(\rho+\gamma)}, \frac{(1-\delta)\eta}{\mu_4}, \frac{\beta(1-\delta)\chi}{\mu_2(\rho+\gamma)}\right) \tag{12}$$

Theorem 2. The supplier's safety organization effort is directly proportional to the coefficient of influence of the supplier's safety organization on the supply chain safety management utility and the manufacturer's share of utility gained by the given supplier. The manufacturer's safety organization effort is proportional to the coefficient of influence of the manufacturer's safety organization on the supply chain safety management utility and inversely proportional to the manufacturer's share of utility gained by the given supplier. The supplier's safety R&D effort is directly proportional to the coefficient of the effect of the safety level on the utility function and the share of utility gained by the manufacturer given the supplier, and the effort is inversely proportional to the rate of the degradation of the safety level. The supplier's safety R&D effort is directly proportional to the coefficient of the effect of the safety level on the utility function and inversely proportional to the share of utility gained by the manufacturer, given the supplier and the rate of the degradation of the safety level. The proof process can be found in Eq. (13).

$$\text{Proving}: \frac{\partial M_g{}^1}{\partial\delta} > 0, \frac{\partial R_g{}^1}{\partial\delta} > 0, \frac{\partial M_z{}^1}{\partial\delta} < 0, \frac{\partial R_z{}^1}{\partial\delta} < 0, \frac{\partial R_g{}^1}{\partial\chi} > 0, \frac{\partial R_z{}^1}{\partial\chi} > 0, \frac{\partial R_g{}^1}{\partial\gamma} < 0, \frac{\partial R_z{}^1}{\partial\gamma} < 0 \tag{13}$$

4.2. The stackelberg game situation under the manufacturer's safety organization supervision

In order to maintain the reputation of the supply chain, the manufacturer, as the dominant firm, monitors the safety organization of its suppliers. The manufacturer's monitoring behavior is assumed to incur safety regulation costs, while the total utility of safety management can be seen as a function of safety organization, safety R&D and safety regulation efforts (Eq. (14)).

$$U(t)^* = \varepsilon M_g(t) + \eta M_z(t) + \varphi G_z(t) + \chi S(t) \tag{14}$$

At the same time, the cost of safety supervision is: $C(G_z) = 0.5\mu_5 G_z{}^2$:

In the Stackelberg game, the supply chain strategy becomes a manufacturer-led decision system. The manufacturer first decides on its safety R&D, safety organization and safety regulation efforts. The supplier then decides on its own strategy after observing the manufacturer's strategy. A backward induction approach can be used. The optimal control strategy of the supplier is solved first (Eq. (15)):

$$\rho V_g(S) = \max_{M_g, R_g}\left\{\delta\left[\varepsilon M_g(t) + \eta M_z(t) + \chi S(t)\right] - \frac{\mu_1}{2}R_g{}^2 - \frac{\mu_3}{2}M_g{}^2 + V_g{}'(S)\left[\alpha R_g + \beta R_z - \gamma S(t)\right]\right\} \tag{15}$$

The safety R&D and safety organization efforts to maximize the solution strategies (Eq. (16)):

$$\left(M_g, R_g\right) = \left(\frac{\delta\varepsilon}{\mu_3}, \frac{\alpha V_g{}'(S)}{\mu_1}\right) \tag{16}$$

Under the Stackelberg game, the manufacturer formulates its own optimal strategy, based on the expected decisions of its suppliers. On this basis, the manufacturer's HJB equation is (Eq. (17)):

$$\rho V_z(S) = \max_{M_z, R_z}\left\{(1-\delta)\left[\varepsilon M_g(t) + \eta M_z(t) + \varphi G_z(t) + \chi S(t)\right] - \frac{\mu_2}{2}R_z{}^2 - \frac{\mu_4}{2}M_z{}^2 - \frac{\mu_5}{2}G_z{}^2 + V_z{}'(S)\left[\alpha R_g + \beta R_z - \gamma S(t)\right]\right\} \tag{17}$$

Substituting this into the above equation (from Eq. (18) and (19))

$$\rho V_z(S) = \max_{M_z, R_z}\left\{(1-\delta)\left[\frac{\delta\varepsilon^2}{\mu_3} + \eta M_z(t) + \varphi G_z(t) + \chi S(t)\right] - \frac{\mu_2}{2}R_z{}^2 - \frac{\mu_4}{2}M_z{}^2 - \frac{\mu_5}{2}G_z{}^2 + V_z{}'(S)\left[\frac{\alpha^2 V_g{}'(S)}{\mu_1} + \beta R_z - \gamma S(t)\right]\right\} \tag{18}$$

$$\text{yields}: \left(M_z, R_z, G_z\right) = \left(\frac{(1-\delta)\eta}{\mu_4}, \frac{\beta V_z{}'(S)}{\mu_2}, \frac{(1-\delta)\eta}{\mu_5}\right) \tag{19}$$

Substituting this into $\rho V_z(S), \rho V_g(S)$, one can see from the previous section that the linear function of S is the solution of the HJB equation. The utility situation can be obtained through the HJB equation (Eq. (20)):

$$V_g{}^2=\left(\frac{\chi\delta}{\rho+\gamma}\right)S+\frac{\delta^2\varepsilon^2}{2\rho\mu_3}+\frac{\delta(1-\delta)\eta^2}{\rho\mu_4}+\frac{\chi^2\delta^2\alpha^2}{2\mu_1\rho(\rho+\gamma)^2}+\frac{\chi^2\delta(1-\delta)\beta^2}{\mu_2\rho(\rho+\gamma)^2}$$

$$V_z{}^2=\left[\frac{(1-\delta)\chi}{\rho+\gamma}\right]S+\frac{(1-\delta)\delta\varepsilon^2}{\rho\mu_3}+\frac{(1-\delta)^2\eta^2}{2\mu_4\rho}+\frac{\alpha^2\chi^2(1-\delta)\delta}{\mu_1(\rho+\gamma)^2\rho}+\frac{(1-\delta)^2\chi^2\beta^2}{2\mu_2(\rho+\gamma)^2\rho}+\frac{(1-\delta)^2\varphi\eta}{\rho\mu_5}-\frac{(1-\delta)^2\eta^2}{2\rho\mu_5} \tag{20}$$

$$V_W{}^2=\left(\frac{\chi}{\rho+\gamma}\right)S+\frac{2\delta\varepsilon^2-\delta^2\varepsilon^2}{2\rho\mu_3}+\frac{\eta^2-\delta^2\eta^2}{2\rho\mu_4}+\frac{2\chi^2\delta\alpha^2-\chi^2\delta^2\alpha^2}{2\mu_1\rho(\rho+\gamma)^2}+\frac{\chi^2(1-\delta^2)\beta^2}{2\mu_2\rho(\rho+\gamma)^2}+\frac{(1-\delta)^2\varphi\eta}{\rho\mu_5}-\frac{(1-\delta)^2\eta^2}{2\rho\mu_5}$$

From this, the optimal effort level of Stackelberg equilibrium can be obtained (Eq. (21)):

$$\left(\mathrm{M}_g{}^2,R_g{}^2,\mathrm{M}_z{}^2,R_z{}^2,G_z^2\right)=\left(\frac{\delta\varepsilon}{\mu_3},\frac{\alpha\chi\delta}{\mu_1(\rho+\gamma)},\frac{(1-\delta)\eta}{\mu_4},\frac{(1-\delta)\chi\beta}{\mu_2(\rho+\gamma)},\frac{(1-\delta)\eta}{\mu_5}\right) \tag{21}$$

Theorem 3. In the case of the manufacturer's safety regulation of suppliers and the manufacturer's own safety organization, safety R&D effort and the supply chain's safety organization, the safety R&D effort does not change under the Stackelberg game, compared to the Nash game. In contrast, the manufacturer's safety regulation effort is directly proportional to the coefficient of impact with the manufacturer's safety organization on the supply chain safety management utility; the effort is also inversely proportional to the share of utility gained by the manufacturer, given the supplier.The proof process can be found in Eq. (22).

$$\text{Proving}:\left(\mathrm{M}_g{}^2,R_g{}^2,\mathrm{M}_z{}^2,R_z{}^2\right)=\left(\mathrm{M}_g{}^1,R_g{}^1,\mathrm{M}_z{}^1,R_z{}^1\right).\frac{\partial G_z}{\partial\eta}>0,\frac{\partial G_z}{\partial\delta}<0. \tag{22}$$

Theorem 4. In a Stackelberg equilibrium with manufacturer safety regulation, the supplier's utility is the same as in the Nash equilibrium. Meanwhile, the manufacturer's utility is greater than in the Nash equilibrium when $\varphi>\frac{\eta}{2}$ and less than in the Nash equilibrium when $\varphi<\frac{\eta}{2}$. The total supply chain utility also depends on the marginal coefficient of the manufacturer's safety regulation. Pareto improvement is achieved when the total utility of the supply chain is higher than the Nash equilibrium, and vice versa when the total utility of the supply chain will be lower than the Nash equilibrium.The proof process can be found in Eq. (23).

$$\text{Proving}:V_z{}^2-V_z{}^1=V_W{}^2-V_W{}^1=\frac{(1-\delta)^2(2\varphi\eta-\eta^2)}{2\rho\mu_5}=\frac{(1-\delta)^2\eta(2\varphi-\eta)}{2\rho\mu_5} \tag{23}$$

The first question is demonstrated here. Specifically, the coefficient of influence of manufacturer safety organization supervision on the utility of supply chain safety management determines the efficiency of safety organization cooperation, and the scientific means of organizational supervision lead to improved supply chain utility under safety organization cooperation. For example, Uniqlo has improved the operating conditions of its Indonesian suppliers through various and effective means [43]. *The improvements have played a positive role in improving the safety level of suppliers and brand reputation.*

4.3. Stackelberg process under the manufacturer's safety R&D subsidy

Manufacturers have an incentive to subsidize their suppliers' safety R&D practices, in order to improve the performance of their components. Assume that the manufacturer subsidizes the supplier's safety R&D at a rate of θ. The decision problem evolves into a Stackelberg non-cooperative game.

Under the Stackelberg game, the supply chain strategy becomes a manufacturer-led decision system. The manufacturer first decides its own safety R&D, safety organization and safety regulation efforts. Then, after observing the manufacturer's strategy, the supplier decides on its own strategy. A backward induction approach can be used. The optimal control strategy of the supplier is solved first (Eq. (24):

$$\rho\mathrm{V}_g(S)=\max_{M_g,R_g}\left\{\delta\left[\varepsilon M_g(t)+\eta M_z(t)+\chi S(t)\right]-\frac{\mu_1}{2}(1-\theta)\mathrm{R}_g{}^2-\frac{\mu_3}{2}\mathrm{M}_g{}^2+V_g^{'}(S)\left[\alpha R_g+\beta R_z-\gamma S(t)\right]\right\} \tag{24}$$

Maximize safety R&D and safety organization efforts by the strategy (Eq. (25)):

$$\left(\mathrm{M}_g,R_g\right)=\left(\frac{\delta\varepsilon}{\mu_3},\frac{\alpha V_g^{'}(S)}{\mu_1(1-\theta)}\right) \tag{25}$$

In the Stackelberg game, manufacturers formulate their optimal strategies based on the expected decisions of suppliers. On this basis, the manufacturer's HJB equation is (Eq. (26)):

$$\rho \mathrm{V}_z(S) = \max_{M_z, R_z}\left\{(1-\delta)\left[\varepsilon\frac{\delta\varepsilon}{\mu_3} + \eta M_z(t) + \chi S(t)\right] - \frac{\mu_2}{2}\mathrm{R}_z^{\,2} - \frac{\mu_4}{2}\mathrm{M}_z^{\,2} - \frac{\theta\mu_1}{2}\left(\frac{\alpha V_g^{'}(S)}{\mu_1(1-\theta)}\right)^2 + V_z^{'}(S)\left[\alpha\frac{\alpha V_g^{'}(S)}{\mu_1(1-\theta)} + \beta R_z - \gamma S(t)\right]\right\} \tag{26}$$

Taking the derivative yields Eq. (27):

$$(\mathrm{M}_z, R_z, \theta) = \left(\frac{(1-\delta)\eta}{\mu_4}, \frac{\beta V_z^{'}(S)}{\mu_2}, 1-\frac{\sqrt{2}}{2}\right) \tag{27}$$

Substituting this into $\rho \mathrm{V}_z(S), \rho \mathrm{V}_g(S)$ (Eq. (28)):

$$\rho \mathrm{V}_g(S) = \max_{M_g, \mathrm{R}_g}\left\{\delta\left[\frac{\delta\varepsilon^2}{\mu_3} + \frac{(1-\delta)\eta^2}{\mu_4} + \chi S(t)\right] - \frac{\alpha^2 V_g^{'}(S)^2}{\sqrt{2}\mu_1} - \frac{\delta^2\varepsilon^2}{2\mu_3} + V_g^{'}(S)\left[\frac{2\alpha^2 V_g^{'}(S)}{\sqrt{2}\mu_1} + \frac{\beta^2 V_z^{'}(S)}{\mu_2} - \gamma S(t)\right]\right\}$$

$$\rho \mathrm{V}_z(S) = \max_{M_z, R_z}\left\{(1-\delta)\left[\frac{\delta\varepsilon^2}{\mu_3} + \frac{(1-\delta)\eta^2}{\mu_4} + \chi S(t)\right] - \frac{\beta^2 (V_z^{'})^2}{2\mu_2} - \frac{(1-\delta)^2\eta^2}{2\mu_4} - \frac{\left(\left(1-\frac{\sqrt{2}}{2}\right)\alpha^2 V_g^{'}(S)\right)^2}{\mu_1} + V_z^{'}(S)\left[\frac{2\alpha^2 V_g^{'}(S)}{\sqrt{2}\mu_1} + \frac{\beta^2 V_z^{'}(S)}{\mu_2} - \gamma S(t)\right]\right\} \tag{28}$$

Under the Stackelberg game, the manufacturer formulates its own optimal strategy, based on the expected decisions of its suppliers. On this basis, the manufacturer's HJB equation is (Eq. (29)):

$$\begin{aligned}
V_g^{\,3} &= \left(\frac{\chi\delta}{\rho+\gamma}\right)S + \frac{\delta^2\varepsilon^2}{2\rho\mu_3} + \frac{\delta(1-\delta)\eta^2}{\rho\mu_4} + \frac{\sqrt{2}\alpha^2\delta^2\chi^2}{2\rho\mu_1(\rho+\gamma)^2} + \frac{\chi^2\delta^2\alpha^2}{\mu_1\rho(\rho+\gamma)^2} + \frac{\chi^2\delta(1-\delta)\beta^2}{\mu_2\rho(\rho+\gamma)^2} \\
V_z^{\,3} &= \left[\frac{(1-\delta)\chi}{\rho+\gamma}\right]S + \frac{(1-\delta)\delta\varepsilon^2}{\rho\mu_3} + \frac{(1-\delta)^2\eta^2}{2\mu_4\rho} + \frac{\alpha^2\chi^2\delta}{\mu_1(\rho+\gamma)^2\rho}\left(\sqrt{2} - \frac{\sqrt{2}}{2}\delta - \delta\right) + \frac{(1-\delta)^2\chi^2\beta^2}{2\mu_2(\rho+\gamma)^2\rho} \\
V_W^{\,3} &= \left(\frac{\chi}{\rho+\gamma}\right)S + \frac{2\delta\varepsilon^2 - \delta^2\varepsilon^2}{2\rho\mu_3} + \frac{\eta^2 - \delta^2\eta^2}{2\rho\mu_4} + \frac{\chi^2\delta\alpha^2}{\mu_1\rho(\rho+\gamma)^2}\left(\sqrt{2} - \delta\right) + \frac{\chi^2(1-\delta^2)\beta^2}{2\mu_2\rho(\rho+\gamma)^2}
\end{aligned} \tag{29}$$

The optimal level for the Stackelberg equilibrium can thus be obtained as follows (Eq. (30)):

$$\left(\mathrm{M}_g^{\,3}, R_g^{\,3}, \mathrm{M}_z^{\,3}, R_z^{\,3}, \theta\right) = \left(\frac{\delta\varepsilon}{\mu_3}, \frac{\sqrt{2}\alpha\chi\delta}{\mu_1(\rho+\gamma)}, \frac{(1-\delta)\eta}{\mu_4}, \frac{(1-\delta)\chi\beta}{\mu_2(\rho+\gamma)}, 1-\frac{\sqrt{2}}{2}\right) \tag{30}$$

Theorem 5. The manufacturer's safety organization effort and safety R&D effort, and the supplier's safety organization effort did not change when the manufacturer gave the supplier R&D subsidies, compared to the Nash equilibrium and when the manufacturer regulated only the safety organization. Meanwhile, the supplier's safety R&D effort increased. The proof process can be found in Eq. (31).

$$\text{Proving}: \left(\mathrm{M}_g^{\,3}, \mathrm{M}_z^{\,3}, R_z^{\,3}\right) = \left(\mathrm{M}_g^{\,2}, \mathrm{M}_z^{\,2}, R_z^{\,2}\right) = \left(\mathrm{M}_g^{\,1}, \mathrm{M}_z^{\,1}, R_z^{\,1}\right), R_g^{\,3} > R_g^{\,2} = R_g^{\,1} \tag{31}$$

Theorem 6. In the case where the manufacturer gives the supplier a safety R&D subsidy, the supplier's utility is greater than that in the Nash equilibrium, and the manufacturer's safety organization is regulated. Meanwhile, the manufacturer's utility, the total utility of the supply chain, and the Nash equilibrium are related to the size of the manufacturer's utility. When $\delta < 2-\sqrt{2}$, the manufacturer's utility is greater than that in the Nash equilibrium. When $\delta > 2-\sqrt{2}$, the manufacturer's utility is less than in the Nash equilibrium. At the same time, when $\delta > 2-\sqrt{2}$, the total supply chain utility is greater than in the Nash equilibrium, and when $\delta < 2\sqrt{2}-2$, the total supply chain utility is less than that in the Nash equilibrium. When $\varphi > \frac{\mu_5\alpha^2\chi^2\delta(2\sqrt{2}-2-\sqrt{2}\delta)}{2\mu_1\eta(\rho+\gamma)^2(1-\delta)^2} + \frac{\eta}{2}$, the manufacturer's utility is lower than the manufacturer's safety organization regulation; when $\varphi < \frac{\mu_5\alpha^2\chi^2\delta(2\sqrt{2}-2-\sqrt{2}\delta)}{2\mu_1\eta(\rho+\gamma)^2(1-\delta)^2} + \frac{\eta}{2}$, the manufacturer's utility is higher than the manufacturer's safety organization regulation. Also, in the case where $\varphi > \frac{\mu_5\alpha^2\chi^2\delta(2\sqrt{2}-2-\delta)}{2\mu_1\eta(\rho+\gamma)^2(1-\delta)^2} + \frac{\eta}{2}$, the total supply chain's utility is lower than the manufacturer's safety organization regulation, and in the case where $\varphi < \frac{\mu_5\alpha^2\chi^2\delta(2\sqrt{2}-2-\delta)}{2\mu_1\eta(\rho+\gamma)^2(1-\delta)^2} + \frac{\eta}{2}$, the total supply chain's utility is higher than the manufacturer's safety organization regulation.The proof process can be found in Eq. (32).

Proving:

$$V_g{}^3 - V_g{}^1 = \frac{(\sqrt{2}-1)\alpha^2\delta^2\chi^2}{2\rho\mu_1(\rho+\gamma)^2} > 0, V_g{}^3 - V_g{}^2 = \frac{(\sqrt{2}-1)\alpha^2\delta^2\chi^2}{2\rho\mu_1(\rho+\gamma)^2} > 0$$
$$V_z{}^3 - V_z{}^1 = \frac{\alpha^2\chi^2\delta}{\mu_1(\rho+\gamma)^2\rho}\left(\sqrt{2}-1-\frac{\sqrt{2}}{2}\delta\right), V_z{}^3 - V_z{}^2 = \frac{\alpha^2\chi^2\delta}{\mu_1(\rho+\gamma)^2\rho}\left(\sqrt{2}-1-\frac{\sqrt{2}}{2}\delta\right) + \frac{(1-\delta)^2\eta(\eta-2\varphi)}{2\rho\mu_5} \quad (32)$$
$$V_W{}^3 - V_W{}^1 = \frac{\alpha^2\delta^2\chi^2}{\rho\mu_1(\rho+\gamma)^2}\left(\sqrt{2}-1-\frac{\delta}{2}\right), V_W{}^3 - V_W{}^2 = \frac{\alpha^2\delta^2\chi^2}{\rho\mu_1(\rho+\gamma)^2}\left(\sqrt{2}-1-\frac{\delta}{2}\right) + \frac{(1-\delta)^2\eta(\eta-2\varphi)}{2\rho\mu_5}$$

Theorem 6 *answers the second question. Specifically, strong alliances do not improve supply chain performance, and a strong manufacturer working with a weak supplier on safety R&D would be more efficient. Directly contrary to what happened to CATL earlier, Aotearoa, a power supply supplier with a market capitalisation of just over $3 billion, has worked intensively with domestic automotive giant BYD. As a result, Aotearoa's safety management has been well recognized as the only nuclear safety-grade high-frequency switching power supply provider in the country.*

4.4. The situation under the manufacturer's simultaneous safety organization supervision and safety R&D subsidy strategy for suppliers

In order to maintain the reputation of the supply chain, the manufacturer, as the dominant firm, will supervise the safety organization of its suppliers. The manufacturer's supervisory behavior is assumed to incur safety supervision costs, while the total utility of safety management can be seen as a function of safety organization, safety R&D and safety supervision efforts (Eq. (33)).

$$\mathrm{U}(t)^{**} = \varepsilon M_g(t) + \eta M_z(t) + \varphi G_z(t)^* + \chi S(t) \quad (33)$$

Simultaneously, the cost of safety supervision is: $\mathrm{C}(\mathrm{G}_z{}^*) = \frac{\mu_5}{2} G_z{}^{*2}$.

At the same time, in order to improve the performance of the component, the manufacturer has an incentive to subsidize the safety R&D practices of suppliers. Suppose that the manufacturer subsidizes the supplier's safety R&D at a rate of θ^*. The decision problem evolves into a Stackelberg non-cooperative game. Under the Stackelberg game, the supply chain strategy becomes a manufacturer-led decision system. The manufacturer first decides on its own safety R&D, safety organization, safety regulatory effort and safety R&D subsidy rate. Then, after observing the manufacturer's strategy, the supplier decides its own strategy. A backward induction approach can be used. The optimal control strategy of the supplier is solved first.

The objective function of the supplier is (Eq. (34)):

$$\rho \mathrm{V}_g(S) = \max_{M_g, \mathrm{R}_g}\left\{\delta\left[\varepsilon M_g(t) + \eta M_z(t) + \chi S(t)\right] - \frac{\mu_1}{2}(1-\theta^*)\mathrm{R}_g{}^2 - \frac{\mu_3}{2}\mathrm{M}_g{}^2 + V_g{}'(S)\left[\alpha R_g + \beta R_z - \gamma S(t)\right]\right\} \quad (34)$$

Maximize safety R&D and safety organization efforts for solving strategies (Eq. (35)):

$$\left(\mathrm{M}_g, R_g\right) = \left(\frac{\delta\varepsilon}{\mu_3}, \frac{\alpha V_g{}'(S)}{\mu_1(1-\theta^*)}\right) \quad (35)$$

Under the Stackelberg game, the manufacturer formulates its own optimal strategy, based on the expected decisions of its suppliers. Substituting the above equation, the manufacturer's HJB equation is (Eq. (36)):

$$\rho \mathrm{V}_z(S) = \max_{M_z, R_z}\left\{(1-\delta)\left[\frac{\delta\varepsilon^2}{\mu_3} + \eta M_z(t) + \varphi G_z{}^*(t) + \chi S(t)\right] - \frac{\mu_2}{2}\mathrm{R}_z{}^2 - \frac{\mu_4}{2}\mathrm{M}_z{}^2 - \frac{\mu_5}{2}G_z{}^2 - \frac{\mu_1}{2}\theta^*\mathrm{R}_g{}^2 + V_z{}'(S)\left[\frac{\alpha^2 V_g{}'(S)}{\mu_1} + \beta R_z - \gamma S(t)\right]\right\} \quad (36)$$

A derivation of the above gives the manufacturer's safety organization effort, safety R&D effort, safety regulation effort, and safety R&D subsidy rate (Eq. (37)):

$$\left(\mathrm{M}_z{}^4, R_z{}^4, G_z{}^4, \theta^*\right) = \left(\frac{(1-\delta)\eta}{\mu_4}, \frac{\beta V_z{}'(S)}{\mu_2}, \frac{(1-\delta)\eta}{\mu_5}, 1 - \frac{\sqrt{2}}{2}\right) \quad (37)$$

Substituting this into $\rho \mathrm{V}_z(S), \rho \mathrm{V}_g(S)$ (Eq. (38)):

$$V_g{}^4 = \left(\frac{\chi\delta}{\rho+\gamma}\right)S + \frac{\delta^2\varepsilon^2}{2\rho\mu_3} + \frac{\delta(1-\delta)\eta^2}{\rho\mu_4} + \frac{\sqrt{2}\alpha^2\delta^2\chi^2}{2\rho\mu_1(\rho+\gamma)^2} + \frac{\chi^2\delta^2\alpha^2}{\mu_1\rho(\rho+\gamma)^2} + \frac{\chi^2\delta(1-\delta)\beta^2}{\mu_2\rho(\rho+\gamma)^2}$$

$$V_z{}^4 = \left[\frac{(1-\delta)\chi}{\rho+\gamma}\right]S + \frac{(1-\delta)\delta\varepsilon^2}{\rho\mu_3} + \frac{(1-\delta)^2\eta^2}{2\mu_4\rho} + \frac{\alpha^2\chi^2\delta}{\mu_1(\rho+\gamma)^2\rho}\left(\sqrt{2} - \frac{\sqrt{2}}{2}\delta - \delta\right) + \frac{(1-\delta)^2\chi^2\beta^2}{2\mu_2(\rho+\gamma)^2\rho} + \frac{(1-\delta)^2\varphi\eta}{\rho\mu_5} - \frac{(1-\delta)^2\eta^2}{2\rho\mu_5}$$

$$V_W{}^4 = \left(\frac{\chi}{\rho+\gamma}\right)S + \frac{2\delta\varepsilon^2-\delta^2\varepsilon^2}{2\rho\mu_3} + \frac{\eta^2-\delta^2\eta^2}{2\rho\mu_4} + \frac{\chi^2\delta\alpha^2}{\mu_1\rho(\rho+\gamma)^2}\left(\sqrt{2}-\delta\right) + \frac{\chi^2(1-\delta^2)\beta^2}{2\mu_2\rho(\rho+\gamma)^2} + \frac{(1-\delta)^2\varphi\eta}{\rho\mu_5} - \frac{(1-\delta)^2\eta^2}{2\rho\mu_5} \tag{38}$$

From this, the optimal effort level of the Stackelberg equilibrium can be obtained (Eq. (39)):

$$\left(M_g{}^4, R_g{}^4, M_z{}^4, R_z{}^4, G_z{}^4, \theta^*\right) = \left(\frac{\delta\varepsilon}{\mu_3}, \frac{\sqrt{2}\alpha\chi\delta}{\mu_1(\rho+\gamma)}, \frac{(1-\delta)\eta}{\mu_4}, \frac{(1-\delta)\chi\beta}{\mu_2(\rho+\gamma)}, \frac{(1-\delta)\eta}{\mu_5}, 1-\frac{\sqrt{2}}{2}\right) \tag{39}$$

Theorem 6: When the manufacturer provides both the supplier safety organization supervision and the safety R&D subsidy, the manufacturer's safety organization effort and safety R&D effort, and the supplier's safety organization effort do not change. This is compared to the Nash equilibrium and when the manufacturer gives only the supplier safety organization supervision. Meanwhile, the supplier's safety R&D effort increases, compared to the Nash equilibrium and when the manufacturer gives only the supplier safety organization supervision. The supplier's safety R&D effort was the same as when the manufacturer only gave the supplier a safety R&D subsidy. The proof process can be found in Eq. (40).

$$\text{Proving } \left(M_g{}^4, M_z{}^4, R_z{}^4\right) = \left(M_g{}^3, M_z{}^3, R_z{}^3\right) = \left(M_g{}^2, M_z{}^2, R_z{}^2\right) = \left(M_g{}^1, M_z{}^1, R_z{}^1\right), R_g{}^4 = R_g{}^3 > R_g{}^2 = R_g{}^1 \tag{40}$$

Theorem 7. *When the manufacturer gives both safety organization supervision and safety R&D subsidies to the supplier, the supplier's utility is the same as when the manufacturer gives only safety R&D subsidies to the supplier. In addition, the supplier's utility is greater than in the case of the Nash equilibrium and when the manufacturer gives only safety organization supervision to the supplier. The total utility of the supply chain is greater than the case when the manufacturer only gives the supplier the safety R&D subsidy.*

Theorem 8. The manufacturer's utility is greater than that in the Nash equilibrium when $\varphi > \frac{\mu_5\alpha^2\chi^2\delta(2-2\sqrt{2}+\sqrt{2}\delta)}{2\mu_1\eta(\rho+\gamma)^2(1-\delta)^2} + \frac{\eta}{2}$, and less than that in the Nash equilibrium when $\varphi < \frac{\mu_5\alpha^2\chi^2\delta(2-2\sqrt{2}+\sqrt{2}\delta)}{2\mu_1\eta(\rho+\gamma)^2(1-\delta)^2} + \frac{\eta}{2}$. When $\delta < 2-\sqrt{2}$, the manufacturer's utility is greater than when the manufacturer only gives supervision to the supplier safety organization. When $\delta > 2-\sqrt{2}$, the manufacturer's utility is less than the situation in which the manufacturer is only supervised by the supplier's safety organization. When $\varphi > \frac{\mu_5\alpha^2\chi^2\delta(3-3\sqrt{2}+\sqrt{2}\delta)}{2\mu_1\eta(\rho+\gamma)^2(1-\delta)^2} + \frac{\eta}{2}$, the supply chain's total utility is greater than in the Nash equilibrium. When $\varphi < \frac{\mu_5\alpha^2\chi^2\delta(3-3\sqrt{2}+\sqrt{2}\delta)}{2\mu_1\eta(\rho+\gamma)^2(1-\delta)^2} + \frac{\eta}{2}$, the supply chain's total utility is less than in the Nash equilibrium.The proof process can be found in Eq. (41).

Proving:

$$\begin{aligned}
&V_g{}^4 - V_g{}^1 = V_g{}^4 - V_g{}^2 = \frac{(\sqrt{2}-1)\alpha^2\delta^2\chi^2}{2\rho\mu_1(\rho+\gamma)^2} > 0, V_g{}^4 = V_g{}^3\\
&V_z{}^4 - V_z{}^1 = \frac{\alpha^2\chi^2\delta}{\mu_1(\rho+\gamma)^2\rho}\left(\sqrt{2}-1-\frac{\sqrt{2}}{2}\delta\right) + \frac{(1-\delta)^2\eta(\eta-2\varphi)}{2\rho\mu_5}, V_z{}^4 - V_z{}^2 = \frac{\alpha^2\chi^2\delta}{\mu_1(\rho+\gamma)^2\rho}\left(\sqrt{2}-1-\frac{\sqrt{2}}{2}\delta\right)\\
&V_z{}^4 - V_z{}^3 = \frac{(1-\delta)^2\eta(\eta-2\varphi)}{2\rho\mu_5}\\
&V_W{}^4 - V_W{}^1 = \frac{\alpha^2\delta^2\chi^2}{\rho\mu_1(\rho+\gamma)^2}\left(\sqrt{2}-1-\frac{\sqrt{2}}{2}\delta\right) + \frac{(1-\delta)^2\eta(\eta-2\varphi)}{2\rho\mu_5} + \frac{(\sqrt{2}-1)\alpha^2\delta^2\chi^2}{2\rho\mu_1(\rho+\gamma)^2},\\
&V_W{}^4 - V_W{}^2 = \frac{\alpha^2\delta^2\chi^2}{\rho\mu_1(\rho+\gamma)^2}\left(\frac{3\sqrt{2}-3-\delta}{2}\right) > 0\\
&V_W{}^4 - V_W{}^3 = \frac{(1-\delta)^2\eta(\eta-2\varphi)}{2\rho\mu_5}
\end{aligned} \tag{41}$$

Theorem 8 answers the third question. Specifically, two different scenarios emerge for the constraint on manufacturer safety regulation to make the supply chain Pareto-improved. This is relative to the Nash equilibrium under the dual cooperation model, compared to the single cooperation model. The crowding-out effect occurs when $\delta > \frac{6-3\sqrt{2}}{2}$ and the constraints are more stringent. Meanwhile, $\delta < \frac{6-3\sqrt{2}}{2}$ and the constraints are relatively weaker when the efficiency of safety organization cooperation is increased. The crowding-out effect occurs when the constraints are more stringent, while the constraints are relatively weaker when the efficiency of safety organization cooperation is increased. This finding also suggests that there is a squeezing-out effect under dual safety cooperation in the presence of a strong manufacturer, where external R&D subsidies become dependent on the supplier and thus lack in organizational management [44].

5. Numerical analysis and simulation

In game theory research, using MATLAB tools for numerical simulation can better visualize model conclusions and provide empirical basis for subsequent policy research [45]. This section provides validation of manufacturers and suppliers in different safety management game scenarios. To obtain the simulation data, it is assumed here that: $\rho = 0.1, \varepsilon = 0.3, \eta = 0.2, \chi = 0.6, \mu_1 = 0.1, \mu_2 = 0.2, \mu_3 = 0.1, \mu_4 = 0.2, \mu_5 = 0.1, \alpha = 0.4, \beta = 0.3, \gamma = 0.8$. Then, the utility of the manufacturer, the supplier and the whole supply chain system under various different game scenarios can be fitted using Matlab. The results are shown in Figs. 4, 5, 6, 7, and 8.

Fig. 4 shows that manufacturer regulation of supplier safety organizations does not increase supplier utility. In addition, supplier utility is only increased when manufacturers subsidize safety R&D for suppliers.

Figs. 5 and 6 show that the coefficient of the distribution of safety management utility and the coefficient of the influence of manufacturer safety organization regulation determine the total utility under different games. When the manufacturer is more powerful and the safety organization regulation is more efficient, the total utility at the Nash equilibrium is the lowest, and the total utility with both safety organization regulation and safety R&D subsidy is the highest. Finally, the total utility under safety organization regulation is greater than the total utility under the safety R&D subsidy.

Fig. 7 and Fig. 8 show that, when the manufacturer is relatively weak and the safety organization supervision efficiency is low, the total utility of the Nash equilibrium is the highest, and the total utility of safety organization supervision and safety R&D subsidies is the lowest. Also, the total utility under the safety organization supervision is smaller than that under the safety R&D subsidies.

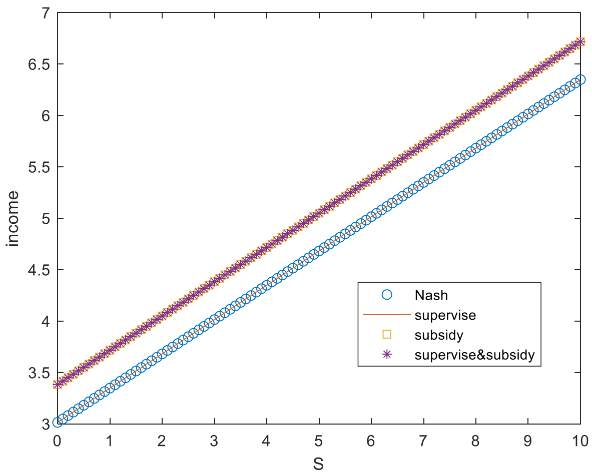

Fig. 4. Comparison of supplier income in four cases.

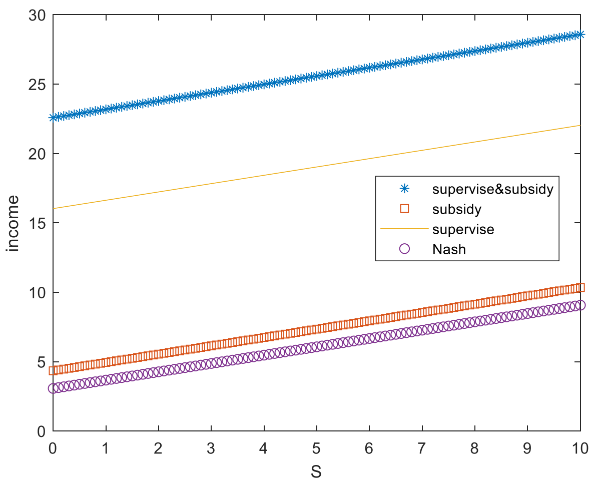

Fig. 5. Comparison of manufacturers' benefits when the supplier ratio is 0.1 and the safety organization coefficient is 0.9.

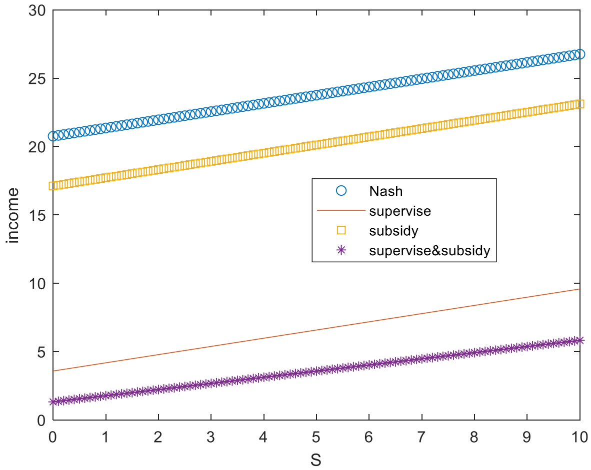

Fig. 6. Comparison of manufacturers' benefits when the supplier ratio is 0.9 and the safety organization coefficient is 0.1.

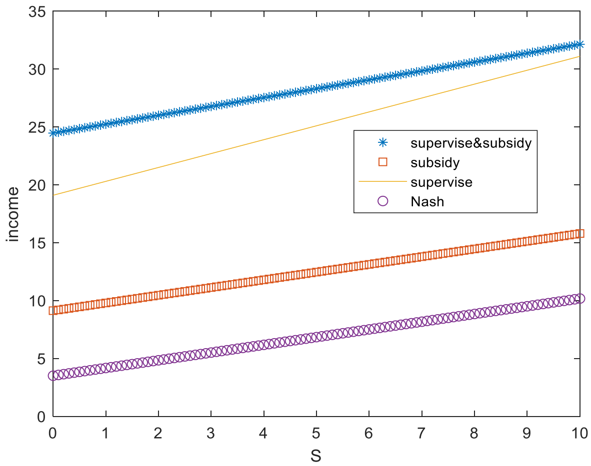

Fig. 7. Comparison of total revenue of supply chain when the supplier ratio is 0.1 and the safety organization coefficient is 0.9.

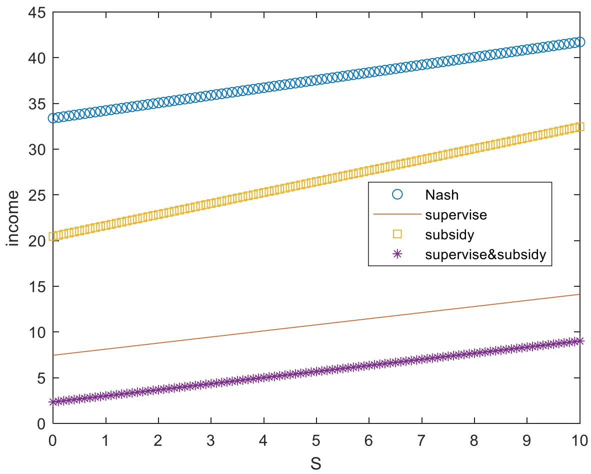

Fig. 8. Comparison of total revenue of supply chain when the supplier ratio is 0.9 and the safety organization coefficient is 0.1.

In order to achieve Pareto improvement in safety management cooperation between manufacturers and suppliers, for one thing, strong manufacturers should provide safety cooperation opportunities. In addition, manufacturers should improve the efficiency of safety organization and supervision, and fully explore the level of safety cooperation between the upstream and downstream of the supply chain.

6. Conclusion

This paper proposes a binary safety management system, highlighting an innovative perspective in the context of information technology development. In addition, two safety management tools are defined: safety organization and safety research and development. The dynamic change characteristics of the safety level are considered, and differential games are applied to analyze the optimal safety management decision in the supply chain under four different game scenarios. The results show that the coefficient of the distribution of safety management utility and the coefficient of the influence of the manufacturer's safety organization regulation determine the total utility under different games. Also, when the manufacturer is more powerful and the safety organization regulation is more efficient, the total utility under the safety cooperation between the manufacturer and supplier can reach Pareto improvement.

This paper's contributions are mainly in two aspects. The theoretical contribution is the definition of a new binary system of safety management, which helps to better characterize safety management tools under new technological conditions and policy environment. The dynamic equilibrium of supply chain safety management is described through differential games, and new ideas are provided for the research related to supply chain safety management. The practical contribution is the provision of a reference for the decision making of safety management cooperation behavior in the supply chain. To be specific: 1) The core manufacturer's safety organization regulation plays an important role in raising suppliers' awareness of social responsibility; strong regulation will also improve the safety level of the whole supply chain. This also provides a basis for multinational corporations to help developing country suppliers improve their safety production environment. For example, retailers such as Primark and H&M have signed safety production agreements in Bangladesh factories to help suppliers improve work safety conditions in Bangladesh [46]. 2) In supply chain safety cooperation, one partner is often required to be dominant, and a strong manufacturer is often better able to guarantee the execution of safety cooperation. Some globally renowned industry leaders are willing to provide technology to improve clean production and safety to their suppliers in developing countries in order to demonstrate their corporate social responsibility. For example, Dow Chemical promotes process safety technology to Chinese suppliers, improving the intrinsic safety level of the Chinese chemical industry [47].3) In safety R&D cooperation, the R&D subsidies provided by a strong dominant firm will have a crowding-out effect, due to insecure R&D cooperation. This will reduce the efficiency of cooperation due to the subsidies' asset-specific nature. Therefore, manufacturers can provide indirect support to suppliers in supply chain safety R&D cooperation by building R&D platforms and licensing technologies. This will help to reduce the crowding-out effect of dual cooperation. This also provides a solution for the global promotion of safety production technology in high-risk industries.

This paper still has some shortcomings. There are more factors that influence corporate safety management behavior, and the model assumptions could be enriched. Further research could consider a case where the state function is non-linear under multiple influencing factors. Supply chain safety management cooperation between multiple manufacturers and suppliers could also be considered.

Funding

This work was supported by the National Natural Science Foundation of China [grant numbers 71874072, 72074099, and 72004081].

Data availability statement

No data was used for the research described in the article.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Binbin he: Writing – review & editing, Writing – original draft. **Qiang Mei:** Conceptualization. **Suxia Liu:** Conceptualization. **Jingjing Zhang:** Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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