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Original Paper

A STAMP-Game model for accident analysis in oil and gas industry

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ABSTRACT

Accidents in engineered systems are usually generated by complex socio-technical factors. It is beneficial to investigate the increasing complexity and coupling of these factors from the perspective of system safety. Based on system and control theories, System-Theoretic Accident Model and Processes (STAMP) is a widely recognized approach for accident analysis. In this paper, we propose a STAMP-Game model to analyze accidents in oil and gas storage and transportation systems. Stakeholders in accident analysis by STAMP can be regarded as players of a game. Game theory can, thus, be adopted in accident analysis to depict the competition and cooperation between stakeholders. Subsequently, we established a game model to study the strategies of both supervisory and supervised entities. The obtained results demonstrate that the proposed game model allows for identifying the effectiveness deficiency of the supervisory entity, and the safety and protection altitudes of the supervised entity. The STAMP-Game model can generate quantitative parameters for supporting the behavior and strategy selections of the supervisory and supervised entities. The quantitative data obtained can be used to guide the safety improvement, to reduce the costs of safety regulation violation and accident risk.

1. Introduction

Due to their characteristics of inflammability and explosibility, oil storage and transportation are prone to fire and explosion accidents. Therefore, it is crucial to ensure the safety of oil and gas storage and transportation systems by drawing upon lessons learned from accident analysis.

Conventional methods of analysis include Fault Tree Analysis (FTA), Event Tree Analysis (ETA), and Human Factors Analysis and Classification System (HFACS) (Wiegmann and Shappell, 2003). The driving idea is “event-driven”, whereby, accidents are generated by a series of abnormal events. The causes of accidents and abnormal incidents such as unsafe acts (Wang and Fu, 2022; Zeng et al., 2023) can be searched through a step-by-step retrospective approach of analysis, which is explicit and intuitive. Nevertheless, with the increase of system complexity and events coupling, any causal chain model is hard to deliver for explaining the causal evolution of accidents in the complex socio-technical systems of day. Then, to investigate the causes of accidents in such systems, a system engineering perspective must be adopted.

System theory methods have better applicability and popularity for the identification of accident contributory factors and the analysis of accident causality (Rad et al., 2023). System engineering models comprehensively consider the interaction of society and technology, and their subsystems (Wu et al., 2020). Specifically, system-theoretic accident methods include the socio-technological system risk management framework (Rasmussen, 1997), the accident map (AcciMap) model (Rasmussen and Svedung, 2000), the functional resonance analysis method (FRAM) (Hollnagel, 2012), and the system theory accident model and process (STAMP) (Leveson, 2004). In particular, the latter has been widely applied (Patriarca et al., 2021). For instance, it has been used in aerospace systems (Lu et al., 2015; Takuto et al., 2014), lithium-ion grid energy storage (Rosewater and Williams, 2015), coal mining (Düzgün and

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Leveson, 2018), and deepwater well control safety (Meng et al., 2018). Various applications are found also in the analysis of oil storage and transportation accidents (Oueidat et al., 2015). For example, Elliott (2017) used causal analysis based on system-theoretic (CAST) to study the Buncefield oil depot explosion in the United Kingdom, and studied inappropriate behaviors at each layer, from managers to equipment. Li et al. (2020) utilized the CAST model to analyze the cause of a major explosion accident of an underground gas pipeline. As a result of its study, measures of correction to the safety structure of the underground gas pipeline system have been proposed at each level of control failure.

This research aims to establish a user-friendly and reliable method for accident analysis. To this end, an accident analysis model specifically tailored for oil and gas storage and transportation systems has been developed. The suggestions for enhancing safety of systems can be proposed by qualitative and quantitative accident analysis.

STAMP can provide deep insights into accident causes, by discovering direct and indirect factors from a systemic perspective (Xing et al., 2020). It allows for reliable accident analysis and comprehensive suggestions for the correction of the safety systems (Goncalves Filho et al., 2019). However, STAMP remains a qualitative model and as such it does not allow performing a quantitative analysis of the causes of accidents (Zhang et al., 2021). It is also difficult to achieve a recognized interpretation of the qualitative analysis results. Quantitative analysis can be used to propose policy recommendations through sensitivity analysis of the relevant parameters. For example, in oil and gas industry, Jiang et al. (2022a) examined the sensitivity of key parameters in a computable general equilibrium (CGE) model and presented policy implications for employing carbon trading to curb oil consumption. Based on the quantitative analysis of the monopolistic market structure and other parameters in the CGE model, the policy implications under different natural gas market reforms were proposed (Jiang et al., 2022b). In this paper, we integrate the STAMP model with game theory to construct a game model between the supervisory and supervised entities of an oil storage and transportation system. In this way, we can investigate competition and cooperation between the stakeholders involved in the accidents, treating them as players of the game. We use game theory to provide a quantitative basis for analyzing the stakeholders' behaviors in an accident. The introduction of game theory parameterizes the strategy choices of agencies in the STAMP model. The correlations between the behavior and decision-making of the accident participants are obtained. These outcomes can assist safety engineers and managers in accident investigation and risk prevention. Game theory studies how two or more players make strategic choices to maximize returns. A player's strategy choice is affected by other players, and its benefits are also determined by the decisions of all players involved in the game model. Many scholars incorporated game theory into system safety analysis to obtain comprehensive results. Feng et al. (2020) integrated game theory with system dynamics to establish a safety regulation for railway transportation. Xing et al. (2020) constructed an urban pipeline accident model to analyze the control deficiencies of the government and enterprises, combining STAMP and game theory. Hamim et al. (2021) proposed a mixed approach combining Accimap, STAMP-CAST, and perceptual cycle model (PCM) for collision investigation to provide a comprehensive explanation of an incident.

In this paper, we consider taking the 2005 explosion accident at the Buncefield oil depot in UK as a case study to analyze the causes of oil and gas storage and transportation accidents. Compared with studies on explosion risk assessment (Yuan et al., 2019) and explosion mechanism (Liberman et al., 2018) of the Buncefield accident, there are few studies on the analysis of the Buncefield accident from the perspective of management and systems engineering. In comparison with studies carried out by other scholars (Elliott, 2017), our analysis of the Buncefield case is conducted from a macro perspective, instead of delving into the details of the equipment. Furthermore, we introduce quantitative analysis based on game theory into our model, resulting in more objective findings from the risk analysis. Additionally, we introduce a discount factor to consider the influence of the time factor and make the game model more realistic. We discuss the relationship between players' strategy choices and risk-influencing factors, analyze the sensitivity of different strategies of accident participants and present effective policy recommendations. The STAMP-Game model is universal and easy for decision-makers to understand. It helps the supervisory and supervised entities to make macro-strategy choices and effectively prevent similar accidents.

The contributions of this paper are summarized as follows. First, we incorporate the STAMP model with game model to study the causes of accidents in complex and coupled socio-technical systems from a systematic perspective. Second, to improve the safety of oil storage and transportation systems, we conduct a qualitative and quantitative analysis to investigate the behaviors and strategies of participants, and propose policy recommendations based on the findings. Third, we introduce a discount factor to dynamically study the supervisory and supervised entities in the game.

The rest of the paper is organized as follows. Section 2 describes the methodology behind the STAMP-Game model. Section 3 is devoted to constructing the model for the oil storage and transportation system case. Section 4 discusses the results obtained. Section 5 concludes the paper.

2. Methodology

Multiple parties are involved in maintaining safe operations by preventing oil and gas storage and transportation accidents. These parties are viewed as stakeholders in the qualitative STAMP model for accident analysis and as players in the game model for its quantitative impact. As shown in Fig. 1, game theory empowers the STAMP model for quantitative analysis. The safety requirements and constraints for the stakeholders resulting from the analysis by the STAMP model provide the basis for application of the game model to classify players into two types: supervisory entities and supervised entities. The game model allows analyzing the influencing factors in the game by calculating the players' benefits, which allows explaining the influence of the behaviors and strategies from the STAMP model. The game conclusions can not only explain behaviors and strategies, but also provide a quantitative basis for investigating the decision-making environment and process, related inappropriate control behaviors and mental model defects of the stakeholders in the considered STAMP model. Then, the integration of the two models allows deriving a comprehensive analysis of the accident causes from a system perspective.

Supervised entities tend to pursue profit. If ignoring safety protections, the cost of dealing with potential accidents can be greatly increased. Thus, to avoid accidents, supervisory entities are inclined to adopt full supervision and increase supervisory intensity. To consider the influence of time on the strategies of supervisory and supervised entities, we introduce a discount factor, which allows for characterizing the time preferences in the model. The steps of implementing this model are as follows:

(1) Step one amounts to defining the accident scenario through determining the accident boundaries, identifying the parties involved in the accident, clarifying the safety requirements and constraints, and establishing a hierarchical safety control structure.

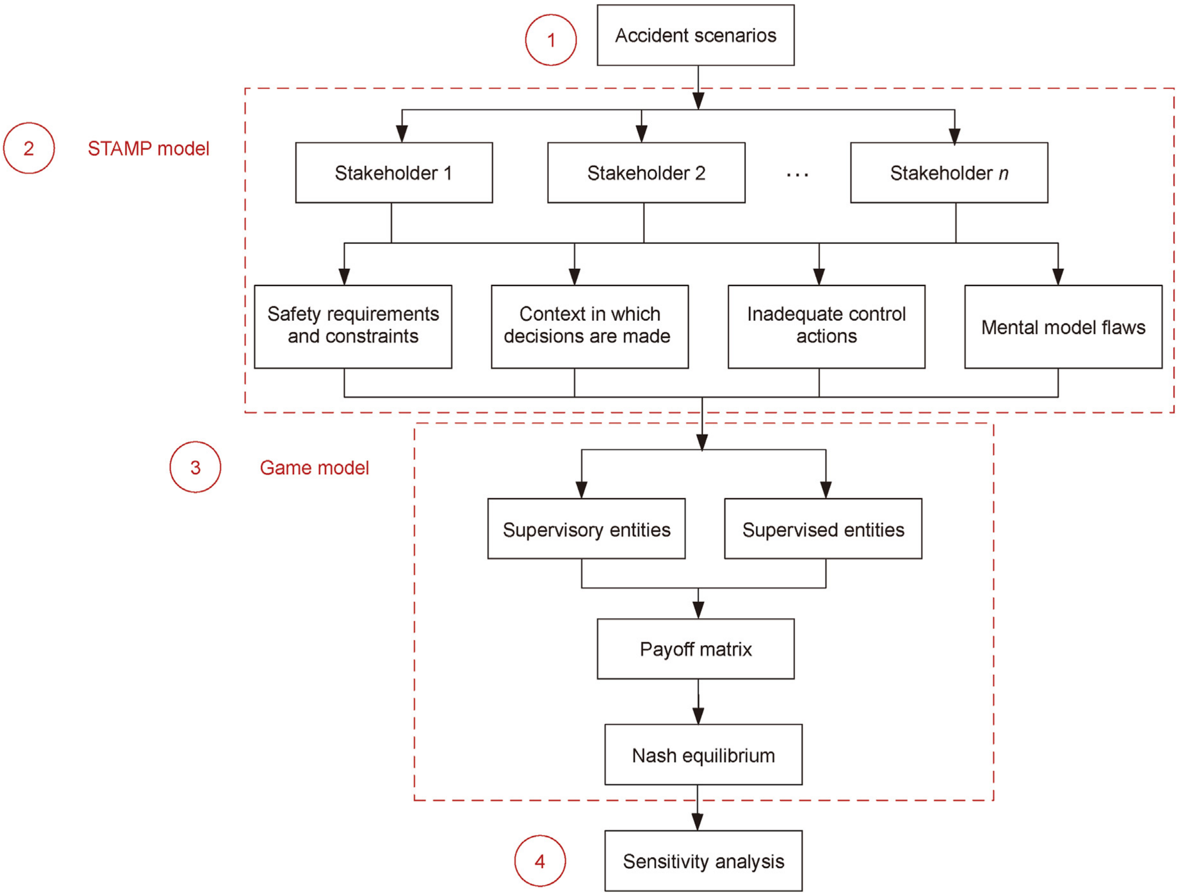


Fig. 1. The procedure for the development of the STAMP-Game model.

(2) Step two relates to the construction of a STAMP model by analyzing the accident, including the associated decision-making environment, inappropriate control behaviors and mental model defects of the involved stakeholders.
(3) Step three regards the definition of a game model. Based on the STAMP outcomes, we apply game theory to analyze the roles of supervisory and supervised entities in the accident.
(4) The final step is sensitivity analysis: we analyze the causes of accidents and propose preventive measures to satisfy the safety requirements.

2.1. Accident scenarios

The accident investigation report can be used to determine the boundaries of the accident and analyze the behaviors and strategies of stakeholders. By considering the interactions between the individual subsystems, we can define the safety constraints and the hierarchical control structures for accidents. Considering the mutual effects of the parties' behaviors and strategies, we examine the correlations between the supervisory and supervised entities related to cooperation dynamics with incomplete information in the accident analysis.

2.2. STAMP model

The complex couplings and interactions between system components can affect system safety (Fagundes et al., 2021). To ensure system safety, proper control and constraints should be imposed on the coupling and interaction among the different parties involved. STAMP can provide the control structure to identify and manage the responsibilities of the actors and control the effectiveness of the system components (Woolley et al., 2020). The STAMP model regards the accident occurrence as the result of control with incomplete implementation or insufficient safety constraints (Hulme et al., 2021). The STAMP model establishes a hierarchical safety control structure to be applied for ensuring system safety by identifying restraints on procedural defects and improvements in safety control (Ceylan et al., 2021; Sun et al., 2021). The STAMP analysis can be conducted by the following steps (Leveson, 2012):

(1) The first step determines the system safety constraints.
(2) The second step defines the hierarchical safety control structure.
(3) The third step identifies potentially inappropriate control behaviors.
(4) The final step analyzes the causes of inappropriate control.

Based on the STAMP model, the accident is regarded as originating from single or multiple risk-influencing factors (Leveson, 2012). They usually include:

(1) The controller fails to ensure the safety constraints, including inappropriate or insufficient control behaviors, providing or maintaining necessary control behaviors at the wrong time, and loss or inadequacy of process feedback.
(2) The correct control behaviors are not performed.

2.3. Game model

Game theory can be applied for the safety analysis of complex socio-technical systems wherein multiple parties are involved (Staton et al., 2021). In the game model, the parties are players who obey the hypothesis of being “rational persons” to maximize their interests. Parties usually include the government, the board of directors, enterprises, contractors and other entities. Under the supervision and control by the government, the board of directors, the enterprises and contractors can obtain profits through carrying out production and operation activities. According to their different roles and tasks, these stakeholders can be categorized as supervisory and supervised entities. The game is, therefore, modeled as a two-person game.

The supervisory entity first decides the supervisory strategy, in terms of supervision intensity and investment. The supervised entity designs and develops the protection strategy, in terms of protection intensity and input cost. After the supervisory entity selects the strategy, the supervised entity can choose the corresponding strategy. Before making decisions, the players cannot fully realize each other's situation. Thus, the game belongs to the category of incomplete information-game (Liu et al., 2022). Therefore, this work sets up a two-person, dynamic, and incomplete information-type game model to study the game strategies and corresponding benefits.

In the game process, each strategy of a player corresponds to a benefit outcome (i.e., the game return). The players' strategies form a strategy set. If each player's strategy is the optimal one in the strategy set, the game reaches the Nash equilibrium state. The Nash equilibrium emerges dynamically by the interaction of players, and a change in the strategy of any player can modify the Nash equilibrium.

2.4. Sensitivity analysis

Sensitivity analysis allows delving into the competition and cooperation behavior between stakeholders in the accident. To analyze the impact of influencing factors on players' behaviors and strategies, we use quantitative parameters to characterize the strategies of the parties involved in the game and obtain their corresponding benefits from the game played. In this way, we quantitatively study the correlations between parameters and participant behaviors.

3. STAMP-Game based causal analysis of oil transportation accidents

Oil storage and transportation accidents can lead to significant economic losses and negative social impacts. For this reason, they have attracted widespread attention from the perspective of safety engineering. Here, we consider the Buncefield accident as a case study to illustrate the applicability of the methodology.

This section is organized as follows. First, we utilize the STAMP model to clarify the system safety constraints, define a hierarchical safety control structure and analyze the control deficiencies of the stakeholders involved in the Buncefield accident. By identifying the causes of the accident at each layer from enterprise management to equipment, we obtain the detailed causes and potential relationships determining the accident. Subsequently, we apply the game model to describe the strategy and benefit of the supervisory and supervised entities in the system. Eventually, we conduct a sensitivity analysis to capture the evolutionary behavior of the accident system; this allows for identifying causes and selecting emergency measures.

3.1. Accident scenario: the Buncefield oil depot explosion

The Buncefield oil depot explosion was a fire and explosion accident in the United Kingdom in 2005. The accident has led to oil leakage, pollution environment, injuries and economic losses. On the evening of December 10, 2005, a batch of unleaded gasoline was transported to Hertfordshire Oil Storage Ltd. (HOSL) No. 912 storage tank. HOSL is a joint venture between TOTAL UK and Chevron, wherein the former is responsible for routine operations. During the oil filling operation in the early morning of December 11, both the Automatic Tank Gauging (ATG) and Independent High-Level Switch (IHLS) of the storage tank failed. Hence, oil injection continued and gasoline overflowed from the vent on the ceiling of the tank, evolving into a vapor cloud and explosion. More than 40 people were injured in the accident. The fire burned for 5 days and damaged over 20 nearby storage tanks. The direct economic loss amounted to 344 million dollars (Atkinson, 2017).

3.2. STAMP model of Buncefield accident

The accident safety control structure of the Buncefield accident is shown in Fig. 2. According to the safety control structure, the STAMP model is applied to investigate the causes of the accident related to each party, and including the safety requirements and constraints, decision-making environment, inappropriate control behaviors and mental model defects.

3.2.1. HOSL supervision department

In the control room of the HOSL supervision department, there is only one screen to display the ATG operation status of the storage tanks. On the night of the accident, since the supervisor was monitoring the liquid level of 4 storage tanks simultaneously, but an abnormality in the No. 912 tank was not noticed in time resulting in the failure of ATG in this tank. In addition, because of receiving gasoline from several pipelines simultaneously that night, the personnel did not succeed in identifying the filling of corresponding pipeline storage tanks. Moreover, the shift staff did not inform the successive team that the No. 912 storage tank was being filled with oil. Thus, the substituting team did not pay particular attention to that storage tank. Furthermore, the supervisors were accustomed to taking measures only after being alarmed.

Thus, the operators did not pay attention to No. 912 tank because the failed ATG did not send out any automatic alarm.

It is interesting to note that from August 2005 to the accident in December 2005, the ATG had been reported to experience 14 failures. The department head had asked the equipment contractor in Motherwell to take care of these failures but no maintenance was recorded, whereas the failures information and their solutions were recorded and reported. Yet, the cause of these failures has never been discovered and completely resolved. With respect to this, the control defects of the HOSL regulatory authority are shown in Fig. 3.

3.2.2. HOSL technical department

HOSL technical department is responsible for testing the functions of IHLS. IHLS can be used to control both high and low liquid level conditions. During the test, when the IHLS check handle is pulled up to simulate high liquid level conditions, IHLS sends a signal to close the valve. IHLS needs to control the high liquid level of the storage tank. Therefore, IHLS is equipped with a padlock to keep the check handle in the working position of the high liquid level control state. Notably, the padlock needs to be removed during the test and reset after the test, respectively. However, the padlock supplier Motherwell Company selected a padlock, which is not conforming to the safety requirements of HOSL storage tanks.

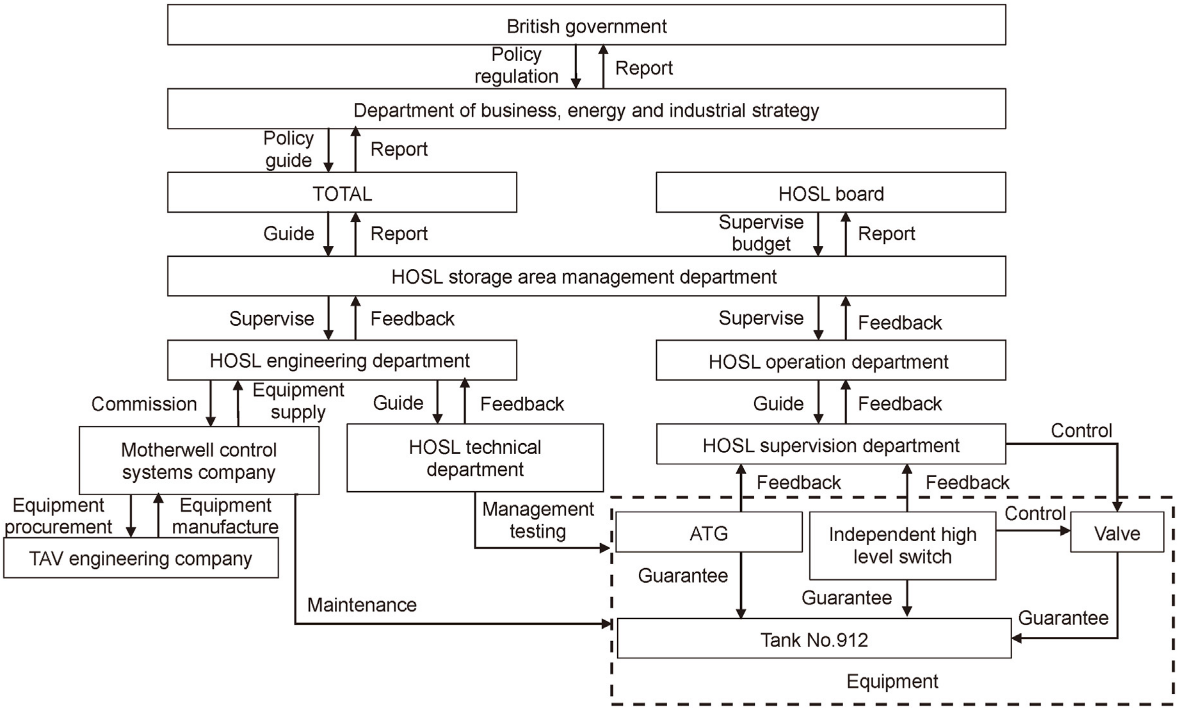
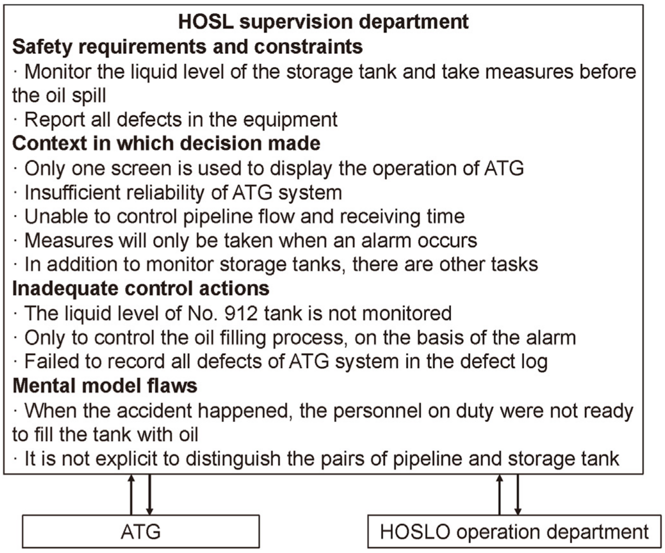


Fig. 2. The hierarchical safety control structure of the Buncefield accident.



HOSL supervision department

Safety requirements and constraints

· Monitor the liquid level of the storage tank and take measures before the oil spill

· Report all defects in the equipment

Context in which decision made

· Only one screen is used to display the operation of ATG

· Insufficient reliability of ATG system

· Unable to control pipeline flow and receiving time

· Measures will only be taken when an alarm occurs

· In addition to monitor storage tanks, there are other tasks

Inadequate control actions

· The liquid level of No. 912 tank is not monitored

· Only to control the oil filling process, on the basis of the alarm

· Failed to record all defects of ATG system in the defect log

Mental model flaws

· When the accident happened, the personnel on duty were not ready to fill the tank with oil

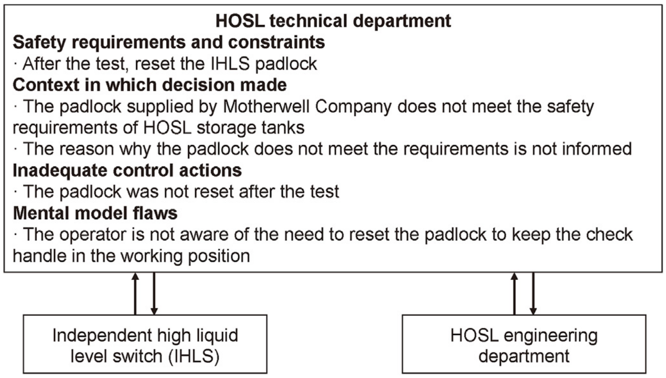
· It is not explicit to distinguish the pairs of pipeline and storage tank

Fig. 3. Constraint failures of the HOSL supervision department.

The HOSL technical department was not aware of the vulnerabilities in the selection and installation of the padlock. And the padlock was not reset after the test, resulting in the IHLS being in a non-operational state. The control defects of the HOSL technical department are shown in Fig. 4.

3.2.3. *TAV Engineering Company*

TAV Engineering Company lacks sufficient understanding of equipment safety requirements. When IHLS needs to control the high liquid level of the storage tank, IHLS turns out to be defective for controlling high and low liquid levels in design and production. TAV failed to inform the padlock supplier (Motherwell Company) of



HOSL technical department

Safety requirements and constraints

· After the test, reset the IHLS padlock

Context in which decision made

· The padlock supplied by Motherwell Company does not meet the safety requirements of HOSL storage tanks

· The reason why the padlock does not meet the requirements is not informed

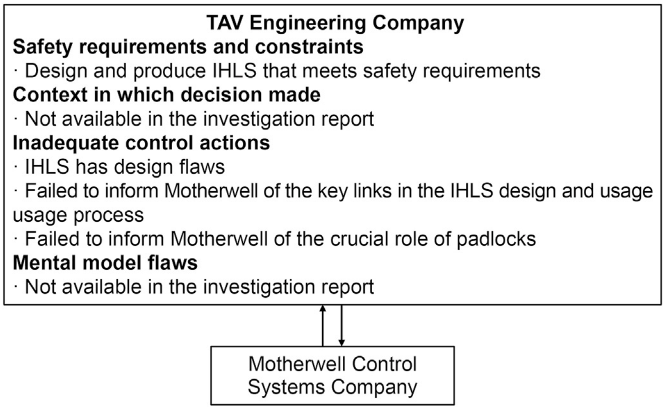
Inadequate control actions

· The padlock was not reset after the test

Mental model flaws

· The operator is not aware of the need to reset the padlock to keep the check handle in the working position

Fig. 4. Constraint failures of the HOSL technical department.



TAV Engineering Company

Safety requirements and constraints

· Design and produce IHLS that meets safety requirements

Context in which decision made

· Not available in the investigation report

Inadequate control actions

· IHLS has design flaws

· Failed to inform Motherwell of the key links in the IHLS design and usage usage process

· Failed to inform Motherwell of the crucial role of padlocks

Mental model flaws

· Not available in the investigation report

Fig. 5. Constraint failures of TAV Engineering Company.

the key points of the design and usage in IHLS, as well as the key role of the padlock. TAV's control defects are shown in Fig. 5.

3.2.4. Motherwell Control System Company

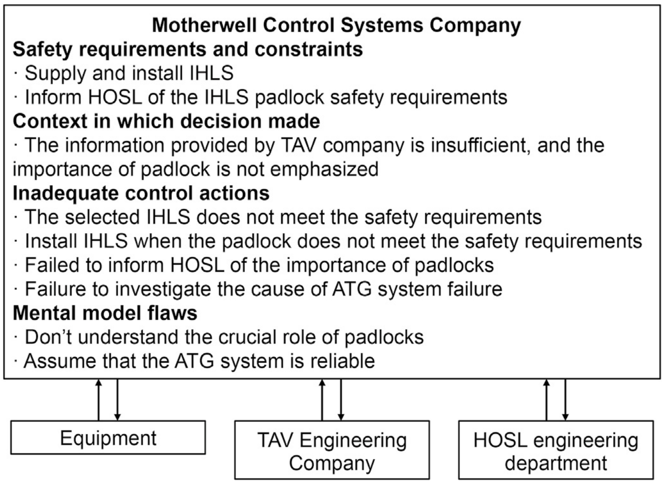
Motherwell Control System Company lacks the understanding of equipment safety requirements. The IHLS purchased from the TAV company did not meet the safety requirements of HOSL storage tanks. Since TAV did not provide sufficient information to Motherwell, the employees of Motherwell knew little about the importance of padlocks. Hence, IHLS was installed even when the padlocks did not reach the safety requirements. Motherwell had been asked by HOSL regulatory authorities to maintain the ATG system several times, however, Motherwell did not investigate the cause of the failure and accordingly never doubted the reliability of the system. Motherwell Control System's control defect is shown in Fig. 6.

3.2.5. HOSL operation department

HOSL operation department failed to establish sound safety operating procedures. For example, only one screen is used to display ATG operation status and, thus, the process supervisors can simultaneously monitor the liquid level of only one storage tank at a time. However, multiple storage tanks were filled with oil, without proper planning of the transportation process. The shift regulated system was imperfect and the substitute team did not obtain enough information in advance to manage the filling process properly. The fault recording procedure was imperfect and the supervisory department did not record all equipment defects in the log. The operating department had a precedent in allowing storage tanks to continue to operate when IHLS was not working properly, which made the technical department and contractors seriously ignore the importance of IHLS. In addition, a department manager had resigned shortly before the accident due to excessive working pressure, but the operation department did not effectively reduce the fatigue of the employees, therefore, the employees might be working under stress. Accordingly, the control defects of the HOSL operation department are shown in Fig. 7.

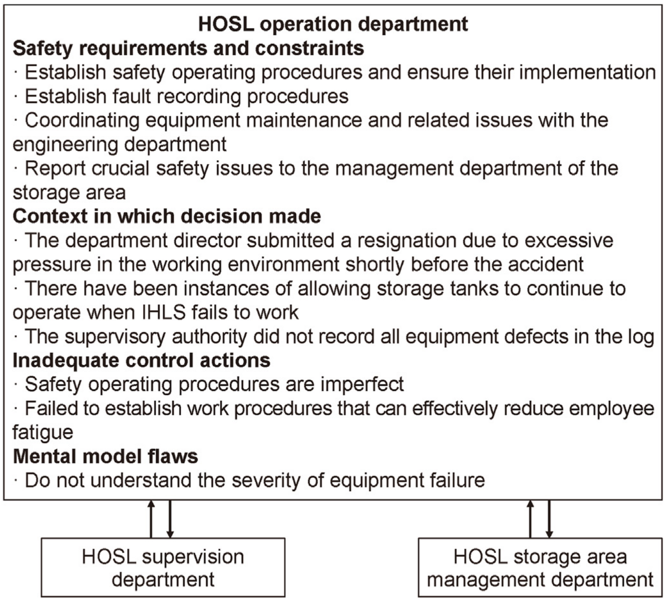
3.2.6. HOSL engineering department

The HOSL engineering department failed to supervise the equipment ordering, installation and testing procedures. It did not discover that the IHLS did not respect the safety requirements. To keep the check handle in the working position, the padlock on the IHLS needs to be reset, but this procedure was not executed. Since the supervision department did not record and report all failures, the engineering department failed to understand the severity of the ATG system failure and to proceed timely to repair the equipment failure. Accordingly, the control defects of the HOSL engineering department are shown in Fig. 8.



Motherwell Control Systems Company
Safety requirements and constraints
· Supply and install IHLS
· Inform HOSL of the IHLS padlock safety requirements
Context in which decision made
· The information provided by TAV company is insufficient, and the importance of padlock is not emphasized
Inadequate control actions
· The selected IHLS does not meet the safety requirements
· Install IHLS when the padlock does not meet the safety requirements
· Failed to inform HOSL of the importance of padlocks
· Failure to investigate the cause of ATG system failure
Mental model flaws
· Don't understand the crucial role of padlocks
· Assume that the ATG system is reliable

Fig. 6. Constraint failures of Motherwell Control Systems Ltd.



HOSL operation department
Safety requirements and constraints
· Establish safety operating procedures and ensure their implementation
· Establish fault recording procedures
· Coordinating equipment maintenance and related issues with the engineering department
· Report crucial safety issues to the management department of the storage area
Context in which decision made
· The department director submitted a resignation due to excessive pressure in the working environment shortly before the accident
· There have been instances of allowing storage tanks to continue to operate when IHLS fails to work
· The supervisory authority did not record all equipment defects in the log
Inadequate control actions
· Safety operating procedures are imperfect
· Failed to establish work procedures that can effectively reduce employee fatigue
Mental model flaws
· Do not understand the severity of equipment failure

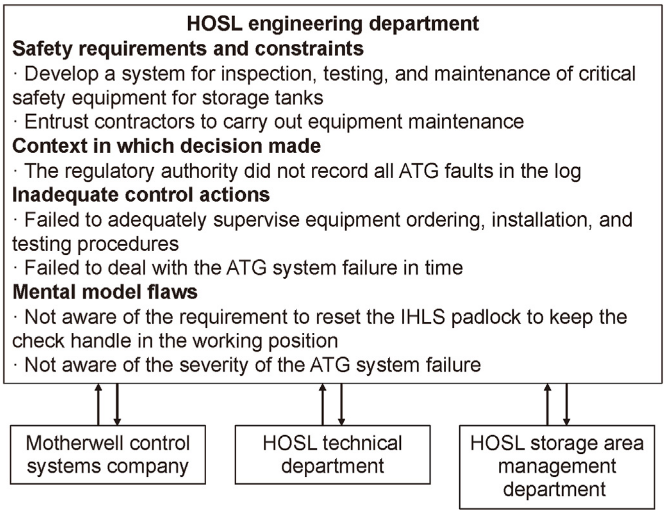
Fig. 7. Constraint failures of the HOSL operation department.

3.2.7. HOSL reservoir area management department

The HOSL reservoir area management department lacked of professional knowledge and resources, failed to guide the operation department and engineering department, and did not realize the severity of equipment failure. The management department of the reservoir area failed to solve the problem of the high work pressure of employees. Accordingly, the control defects of the HOSL reservoir area management department are shown in Fig. 9.

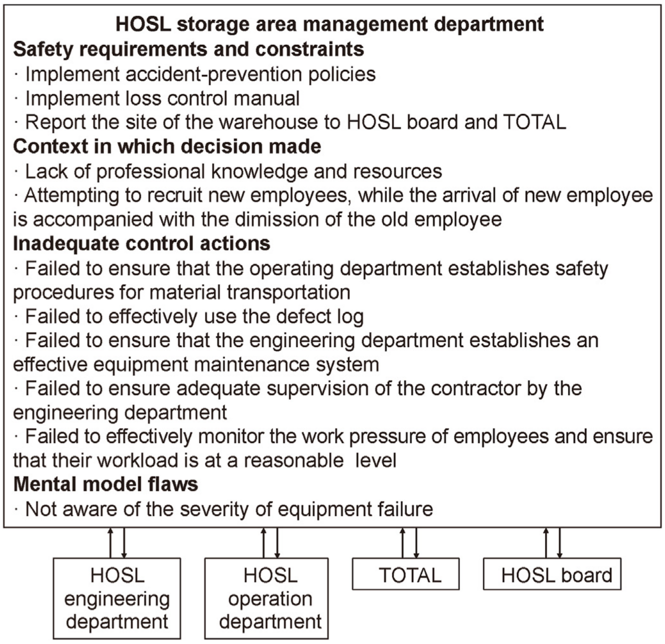
3.2.8. TOTAL UK Company

TOTAL UK Company failed to guide the implementation of the Loss Control Manual and to check whether the Loss Control Manual



HOSL engineering department
Safety requirements and constraints
· Develop a system for inspection, testing, and maintenance of critical safety equipment for storage tanks
· Entrust contractors to carry out equipment maintenance
Context in which decision made
· The regulatory authority did not record all ATG faults in the log
Inadequate control actions
· Failed to adequately supervise equipment ordering, installation, and testing procedures
· Failed to deal with the ATG system failure in time
Mental model flaws
· Not aware of the requirement to reset the IHLS padlock to keep the check handle in the working position
· Not aware of the severity of the ATG system failure

Fig. 8. Constraint failures of the HOSL engineering department.


HOSL storage area management department

Safety requirements and constraints

· Implement accident-prevention policies

· Implement loss control manual

· Report the site of the warehouse to HOSL board and TOTAL

Context in which decision made

· Lack of professional knowledge and resources

· Attempting to recruit new employees, while the arrival of new employee is accompanied with the dimission of the old employee

Inadequate control actions

· Failed to ensure that the operating department establishes safety procedures for material transportation

· Failed to effectively use the defect log

· Failed to ensure that the engineering department establishes an effective equipment maintenance system

· Failed to ensure adequate supervision of the contractor by the engineering department

· Failed to effectively monitor the work pressure of employees and ensure that their workload is at a reasonable level

Mental model flaws

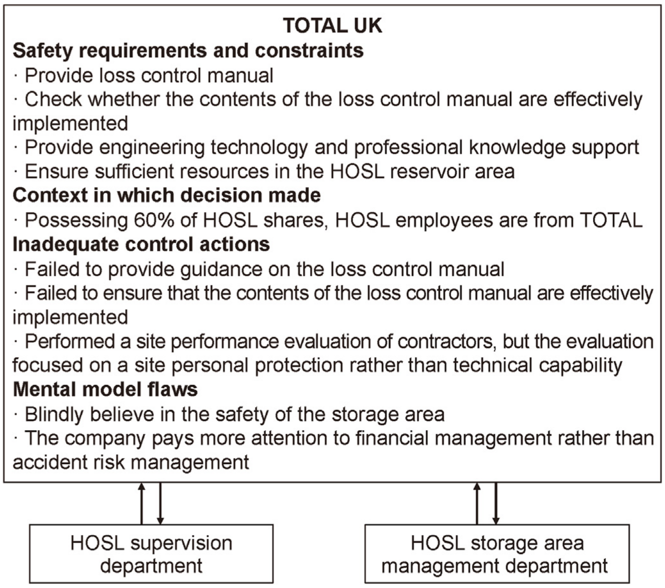
· Not aware of the severity of equipment failure

Fig. 9. Constraint failures of the HOSL storage area management.

was effectively implemented. This led to insufficient risk identification, defect records and equipment maintenance in the reservoir area. At the same time, the high working pressure made it difficult for the departments to complete their work, also with inadequate information. Moreover, the company had conducted an on-site performance evaluation of contractors but mainly focused on personal protection procedures rather than technical knowledge and skills. The control defects of TOTAL UK are shown in Fig. 10.

3.2.9. *HOSL board of directors*

The HOSL board of directors held a conference twice a year. At the meeting, the manager of the management department of the reservoir area reported on health, safety and environmental issues. Given this, it is therefore hard to provide timely feedback on the number of employees being insufficient. The board of directors was seriously ineffective in overseeing the company and failed to perform its duties under the Control of Major Accident Hazard Regulations (COMAH). The control defects of the HOSL board of directors are shown in Fig. 11.


TOTAL UK

Safety requirements and constraints

· Provide loss control manual

· Check whether the contents of the loss control manual are effectively implemented

· Provide engineering technology and professional knowledge support

· Ensure sufficient resources in the HOSL reservoir area

Context in which decision made

· Possessing 60% of HOSL shares, HOSL employees are from TOTAL

Inadequate control actions

· Failed to provide guidance on the loss control manual

· Failed to ensure that the contents of the loss control manual are effectively implemented

· Performed a site performance evaluation of contractors, but the evaluation focused on a site personal protection rather than technical capability

Mental model flaws

· Blindly believe in the safety of the storage area

· The company pays more attention to financial management rather than accident risk management

Fig. 10. Constraint failures of Total UK Ltd.

3.3. *Model of the game between supervisory and supervised entities*

The participants in the game model are divided into the supervisory entity and the supervised entity. To maximize returns, each player has two alternative strategies “full safety investment” and “partial safety investment”: that is, the supervisory entity can choose from “full supervision” and “partial supervision”, the supervised entity's strategies include “full protection” and “partial protection”. The following describes the strategic alternatives of the two players in the designed game model.

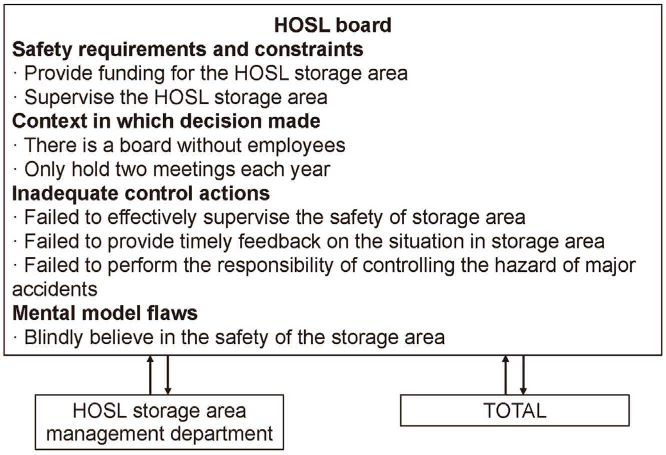
3.3.1. *Supervisory entity*

The supervisory entity supervises the operation of the supervised entity. It decides the strictness of the supervision and pays the corresponding cost. If an accident occurs, the supervisory entity needs to pay a fine to a supervisory entity at a higher level. We introduce the following quantitative parameters to characterize the strategy of the supervisory entity: supervisory strength, supervisory cost, accident penalty and discount factor to account for timing of decisions.

(1) The supervision strength of the supervisory entity on the supervised entity is parameterized as α $(0 \le \alpha \le 1)$: $\alpha = 0$ describes the fact that the supervisory entity chooses “unregulated” and $\alpha = 1$ expresses that the supervisory entity chooses “full supervision”; a value between 0 and 1 suggests that the supervisory entity selects “partial supervision”; a large value of α represents that the supervision is strict.

(2) There are supervision costs for the supervision entity to conduct the safety supervision tasks. The supervision costs increase with the supervision intensity. When the supervisory entity chooses “comprehensive supervision”, the required supervision cost is C and it is assumed that there is a linear relationship between the supervision intensity and the supervision cost. In other words, when the supervision intensity is α, the corresponding supervision cost is αC.

(3) When the supervisory entity chooses “unsupervised”, the fine is F. Assuming that a linear relationship exists also between the supervision intensity and the fine when the


HOSL board

Safety requirements and constraints

· Provide funding for the HOSL storage area

· Supervise the HOSL storage area

Context in which decision made

· There is a board without employees

· Only hold two meetings each year

Inadequate control actions

· Failed to effectively supervise the safety of storage area

· Failed to provide timely feedback on the situation in storage area

· Failed to perform the responsibility of controlling the hazard of major accidents

Mental model flaws

· Blindly believe in the safety of the storage area

Fig. 11. Constraint failures of the HOSL Board.

supervision intensity is α, the fine is $(1-\alpha)F$. The supervisory entity pays the fine to the higher-level supervisory entity. If the supervisory entity chooses “full supervision”, there is no fine to pay when an accident occurs.

(4) The discount factor δ $(0 \leq \delta \leq 1)$ is a function of the time preference attitude and time delay (Zheng and Nie, 2006), which can be used to express the patience of players. “Patience” refers to the psychological and economic bearing capacity of participants: players with strong psychological and economic may eventually get more benefits.

The discount factor is the current equivalent of 1 share over time t, and it can be calculated (González-Hernández et al., 2007):

$$\delta = \left(\frac{1}{1+k}\right)^{t} \tag{1}$$

where δ is the discount factor indicating the patience of a participant, k denotes a fixed interest rate (González-Hernández et al., 2007), t represents the time interval for insufficient safety protection and acceptance of accident penalty. When t is large, δ becomes small: this describes the fact that the supervised entity lacks patience and is more concerned with the current interests. On the contrary, when t is small, δ is large, indicating that the supervised entity has patience and a longer-term interest perspective. In our case, we assume that the discount factor of the supervisory entity is $\delta = 1$, which means that the supervisory entity is patient and gives importance to long-term interests in the game.

3.3.2. *Supervised entity*

The supervised entity determines the degree of safety protection and pays the corresponding costs. If the supervised entity is found to not fulfill the responsibility of safety protection, it shall pay a fine to the supervisory entity. The following parameters are introduced to characterize quantitatively the strategy of the supervised entity: protection intensity, profit, protection cost, accident probability, fines, accident loss and discount factor.

(1) The strength of the supervised entity's protection of personnel and equipment is denoted as β $(0 \leq \beta \leq 1)$: $\beta = 0$ indicates that the supervised entity chooses “unprotected”; $\beta = 1$ denotes that the supervised entity selects “full protection”; when β is between 0 and 1, the supervised entity chooses a strategy of “partial protection”; a large β means good safety protection; otherwise, the protection is insufficient.

(2) The supervised entity carries out production and operation activities, and obtains corresponding profits, denoted as M.

(3) There is a protection cost for the supervised entity to perform safety protection, and the protection cost increases with the increase of the protection intensity. When the supervised entity chooses “full protection”, the required protection cost is N. The following linear relationship is assumed between the protection intensity and the corresponding cost: when the supervision intensity is β, the required supervision cost is βN.

(4) The accident probability is denoted as p: when the supervised entity chooses “full protection”, the accident probability is p_1; when “unprotected” is selected, the accident probability is p_2. It is assumed that there is a linear relationship between the protection intensity and the accident probability as follows: when the supervised entity selects “partial protection” and the protection intensity is β, the accident probability is $(1-\beta)p_2$.

(5) When the supervised entity chooses “unprotected”, the fine is Q. If there is no accident, the fine is Q_1; if an accident occurs, the fine becomes Q_2. Assuming that there is a linear relationship between the protection intensity and fines, when the protection intensity is β, the fines for the supervised entity are $(1-\beta)Q_1$ and $(1-\beta)Q_2$, respectively. In the event of an accident, the supervised entity is fined Q_2 by the higher-level supervisory entity. If the supervised entity chooses “full protection”, there is no fine in the wake of an accident.

(6) The accident loss is denoted as R.

(7) A small discount factor δ means small patience of the players: that is, the supervised entity focuses on the short-term interests and refuses to fully fulfill the responsibility of safety protection; a large δ represents great patience by the player, and then, the supervised entity gives importance to long-term interests.

3.3.3. *Mixed strategy Nash equilibrium*

By combining the designed parameters, we can calculate the expected benefit of each strategy, on the basis of the payoff matrix reported in Table 1.

Let x represent the probability that the supervisory entity chooses “full supervision” and y represent the probability that the supervised entity selects “full protection”. The probabilities of the two players choosing “partial supervision” and “partial protection” are $(1-x)$ and $(1-y)$, respectively. Assuming that y is given, the expected payoff function E_1 of the supervisory entity to choose “full supervision” is

$$E_1 = -Cy + [-C + (1-\beta)Q_1\delta](1-y) \tag{2}$$

When the supervisory entity chooses “partial supervision”, the expected payoff function E_2 is:

$$\begin{aligned} E_2 = {} & [-\alpha C - p_1(1-\alpha)F]y + [-\alpha C \\ & - (1-\alpha)(1-\beta)p_2F + \alpha(1-\beta)Q_1\delta](1-y) \end{aligned} \tag{3}$$

Letting $E_1 = E_2$, the solution is:

$$y = \frac{C + (1-\beta)(Q_1\delta - p_2F)}{p_1F - (1-\beta)p_2F + (1-\beta)Q_1\delta} \tag{4}$$

Assuming x is given, the expected payoff function E_3 for the supervised entity selecting “full protection” is:

$$E_3 = M - N - Rp_1 \tag{5}$$

The expected payoff function E_4 for the supervised entity choosing “partial protection” is:

$$\begin{aligned} & E_4 = [M - \beta N - (1-\beta)(Q_1 + Q_2p_2 + Rp_2)\delta]x + \\ & [M - \beta N - (1-\beta)Rp_2\delta - \alpha(1-\beta)(Q_1 + Q_2p_2)\delta](1-x) \end{aligned} \tag{6}$$

Letting $E_3 = E_4$, one obtains:

$$x = \frac{(1-\beta)N + Rp_1 - (1-\beta)Rp_2\delta - \alpha(1-\beta)(Q_1 + Q_2p_2)\delta}{(1-\alpha)(1-\beta)(Q_1 + Q_2p_2)\delta} \tag{7}$$

Equations (4) and (7) are the mixed strategy Nash equilibria of the game. As Eq. (7) contains parameters of the strategies of both the supervisory entity and the supervised entity, this formula is chosen for the following analysis.

Table 1
Payoff matrix of the supervisory and supervised entities.

Strategies of the supervisory entity	Strategies of the supervised entity	
	Full protection	Partial protection
Full supervision	$-C$, $M-N-Rp_1$	$-C+(1-\beta)Q_1\delta$, $M-\beta N-(1-\beta)(Q_1+Q_2p_2+Rp_2)\delta$
Partial supervision	$-\alpha C-p_1(1-\alpha)F, M-N-Rp_1$	$-\alpha C-(1-\alpha)(1-\beta)p_2F+\alpha(1-\beta)Q_1\delta, M-\beta N-(1-\beta)Rp_2\delta-\alpha(1-\beta)(Q_1+Q_2p_2)\delta$

3.4. Sensitivity analysis

To quantify the relevance of causes to the behaviors and decision-making choices of participants, we assign values to the game parameters and perform sensitivity analysis for the corresponding different strategies of the supervisory and supervised entities. Since the authors are familiar with Chinese law, the parameter values of the accident penalties and safety costs in this paper are determined by Law of the People's Republic of China on Work Safety. The values of Q_1, Q_2, and N are reasonable assumptions based on the Law of the People's Republic of China on Work Safety and other realistic circumstances. In the aforementioned clause, when the safety protection of the supervised entity is not in place and has not been corrected, the supervised entity will be fined with more than 10^5 CNY and less than 2×10^5 CNY. When a serious accident occurs, the supervised entity will be fined with more than 10^7 CNY and less than 2×10^7 CNY. Thus, Q_1 ($Q_1 \in [10^5, 2 \times 10^5]$) and Q_2 ($Q_2 \in [10^7, 2 \times 10^7]$) are assigned 1.5×10^5 and 1.74×10^7 in this paper, respectively. N denotes the protection cost of the supervised entity and its value is determined by the safety measure investment of companies. R indicates that accident economic loss originated from the accident investigation report. The values of P_1 and P_2 are calculated by expert judgment. Due to the limited data, the values of α, x, β, and δ are determined based on assumptions within the defined range and literature (Xing et al., 2020). To discuss the effect of different values on the results, we performed a sensitivity analysis. The parameter values are given in Table 2.

3.4.1. Perspective of the supervisory entity

Based on the analysis in Section 3.2, we analyze the influence of the intensity and cost of supervision and protection on the game participants' behaviors and strategies from the perspective of the supervisory entities. When we analyze the impact of a variable value on the target object, we assume that the remaining variables are fixed. For example, to analyze the effect of a change in N on x,we assume that all other parameters are constant or keep their original values. Then, Eq. (7) quantifies into Eq. (8):

$$x = \frac{N}{2.424 \times 10^4} - 14.953 \tag{8}$$

Similarly, we can quantify Eq. (7) into Eqs. (9)–(11) to analyze the influence of Q_1, Q_2, α, β on x.

$$x = \frac{63.4375 \times 10^5}{\left(Q_1 + 10^{-4} \times Q_2\right)} - 4 \tag{9}$$

$$x = -\frac{1}{(1-\alpha) \times 6.1538} + 1 \tag{10}$$

$$x = \frac{0.1460}{(1-\beta)} - 0.5429 \tag{11}$$

Based on the above-mentioned equations, we concluded the following four conclusions of Fig. 12, described below.

Conclusion 1: As shown in Fig. 12(a), all other conditions fixed, the probability x for the supervisory entity to choose “full supervision” is positively correlated with the protection cost N. As N increases, supervised entities prefer to choose “partial protection”. Following above trends, the supervisory entity needs to conduct more stringent supervision to ensure that the safety protection of the supervised entity is properly in place, which means that the probability of the regulatory entity choosing “full supervision” (i.e., x) increases.

Conclusion 2: As depicted in Fig. 12(b), when all other conditions are determined, x is negatively correlated with fines Q_1 and Q_2. With the growth of fines Q_1 and Q_2, the supervised entity tends to choose “comprehensive protection”. Correspondingly, the supervisory entity does not have to invest plenty of time and cost to select “comprehensive supervision”.

Conclusion 3: As shown in Fig. 12(c), when all other conditions are fixed, x is negatively correlated with the supervisory intensity α. As α increases, the responsibilities and penalties assumed by the supervised entity increase after an accident. Consequently, supervised entities prefer to promote safety protection to reduce the probability of being penalized due to accidents. To save operational cost, the supervisory entity tends to decrease the probability of full supervision.

Conclusion 4: As shown in Fig. 12(d), when all other conditions are determined, x is positively correlated with protection strength β. As β increases, the supervised entity is inclined to choose partial protection for increasing revenue. To avoid inadequate safety

Table 2
Parameters of the game model.

Players	Parameters	Value	Note
Supervisory entity	Supervisory intensity α	0.8	$0 \le \alpha \le 1$
	Choosing the probability of “full supervision” x	0.8	$0 \le x \le 1$
Supervised entity	Protection intensity β	0.8	$0 \le \beta \le 1$
	Protection cost N	3.67×10^5	Unit: CNY
	Accident probability with full protection p_1	10^{-6}	$0 \le p_1 \le 1$
	Accident probability without protection p_2	10^{-4}	$0 \le p_2 \le 1$
	Fine without the occurrence of accident Q_1	1.5×10^5	Unit: CNY
	Fine with the occurrence of accident Q_2	1.74×10^7	Unit: CNY
	Accident loss R	3.54×10^9	Unit: CNY
	Discount factor δ	0.8	$0 \le \delta \le 1$

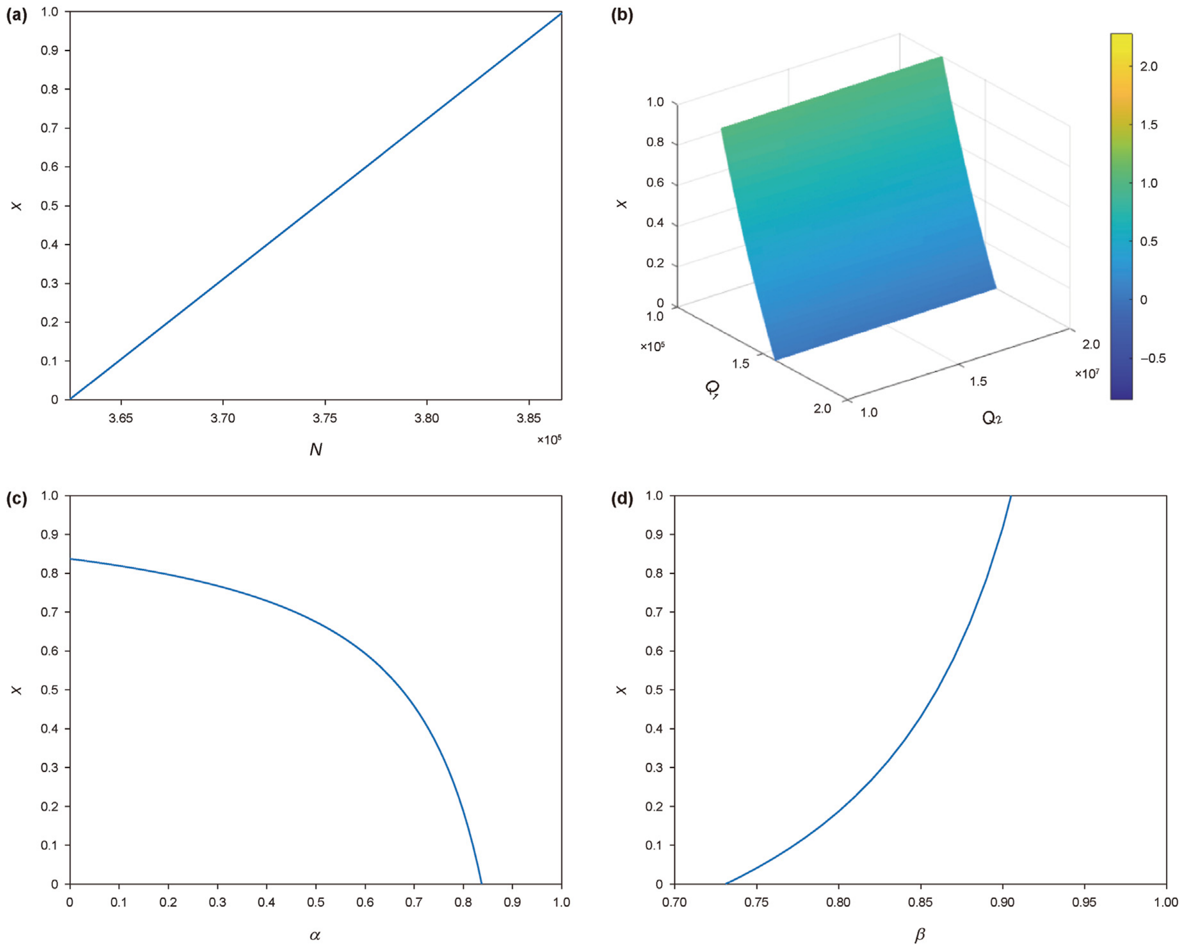


Fig. 12. (**a**) Relationships between probability *x* of the supervisory entity and protection cost *N*. (**b**) Relationships between probability *x* of the supervisory entity and fines Q_1, Q_2. (**c**) Relationships between probability *x* of the supervisory entity and supervisory intensity *α*. (**d**) Relationships between probability *x* of the supervisory entity and protection intensity *β*.

protection, the supervisory entity usually enhances full supervision.

3.4.2. Perspective of the supervised entity

From the perspective of the supervised entity, quantify Eq. (7) into Eq. (12) and obtain three main conclusions regarding the relationships among supervisory intensity, protection cost, accident penalty, and discount factor:

$$\delta=\frac{(1-\beta)N+Rp_1}{(1-\alpha)(1-\beta)(Q_1+Q_2p_2)x+\alpha(1-\beta)(Q_1+Q_2p_2)+(1-\beta)Rp_2} \tag{12}$$

Given the values for the involved variables, Eq. (12) can be converted into Eqs. (13)–(16):

$$\delta=2.0022\times10^{-6}N+0.0354 \tag{13}$$

$$\delta=\frac{4.0073\times10^{5}}{\left(Q_1+10^{-4}\times Q_2\right)+3.6875\times10^{5}} \tag{14}$$

$$\delta=\frac{12.6965}{(\alpha+4)+11.6830} \tag{15}$$

$$\delta=0.7348+\frac{0.0071}{1-\beta} \tag{16}$$

We use these equations to analyze the relations of Q_1, Q_2, α, β to δ. The results are shown in Fig. 13 and the following conclusions.

Conclusion 5: As shown in Fig. 13(a), when all other conditions are fixed, the discount factor δ and the protection of the supervised entity cost *N* are positively correlated. According to Conclusion 1, the probability *x* of the supervisory entity choosing “full supervision” grows as *N* increases. To avoid being punished for inadequate safety protection, the supervised entity tends to invest sufficient protection costs. This shows that the supervised entity takes the non-occurrence of accidents as a long-term goal and pays attention to long-term interests.

Conclusion 6: As shown in Fig. 13(b), when the other conditions are fixed, δ is negatively correlated with fines Q_1 and Q_2. According to Conclusion 2, the probability *x* of the supervisory entity choosing “comprehensive supervision” decreases as fines increase. To maximize interests, the supervised entity tends to take risks and choose “partial protection”, hoping to evade the supervision of the supervisory entity. If such behavior occurs, it indicates that the supervised entity is focused on short-term interests and has a higher risk of being fined due to accidents.

Conclusion 7: It can be seen from Fig. 13(c) that when all other conditions are predefined, δ is negatively correlated with

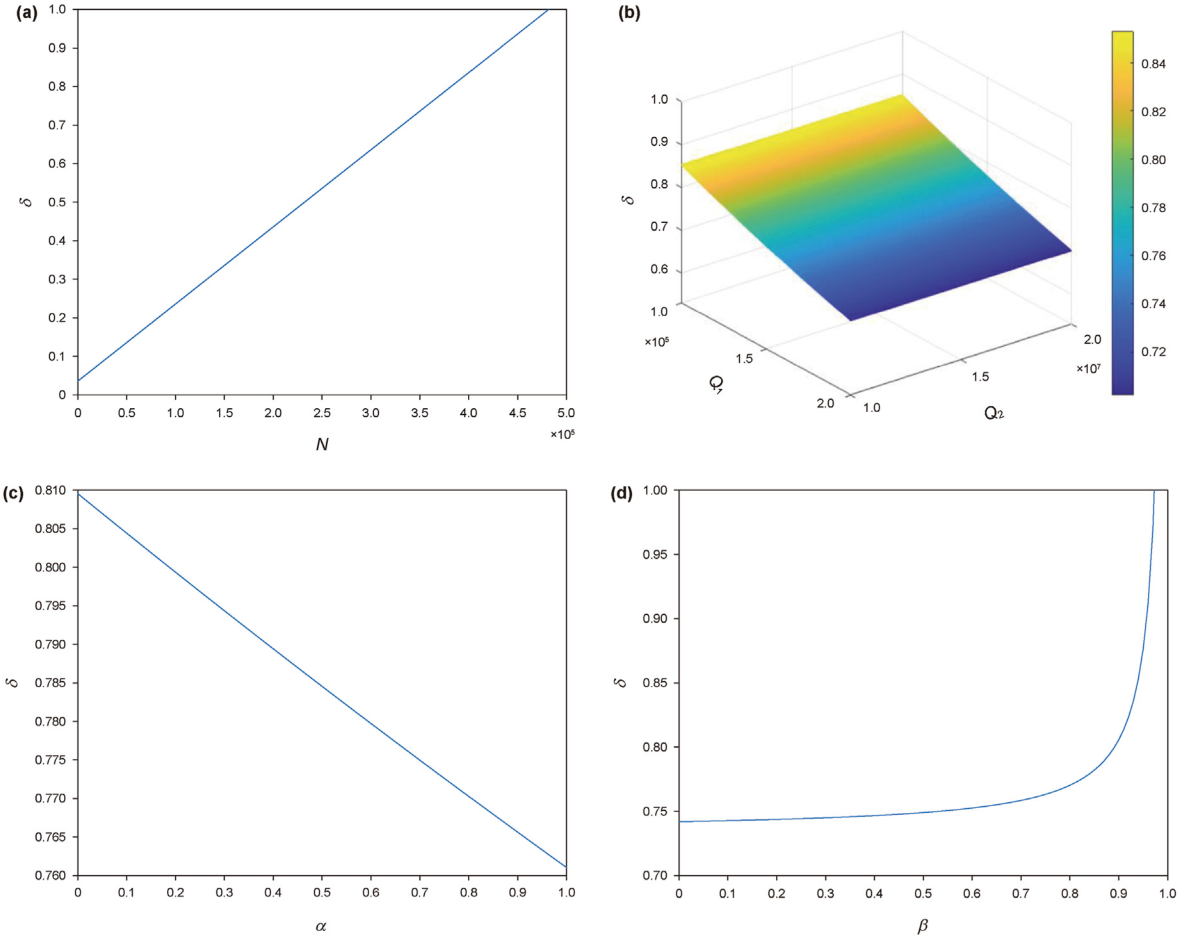


Fig. 13. (**a**) Relationships between discount factor δ of the supervised entity and protection cost N. (**b**) Relationships between discount factor δ of the supervised entity and fines Q_1、Q_2. (**c**) Relationships between discount factor δ of the supervised entity and supervisory intensity α. (**d**) Relationships between discount factor δ of the supervised entity and protection intensity β.

supervisory intensity α. The growth of supervisory intensity decreases the probability of the supervisory entity choosing "full supervision". This result can extend the time interval of the supervisory entity from the beginning of supervision to the implementation of penalties. Eq. (1) in Section 3.3 shows that a larger time value indicates that the supervised entity prioritizes short-term interests over long-term stability and growth, due to a lack of sufficient financial and psychological capacity. Meanwhile, if strict supervision leads to excessive investment costs, the supervised entity tends to implement cost-cutting strategies, such as partial safety protection, to increase profitability.

Conclusion 8: It can be seen from Fig. 13(d) that when all other conditions are fixed, δ is positively correlated with protection intensity β. An increase in β indicates that the supervised entity chooses adequate safety protection investment to avoid accidents, paying more attention to long-term benefits. An inflection point has been found around $\beta = 0.85$: after that β increases, δ grows significantly. That is, under the current parameter settings, once the protection of the supervised entity exceeds this value, the degree of emphasis on long-term benefits is significantly increased.

To verify the reliability of the obtained results, we compared our results with the Buncefield oil depot explosion accident investigation report. We summarized the supervised entities prefer to choose "partial protection". When the supervisory entity needs to conduct stringent supervision, the probability of choosing "full supervision" by the supervised entity increases. The literature (Herbert, 2010) concluded that the supervised entity lacks of awareness the loss of containment of significant quantities of petrol and its implications in accidents. The supervised entity chose "partial protection". With the increasing in fines, the supervised entity tends to choose "full protection" or "comprehensive protection". These results also are demonstrated in Conclusions 1 and 2. Meanwhile, we compared related research in this field. Selvik et al. (2021) proposed to use SMART (Specificity, Measurability, Achievability, Relevancy, and Time-based) acronym to assess the quality of performance indicators for safety management based on the Buncefield incident. Their work showed the significance of maintaining the level gauge and tank overflow that protecting against loss of containment. These are consistent with Conclusion 3 in Fig. 12 and Conclusions 7 and 8 in Fig. 13. We discussed the effectiveness of the supervisory entity and the protection attitude of the supervised entity, which was also concerned in the above-referenced studies (Selvik et al., 2021). This partially confirms that the proposed approach can construct an effective STAMP-Game model for accident analysis in oil and gas industry.

4. Discussion

We integrated the STAMP model with game theory to quantitatively investigate the participant behaviors and strategy selections for causal analysis of the Buncefield oil depot explosion in oil and gas industry. In the case study, we discussed aspects that contribute to strengthening the effectiveness of supervisory entities and increasing the protection attitude of supervised entities.

4.1. *Effectiveness of the supervisory entity*

The supervisory entity first chooses a strategy, whose corresponding decisions affect the strategy of the supervised entity. Supervisory entities can take the following countermeasures to strengthen the effectiveness of their supervision:

(1) The supervisory entity can flexibly change the strategy. This can be seen from Conclusions 1, 2, 5, and 6 (Section 3.4) of the case study, whereby the supervised entity considers the decision of the supervisory entity. Then, for the effectiveness of supervision, the supervisory entity needs to flexibly change strategies during the game, making additional “secondary decisions” and “multiple decisions” after the initial one. This makes it difficult for the supervised entity to predict the supervisory entity's strategy by the supervised entity, so that, the probability of it choosing “partial protection” is small.

(2) From Conclusion 4 (Section 3.4), it can be seen that the increase in the probability of “comprehensive supervision” can improve the safety protection of the supervised entity. From Conclusion 8 (Section 3.4), it is seen that the supervised entity with long-term interests enhances its protection intensity. If the safety record of the supervised entity is sound, the supervisory entity can relax the supervision and pay more attention to other supervised entities with poor safety records. Thus the supervision cost can be allocated reasonably.

(3) The goal of supervision is to manage the discount factor of the supervised entity. It can be seen from Conclusions 3 and 7 (Section 3.4) that strict supervision can make the supervised entity focus on current interests due to excessive investment. Therefore, the supervisory entity needs to improve supervision efficiency for reducing supervision intensity and cost. Additionally, the supervisory entity can encourage the positive attitude of the supervised entity to safety protection by rewarding the supervised entity with sound safety records.

4.2. *The protection attitude of the supervised entity*

The supervised entity selects the strategy according to the strategy of the supervisory entity. It is straightforward to reduce the supervision cost and accident probability by improving the safety protection attitude of the supervised entity.

(1) The supervised entity can timely maintain the equipment. Before the Buncefield oil depot explosion accident, the ATG system for monitoring the tank liquid level failed 14 times and this was not followed up by repair. The supervised entity needs to timely deal with the faults.

(2) The supervised entity can refine the personnel training and management. The Buncefield accident revealed that there were omissions in the employee shifts communication and management, and in the equipment operation. The analysis showed that employees were under high work pressure for a long time due to insufficient staff. The supervised entity needs to enhance employee training and management, and focus on employee working status.

4.3. *Policy suggestions*

The policy proposals are presented in terms of the STAMP model and game theory, respectively.

(1) The STAMP model can be used to optimize the safety management system and improve its efficiency. When investigating the Buncefield accident as a case study, a diagram is employed to illustrate the hierarchical safety control structure. Through this method, we can explicitly depict inappropriate control behaviors of stakeholders and their relations. Therefore, we can define the accident liability of involved entities and propose corresponding prevention policies and standardized procedures.

(2) Game theory divides stakeholders into two parts: supervisory and supervised entities. In the game process between the supervisory and supervised entities, the supervisory entities have accumulated management experience while constantly changing their strategies. Each supervised entity is exposed to accidents for different reasons. Therefore, it is necessary to select strategies for different supervised entities. To achieve optimal interests, the supervisory entities need to perform classification and safety check based on the characteristics of the supervised entities. Regarding the supervised entities, the strategy choices in the game process should be inclined to choose comprehensive protection. To maximize the benefits, the supervised entities are supposed to determine the risk levels of production units. From the perspective of system safety, the high-risk system units need to be fully protected. The classification-based protection can improve protection efficiency and reduce accident fines for supervised entities.

5. Conclusion

In this paper, we have proposed an accident risk analysis method that integrates the STAMP model and game theory. We applied the method to analyze the explosion accident at the Buncefield oil depot. Based on the accident analysis, we provided correction measures for preventing similar accidents. The obtained results can be used for accident prevention in the oil and gas storage and transportation systems. Based on the study, we summarize the following conclusions.

(1) In the analysis of oil storage and transportation accidents, the proposed STAMP-Game model can identify the causes of accidents from the perspective of system engineering. The in-depth accident analysis with the STAMP-Game model can assist in explaining the behaviors and strategy choices of the involved parties and guide the determination of targeted correction measures for safety improvement.

(2) The STAMP-Game model is capable of analyzing equipment failures and human errors in complex socio-technical systems. It provides outcomes that can be beneficial to prevent similar accidents through risk control measures.

(3) We discussed the accident causes and the strategy selections of supervisory and supervised entities. Strengthening the supervision effectiveness of supervisory entities and improving the safety protection attitude of supervised entities will reduce supervision costs and accident risk.

Regarding the limitation of this study, the data utilized in the STAMP-Game model needs to be more convincing by considering system characteristics, dynamic risk status, safety regulations, domain knowledge, and expert expertise. To demonstrate the universality of the proposed STAMP-Game model, more case studies on various engineering systems can be conducted. In future research, the STAMP-Game model can be improved by considering the public entity nearby the hazardous systems.

CRediT authorship contribution statement

Huixing Meng: Investigation, Methodology, Writing- Original draft preparation, Validation. **Xu An:** Investigation, Visualization, Writing- Original draft preparation. **Daiwei Li:** Investigation, Visualization, Writing- Original draft preparation. **Shijun Zhao:** Writing- Reviewing and Editing. **Enrico Zio:** Writing- Reviewing and Editing. **Xuan Liu:** Writing- Reviewing and Editing. **Jinduo Xing:** Methodology, Conceptualization, Writing- Reviewing and Editing.

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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Abbreviations and symbols

ATG	Automatic Tank Gauging
CAST	Causal Analysis based on system theory
COMAH	Control of Major Accident Hazard Regulations
ETA	Event Tree Analysis
FTA	Fault Tree Analysis
FRAM	Functional Resonance Analysis Method
HFACS	Human Factors Analysis and Classification System
HOSL	Hertfordshire Oil Storage Ltd.
IHLS	Independent High-Level Switch
PCM	Perceptual Cycle Model
STAMP	System-Theoretic Accident Model and Processes
C	Supervision cost
F	Supervisory entities' fines under without choosing supervision
N	Protection cost
p_1	Accident probability with full protection
p_2	Accident probability without protection
Q_1	Fine without the occurrence of accident
Q_2	Fine with the occurrence of accident
R	Accident loss
x	Choosing the probability of “full supervision”
y	Choosing the probability of “full protection”
α	Supervisory intensity
β	Protection intensity
δ	Discount factor

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