

Article

Evolution Mechanism of Major and Extraordinary Accidents Based on an Energy Transfer Model: A Case Study

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Abstract

To improve risk prevention and safety management in high-risk industrial systems, this study integrates energy transfer theory and system dynamics to analyze the mechanisms of major and extraordinary accidents. It further investigates the catastrophic explosion of Tianjiayi Chemical Co., Ltd. on 21 March 2019 in Xiangshui, China—a complex-system failure that caused extensive casualties and property damage. By refining the energy transfer model using system dynamics, the accident is analyzed through the lens of a hazardous energy constraint failure. Simulation results demonstrate that the incident arose from the coupled interaction of multi-level risk factors, exhibiting pronounced nonlinear and synergistic characteristics. The collapse of energy containment barriers led to an uncontrolled release of stored chemical energy, which critically escalated the accident. Personnel errors, managerial deficiencies, and material hazards were identified as primary contributors to systemic vulnerability. The findings offer a mechanistic understanding of energy-driven accident evolution and provide actionable insights for enhancing engineering safety management and preventing major accidents in chemical industrial parks.

Keywords: accident evolution; energy transfer theory; system dynamics; risk mechanism; case study

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1. Introduction

Work safety is a crucial safeguard for the stable development of the national economy. In recent years, China's overall work safety situation has shown continuous improvement. However, with the acceleration of economic restructuring and industrial upgrading, the production layout of the chemical industry is increasingly shifting towards park-based and cluster-based developments 1. As regions where high-risk energy carriers are concentrated, chemical industrial parks face complex systemic risks due to the inherent major hazards within these areas, as well as the coupling and superposition of risks between enterprises 2. Over the past decade, several major incidents have occurred, including the 12 August 2015 Tianjin Port Ruihai Company

hazardous materials warehouse fire and explosion, the 28 November 2016 Shenghua Chemical explosion and fire in Zhangjiakou, Hebei Province, the 12 July 2017 Hengda Technology explosion and fire in Yibin, Sichuan, and the 12 March 2019 Xinghua explosion in Jiangsu. These incidents have resulted in severe casualties and property losses. Additionally, these incidents highlight continuous vulnerabilities in chemical industrial parks related to risk identification, hidden hazard management, and safety control. Thus, the continued pressure to prevent major and particularly serious accidents remains significant.

Given the complex nature of major accidents in the chemical industry, scholars have conducted extensive research on their causal mechanisms and evolutionary patterns. Early studies primarily relied on linear causal models, such as the Bodde chain of causation model 3, hazard source theory 4, and the Human Factors Analysis and Classification System (HFACS) model 5. While these models effectively identify direct causes of accidents and the relationships among human, mechanical, environmental, and managerial factors, they have limitations in capturing the multi-factor coupling and nonlinear dynamic evolution of such incidents 6. With the development of complex systems theory, researchers have progressively introduced approaches such as complex network models 7, trajectory crossing theory 8, and energy transfer theory 9 into accident analysis. These methodologies provide insights into risk propagation pathways and critical causal nodes from a systemic perspective. For instance, Fu et al. 10 developed a comprehensive logical analysis procedure for accident causes based on Fault Tree Analysis (FTA) and 24Model theory, integrated with the Why-Because method. Song et al. 11 proposed a scenario simulation method for chemical plant fire-explosion accidents based on fuzzy Bayesian networks, adopting a “scenario-response” research approach. Liu et al. 12 constructed a cohesive network analysis framework for chemical accidents to examine causal relationships among cohesive nodes. Vairo et al. 13 proposed an analytical framework for emergent risks in complex systems from a Bayesian perspective, which provides systematic insights into risk uncertainty quantification and predictive modelling of hazard evolution. Wen and Khan 14 proposed a precursor-based multi-class Bayesian meta-learning method for rare event prediction in process systems, providing a targeted solution to the data scarcity challenge in chemical risk forecasting.

Considering the continuous release, transfer, and dissipation of energy inherent in chemical production systems, analyzing accident mechanisms from the perspective of hazard energy constraint failures presents a novel research direction for complex systems. Zhou et al. 15 introduced a comprehensive analytical framework to explain the complexity of the Hangzhou subway collapse, using an improved accident energy release model and network theory. Zhang et al. 16 developed an energy-transfer-based safety risk estimation model for construction projects, enabling a quantitative analysis of dynamic energy flow characteristics. Additionally, Zhang et al. 17 explored the dynamic mechanisms of accident risk formation and propagation from an energy perspective, emphasizing energy constraint failures. Overall, while existing research has largely remained at the qualitative analysis stage, there has been limited exploration of the dynamic mechanisms underlying energy constraint failures and the coupling relationships within these systems, particularly within the context of complex chemical industrial park systems, which require further in-depth research.

This paper integrates energy transfer models with system dynamics methodologies, using the Jiangsu Xiangshui “3·21” major chemical production explosion as a case study. It analyzes the mechanisms of accident occurrence and their evolutionary processes, focusing on both production factors and management elements. By incorporating simulation results, key factors and sensitive links were identified to provide insights for

accident prevention, control measures, emergency response, and safety management in chemical industrial parks.

2. Theoretical and Methodological Framework

2.1. Theoretical Overview

The Accident Energy Transfer Theory, proposed by American safety expert Haddon, is an accident control theory based on the premise that accidents result from abnormal or unintended energy transfers¹⁸. This theory frames accidents as an energy control problem, emphasizing that the effective containment of hazardous energy is crucial to safety management. It consists of four primary steps. In the first step, hazardous energy factors are systematically identified through the analysis of historical accident causes. In the second step, root causes of hazardous energy containment failures are examined. In the third step, dynamic processes and pathways of energy transfer and transformation are then characterized. In the final step, control strategies for hazardous energy containment are proposed, aimed at reducing accident probability by intervening in abnormal energy conversions.

Compared to traditional linear accident causation models, the energy transfer model more effectively uncovers the physical essence of accident occurrence, particularly in identifying potential hazards arising from uncontrolled energy in hazardous chemical production processes¹⁹. By analyzing energy transfer pathways, this model provides a theoretical framework for systematic accident causation analysis and energy control. In doing so, it facilitates a clearer explanation of the evolution and impact mechanisms of safety hazards, as exemplified by the Xiangshui “3·21” accident.

System dynamics (SD) is a quantitative simulation method used to study the feedback behavior and dynamic trends of complex systems²⁰. Its core methodology is structured around five key steps: first, define the system boundaries to delineate the problem and its key variables. Second, map the causal relationships between variables and construct a causal diagram. Third, develop a feedback loop system dynamics stock–flow model to reveal the relationships among variables. Fourth, mathematically formalize the model to capture interactions within the system and perform simulations using computer software. Fifth, propose management strategies and recommendations based on the simulation results and trend analysis.

Based on the core methodology, this paper uses the Xiangshui “3·21” major chemical explosion as a case study. By integrating the specific conditions of chemical industrial parks, this paper systematically analyzes the factors influencing the accident. It further clarifies the causal feedback relationships, constructs a system dynamics model to represent the evolution of the accident, and utilizes Vensim-PLE software(7.3.5 version) to simulate and analyze the dynamic progression of the incident.

2.2. Background of the Xiangshui “3·21” Major Chemical Explosion Accident

The Jiangsu Xiangshui “3·21” Tianjiayi Chemical Co., Ltd. Extraordinary Major Explosion Accident (hereinafter referred to as the Xiangshui “3·21” Chemical Explosion) occurred at Tianjiayi Company in Xiangshui County, Jiangsu Province. Established on 5 April 2007, Tianjiayi Company is in the southeastern part of the Ecological Chemical Industrial Park. The company’s main products included m-phenylenediamine (17,000 tons/year), o-phenylenediamine (2500 tons/year), p-phenylenediamine (500 tons/year), m-hydroxybenzoic acid (500 tons/year), 3,4-diaminotoluene (300 tons/year), para-toluidine (500 tons/year), and trimethylaniline (500 tons/year). These chemicals are primarily used in the production of pesticides, dyes, pharmaceuticals, and other related products. The specific layout of the company and the scope of the accident’s impact are illustrated in Figure 1.

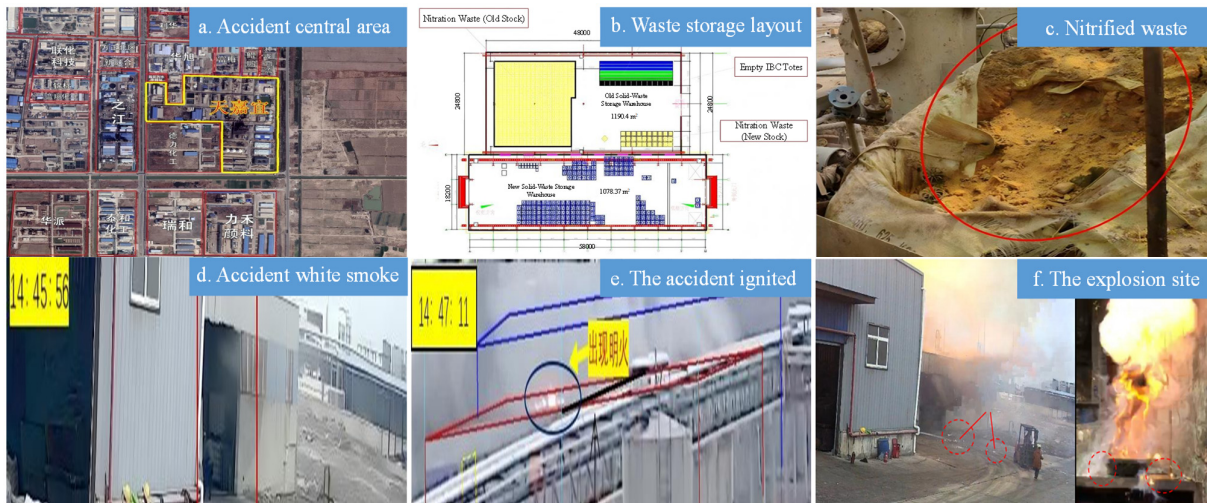


Figure 1. Overview of the Xiangshui “March 21” Major Chemical Explosion Accident.

The study primarily relied on accident investigation reports as its main source of information. On 21 March 2019, at 14:45:35, faint white smoke appeared from the centre of the roof of the old solid waste storage facility. By 14:45:56, smoke began to spread outward from the south gate of the facility, moving from east to west and gradually expanding and intensifying. At 14:46:57, workers inside the new solid waste storage facility detected the fire. Carrying two fire extinguishers, the workers ran from the north gate towards the south gate to extinguish the flames. At 14:47:03, thick black smoke began to billow from the southern side of the roof of the old solid waste storage facility. By 14:47:11, the central section of the roof was burned through, revealing visible flames as the fire rapidly intensified. At 14:48:44, the video feed was interrupted, indicating the occurrence of an explosion. The time from the emergence of the pale white smoke to the explosion was 3 min and 9 s. The explosion destroyed most of the chemical production units and structures within a 300 m radius of its epicentre, resulting in significant casualties. A total of 78 people lost their lives, and the accident triggered eight additional fires in the surrounding area.

2.3. Accident Analysis Framework for Energy Transfer Models in Integrated System Dynamics

The Xiangshui “3-21” major chemical explosion was a complex incident involving multiple interconnected risk events of various types, forming an SD model throughout the entire accident process²¹. While the energy transfer model aids in understanding the core nature of the accident and analyzing causal relationships, it is insufficient for fully explaining the interconnections between risk events²². In order to gain a deeper understanding of the dynamic progression of the accident, system dynamics can be employed to establish relationships among sub-risk events and clarify the connections between energy transfer nodes. The analysis workflow, based on both the energy transfer model and the accident SD model, is illustrated in Figure 2. Using the Xiangshui “3-21” Chemical Major Explosion investigation report and the relevant literature as primary sources of information, the methodological steps are presented as follows: Identify energy factors, analyze the causes of energy constraint failures, and conduct energy transfer analysis based on the energy transfer model. In addition, construct causal models and energy transfer variation models. Develop an accident simulation model using system dynamics methodology to reveal the dynamic interplay and complexity of risk events throughout the accident progression.

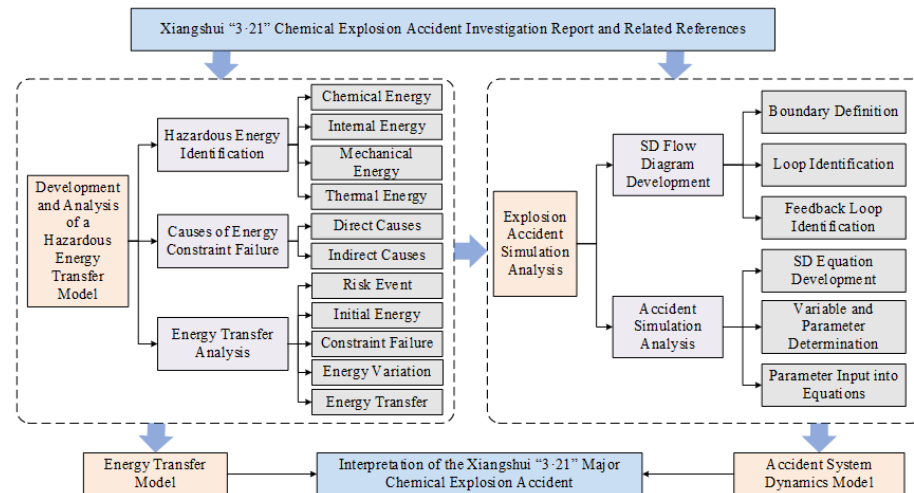


Figure 2. Analysis Process for the Xiangshui “3-21” Major Chemical Explosion Accident Based on the Energy Transfer Model.

3. Formation and Evolution Process of the Xiangshui “3-21” Major Chemical Explosion Accident

3.1. Hazardous Energy Identification Analysis

The development and evolution of accidents in chemical industrial parks are influenced by multiple factors, exhibiting typical characteristics of nonlinear complex systems. Fire and explosion incidents represent a primary category of chemical safety accidents, featured by high occurrence frequency, wide impact scope and extremely severe aftermaths. For instance, in the Xiangshui “3-21” major chemical explosion, the key risk events identified included: (1) long-term illegal storage of nitration waste in the old solid waste warehouse of Tianjiayi Company; (2) continuous heat release from the nitration waste; (3) ambient temperature rise triggering the spontaneous combustion of waste; (4) rapid fire spread across the entire pile with surface combustion; and (5) violent decomposition of nitration waste causing explosions. Energy served as the root cause of risk incidents and a fundamental hazard factor, with distinct energy sources often present across different types of accidents. Based on the analysis of the five risk events in this accident (see Table 1), the hazardous energy sources and types associated with each risk event were identified, as shown in Table 2.

Table 1. Risk Event Analysis of the Xiangshui “3-21” Major Chemical Explosion Accident.

Stage	Event Description	Risk Event
Phase One	The nitrated waste stored in Tianjiayi Company’s old solid waste warehouse had been stored for over seven years at its longest.	Long-term illegal storage of nitration waste
Phase Two	Nitrated waste possesses self-decomposition properties, releasing heat during decomposition, with the decomposition rate accelerating as temperature rises.	Thermal decomposition of nitration waste
Phase Three	Under conditions of dense stacking and poor ventilation, accumulated heat within portions of the long-term stored waste caused temperatures to rise continuously. When temperatures reached the autoignition threshold, spontaneous combustion occurred.	Spontaneous combustion of nitration waste

Phase Four	The fire rapidly spread throughout the entire stack, causing the surface to burn intensely.	Combustion of entire piles of nitration waste
Phase Five	Internal temperatures rose sharply, triggering violent decomposition and explosions within the waste. This simultaneously detonated all nitration waste stored within the warehouse.	Explosion of nitration waste

Table 2. Hazardous Energy Sources and Classification of the Xiangshui “3·21” Major Chemical Plant Explosion Production Accident.

Risk Events	Energy Generation and Storage	Energy Source	Energy Type
Long-term storage of nitration waste	Nitration Waste	Long-term stored nitrated waste	Chemical Energy
Exothermic decomposition of nitration waste	Nitration Waste and Air	Decomposed nitrated waste	Chemical Energy, Thermal Energy
Spontaneous combustion of nitration waste	Nitration Waste	Decomposed nitrated waste, air	Chemical Energy, Internal Energy, Thermal Energy
Combustion of entire stacks of nitration waste	Nitration Waste and Surrounding Chemicals	Spontaneously combusted nitrated waste	Chemical Energy, Internal Energy, Thermal Energy
Explosion of nitration waste	Nitration Waste and Nearby Personnel and Objects	Nitrated waste, surrounding chemicals	Internal Energy, Mechanical Energy

Generally, the greater the energy a system possesses, the greater its potential danger and hazard²³. Dangerous energy transfer changes represent the fundamental cause of accidents. Analyzing the evolution mechanism of the Xiangshui “3·21” accident from the perspective of energy transfer allows for a deeper understanding of accident progression in chemical industrial parks. The identified risk events represent the temporal evolution stages of hazardous energy accumulation and release. Meanwhile, the personnel, equipment, materials, management, and environmental subsystems describe the causal factors that influence each stage of accident evolution by affecting hazardous energy generation, transfer, and constraint effectiveness.

3.2. Analysis of Energy Constraint Failure Causes

Based on the analysis and identification of hazardous energies described above, the causes of energy constraint failure were examined from both direct and indirect accident factors. The causal evolution process of the accident is outlined in Figure 3.

The direct factors contributing to accidents primarily include personnel, equipment, environmental, and material elements. From the perspective of accident causation logic, personnel are the core element in the evolution of industrial park accidents, serving as both initiators and victims. Violations of operating procedures, insufficient safety awareness, and a lack of professional skills can trigger accidents. Unsafe conditions of physical assets significantly increase the likelihood of accidents, such as malfunctioning monitoring and early warning systems, low equipment integrity, and missing or improperly connected protective devices that hinder the identification of hazardous conditions. The dense concentration of enterprises within chemical industrial parks exacerbates the risk of accident propagation, especially when site selection is inadequate,

protective separation distances are insufficient, or facility safety conditions fail to meet standards. Environmental factors—such as poor ventilation or extreme natural conditions—further amplify systemic vulnerabilities. Additionally, material management practices directly influence the severity of accident consequences, with factors including the standardization of zoned storage, the comprehensiveness of hazardous chemical registration and labelling, and the compliance of storage conditions and chemical properties with safety standards.

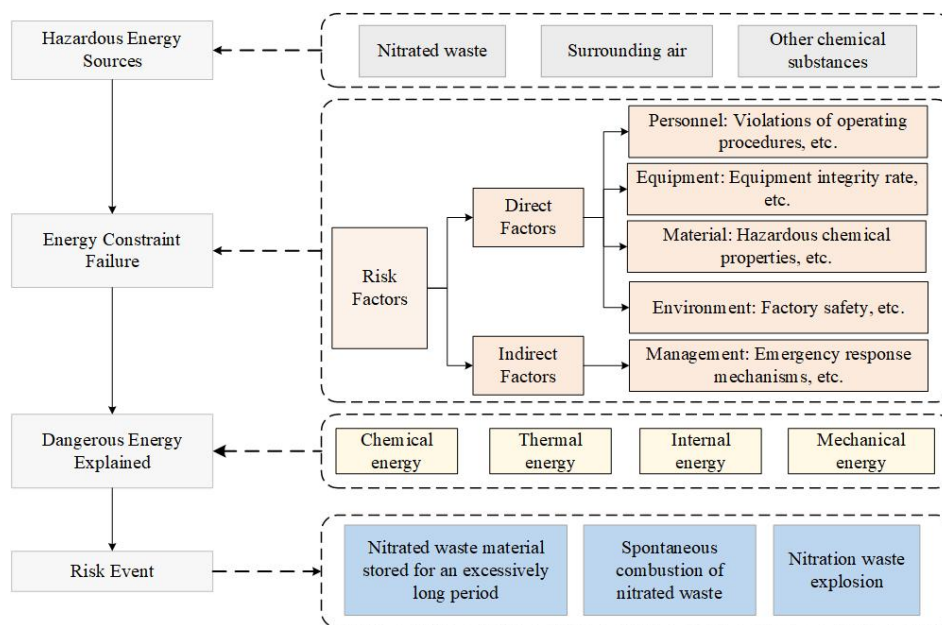


Figure 3. Evolutionary Process of Causes and Effects in the Xiangshui “3-21” Major Chemical Accident.

Indirect factors primarily manifest at the management level. Deficiencies in management systems, unclear division of responsibilities, insufficient safety training, and weak oversight mechanisms can indirectly contribute to accidents by weakening the effectiveness of energy constraint systems.

3.3. Analysis of Energy Transfer Transformation Processes

Dangerous energy transfer changes constitute the fundamental cause of accidents. Analyzing the March 21 Tianjiayi Chemical Explosion from an energy transfer perspective reveals the mechanism of its risk evolution. Different from general fire and explosion accidents, the Xiangshui “3-21” accident exhibited several distinctive characteristics in its energy evolution process. First, the long-term illegal storage of nitrated waste led to continuous hazardous energy accumulation over an extended period. Second, nitrated waste possesses self-accelerating decomposition characteristics, whereby heat generated during decomposition further accelerates subsequent reactions, forming a positive feedback mechanism of thermal runaway. Third, dense stacking and poor ventilation conditions promoted localized heat concentration, eventually causing spontaneous ignition. Finally, the explosion involved multiple hazardous chemicals, resulting in secondary energy release and cascading amplification of accident consequences. Based on the energy transfer pathway, the accident process can be divided into four stages: energy accumulation, energy release, energy diffusion, and energy destabilization, as shown in Figure 4.

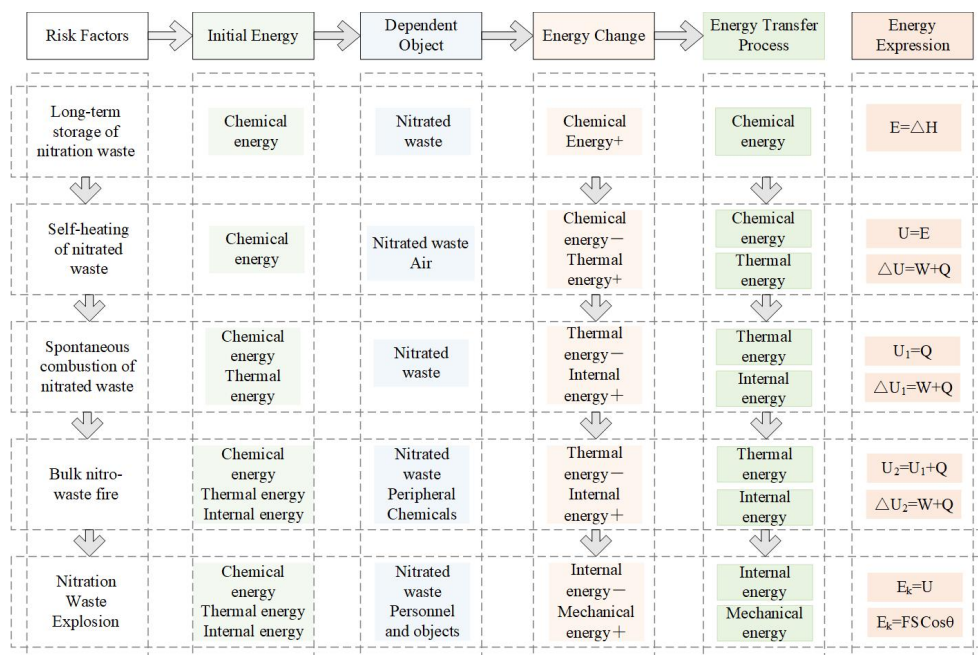


Figure 4. Risk Hazards and Energy Relationship Diagram for the Xiangshui “3·21” Major Chemical Explosion Accident.

During long-term storage and decomposition reactions, nitrated waste gradually accumulates and releases heat, continuously converting chemical energy within the system into thermal energy. When the accumulation of thermal energy exceeds the system’s self-limiting threshold, sustained temperature increases accelerate the self-decomposition of nitration waste, rapidly releasing chemical energy as both thermal and internal energy. At this point, the failure of the energy constraint system allows hazardous energy to transfer to the surrounding media in the form of high temperature and pressure. This results in the generation of an explosive shockwave and a high-temperature flame zone, causing damage to nearby facilities and personnel. From the perspective of energy transfer, it is evident that the abnormal transfer of chemical energy—specifically thermal and internal energy—constitutes the core chain of accident evolution. The destabilization of the energy confinement system marks the critical juncture at which the accident transitions from a state of potential risk to that of a catastrophic instability. As illustrated by the energy pathways in Figure 4, material factors, reaction control, and storage management within chemical production processes significantly influence the accumulation and release of energy.

Therefore, the energy evolution pathway in the Xiangshui accident is characterized not only by general processes of energy accumulation and release, but also by thermal runaway and cascading energy amplification induced by the physicochemical properties of nitrated waste and multi-hazard coupling effects. Figure 4 illustrates the transformation pathways between risk hazards and energy in the Xiangshui “3·21” chemical explosion accident, highlighting the accumulation, release, and transfer characteristics of hazardous energy. It provides a theoretical foundation for the quantitative modelling of the accident’s causal mechanisms.

4. Modelling of Management Factors in the Xiangshui “3·21” Major Chemical Explosion Accident

4.1. System Dynamics Analysis Steps

The steps for system dynamics analysis can be summarized as follows: clarify the modelling objectives, identify influencing factors, and define system boundaries by utilizing the investigation report of the “3·21” major chemical explosion accident, the relevant literature, and field research. Identify causal relationships among the influencing factors, determine feedback loops, construct stock–flow diagrams, and establish system dynamics (SD) equations. Determine parameters for each variable and input them into the equations for simulation and testing. If the model passes validation, conduct scenario simulations and comparative analyses to conclude. If it fails, revert to the initial state and proceed with further refinement and testing.

4.2. Identification of Influencing Factors and Determination of Boundaries for the SD Model of Risk Management in the Xiangshui “3·21” Major Chemical Explosion Accident

The influencing factors incorporated into the SD model were systematically extracted from the official accident investigation report through qualitative content analysis. Rather than being subjectively selected, each factor was identified according to explicit descriptions of accident causes, enterprise deficiencies, and management failures reported by the State Council Investigation Team. The extracted factors were subsequently classified into five interacting subsystems: personnel, equipment, materials, management, and environment, based on their respective roles in hazardous energy accumulation, transfer, and constraint, following the principles of energy transfer theory and system dynamics²⁴.

The five subsystems jointly describe the generation, accumulation, transfer, and control of hazardous energy throughout the accident evolution process. Table 3 summarizes the influencing factors identified for each subsystem, together with the supporting evidence used for factor identification derived from the official accident investigation report. These influencing factors mainly represent the mechanisms contributing to accident occurrence through hazardous energy accumulation and transfer, whereas factors related to emergency response and post-accident intervention are regarded as consequence mitigation factors and are incorporated separately into the system dynamics model assumptions. The evidence presented in Table 3 provides an empirical basis for the identification, classification, and causal relationship construction of the influencing factors in the SD model.

Table 3. Subsystems and Influencing Factors of the Risk Management System for the accident.

Subsystem	Influencing Factor	Evidence Supporting Factor Identification
Personnel Subsystem	Lack of professional expertise	Limited understanding of hazardous waste characteristics
	Non-compliant operations	Frequent violations of operating procedures
	Failure to use protective equipment	Inadequate implementation of personal protection
	Insufficient safety awareness	Formalistic safety inspections and weak risk awareness
Equipment Subsystem	Low equipment integrity rate	Inadequate maintenance of safety facilities
	Missing early warning devices	Lack of effective hazard monitoring and warning
	Poor condition of protective equipment	Insufficient reliability of protective facilities
	Unconnected devices	Weak information integration and equipment monitoring
Materials Subsystem	Non-segregated storage	Mixed storage of hazardous waste
	Incomplete hazardous chemical registration	Inadequate hazardous waste inventory management
	Unsafe hazardous chemical properties	Self-decomposition and continuous heat release
	Non-compliant storage practices	Long-term illegal storage of hazardous waste
	Non-standard labeling	Inadequate hazardous waste identification

Management Subsystem	Inadequate emergency response mechanisms	Weak emergency preparedness capability
	Incomplete supervision systems	Long-term ineffective safety supervision
	Lack of regular safety training	Insufficient employee safety training
	Insufficient management personnel	Weak implementation of safety management
	Unclear accountability systems	Undefined safety responsibilities
Environmental Subsystem	Low plant safety standards	Deficiencies in production safety conditions
	Insufficient protective spacing within industrial parks	Inappropriate enterprise layout planning
	Poor environmental ventilation	Heat accumulation caused by poor ventilation
	Unsafe working conditions	Unsafe operating environment
	Non-compliant site selection for industrial parks	Inadequate industrial park planning
	Adverse natural environmental conditions	High-temperature accelerated thermal accumulation

Although hazardous energy itself is difficult to measure directly during accident evolution, the SD model quantitatively integrates energy transfer theory by representing the key management factors that govern hazardous energy generation, accumulation, transfer, and constraint. Specifically, the personnel, equipment, material, management, and environmental subsystems are treated as proxy variables reflecting the effectiveness of hazardous energy control. Changes in these subsystem states correspond to variations in hazardous energy accumulation and constraint capability throughout accident evolution. Therefore, rather than modelling the physical quantity of hazardous energy explicitly, the proposed SD model quantitatively captures the dynamic evolution of the mechanisms governing hazardous energy transfer.

Basic assumptions of the Model:

1. The direct cause of the major chemical explosion accident in Xiangshui is attributed solely to specific human, material, environmental, and equipment factors, excluding accidents caused by natural disasters or force majeure.
2. Management factors are considered solely in terms of their impact after the accident has occurred.
3. Human factors primarily focus on the influence of unsafe human behavior on the progression and evolution of the accident.

4.3. Analysis of Risk Management SD Flowchart for the Xiangshui “3·21” Major Chemical Explosion Accident

The stock–flow structure was established according to the characteristics of hazardous energy evolution and safety management processes in chemical production systems. Five subsystem safety levels (personnel, equipment, materials, management, and environment), together with the integrated safety management level, were defined as stock variables because they represent accumulated system safety states that evolve gradually over time and reflect the overall effectiveness of hazardous energy constraints.

The flow variables were defined as the rates of change in these accumulated states, including processes such as personnel capability improvement, equipment deterioration, management enhancement, environmental condition changes, and material risk accumulation. These flow processes continuously influence the accumulation or depletion of system safety capacity and determine the dynamic evolution of accident risks.

From the perspective of energy transfer theory, major chemical accidents are not instantaneous events but dynamic processes characterized by long-term hazardous energy accumulation, delayed management interventions, and nonlinear feedback interactions. Therefore, the stock–flow structure is particularly suitable for representing the progressive degradation of energy constraint systems, the accumulation and release of hazardous energy, and the dynamic evolution of accident risks in chemical industrial parks.

Based on the identified subsystem interactions and the characteristics of hazardous energy evolution, five subsystem safety levels and one integrated safety management level were selected as stock variables to describe the evolution of system safety states at different time points. Seven rate variables were selected as flow variables to characterize the dynamic changes in these stock variables over time. Additionally, twenty-four auxiliary variables were adopted to objectively characterize the system features. Using Vensim software, the feedback loops of safety management in chemical industrial parks were analyzed. The resulting system dynamics (SD) flowchart for risk management of the Xiangshui “3·21” Major Chemical Explosion Accident is presented in Figure 5.

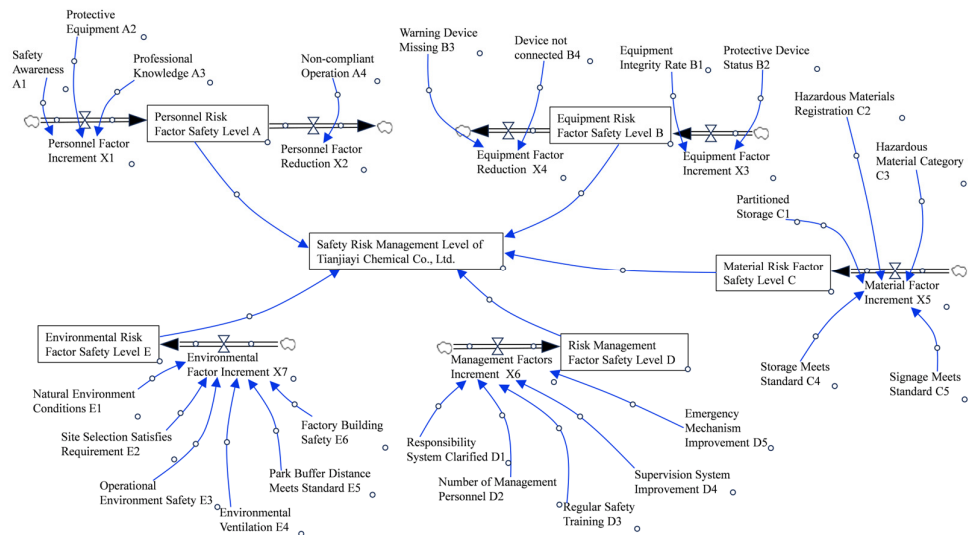


Figure 5. Risk Management SD Flowchart for the Xiangshui “3·21” Major Chemical Explosion Accident.

Hazardous energy is not represented as an independent stock variable because the accident investigation report does not provide continuous quantitative measurements of energy generation or transfer. Instead, the dynamic evolution of hazardous energy is indirectly represented through subsystem state variables that determine the effectiveness of hazardous energy generation, accumulation, transfer, and constraint.

The causal relationships in the SD model were established based on the accident investigation report, energy transfer theory, and previous studies on chemical accident evolution. To maintain causal consistency, only relationships with clear physical mechanisms or management logic were incorporated into the model. Positive and negative causal links were determined according to whether an increase in one variable would promote or inhibit changes in another variable.

In the proposed SD model, safety investment is not treated as a direct determinant of accident occurrence. Instead, additional investment is assumed to improve the safety states of the personnel, equipment, material, management, and environmental subsystems through training, equipment maintenance, process optimization, and organizational supervision. These improvements collectively enhance the effectiveness of hazardous energy constraints, thereby reducing the likelihood of hazardous energy release and mitigating accident risk. Therefore, the influence of safety investment is represented indirectly through changes in subsystem safety levels rather than by introducing an independent accident probability function. Furthermore, several assumptions were adopted during model construction: (1) the external socio-economic environment remains unchanged during the simulation period; (2) causal relationships

among variables are assumed to be stable over time; and (3) the effects of influencing factors are represented through aggregated subsystem interactions rather than individual behavioral variations.

5. Simulation Analysis of Management Failure Evolution in the Xiangshui “3·21” Major Chemical Explosion Accident

5.1. Simulation Parameter Settings

The study simulates the major chemical explosion accident that occurred on March 21, involving Tianjiayi Chemical Co., Ltd in Xiangshui of China. Using system dynamics modelling theory, this study treats the company’s safety risk management as a system, identifying its management personnel, environment, equipment, materials, and processes as subsystems²⁵. Through the analysis of the heterogeneous risk factors within these subsystems, a System Dynamics (SD) model for Tianjiayi Chemical Co., Ltd.’s safety risk management is constructed. Evolutionary simulation and validation of the model provide a novel approach for formulating precise management decisions to identify safety risks in chemical enterprises. Drawing on the relevant literature and accident investigation reports, selected production risk management indicator variables for chemical industrial parks were quantitatively graded²⁶, yielding the following evaluation levels: Excellent (≥ 90), Good (80–89), Moderate (70–79), Passing (60–69), and Failing (< 60). The weights of the influencing factors were determined using the entropy-weight method. To reduce subjectivity, all indicator data were first normalized in line with standard entropy-weight procedures, after which information entropy and indicator divergence coefficients were calculated to obtain the final weights. In this study, the entropy-weight method was applied to determine the relative importance of the evaluation indicators based on the indicator data matrix, and the obtained weights were subsequently incorporated into the SD model as weighting coefficients. The initial safety levels of the five subsystems were determined independently through expert evaluation using a 100-point scoring system. Unlike the entropy-weight calculation, which was used to determine the relative importance of indicators, the expert evaluation was used only to obtain the initial state values of the SD model. The average scores provided by the experts were adopted as the initial values of the corresponding subsystems. The simulation modelling was then performed based on the computed data. The weight values for the five subsystems—Personnel, Equipment, Materials, Management, and Environment—and their corresponding factors are as follows: (WA, WB, WC, WD, WE) = (0.33, 0.14, 0.12, 0.31, 0.10), (WA1, WA2, WA3, WA4) = (0.36, 0.30, 0.18, 0.16), (WB1, WB2, WB3, WB4) = (0.27, 0.25, 0.26, 0.22), (WC1, WC2, WC3, WC4, WC5) = (0.16, 0.18, 0.23, 0.25, 0.18), (WD1, WD2, WD3, WD4, WD5) = (0.19, 0.22, 0.21, 0.13, 0.25), and (WE1, WE2, WE3, WE4, WE5, WE6) = (0.14, 0.16, 0.21, 0.23, 0.14, 0.12). Based on the actual safety risk conditions at Tianjiayi Chemical Co., Ltd. in Xiangshui, China, a panel of 30 experts from chemical enterprises, universities, and research institutes was invited to evaluate the initial safety levels of five subsystems: personnel, machinery, environment, management, and materials. The expert evaluation was conducted using a structured questionnaire based on a 100-point scoring scale, where higher scores represented better safety performance of the corresponding subsystem. Each expert independently evaluated the five subsystem states, and the arithmetic mean values of the 30 expert scores were calculated and used as the initial simulation parameters. Expert selection was guided by criteria including relevant professional expertise, knowledge of chemical safety practices, and prior involvement in safety evaluation or risk management activities, aiming to ensure the objectivity and representativeness of the scoring process. The corresponding initial average scores for each subsystem were as follows: 74, 66, 63, 71, and 65. A weighted calculation of these

values yielded an initial overall safety management level of 69.8701 for Tianjiayi Chemical Co., Ltd. It should be noted that the value of 69.8701 represents the initial comprehensive safety management level obtained from expert evaluation under the 100-point scoring system. In the subsequent SD simulation, this value was used as the initial state information of the system, while the dynamic evolution results were generated through the accumulation and interaction of multiple subsystem variables. Therefore, the simulation outputs in Figure 6 represent the relative evolution values of the SD model rather than the direct 100-point evaluation scores.

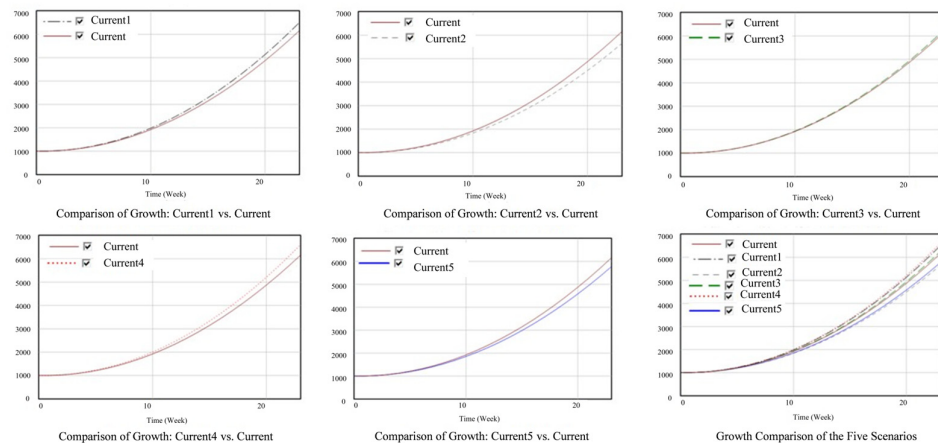


Figure 6. Simulation Results of Overall Safety Risk Management Evolution for the Xiangshui “3·21” Major Chemical Explosion Accident Under Different Scenarios.

Considering that the effects of safety investment and management interventions usually exhibit time-lag characteristics, delay functions were introduced into the SD model. The delay1I function was used to represent short-term delays in subsystem responses, such as personnel training and equipment improvement effects. The delay3 function was employed to describe multi-stage management adjustment and feedback processes. Furthermore, the smooth function was introduced to eliminate unrealistic abrupt fluctuations and to better characterize the gradual evolution of the overall safety management level. The delay parameters were selected according to the practical characteristics of safety management processes in chemical enterprises and with reference to previous system dynamics studies.

Using the identified safety risk factors and the system dynamics flow diagram for the chemical industrial park, the weights for each factor were selected as variable coefficients to establish the system dynamics (SD) equation for the company’s safety management. The main variable SD equation is shown in Table 4.

Table 4. Structural Equation Model of the Safety Management Framework for the Xiangshui “3·21” Major Chemical Explosion Accident.

Serial Number	System Dynamics Structural Equation
(1)	Auxiliary equation: $L = \text{smooth}(\text{delay3}((A \times WA + B \times WB + C \times WC + D \times WD + E \times WE)/5, 3), 5)$
(2)	State Equation: $A = X1 - X2$ Rate equation: $X1 = \text{delay1I}(A1 \times WA1 + A2 \times WA2 + A3 \times WA3, 0.5, 0)$ Rate equation: $X2 = \text{delay1I}(A4 \times WA4, 0.5, 0)$
(3)	State Equation: $B = X3 - X4$

	Rate equation: $X3 = \text{delay1I}(B1 \times WB1 + B2 \times WB2, 0.5, 0)$
	Rate equation: $X4 = \text{delay1I}(B3 \times WB3 + B4 \times WB4, 0.5, 0)$
(4)	State Equation: $C = X5$ Rate equation: $X5 = \text{delay1I}(C1 \times WC1 + C2 \times WC2 + C3 \times WC3 + C4 \times WC4 + C5 \times WC5, 0.5, 0)$
(5)	State Equation: $D = X6$ Rate equation: $X6 = \text{delay1I}(D1 \times WD1 + D2 \times WD2 + D3 \times WD3 + D4 \times WD4 + D5 \times WD5, 0.5, 0)$
(6)	State Equation: $E = X7$ Rate equation: $X7 = \text{delay1I}(E1 \times WE1 + E2 \times WE2 + E3 \times WE3 + E4 \times WE4 + E5 \times WE5 + E6 \times WE6, 0.5, 0)$

5.2. Model Simulation Results

Based on the SD equation, parameters were substituted into the system dynamics model for safety management of the major chemical explosion accident. The simulation was conducted over a duration of 23 weeks, with a step size of 1 week. The target safety risk management level was set at 90. The safety investment growth rates for the five subsystems—personnel, machinery, environment, management, and materials—were treated as single-factor variables. While maintaining the safety investment rates of the other four subsystems constant, the growth rate for the safety investment of each subsystem was sequentially adjusted, as shown in Table 5. Using Vensim-PLE software, the simulation modelled the overall trend in the safety risk management level of the chemical industrial park.

Table 5. Different Growth Rate Scenarios for Each Subsystem in the Risk Management of the Xiangshui “3·21” Major Chemical Explosion Accident.

Solution	LA	LB	LC	LD	LE
Current	0.20	0.20	0.20	0.20	0.20
Current1	0.28	0.18	0.18	0.18	0.18
Current2	0.18	0.28	0.18	0.18	0.18
Current3	0.18	0.18	0.28	0.18	0.18
Current4	0.18	0.18	0.18	0.28	0.18
Current5	0.18	0.18	0.18	0.18	0.28

Initially, the safety investment growth rates for the five subsystems—labor (LA), machinery (LB), materials (LC), management (LD), and environment (LE)—were set to identical values. Subsequently, the growth rates for each subsystem were adjusted individually to observe the trends and rates of change in the overall safety management level of the chemical industrial park. This process was employed to assess the impact of each subsystem on the model.

The simulation results for the overall safety risk management level of Tianjiayi Chemical Co., Ltd in Xiangshui, China under various scenarios are presented in Figure 6. The findings reveal that the overall safety management level of the chemical industrial park showed an upward trend throughout the study period, consistent with the actual safety risk management conditions at the park. This confirms the validity and feasibility of the parameters selected for the study²⁷. In Figure 6, the vertical axis represents the simulated values of the overall risk management level generated by the SD model under different scenarios. These values are not equivalent to the initial 100-point safety evaluation scores, because the SD model describes the dynamic accumulation and interaction process among personnel, equipment, materials, management, and environmental subsystems. The increasing trends reflect the improvement of the overall safety management system under different intervention scenarios rather than changes in the original scoring scale.

5.3. Results and Discussion

It should be noted that the purpose of the SD simulation is not to directly reproduce the physical explosion process itself, but rather to reveal the dynamic evolution mechanism of the underlying safety management deficiencies and hazardous energy accumulation that ultimately contributed to the accident. The changes in safety management levels represent the gradual strengthening or weakening of the system's capability to constrain hazardous energy.

From the perspective of energy transfer theory, major accidents generally emerge through long-term accumulation of hazardous conditions, progressive degradation of energy containment capacity, and nonlinear interactions among multiple subsystems. Therefore, the SD model serves as a tool for explaining the pre-accident evolution mechanism and identifying key leverage points for accident prevention rather than simulating the instantaneous explosion event.

As shown in Figure 6, during the initial management phase, Tianjiayi Chemical Co., Ltd in Xiangshui, China exhibited the lowest safety risk management level throughout the study period. However, due to the presence of pre-existing safety regulations and systems, the initial production safety management level remained at a certain baseline value. Over time, the safety risk management level steadily increased, reflecting the gradual improvement in the capabilities of production personnel, ongoing upgrades to production equipment, enhanced material handling processes, and the refinement of the production supervision system. The influence weights of the various factors, ranked from highest to lowest, are as follows: personnel, management, material, environmental, and equipment factors. The "Current Plan" represents the baseline scenario. The safety risk management levels of Current1, Current3, and Current4 surpass the baseline plan, indicating that increasing the investment in personnel, material, and management factors accelerates the improvement of the safety risk management level. This underscores the significant influence of personnel, material, and management factors, while equipment and environmental factors exert relatively minor impacts. Therefore, for chemical enterprises like Tianjiayi Chemical Co., Ltd., the personnel, management, and material subsystems play a dominant role in enhancing the safety risk management levels within chemical industrial parks.

Based on the identified factors influencing the subsystems, the key management factors for the personnel subsystem included professional knowledge, non-compliant operations, protective equipment, and safety awareness. Regarding the material subsystem, the key management factors were segregated storage, hazardous chemical registration, chemical properties, compliance with storage standards, and adherence to labelled standards. The key factors for the management subsystem included emergency response mechanisms, supervision systems, regular safety training, the number of management personnel, and accountability systems. Insufficient attention to these management factors could lead to unsafe actions, contributing to the accumulation of hazardous energy. Unsafe actions and conditions within the personnel, management, and material subsystems, along with the associated hazardous energies, are summarized in Table 6.

Table 6. List of Unsafe Behaviors or States of Subsystems and Harmful Energy Sources.

Subsystem	Unsafe Practices and Conditions	Harmful Energy
Personnel Subsystem	Failure to use safety equipment; non-compliant production operations	Mechanical Energy
Management Subsystem	Lack of effective oversight, accountability systems, and emergency response mechanisms	Chemical Energy, Mechanical Energy
Material Subsystem	Unzoned storage, unlabeled hazardous chemicals	Chemical Energy

The analysis of simulation results for the overall risk management level of the Xiangshui chemical explosion accident, under different scenarios, reveals that the key management factors in hazardous chemical production are personnel, management, and materials. Mechanical and chemical energy serve as the primary sources of hazardous energy. The results suggest that major chemical accidents should be managed from the perspective of hazardous energy accumulation and constraint effectiveness rather than solely focusing on immediate accident triggers. Safety governance should therefore emphasize early identification of energy accumulation processes, dynamic monitoring of management deficiencies, and timely interventions in key subsystems such as personnel, materials, and management. It should be emphasized that the increase in safety investment does not directly reduce accident risk. Rather, safety investment enhances the capability of the personnel, equipment, management, material, and environmental subsystems to constrain hazardous energy. The improved subsystem performance delays or interrupts hazardous energy accumulation and transfer, thereby reducing the likelihood of accident evolution. Consequently, the relationship between safety investment and accident risk is represented as an indirect causal pathway mediated by subsystem safety performance.

Accordingly, the personnel, management, and material subsystems form the core components of the risk management system. To address hazardous energy, two key measures should be implemented: hazardous energy early warning and hazardous energy isolation. The following specific recommendations are proposed:

(1) The system platform should provide hazardous energy alerts by monitoring hazardous chemical production processes through various sensors and machine vision technology. Pre-set warning thresholds should trigger automatic alarms when hazardous energy levels or unsafe behaviors exceed these limits. This activates the early warning mechanism, prompting workers to evacuate promptly and implement appropriate emergency response measures to ensure safety. This approach promotes the systematization and digitalization of safety management in hazardous chemical production.

(2) Energy isolation should involve the prevention of the accumulation and coupling of hazardous energy by introducing physical barriers. Personnel management should emphasize safety training, including the establishment of an onboarding program for new employees and the provision of safety skills training to enhance staff expertise and safety awareness. When storing materials, hazardous chemicals should be segregated into designated zones, with storage areas chosen based on material properties, such as well-ventilated, shaded, or low-temperature locations. Compliance with storage standards must be rigorously verified. The supervision system should serve as a critical safeguard against accidents. Regular inspections, conducted by sufficient personnel, are essential for overseeing production activities. Specialized inspection plans must be developed, including daily checks at workstations, weekly checks in workshops, and monthly checks by management to ensure accountability.

The simulation results are generally consistent with the conclusions of the official accident investigation report. Both analyses indicate that deficiencies in management practices, inadequate personnel safety behaviors, and failures in hazardous material management were the primary contributors to the accident. This consistency provides preliminary validation of the proposed model. Compared with conventional post-accident investigations, the proposed approach offers additional advantages by revealing the dynamic interactions and feedback mechanisms among multiple subsystems. Rather than identifying only direct causes after accident occurrence, the integrated framework enables the identification of risk accumulation processes, key leverage points, and potential intervention opportunities before catastrophic failures emerge.

6. Conclusions

This paper uses the major chemical explosion accident in Xiangshui on March 21 as a case study. Through the lens of energy transfer and incorporating SD methodology, it systematically analyzes the causal mechanisms of the accident and the evolution patterns of hazardous energy. The key findings are as follows:

(1) The occurrence of the accident resulted from the coupling of multiple risk factors and the gradual failure of the energy constraint system. Complex interactions among personnel, management, materials, and environmental elements directly and indirectly triggered the release and transfer of hazardous energy. The analysis indicates that destabilization of the energy constraint system was the critical mechanism that led to the transition of the accident from a latent to an uncontrolled phase. Furthermore, abnormal transfer of hazardous energy constituted the core chain of events in major and particularly severe safety incidents.

(2) By integrating SD theory, a risk management SD flowchart was developed, based on both direct and indirect factors contributing to energy constraint failures. The results indicate that personnel, management, and material factors are the primary subsystems influencing accident formation and system risk levels. A rational allocation of safety investments, improved management feedback mechanisms, and the implementation of hazardous energy early warning and isolation measures can significantly enhance the system's safety risk management levels, thereby stabilizing the system.

The research offers several meaningful contributions. First, it proposes an integrated analytical framework combining energy transfer theory and system dynamics to reveal the dynamic mechanisms underlying major accident evolution and hazardous energy constraint failures. Second, the study identifies key leverage points within the personnel, management, and material subsystems, providing actionable insights for risk prevention and safety governance in chemical industrial parks. The study focuses on the Xiangshui "3-21" accident, the underlying mechanisms of hazardous energy accumulation, management deficiencies, and progressive degradation of energy constraint capacities are common characteristics of many high-risk industrial systems. Therefore, the proposed framework may also provide useful references for accident prevention and safety management in other contexts, such as petrochemical facilities, transportation infrastructure systems, underground engineering projects, and industrial parks.

Despite the contributions of this study, several limitations should be acknowledged. Firstly, the analysis is based on a single major chemical accident case, which may limit the generalizability of the findings to other industrial contexts. Secondly, some model parameters rely on expert judgment and secondary accident reports, which may introduce a degree of subjectivity. In addition, the system dynamics model inevitably simplifies complex real-world interactions among technical, organizational, and environmental factors. Next, hazardous energy was represented indirectly through subsystem state variables rather than through explicit physical measurements of energy generation, accumulation, and transfer. Future studies may combine thermodynamic models, energy flow analysis, or real-time sensor data with SD to establish a more explicit quantitative representation of hazardous energy evolution. The SD model does not explicitly quantify the mathematical relationship between safety investment, barrier performance, failure probability, and accident risk. Future research may integrate reliability-based barrier models or probabilistic risk assessment methods to establish a more rigorous quantitative coupling mechanism. Also, future studies can establish a more comprehensive expert evaluation database and integrate statistical consistency analysis to further enhance the transparency and reproducibility of the weighting and initialization process. The simulated index values are mainly used to compare relative changes among scenarios rather than absolute safety scores. The difference between the expert-based initial

evaluation scale and the SD simulation output scale may affect direct numerical interpretation. Future research will further explore scale calibration methods to establish a more explicit correspondence between expert evaluation results and dynamic simulation outputs.

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