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A Study on the Sustainability of Petrochemical Industrial Complexes Through Accident Data Analysis

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Abstract: The increase in energy demand due to industrial development and urbanization has resulted in the development of large-scale energy facilities. Republic of Korea's petrochemical industrial complexes serve as prime examples of this phenomenon. However, because of complex processes and aging facilities, many of which have been in operation for over a decade, these industrial complexes are prone to process-deviation-related accidents. Chemical accidents in energy facilities involving high-pressure liquids or gases are especially dangerous; therefore, proactive accident prevention is critical. This study is also relevant to corporate environment, social, and governance (ESG) management. Preventing chemical accidents to protect workers from injury is critical for business and preventing damage to surrounding areas from chemical accidents is a key component of ESG safety. In this study, we collected accident data, specifically injury-related incidents, from Republic of Korea's petrochemical industrial complexes, which are the foundation of the energy industry. We analyzed the causes of accidents in a step-by-step manner. Furthermore, we conducted a risk analysis by categorizing accident data based on the level of risk associated with each analysis result; we identified the main causes of accidents and "high-risk process stages" that posed significant risk. The analysis reveals that the majority of accidents occur during general operations (50%, 167 cases) and process operations (39%, 128 cases). In terms of incident types, fire/explosion incidents accounted for the highest proportion (43%, 144 cases), followed by leakage incidents (24%, 78 cases). Furthermore, we propose a disaster safety artificial intelligence (AI) model to prevent major and fatal accidents during these high-risk process stages. A detailed analysis reveals that human factors such as accumulated worker fatigue, insufficient safety training, and non-compliance with operational procedures can significantly increase the likelihood of accidents in petrochemical facilities. This finding emphasizes the importance of introducing measurement sensors and AI convergence technologies to help humans predict and detect any issues. Therefore, we selected representative accident cases for implementing our disaster safety model.

Keywords: petrochemicals; energy; ESG safety; proactive accident prevention; internet of things; monitoring and diagnostic technology

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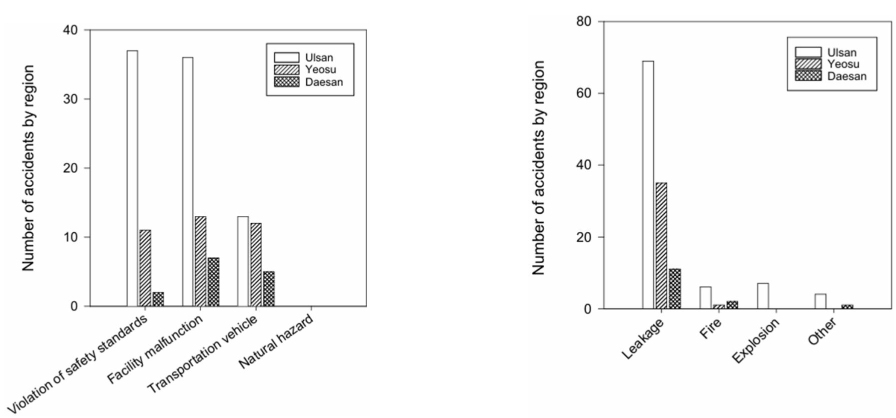
1. Introduction

The rapid development and expansion of industrial sectors has resulted in the concentration of human resources and materials in urban centers [1]. Energy facilities are concentrated in these areas to support rapidly growing cities [2]. Energy is essential for industrial development and economic activities and contributes significantly to economic growth [3]. However, modern cities have witnessed the indiscriminate installation of energy-related storage and transportation facilities that are prone to accidents caused by worker's negligence or process failures [4]. These incidents can quickly escalate to human casualties, causing physical and material damage within minutes [5]. In energy facilities, the storage and transport of high-pressure liquids and gases [6] present a substantial hazard, with the potential to cause complex chemical accidents with devastating consequences [7]. Petrochemical industrial complexes, which primarily consist of energy refining and storage facilities, frequently house hazardous materials, such as petroleum products, ethylene, and flammable liquids and gases; therefore, the need for proactive accident prevention strategies and countermeasures is more critical [8].

The chemical accident status provided by the Chemical Safety Agency under the Ministry of the Environment of Republic of Korea is listed in Table 1 [9]. Using these data, we analyzed 136 chemical accidents that occurred in Republic of Korea's three major petrochemical industrial complexes (Ulsan, Yeosu, and Daesan) over the past decade, categorizing them by cause and type, as shown in Figure 1. An analysis of accident causes reveals that the majority of incidents in domestic petrochemical complexes occur during operation and maintenance, primarily due to safety standard violations or facility defects arising during tasks. Analysis of accident type indicates that leakage accidents are the most common. With most facilities in Republic of Korea's petrochemical complexes operating for over a decade, aging infrastructure has become a significant issue. Consequently, leakage accidents, which are difficult for workers to detect or predict in advance, occur frequently [10].

Table 1. Petrochemical chemical accident status (2014–January 2024).

City	Number of Incidents	City	Number of Incidents
Seoul	25	Incheon	39
Gyeonggi-do Province	224	Daejeon	22
Gangwon-do Province	12	Sejong	6
Chungcheongbuk-do Province	51	Gyeongsangbuk-do Province	90
Chungcheongnam-do Province	76	Gyeongsangnam-do Province	44
Jeollabuk-do Province	49	Gwangju	11
Jeollanam-do Province	61	Ulsan	86
Jeju-do Province	3	Daegu	22
Busan	44		



(**a**) (**b**)

Figure 1. Types of petrochemical accidents: (**a**) classification by accident type; (**b**) classification by device.

To ensure the development and safety of large-scale national industrial complex energy infrastructure, it is essential to develop various devices capable of predicting and detecting changes in hazardous chemicals, abnormal reactions, and leaks [11]. Not only is it important to develop entirely new technologies, but there is also a need to research strategies for "safety detection optimization" that enhance operability and ease of use, efficiently utilizing existing sensor equipment. Based on advances in information and communication technology, industries worldwide are shifting toward the Fourth Industrial Revolution paradigm [12]. Digital technologies, such as the Internet of Things (IoT), artificial intelligence (AI), and big data, have significantly improved the quality of human life [13].

Republic of Korea's petrochemical industrial complexes, crucial to the energy industry, were rapidly installed during the industrialization period, making monitoring and diagnostic technologies vital for detecting and preventing accidents related to aging facilities [14]. Introducing digital technologies to detect and prevent risks in complex petrochemical working environments can reduce human casualties [15]. Digital technologies can improve workplace safety and productivity by facilitating accurate decision-making [16]. Thus, introducing digital technologies as safety strategies in industrial settings is necessary. This approach not only prevents environmental pollution from chemical accidents that affect the air, soil, and water, but also reduces the impact of accidents on workers and surrounding communities, thereby lowering the risk of corporate losses [17]. This approach not only reduces accidents but also strengthens environmental protection and community safety, supporting the development of strategies to address social issues such as environmental, social, and governance (ESG) management by companies [18–21].

The purpose of this study was to examine the different types of chemical accidents that occurred in Republic of Korea petrochemical industrial complexes based on the risk levels associated with various tasks. By analyzing the current situation, we propose the digital technologies required for proactive accident prediction and response in process safety inspections, thereby preventing large-scale and fatal accidents in the energy infrastructure.

2. Research Subjects and Analytical Methods

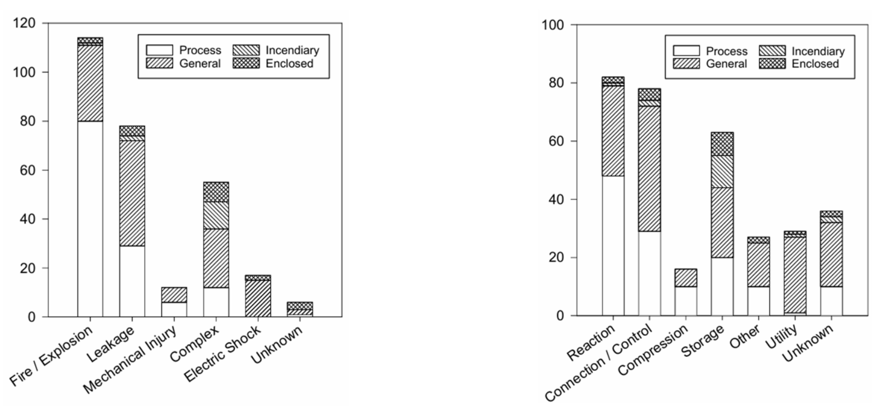
In this study, we examined the risks and trends associated with different types of petrochemical industrial complexes in Republic of Korea. A total of 331 accidents were reported in these complexes between 2005 and 2023. Safety-related tasks are generally classified as hot, general, confined space, electrical, and radiological, as well as hazardous material handling and heavy equipment operations [22]. Table 2 contains detailed descriptions for each study type. Accident data from petrochemical industrial complexes primarily comprised incidents that occurred during operation and maintenance (Figure 2b). Consequently, the 331 accident cases were classified into four categories according to the nature of the task during which they occurred: general, hot, confined space, and process work.

Table 2. Safety procedures: types of work and their description.

Type	Contents
Hot work	Welding, cutting, grinding, drilling, and other tasks that generate flames or sparks
General work	Tasks involving potential hazards other than those associated with hot work
Confined space work	Operations conducted in confined spaces where there is a risk of asphyxiation or the presence of flammable gases
Lockout/tagout	Inspection and maintenance operations that involve power shutdown

Radiation work	Non-destructive inspection tasks or maintenance of facilities using radiation
Working at heights	Tasks performed at elevated locations using scaffolding, ladders, etc.
Heavy equipment operations	Handling, lifting, and performing repairs or inspections using heavy equipment

The work procedures for each category were analyzed using risk assessment techniques. Some of the most common risk assessment methods include man, machine, material, and method (4M) risk assessment; checklist method; what-if analysis, hazard, and operability studies (HAZOP); job safety analysis (JSA); fault tree analysis (FTA); event tree analysis (ETA); and cause–consequence analysis (CCA) [23]. In this study, a detailed analysis was performed using the JSA method to identify various risks associated with work procedures and establish corresponding countermeasures. JSA is an analytical method that observes and analyzes tasks in a step-by-step manner to identify hazards involved in each step and proposes alternatives for safe work procedures [24,25]. Common process flowcharts were developed using the JSA technique by identifying and generalizing the correlations between different work procedures. Based on these flowcharts, the petrochemical industrial complex accident data were classified and analyzed according to the work procedures. The processes were analyzed by categorizing the procedures into raw material handling, reaction, heat exchange, compression, separation/purification, storage, and transportation/piping. The initial classification of work types and processes reveals that general, process, confined space, and hot work account for 167 (50%), 128 (39%), 19 (6%), and 17 (5%) cases, respectively. Next, based on the work type and process classification, the data were further categorized according to accident type and equipment. The main accident types were fires/explosions, trauma, blackouts/electrocutions, leakages, and compounds. Trauma includes incidents, such as collapse, destruction, breakage, hits, falling, and entrapment. The compound type includes cases in which two types of accidents occurred simultaneously. Analysis of accident types analysis reveals that fires/explosions are the most frequent (144 cases [43%]), followed by leakage (78 cases [24%]), trauma (74 cases [22%]), and compound accidents (24 cases [7%]). Regarding equipment, reactions are the most frequent (82 cases [25%]), followed by connections/controls (78 cases [23%]), storage (63 cases [19%]), unknown (36 cases [11%]), utilities (29 cases [9%]), others (27 cases [8%]), and compression (16 cases [5%]). The results are shown in Figure 2.



(**a**) (**b**)

Figure 2. Types of petrochemical accidents: (**a**) classification by accident type; (**b**) classification by device.

In this paper, we propose an IoT validation model that utilizes sensor equipment capable of mechanically detecting abnormal situations and calculating the risk of accidents based on these data. To accomplish this, we chose two representative accident cases, specifically those involving the use of measurement sensors and intelligent convergence technologies, from 331 incidents in petrochemical industrial complexes. These cases were thoroughly analyzed to determine the root causes of accidents, and specific strategies for applying the validation model were proposed.

3. Results and Discussion

3.1. Chemical Accidents in General Work

3.1.1. Classification of Chemical Accident Data in General Work

General work was categorized into six stages: task recognition, safety education and personal protective equipment (PPE) usage, prework preparation, hazard identification, work execution, and task completion (Table 3). This process covers the entire procedure from the preparation to completion of task. General work involves inherent risks and hazards, excluding hot tasks. Unlike other work types, general work accidents include slips, trips, falls, entrapment, and falls from heights [26]. Slips, trips, and falls occur due to obstacles, environmental factors, or falling objects [26]. Entrapment involves body parts caught between moving or stationary machine parts [26], whereas falls from heights involve falling from structures, machinery, or ladders [26]. Identifying potential hazards in the fourth stage is critical for determining the presence of these risks. Other risks such as fire, explosion, asphyxiation, burns, crushing, electrical hazards, noise, dust, and toxic substance exposure may also be present during general work activities.

Table 3. List of the general work procedure.

Step	Contents
1	Work planning
2	Safety education and personal protective equipment usage
3	Prework preparations
4	Identifying potential hazards
5	Work execution
6	Work completion

3.1.2. Incident Distribution by Stage in General Work Chemical Accidents

The distribution of chemical accidents by stage in general work is shown in Figure 3. A detailed analysis reveals that accidents occurred most frequently during the work execution stage (57 cases [34%]), followed by identification of potential hazards (56 cases [33%]), safety education, and PPE usage (36 cases [22%]). Notably, the safety education and PPE usage stages had a higher rate of accidents than the other stages, implying that accidents, particularly falls and entrapments, are often caused by inadequate safety training or a lack of PPE. Furthermore, when reclassified according to accident type and equipment, trauma was the most prevalent accident among the 167 general work accidents, accounting for 66 cases. Accidents were most commonly associated with utility equipment (44 cases).

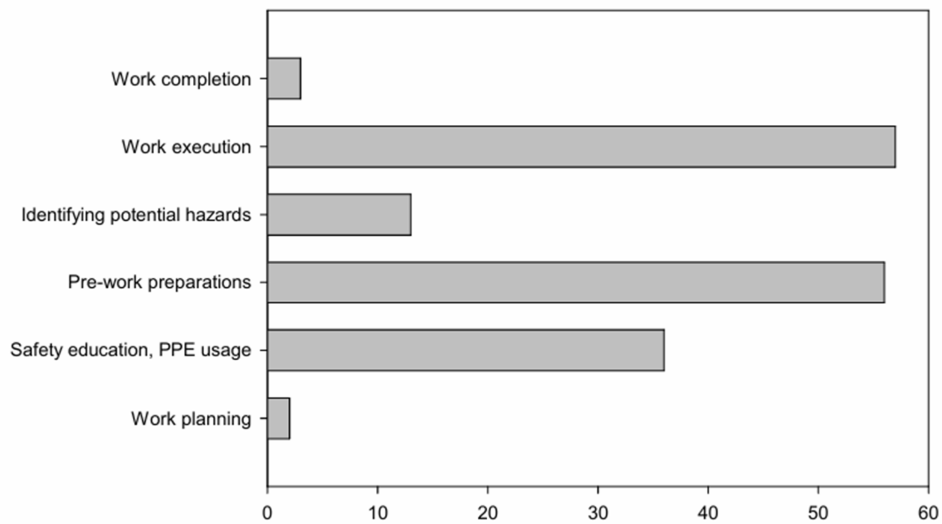


Figure 3. Pie chart showing the proportion of chemical accidents by general work stage.

3.2. Hot-Work Chemical Accidents

3.2.1. Classification of Hot-Work Chemical Accident Data

Hot work refers to tasks involving the use of open flames or high temperatures, such as welding, cutting, grinding operations, or other activities that may generate sparks [27]. Even in the absence of nearby flammable materials, high-temperature flames, or scattering of sparks can lead to fires [28]. Particularly in locations with combustible materials, failure to conduct proper checks and safety measures before starting hot work can result in sparks igniting flammable substances, leading to major fire incidents [29–31]. Therefore, recognizing the risks and adhering to these considerations before performing hot work is essential. These considerations include whether the work is being conducted in a confined space, condition of the equipment and piping involved, need for supervision during the task, and presence of flammable or toxic substances [27,32]. A schematic of the hot work considered in this study is listed in Table 4. This schematic is similar to the general work procedure but includes additional stages such as valve isolation, residual concentration measurement, purging and venting, and fire watches.

Table 4. List of the hot-work procedure.

Step	Contents
1	Hot-work planning
2	Safety education and personal protective equipment usage
3	Identification of ignition sources
4	Identifying potential hazards
5	Valve isolation and residual concentration measurement
6	Purging and venting
7	Deployment of fire watch and fire suppression equipment
8	Hot-work execution
9	Post-work safety measures
10	Work completion

3.2.2. Incident Distribution by Stage in Hot-Work Chemical Accidents

The distribution of chemical accidents by hot-work stage reveals that purging and venting account for the majority of incidents with seven cases (41%; Figure 4). This suggests that accidents frequently occur as a result of failure to follow basic safety procedures during purging, which are required for inspecting and maintaining containers containing flammable or toxic gases. Additionally, 14 of the 17 hot-work accidents were classified as fire or explosion incidents, with the majority occurring during welding operations on storage equipment.

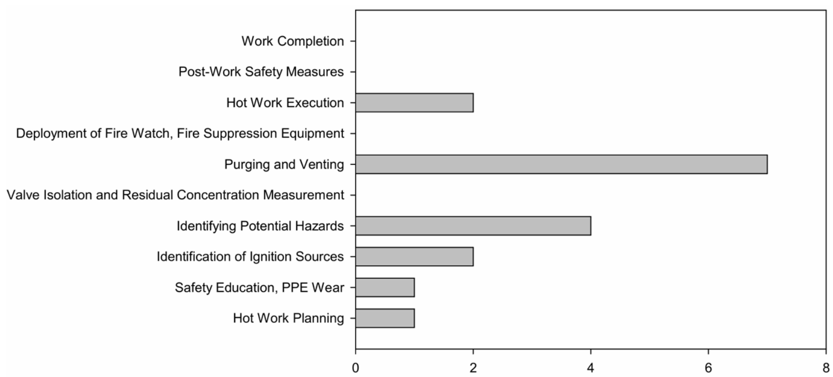


Figure 4. Pie chart showing the proportion of chemical accidents by hot-work stage.

3.3. Confined-Space Work Chemical Accidents

3.3.1. Classification of Confined-Space Work Chemical Accident Data

Tasks in confined spaces can lead to asphyxiation if not properly managed. A schematic diagram of confined-space work was created using the procedures used in such environments, and the results are presented in Table 5. Work execution is the stage in which a worker actually performs the task. Process shutdown refers to halting operations and removing hazardous materials before starting the work. Purging is the process of removing toxic or flammable gases or replacing them with inert gases to create a safe working environment, which is essential not only for preventing toxic exposure but also for minimizing the risk of fire and explosion. Ventilation involves circulating air within the workspace to prevent the accumulation of toxic gases and avoid oxygen deficiency. Typically, a confined space can be completely enclosed, have limited ventilation, or contain hazardous gases, even if one side is open, leading to an oxygen-deficient environment during work [33,34]. The invisible hazards in these spaces often involve asphyxiation [35]. Industrial safety and health regulations classify confined spaces into 18 categories, including reaction vessels, raw material storage tanks, welding and nondestructive testing piping, air purification units, manholes, and reactors [36]. The developed schematic includes an additional entry permit stage, in which a supervisor must confirm the safety of the confined space before work can begin, reflecting the unique characteristics of confined space environments.

Table 5. List of the confined-space work procedure.

Step	Contents
1	Confined-space identification
2	Safety education and personal protective equipment usage
3	Hazard assessment
4	Process shutdown, material removal
5	Purging and ventilation
6	Gas concentration measurement
7	Confined-space entry permit
8	Work execution
9	Post-work safety measures
10	Work completion

3.3.2. Incident Distribution by Stage in Confined-Space Work Chemical Accidents

After investigating chemical accidents in confined spaces, we found that the majority of incidents (10 cases, 52%) occurred during Stage 6, which involved gas concentration measurement, and Stage 8, which involved the work process itself (Figure 5). Therefore, accidents are more likely to occur during gas concentration checks and when performing tasks in confined spaces. When reclassified by accident type and equipment, 15 of the 19 confined-space accidents were clearly related to the leakage of chemicals from containers, which had the highest frequency. Furthermore, eight chemical accidents occurred in storage equipment, which was the most commonly involved equipment type in these incidents.

Figure 5. Pie chart showing the proportion of chemical accidents by confined-space work stage.

3.4. Process Chemical Accidents

3.4.1. Classification of Process Chemical Accident Data

In industrial settings, "process" refers to a series of steps involved in converting inputs into outputs [37]. Specifically, they include the stages and tasks required to complete a product. Petrochemical processes involve a series of transformations of raw materials through the production equipment, resulting in a continuous chain. For the Republic of Korean petrochemical industry, this process primarily involves feeding naphtha into a Naphtha Cracking Center (NCC) to produce basic petrochemical products, which can be broadly divided into naphtha tanking, pyrolysis, quenching, compression, and refining stages [38]. Table 6 presents a schematic of the process, highlighting the equipment and devices such as the reactors, pumps, and separation units. The raw material stage refers to incidents occurring during or due to the introduction of raw materials (liquid) into the equipment, resulting in direct accidents.

Table 6. List of the process operation procedure.

Step	Contents
1	Raw material
2	Transportation, plumbing, etc.
3	Pump
4	Heat exchanger
5	Reactor
6	Separation
7	Storage tank

3.4.2. Incident Distribution by Stage in Process Chemical Accidents

The highest number of incidents occurred during the raw material stage (25 cases [19%]), followed by transportation and piping (23 cases [18%]), storage tanks (22 cases [17%]), reactors (20 cases [16%]), heat exchangers (17 cases [13%]), compressors (15 cases [12%]), and separation and refining (6 cases [5%]; Figure 6). This indicates that a large proportion of chemical accidents occur during the introduction of raw materials into equipment. Reactors had the most incidents (14), followed by storage equipment, connections, controls, and compressors. Notably, fires and explosions are the most common types of chemical accidents that occur during manufacturing process.

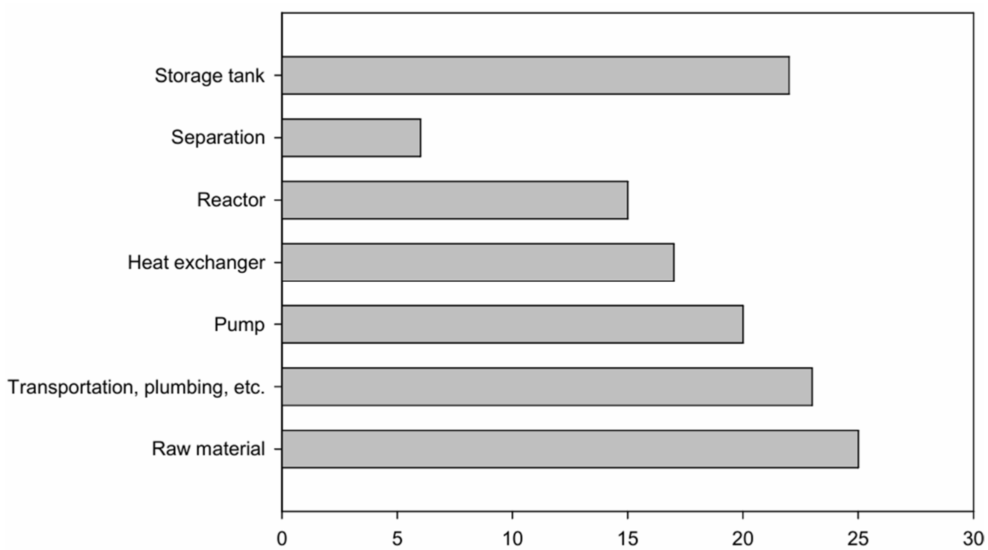


Figure 6. Pie chart showing the proportion of chemical accidents by process operation stage.

3.5. Development of New Technologies Based on Work and Process Classification Results

An analysis of accident data from the previous 19 years reveals that the majority of incidents occurred during the execution phase of general work (57 cases), raw material stage in process work (25 cases), purge and vent stages in hot work (7 cases), and gas concentration measurement and work stages in confined-space work (5 cases each). Based on these findings, key causes should be identified in order to develop effective chemical accident prevention strategies.

The causes of the accidents were reclassified and categorized according to the 4M guidelines for hazardous risk factors [39]; the classification includes human factors, such as worker characteristics and management neglect, and material factors, such as equipment defects related to specific tasks (Table 7). Human factors play a significant role in accident risk within petrochemical facilities. For instance, prolonged shifts and high-stress work environments contribute to worker fatigue, which can reduce attention levels and slow reaction times during critical tasks. Fatigue, in particular, is a pervasive issue in environments where continuous operation demands extended working hours. Additionally, high-stress situations, often exacerbated by complex operational procedures or tight production schedules, increase the likelihood of human error. This risk is further heightened when workers lack adequate safety training, as untrained or underprepared workers may struggle to respond effectively to unexpected hazards. Our analysis shows that accidents often correlate with these human factors, emphasizing the need for targeted interventions—such as optimized shift scheduling, stress management programs, and comprehensive safety training—to mitigate accident risks associated with human factors. A comprehensive analysis of accident causes reveals that human factors could not be excluded at any stage. However, we found that the impact of human factors is attributable to the inherent limitations of human ability rather than simple errors. For example, unexpected high-temperature reactions or thermal runaway of chemicals during process operations are beyond a worker's ability to predict or detect. Similarly, accidents occurring from actions, such as valve opening or incomplete purging during maintenance, are categorized as human factors. Therefore, the primary strategy for accident prevention at this stage involves the deployment of disaster safety technologies that can assist in prediction and detection to supplement human efforts.

Table 7. Classification of accident causes.

Type		Contents
Human factors	Human factors	Worker characteristics, lack of attention, and human error
Physical factors	Preventive measures	Work permit, risk assessment, and equipment database management
	Work and operation	Preparation before and after work, personal protective equipment, equipment defects, manual operations, and hazardous tasks
	Maintenance	Internal material removal and cleaning, equipment inspection, and piping welding
	Monitoring	Valves, piping, manholes, and equipment condition diagnosis
	Accident response	Integrated control and alarm systems

We propose an empirical IoT model for detecting abnormal situations using sensor equipment and assessing the risk of accidents based on these detections. We identified the four most hazardous stages in Republic of Korea's aging petrochemical industrial complexes by analyzing the risk stages of processes and work procedures. Among accidents that occurred during these stages, two representative cases with significant damage caused by human factors were chosen.

The two representative accident cases were a compressor connection rupture and one involving the lower piping of a sulfuric acid tank. The rupture of a three-stage discharge-expansion joint in the compressor caused a large leakage of naphtha cracking gas [40]. This accident was caused by a lack of preventive measures and situation monitoring. The sulfuric acid tank lower piping accident occurred when the bellows at the bottom of the sulfuric acid tank ruptured, resulting in the dispersal of 98% of the sulfuric acid [41]. This accident was also attributed to inadequate prevention, maintenance, and monitoring measures. Detailed analyses of each accident process are presented in Tables 8 and 9, and the work diagrams for each process are presented in Tables 10 and 11. The application of accident prevention technologies and proposed improvements and utilization methods for these processes are also described.

Table 8. Accident resulting from compressor connection failure—process overview.

Type	Contents
Process definition	Operation of a real-time leakage risk assessment system for compression equipment (e.g., compressors) and a degradation (fatigue, wear, etc.) risk assessment system for facilities
Key components	Gas leakage risk assessment system using fixed-point low-level gas leak sensors on compression equipment (such as compressors) with potential leakage risks

	Hazardous area alert system based on gas sensor data and consequence analysis (CA) gas dispersion model analysis
	Facility degradation risk assessment system utilizing stress (pressure) sensors and thickness sensors related to key influencing factors in compression equipment (such as fatigue and wear)

Table 9. Incident in the sulfuric acid tank subsurface piping—process overview.

Type	Contents
Process definition	Real-time leakage risk assessment system operation for hazardous substances, equipment degradation (such as chemical reactions, fatigue, and wear) and abnormal high-pressure preparedness
Key components	Gas leakage risk assessment system utilizing fixed-point low-level gas leak sensors on equipment for identifying leak risk locations due to hazardous substances, equipment degradation (such as chemical reactions, fatigue, and wear), and abnormal high pressure
	Gas sensor data and hazardous area alert system based on consequence analysis (CA) and gas dispersion model analysis

Table 10. Process operation schematic and utilization methods.

Type	Before			
Work Configuration	**Reaction**	**Cooling**	**Neutralization/Washing**	**Distillation**
Utilization method			Pre-accident unnoticed minor leaks and inadequate management of equipment susceptible to degradation (such as fatigue and wear)	
Type	**After**			
Work Configuration	**Reaction**	**Cooling**	**Neutralization/Washing**	**Distillation**
Utilization method			Pre-accident assessment of signs and risk through changes in minor leak characteristics, and risk information alert through risk assessment of equipment vulnerable to degradation (such as fatigue and wear)	

Table 11. Process operation schematic and utilization methods.

Type	Before		
Work Configuration	**Reaction Cooling**	**Neutralization/Washing**	**Distillation**
Utilization method		Unawareness of explosion risk due to failure to review material characteristics during design, improper construction of components and facilities, and equipment malfunction in maintaining functionality	

Type	After		
Work Configuration	**Reaction Cooling**	**Neutralization/Washing**	**Distillation**
Utilization method		Enhancement of material reaction review during design, strengthened installation and supervision of components, and a system evaluating signs and risks for improved safety prior to accidents, with risk information alerts	

As mentioned previously, we proposed an IoT-based disaster safety technology that can assist and complement human factors. In addition, we conducted a comprehensive review of the literature of previously proposed disaster-safety IoT technologies. Among these, we selected technologies suitable for application to the identified accident cases (Table 12).

Table 12. Review of disaster-safety IoT technologies.

Type	Contents
Gas sensors	MEMS-based metal oxide semiconductor gas sensors that are known for their excellent cost, size, and performance, makes them popular in petrochemical monitoring [42].
Toxic and explosive gas sensors	Sensors that use real-time data stored in a database server to automatically run atmospheric dispersion prediction modeling programs in the event of toxic gas leak. They are designed to communicate via IEEE 1451.x standard interfaces and produce predictive scenario results [43].
Explosive gas sensors	Sensors that continuously detect leakage amounts and can detect gases like liquefied natural gas (LNG) butane, methane, acetylene, ethylene, and carbon dioxide. They are certified by Republic of Korea Fire Verification Corporation or industrial technology testing organizations [43].
Fire and explosive gas sensors	On-site fire and gas detection, with real-time information transmission to a comprehensive disaster management system, and monitoring services [43].
Fire sensors	Sensors alert the operation terminal of signal failure in the event of sensor malfunctions [43].
Intelligent smart fire sensors	Combining heat and smoke sensing to collect temperature measurement data [43].
Gas detection sensors	Detecting harmful and toxic gases such as methane (CH_4) and carbon monoxide (CO), and issuing appropriate warnings [44].
Toxic gas detection sensors	Monitoring and storage of information on toxic gas concentrations, temperature, and humidity indoors over extended periods [44].
Pipe damage detection sensors	Detecting real-time damage locations in existing pipelines [45].
Perforation sensors	Detection of pipeline vibration signals and potential signals for data collection requires three installations for monitoring and transmission through wireless networks, with a detection sensitivity of more than 1000 mV [43].

Weather observation sensors	Sensors that are integrated with atmospheric dispersion programs and capable of interfacing via IEEE 1451.x standard [43].
Seismic detection sensors	Sensors with RS-232C, RS-422, RS-485, and TCP/IP interfaces for self-diagnosis and sensor signal correction. The accelerometer temperatures ranging from −10 °C to 50 °C [43].
Image sensors	Sensors that detect shading changes in colorimetric strips reacting to various hazardous gases [44].
Toxic gas leak monitoring	Utilization of wireless sensor networks (WSN) for networking and concentration detection to identify hazardous gas leak areas [45].
Fire and gas surveillance monitoring	It uses Zigbee to provide attendance registration, real-time precise location tracking, dynamic gas concentration monitoring, real-time data transmission, and hazard alerts [46].
Gas leak monitoring	It enables real-time detection and control of gas leaks [47].
Plant monitoring	It is widely deployed with wireless sensor nodes (static or mobile) across large petrochemical plants for efficient and reliable detection of hazardous areas. It supports production monitoring, pollution analysis, leak detection, and asset tracking [48].
Body information monitoring	It offers methods for continuously monitoring various body metrics like blood pressure, heart rate, and body temperature [49]
Pipe monitoring	Detection of three types of cracks in thin aluminum beams within 1–2 s of excitation time. Crack detection is most effective when the amplitude exceeds 80 V [50].
Smart helmets	The integration of static sensor nodes and wearable equipment, including an STM32 processing chip, various environmental sensors, a camera, a GPS positioning module, and a heart rate sensor [51].
Safety tag systems	Use of acceleration sensors to detect worker immobility. Alerts are made via Piezo buzzers and LEDs, with the danger state communicated through LoRa communication modules. The system is designed based on SOP analysis and feedback from fire field personnel [52].
Command systems	The system receives risk signals from safety tags and can issue evacuation.
Control server systems	Real-time data collection from command terminals, providing on-site status and evacuation orders to 119 comprehensive situation rooms or control centers [53].
Production process planning and control systems	Digital twin (DT) technology helps to improve safety in the petrochemical industry through dynamic and real-time monitoring, leak warnings, and process safety alerts [54].
Ergonomic design systems	HSEE focuses on safety and health as the central axis of the workplace, fostering continuous improvement and proactive risk management for a safer and more sustainable work environment in the petrochemical industry [54].

Building safety barrier model systems	BIM is used to quickly identify on-site risks in real-time, collects personnel movement information using location sensors, and enables virtual construction site management, personnel information management, task information management, and risk area monitoring [55].
Data analysis and monitoring systems	Node-RED is used in software development to connect graphical blocks. Integrates easily with web services and a wide range of hardware devices, while operating with low power requirements [56].

With the advent of IoT, the importance of data collection and utilization has grown significantly [57]. Digital technologies, particularly in the petrochemical industry, are quickly gaining traction [58], and sensor-based technologies are becoming increasingly critical in the current industrial climate. Specifically, "smart detection sensors," such as gas sensor terminals, can play a fundamental role in environmental safety by proactively preventing potential hazards [59].

Ref. [60] proposed using IoT as a countermeasure to prevent confined-space accidents. They determined that various hazardous gases can be monitored and that real-time monitoring can prevent accidents in confined spaces, thereby minimizing damage if an accident occurs.

Additionally, [61] described how IoT-integrated devices can provide real-time tracking of toxic gas leaks in large-scale industries, thereby contributing to sustainable global growth, increased productivity, and improved workplace safety.

Ref. [62] explained that IoT sensors can control various industrial processes such as pressure and flow rates in chemical plants and monitor parameters such as temperature to detect and predict potential issues. This function ultimately reduces the accident risk and improves the safety of efficient operations.

Ref. [63] identified IoT as a paradigm for safely performing maintenance tasks on large-scale plants. The proposed system supports maintenance workers by guiding them through step-by-step procedures, and allows real-time monitoring of the plant, machinery, and workers. It also enables the approval and display of the next steps according to procedures defined by managers or supervisors. Testing of actual industrial processes has demonstrated that infrastructure contributes to the improvement of worker safety.

Ref. [64] introduced IoT technologies (PDA and RFID) for safety management in oil storage facilities and used the system at two oil storage sites in China for eight months. Following deployment, the system proved to be reliable and useful for safety management.

Ref. [54] suggested using digital twin technology (DT and HSEE) with IoT to enhance safety in the petrochemical industry. This approach enables the efficient operation and maintenance of petrochemical equipment, reduces the frequency and costs of accidents, improves worker health and safety, and ultimately enhances plant safety.

Ref. [11] explained that well-developed wireless sensors and devices can monitor the operational environment of oil and gas production plants, thereby promoting a safe and healthy workplace.

Thus, the IoT technology enables the monitoring and interaction of objects, making it highly useful for safety management. This promotes a safer and more sustainable working environment while optimizing production and operations.

Based on the aforementioned representative accident cases, the appropriate digital technology models were chosen. IoT sensor terminals, which are equipped with wireless communication and sensing capabilities, help detect and collect data form the surrounding environment [65,66]. Installing IoT sensor terminals enables monitoring of worker access and composition of the internal environment during operations, thereby aiding in accident prevention [67]. Fixed miniature gas leak sensors can be installed in high-risk areas, such as high-pressure equipment, poorly designed or installed facilities, and locations with insufficient inspection and management. Analyzing and predicting changes in leak data under normal conditions can help detect potential leaks [68,69]. Real-time leak detection and risk assessment systems that measure radiant heat from equipment can continuously monitor gas leaks and abnormal equipment conditions, allowing the real-time risk analysis. This can contribute to the proactive prediction and prevention of gas leak accidents using gas-dispersion modeling algorithms.

3.6. Discussion

The comprehensive discussion of the analysis results for improving the safety of petrochemical industrial complexes is summarized by work process, with major causes of accidents shown in Table 13.

Table 13. Major accident analysis results in petrochemical industrial complexes.

Category	Type	Accident Rate	Main Cause of Accidents
By work type	General work	50% (167 cases)	Work execution stage: 34% (57 cases), identification of potential hazards: 33% (56 cases)
	Process work	39% (128 cases)	Raw material stage: 19% (25 cases), transportation/piping: 18% (23 cases)
	Confined-space work	6% (19 cases)	Gas concentration measurement: 26% (10 cases), work execution: 26% (10 cases)
	Hot work	5% (17 cases)	Purging and venting stage: 41% (7 cases)
Category	**Type**		**Main Cause of Accidents**
By accident type	Fire/explosion		43% (144 cases)
	Leakage		24% (78 cases)
	Trauma		22% (74 cases)
	Compound accident		7% (24 cases)
Category	**Type**		**Main Cause of Accidents**
By equipment type	Reactor		25% (82 cases)
	Connections/control		23% (78 cases)
	Storage		19% (63 cases)
	Unknown		11% (36 cases)

The majority of general work accidents (67%) occur in the execution phase and are influenced by factors such as the presence of residual hazardous materials. This indicates that human factors play a significant role in accident occurrence during this stage.

The analysis by accident type shows that fire/explosion incidents account for the highest proportion at 43%, followed by leakage at 24% and trauma at 22%. This finding underscores the necessity of real-time monitoring systems to detect and respond to incidents in the early stages.

The equipment analysis indicates that reactors (25%), connection/control (23%), and storage (19%) have the highest accident rates. This highlights the need for establishing systematic management systems for these types of equipment.

4. Conclusions

This study analyzed accident cases based on the risk levels associated with various operations in domestic petrochemical industrial complexes to derive the following insights for strengthening accident prediction and response measures.

First, given the spatial characteristics of national industrial complexes, it is challenging to predict the scale and scope of damage in the event of an accident. Therefore, it is essential to develop and implement technologies capable of rapid detection and response during the early stages of an accident. This approach is expected to effectively minimize damage from accidents.

Second, this study acknowledges limitations within the dataset, particularly the absence of continuous monitoring data and specific variables such as equipment conditions and human factors like worker fatigue, which restrict comprehensive evaluation of potential risk factors. Future research should focus on collecting more comprehensive, real-time data, including consistent monitoring of human and equipment factors, to enable more refined risk assessments and enhance the effectiveness of preventive measures.

Third, this study rigorously applied job safety analysis (JSA) to categorize accidents by stage and identify high-risk areas in petrochemical processes. This categorization allows for the development of targeted intervention strategies in stages with high accident frequencies, which plays a crucial role in enhancing workplace safety.

Finally, as digital technologies generate vast amounts of data, there is a risk of privacy infringement. This study did not fully address these privacy issues, and future research should develop solutions to mitigate privacy concerns, along with an in-depth examination of ethical and legal aspects associated with technology implementation.

We hope that the analysis and insights presented in this study will contribute meaningfully to strengthening the accident response capabilities of petrochemical industrial complexes.

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