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Hazard Identification and Risk Assessment During Simultaneous Operations in Industrial Plant Maintenance Based on Job Safety Analysis

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Abstract: The risk of accidents during simultaneous operations (SIMOPS) in plant maintenance has been increasing. However, research on methods to prevent such accidents has been limited. This study aims to develop a novel framework, hazard identification and risk assessment of simultaneous operations (HIRAS), for identifying and evaluating potential hazards during concurrent tasks. The framework developed herein is expected to be an effective safety management tool that can help prevent accidents during these operations. To this end, the job location and hazard information in job safety analysis (JSA) were standardized into four attributes. The standardized information was then synchronized spatially and temporally to develop a HIRAS model that identifies and assesses the impact of hazards between operations. The model was tested using 40 JSA documents corresponding to maintenance operations at Company P, a South Korean steel-making company. The model was tested in two scenarios: one with planned operations and the other with unplanned operations in addition to planned operations. The performance evaluation results of the first scenario showed an F1-score of 98.33%. In this case, a recall of 97.52% means that the model identified 97.52% of the hazard-inducing factors. The second scenario was compared with the results of a review by six subject matter experts (SMEs). The comparison of the results identified by the SMEs and the model showed an accuracy of 89.3%. This study demonstrates the potential of JSA, which incorporates the domain knowledge of workers and can be used not only for individual tasks but also as a safety management tool for surrounding operations. Furthermore, by improving the plant maintenance work environment, it is expected to prevent accidents, protect workers' lives and health, and contribute to the long-term sustainable management of companies.

Keywords: simultaneous operations (SIMOPS); job safety analysis (JSA); hazard identification and risk assessment of simultaneous operations (HIRAS); plant maintenance; Zettelkasten method; hazard identification; risk assessment; GPT 3.5

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1. Introduction

1.1. Background of Study

Historically, interest in safety began with the occurrence of accidents [1]. In 1987, during major refurbishment work at the Marathon Oil refinery, a simultaneous operations (SIMOPS) accident injured 100 people. In 1988, 167 people died on the Piper Alpha offshore platform due to a lack of communication between workers during two maintenance operations.

SIMOPS refers to the coordination and management of two or more potentially hazardous activities taking place simultaneously in the same area [2]. For instance, SIMOPS management is necessary in scenarios such as constructing a new bridge while maintaining

traffic flow on an existing one, welding pipes in a petrochemical plant while handling flammable materials in adjacent units, and performing maintenance on a nuclear power plant while continuing to generate electricity.

SIMOPS are especially common in complex industries like oil and gas [3]. In offshore drilling, a typical SIMOPS scenario could involve drilling activities happening on a platform while maintenance crews are performing repairs on the rig and another team is conducting crane operations to transfer equipment.

Investigations into the cause of major accidents in the oil and gas sector have revealed that SIMOPS are a major factor in such accidents [4]. SIMOPS are situations where two or more tasks are carried out in close temporal and spatial proximity. SIMOPS activities, if uncoordinated, could pose risks to safety, environment, or equipment. Therefore, careful safety management during SIMOPS is necessary.

The 1987 Marathon Oil refinery accident and the 1988 Piper Alpha offshore platform accident highlight the need for caution during SIMOPS. These incidents led to efforts in the oil and gas industry to prevent accidents during SIMOPS [5]. The International Marine Contractors Association (IMCA) developed and issued guidelines for preventing SIMOPS accidents [6]. SIMOPS risks are not limited to specific sectors, such as the oil and gas industry. In 2020, an accident occurred during maintenance operations at the Evergreen Packaging plant, prompting the U.S. Chemical Safety and Hazard Investigation Board to recommend the development and implementation of an accident prevention program during SIMOPS [7].

Japan's Industrial Safety and Health Act provides a comprehensive framework for protecting workers from workplace hazards. While the Act does not explicitly mention SIMOPS, its general principles and requirements apply to such operations [8]. Japan's Ministry of Health, Labor and Welfare (MHLW) is the government agency responsible for enforcing the Industrial Safety and Health Act. It has taken several measures to address the risks associated with SIMOPS work. The concept of on-site safety and health management system, or total management, was specifically implemented for the construction and shipbuilding sectors.

While there is not a specific term SIMOPS widely used in Chinese regulations, the Chinese government has implemented a comprehensive framework of safety regulations and standards to prevent industrial accidents [9], particularly in high-risk industries such as oil, gas, and construction. State-owned enterprises like the China National Petroleum Corporation (CNPC) have developed detailed Health, Safety, and Environmental (HSE) management systems [10]. As the primary regulatory body for workplace safety in China, State Administration of Work Safety (SAWS) has issued numerous regulations and standards aimed at preventing industrial accidents [11].

Germany's Occupational Safety and Health Act (ArbSchG) and the German Social Accident Insurance (DGUV)'s accident prevention regulations set important guidelines for managing workplace safety, including SIMOPS [12,13]. Both laws focus on ensuring that employers and workers take necessary precautions to prevent accidents, particularly in high-risk environments.

In South Korea, public concern about safety accidents due to SIMOPS has been increasing. Accidents such as the 2014 Goyang Terminal accident, the 2017 Taean Power Plant accident, and the 2019 Han Express accident indicate that safety during SIMOPS is not guaranteed [14]. In particular, a report by the Korea Occupational Safety and Health Agency (KOSHA) indicated that the number of SIMOPS accidents in South Korea has been increasing over the past seven years. Therefore, efforts to prevent SIMOPS accidents are necessary. Figure 1 shows the number of occupational fatalities and fatalities due to SIMOPS in South Korea [14,15].

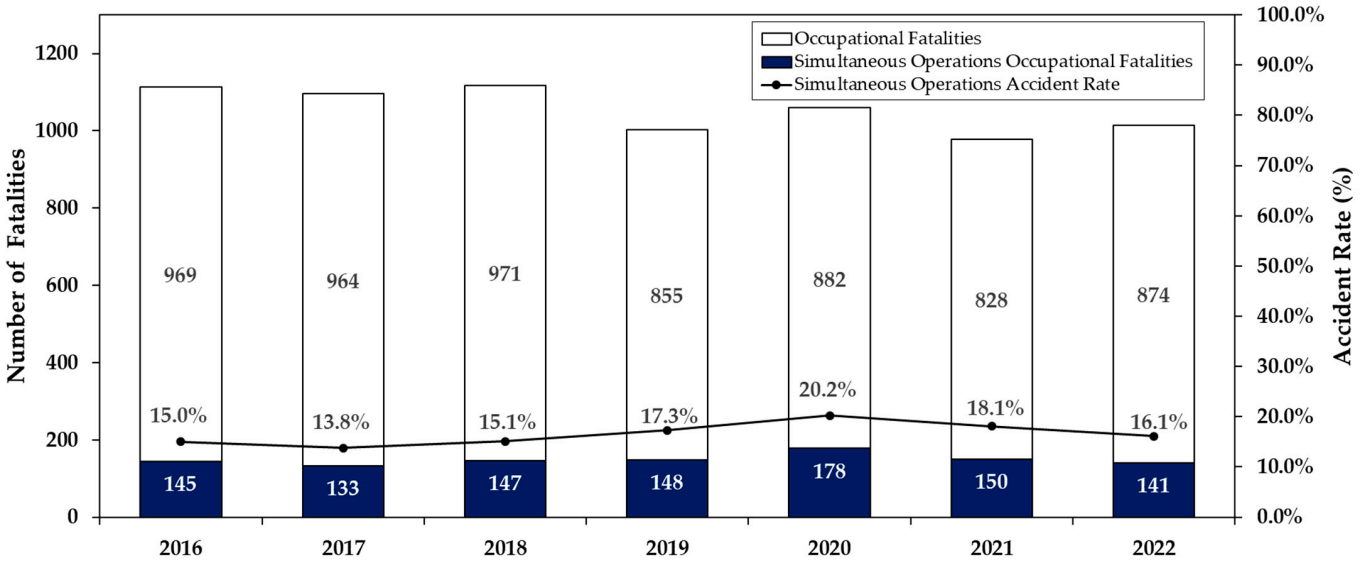


Figure 1. Occupational fatalities and the proportion of occupational fatalities due to SIMOPS during 2016–2022.

The South Korean government has taken the following steps to prevent SIMOPS accidents [16]:

- The 2017 Amendment to the Occupational Safety and Health Act: Article 68 mandates appointing a health and safety coordinator to prevent industrial accidents due to work interference when two or more construction projects are carried out at the same location.
- The 2019 Amendment to the Occupational Safety and Health Act: Article 63 expands the obligation of the contractor with respect to safety and health measures from 22 hazardous locations to the entire workplace.
- The 2021 Amendment to the Occupational Safety and Health Act: Article 64 mandates that the timing, content, and safety and health measures of the operations be confirmed for operations carried out at the same location. The Presidential Decree prescribes adjusting the timing and operation in the case of a fire or explosion risk due to work interference.

Companies are also making efforts to prevent SIMOPS accidents. The leading South Korean steel maker, Company P, has implemented the following processes to prevent SIMOPS accidents during maintenance work:

- System aspects: The Company provides a SIMOPS prediction list and job safety analysis (JSA) by linking an integrated safety and health platform with the enterprise resource planning (ERP) system for work planning. The SIMOPS prediction list is generated based on work dates and equipment classification systems.
- Work planning aspects: Managers from the work planning department, safety managers, and work managers review the SIMOPS predictions in a D-1 meeting before the work begins. Based on the review results, they establish measures such as prohibiting concurrent vertical work, adjusting work execution times, and implementing additional safety measures.
- Work permit aspects: The work permit issuer reviews whether the work is mixed with other teams for upstream, downstream, or interlocking equipment. If SIMOPS are confirmed, the work permit issuer facilitates a toolbox meeting (TBM) during which work supervisors inspect the equipment on-site, identify potential hazards, and establish countermeasures [17].
- Work execution aspects: Workers are invited to a TBM with the operations and equipment supervisors for individual tasks as well as a TBM with the related equipment task supervisors.

Although these processes are effective in preventing SIMOPS accidents, they have drawbacks. The time required for individual task TBMs is not uniform, leading to delays when additional TBMs are required. The time required for additional TBMs increases with an increase in the number of SIMOPS, thereby potentially shortening the time available for maintenance work. Furthermore, prioritizing multiple targets during additional TBMs can be challenging.

The risks associated with SIMOPS in plant maintenance are expected to increase in the future. As companies constantly strive to improve quality and productivity [18], many production activities in industrial sites are mechanized and automated, leading to an inevitable increase in maintenance work and personnel [19–22]. Maintenance work in plants is a high-risk activity compared to other tasks. From 2000 to 2011, 80 out of 184 major accidents in the process industry in the U.S. and Europe were related to maintenance work [23]. Therefore, the increase in maintenance SIMOPS in plants corresponds to a higher probability of workers being exposed to accident risks.

A process for identifying and assessing work hazards before starting work is crucial for preventing accidents [24]. JSA can help identify and assess work hazards [25] and has been long used in various industries such as oil, construction, automation, mining, and shipbuilding [26]. In JSA, the task is divided into sequential steps, the hazards at each step are identified and assessed, and hazard risk mitigation measures are established [27]. Figure 2 depicts the JSA process currently implemented in Korea.

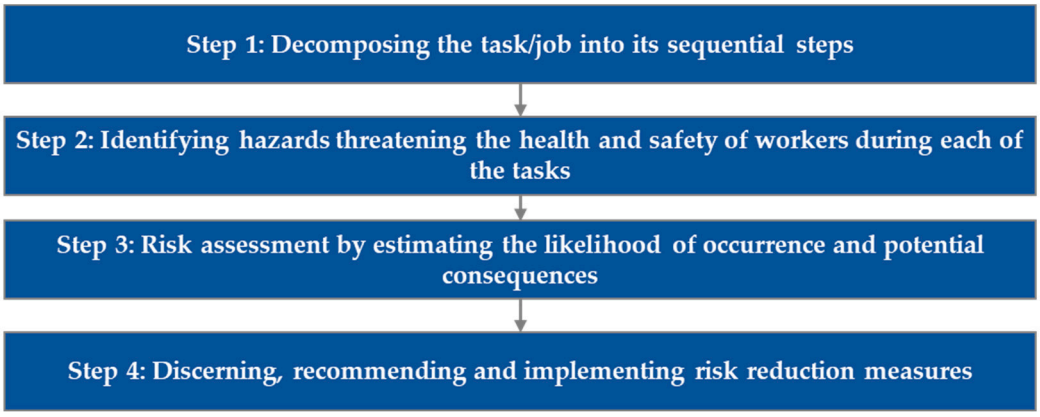


Figure 2. General steps of JSA.

Although JSA has been effectively used as a hazard identification tool, its limited scope of identification has been pointed out as a drawback. JSA focuses solely on the task being performed, and identifying hazards in surrounding tasks via JSA is difficult [27,28]. The limitation in the scope of identification can be attributed to two factors. First, the complexity of modern industries has significantly increased compared to that when JSA was first developed [29]. Therefore, even planned tasks may be surrounded by other tasks, making it difficult to identify hazards. Second, unplanned tasks or modifications to tasks are often encountered during maintenance work. Identifying hazards in advance for unplanned tasks is impossible because the tasks are unexpected. Surrounding tasks are inevitably variable due to unplanned work [30]. Therefore, owing to the limitation in the scope of identification, effectively preventing SIMOPS accidents via JSA is challenging.

1.2. Problem Statement and Research Objectives

Despite the strengthened government regulations and proactive SIMOPS accident prevention measures by the companies, research on hazard identification and assessment related to SIMOPS has received limited attention [31]. Although SIMOPS-related hazard identification has been investigated in the oil, gas production, and construction sectors, studies on SIMOPS-related hazard identification in plant maintenance are limited.

Company P, the biggest steel-maker in South-Korea, regularly conducts maintenance work, including major annual overhauls that last more than seven days, as well as intermediate and regular maintenance. Managers meticulously review dozens of tasks daily to prevent SIMOPS accidents. In addition, supervisors and workers dedicate significant amounts of time to joint TBMs before task execution. For instance, at S plant, one of the 29 plants of the P steel mill, more than 20 tasks, involving over 70 personnel, are carried out every day during major overhauls. In large-scale plant maintenance work, the complexity and variability of tasks can increase the cognitive load on managers and supervisors. Moreover, the increased time required for accident prevention measures can prolong the repair period, affecting production and ultimately impacting company profits. Therefore, a new methodology that can efficiently prevent SIMOPS accidents and optimize the review process is needed.

This study focuses on preventing accidents during SIMOPS in plant maintenance work. This study aims to contribute to accident prevention in SIMOPS by effectively identifying and assessing hazards between tasks in a complex and variable environment based on JSA. The authors investigated the identification and assessment of hazards associated with simultaneous tasks in plant maintenance operations. As a result of this research, we have developed a novel framework, hazard identification and risk assessment of simultaneous operations (HIRAS) framework. This framework not only identifies hazards but also establishes interrelationships between JSAs, allowing for a more in-depth analysis and evaluation of risks associated with concurrent tasks.

An understanding of the inter-task impact is necessary for identifying and assessing hazards resulting from interactions between different tasks. To achieve this, the authors adopted the Zettelkasten method, which generates meaningful information through the formation of relationships between information, to analyze hazards associated with simultaneous operations and construct a network-structured knowledge base [32]. Through this process, they gained the idea for developing the R-JSA synchronization model, a core component of the HIRAS framework. Furthermore, we employed Generative Pre-trained Transformer (GPT) 3.5 and GPT prompts to classify disaster types, enabling the integration of diverse data into an integrated knowledge system.

The hazards addressed in this study are not unforeseen harmful risk factors, but rather the hazards that may arise during simultaneous operations in maintenance work sites, and most of these hazards are predictable. These hazards are predominantly documented in JSA. Given the significance of JSA in identifying these hazards, this study places an emphasis on leveraging JSA.

1.3. Research Process

This manuscript is organized as follows. In Section 2, we conduct a comprehensive review of the existing literature on JSA. Section 3 explains the Zettelkasten methodology, a concept applied for the development of HIRAS. Section 4 describes the methodology used to construct the HIRAS. The methodological framework of this study is divided into three components. Section 4.1 details the data structuring procedure, synchronization of variables, and attributes of the variables. Section 4.2 explains the generation of synchronized data, methods for identifying the target and source jobs, and methods for identifying hazards in source jobs. Section 4.3 presents the derivation of formulas to prioritize identified hazards. Section 5 presents two scenarios to evaluate the validity of the developed framework, wherein various evaluation metrics are used to verify the effectiveness of the framework. The data used in this study were collected from JSA and SIMOPS accident cases at Company P, as recorded in the OSHRI reports. The components and attributes were compared and analyzed to clearly define the research targets. The study is summarized in Figure 3.

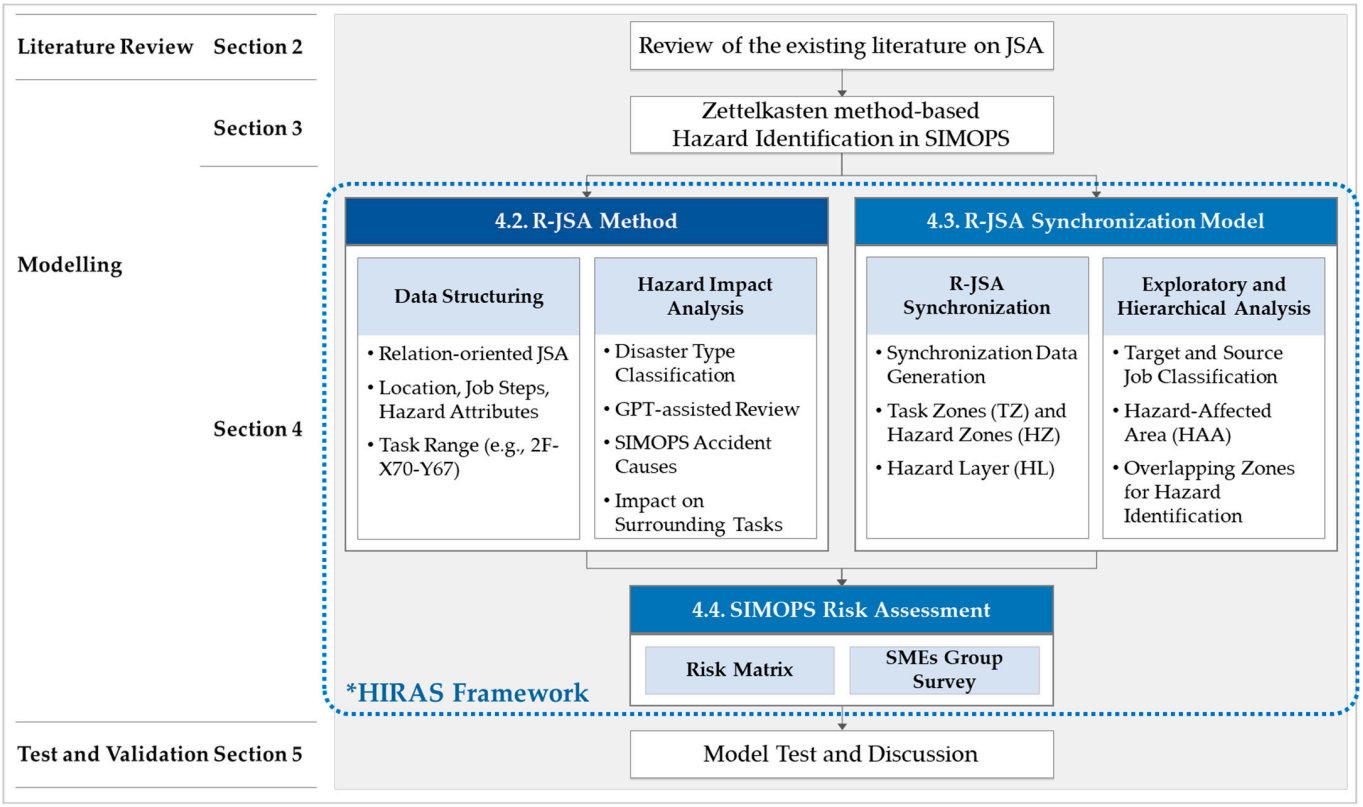


Figure 3. Overall research process.

2. Literature Review

This section categorizes the previous studies into a total of four groups: one group focusing on hazard identification and assessment methodologies, and three categories for prior research related to JSA.

2.1. Methodologies for Hazard Identification and Risk Assessment in the Construction Sector

Hazard identification and risk assessment (HIRA) is a collective term that encompasses all activities involved in identifying hazards and evaluating risk at facilities. The public or the environment are consistently controlled within each organization's risk tolerance level. Tools for simple hazard identification or qualitative risk analysis include checklists, what-if analysis, hazard and operability studies (HAZOP), and failure modes and effect analysis (FMEA) [33].

Checklists offer a straightforward and time-efficient approach to hazard identification, making them suitable for routine safety inspections [33]. What-if analysis, on the other hand, encourages creative thinking by posing hypothetical scenarios such as "What if...?" However, its effectiveness hinges on the analyst's experience and knowledge, and it may lack a systematic framework [33]. FMEA and HAZOP are more rigorous methodologies that are employed when a detailed analysis of system or process safety is imperative [33]. JSA is particularly valuable when objective data are required to assess and mitigate risks [34]. Moreover, the International Organization for Standardization (ISO) 45001 provides a comprehensive framework for establishing and maintaining an occupational health and safety management system within an organization [35]. Table 1 presents a detailed comparison of these methods, highlighting their key characteristics, strengths, and weaknesses.

Table 1. Comparing hazard identification and risk assessment methods in construction sector.

Methods	Characteristics	Advantages	Disadvantages	Application Areas
Checklist	Inspection based on a predefined list of hazards	Simple, fast, standardized	Difficulty in identifying new hazards, reliance on checklist completeness	General hazard identification, regular inspections
What-If Analysis	Assumption of various scenarios through questions like "What if...?"	Encourages creative thinking; can identify unexpected hazards	Subjectivity of the analyst, lack of systematic approach	In-depth analysis of specific tasks or systems
FMEA	Analysis of failure modes for each component of a system	Systematic risk analysis, identification of potential hazards	Time-consuming; requires expertise	Analysis of complex systems; design stage
HAZOP	Review of all functions of a system at the design stage	Prevention of hazards at the design stage; improvement of system safety	Requires specialized training; time-consuming	Design stage; process safety
JSA	Evaluation based on objective data	Accurate risk assessment; provides basis for improvement	Requires measurement equipment and specialized personnel	Measurement of specific hazards such as hazardous substance exposure, noise, and vibration
ISO 45001	Establishment of an organization-wide occupational health and safety management system	Systematic risk management; continuous improvement	Requires significant time and effort to establish and maintain the system	Overall occupational health and safety management of the organization

2.2. Origins and Limitations of Job Safety Analysis (JSA)

Previous studies on the origins and limitations of JSA were reviewed to better understand the development of JSA methodologies. The origins, processes, terms, and formats of JSA are as follows. Taylor applied systematic management methods by breaking down tasks performed by individual workers to enhance efficiency and studied the effects of scientific management [36]. Heinrich et al. introduced a method to analyze tasks and effectively match employees by considering their characteristics to prevent accidents. They proposed the term "JSA" and emphasized the benefits of accident prevention [37]. Glenn noted that Bennett's 1950 proposal of a three-column worksheet, structured around "task steps", "hazards", and "hazard controls", has endured as the bedrock format for contemporary JSA [38].

Fine and Kinney conducted a risk estimation study to prioritize hazard controls for accident prevention; they quantified the relative severity of identified potential hazards as risk scores [39]. The currently used combination of accident probability and severity in risk estimation appears to have originated from this study.

Brid and Germain indicated that JSA conducted in accordance with the relevant guidelines could be useful for major activities such as employee training, task instructions, and accident investigations [40]. The Occupational Safety and Health Administration recommended a job hazard analysis (JHA) to address workplace hazards and reduce worker injury and illness [25]. Friend and Kohn emphasized the importance of JSA in system safety for systematically identifying and controlling hazards at each task step [41]. Zheng described JSA as one of the most important on-site risk management methods for identifying hazards at each task step and eliminating or minimizing risks [42].

However, Hollnagel et al. emphasized that pre-1970s safety management was based on relatively simple and independent systems, whereas the complexity of current industrial systems necessitates methods that account for interdependence and variability. He argued

for integrating the old and new perspectives on safety instead of replacing the old perspective [1]. Zheng et al. developed a visual cognitive model to improve hazard identification at construction sites, analyzing eye-tracking data from experts and novices in 16 simulated field scenes [43]. The findings of this study provide insights into potential improvements for safety training and management. Hong and Cho proposed a location tracking system that leverages personal ID recognition, QR code scanning, and computer vision algorithms to enhance preemptive risk recognition and real-time safety monitoring in various work environments [44].

2.3. JSA for Individual Tasks

Heinrich proposed the domino theory, wherein he argued that a series of events leads to injury; however, eliminating a single component in the series of events can break the chain and prevent accidents [45]. JSA can be considered to be a methodology that helps eliminate unsafe actions or conditions in the domino theory. JSA-related research can be divided into studies on (1) hazard identification, (2) hazard control, (3) risk assessment, and (4) automation and efficiency.

Research on hazard identification focuses on clear identification and rapid detection of potential hazards. Patrucco et al. developed the Computer Image Generation for Job Simulation method to effectively use JSA techniques. The method helped visualize worker activities in the workspace, and consequently, hazard identification was faster and more intuitive than that in traditional methods [46]. Zheng et al. proposed the Energy Source-Based Job Safety Analysis method for effective hazard identification. The method provided categories to identify hazards at each job step, and the total recordable incident rate was 50% lower than that in similar projects using traditional JSA [42].

In research related to hazard control measures, Chi et al. applied ontology-based text classification to National Institute for Occupational Safety and Health (NIOSH) Fatality Assessment and Control Evaluation (FACE) reports, OSHA standards, and the Center to Protect Workers' Rights (CPWR) Construction Solutions data to develop the Construction Safety Domain Ontology System, which reduced the effort required for JSA. This proved to be an excellent reference during the review of control measures [47]. Li et al. pointed out that the risk level could continuously increase in repetitive tasks and suggested that incorporating resilience engineering into hazard control measures could reduce risk levels [48].

In research related to risk assessment, Li et al. developed a new risk assessment method that incorporated the concept of cumulative risk to improve the stability and safety of operations at gas transmission stations. They demonstrated the practical applications of the concept of cumulative risk and showed that it improved the reliability of JSA [49]. Li et al. examined the differences in risk caused by detailed sequence changes at each task step. They integrated a graphical model based on Petri nets into JSA to achieve intuitive, logical, and chronological risk assessment at each step. This method was particularly effective for non-routine tasks [50].

In research related to the automation and efficiency of JSA, Ikuma et al. combined lean production strategies with JSA to reduce high injury rates in the construction industry. They showed that worker exposure to hazards could be decreased or eliminated by reducing unnecessary motions and optimizing the work environment at each process step [51]. Wang and Boukamp aimed to reduce the time required for JHA of complex tasks. They developed "JHA Adviser" by organizing previous JHA knowledge through ontology modeling to reuse useful information. JHA Adviser facilitated access to safety management knowledge and reduced the time required for new JHAs [52]. Zhang et al. developed a construction safety ontology to automate job safety analysis and integrated it with building information modeling (BIM). They demonstrated its utility to safety supervisors within a limited scope. However, owing to the limitations in updating the field conditions and schedules, user judgment is necessary for evaluating the results [53].

2.4. JSA for Inter-Task Relationships

Rozenfeld et al. noted that JSA was primarily a tool for analyzing the risks of the job being performed, and JSA could not identify factors that increased the existing risks or factors that created new risks via interactions between multiple SIMOPS [28]. Therefore, independent analysis of individual tasks is insufficient, and analyzing the relationships between tasks is necessary.

Related research has attracted attention in the oil and gas production and construction sectors. The IMCA issued Guidance on Simultaneous Operations for identifying and managing SIMOPS during exploration, construction, and production at sea [6]. Marucco assessed the SIMOPS risk to evaluate additional risks due to SIMOPS during the commissioning of a new USD 1.65 billion petrochemical complex. Through SIMOPS evaluation workshops and action tracking management involving participants from various areas, they achieved 65 million man-hours without a lost-time injury (LTI) [54]. Baybutt proposed processes and checklists for using each tool and provided specific guidelines for identifying risks due to negative interactions between tasks during SIMOPS. Additionally, while the need for SIMOPS reviews started in the marine sector, he suggested that it is also desirable to apply it to the land sector [5].

Sacks et al. developed the Construction Hazard Assessment with Spatial and Temporal Exposure (CHASTE) model to protect workers on construction sites from exposure to risks posed by workers from other unrelated teams. This model assessed risks by considering spatial and temporal exposure and overlap, and it could help managers adjust plans for risk mitigation or take appropriate preemptive actions [55]. Rashidi Nasab et al. noted the lack of previous research on SIMOPS in construction projects and presented a practical framework for monitoring and assessing overlapping construction activities using the "source–target" matching concept based on BIM [31]. Fan et al. proposes a dynamic quantitative risk assessment (DQRA) methodology using Bayesian networks (BNs) to address the time-varying risks of liquefied natural gas (LNG) bunkering SIMOPS [56]. A case study of truck-to-ship LNG bunkering demonstrates that the methodology effectively captures the dynamic risk changes over time, providing a more accurate risk assessment compared to traditional static approaches.

2.5. Limitations of Previous Research and Objectives of This Study

The literature review revealed that traditional job safety analyses cannot clearly identify risks in the context of inter-job relationships. The novel approaches proposed to overcome these limitations in the offshore oil and gas industry as well as the construction sector have some constraints. Although the SIMOPS process in the offshore oil and gas industry is systematic and comprehensive, it requires extensive data collection and numerous participants. Consequently, the time required for JSA increases with increasing task complexity, and the method does not allow for the addition of unplanned tasks or the introduction of changes. In contrast, automated tools can be applied without restrictions on the scale of the target tasks in the construction sector. The databases for automation are based on expert opinions or accident cases. Although the databases include detailed information on the tasks, identifying the specific conditions and work environments of maintenance tasks is difficult. In industrial sites, the work methods and hazards for the same type of task can vary depending on conditions such as weight, size, and whether the environment is indoors or outdoors. Moreover, database expansion is necessary when new types of tasks are introduced. From a tool operation perspective, matching tasks with schedule and location information and judging the risk-related information requires separate personnel.

This study proposes a JSA-based framework to overcome these limitations. The proposed framework standardizes the domain knowledge of task experts reflected in the JSA into attributes and uses an automated model to consider the specificity and operational flexibility of the tasks. This approach is expected to identify and assess the impact of hazards between tasks during SIMOPS.

3. Hazard Identification in SIMOPS Based on the Zettelkasten Method

This study proposes a novel method to develop HIRAS, employing JSA to identify hazards associated with concurrent tasks, drawing inspiration from the Zettelkasten method. The Zettelkasten method, developed by Niklas Luhmann, is a note-taking and knowledge management system that effectively organizes and connects ideas to build knowledge in a systematic manner [32]. The primary objective of the Zettelkasten method is to create a dynamic network of interrelated ideas [32]. Rather than simply listing information, it facilitates a deeper understanding and utilization of knowledge by establishing connections between ideas. In order to gather hazard information from surrounding operations in a JSA, it was necessary to establish points of connection and a structured knowledge system. In this study, the Zettelkasten method was applied to transform the SIMOPS-related information present in JSAs into structured data. Through this process, individual hazard information was connected and relational information between tasks was generated, resulting in the construction of an integrated knowledge system with a network-based structure.

Another strength of the Zettelkasten method is its similarity to the way the human brain processes and connects information. By linking and integrating individual pieces of information, it helps to build a knowledge system, which in turn facilitates the generation of new knowledge [57]. In other words, by encouraging connections between various concepts, it aids in the development of original ideas. In this study, the Zettelkasten method was applied to the development of the HIRAS framework, and it was utilized as a source of insight for developing the core R-JSA synchronization model within HIRAS.

The Zettelkasten method builds a knowledge system wherein individual pieces of information are connected and integrated to generate new information [57]. The choice of connection points is crucial because connection points determine the generated information [57]. The SIMOPS information was generated by choosing the following connection points: date and location corresponding to the temporal and spatial attributes, respectively, were chosen as the connection points from individual JSAs; task and hazard attributes were chosen as the connection points to generate inter-task effects. JSAs are interconnected in the R-JSA synchronization model via the date, location, and attribute connections. A schematic of the R-JSA synchronization model with the Zettelkasten method is shown in Figure 4.

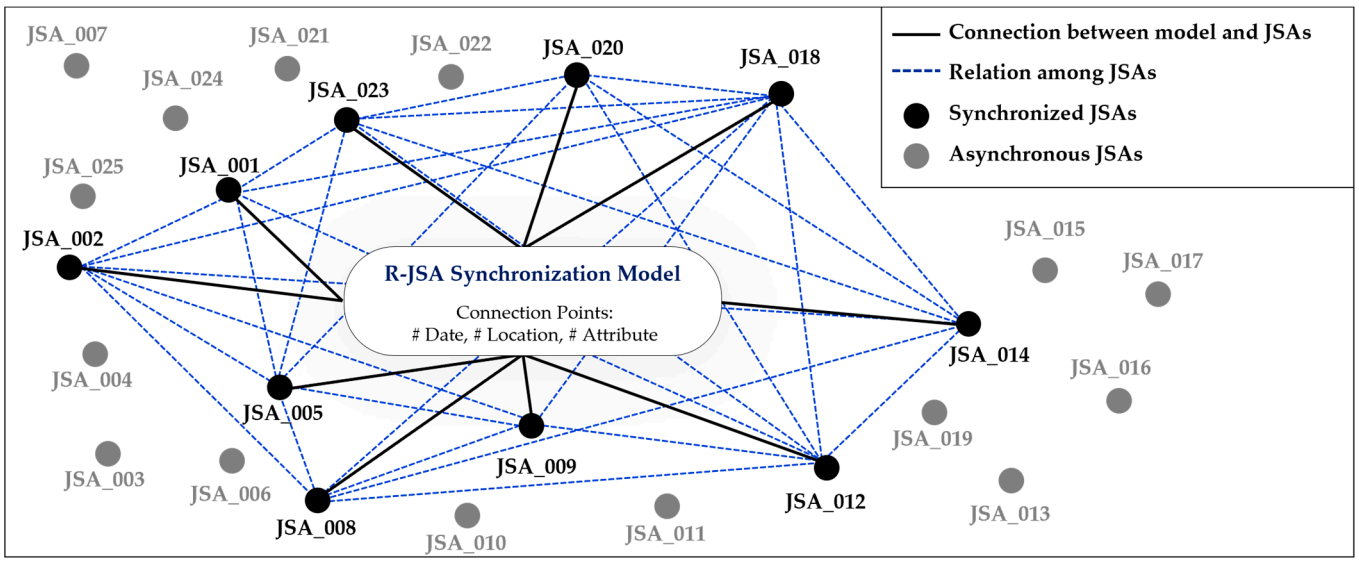


Figure 4. Schematic of the R-JSA synchronization model and JSA.

The connection points between the JSAs were chosen by matching the SIMOPS components and inter-task effects with the JSA components. The matched JSA information was converted into a form recognizable by the model via systematic structuring. Task locations

were converted into coordinates, task attributes into ranges, and hazard attributes into direction, range, and residue. The details of this conversion are provided in Section 4.2. The converted information was used in the R-JSA synchronization model to model real-time SIMOPS situations by connecting information corresponding to the same date and floor, and SIMOPS-related hazards were identified. These aspects are detailed in Section 4.3. Figure 5 shows a schematic of the SIMOPS components used to develop the R-JSA synchronization model.

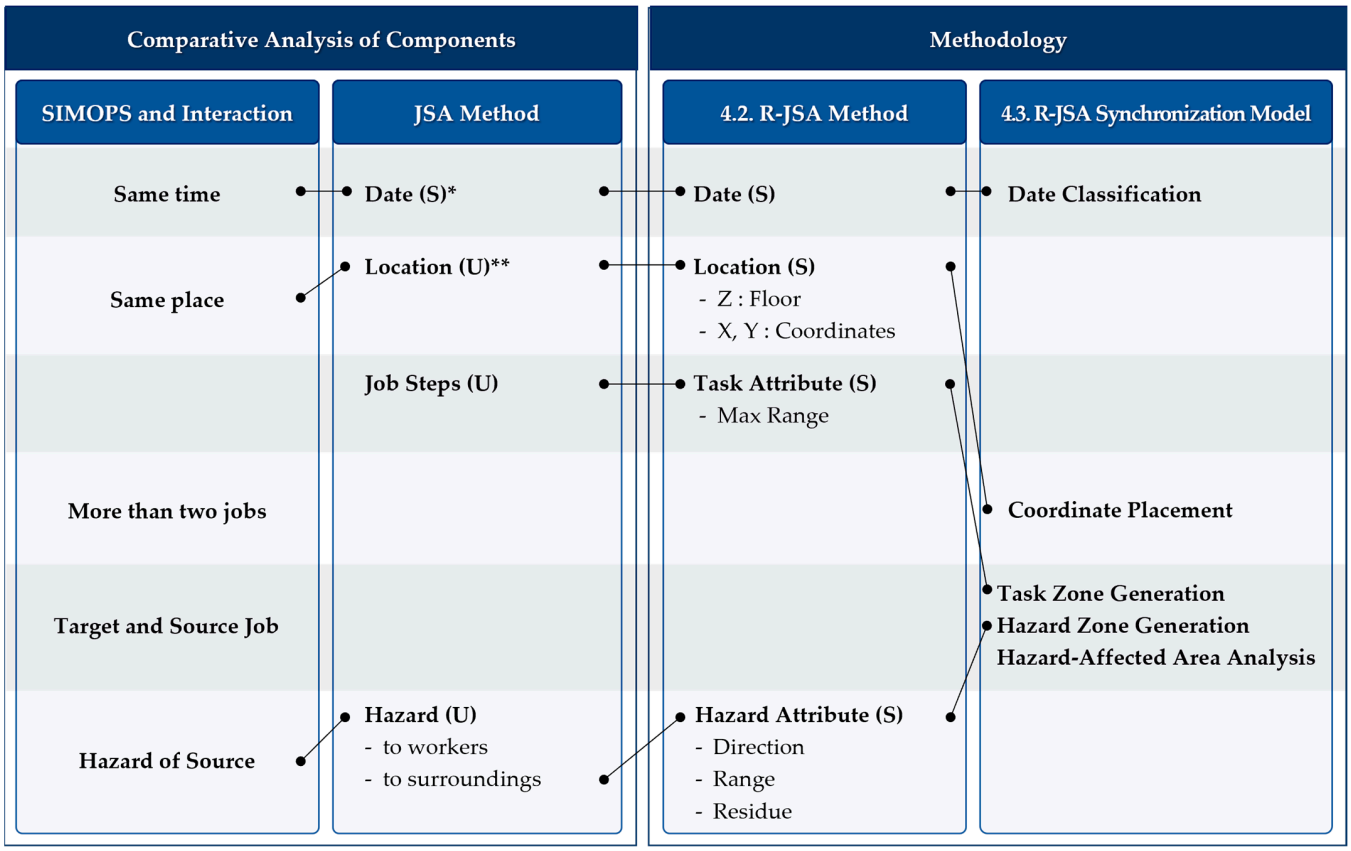


Figure 5. Connecting the components between SIMOPS and the R-JSA synchronization model. (S) *: Structured data, (U) **: unstructured data.

4. Modeling

Section 4 provides a comprehensive description of the development of a HIRAS model designed to identify and evaluate potential hazards arising from concurrent tasks.

4.1. HIRAS Framework

In this study, the Zettelkasten method was applied to develop HIRAS. HIRAS was used to identify and assess possible hazards during SIMOPS using JSA.

The HIRAS framework comprises three components: (i) the relation-oriented JSA (R-JSA) method, which generates the required data from JSA to build a database; (ii) the R-JSA synchronization model, which analyzes data to identify hazards during SIMOPS; and (iii) SIMOPS risk assessment (S-RA), which evaluates and prioritizes the identified risks. The components are detailed below.

- R-JSA method: This methodology aims to standardize JSA data to build an open database. Coordinates are assigned to task locations and the attributes of tasks and hazards are structured to standardize the data. Errors in data entry are prevented via quantified hazard classifications, GPT validation, and criteria for hazards that cause accidents during SIMOPS.

- R-JSA synchronization: This model uses data obtained from R-JSA to synchronize hazard information for tasks in a spatially and temporally coordinated manner and analyzes inter-task effects. This analysis involves the generation of synchronized data, exploratory analysis, and hierarchical analysis, which provides a basis for identifying and assessing hazards in SIMOPS.
- S-RA: S-RA focuses on evaluating the identified hazards and determining the priority of actions using the information on the risk level of the source job and the SIMOPS factor derived from expert group discussions.

The HIRAS framework integrates these components to systematically identify and evaluate hazards that may occur during SIMOPS, thereby contributing to improving workplace safety. Figure 6 shows a conceptual map of the HIRAS framework.

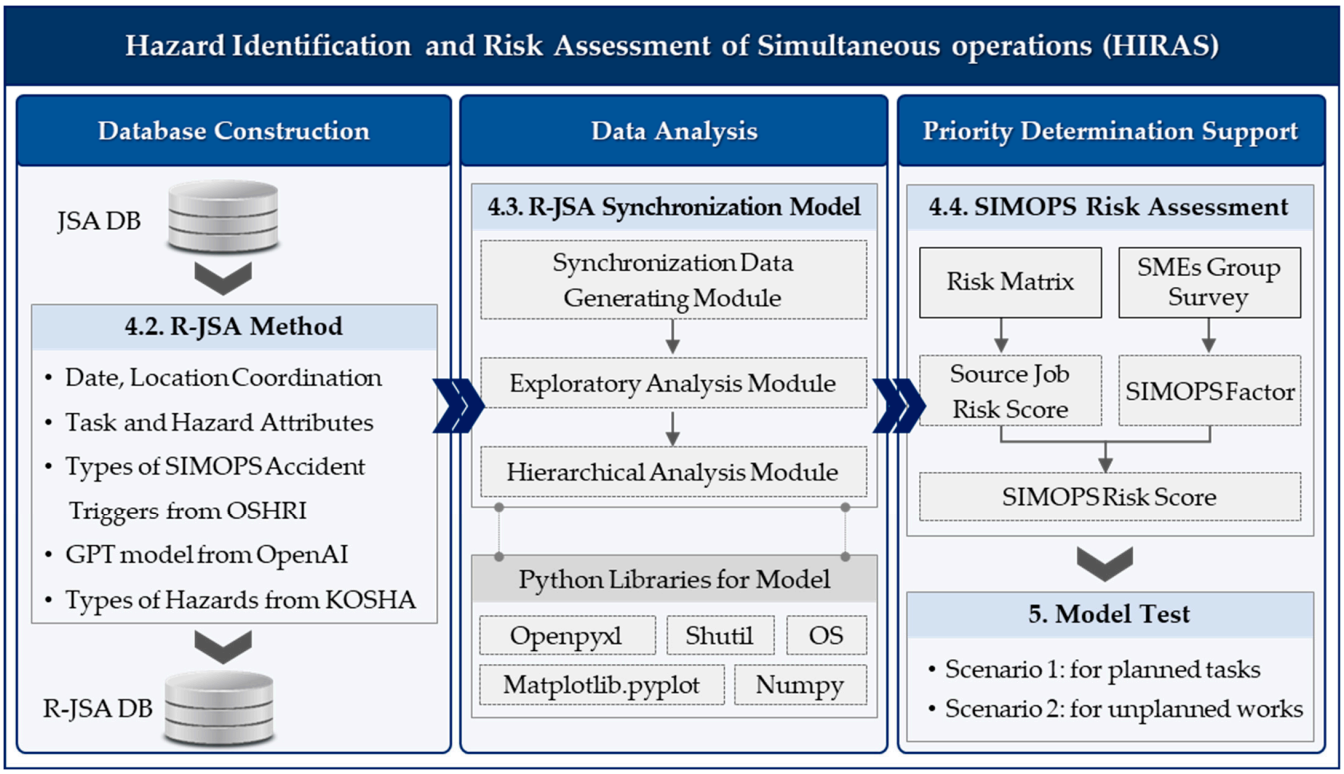


Figure 6. The system architecture of HIRAS.

4.2. Data Structuring Through a Relation-Oriented JSA Method

The R-JSA method standardizes JSA information into attribute values, and thus plays a crucial role in ensuring that the HIRAS framework is open and flexible. Moreover, the R-JSA method helps prevent the omission or overinclusion of review targets by the author. To achieve this, the improved components in the JSA methodology are the location, job steps, and hazard.

The location information was classified into floors and was coordinated on a coordinate plane of the respective floor. For example, the location "2F B Facility" was converted and entered as "2F-X70-Y67" in the standardized form. A range attribute was included to quantitatively express the scope of each task. For example, a range attribute value of five for a task step indicates the task area occupies five squares horizontally and vertically from the location in the coordinate system. Hazard attributes were added to systematize the impact on surrounding tasks, including disaster type classification, confirmation of impact on surrounding tasks, and hazard attributes. Hazard attributes were divided into three categories: range, direction, and residue. Figure 7 shows a JSA form reflecting these improvements, with the reflected parts separately marked. In Figure 7, the blue boxes

denote the field engineer's input, while the yellow sections highlight areas where GPT assistance is involved during the initial review by the first person.

JOB SAFETY ANALYSIS	JOB TITLE	JSA NO	DATE
	Replacing Hydraulic Valve and Hose for B Facility Manipulator	JSA_14	2024-01-01
TITLE OF PERSON WHO DOES JOB	**NUMBER OF WORKERS**	**SUPERVISOR**	**SAFETY SUPERVISIOR**
David	4	Carter	Joseph
COMPANY/ORGANIZATION	**DEPARTMENT**	**PLANT/LOCATION**	**LOCATION COORDINATES**
ABC Tech	Maintenance	A Plant/2F BFacility	2F-X70-Y67
PERSONAL PROTECTIVE EQUIPMENT	**ANALYSIS BY**	**REVIEWED BY**	**APPROVED BY**
Gloves, Eye Protection, Safety Shoes,	Daniel	Henry	Jackson

JOB ANALYSIS			HAZARDS ANALYSIS											RECOMMEND ACTION OR PROCEDURE
SEQUENCE OF BASIC JOB STEPS		[1]TR	POTENTIAL HAZARDS	TYPES OF HAZARDS			[3]IOSO	ATTRIBUTE			RISK ASSESSMENT			
				1ST	2ND	[2]S		[4]HR	[5]D	[6]R	[7]S	[8]P	[9]RR	
1	Power off and perform ILS	2	Potential pinching due to equipment operation	Entrap-ment	Entrap-ment	✓					3	3	9	Power shutdown, lockout, and tagout procedures
2	Disassemble valves and hoses	8	Possibility of falling during work around openings	Fall	Fall	✓	✓	10	[10]HV-		3	4	12	Conducting work after installing safety handrails
3	Install valves and hoses	8	Impact risk from residual pressure in the piping	Struck by	Struck by	✓					3	4	12	During disassembly, confirm and remove residual pressure with bolts slightly loosened before complete disassembly
4	Install valves and hoses	8	Hand collision hazard due to detachment when operating the pneumatic tool with excessive force	Struck against	Struck against	✓					2	4	8	Secure work space and maintain proper posture during work
5	Install valves and hoses	8	Tipping risk from spilled oil	Fallen over	Fallen over	✓	✓	8	[11]H	✓	2	4	8	Regular inspection of work floor conditions and leakage removal
6	Tidying up	8	Slip and trip hazards due to inadequate cleaning	Slip	Slip	✓					2	4	8	Thorough cleaning and organization of the work floor

Figure 7. Example of a relation-oriented JSA form. [1] TR: Task range; [2] S: selection; [3] IOSO: impact on surrounding operations; [4] HR: hazard range; [5] D: direction; [6] R: residue; [7] S: severity; [8] P: probability; [9] RR: risk rating; [10] HV-: the downward direction of the horizontal and vertical; [11] H: horizontal.

The impact of hazards on surrounding tasks was evaluated as follows:

- Classification of disaster types: Disaster types were classified to structure the hazards corresponding to individual tasks. As classification criteria may vary across industries, the 22 criteria detailed by KOHSA were used herein [58]. The classification was conducted in three steps. First, the worker classified the types, and GPT was used to assist classification. The role, classification criteria, and output format were specifically presented in the GPT prompt. The GPT prompts were combined with JSA hazards using text concatenation functions in Google Sheets, and the GPT API was used for classification. Discrepancies between the two results were reviewed. The accuracy and reliability of the classification were improved by reviewing and supplementing the results provided by AI. Figure 8 shows a part of the prompt used for disaster-type classification.

 # Instructions
You are a safety management expert.
Based on the definitions of types of accidents below, please classify the input sentence into the appropriate type of accident.
After classification, output the result as the type of accident. Do not output any other content.

 # Definitions of Types of Accidents
- Falling: "Falling from a height refers to a person falling from a high place such as a building, structure, scaffold, tree, ladder, etc., due to gravity."
- Slipping: "Slipping refers to a person slipping or falling almost flat or on a slope, stairs, etc."
- Collapsing, overturning: "Collapsing or overturning of objects refers to cases where objects leaning or standing collapse or overturn, and construction machinery such as forklifts overturn during operation or work."

(ellipsis)

 # Input Sentence
-

Figure 8. GPT prompt for disaster type classification.

- Confirmation of impact on surrounding tasks: Disaster types that could cause accidents during SIMOPS were selected. Clear classifications were applied to eliminate variations among authors and ensure consistent results. The classification criteria were based on the results from a study conducted by the Korea Occupational Safety and Health Research Institute, wherein 4641 accidents that occurred from 2016 to 2020 were analyzed according to objective criteria. Among these accidents, 426 were classified as SIMOPS accidents, and seven types of SIMOPS accident causes were identified [14]. If the results of the disaster type classification corresponded to one of the seven SIMOPS accident causes, the hazard attributes were reviewed. As other types of accident causes do not affect surrounding tasks, the hazard attributes were not reviewed in those cases. Figure 9 shows the criteria and process for determining the impact on surrounding tasks.

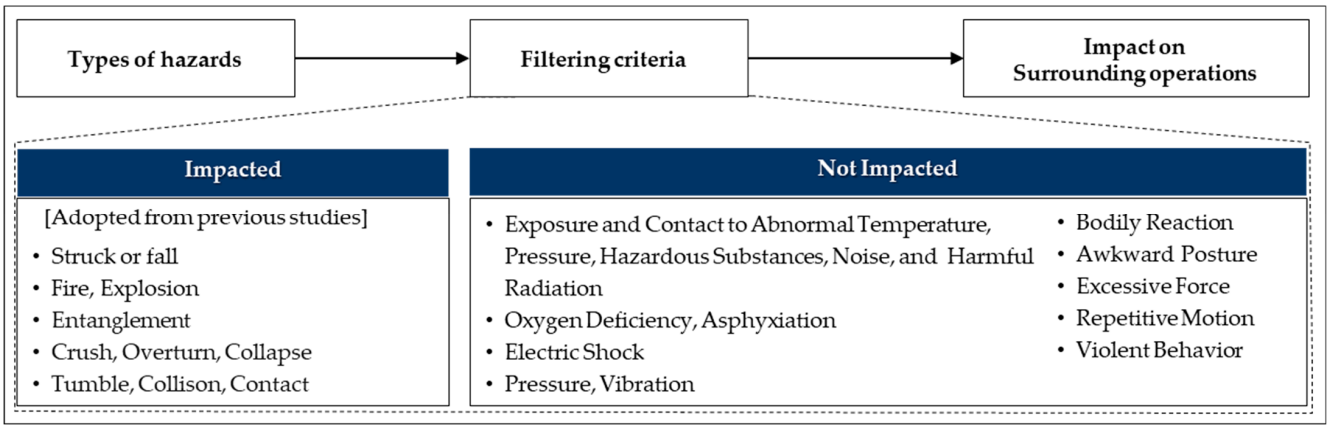


Figure 9. Criteria and process for selecting items with potential for SIMOPS accidents among disaster types.

- Direction of the hazard: Four directions were considered: horizontal, horizontal and upper, horizontal and lower, and horizontal and both upper and lower. The same hazard can occur in different directions depending on the work environment. For example, in the case of a fire, the direction can vary depending on the exposure and composition of the space as well as the source of fire, such as gas or oil. Therefore, environmental factors were considered based on the worker's domain knowledge.
- Range of work and hazard: The maximum range that could be affected was considered following the reviewed direction.
- Presence of residual hazard attributes: The risk of a hazard may not be eliminated after task completion. For example, a worker might be exposed to asphyxiation or

poisoning risks from gases accumulated during a previous task. Therefore, the residual attributes of hazards in the target task were considered [59].

The worker's domain knowledge about the impact on surrounding tasks can be standardized by reviewing the attributes of work and hazards. Moreover, the disaster type classification and confirmation of impact on the surrounding tasks prevent omissions and overinclusion of entries by the author, while the remaining processes ensure an open framework.

4.3. R-JSA Synchronization Model for Identifying Hazards in Simultaneous Operations

The R-JSA synchronization model synchronizes information extracted from JSAs of planned tasks into a coordinate system by matching the temporal and spatial conditions during actual SIMOPS and analyzes the inter-task impacts. This process is automatically performed by the JSA synchronization algorithm according to the following three steps:

4.3.1. Data Generation

The data generation algorithm, schematically shown in Figure 10, is applied as follows:

① Extract date, location, and attribute information from R-JSA. Use date information to classify tasks on the same date and location information to classify tasks on the same floor.
② For each floor, create a task zone (TZ) using the X and Y coordinates of the job and the task range, and create a hazard zone (HZ) using the hazard attributes.
③ Combine the HZs to create a single hazard layer (HL).

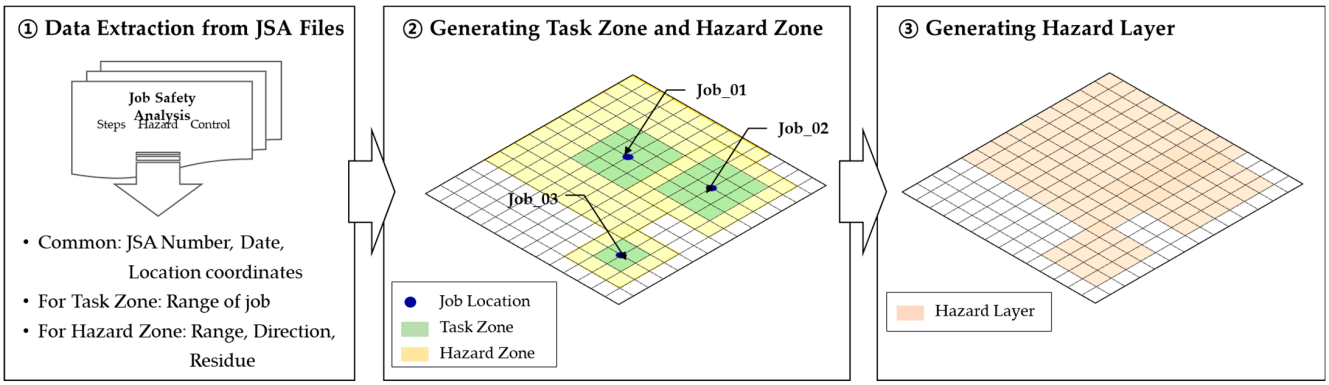


Figure 10. Schematic of data generation for R-JSA synchronization.

The generated data have the following components:

- TZ: date, location coordinates, and task range. TZ indicates the location and range of all tasks in the coordinate system.
- HZ: date, location coordinates, hazard direction, hazard range, and residue. HZ indicates the range of identified hazards based on location coordinates. The hazard may be extended upwards and downwards depending on the direction. If there are residual attributes, the HZ is not reset in the system, even if the task date changes. Resetting occurs after affecting other task TZs following the date change.
- HL: combines all HZs on a workplace floor to create a single layer. Hazards transmitted from other floors are also included on the basis of the hazard direction. This plays a crucial role in comprehensively identifying hazards from multiple surrounding tasks. Equation (1) represents the HL [60].

$$\text{Hazard Layer} = \bigcup_{i=1}^{n} HZ_i \quad (1)$$

where the hazard layer is the set of all HZs on a particular floor, HZ denotes the hazard coordinates, and i is the iterative variable representing each HZ.

4.3.2. Exploratory Analysis: Target–Source Job Identification

Target jobs affected by surrounding tasks and source jobs impacting surrounding tasks are identified based on the generated data. The jobs were classified as target and source jobs as follows: if the hazard-affected area (HAA) is in the TZ, it is a target job; if it is in the HZ, it is a source job. For example, in Figure 11, Job_02 is classified as a target job because its TZ overlaps with the HL, creating an HAA. The overlapping area lies within the HZ of Job_01, and hence, Job_01 is a source job.

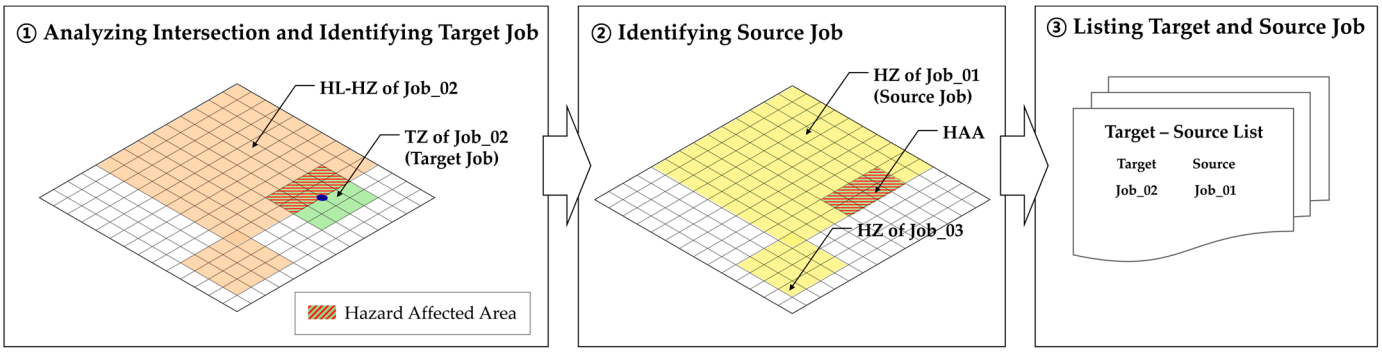


Figure 11. Schematic of exploratory analysis for target–source job identification.

- HAA: HAA represents the area wherein TZ_i is affected by the HZ of surrounding tasks as identified from the overlapping area between TZ_i and HL. In this case, the HZ_i of the target $Task_i$ must be excluded from the HL. Equation (2) represents the HAA [60].

$$\text{Hazard Affected Area} = (\text{HL} - HZ_i) \cap TZ_i \quad (2)$$

where the hazard-affected area corresponds to the area wherein the target job is affected by the hazards due to the source job, HL denotes the hazard layer, HZ denotes the hazard coordinates, TZ denotes the task coordinates, and i is the task being reviewed.

- The HAA for all scheduled jobs is calculated. The HAA serves as the basis for classifying the jobs into four categories: (i) If the HAA coordinate is within the TZ, the task is classified as a target job; this indicates that the task is affected by the hazards due to surrounding tasks. (ii) If the HAA is within the HZ, the task is classified as a source job; this indicates that the task poses hazard risks to surrounding tasks. (iii) If the HAA coordinate lies in both TZ and HZ, the task is classified as both a target and a source job. (iv) If the HAA coordinate lies in neither TZ nor HZ, the task is excluded from SIMOPS hazard review.

4.3.3. Hierarchical Analysis: Target-Hazard Identification

The analysis is conducted for each target job and source job pairing. The overlapping area between the TZ of the target job and the HZ of the source job is calculated. The number of HZs may vary depending on the number of hazards due to the source job. This identifies the source hazards and the HAA affecting the target job. Figure 12 shows a schematic of this process.

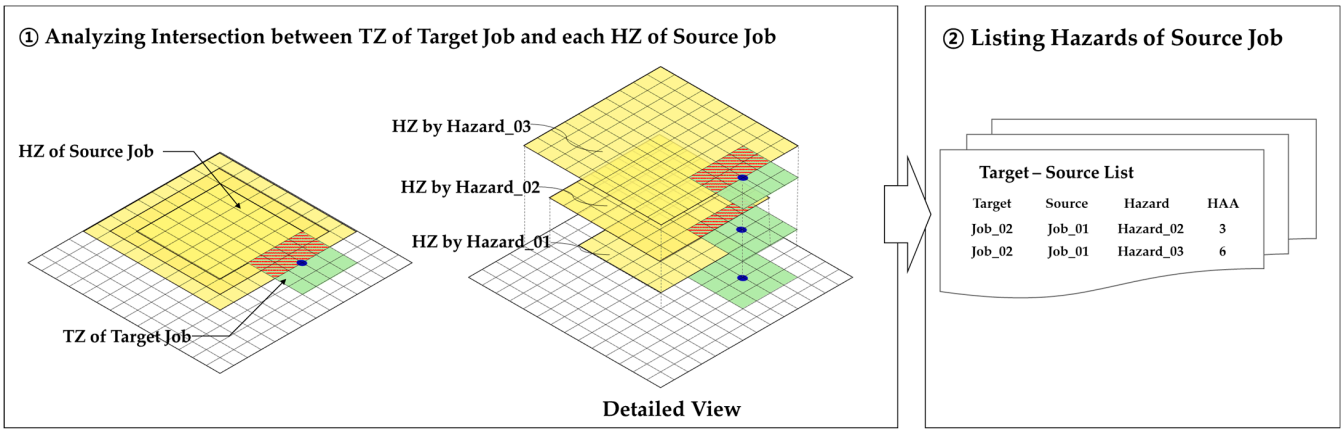


Figure 12. Schematic of hierarchical analysis for identifying source job hazards.

4.4. SIMOPS Risk Assessment

Risk assessment comprises a combination of the probability and severity of an accident expressed as a matrix. It allows for a quantitative comparison of risk priorities [49]. Table 2 shows the risk assessment matrix used to calculate the risk score [61].

Table 2. Risk assessment matrix.

Risk Score		Severity (S)			
		Minor	Marginal	Critical	Fatality
Probability (P)	Very likely	10	13	15	16
	Probable	6	9	12	14
	Possible	3	5	8	11
	Unlikely	1	2	4	7

In this study, the previous risk assessment procedure was modified to calculate the risk level of hazards in SIMOPS. The most common method used in risk evaluation is the risk priority number (RPN), which is widely adopted due to its simplicity and convenience [62]. However, while RPN is suitable for calculating the risk level of individual tasks, it has limitations in evaluating the degree of risk in simultaneous operations, as addressed in this study. To assess how the risk in one operation affects surrounding tasks during simultaneous operations, this study developed a new equation called the SIMOPS Risk Score by incorporating factors such as work area, hazard area, and the number of workers into the traditional RPN.

The base risk score was extracted from the JSA of the source job, and three additional variables derived from the R-JSA synchronization model were used. These variables, which indicate the SIMOPS hazard level, were derived in consultation with safety experts. The risk level increases with the size of the hazard area within the work area and the number of workers in the hazard area. Therefore, TZ, HAA, and the number of workers (N) were selected. These were integrated into the existing risk assessment formula and were used as variables for the SIMOPS risk assessment. The SIMPOS risk score was calculated as shown in Equation (3).

$$\text{SIMOPS Risk Score} = P_S \times S_s \times \frac{HAA}{TZ} \times N\,, \tag{3}$$

where SIMOPS Risk Score represents the risk level of hazards in SIMOPS, P_S is the probability of the source hazard, S_s is the severity of the source hazard, HAA is the hazard-affected area, TZ is the task zone, and N is the number of workers in the TZ.

Once the risk level of the identified hazards in SIMOPS has been calculated by the model, priorities are established accordingly.

5. Test and Validation

5.1. Test Setup

The performance of the proposed HIRAS in identifying and assessing the hazards due to inter-task interactions in a SIMOPS environment was evaluated as follows:

- Data collection and preprocessing: 40 JSAs used in actual maintenance work were collected. Sensitive information on individuals and companies was selectively used. The location coordinates and attributes necessary for the R-JSA synchronization model were then added and standardized via the R-JSA method.
- Experimental design: A three-story plant with a floor area of 90,000 m^2 was assumed. To simulate SIMOPS, the tasks were scheduled over two consecutive days to reflect the residual attributes as hazards. Two scenarios were chosen to evaluate the identification capability and utility of the model in actual work environments. The first was a scenario with planned work alone, and the second was a scenario where unplanned work was added to the planned work.
- Details of the model used: Disaster types were classified using the GPT-3.5 model via the OpenAI API in Google Sheets using function calls. GPT-3.5, developed by OpenAI, is widely used for natural language processing and generation tasks. The model was pre-trained on a large text dataset and can understand the context and perform classification tasks. The R-JSA synchronization model developed was implemented in Python version 3.11. Scripts were written and executed using Visual Studio version 1.86; the modules openpyxl, os, shutil, matplotlib.pyplot, and numpy were used.
- Evaluation criteria: The rate of identification of hazards leading to SIMOPS accidents was adopted as the criterion. This criterion was used as an indicator to measure the effective identification of hazards in complex work environments. The identification results were validated via a confusion matrix. The validation was based on the simulation results of the model. As the actual accidents are potential, the simulation accuracy of the model does not imply the accuracy of accident prediction.

5.2. Performance Metrics for Model Test

A confusion matrix was used to verify the model's performance by comparing actual values with predicted values [63]. Table 3 shows the confusion matrix used in this study.

Table 3. Confusion matrix for the JSA synchronization model.

		Predictive Value	
		Positive	**Negative**
Actual Value	Positive	True Positive (TP)	False Negative (FN)
	Negative	False Positive (FP)	True Negative (TN)

The cells in the confusion matrix are defined as follows:

- True positive (TP): Cases that are actually positive and correctly predicted as positive.
- False negative (FN): Cases that are actually positive and incorrectly predicted as negative.
- False positive (FP): Cases that are actually negative and incorrectly predicted as positive.
- True negative (TN): Cases that are actually negative and correctly predicted as negative.

The confusion matrix allows for the calculation of accuracy, precision, recall, and F1-score as follows [63,64].

- Accuracy is the ratio of correct predictions to total predictions, as defined in Equation (4).

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \times 100\% \quad (4)$$

- Precision is the ratio of correctly predicted positive instances to all instances predicted as positive, as defined in Equation (5).

$$Precision = \frac{TP}{(TP + FP)} \times 100\% \quad (5)$$

- Recall is the ratio of correctly predicted positive instances to all actual positive instances, as defined in Equation (6).

$$Recall = \frac{TP}{(TP + FN)} \times 100\% \quad (6)$$

- The F1-score is the harmonic mean of precision and recall, as defined in Equation (7). The F1-score provides a comprehensive measure of the model's performance.

$$\text{F1} - \text{Score} = 2 \times \frac{(Precision \times Recall)}{(Precision + Recall)} \quad (7)$$

The predictive value is the result calculated by the R-JSA synchronization model, whereas the actual value is derived using the rule-based system validation methodology proposed by Knauf. The methodology proposed by Knauf compares the system-generated results with the final results reviewed by experts in the relevant field. It evaluates the reliability of the methodology by assessing how closely the results of the proposed methodology align with expert judgment [65]. The SME team consisted of six field managers with over ten years of safety management experience at P steel mill. Table 4 details the qualifications of the SMEs.

Table 4. Qualifications of the SMEs that participated in the test.

Expert Code	Year of Experiences	Discipline
A	12	Capital Investment, Maintenance Management
B	13	Maintenance Management
C	11	Capital Investment, Maintenance Management
D	17	Capital Investment
E	10	Maintenance Management
F	23	Maintenance Management

5.3. Implementation and Results

5.3.1. Scenario 1: Identification and Assessment of Hazards among Multiple Planned Tasks

The first scenario in this study focuses on the identification and evaluation of hazards that may arise from the execution of several planned tasks. The first scenario was conducted in two stages according to experimental conditions. First, the equipment managers reanalyzed 37 JSAs relationally. During the analysis, only items in the JSA that affected the surrounding tasks were selected and evaluated. The manager initially classified the hazard types according to KOSHA standards, followed by a secondary classification using a GPT-based prompt in Google Sheets, which indicates the matching status. The manager reviewed and re-evaluated any discrepancies. Items that could potentially cause SIMOPS accidents were automatically selected using Excel functions, and the manager made the final decision considering the task and site conditions. This iterative verification alternating between the manager and the system minimized the possibility of omission and overinclusion. The hazard range, direction, and residue attributes of the selected hazards were evaluated.

Next, R-JSAs were synchronized temporally and spatially, and the inter-task impacts were analyzed. The process was automated by collecting the evaluated R-JSA files into one folder and executing the R-JSA synchronization model developed in this study. The

R-JSAs were classified by task date for temporal synchronization and by floor coordinates for spatial synchronization. Table 5 lists the tasks by date and floor.

Table 5. Work data and floor-wise job list for Scenario 1.

Classification	Day1	Day2
1st Floor	Job_01, 02, 03, 22, 24, 25, 28	Job_04, 05, 23, 27, 29
2nd Floor	Job_07, 08, 13, 14, 35, 36, 37	Job_09, 10, 11, 12, 15, 16
3rd Floor	Job_18, 30, 34, 38, 39, 40	Job_ 20, 21, 26, 31, 32, 33

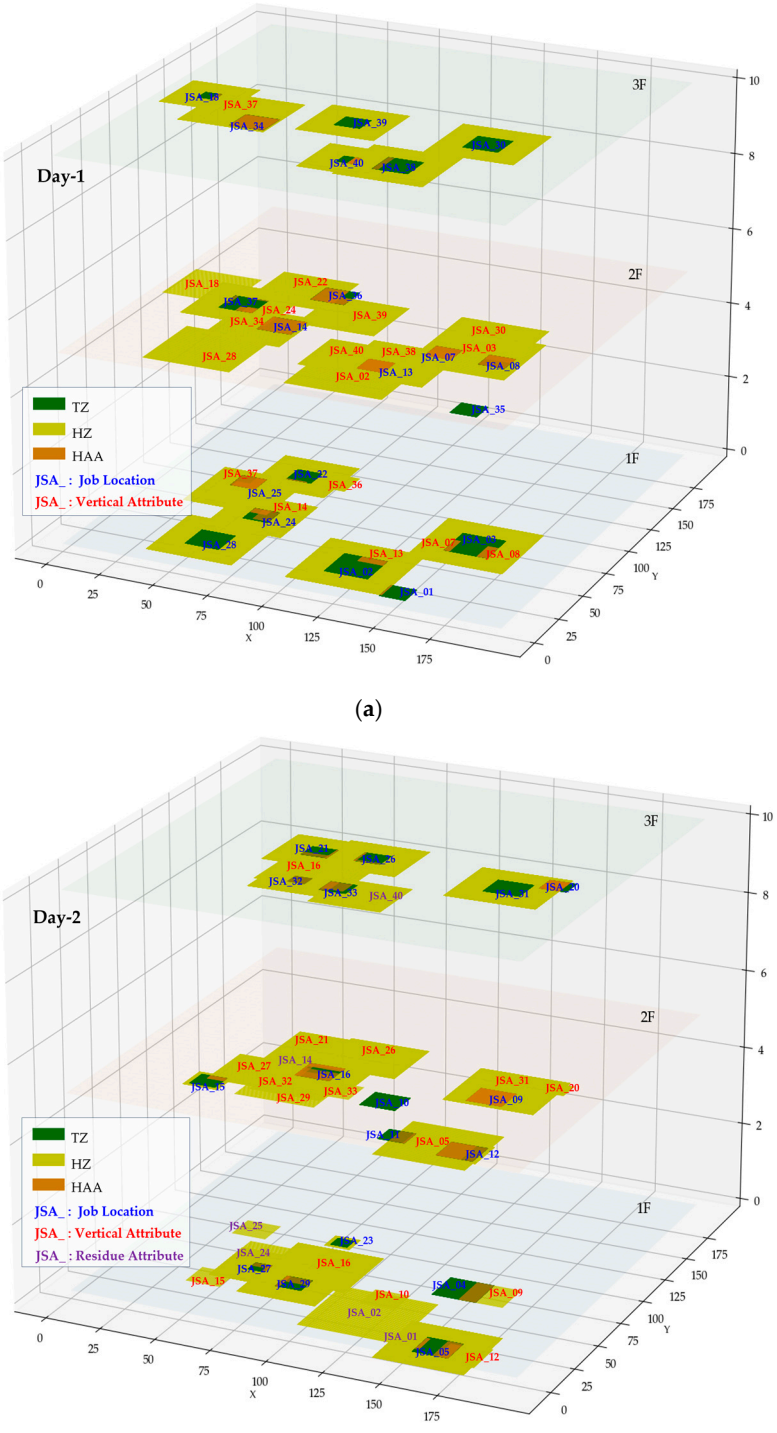
Next, the tasks were placed in a coordinate system based on the coordinates of each task, and the TZ and HZ coordinate data were generated based on the task and hazard attributes. The HZ data were processed as follows: if there was a vertical attribute in the HZ, coordinates were assigned to the related floor HL; if there was a residual attribute, the HZ coordinates were assigned to the coordinate system for the second day. For example, although Job_14 was performed on the second floor, the hazard in Step 2 had a downward vertical attribute; therefore, the same HZ coordinates were assigned to the first-floor plane. Once the actual work situation was modeled, it was analyzed to identify the target jobs and source jobs as well as the hazards due to source jobs affecting target jobs. Finally, a SIMOPS risk score was calculated for the identified results, and priorities were assigned.

The target job–source job list generated from the first scenario included 119 cases: 72 on the first day and 47 on the second day. The list was sorted based on the SIMOPS risk score, and the priority of each item was indicated. To coordinate between jobs, information on the safety managers of Target and source jobs and information on the hazards were provided. For example, the hazard in Step 2 of Job_14 was found to affect JSA_24. Table 6 shows a part of the identified target job–source job list.

Table 6. Target job–source job list and priority identified in Scenario 1.

Target Job		Source Job			SIMOPS Risk Score	Priority
JSA Number	Safety Supervisor	JSA Number	Safety Supervisor	Job Steps of Hazard		
JSA_14	Joseph	JSA_24	Isaac	5	160	1
JSA_14	Joseph	JSA_24	Isaac	10	160	2
JSA_34	Tyler	JSA_37	Zachary	3	160	3
JSA_34	Tyler	JSA_37	Zachary	6	160	4
JSA_25	Dylan	JSA_37	Zachary	3	120	5
JSA_25	Dylan	JSA_37	Zachary	6	120	6
JSA_07	Michael	JSA_03	Oliver	6	120	7
JSA_07	Michael	JSA_03	Oliver	8	120	8
JSA_08	Jackson	JSA_03	Oliver	6	120	9
JSA_08	Jackson	JSA_03	Oliver	8	120	10
JSA_13	Samuel	JSA_02	Benjamin	4	120	11
JSA_13	Samuel	JSA_02	Benjamin	6	120	12
JSA_13	Samuel	JSA_38	Nicholas	3	120	13
JSA_13	Samuel	JSA_38	Nicholas	4	120	14
JSA_13	Samuel	JSA_38	Nicholas	5	120	15
JSA_13	Samuel	JSA_38	Nicholas	8	120	16
JSA_13	Samuel	JSA_38	Nicholas	9	120	17
JSA_36	Christian	JSA_22	Christopher	3	110	18
JSA_36	Christian	JSA_22	Christopher	4	110	19
JSA_24	Isaac	JSA_14	Joseph	2	88	20

The results of the analysis were visualized to obtain an intuitive understanding. The color codes and meanings of the components are detailed below. Figure 13 shows a visualization of the results of the analysis for the first and second days of Scenario 1.



(**a**)

(**b**)

Figure 13. Results of the analysis for Scenario 1: (**a**) first day; (**b**) second day.

- The green rectangle represents TZ, the maximum area of the task.
- The yellow rectangle represents HZ, the maximum hazard area of the task.
- The orange rectangle represents HAA, the area where TZ is affected by the HZ of surrounding tasks.
- Blue text indicates the source of TZ and HZ.
- Red text indicates the source of the vertical attribute HZ.
- Purple text indicates the source of the residual attribute HZ. For example, there is no residual attribute hazard area on the first day due to the absence of previous work

information. On the second day, the residual hazard attribute for Step 5 from the JSA_14 on the first day appears as HZ.

A confusion matrix based on the final results produced by the SMEs was used to validate the model. In Scenario 1, a total of 4781 inter-task interactions were reviewed. The model correctly identified 118 SIMOPS hazards (TP), three missing cases (FN), and incorrectly identified one case (FP). The performance metrics of the model are shown in Table 7.

Table 7. Validation results of the JSA synchronization model for Scenario 1.

Value				Performance			
TP	**FN**	**FP**	**TN**	**Accuracy (%)**	**Precision (%)**	**Recall (%)**	**F1-Score (%)**
118	3	1	4659	99.92	99.16	97.52	98.33

5.3.2. Scenario 2: Identification and Assessment of Hazards during Unplanned Work

The second scenario considered in this study simulated unplanned work: a situation wherein three additional tasks were added to the day 2 task list after the completion of the previous experiment was assumed. The model conducted an analysis including the three additional R-JSAs analyzed by the equipment manager. The SMEs were able to confirm the analysis information for 37 planned tasks from Scenario 1. The SMEs examined the hazards due to surrounding tasks through the JSAs of the additional tasks and the location maps of the tasks. The average number of hazards individually identified by the SMEs was 11, which is 38.7% of the results identified by the model. When individual identification results were combined, it increased to 25, corresponding to an identification rate of 89.3%. A significant difference was confirmed between the individual and combined results. As the combined results converged at a higher level, the experiment was concluded. Table 8 shows the results of identification obtained using the model compared to those of the SMEs in Scenario 2.

Table 8. Identification results obtained using the model compared to SME results in Scenario 2.

Model			SMEs					
Target Job	**Source Job**							
JSA Number	**JSA Number**	**Job Steps of Hazard**	**A**	**B**	**C**	**D**	**E**	**F**
JSA_17	JSA_21	3	☐	☐	☐	☐	✓	☐
JSA_17	JSA_21	6	☐	☐	☐	☐	☐	☐
JSA_19	JSA_17	4	☐	✓	☐	☐	☐	☐
JSA_19	JSA_17	7	☐	✓	☐	☐	☐	☐
JSA_21	JSA_17	4	☐	✓	☐	☐	☐	✓
JSA_21	JSA_17	7	☐	✓	☐	☐	☐	✓
JSA_17	JSA_26	5	☐	☐	☐	☐	✓	✓
JSA_17	JSA_26	6	☐	☐	☐	☐	✓	☐
JSA_06	JSA_10	2	✓	✓	✓	✓	✓	✓
JSA_23	JSA_17	2	✓	☐	☐	✓	☐	✓
JSA_23	JSA_17	3	✓	☐	☐	☐	☐	✓
JSA_23	JSA_17	6	✓	☐	☐	✓	☐	☐
JSA_23	JSA_17	9	✓	☐	☐	☐	☐	☐
JSA_26	JSA_17	4	☐	☐	☐	☐	☐	☐
JSA_26	JSA_17	7	☐	☐	☐	☐	☐	☐
JSA_17	JSA_21	4	☐	✓	☐	☐	☐	✓
JSA_23	JSA_17	4	✓	☐	✓	☐	✓	✓
JSA_23	JSA_17	7	✓	☐	✓	☐	☐	✓
JSA_06	JSA_02	3	✓	☐	☐	☐	☐	☐
JSA_19	JSA_21	3	✓	✓	✓	✓	✓	✓
JSA_19	JSA_21	6	✓	✓	✓	✓	☐	✓
JSA_17	JSA_19	2	✓	✓	☐	☐	☐	☐
JSA_17	JSA_19	5	✓	✓	☐	☐	✓	✓
JSA_17	JSA_16	5	✓	✓	✓	✓	✓	✓
JSA_16	JSA_17	4	☐	☐	✓	☐	☐	✓
JSA_16	JSA_17	7	☐	☐	✓	☐	☐	✓
JSA_19	JSA_26	5	☐	☐	☐	✓	✓	☐
JSA_19	JSA_26	6	☐	☐	☐	✓	✓	☐

5.4. Discussion

The key performance metric of the JSA synchronization model in Scenario 1 was its ability to accurately identify hazards during SIMOPS with a high recall rate of 97.52%. The recall rate indicates that the model effectively identifies hazards and can contribute to preventing risks during SIMOPS. The excellent performance metrics of the model can be attributed to the improvements to the existing JSA data via the R-JSA methodology. The improved input data played a crucial role in improving the model output results. Nonetheless, there were three missed cases (FN) and one incorrectly identified case (TP). The reasons can be attributed to omissions and errors. Although SMEs can identify missing information in JSAs during the final review, the model cannot generate new information from the R-JSA, leading to omissions. The TP was attributed to incorrect data entry by the responsible worker for the direction attribute in the R-JSA. The quality of input data significantly impacts the results, highlighting the need for continuous efforts to improve data completeness and accuracy. The results of Scenario 1 affirmed Moravec's paradox [66]—computers easily perform complex calculations while humans excel in intuitive understanding. Thus, better outcomes can be obtained by complementing the strengths of both the model and humans.

Scenario 2 demonstrated that the SIMOPS process with multiple experts is useful in identifying hazards in SIMOPS via the differences between individual and integrated identification results by SMEs. However, the results highlighted the limitation of the SIMOPS process in responding immediately to variable situations such as unplanned tasks, thereby confirming the utility of the model.

During interviews, SMEs reported that they could pay sufficient attention to identify and correct missing or incorrect information in the detailed target–source list and visualizations obtained from the model in Scenario 1. In contrast, despite sufficient information on the existing and additional tasks, the identification rate was low in Scenario 2. The SMEs reported that they repeatedly rechecked the information on surrounding tasks while reviewing additional tasks with drawings and JSAs, making inference difficult due to the diversity of hazard attribute variables. The results of Scenario 2 highlight the limitations of human memory and inference ability. These results are supported by research findings which indicate that working memory and inference share cognitive capacity. Working memory refers to a cognitive system that maintains a certain amount of information temporarily, while inference refers to the act of drawing conclusions from given information. As the number of variables increases, the increasing complexity of interrelationships leads to poor inference [67].

The following insights were obtained from both scenarios. The results obtained in this study indicate that HIRAS can help reduce the load on working memory from a cognitive capacity perspective and help support inference on inter-task relationships. Therefore, safety managers can focus on productive work, such as identifying missed hazards, coordinating tasks, and developing countermeasures based on the provided information. Moreover, HIRAS can be used for the rational allocation of resources, such as effort, time, and cost, to manage hazards. Job managers and workers can identify the target job they are performing, check the source job information, and use the information for mutual coordination. A limitation of HIRAS is that some items may be omitted due to the quality of JSAs. However, as JSAs are evaluated annually and updated as needed, the likelihood of missing items is expected to gradually decrease.

The relevance and contribution of this study can be summarized as follows. First, by demonstrating that hazards in SIMOPS can be identified using JSAs, this study shows that the limitations of JSAs pointed out in previous studies can be addressed. Thus, JSAs can be used not only as a tool for analyzing individual task risks but also as an effective tool for identifying hazards in SIMOPS environments. Second, previous research on identifying hazards in SIMOPS has focused on general tasks because they are based on information derived from expert judgment. In contrast, this study uses hazard information identified by the managers responsible for each task, including the specificity of individual tasks and

work environment factors. Moreover, because hazard information is updated regularly or as needed, it reflects the actual information in changing work environments. Third, this study considers the impact of residual hazards on subsequent tasks. To the best of our knowledge, the impact of residual hazards has not been considered in previous studies. Thus, HIRAS helps us to conduct a more comprehensive analysis of safety management during SIMOPS.

Although HIRAS was developed as a proof of concept (PoC), comprehensive validation confirmed two points: (i) it can derive new information on inter-task impacts during SIMOPS from JSAs; (ii) it can reduce the cognitive burden on safety managers in complex and variable work environments. This study is distinct from previous studies because it focuses on identifying and assessing hazards in SIMOPS based on JSA and targets plant maintenance work.

6. Conclusions

6.1. Summary and Contributions

This study proposed a new safety management tool, "HIRAS," to identify and assess hazards between SIMOPS during plant maintenance work. The traditional JSA methodology is useful for the safety management of individual tasks; however, managing the safety of surrounding tasks via JSA is challenging. Industrial sites continue to evolve, becoming more complex and variable. Hence, research on methods for ensuring worker safety and minimizing potential hazards is essential when it comes to responding to the changes in industrial environments. The framework developed in this study can identify and assess the impacts of hazards resulting from interactions between tasks by synchronizing existing JSA information temporally and spatially. The R-JSA method was developed herein to systematically standardize unstructured data, such as task locations and hazard information. The results of the R-JSA method were used to develop the R-JSA synchronization model for task synchronization and hazard impact analysis. The S-RA formula was used to prioritize the results generated by the model based on the risk levels. The HIRAS framework was validated through two scenarios, demonstrating its utility for SIMOPS safety management.

The contributions of this study are summarized in the following three points. First, it proposes a new approach that extends the use of JSA beyond individual task safety management to include the safety management of surrounding tasks. This suggests that by leveraging the domain knowledge of task managers and synchronizing JSAs, hazards in surrounding tasks can be identified and assessed. Second, it enables safety managers to direct their focus toward preventive tasks. The visualization of target and source jobs and detailed lists helps reduce the cognitive burden of identifying hazards in complex and variable environments. Finally, by using easily accessible and regularly updated JSAs, it offers small workplaces with limited safety management personnel an effective way to enhance safety during SIMOPS. Major accidents can be prevented by improving safety in plant maintenance work environments wherein multiple tasks are performed simultaneously. Ultimately, the results of this study are expected to contribute to sustainable business management and the protection of worker lives and health in hazardous environments.

6.2. Limitations and Future Work

This study has two main limitations. First, it does not account for changes in TZ and HZ over time. The maximum range during task execution is considered for both the TZ and HZ. Adding a feature to specify time for selected parts of the maximum range could increase realism regarding zone changes during tasks. Standard times, such as mornings and afternoons, are recommended. Highly detailed units may not accommodate changes in task progress due to the work environment. Second, the quality of input data, the JSAs, has a decisive impact on the results. This limitation can be gradually addressed if employers and employees actively participate in systematically managing the data through digitization.

The HIRAS developed in this study represents a significant step forward, but further research is required to address its limitations and realize its full potential. Future research should focus on integrating HIRAS with existing enterprise systems, such as ERP and safety management systems, to facilitate its practical application in industrial settings.

Although this study focused on industrial plant maintenance, the results are applicable to other fields using JSA. We expect that future research based on this study on preventing SIMOPS accidents will contribute to improving safety levels in industrial sites and corporate sustainability management.

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Abbreviations

The following abbreviations and parameters are used in this paper:

ERP	Enterprise Resource Planning.
FMEA	Failure Modes and Effect Analysis.
GPT	Generative Pre-trained Transformer.
HAA	Hazard-Affected Area.
HAZOP	Hazard and Operability Studies.
HIRAS	Hazard Identification and Risk Assessment of Simultaneous operations.
HL	Hazard Layer.
HZ	Hazard Zone.
IMCA	The International Marine Contractors Association.
ISO	International Organization for Standardization.
JSA	Job Safety Analysis.
KOSHA	Korea Occupational Safety and Health Agency.
PoC	Proof of Concept.
R-JSA	Relation-oriented JSA method.
RPN	Risk Priority Number.
SIMOPS	SIMultaneous OPerations.
S-RA	SIMOPS Risk Assessment.
TBM	ToolBox Meeting.
TZ	Task Zone.

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