Eduvest – Journal of Universal Studies
Volume 6 Number 6, June, 2026
p- ISSN 2775-3735- e-ISSN 2775-3727

Systemic Modeling of Procedure Noncompliance and Safety Incidents in Chemical Manufacturing

Vivi Lailatul Rohmah*, A.A. BGS. Dinariyana Dwi Putranta, Adithya Sudiarno Institut
Teknologi Sepuluh Nopember, Indonesia
Email: vivilailatul29@gmail.com*, kojex@its.ac.id, adithya_sudiarno@ie.its.ac.id

Keywords:
Occupational Safety; Process Safety Management; RCA; HFACS; System Dynamics; Procedure Non-compliance

Abstract

This research analyzes the systemic causes of procedural non-compliance and safety incidents in the chemical manufacturing industry using an integrated approach combining Process Safety Management (PSM), Root Cause Analysis (RCA), the Human Factors Analysis and Classification System (HFACS), and System Dynamics. The PSM audit identified significant non-compliance within the Operating Procedures and Management of Change (MOC) elements, which were found to be the primary contributors to recurring incidents. RCA results indicate that technical and procedural deficiencies dominate the causal structure, while HFACS reveals that unsafe acts, inadequate supervision, and organizational influences substantially exacerbate procedural deviations. Qualitative findings from interviews, RCA, and HFACS were quantified through questionnaires, enabling statistical analysis of variables such as SOP compliance, training effectiveness, supervision quality, and safety culture. The System Dynamics model illustrates the causal interactions among training, supervision, risk perception, safety culture, SOP compliance, and incident frequency. Policy simulation results demonstrate that formal policy interventions are the most effective in suppressing incident escalation, technical interventions show limited standalone impact, and educational–behavioral interventions yield gradual improvements. The strongest risk reduction is achieved through multidimensional policy integration. Model validation using historical incident data shows close alignment between simulation trends and actual patterns, confirming model reliability. Thus, procedural non-compliance and safety incidents are driven by complex interactions among technical, human, and organizational factors, highlighting the need for integrated safety management strategies in high-risk industrial environments.

INTRODUCTION

The chemical industry is one of the high-risk sectors that requires special attention in the implementation of Occupational Safety and Health (OSH) (Achumie et al., 2022; Amrin & Purwojatmiko, 2025; Hollá et al., 2024; Kineber et al., 2023). These risks arise from the involvement of hazardous chemicals, which can cause fires, explosions, or exposure to toxic substances that affect workers' health. In addition, there is the potential for environmental pollution and injuries due to the use of machinery and heavy equipment. Therefore, the implementation of a good OSH system is very important to minimize these potential hazards (Anik et al., 2024). One of the most widely used approaches is ISO 45001:2018, which emphasizes risk-based management and the participation of all levels of the organization. However, implementation in the field still faces challenges in terms of consistency, safety culture, and worker involvement. Data from the Ministry of Manpower of the Republic of Indonesia recorded 462,241 work accidents throughout 2024, an increase of 5.7% compared to the previous year (Kemnaker Indonesia, 2024). This shows that the existing OSH management system is not yet fully effective in preventing incidents (De Merich et al., 2022; Johanes et al., 2023; Marhavilas et al., 2022; Musungwa & Kowe, 2022; Vitrano et al., 2023; Vitrano & Micheli, 2024).

To strengthen OSH systems in high-risk industries, *Process Safety Management* (PSM) is the recommended approach. PSM emphasizes the integration of technology, operational procedures, and management to prevent systemic major accidents. OSHA standards define 14 key elements, including process hazard analysis, change management, training, and worker involvement (OSHA, 2000). However, research shows that partial implementation of PSM is not effective. (Nwankwo et al., 2020) assert that major incidents are often caused by a weak safety culture and managerial leadership, while Ab Rahim et al. (2024) emphasize that PSM audits can identify systemic vulnerabilities that are not detected in conventional OSH audits. This study was conducted at a high-temperature textile chemical manufacturing company that is ISO 45001:2018 certified, but still experienced 22 incidents throughout 2024–2025, including chemical spills, forklift accidents, fires, and repeated procedural violations. This fact indicates a systemic problem that cannot be explained by just one cause- (González-Moles et al., 2022; Sturmberg & Marcum, 2024). Factors such as weak supervision, inadequate training, productivity pressure, a weak safety culture, poor monitoring, and a failure of cross-departmental communication contributed to the recurring incidents (Naumann et al., 2020; Park & Park, 2024). To identify the root causes of incidents, *Root Cause Analysis* (RCA) is used with *a fishbone diagram* that classifies causes into 6M categories (*Man, Machine, Method, Material, Environment, Management*). RCA has proven to be effective, but it is still general in nature and has not been able to explain the hierarchical interactions between individual behaviour, supporting conditions, supervision, and organizational influences. Therefore, this study complements RCA with *the Human Factors Analysis and Classification System* (HFACS), which outlines four levels of causes: *unsafe acts, preconditions, unsafe supervision*, and *organizational influences*. HFACS enables a systematic and in-depth analysis of human and organizational factors, as demonstrated by (Materna et al., 2023), who successfully reduced human-based errors by 20% through strengthened supervision and training.

Additionally, this study uses questionnaires to obtain quantitative data on risk perception, procedure compliance, and safety culture to reinforce the qualitative analysis results. As a complement, *System Dynamics* is used to describe the interactions between causal factors in the form of *feedback* loops. Previous studies have shown the effectiveness of this approach in mapping the complexity of safety systems (Naumann et al., 2020; Park & Park, 2024; Zhang et al., 2023). In this study, the *System Dynamics* model was built based on the results of PSM, RCA, and HFACS analyses. The variables modeled include the frequency and quality of OSH training, the effectiveness of supervision, risk perception, procedure compliance, incident frequency, workload, management support, and organizational safety culture. These variables are interconnected in dynamic loops; for example, increased training improves compliance, reduces incidents, strengthens safety culture, and ultimately improves risk perception. Thus, the urgency of using a combined approach of PSM, RCA, HFACS, and *System Dynamics* lies in its ability to provide comprehensive analysis from the micro level (worker actions), meso level (supervision), to the macro level (organizational culture and policies). The integration of these four approaches is expected to address the complexity of occupational safety issues in the chemical industry in a comprehensive and sustainable manner.

RESEARCH METHOD

This research was a mixed study with an exploratory case study approach that aims to systematically understand the causes of non-compliance with safety procedures and their relationship to work incidents in the chemical manufacturing industry. The approach was carried out in stages, starting with an audit to evaluate the implementation of the 14 elements *of Process Safety Management* (PSM) identified at the research site. This audit was used to identify elements that were not yet *compliant* and required further investigation. Next, analysis was conducted using the *Root Cause Analysis* (RCA) method to uncover the root causes in the *Process Hazard Analysis* (PHA) element, as well as *the Human Factors Analysis and Classification System* (HFACS) to examine human factors and organizational weaknesses. The results of the audit, RCA, and HFACS integration were used as the basis for systemic modelling using the *System Dynamics* approach, which was visualized in the form of *a Causal Loop Diagram* (CLD) and *Stock and Flow Diagram* (SFD). This modelling aimed to understand the patterns of cause-and-effect relationships and feedback between variables in the occupational safety system.

The applications used for modelling are Vensim PLE for CLD and Powersim Studio 10 for SFD and simulation, software that can be used for dynamic model development. *The outputs* of this study include: a map of *non-compliant* PSM elements, root cause findings and human factor classifications, and a dynamic model that illustrates how non-compliance with safety systems can contribute to work incidents. This model is expected to form the basis for recommendations for comprehensive safety system improvements.

Data Collection Techniques

To obtain comprehensive data, this study used several data collection techniques, as follows: Semi-Structured Interviews, conducted with 10 key informants selected *purposively*, including operators, supervisors, K3/QHSE personnel, managers, and emergency response officers. The interview guide was compiled based on the results of the PSM audit and the RCA and HFACS frameworks. The interviews lasted between 30 and 60 minutes and were recorded with the informants' consent.

The following are examples of interview questions per informant category:

Table 1. Interview question guide

Informant Category	Sample Questions
Operator	What challenges do you face in implementing safety procedures, and how do your coworkers react when safety procedures are violated, such as the use of PPE?
Shift Supervisor	What steps do you take when you discover a violation of standard operating procedures (SOP) in the work area, and how effective do you think supervision is in preventing accidents?
K3/QHSE Team	What are the most common findings from internal OSH audits over the past three years, and how effective do you think training is in changing worker behaviour?
Manager	What do you consider to be the most critical policy in preventing workplace incidents, and how do you balance productivity with compliance to SOPs?
Emergency Response Team	What challenges did the team face during the last emergency response simulation, and do you think the emergency training has been sufficiently effective? Why?

Source: Primary interview data, 2025

Document review was also performed by analyzing accident reports, internal and external audit results, SOPs, training records, and emergency response documentation to support interview data and identify patterns in PSM implementation, while field observation was conducted on a limited non-participatory basis to record work behavior, compliance with SOPs, and actual conditions of OSH implementation. A questionnaire was used to quantify qualitative data from interviews, RCA, and HFACS, distributed to workers across all work units to measure risk perception, procedure compliance, supervision effectiveness, and safety culture, serving as empirical validation before being entered into dynamic system modeling. System Dynamics modeling was then employed, where quantifiable data from audits, documents, interviews, and questionnaires such as number of violations, incidents, and effectiveness of training and SOPs were used as input in developing CLD and SFD models using applications like Vensim PLE and Powersim Studio 10 to simulate intervention scenarios for non-compliant PSM elements. Finally, triangulation and validation were performed to test data consistency through comparisons between sources (interviews, documents, observations), and expert validation was conducted by discussing the results of RCA, HFACS, and dynamic models with K3 personnel or work unit managers.

Data Analysis Techniques

Data analysis in this study was conducted through a combination of qualitative and quantitative approaches, beginning with an analysis of the audit results of 14 elements of Process Safety Management (PSM) based on document data and interviews to identify compliant and non-compliant elements, which formed the basis for determining the focus of further analysis. Qualitative analysis was then performed on interview data using thematic analysis with reference to the Root Cause Analysis (RCA) framework to identify root causes of PSM elements that were not effectively implemented, as well as the Human Factors Analysis and Classification System (HFACS) to classify the contribution of human and organizational factors to procedural non-compliance. Supporting documents such as accident reports, SOPs, internal audit results, and training data were reviewed to reinforce findings from interviews and audits, while quantitative analysis using questionnaires served to quantify qualitative data from interviews, RCA, and HFACS, with the results providing empirical validation before being incorporated into dynamic system modeling. Findings from audits, RCA, and HFACS were then used as the basis for developing a dynamic model using the System Dynamics approach, specifically in the form of Causal Loop Diagrams (CLD) and Stock and Flow Diagrams (SFD) to map interrelationships between safety system variables, with quantitative data such as violation frequency, incidents, and training participation used to build model parameters and simulations performed using Powersim Studio 10. Finally, validation was carried out through data triangulation and discussion of results with experts or internal company parties to ensure the accuracy of findings and interpretation of the model, with simulation results used to compile systemic recommendations for improving work safety.:

RESULT AND DISCUSSION

Process Safety Management (PSM) Audit

An internal audit of 14 PSM elements revealed significant non-compliance with *Operating Procedures* (OP) and *Management of Change* (MOC). These two elements are the root causes of recurring incidents. Several other elements such as *Training, Mechanical Integrity*, and *Hot Work Permit* also showed weaknesses, although not as significant as OP and MOC. These findings confirm that procedural and managerial weaknesses are dominant factors in the process safety system.

Table 2. Results of Internal Audit of 14 PSM Elements

No	PSM Element	Score (0-5)	Category	Priority	Audit results
1	*Employee Participation*	3	*Partial Compliance* (moderate)	No	Workers are involved in training/simulations, but only some are involved in audit activities and evaluations are not disseminated to all levels.
2	*Process Safety Information*	2	*Partial Compliance* (low)	Yes	Documentation is not centralized, access is difficult, no formal system in place
3	*Process Hazard Analysis (PHA)*	3	*Partial compliance* (moderate)	No	Management understands the contents of the PHA, but operators do not yet understand it, and QHSE has not ensured that all processes are included in the table.
4	*Operating Procedures*	1	*Not Comply*	Yes	SOP available, but repeated violations due to production target pressure, manual work (inputting bags into the reactor, standing for long periods) at risk of not being equipped with assistive devices
5	*Training*	2	*Partial compliance* (low)	Yes	*Gap* between documentation and practice.
6	*Contractors*	3	*Partial compliance* (moderate)	No	Induction conducted, verification exists, but supervision is only by Maintenance, no record of contractor violations
7	*Pre-startup Safety Review*	2	*Partial compliance* (low)	Yes	*Commissioning history is* not centralized and difficult to access.
8	*Mechanical Integrity*	2	*Partial compliance* (low)	Yes	*Gap* between documentation and practice, inconsistent follow-up on findings, risky manual work still being performed

9	*Hot Work Permit*	2	*Partial Compliance* (low)	Yes	Form exists, but supervision is minimal, does not involve QHSE
10	*Management of Change (MOC)*	1	*Not Comply*	Yes	Changes are submitted to the section and reported at management meetings, but there are no procedures to control the mechanism.
11	*Incident Investigation*	3	*Partial Compliance* (moderate)	No	The investigation was conducted, but the results were only reported to section level supervisors and above.
12	*Emergency Planning & Response*	3	*Partial Compliance* (moderate)	No	Simulations exist, but evaluation results are not disseminated, and worker understanding is not uniform
13	*Compliance Audits*	3	*Partial Compliance* (moderate)	No	Audits exist, but follow-up is inconsistent and dissemination is limited.
14	*Trade Secrets*	5	*Comply*	No	Access to information is restricted in accordance with policy, distribution controls are carried out in accordance with procedures

Source: Company internal audit data, processed by author, 2025

***Root Cause Analysis* (RCA)**

RCA analysis using *a fishbone diagram* identified the factors causing the incident in the 6M categories (*Man, Machine, Method, Material, (Mother Nature) Environment, Management*). The dominant factors were technical and procedural, such as poorly maintained equipment, inconsistent SOPs, and weak supervision.

1) *Operating Procedures* (OP) revealed that workers often did not follow SOPs consistently, documentation was not updated, and training was inadequate.

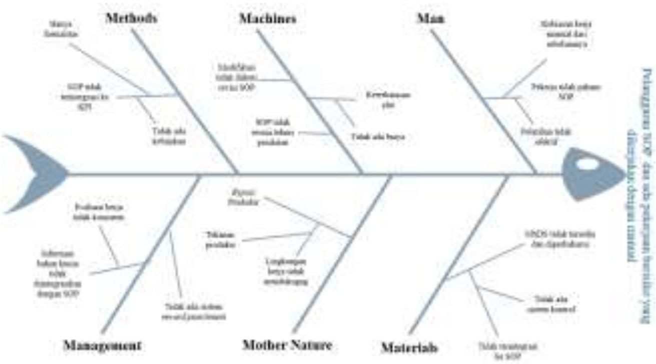


Diagram 1. Fishbone of an Operating Procedure (OP)
Source: Author's RCA analysis, 2025

2) *The Management of Change* (MOC) analysis showed *that* the main weaknesses were technical changes that were not followed by procedure revisions, lack of socialization, and weak supervision.

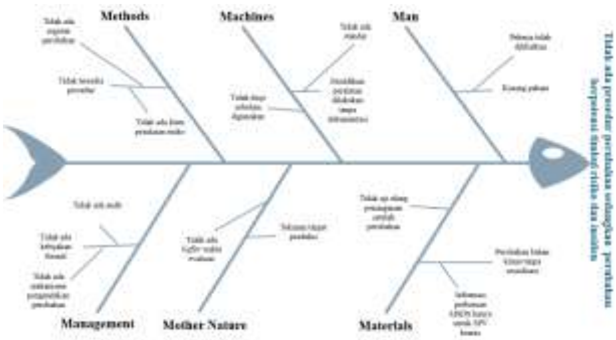


Diagram 2. Management of Change (MOC) Fishbone
Source: Author's RCA analysis, 2025

3) Other factors such as *Process Safety Information, Training, Pre-startup Safety Review, Mechanical Integrity,* and *Hot Work Permit* also show similar root causes, namely weak procedures, supervision, and cross-departmental communication.

The RCA analysis confirms that technical and procedural factors are the dominant causes of incidents, with a significant contribution from inconsistent management aspects.

***Human Factors Analysis and Classification System* (HFACS)**

An analysis using *the Human Factors Analysis and Classification System* (HFACS) was conducted to identify the contribution of human and organizational factors to procedural non-compliance and safety incidents. HFACS provides a systematic four-level framework of causes, namely *unsafe acts, preconditions for unsafe acts, unsafe supervision*, and *organizational influences*.

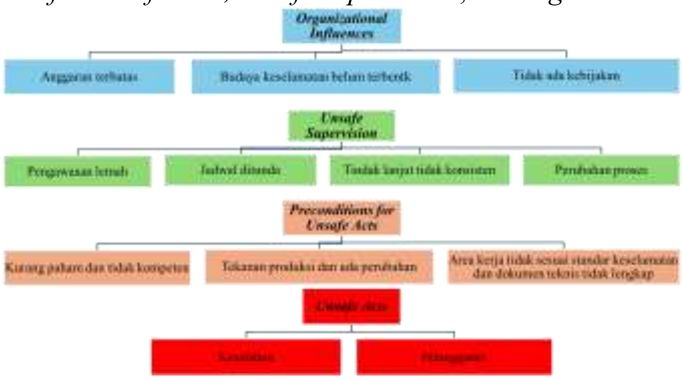


Diagram 3. HFACS Analysis Results
Source: Author's HFACS analysis, 2025

At the *unsafe acts* level, it was found that workers often violated SOPs, acted carelessly, and bypassed procedures in order to speed up their work. This indicates weak operational discipline and low risk perception at the individual level. *The preconditions for unsafe acts* level highlights supporting factors that influence unsafe behaviour, such as fatigue due to high workloads, productivity pressures, and inadequate training quality. Psychological conditions and a stressful work environment also increase the likelihood of procedure violations. The *unsafe supervision* level shows that direct supervision is inconsistent, there is a lack of follow-up on violations, and routine monitoring is weak. Ineffective supervision causes procedural deviations to not be corrected immediately and to be repeated in the long term. The level *of organizational influences* confirms that a strong safety culture has not yet been established within the company, policies are not consistently enforced, and cross- part mental communication remains weak. These organizational factors exacerbate procedural non-compliance and increase the risk of recurring incidents. The HFACS analysis shows a pattern consistent with the RCA findings, namely that non-compliance with procedures is not only caused by technical factors, but is also the result of systemic interactions between individual behaviour, supporting conditions, weaknesses in supervision, and organizational influences. Thus, improving the safety system requires interventions that target all four levels of HFACS in an integrated manner.

Questionnaire

Analysis using *the Human Factors Analysis and Classification System* (HFACS)

The questionnaire was used to quantify qualitative data obtained from interviews, RCA, and HFACS. The questionnaire instrument was designed to measure key variables related to safety procedure compliance, training effectiveness, supervision quality, risk perception, and organizational safety culture.

The results of the questionnaire score distribution are shown in the variable score distribution table, which shows that the level of compliance with SOPs is still low. Most respondents assessed that training was not yet optimal, both in terms of frequency and quality of material. Direct supervision is also considered weak, with inconsistent monitoring and a lack of follow-up on violations. In addition, a strong organizational safety culture has not yet been established, as evidenced by the low level of management commitment to consistently enforcing safety policies.

Table 3. Distribution of Variable Scores

Variable	*Mean*	*Median*	*Std. Deviation*	*Min*	*Max*	Normalization (0–1)
SOP Compliance	4.3	4.25	0.46	3.5	5.00	0.83
Production Pressure	3.82	4.00	0.75	1.67	5.00	0.70
Unsafe Acts	4.19	4.00	0.53	3.0	5.00	0.80
Change Management (MOC)	3.98	4.0	0.48	3.0	5.0	0.75
Work Permit (Hot Work Permit)	4.01	4.00	0.53	3	5.0	0.75
Safety Supervision	3.86	4.0	0.64	2.0	5.00	0.71
High-risk jobs	3.94	4.00	0.59	2.25	5.00	0.74
Follow-up on Findings	3.85	4.00	0.65	2.67	5.0	0.71
Equipment Maintenance/Repair (MI)	3.69	3.75	0.58	2.5	5.0	0.67
Training	3.86	4.00	0.52	2.75	5.00	0.72
MSDS / *Process Safety Info*	3.81	4.00	0.84	1.00	5.00	0.70
Commissioning (PSSR)	3.66	3.75	0.61	2.75	5.0	0.67

Source: Primary questionnaire data, processed using SPSS, 2025

Analysis per variable shows a relationship between workers' risk perception and their level of procedural compliance. Workers with low-risk perception tend to violate SOPs more often, while workers with high-risk perception show better compliance. This confirms the importance of interventions that focus on increasing risk perception through training and safety culture campaigns. Triangulation of questionnaire results with RCA and HFACS reinforces the finding that human and organizational factors contribute significantly to recurring incidents. The questionnaire provides quantitative evidence consistent with qualitative analysis, thereby strengthening the validity of the research results.

***System Dynamics* Analysis**

***System Dynamics* Model Structure**

System Dynamics Analysis is conducted to map the causal relationships between variables identified through PSM, RCA, HFACS audits, as well as questionnaire and regression results. This approach is used to describe systemic interactions in the form of *causal loop diagrams* (CLD) and *stock–flow diagrams* (SFD), so that dominant patterns and *leverage points* can be comprehensively identified.

Variable Identification

The occupational safety system dynamics model is constructed by integrating the results of questionnaires, SPSS regression, and RCA/HFACS findings. Variables in the model are classified into *stock, flow,* and *auxiliary,* so that causal relationships can be visualized consistently in CLD and SFD:

1) *Stock*: cumulative variables that represent conditions or states that persist in the system.
2) *Flow*: rate variables that influence changes in stock over time.
3) *Auxiliary*: auxiliary variables that explain causal relationships or serve as non-accumulative indicators needed to form dynamic *loops*.

Table 4. System Dynamics Model Variables

Variable	Type	Description
Incidence	*Stock*	The number of safety incidents that occur within a certain period, serving as the main indicator of the system's impact.
Work permit	*Stock*	The accumulation of permits issued for risky work, serving as an administrative mechanism that influences unsafe acts.
Addition of Risky Permits	*Flow*	The administrative process that increases the number of works permits due to high-risk work.
Incident Frequency	*Flow*	The flow of incident occurrences per unit of time, which affects the accumulation of incidents and the average number of incidents per year.
SOP Compliance	*Auxiliary*	The main controller of *unsafe acts*, significant in regression ($\beta = 0.738$, $p < 0.001$).
Training	*Auxiliary*	Reinforces SOP compliance, plays a role in the balancing loop despite a moderate regression effect ($\beta = 0.197$, $p = 0.139$).
MSDS	*Auxiliary*	Significant administrative control over incidents ($\beta = 1.709$, $p = 0.047$) and work permits.
Hazardous Work	*Auxiliary*	The primary trigger for work permits, significant in regression ($\beta = 0.615$, $p < 0.001$).
Permit Coefficient	*Auxiliary*	Administrative parameters that regulate the rate of work permits.
Production Pressure	*Auxiliary*	Disturbing factors that increase unsafe acts, forming a reinforcement loop.
Safety Supervision	*Auxiliary*	Operational control, relevant in RCA/HFACS even though not significant in regression.
Commissioning	*Auxiliary*	Technical variables with low scores, consistent with PSSR audit
Equipment Maintenance/Repair	*Auxiliary*	Technical variables that affect system reliability.
Change Management (MOC)	*Auxiliary*	Managerial variables that affect the system's readiness for change.
Average Incidents per Year	*Auxiliary*	Long-term trend indicator, derived from incident *stock* and incident frequency *flow*.

Source: Variable identification from system dynamics modeling, 2025

***Causal Loop Diagram* (CLD)**

The following *Causal Loop Diagram* (CLD) illustrates the causal and feedback relationships between variables that influence incident frequency in chemical manufacturing environments. This diagram consists of five reinforcing loops (R1–R5) and one *balancing* loop (B1), which systematically explain the dynamics of procedural noncompliance and safety incidents.

***Reinforcing Loop* (R)**

These *loops* reinforce changes in the same direction, potentially leading to increased risk if not controlled:

1) R1: High production pressure encourages work acceleration, which can potentially reduce compliance with SOPs. This non-compliance increases *unsafe acts* and incident frequency. If follow-up is not accompanied by SOP reinforcement, production pressure remains dominant and this *loop* reinforces the incident cycle.
2) R2: Incidents drive increased monitoring. Consistent monitoring improves SOP compliance, suppresses *unsafe acts*, and reduces incidents. If monitoring weakens, this *loop* reinforces incidents.
3) R3: Incidents trigger increased training. Effective training strengthens SOP compliance, reduces *unsafe acts*, and suppresses incidents. This *loop* demonstrates the importance of continuous training.

4) R4: Incidents drive equipment maintenance. Good maintenance reduces technical risks, reduces *unsafe acts*, and suppresses incidents. This *loop* reinforces operational stability.
5) R5: Incidents resulting from process changes drive the strengthening of MOC and *commissioning*. Effective change mechanisms ensure that SOPs are updated, reduce risky work, and reduce *unsafe acts*.

***Balancing Loop* (B)**
This *loop* stabilizes the system and reduces risk:
1) B1**:** An increase in risky work drives the issuance of work permits. The more permits, the stronger the administrative control over risky work. This loop functions as a balancing mechanism to prevent risk escalation.

The CLD structure shows that incident frequency is the result of complex interactions between technical factors (maintenance, *commissioning*), human factors (training, *unsafe acts*), organizational factors (MOC, supervision), and administrative factors (work permits, MSDS). *The* reinforcing *loops* (R1–R5) explain how system weaknesses can amplify risk, while *the* balancing *loop* (B1) shows that there are administrative control mechanisms that can prevent escalation.

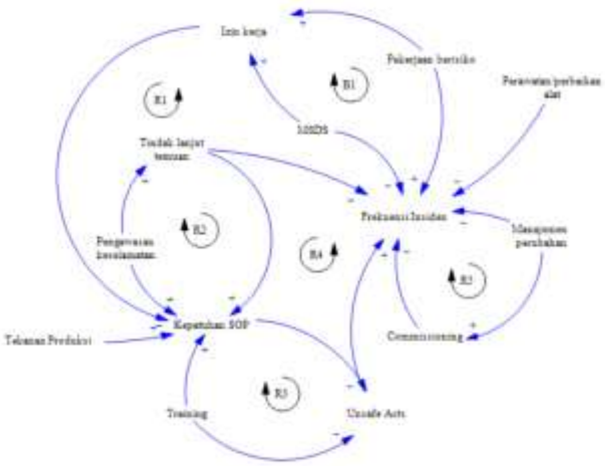


Diagram 4. Causal Loop (CLD)
Source: System dynamics modeling using Vensim PLE, 2025

Stock and Flow Diagram
The Stock and Flow Diagram (SFD) was developed using **Powersim** software to model the dynamics of procedural non-compliance and safety incidents in chemical manufacturing. This model consists of two stocks (*Total Incidents* and *Work Permits*), a number of *flows*, and *auxiliary variables* that influence the rate of change.

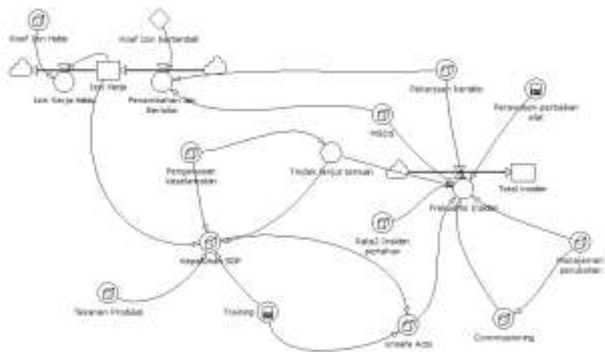


Diagram 5. Stock and Flow (SFD)
Source: System dynamics modeling using Powersim Studio 10, 2025

Stock

1) Incidents

Represents the accumulation of incidents over time. Increases through *the* Incident Frequency *flow.*

2) Work Permits

Stores the number of active risky work permits. Increases through *the* Add Risky Permit *flow* and decreases through Permit Closure.

Flow

1) Incident Frequency

The rate of events that increase the incident stock.

2) Addition of Risky Permits

The rate of work permit issuance that increases the work permit inventory.

Auxiliary* and *Connector

In the *Stock and Flow Diagram* model, *auxiliary* and *connector* variables function as controllers that modulate the rate of change in *the* main *flow*. SOP compliance is a central variable that suppresses *unsafe acts*, while training plays a role in strengthening compliance by improving workers' understanding of safety procedures. Conversely, production pressure actually encourages *unsafe acts* because workers are driven to ignore procedures in order to meet output targets. Safety supervision acts as a corrective mechanism, as consistent supervision can reduce *unsafe acts* and lower the frequency of incidents.

From a technical perspective, equipment maintenance and repair (*Mechanical Integrity*) contribute to reducing the risk of equipment failure that could trigger incidents, while weak *commissioning (Pre-startup Safety Review)* increases risky work- s and heightens the likelihood of *unsafe acts*. At the managerial level, change management (MOC) ensures that any changes to processes or equipment are properly controlled so as not to increase the risk burden. In addition, administrative factors such as work permits and MSDS serve as formal control mechanisms. An increase in risky work will trigger an increase in work permits, but a larger stock of permits will increase the permit coefficient, which will then slow down the issuance of new permits as a form of balancing loop. Finally, follow-up on findings plays a role in reducing the frequency of incidents when implemented effectively, as each finding that is followed up strengthens the overall risk control system.

With this structure, SFD is able to visualize how safety incidents are the result of complex interactions between technical, human, managerial, and administrative factors. The model shows that there are five reinforcing *loops* (R1–R5) that can increase risk if not controlled, as well as one balancing *loop* (B1) that serves to restrain the escalation of risky work through the work permit mechanism. This structure forms the basis for *baseline* simulations and policy interventions in the next stage.

Model Verification

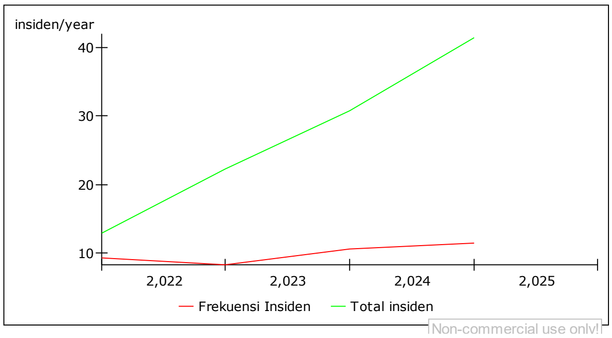
The verification stage was conducted to ensure that the dynamic system model that had been constructed was structurally correct and could represent real conditions in the field. Verification focused on the internal consistency of the model. Verification was carried out to ensure that the model had been designed in accordance with the rules of dynamic system modeling. Checks were carried out on the model structure, unit consistency, and the basic behavior *of stocks* and *flows*. The verification results show that the relationships between variables are consistent with *the Causal Loop Diagram* (CLD) and *Stock and Flow Diagram* (SFD), each equation has unit consistency, and stock behavior follows a logical flow direction. Thus, the model is declared to have met structural and dimensional consistency and is ready to proceed to the *baseline* simulation stage.

***Baseline* Simulation**

Baseline simulation was conducted to obtain an overview of the basic behavior of the occupational safety system without additional policy interventions. This *baseline* serves as a reference for assessing the validity of the model and as a comparison for the intervention scenarios that will be implemented in the next stage. The purpose of the *baseline* simulation is to show the dynamics of incident accumulation and risky work permits based on the model structure that has been built, identify patterns of annual incident trends and risky work permits under normal conditions (without additional policies), and provide simulation data that will be used in model validation tests against actual data. The simulation period is set for four years (2022–2025) to align with the company's incident data.

Baseline Simulation Analysis

1) The annual incident frequency shows a fluctuating pattern, with a value of 9.35 incidents/year in 2022, decreasing to 8.38 incidents/year in 2023, then increasing again to 10.66 incidents/year in 2024, and reaching 11.46 incidents/year in 2025. This pattern reflects the influence of internal factors such as production pressure, weak *commissioning*, and unstable SOP compliance that has not been fully controlled.
2) The cumulative total incidents show a consistent upward trend, namely 13 incidents in 2022, 22.35 incidents in 2023, 30.73 incidents in 2024, and 41.39 incidents in 2025. This confirms that incidents are cumulative and will continue to increase if there is no systemic intervention capable of slowing down the rate of *unsafe acts* and risky work. In other words, the total number of incidents will continue to rise, but with the right intervention, the increase can be controlled so that it is not extreme.



Graph 6. Baseline Simulation
Source: Baseline simulation using Powersim Studio 10, 2025

Overall, the *baseline* simulation shows that the safety system in actual conditions is still dominated by *reinforcing loops* that encourage an increase in incidents, while *balancing loops* through work permit mechanisms are not yet strong enough to prevent risk escalation. This *baseline* serves as a basis for comparing the effectiveness of various policy intervention scenarios that will be simulated in the next stage, with the main indicator being a slowdown in the rate of increase in incidents compared to *the baseline*.

Model Validation

Validation is carried out to ensure that the model that has been verified and tested in the *baseline* simulation is in accordance with empirical conditions. Validation is carried out by comparing the simulation results with actual data and statistical tests using *the Welch Confidence Interval* (WCI). The purpose of validation is to assess the suitability of the model structure with theory and audit results, compare the *baseline* simulation pattern with historical incident data, and statistically test whether there are significant differences between the simulation results and actual data.

Table 5. Validation Model

Year	Actual Data	Simulation Model
2022	9.0	13.00
2023	19.00	22.35
2024	28.00	30.73
2025	42.00	41.39
Average	10.50	9.19
ST	14.01	12.09
N	4	4
N-1	3	3

Source: Secondary company data and baseline simulation results, 2025

The WCI test is used to assess whether there is a significant difference between the actual data average and the simulation results.
WCI formula:

$$Df = \frac{\left(\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}\right)^2}{\left[\left(\frac{S_1^2}{n_1}\right)^2 / (n_1 - 1) + \left(\frac{S_2^2}{n_2}\right)^2 / (n_2 - 1)\right]}$$

$$hw = t_{df, \alpha/2} \sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}$$

$$P[(\bar{x}_1 - \bar{x}_2) - hw \leq \mu_1 - \mu_2 \leq (\bar{x}_1 - \bar{x}_2) + hw]$$

Calculation results:
1) Actual data average: 10.50
2) Simulation average: 9.19
3) Standard deviation of actual data: 14.01
4) Simulation standard deviation: 12.09
5) Table t-value ($\alpha = 0.05$): 2.1788
6) Confidence interval: [−18.8542; 21.4692]
7) Since the value 0 is within the confidence interval range, the null hypothesis (Ho: no difference) is accepted.

Based on the results of the Welch Confidence Interval test, there is no significant difference between the actual data and the *baseline* simulation results. Thus, the model is statistically valid and suitable for use in safety policy simulations in the next stage.

Intervention Simulation

Intervention simulations were conducted to evaluate the effectiveness of various occupational safety policies in reducing the frequency of incidents and controlling risky work permits. The interventions were implemented after the model was declared structurally and statistically valid. Each scenario was modelled with parameter changes or the addition of control variables, then compared with *the baseline* simulation results.

1) Scenario 1: Addition of OSH Policy Variables

The first scenario models systemic intervention through the addition of OSH Policy variables as reinforcements to the occupational safety control structure. These variables are included in the model as *auxiliary* elements that serve to strengthen *the balancing loop* in *the causal loop diagram*, enabling the system to respond more quickly to potential risks and operational violations. OHS policies in this scenario include strengthening the SOP compliance audit mechanism, implementing a safety-based *reward-punishment* system, and mandatory periodic retraining. With these policies in place, the control structure becomes more adaptive to *unsafe acts* and risky work.

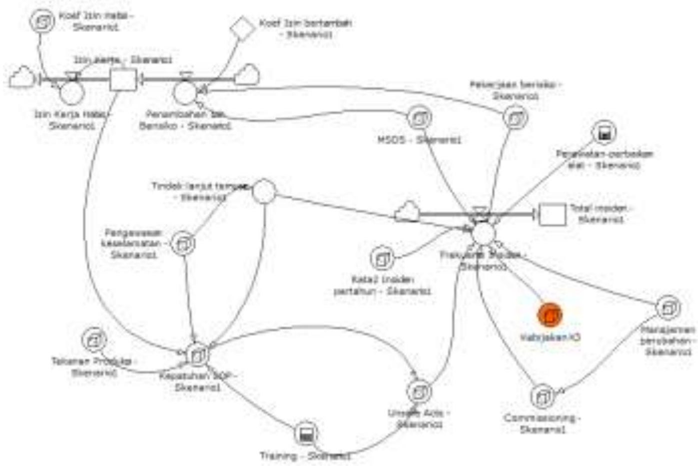


Figure 7. Scenario 1
Source: Scenario 1 modeling using Powersim Studio 10, 2025

The simulation was conducted for the period 2022–2025 and compared with *the baseline*.

Table 6. Simulation Results for Scenario 1: OHS Policy

Year	Total Incidents – *Baseline*	Total Incidents – Scenario 1
2022	13	13
2023	27.07	27.37
2024	36.68	34.25
2025	45.35	41.14

Source: Powersim Studio 10 simulation results, 2025

The simulation results show that the total incidence remains cumulative and the graph increases from year to year. However, compared to *the baseline*, the rate of increase in incidents in scenario 1 is more controlled. This can be seen in 2024 and 2025, where the total incidents in scenario 1 are lower than *the baseline* (34.25 vs. 36.68 in 2024; 41.14 vs. 45.35 in 2025).

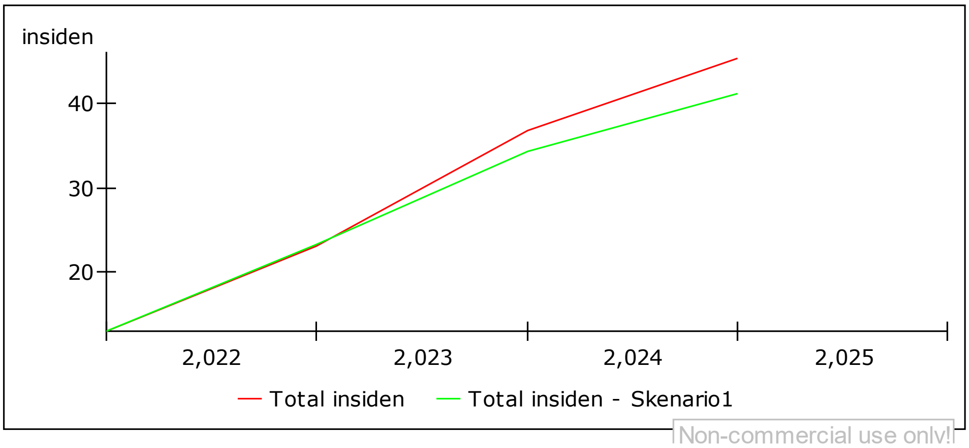


Figure 8. Simulation graph for Scenario 1
Source: Scenario 1 simulation using Powersim Studio 10, 2025

Thus, the addition of the OSH Policy variable does not eliminate incidents, but slows down the rate of incident growth so that the cumulative trend is flatter. This intervention strengthens the control structure and improves the system's response to potential risks. Therefore, this scenario is worth considering as a formal policy in a dynamic system-based occupational safety system.

2) Scenario 2: 50% Reduction in Manual Risky Work

The second scenario models technical intervention through a 50% reduction in manual hazardous work. This variable is included in the model to strengthen the *balancing loop* by reducing workers' direct exposure to hazardous activities. The reduction of risky manual work in this scenario includes the automation of chemical lifting processes, the use of mechanical equipment for heavy work, and the application of sensor systems on forklifts and production machines. With the reduction of risky manual activities, the safety system is expected to be more controllable because the main sources of risk can be minimized.

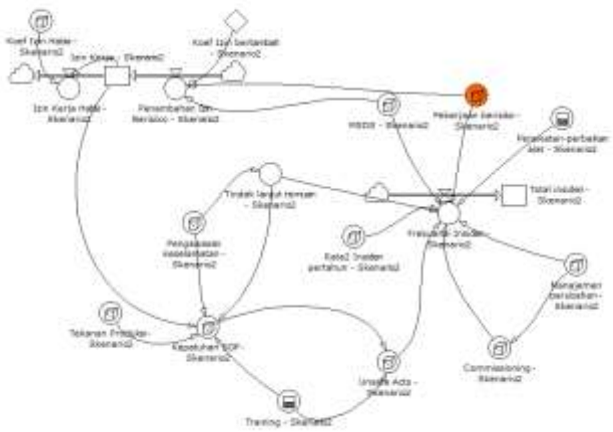


Figure 9. 2 seconds
Source: Scenario 2 modeling using Powersim Studio 10, 2025

Table 7. Simulation Results for Scenario 2

Year	Total Incidents (*Baseline*)	Total Incidents – Scenario 2
2022	13	13
2023	27.03	22.88
2024	39.67	33.90
2025	49.87	46.55

Source: Powersim Studio 10 simulation results, 2025

The simulation results show that the total number of incidents remains cumulative and the graph increases from year to year. However, compared to *the baseline*, the rate of increase in incidents in scenario 2 is more controlled. This can be seen in 2023 to 2025, where the total incidence in scenario 2 is lower than *the baseline* (26.41 vs. 27.07 in 2023; 33.72 vs. 36.68 in 2024; 39.86 vs. 45.35 in 2025).

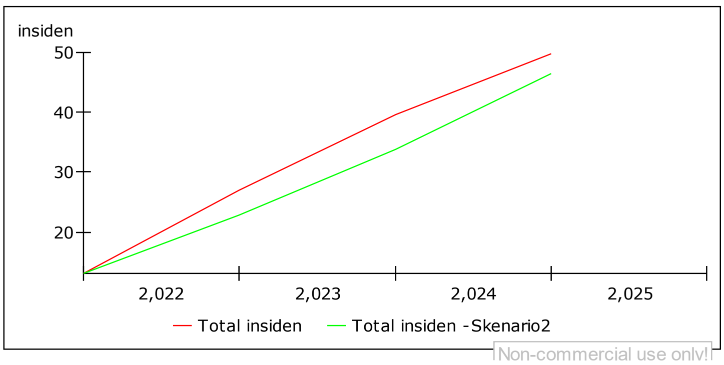


Figure 10. Simulation graph of Scenario 2
Source: Scenario 2 simulation using Powersim Studio 10, 2025

Thus, a 50% reduction in risky manual work does not eliminate incidents, but slows down the rate of incident growth so that the cumulative trend is flatter. This intervention shows that a technical approach that directly targets the source of risk can be a quick and high-impact strategy in occupational safety systems. Therefore, this scenario is worth considering as a priority technical policy in operational risk control.

3) Scenario 3: 50% Reduction in Manual Risky Work and *Unsafe Acts*, Training Increased to 100%

The third scenario models a combined intervention targeting technical and behavioural factors. The variables included are a 50% reduction in risky manual work, a 50% reduction in *unsafe acts*, and an increase in safety training to cover 100% of workers. This intervention includes the implementation of automation systems for hazardous manual work, strict monitoring of unsafe behaviour in the field, and comprehensive safety training for all workers. Training includes the use of personal protective equipment, emergency simulations, and periodic SOP *refreshers*.

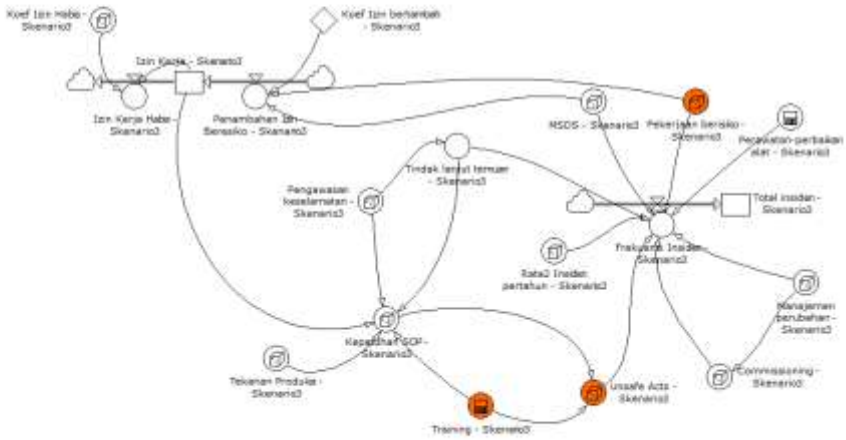


Figure 11. seconds for Scenario 3

Source: Scenario 3 modeling using Powersim Studio 10, 2025

The simulation was conducted for the 2022–2025 period and compared with *the baseline*.

Table 8. Simulation Results for Scenario 3

Year	Total Incidents (*Baseline*)	Total Incidents – Scenario 3
2022	13	13
2023	26.26	22.75
2024	35.71	34.09
2025	44.02	42.49

Source: Powersim Studio 10 simulation results, 2025

The simulation results show that the total incidence remains cumulative and the graph increases from year to year. However, compared to *the baseline*, the rate of increase in incidence in scenario 3 is more controlled. The effects of the intervention begin to appear in the second year, where the total incidence is lower than the baseline (25.92 vs. 27.07 in 2023; 32.84 vs. 36.68 in 2024; 38.41 vs. 45.35 in 2025).

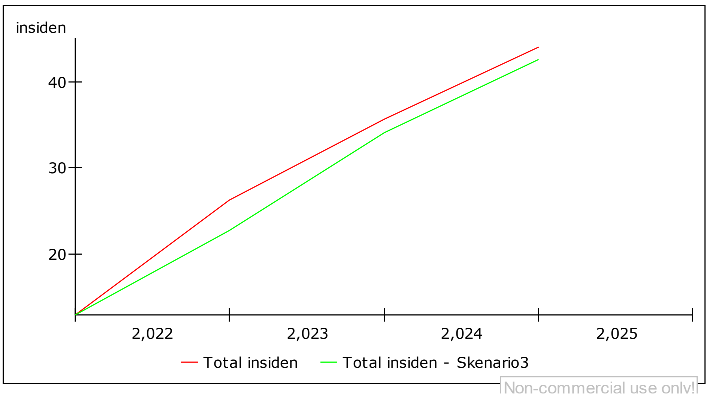


Figure 12. Simulation graph for Scenario 3
Source: Scenario 3 simulation using Powersim Studio 10, 2025

Thus, the combination of reducing risky manual work, controlling *unsafe acts*, and 100% training does not eliminate incidents, but slows the rate of incident growth gradually and consistently. These educational and behavioral interventions take time to show an impact, but provide more stable and systemic results than single interventions.

4) Scenario 4: Combination of the three scenarios

The fourth scenario models a combined intervention of all previously tested variables, namely the addition of OSH policies, a 50% reduction in risky manual work, a 50% control of *unsafe acts*, and 100% safety training coverage. This intervention is designed to strengthen the overall control structure, in terms of policy, technical aspects, and behavior.

This combined intervention includes the implementation of periodic SOP compliance audits, automation of hazardous manual work, strict supervision of unsafe acts, and comprehensive safety training for all workers. With this combination, the safety system is expected to be more stable because each risk factor is addressed simultaneously.

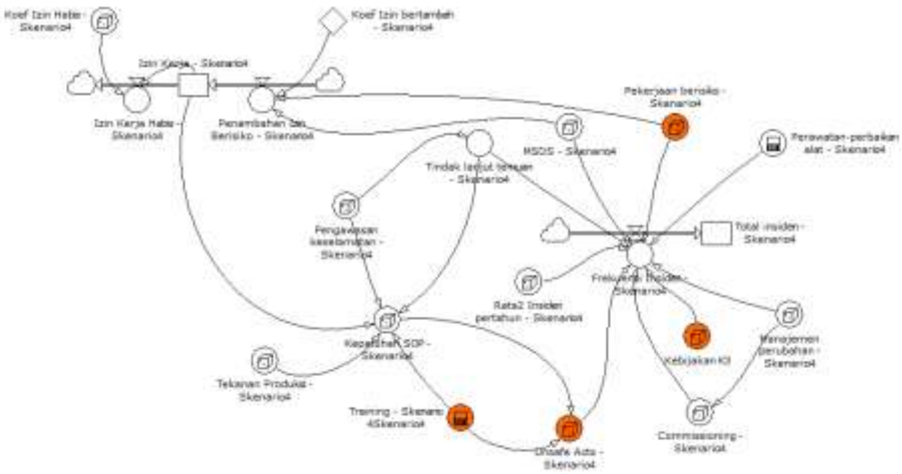


Figure 13. 4 seconds
Source: Scenario 4 modeling using Powersim Studio 10, 2025

Table 9. Simulation Results for Scenario 4

Year	Total Incidents (*Baseline*)	Total Incidents – Scenario 4
2022	13	13
2023	23.65	20.45
2024	32.25	29.04
2025	43.69	37.08

Source: Powersim Studio 10 simulation results, 2025

The simulation results show that the total number of incidents remains cumulative and the graph increases from year to year. However, compared to the baseline, the rate of increase in incidents in scenario 4 is the most controlled. This can be seen in 2023 to 2025, where the total incidence in scenario 4 is lower than *the baseline* (25.41 vs. 27.07 in 2023; 31.92 vs. 36.68 in 2024; 36.12 vs. 45.35 in 2025).

Figure 14. Simulation graph for scenario 4
Source: Scenario 4 simulation using Powersim Studio 10, 2025

Thus, the combination of all interventions did not eliminate incidents, but slowed the rate of incident growth most significantly compared to other scenarios. This combined intervention shows that a comprehensive approach involving policy, technical, and behavioral measures provides more optimal results in controlling occupational safety risks. Therefore, this scenario should be considered as the main strategy in a dynamic system-based occupational safety system.

Comparison of Effectiveness Between Scenarios

A comparison of simulation results between scenarios shows that all interventions have an impact on the rate of increase in incidents, although the graph still shows a cumulative upward trend from year to year. The effectiveness of the intervention can be seen from the flatter curve and the consistency of the slowdown compared to *the baseline*.

Table 10. Summary of Simulation Results Between Scenarios

Year	*Baseline*	Scenario 1	Scenario 2	Scenario 3	Scenario 4
2022	13.00	13.00	13.00	13.00	13.00
2023	26.31	25.40	25.75	23.62	20.99
2024	36.72	32.32	38.14	34.21	30.30
2025	46.69	42.85	48.94	43.45	39.42

Source: Powersim Studio 10 simulation results, 2025

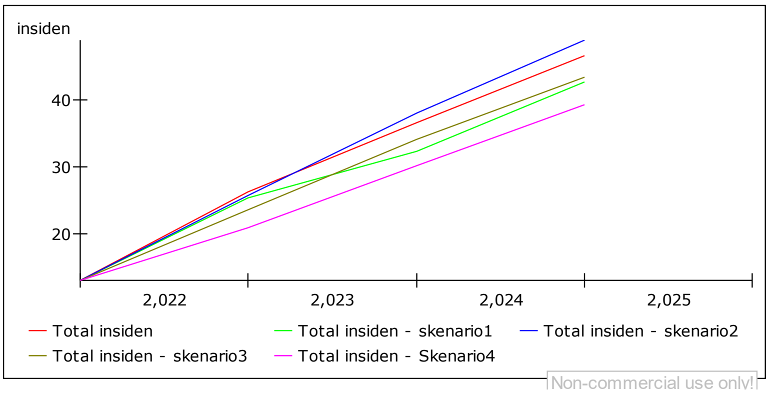


Figure 15. Comparison Chart of Effectiveness Between Scenarios
Source: Compilation of simulation data, 2025

Comparative Analysis

1) Scenario 1 (K3 Policy): Most significant compared to scenarios 2 and 3 because it directly addresses the root cause of the problem through policy strengthening, compliance audits, and the implementation *of rewards and punishments*. This formal policy strengthens the control structure so that the system is more responsive to unsafe acts and risky work.
2) Scenario 2 (50% Reduction in Manual Risky Work): Effective on the technical side by reducing direct risk exposure through automation of heavy work, use of mechanical tools, and safety sensors. However, this intervention does not strengthen compliance and supervision aspects, so its impact is relatively limited compared to formal policies.
3) Scenario 3 (100% Training, *Unsafe Acts* −50%, Risky Work −50%): Provides a gradual and stable reduction through educational and behavioral interventions. Comprehensive training improves worker competence, while controlling *unsafe acts* suppresses risky behavior. However, the effect is not as strong as formal policies because it takes longer to show consistent results.
4) Scenario 4 (Combination of All Interventions): Most significant overall because it combines policy, technical, and behavioral interventions. The synergistic effect of the combination of interventions results in simultaneous suppression of all critical causal pathways, so that the rate of increase in incidents is the most controlled compared to other scenarios.

Scenario 1 is the most significant intervention compared to scenarios 2 and 3. Scenario 4 is the most effective overall because it integrates OSH policies with technical and behavioral interventions, thereby providing a systemic and sustainable impact on incident reduction.

CONCLUSION

This study aimed to analyze the systemic causes of procedural non-compliance and safety incidents in the chemical manufacturing industry using an integrative approach between Process Safety Management (PSM), Root Cause Analysis (RCA), Human Factors Analysis and Classification System (HFACS), and System Dynamics. The PSM audit revealed that most elements were in the Partial Comply category, with Operating Procedures and Management of Change (MOC) in Not Comply status, confirming fundamental gaps in the process safety system. RCA through fishbone analysis identified dominant root causes from technical and procedural factors, including inconsistent SOP implementation, unintegrated documentation, suboptimal maintenance, and uncontrolled change mechanisms, while HFACS confirmed that unsafe acts are rooted in preconditions, unsafe supervision, and organizational influences. The System Dynamics model successfully mapped causal relationships and, through policy simulations, demonstrated that formal policy interventions most significantly slow the rate of incident increase, technical interventions have a limited but rapid impact, educational and behavioral interventions result in gradual and stable decline, and multi-dimensional combinations provide the strongest synergistic effect. Model validation with actual data from the 2022–2025 period showed acceptable error rates, confirming the model's reliability. Overall, this study confirms that non-compliance and safety incidents result from systemic interactions between technical, human, and organizational factors, requiring multidimensional policies rather than partial solutions, and the developed dynamic system model provides a comprehensive and sustainable basis for strengthening occupational safety management in high-risk industries. This study aimed to analyze the systemic causes of procedural non-compliance and safety incidents in the chemical manufacturing industry using an integrative approach between Process Safety Management (PSM), Root Cause Analysis (RCA), Human Factors Analysis and Classification System (HFACS), and System Dynamics. The PSM audit revealed that most elements were in the Partial Comply category, with Operating Procedures and Management of Change (MOC) in Not Comply status, confirming fundamental gaps in the process safety system. RCA through fishbone analysis identified dominant root causes from technical and procedural factors, including inconsistent SOP implementation, unintegrated documentation, suboptimal maintenance, and uncontrolled change mechanisms, while HFACS confirmed that unsafe

acts are rooted in preconditions, unsafe supervision, and organizational influences. The System Dynamics model successfully mapped causal relationships and, through policy simulations, demonstrated that formal policy interventions most significantly slow the rate of incident increase, technical interventions have a limited but rapid impact, educational and behavioral interventions result in gradual and stable decline, and multi-dimensional combinations provide the strongest synergistic effect. Model validation with actual data from the 2022–2025 period showed acceptable error rates, confirming the model's reliability. Thus, this study confirms that non-compliance and safety incidents result from systemic interactions between technical, human, and organizational factors, requiring multidimensional policies rather than partial solutions, and the developed dynamic system model provides a comprehensive and sustainable basis for strengthening occupational safety management in high-risk industries. Companies need to strengthen the implementation of *Operating Procedures* (OP) and *Management of Change* (MOC) by ensuring that every technical and procedural change is always followed by document revisions, socialization, and consistent supervision. Training programs must be improved in terms of both frequency and quality, with a focus on increasing risk perception and establishing a strong safety culture. Direct supervision also needs to be improved through routine monitoring, follow-up on violations, and providing clear feedback to workers. Management must consistently enforce safety policies and build an organizational culture that places safety as a top priority. From an academic perspective, further research is recommended to develop a more comprehensive System Dynamics model by incorporating additional variables, such as economic factors, external policies, and the psychosocial aspects of workers, in order to provide a broader picture of occupational safety dynamics in the industry. In addition, comparative studies between industrial sectors can be conducted to test the generalization of the model and strengthen academic contributions to the development of occupational safety theory. With the implementation of these practical and academic recommendations, it is hoped that the frequency of incidents can be significantly reduced while enriching the academic literature in the field of occupational safety.

REFERENCES

Ab Rahim, M. S., Reniers, G., Yang, M., & Bajpai, S. (2024). Risk assessment methods for process safety, process security and resilience in the chemical process industry: A thorough literature review. *Journal of Loss Prevention in the Process Industries, 88*, Article 105274. https://doi.org/10.1016/j.jlp.2024.105274

Achumie, G. O., Oyegbade, I. K., Igwe, A. N., Ofodile, O. C., & Azubuike, C. (2022). A conceptual model for reducing occupational exposure risks in high-risk manufacturing and petrochemical industries through industrial hygiene practices. *Industrial Hygiene and Safety Journal*.

Amrin, & Purwojatmiko, B. H. (2025). Balancing growth and safety: Rethinking occupational health and safety management in Indonesia's chemical industry. *E3S Web of Conferences, 681*, Article 05001.

Anik, A. H., Toha, M., & Tareq, S. M. (2024). Occupational chemical safety and management: A case study to identify best practices for sustainable advancement of Bangladesh. *Hygiene and Environmental Health Advances, 12*, Article 100110.

De Merich, D., Gnoni, M. G., Guglielmi, A., Micheli, G. J., Sala, G., Tornese, F., & Vitrano, G. (2022). Designing national systems to support the analysis and prevention of occupational fatal injuries: Evidence from Italy. *Safety Science, 147*, Article 105615. https://doi.org/10.1016/j.ssci.2021.105615

González-Moles, M. Á., Aguilar-Ruiz, M., & Ramos-García, P. (2022). Challenges in the early diagnosis of oral cancer, evidence gaps and strategies for improvement: A scoping review of systematic reviews. *Cancers, 14*(19), 4967. https://doi.org/10.3390/cancers14194967

Hollá, K., Kuricová, A., Kočkár, S., Prievozník, P., & Dostál, F. (2024). Risk assessment industry driven approach in occupational health and safety. *Frontiers in Public Health, 12*, Article 1381879. https://doi.org/10.3389/fpubh.2024.1381879

Johanes, M., Mark, M., & Steven, J. (2023). A global review of implementation of occupational safety and health management systems for the period 1970–2020. *International Journal of Occupational Safety and Ergonomics, 29*(2), 821–836. https://doi.org/10.1080/10803548.2022.2031796

Kemnaker Indonesia. (2024). *Kasus kecelakaan kerja, Februari tahun 2024*. Satu Data Kementerian Ketenagakerjaan. https://satudata.kemnaker.go.id/data/kumpulan-data/1872

Kineber, A. F., Antwi-Afari, M. F., Elghaish, F., Zamil, A. M. A., Alhusban, M., & Qaralleh, T. J. O. (2023). Benefits of implementing occupational health and safety management systems for the sustainable construction industry: A systematic literature review. *Sustainability, 15*(17), 12697. https://doi.org/10.3390/su151712697

Marhavilas, P. K., Pliaki, F., & Koulouriotis, D. (2022). International management system standards related to occupational safety and health: An updated literature survey. *Sustainability, 14*(20), 13282. https://doi.org/10.3390/su142013282

Materna, M., Maternová, A., Kamenická, D., & Chodelka, F. (2023). The influence of human factor on aviation accidents in Slovakia through HFACS framework: A comprehensive study. *Transportation Research Procedia, 75*, 173–182. https://doi.org/10.1016/j.trpro.2023.12.115

Musungwa, T., & Kowe, P. (2022). Effects of occupational health and safety management systems implementation in accident prevention at a Harare beverage company. *Cogent Engineering, 9*(1), Article 2124638. https://doi.org/10.1080/23311916.2022.2124638

Naumann, R. B., Sandt, L., Kumfer, W., LaJeunesse, S., Heiny, S., & Lich, K. H. (2020). Systems thinking in the context of road safety: Can systems tools help us realize a true "safe systems" approach? *Current Epidemiology Reports, 7*(4), 343–351. https://doi.org/10.1007/s40471-020-00248-8

Nwankwo, C. D., Theophilus, S. C., & Arewa, A. O. (2020). A comparative analysis of process safety management (PSM) systems in the process industry. *Journal of Loss Prevention in the Process Industries, 66*, Article 104171. https://doi.org/10.1016/j.jlp.2020.104171

Occupational Safety and Health Administration. (2000). *Process safety management* (OSHA Publication No. 3132). U.S. Department of Labor. https://www.osha.gov/sites/default/files/publications/osha3132.pdf

Park, Y., & Park, D. J. (2024). System dynamics approach for assessing the performance of safety management systems in petrochemical plants. *Journal of Loss Prevention in the Process Industries, 90*, Article 105324. https://doi.org/10.1016/j.jlp.2024.105324

Sturmberg, J. P., & Marcum, J. A. (2024). From cause and effect to causes and effects. *Journal of Evaluation in Clinical Practice, 30*(2), 296–308. https://doi.org/10.1111/jep.13940

Vitrano, G., & Micheli, G. J. L. (2024). Effectiveness of occupational safety and health interventions: A long way to go. *Frontiers in Public Health, 12*, Article 1292692. https://doi.org/10.3389/fpubh.2024.1292692

Vitrano, G., Micheli, G. J. L., Guglielmi, A., De Merich, D., Pellicci, M., Urso, D., & Ipsen, C. (2023). Sustainable occupational safety and health interventions: A study on the factors for an effective design. *Safety Science, 166*, Article 106249. https://doi.org/10.1016/j.ssci.2023.106249

Zhang, Y., Wang, S.-X., Yao, J.-T., & Tong, R.-P. (2023). The impact of behavior safety management system on coal mine work safety: A system dynamics model of quadripartite evolutionary game. *Resources Policy, 82*, Article 103497. https://doi.org/10.1016/j.resourpol.2023.103497