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Effectiveness Analysis of Safe Work System Implementation Using the Swiss Cheese Model Approach

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Abstract

Workplace accidents in the mining industry remain a critical global concern due to their impact on worker safety and operational efficiency. A major coal mining company in Indonesia, experienced an increasing number of accidents from 2022 to 2024, despite implementing a five-layer Safe Work System (SBS). This study aims to analyze the causes of these accidents using the Swiss Cheese Model to identify systemic weaknesses across organizational, planning, operational, technological, and contact defense layers. A qualitative case study approach was employed, complemented by descriptive statistical analysis of 2,413 findings from 435 accident reports. Each incident was mapped to the five SBS layers to determine frequency, contribution, and interactions among failures. The results indicate that Layer III (Work Readiness & Monitoring) was the dominant contributor (45.67%), followed by Layers II (Plan Readiness) and I (Organization Roles & Responsibility), highlighting operational deviations influenced by latent managerial and planning weaknesses. Layers IV (Preventive Defense) and V (Contact Defense) played supporting roles, emphasizing the importance of technology and emergency preparedness. The study concludes that accidents are systemic, resulting from alignment failures across multiple defense layers. Strengthening organizational policies, risk-based planning, operational monitoring, and technology integration is essential to improve safety maturity. Future research should explore the application of predictive safety analytics and multi-site comparisons to enhance proactive accident prevention in mining operations.

INTRODUCTION

A work accident is an undesirable and unplanned event that results in an unexpected injury or damage (Bardosh et al., 2022; Biro et al., 2022; Prasad & Suresh, 2023; Sherratt et al., 2023; Wong & Pawlicki, 2025). Mining is one of the main industries that is very important for the economy in Indonesia. Currently, mining activities are associated with various risks both underground and on the surface. This shows that there is an inverse relationship between profitability and reported injuries, where a lack of worker safety practices and investments is the cause of work accidents in mining. Accidents in mining have become one of the serious social problems that can affect the cessation of mining production activities and the sustainable development of the entire economy and society. Although the mining industry has improved in safety, there are still many incidents in the mining industry that have resulted in injuries or even deaths (Zuchri & Erwandi, 2023; Rahimi et al., 2022; Liang et al., 2011).

The International Labour Organization report in 2024 recorded 278,564 work accident cases in Indonesia, with 91.86 percent involving wage recipients and 7.23 percent involving non-wage recipients (Rifdha & Susilawati, 2024). Based on national data from the mining industry in the performance report of the Directorate General of Mineral and Mineral Resources of the Ministry of Energy and Mineral Resources of the Republic of Indonesia in 2024, there were 52 accidents resulting in death, 81 serious accidents, and 10 minor accidents in mineral and coal mining. Thus, a comprehensive analysis of the causes of work accidents can help reduce the occurrence of mining work accidents (Empi & Indra, 2019).

There are indicators that can be the cause of work accidents: namely, human factors, environment, hazards, and equipment/machinery (Rifdha & Susilawati, 2024). According to Liu et al. (2018), humans are at the center of the relationship between software, hardware, and the environment. If there is compatibility between these elements, the system will work smoothly; however, if there is a mismatch, human error will occur. Undetected errors that compromise the integrity of the system create vulnerabilities to operational risk factors and accidents. It is undeniable that mining activities are currently still managed and operated by humans with the potential for human error. According to Reason (1990), human error refers to an event in which a planned sequence of mental or physical activities fails to achieve the expected result (Lööw, 2022).

The Reason theory structure (Shabani et al., 2024), which resembles Swiss Cheese, describes the accident process. Layers of cheese depict the things involved in a safety system, while the holes in each layer indicate weaknesses that have the potential to cause accidents. Basically, there are four layers that constitute the occurrence of an accident: namely, Organizational Influences (the influence of organization and management policies in the occurrence of accidents), Unsafe Supervision (poor supervision), Preconditions for Unsafe Acts (conditions that support the emergence of unsafe acts), and Unsafe Acts (unsafe behavior or actions committed and directly related to the occurrence of accidents) (Samiranto et al., 2015).

A mining industry company in the Berau area, East Kalimantan, operates in a sector with a high potential risk of accidents ranging from mild to fatal. From 2022 to 2024, accidents at this company increased year over year, to determine the factors causing accidents each year, it is necessary to conduct a detailed analysis process study to identify what influences the increase in accidents so that further improvements can be made based on the results of investigations that have been carried out well and on target.

In the investigation and analysis process of the cause of accidents, a mining industry company in the Berau area, East Kalimantan uses the Layering Safe Working System (Swiss Cheese Model approach) developed by itself according to the needs of the organization. Layer 1 (Organization Roles & Responsibility) emphasizes organizational management, policies, and leadership as the foundation of safety culture with activities including HIRA (Hazard Identification and Risk Assessment); SOPs, Procedures, IK, Standards, and Forms; Do and Don't Policy; 26 High Risk Activities; Golden Rules; Personal Permit (SIMPER/KIMPER);

Management Review; and Regulatory Compliance. Layer 2 (Plan Readiness) focuses on work readiness planning and hazard mitigation before work starts, such as JSA (Job Safety Analysis) activities; weekly and daily work plans; emergency preparedness; SAP (Safety Accountability Program); design and general arrangement; standardization of tools and equipment; appliance inspection; work environment; and maintenance. Layer 3 (Work Readiness and Monitoring) functions to evaluate work readiness and monitor implementation in the field, such as PSM/Safety Briefing; DOP (Daily Operation Plan); P2H (Daily Work Equipment Inspection); daily work planning; maintenance before loading; and evaluation of the work area condition. Layer 4 (Preventive Defense) contains technology-based prevention efforts and monitoring systems with Fatigue Alarm activities; LOTO (Lock Out Tag Out); Geotech Radar/Marine Radar; in-cabin camera; speed awareness monitoring; and GPS (for position and speed). Layer 5 (Contact Defense) is the last layer of defense against direct contact with dangerous sources, such as PPE (Personal Protective Equipment); guarding/covering rotating objects and pinch points; embankment; ROPS (Roll Over Protection System); emergency response; and safety devices.

In an effort to prevent accidents, a systematic approach is key. As one of the coal mining industry players in Indonesia, the company has adopted the Swiss Cheese Model, in accordance with the recommendations of Reason (1997), to identify system weaknesses and prevent incidents. This approach supports the Safe Work System (SBS), which is part of the BeGems (Berau Coal Green Mining System), with layers of security that serve as a risk barrier, as described in Hollnagel (1999). Hollnagel (1999) explained that a barrier is an obstruction that can prevent or reduce the impact of undesirable consequences. This includes stopping, slowing down, limiting, or in some other way weakening uncontrollable processes. The concept of barriers is used to understand and prevent accidents. If an accident has occurred, it means that one or more barriers have failed. Barrier analysis is often used to describe an accident in terms of conditions that cause the barrier to fail. In addition, Hollnagel (2016) emphasizes the importance of Resilience Engineering in managing risk in modern organizations, which is relevant in digital transformation and automation of mining operations. This approach can support a mining industry company in the Berau area, East Kalimantan in developing an adaptive and proactive system for risk management. Safety regulations such as the Minister of Energy and Mineral Resources Regulation No. 26 of 2018, the Ministry of Energy and Mineral Resources No. 1827/K/30.MEM/2018, and ISO 45001 have provided a strong legal basis for the implementation of safety systems. As reinforcement, Dekker (2019) highlights the evolution of safety theories that can be applied in the mining sector to improve the efficiency and effectiveness of risk management. Therefore, this study aims to analyze the factors that cause accidents at the research site from 2022 to 2024 by implementing the Layering of a mining industry company in the Berau area, East Kalimantan Safe Work System as an investigation framework.

Although a mining industry company in the Berau area, East Kalimantan has implemented a multilayer-based Safe Work System (SBS), the increase in the number of accidents indicates the potential for latent failure. However, until now there has been no study that specifically analyzes the contribution of each SBS layer to accidents using the Swiss Cheese Model approach. Therefore, this study focuses on identifying systemic weaknesses at each SBS layer as a basis for improving the effectiveness of safety systems.

METHODS

Approaches and Types of Research

This research uses a qualitative approach with a case study type of research. This approach was chosen because it is in accordance with the main purpose of the research, which is to conduct an in-depth analysis of the causes of work accidents based on *the Swiss cheese model* approach in the context of *layering* the Safe Work System (SBS). The qualitative approach allows researchers to explore phenomena comprehensively, contextually, and thoroughly through the interpretation of data collected from various sources of information directly in the field. The case study was chosen as a type of research because the focus of this research lies on one specific entity, namely the case of work accidents that occurred at a mining industry company in the Berau area, East Kalimantan during the period from 2022 to 2024. Case studies allow an in-depth analysis of real situations and contexts involving occupational safety systems, including processes, procedures, human behavior, and organizational dynamics related to the occurrence of accident incidents.

In this study, *the Swiss cheese model* was used as the primary analysis lens. This model describes the work safety defense system as layers, each of which has potential loopholes due to active *failures*, unsafe actions by people, and *latent conditions* of system weaknesses (organization/management). When these gaps align, then the potential for accidents becomes a reality. Therefore, this model is very appropriate to be used to analyze how *layering* in the Safe Work System (SBS) can fail to perform its function and contribute to work accidents

Location and time of the study

Research Location

This research was carried out at a mining industry company in the Berau area, East Kalimantan. The research is focused mainly on the mine *operations* division and the occupational safety and health (K3) division, as both have a direct role in the implementation and evaluation of the safe work system (SBS) in the field.

Research Time

The research implementation period lasted for three months, starting from June to August 2025. The series of research activities was carried out through several stages:

1. In June 2025, the management of research permits and the collection of secondary data (accident reports, SOPs, SBS structures), and the scheduling of interviews with key informants
2. In July 2025, in-depth interviews with workers, supervisors, and K3 management will be conducted; Field observation at *the* Lati Site and the Binungan Site; and Documentation of SBS system implementation practices
3. In August 2025, initial data analysis and validation of findings (member check) will be carried out, as well as the preparation of preliminary research results and confirmation with the company

With this time frame, it is hoped that the data obtained can provide a complete picture of the factors causing work accidents and the effectiveness of the occupational safety *layering* system implemented based on the *Swiss cheese model approach*.

Data Collection Sources and Techniques

Data Source

Secondary Data

Secondary data obtained from all accident data in 2022 – 2024 is mapped to 5 SBS layers as the company's official investigation document. The documents used include:

a. Accident *Investigation Report* : Contains a chronology of events, identification of direct and indirect causes, and recommendations for improvement; and is used to trace system failures within each relevant SBS layer
b. Annual accident statistics data: Shows the number, type, location, and trend of work accidents from 2022–2024; and become the basis for the selection of representative cases that will be further analyzed
c. SOP *(Standard Operating Procedure):* Used to compare official procedures and actual implementation in the field; and helps assess compliance with the SBS system
d. Work instructions, JSA *(Job Safety Analysis),* and *Permit to Work*: Represent the technical and procedural layers in the SBS system; and are used to assess the adequacy of control and risk control on a particular job
e. Occupational safety training documents *(Training Records):* Demonstrate the cognitive and technical readiness of workers; and describe the effectiveness of safety education in preventing *unsafe acts*
f. Internal and external safety audits: Provide an independent assessment of SBS implementation and improvement recommendations; and uncover systemic weaknesses in security defense structures
g. Structure and policy of the Safe Work System (SBS): Used to identify and map the layers of defense used and became the basis for analysis of systematic weaknesses using the *Swiss Cheese Model approach*

Data Collection Techniques

This study uses all secondary data in the form of investigation document reports for all accidents in 2022 – 2024 (435 cases) mapped to 5 SBS layers in order to analyze the causes of work accidents based on *the Swiss cheese model* approach and evaluate the contribution of each *layer*

Data Analysis Techniques

In this study, the researcher will conduct *an in-depth analysis* of the data of the investigation report of a mining industry company in the Berau area, East Kalimantan which is then classified based on sub-categories in each layer of the cause of the accident listed as the SBS layer. After the factors causing the accident were classified and the frequency of the percentage was known, then the researcher analyzed the interaction of the factors causing the accident from the *SBS Layering* framework .

As a complement to the document-based qualitative analysis above, this study uses the Descriptive Statistical Analysis *method as* proposed by Sugiyono (2019) to provide a systematic quantitative overview of the data of 435 incidents and 2,413 layer failure findings spread across 56 sub-factors that cause accidents during the period 2022 - 2024. Descriptive statistical analysis was chosen because the purpose of this study is to describe, summarize, and present the characteristics of the data as they are without drawing inferences on the population outside the data framework, in line with the principle *of full population analysis* where all incidents from 2022 to 2024 are analyzed without sampling. Thus, the distribution pattern of accident causes in the five Layers of the Safe Working System can be understood objectively and comprehensively.

The descriptive statistical measures used in this study include four main parameters, namely:

(1) Frequency *(count),* which is the absolute number of failure findings at each *SBS layer* and sub-factor, calculated per year (2022, 2023, 2024) or cumulatively, to identify the most frequent failure points.

(2) Relative percentages, calculated both against the total annual findings (% per year) and against the total overall findings (cumulative % 2022 - 2024), as the basis for a proportional comparison of the contribution of each *layer* and sub-factor.

(3) Average failure per incident, calculated by the formula: the number of findings of a sub-factor divided by the total number of incidents in the year in question (Mean = ∑Findings/∑Incidents), to measure the intensity *of the failure layer* in each event.

(4) Temporal trend distribution, which is a comparison of the three measures above between 2022, 2023, and 2024 to see if the contribution of a *layer*/sub-factor increases, decreases, or stabilizes over time.

The results of the descriptive statistical processing are then presented in the form of frequency-percentage distribution tables, *bar* charts, and Pareto charts to identify the dominant sub-factors *(vital few)* that contribute to the majority of failures. The *Pareto Analysis* approach (Juran, 1951; 80/20 principle) is used specifically on *Layer* 3 which is identified as the most dominant layer (45.7% of total failures), to map the top three sub-factors that are priority for improvement. All calculations were carried out using *Microsoft Excel*, with cross-validation of a mining industry company in the Berau area, East Kalimantan investigation master data to ensure the accuracy of the recapitulation. This descriptive statistical output is the quantitative basis for the qualitative analysis of *the Swiss Cheese Model* in Chapter IV, so that the interpretation of the layering failure mechanism can be based on numerical proof, not assumptions.

Data Validity Techniques

In qualitative research, maintaining the validity of data is an important aspect to ensure that the results of the analysis truly represent the reality in the field. Given that the focus of this study is on the causes of work accidents based on the Swiss cheese model approach, the accuracy and reliability of data from various layers of the safety system must be strictly maintained. Review the suitability of recommendations to SBS (People, Process, Leadership and Technology) frameworks.

Consultation of the results of recommendations with internal safety practitioners (Safety Operation, Safety Evaluator & Data Control) and Safety Investigation & Risk Expert as expert judgment.

Research Ethics

In the implementation of this research, the researcher consistently adheres to the principles of research ethics to ensure that the process of data collection, analysis, and reporting is carried out responsibly and does not harm any party, especially informants from within a mining industry company in the Berau area, East Kalimantan . Research ethics is very important in the context of studies that involve an in-depth analysis of work accidents, because it concerns sensitive data, individual perceptions of safety systems, and potential criticism of the company's managerial or operational structure.

The application of the above research ethical principles is the moral and professional foundation in the implementation of this study, especially considering the topics raised regarding the occupational safety system and its failure factors. By maintaining confidentiality, voluntary participation, and academic honesty, the researcher hopes that the results of this study can be beneficial for the improvement of the safe work system (SBS) at a mining industry company in the Berau area, East Kalimantan without causing negative impacts on the individuals involved.

RESULTS AND DISCUSSION

Results of the Analysis of the Causes of Accidents in the Multi-Layered Safe Work System in 2022–2024

Based on the results of the analysis of the cause of the IPLS SBS accident at a mining industry company in the Berau area, East Kalimantan a total of 2,413 gap findings were found during the period 2022 to 2024, with details of 647 findings in 2022, 707 in 2023, and 1,059 in 2024, showing an increasing trend from year to year.

The first layer, L1 – Organization Roles & Responsibilities, recorded a total of 486 findings or 20.14% of the total findings. The sub-elements with the most findings were SOP (Policy, Procedure, IK, Std & Form) with 123 findings (5.10%), followed by HIRA with 94 findings (3.90%), and Competency Training with 76 findings (3.15%). The elements with the fewest findings were Regulation Compliance and Compliance Assessment, each with only 2 findings.

In the second layer, L2 – Plan Readiness, 507 findings or 21.01% of the total were recorded. The Safety Accountability Program (SAP) sub-element was the most dominant with 127 findings (5.26%), followed by the Work Plan with 68 findings (2.82%) and Maintenance with 69 findings (2.86%). It should be noted that there has been a significant surge in the HSE Campaign in 2024 which has jumped from 3 findings in 2023 to 56 findings.

The third layer, L3 – Work Readiness & Monitoring, is the layer with the largest contribution of findings, namely 1,102 findings or 45.67% of the total. The sub-element of Work Implementation in accordance with SOPs was the highest contributor with 289 findings (11.98%), followed by Work Area Conditions with 224 findings (9.28%), and Work Supervision by Supervisors with 216 findings (8.95%). This indicates that the majority of the causes of accidents come from the aspect of carrying out work in the field.

The fourth layer, L4 – Preventive Defense, recorded 129 findings or 5.35% of the total. The most findings came from CCTV with 62 findings (2.57%) and In Cabin Camera with 60 findings (2.49%), both of which have experienced a sharp increase in 2024. This shows that the use of preventive monitoring technology still needs to be improved.

Finally, the fifth layer, L5 – Contact Defense, recorded 189 findings or 7.83% of the total. The Emergency Response sub-element was the most problematic with 94 findings (3.90%), including a drastic spike in 2024 with 56 findings a significant increase from 24 findings in 2023. This indicates the need to strengthen emergency response capacity in a mining industry company in the Berau area, East Kalimantan work environment.

Cause Distribution Based on Safe Working System (SBS) Layer

The mapping of the causes of incidents in 2022 based on the five layers of the Safe Work System (SBS) shows the distribution as follows:

Table 1 Data on the Number of Analysis of Causes of Layering Accidents in 2022

No.	Layer	Description	Quantity
1	L1	Organization Roles & Responsibilities	117
2	L2	Plan Readiness	142
3	L3	Work Readiness & Monitoring	329
4	L4	Preventive Defense	23
5	L5	Contact Defense	36

This distribution shows that Layer 1 has the largest contribution to the cause of incidents in 2022. The findings in this layer are generally related to policy implementation deviations, procedural inconsistencies, reporting weaknesses, and lack of managerial control over safety processes.

The high contribution of Layer 1 shows that the root of the problem in 2022 is more of a latent condition than an active one. In the theory of the Swiss Cheese Model (Reason, 1997), latent conditions are systemic weaknesses that stem from managerial decisions, organizational policies, or less effective control structures. This condition does not directly cause accidents, but creates an environment that allows active failure to occur in the field.

Layer 3 (Work Readiness & Monitoring) took second place with 329 findings. This layer is related to work readiness, the implementation of safety briefings, the implementation of SAP, direct supervision by supervisors, and the evaluation of the condition of the work area. The high findings at this layer indicate that the operational control function has not been fully functioning consistently.

Meanwhile, Layer 2 (Plan Readiness) shows gaps in risk planning, such as inaccuracy of Job Safety Analysis (JSA), lack of identification of location-specific hazards, and unpreparedness of tools or work areas. Although they are smaller in number than Layers 1 and 3, failures in these layers have the potential to be an initial trigger that is then amplified by weaknesses in the next layer.

Layer 4 (Preventive Defense) shows the lowest number of findings. This indicates that technology failure is not the dominant factor in 2022. In other words, safety problems in that year were more influenced by managerial and operational aspects than technological limitations.

Layer 5 (Contact Defense) shows 36 findings related to PPE use and physical protection. This finding generally appears in cases of minor injury up to MTI, where the last defense is not fully able to withstand the impact of hazard.

Analysis Based on the Safe Working System Layer (SBS)

The mapping of the causes of incidents in 2023 based on the five layers of the Safe Work System (SBS) shows the distribution as follows:

Table 2 Data on the Number of Analysis of Causes of Layering Accidents in 2023

No.	Layer	Description	Quantity
1	L1	Organization Roles & Responsibilities	149
2	L2	Plan Readiness	139
3	L3	Work Readiness & Monitoring	331
4	L4	Preventive Defense	28
5	L5	Contact Defense	60

In general, Layer 1 and Layer 3 are the most dominant contributors to the cause of incidents in 2023. Dominance of Layer 3 – Work Readiness & Monitoring In 2023, there has been a significant increase in findings in Layer 3 compared to 2022. This shows that the factor of work readiness and field supervision is a critical point of the safety system. The findings in this layer are generally related to:

- The supervisor is not on site when the activity takes place
- SAP (Safety Accountability Program) is not implemented consistently
- Evaluation of the condition of the work area is not updated according to field dynamics
- Procedure deviations are not corrected immediately

The dominance of Layer 3 in 2023 shows that active barrier failures are more prominent than in the previous year. If in 2022 the dominance is latent organizational weakness (Layer 1), then in 2023 the failure is more visible at the direct operational stage.

This can be interpreted as a shift in the character of risk from administrative dominant to operationally dominant.

Layer 1 Roles – Organizational Roles & Responsibilities, Layer 1 continues to show a high contribution in 2023. The findings in this layer are generally related to:

1. Deviation of procedure implementation
2. Reporting inconsistencies
3. Lack of control over SAP implementation
4. Weaknesses of managerial evaluation and monitoring

This shows that although operational problems are increasing, the systemic roots remain in the organization's control structure.

In the perspective of the Swiss Cheese Model, this condition indicates that the hole in the latent layer is still not closed, thus increasing the possibility of alignment with the operational layer.

Layer 2 – Plan Readiness, Layer 2 shows consistent contributions in 2023. The findings in this layer indicate that risk planning is not yet fully adaptive to changing operational conditions. Some indications include:

1. JSA is not updated according to changes in work location
2. Hazard identification lacks consideration of dynamic factors
3. Work plan out of sync with tool readiness

This layer serves as an upstream barrier. When the planning is not comprehensive, then the next layer will work under higher risk conditions.

Layer 4 and Layer 5, Layer 4 (Preventive Defense – Technology) show a relatively small number of findings, but an increase compared to 2022. This indicates that the use of technology is starting to play a role in the investigation, although it is not yet a dominant factor.

Layer 5 (Contact Defense) still shows findings related to the use of PPE and physical protection. However, since the number of injuries to humans is relatively small, it can be concluded that the last layer is still quite effective in limiting the impact on workers.

Mapping of Accident Causes Based on 5 SBS Layers

Theoretical Concept of Swiss Cheese Model Layer

The Swiss Cheese model was developed by James Reason as a systemic approach to understanding the occurrence of accidents in high-risk systems (high reliability organizations). This model confirms that accidents are not the result of a single mistake, but rather the consequences of layered defense failures that occur simultaneously.

In this model, each layer of the defense system is illustrated as a slice of cheese that has a "hole" (weakness or latent condition). These holes represent system weaknesses, both active and latent failure. Accidents occur when the holes are aligned (alignment failure), so that the danger can penetrate all layers of defense without being stopped. Conceptually, Reason distinguishes two main types of failures:

1. Active Failure – a direct error in the field (e.g. an unsafe act).
2. Latent Condition – a systemic weakness hidden in an organization's policies, design, oversight, or culture.

Conceptualization of 5 Layers of Safe Working Systems

The approach to mapping the causes of accidents in this study uses the Swiss Cheese model from James Reason, which is then adapted into a 5-Layer Safe Working System (SBS) operational framework safety management structure.

In contrast to the classic approach that only divides *active* and *latent failure*, the SBS model in this study maps safety defense into five operational *layers* that are actually used in the company's system.

Layer I – Organization Roles & Responsibility (Strategic Defense) is a strategic layer that forms the foundation of the safety system, covering elements such as HIRA, SOP (Policy, Procedure, IK), Do & Don'ts Policy, 26 High Risk Activity, Golden Rules, risk management, organizational structure & leadership, internal & external audits, Management of Change, Commissioning, MCU, and industrial relations. This layer is a *latent defense layer*, as its failures are rarely seen directly in the event, but it creates systemic conditions that allow risks to develop.

Layer II – Plan Readiness (Tactical Defense) is a layer of planning readiness before work begins, which includes JSA, work plan (weekly/up plan), engineering preparedness, safety accountability program, tools inspection, HSE campaign, incident investigation & reporting, and safety dashboard & evaluation. This layer serves as a policy translation to an operational plan, so that if it is weak, the risk is not identified preventively and will be passed on to the technical layer.

Layer III – Work Readiness & Monitoring (Operational Defense) is the most dominant layer based on 2022–2024 data, including PSM/safety briefing, PPE, emergency equipment, daily work plan, check before after loading, last minute check, safety patrol, work implementation according to SOPs, fatigue test, and drug/alcohol check. As an active operational defense that works every day in the field, the high number of findings at this layer indicates that the system is still in the operational control phase and has not shifted to strengthening system design.

Layer IV – Preventive Defense (Engineering & Monitoring System) includes technology-based technical controls such as fatigue alarms, Geotech RADAR, in-cabin cameras, speed awareness monitoring, GPS, CCTV, sensors/alarms, and wind indicators. This layer has a higher effectiveness in the risk control hierarchy, so if preventive defense is not optimal, the system will rely on human control in Layers III and V which are probabilistic more prone to error.

Layer V – Contact Defense (Last Barrier) is the last defense before a major impact incident, including PPE, guarding/covering rotating objects, embankments, ROPS, emergency response, fenders, and anchors. This layer is a *damage control barrier*, not *a risk elimination barrier*, so if an accident has reached this layer, it means that the previous layers have failed to function optimally.

Recapitulation of Accident Cause Distribution 2022–2024

Based on the results of the processing of accident investigation data documented in the accident database in 2022, 2023, and 2024, a classification process was carried out for all causal findings into the 5-Layer Safe Work System (SBS) structure. This classification process aims to identify the dominant patterns of defense system failures as well as shifting trends in risk sources over the three-year period of the study. This distribution recapitulation is not only quantitative, but is also used as the basis for systemic analysis to see the consistency or change in failure patterns between layers. With this approach, the cause of an accident is no longer seen as an individual occurrence, but rather as a reflection of the performance of each layer of the company's safety defense.

In general, the results of the processing show an increase in the number of findings from year to year. This improvement can be interpreted in two perspectives. First, the increasing complexity of mining operations in line with the growth of production activities. Second, the depth and quality of investigations have increased, so that more causative factors have been identified compared to the previous year.

The distribution of findings shows that failures are not concentrated at one specific layer, but are spread across all layers of the defense system. However, there are certain layers that consistently show that the number of findings is more dominant than the other layers. This indicates that there are critical control points in the system that need to receive priority attention in safety performance improvement programs. The distribution corresponds to table 3.

Table 3 Results of Accident Cause Contribution Analysis Based on SBS Layer (2022–2024)

No.	Layer	2022	2023	2024	Total	Percentage
1	Layer 1	117	149	220	486	20.14%
2	Layer 2	142	139	226	507	21.01%
3	Layer 3	329	331	442	1102	45.67%
4	Layer 4	23	28	78	129	5.35%
5	Layer 5	36	60	93	189	7.83%
	Total	647	707	1059	2413	100%

Based on the results of the recapitulation of accident investigation data for the period from 2022 to 2024, a total of 2,413 causation findings were obtained that have been classified into 5 Layers of the Safe Work System (SBS). The number of findings shows an increasing trend every year, namely 647 findings in 2022, increasing to 707 findings in 2023, and again increasing significantly to 1,059 findings in 2024. This increase in the number of findings can be interpreted as a result of the increasing complexity of mining operations and the maturation of accident investigation systems that are able to identify causative factors in more detail and systematically. Thus, these data not only show an increase in risk, but also reflect an improvement in the quality of identification and classification of root causes.

The distribution of findings by layer shows that Layer 3 (Work Readiness & Monitoring) is the layer with the largest contribution, with 1,102 findings or 45.67% of the total. Sequentially, the number of findings on this layer is 329 in 2022, 331 in 2023, and increases to 442 in 2024. The dominance of this layer shows that the biggest gap in the defense system is still in the aspects of work readiness and daily operational control, such as the implementation of safety briefings, checking equipment before work, monitoring compliance with SOPs, and monitoring the physical and mental condition of workers. The high proportion in this layer indicates that the safety system still relies heavily on human-based operational control, so the probability of variations and inconsistencies in implementation in the field is relatively high.

Table 4 Pareto Analysis of Layer 3 (Work Readiness & Monitoring) Sub-factor Contribution (2022–2024)

No.	Sub-factor of Layer 3	Findings	%	Cumulative %
1	Work Implementation according to SOPs	289	26.22%	26.22%
2	Work Area Conditions	224	20.33%	46.55%
3	Work Supervision by Supervisors	216	19.60%	66.15%
4	DOP (Daily Operation Plan)	71	6.44%	72.59%
5	Compliance with Safety Signs/IMO Signs	62	5.63%	78.22%
6	Last Minutes Check	61	5.54%	83.76%
7	P2H (incl. Emergency Equipment)	46	4.17%	87.93%
8	P5M (Safety Briefing)	43	3.90%	91.83%
9	Fit to Work (Mental & Physical)	38	3.45%	95.28%
10	Fatigue Test	28	2.54%	97.82%
11	Speak Up	13	1.18%	99.00%
12	Safety Patrol	5	0.45%	99.45%
13	Security Check & Patrol	4	0.36%	99.82%
14	Drugs/Alcohol Influence	2	0.18%	100.00%

Based on Pareto Analysis (Juran, 1951; 80/20 principle), six of the fourteen sub-factors in Layer 3 reach the 80% cumulative threshold and can therefore be classified as the vital few: Work Implementation according to SOPs (26.22%), Work Area Conditions (20.33%), Work Supervision by Supervisors (19.60%), DOP/Daily Operation Plan (6.44%), compliance with Safety Signs/IMO Signs (5.63%), and Last Minutes Check (5.54%), together accounting for 83.76% of the total findings in Layer 3. This confirms that improvement efforts on Layer 3 should be prioritized on these six sub-factors, as they represent the majority of operational failures contributing to accidents.

Layer 2 (Plan Readiness) and Layer 1 (Organization Roles & Responsibility) also showed significant contributions. Layer 2 recorded a total of 507 findings or 21.01%, while Layer 1 recorded 486 findings or 20.14%. Combined, these two layers accounted for 41.15%

of the total causes of accidents over three years. The increase in findings on both layers from year to year shows that planning, supervision, policy, and safety management system factors have a fairly dominant role in shaping risk conditions. This also indicates that the cause of accidents is not only operational, but also influenced by latent systemic weaknesses, such as the lack of optimal integration of risk management in work planning, the inconsistency of supervisory accountability, and the inability to develop fully effective management evaluation mechanisms.

Meanwhile, Layer 4 (Preventive Defense) recorded 129 findings or 5.35%, and Layer 5 (Contact Defense) recorded 189 findings or 7.83%. The relatively smaller proportions of these two layers suggest that most risks can still be identified and controlled before reaching the final stage of defense. However, the existence of the findings in Layer 5 remains an indication that in a number of cases, the risk managed to penetrate several previous layers of defense until it reached the final stage of protection such as PPE, guarding, or the final protection system. From the perspective of the Swiss Cheese Model, this condition describes alignment failure, which is when several layers experience weakness at the same time so that danger can pass through the entire defense system.

Longitudinally, the three-year distribution pattern shows the consistency of Layer 3 dominance without any significant shift towards a more strategic or technical-engineering-based layer. This indicates that the improvement efforts made have not been fully able to reduce dependence on operational controls. In the context of safety maturity, this condition reflects that the organization is still in the transition phase from a reactive to a planned culture. Organizations have been able to identify causative factors more systemically, including at the managerial and planning layers, but strengthening the aspects of system design and technical engineering as a form of primary prevention still needs to be improved.

Thus, the results of this distribution analysis show that the causes of accidents are systemic and layered, with a dominance of operational readiness and monitoring as well as significant contributions from managerial and planning factors. This condition confirms that improving safety performance cannot be focused only on individual disciplines, but must be done through strengthening the overall structure of the defense system, especially on the integration of risk management, actual hazard-based planning, and the development of stronger preventive technical barriers.

Analysis of Interactions Between Layers

An analysis of the interaction between layers was carried out to understand how failures at one layer of the Safe Work System (SBS) affected the other layers until they finally allowed accidents to occur. In the Swiss Cheese approach developed by James Reason, accidents are not seen as the result of a single mistake, but rather as the result of multiple failures that occur simultaneously. This leads to alignment failure, which is a condition when the gaps in several layers of defense are aligned so that danger can penetrate the entire control system.

Based on the distribution of 2,413 findings of accident causes during the 2022–2024 period, it can be seen that Layer III (Work Readiness & Monitoring) is the layer with the largest contribution at 45.67%. Nevertheless, if Layer I (Organization Roles & Responsibility) and Layer II (Plan Readiness) are combined, the contribution reaches 41.15%, which is proportionally almost equivalent to Layer III. This fact shows that operational failures that arise at the work readiness and monitoring layer are not an independent phenomenon, but are greatly influenced by the quality of the management system and planning.

The interaction between layers can be explained through systemic causal flows. Weaknesses in Layer I, such as the lack of optimal integration of risk management in policies and management reviews, will result in Layer II deficiencies in the form of work planning that is less specific to actual risks. When planning is not completely based on dynamic hazards, then in Layer III there will be deviations in the implementation of operations, such as non-compliance with SOPs, inadequate daily monitoring, or ineffective control of the physical and mental condition of workers. If these conditions are not corrected immediately, risks can continue to propagate and potentially penetrate Layer IV (Preventive Defense) based on technological and technical engineering systems, until they can eventually only be controlled by Layer V (Contact Defense) as the last defense.

This pattern of interaction shows that accidents in mining systems are not spontaneous events, but rather the accumulation of a series of interrelated weaknesses. The dominance of Layer III for three consecutive years indicates that safety systems still rely heavily on human-based operational control. Meanwhile, significant contributions to Layer I and Layer II confirm that latent factors at the managerial and planning levels also shape risk conditions in the field. In other words, failures at the operational level are often a manifestation of structural weaknesses that existed at previous layers.

The relatively small distribution of Layer IV and Layer V also provides an important picture of the strengths and weaknesses of the defense system. Layer IV, which reflects technology-based preventive defense, only accounts for 5.35%, while Layer V accounts for 7.83%. This shows that a control system based on technical engineering has not become the dominant barrier in preventing accidents. Greater reliance on administrative controls and operational oversight indicates that the organization is still in the risk control stage after the risk has arisen, rather than at the elimination or prevention engineering stage.

Longitudinally, there is no significant shift in layer dominance from 2022 to 2024. Layer III remains the main point of risk manifestation, while Layers I and II continue to show increasing identification quality as the investigative system matures. This suggests that the investigative system has evolved towards a more systemic approach, but structural improvements have not been able to fully shift the focus of control to a more preventive and design-based level.

This analysis of the interaction between layers reinforces the conclusion that improving safety performance cannot be done partially on a single layer. Strengthening operational discipline without improving risk management and planning will only result in short-term improvements. To prevent alignment failure, strong integration between layers is needed through strengthening strategic policies, actual risk-based planning, increasing the effectiveness of operational monitoring, and developing more reliable technical barriers. Thus, the safety defense system can work synergistically so that the probability of simultaneous failure can be significantly reduced.

Overall, the results of the analysis show that accidents result from an interconnected series of systemic failures, with the main manifestation at the operational layer but the root of the problem often at the managerial and planning layers. These findings are an important basis for formulating strategies to increase safety maturity towards a more proactive and system-based stage.

Analysis Based on 5 Layers of SBS

The analysis based on the 5 Pillars of the Safe Work System (SBS) was conducted to evaluate the extent to which the company's safety system structure is able to function as an effective defense against mining operational risks. If in Subchapters 4.2 and 4.3 the distribution and interaction between the layers of the cause of accidents have been analyzed, then in this section the approach is expanded by assessing how each pillar in the SBS system contributes to the formation of a defense gap (system vulnerability).

The five layers of SBS conceptually reflect the main foundation of the safety system consisting of organizational and leadership roles, planning readiness, work readiness and operational monitoring, technology-based preventive defense, and contact defense as last resort. These pillars are not just administrative categories, but they are structural components that determine the quality of the defense system as a whole.

Based on the distribution of 2,413 findings during the 2022–2024 period, it can be seen that the pillars of work readiness and operational monitoring have the largest contribution to the cause of accidents. This shows that the main challenge for the safety system is still the consistency of the implementation of daily controls in the field. Safety briefing, compliance with SOPs, direct supervision, and control of working conditions have not been able to effectively close the risk gap. This condition indicates that the system is still highly dependent on human reliability, which naturally has variations and potential errors.

The planning and work readiness layers also show significant contributions. Risk-based planning, JSA quality, and supervisory accountability are important factors in shaping the quality of execution in the field. When planning is not fully responsive to changes in dynamic mining conditions, the potential deviation at the operational stage increases. Thus, weaknesses in the planning layer have a direct impact on the effectiveness of the operational layer.

The organizational and leadership layers also show a strategic role in shaping the culture and direction of the safety system. Policy, management commitment, risk management integration, and consistency of review and evaluation are decisive factors in strengthening or weakening the system as a whole. The increase in findings on this pillar over the past three years indicates that there is room for improvement in the integration of safety policies with operational strategies and production targets. An imbalance between production pressure and risk control can create latent conditions that trigger failure in the layers underneath.

Meanwhile, the technology-based preventive defense layer has a relatively smaller contribution than the operational and planning layers. This shows that engineering and technology-based control has not yet become the dominant barrier in the system. In fact, in the hierarchy of risk control, technical engineering has higher effectiveness than administrative control and individual behavior. Greater reliance on operational control than preventive engineering indicates that the system is still in the risk control stage after the risk has arisen, rather than fully at the stage of risk elimination or reduction in the first place.

The contact defense pillar as the last layer shows a relatively small proportion of findings, but its existence remains significant in the context of layered defense systems. When the risk has reached this pillar, it means that some of the previous pillars are not functioning optimally. Thus, the findings on the contact defense pillar are an indicator that alignment failure has occurred and the system failed to stop the risk at an earlier stage.

Overall, the analysis based on the 5 Layers SBS shows that safety system is still dominated by operational and administrative controls, while strengthening on strategic aspects and technical engineering has not been fully optimal. This condition reflects the level of maturity that is in the transition phase from reactive to planned. Organizations have been able to identify system weaknesses more systemically, but the transformation towards a proactive approach based on design and technology still needs further strengthening.

The implication of these findings is the need to reorient the safety improvement strategy with an emphasis on strengthening the organizational and planning pillars as the foundation of the system, as well as increasing investment in technology-based preventive defense. By strengthening these strategic layers, the control burden on the operational layer can be reduced so that the probability of alignment failure between layers can be significantly reduced. This approach is in line with the principle of increasing safety maturity which emphasizes the shift from behavior-based control to system-based control and engineering.

Discussion

The theoretical discussion in this study aims to integrate the results of empirical analysis of the distribution of accident causes, inter-layer interactions, and evaluation based on the 5 Layers of Safe Working System (SBS) with relevant safety and risk management theoretical frameworks. Thus, research findings are not only descriptive, but have a strong conceptual foundation and can be accounted for academically.

Based on the results of the analysis of accident cause data using SBS Layering approach in the 2022–2024 period, it is known that the causes of incidents in mining operational activities have complex and systemic characteristics. The cause of the incident does not stand as a single factor, but is the result of the interaction of various factors including process factors, human factors, and technology factors, which are generally influenced by the organizational condition and the effectiveness of the supervision system.

These findings show that the implementation of work procedures, consistency of supervision, and operational conditions in the field are the main determinants in the occurrence of incidents. Nevertheless, technology factors still have an important role as part of the risk control system, especially in the form of engineering control and monitoring systems.

The variation in the contribution of factors that are quite diverse also shows an imbalance in the effectiveness of safety control systems at various levels of the organization. In some cases, weaknesses at the organizational and planning levels can create conditions that allow operational deviations at the worker level. This confirms that accidents are not solely caused by individual error, but are the result of system failures that occur in layers.

The findings of this study are in line with the Swiss Cheese Model (Reason, 1997) which states that accidents occur due to simultaneous failures at various layers of safety defense. In the context of this study, the failure was identified through the interaction between the organizational (Layer 1), planning (Layer 2), and operational (Layer 3) layers, which formed an alignment failure path to allow incidents to occur.

Furthermore, the results of the research can also be mapped in the framework of the Swiss Cheese Model, where organizational factors play a role as *organizational factors*, weakness of supervision as *unsafe supervision*, working conditions as a *precondition for* *unsafe acts*, and worker behavior as *active failure*. The interaction between these factors shows that accidents are the result of a combination of latent factors and active factors in the work system.

Thus, the results of the analysis show that mining accidents are a systemic phenomenon and are influenced by the interaction of various factors in the safety system. Efforts to improve safety performance cannot only be focused on changing worker behavior, but must be done through strengthening the system as a whole, starting from organizational policies, risk-based planning, to operational control in the field.

The conceptual model produced in this study emphasizes that improving safety must be directed at strengthening integration between layers, so that each layer of defense can function effectively in preventing alignment failure. This approach is expected to be the basis for formulating a more comprehensive and sustainable strategy to increase mining safety maturity.

Conceptual Model of Research Results

Based on the results of the analysis of the distribution of accident causes, interactions between layers of the Safe Work System (SBS), and theoretical discussions referring to the Swiss Cheese Model from James Reason, this study produced a conceptual model that explains the systemic relationship between safety defense structures, failure alignment patterns, and mining safety maturity levels.

The resulting conceptual model confirms that accidents in coal mining systems are not the result of a single factor, but rather the result of dynamic interactions between five layers of defense working in layers. Each layer has a specific role as a risk control barrier, but its effectiveness is greatly influenced by the quality of integration between the layers. Thus, risk is not static, but moves from the strategic layer to the operational layer when there are uncovered weaknesses.

In this model, Layer I (Organization Roles & Responsibility) serves as a strategic foundation that determines the direction of the safety system through policies, risk management integration, and leadership commitment. Layer II (Plan Readiness) acts as a translator of policy into risk-based operational planning. Layer III (Work Readiness & Monitoring) becomes the point of active implementation in the field, where risks are most often manifested. Layer IV (Preventive Defense) serves as a technical barrier based on technology and engineering, while Layer V (Contact Defense) serves as the last protection to minimize impact when the entire previous layer fails.

The results show that the dominance of findings in Layer III and significant contributions in Layers I and II form a top-down risk flow pattern. This means that weaknesses at the managerial and planning levels increase the probability of operational deviations. This conceptual model illustrates that alignment failure most often occurs through the Layers I–II–III interaction pathway, before the risk has the potential to penetrate Layers IV and V. Thus, safety interventions that focus only on individual behavior or operational discipline will not be effective if they are not accompanied by strengthening risk management structures and planning.

This conceptual model also integrates the dimension of safety maturity. In the reactive phase, organizations tend to focus on Layers III and V as the main control points. In the planned phase, organizations begin to strengthen Layer II through risk-based planning. Meanwhile, in the proactive phase, strengthening Layer I and Layer IV is a priority through the integration of strategic risk management and preventive technical engineering. Thus, the shift in layer dominance can be used as an indicator of the maturity level of the safety system.

Structurally, the conceptual model of the research results can be understood as a dynamic system consisting of three main components: a layered defense structure (five layers SBS), interaction and alignment failure mechanisms, and outcomes in the form of safety maturity levels. The relationship between these three components is causal and cyclical. Weakness of the defense structure increases the probability of alignment failure, which is then reflected in the findings of the accident investigation. The results of the investigation then become a feedback loop to strengthen the strategic and technical layers, so that the system moves toward higher maturity.

The conceptual contribution of this research is the development of an integrative model that connects the Swiss Cheese approach, risk control hierarchy, and safety maturity evaluation in a single operational framework applicable to the coal mining industry. This model not only explains how accidents occur, but also shows a path of system improvement through strengthening integration between layers.

Thus, the conceptual model of the research results confirms that improving mining safety performance must be carried out through systemic and layered approaches, with priority on strengthening the strategic layer and risk planning, as well as increasing the effectiveness of technical barriers. Transformation to a proactive safety system can only be achieved if all layers work synergistically and are able to prevent simultaneous alignment failures.

The conceptual model of the results of this study was developed based on the results of data analysis of incident causes in mining operational activities during the 2022–2024 period. The results of the mapping of incident causes showed that accidents were not caused by a single factor, but were the result of the interaction of various factors in the mining safety system.

In this model, organizational factors are placed as the most fundamental layer in the safety system. These factors include safety policies, management commitments, safety leadership, and the safety culture implemented in the organization. The strength of the safety system at the organizational level will determine the effectiveness of the implementation of safety programs at the operational level.

Organizational factors then affect the quality of operational supervision (unsafe supervision) carried out by supervisors in the field. Effective supervision will ensure that all work activities are carried out in accordance with operational standards, procedures, and applicable safety provisions. On the other hand, suboptimal supervision can increase the potential for deviations from safe work procedures.

Furthermore, weaknesses in the level of supervision can create conditions that allow the emergence of preconditions for unsafe acts. This condition includes various factors related to the work system such as suboptimal work methods, less effective operational planning, and equipment and technological conditions that do not fully support work safety.

In this study, the preconditions are divided into two main components: the process factor and the technology factor. The process factor is related to the implementation of work procedures, operating methods, and risk control systems applied in mining activities.

Meanwhile, technological factors are related to the condition of equipment, the engineering control system, and the equipment maintenance system used in operational activities.

The interaction between process factors and technological factors will then affect worker behavior (human factor) in carrying out work activities. If work conditions are not well controlled, the potential for unsafe behavior will increase. These unsafe behaviors can take the form of non-compliance with work procedures, lack of safety awareness, or operational errors made by workers in the field.

If these various factors occur simultaneously, a system failure pathway will be formed that can ultimately trigger a work incident or accident. This condition shows that work accidents in mining activities are a systemic phenomenon that is influenced by various interrelated factors in the safety system.

This conceptual model shows that efforts to improve mining safety performance must be carried out through a systems approach that includes strengthening organizational safety policies, improving the quality of operational supervision, improving work systems, and strengthening worker safety behavior.

CONCLUSION

The study concludes that workplace accidents at a mining industry company in the Berau area, East Kalimantan are the result of systemic and layered failures within the Safe Work System (SBS). Layer III (Work Readiness & Monitoring) consistently contributed most to incidents, with operational deviations such as incomplete compliance with SOPs, insufficient supervision, and inadequate monitoring of work area conditions being dominant. Latent failures in Layer I (Organization Roles & Responsibility) and Layer II (Plan Readiness) significantly influenced these operational risks, demonstrating that managerial and planning weaknesses propagate into the operational stage. Layers IV (Preventive Defense) and V (Contact Defense), though contributing less, highlight the importance of technical barriers and emergency preparedness as the final line of defense. Overall, the findings emphasize the necessity of integrated, systemic safety management that strengthens both strategic and operational layers to minimize alignment failures and enhance safety maturity.

For future research, it is recommended to expand the scope beyond a single company and incorporate longitudinal studies across multiple mining operations to validate the generalizability of the SBS and Swiss Cheese Model integration. Additionally, further studies could explore the effectiveness of advanced technological interventions, such as AI-driven monitoring and predictive safety analytics, in reducing operational failures. Investigating the behavioral and cognitive aspects of workers in relation to adherence to layered safety protocols could also provide deeper insights. Such research would support the development of proactive safety strategies, facilitate continuous improvement of multilayered defense systems, and contribute to the broader advancement of occupational safety in high-risk industries.

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