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System Theory-Based Approach for Hazard Analysis and Control in a Metalliferous Mine

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Abstract

System Theoretic Process Analysis (STPA), introduced by Leveson, represents a modern hazard analysis technique capable of capturing diverse causal scenarios, including non-failure scenarios. This paper presents a case study illustrating the application of STPA for hazard analysis and control in a large metalliferous mine with both opencast and underground operations. To support this initiative, an Information Technology (IT)--enabled system called the AK Safe app was developed based on an integrated approach and system theory. This app facilitated the collection of over 600 hazard control feedback entries from the mine. These entries were subsequently analysed using system dynamic models.

Major Findings: *The study's findings are crucial in identifying inadequate or missing control measures by providing a structured method to examine system hazard control actions and feedback pathways. This analysis enables timely mitigation actions to address identified hazards effectively.*

Keywords: *AK Safe App System, Hazard Control, Key Process Control, Safety Management Plan, Theoretic Process Analysis*

1.0 Introduction

Traditionally, hazard analysis methods like Fault Tree Analysis (FTA), Failure Mode (FM), Effect Critical Analysis (FMECA), Event Tree Analysis (ETA) and Hazard and Operability (HAZOP) have been extensively applied in Indian coal and metal mines. These methods primarily aim to identify events that could lead to or contribute to accidents. However, Howard and Kelley noted that these approaches focus on factors with obvious causal relationships to potential accidents. This narrow focus often overlooks the influence of organisational structures responsible for developing and deploying safety-critical systems.

Accidents frequently result from numerous small decisions made over an extended period, gradually compromising the system's safety. By the time an accident occurs, it may seem inevitable, as different factors could potentially trigger it. In contrast, a system theory-based hazard analysis method not only encompasses all causal scenarios but also identifies a broader range, including non-failure scenarios. This approach aids in identifying inadequate or missing control measures by offering a systematic framework for evaluating control actions and feedback pathways within the system[1].

The application experience of STPA propagated by Leveson reported across industries like Automotive, Aviation, Space Systems, Chemical, Oil and Gas, Nuclear Power, Defence, Healthcare, Medical Devices, Particle Accelerators, National Labs and Universities.

In recent years, mining systems have become increasingly complex. The demand for higher productivity has led to the introduction of new technologies and methods, significantly altering human roles. In this context, the initial application of the STPA concept has

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been envisioned to address process hazard management issues in Mine - -A.

2.0 Mine - A

This mine is located on a hillock rising about 50m from a general topographical level of 580 mRL. The mining operations are fully mechanised using rotary percussive drills, rope shovels with a bucket capacity of 9.2M, hydraulic excavators with a bucket capacity of 4.5M and 10.0M^3 in combination with 50T/ 60T/ 85T/ 100T dumpers. The blasting pattern is 3m burden and 4m spacing in hard rock and 4.5 x 3.5m in medium hard rock and each hole is charged with 140kg to 180kg SMS explosive and 2-4 booster charges with the appropriate number of relays. Blast holes are 165mm in diameter and depth ranges from 9m to 15m.

The open pit workings are expected to be exhausted soon by restricting the depth of about 240m from the surface, i.e., up to 340mRL. Mining below the pit is considered after leaving a barrier pillar of 40m thickness from 340mRL to 300mRL, by mechanised underground blast hole stoping with filling method, with a targeted production of 5MT per annum.

3.0 Mine Hazard Analysis and Control - System Theory Approach

The outlined approach (after Howard and Kelley), includes the following steps:

a. Identify system hazards;
b. Evaluate system-level safety requirements and constraints;
c. Define the control structure of the mine safety system;
d. Identify insufficient process control actions that could lead to hazardous system conditions; and
e. Assess how the safety constraints of the mine system could be compromised, aiming to eliminate, prevent, or manage them in system or component design by:
    i. Developing process models for the components of the mine system; and
    ii. For each identified inadequate control action, analyse the segments of the control loop in which the controller operates to determine if they might contribute to the deficiency or absence of necessary control actions.

3.1 System Theory-Based Integrated Approach

The integrated approach and processes[2], under Indian regulatory guidelines and ISO 45001:2018 expectations, effectively address the issues organisations must manage to ensure system health and safety, as detailed in Figure 1.

Identifying key controls that must be closely monitored those that cannot afford to fail is essential. These controls should be isolated and managed to ensure their effectiveness. Key Process Controls (KPCs) must be regularly evaluated to ensure they meet established performance requirements with minimum performance thresholds set to trigger corrective action when not met. For effective control management, the roles of a custodian, verification officer and owner must be defined[2].

3.2 Mining Process and Hazard Control Framework

The analysis procedure departs from traditional hazard analyses by developing a hierarchical mining process and hazard control structure based on feedback control loops. This structure, illustrated in Figure 2, ensures that safety considerations and guidelines are effectively enforced throughout the overall mining system.

The devised control structure outlines the flow of operational instructions from the head control (mine manager) through Intermediate Control-IC (manager/ work in-charge) to Front Control-FC (supervisor). This structure includes provisions for lateral interactions at the IC and FC levels to avoid overlapping functions and ensure explicit control actions. In specific circumstances, such as mine emergencies, the head control can directly initiate control actions to the controlled process while receiving feedback.

The system proactively addresses potential issues by

a. Preventing faulty control actions due to incomplete or deficient processes and protocols;

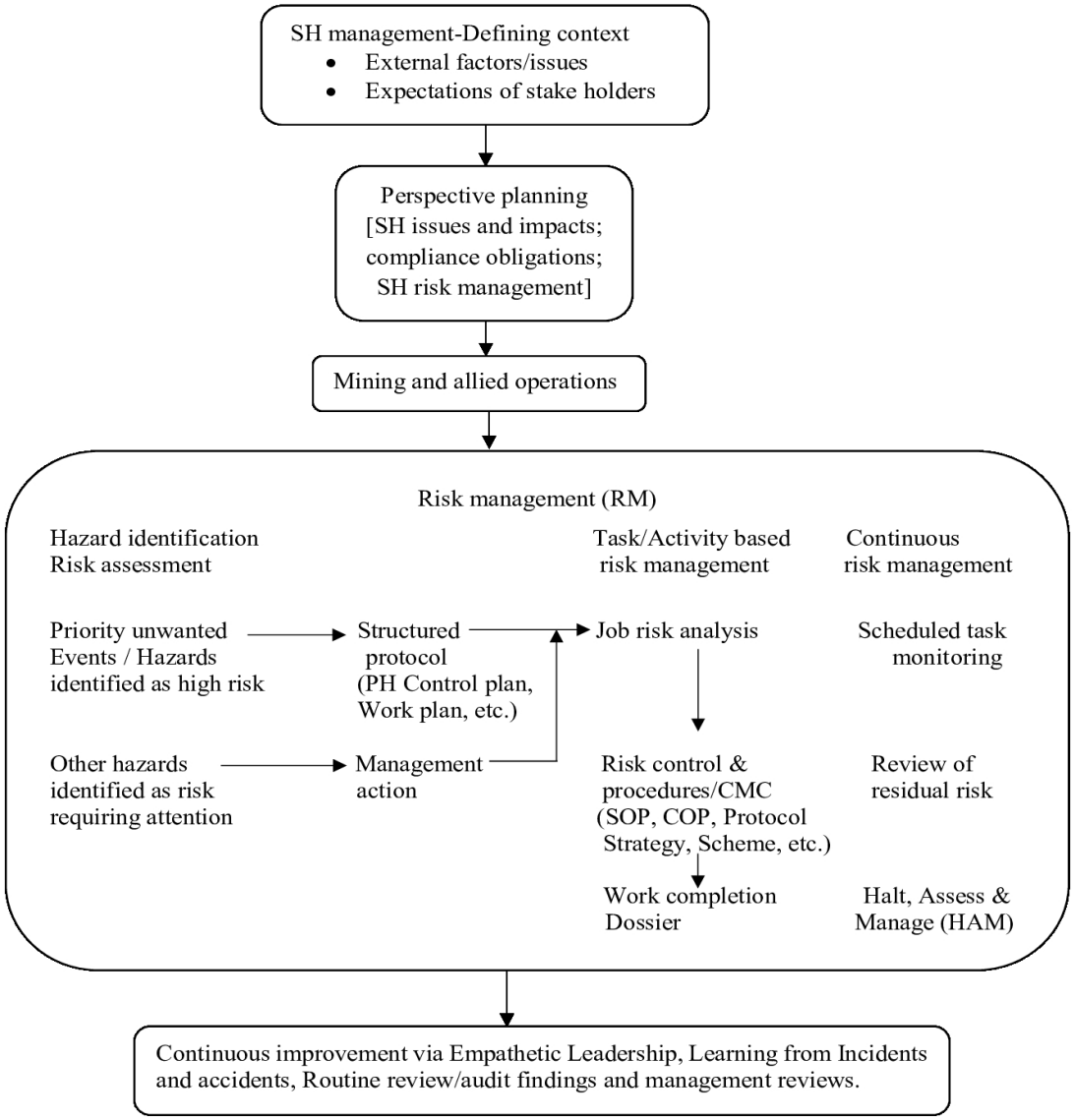


Figure 1. Integrated approach to SH Management[2].

b. Ensuring control actions are directed to the correct entities;
c. Guaranteeing that control actions are issued to entities with the necessary feedback to select safe control actions;
d. Avoiding feedback being sent to entities unable to act on it; and
e. Preventing multiple controllers from issuing conflicting commands to the same entity without detection or resolution.

4.0 OSH Management in Mine - A

In pursuance with Directorate General of Mines Safety (DGMS) guidelines[4-6], the Safety Management Plan (SMP) of the mine, was reviewed, modified and structured, with the formulation of (a) eighteen principal hazard identification and control plans and (b) thirty-eight work plans for mitigation of identified principal hazards. The SMP-Principal Hazard Management Plan (PHMP) was developed by adopting the Integrated

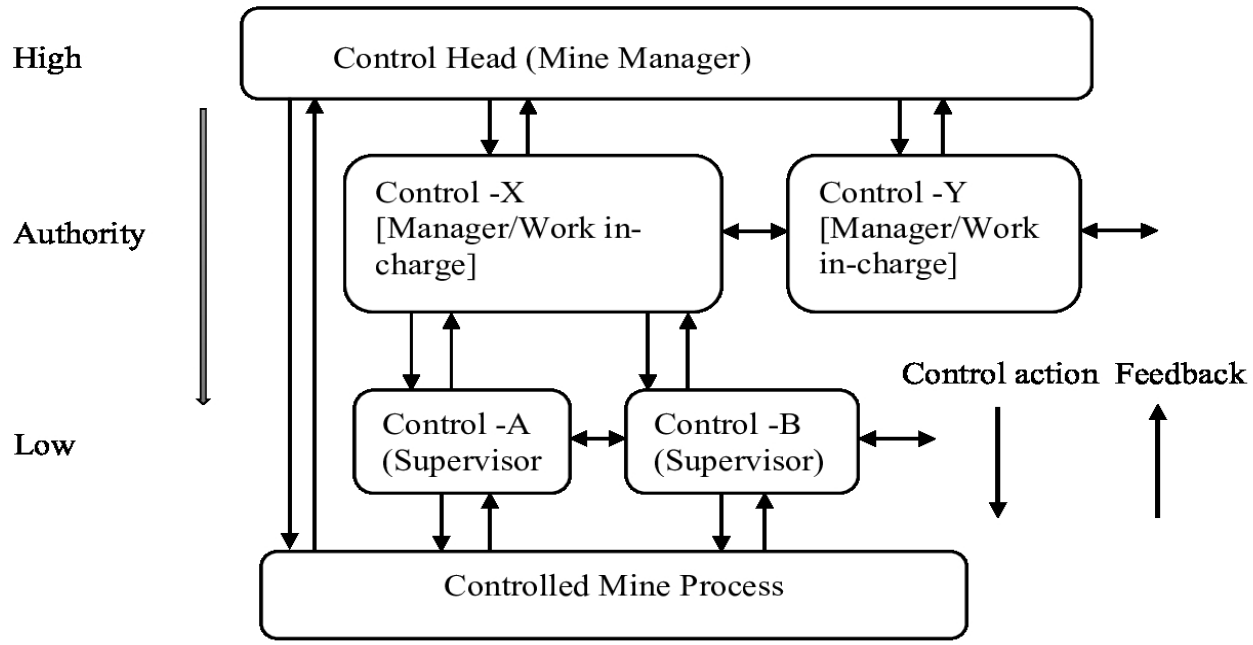


Figure 2. Mining process and hazard control structure[3].

Approach (IA)[2] and system theory. For principal hazard analysis and control, the STPA[7] approach was used.

4.1 Hazard Identification

A formal interaction was held with different categories of workers, supervisory staff and assistant managers both departmental as well as contractual to get to know their perception of hazards associated with different mining activities in the mine. Hazard identification has been done through work process evaluation, consultation with the employees and previous experience of accidents/ incidents at the mine, in respect of following work processes/systems.

(i) Mining pit and dump area operation (Strata control and Danger of inundation)
(ii) Movement of transportation machinery
(iii) Drilling and blasting area operation
(iv) Electrical shutdown;
(v) Underground mine operation (Strata control and Danger of inundation)
(vi) Trough blasting operation (underground workings).

Workplans and protocols contain, among others, details of task(s) to be accomplished for mitigation of hazards with functions of a different competent person(s) responsible for executing the same.

For effective hazard control, inputs from Work plans have been assimilated into the following protocols:

Table 1. Work plans and protocols

Sl. No.	Protocol Details	Work Plan Reference
1.	Protocol for mining pit (strata control) and dump area operation.	Nos. 1 -10
2.	Protocol for drilling and blasting area operation (opencast workings).	Nos.11-17
3.	Protocol for movement of transportation machinery.	Nos.18-24 and 28-31

4.	Protocol for electrical shutdown.	No. 25
5.	Protocol for underground mine operation (regarding strata control).	Nos. 26-27
6.	Protocol for underground mine operation (with reference to the danger of inundation).	Nos. 32-33
7.	Protocol for trough blasting operation (underground workings).	Nos. 34-38

The above protocols were developed by extensive consultation with stakeholders and, in due consideration of current regulatory stipulations, DGMS guidelines and SOPs/COPs developed by mine management.

4.2 Hazard Mitigation

In this step, analysts determine how potentially hazardous control actions can lead to violations of safety constraints. Safety constraint violations were prevented through system design or operational procedures. More ways to enter the hazardous state will be identified as the system design progresses, leading to additional safety constraints[1].

Keeping the above in view, the mitigation scheme for identified principal hazards (including sub-hazards, as the case may be) included the exercise of specifying mechanisms, controls and procedures for each of them. The responsibility was fixed, for completion of each procedure through a work plan with a declared timeline.

5. IT-enabled Process Hazard Control Framework

An IT-enabled process control framework, known as the AK Safe app, has been developed to provide proactive online control monitoring with digital data storage and retrieval capabilities. It is equipped with powerful analytics to assist in making timely and quality safety decisions.

For each identified hazard, there are one or more controls that require close monitoring and verification, ranging from engineering to administrative controls. Before starting a work process, lead operators use a questionnaire to check that the identified controls are in place, answering a series of yes/no questions on a task-by-task basis. In a layered process, supervisors routinely verify the presence of these controls on a shift-by-shift, daily, or weekly basis. Additionally, managers, workplace in-charges, and safety officers review the design and implementation of the controls.

5.1 Process Hazard Control Questionnaire

Drawing inputs from the developed PHMP, including work plans and protocols, a hazard control questionnaire based on STPA with safety constraints was created by a group of field professionals and domain experts in extensive consultation with stakeholders. The basic control structure was enhanced with process models for each control component, using formal yet easily readable models to examine both component behaviour and interactions between components.

Aligned with the doctrine "we trust but verify," the process is interactive and participative. Feedback from key officials is recorded at the execution level and verified at the supervisory and managerial levels. Detailed information about the mine process control structure is provided in Table 2.

The results of the process are incorporated into the PHMP to validate the effectiveness of current controls and identify the need for improvements. These results are recorded in a central database, where appropriate analytics classify deviations in controls and their trends, providing a roadmap for timely rectification. Additionally, the process emphasises the necessity of conducting education and training programs related to specific areas of principal hazard control.

The control analytics embedded in the questionnaire can:

a. Determine the absence of controls.
b. Assess the inadequacy of controls.

Table 2. Mine process control structure

Sl. no	Designation of officials	Number of questions	Feedback (Execution level)	Feedback Verification (Supervisory)	Feedback Verification (Managerial)
1.	Driller	08	√		
2.	Driller Helper	05	√		
3.	Blaster	22	√		
4.	Blaster helper	06	√		
5.	Explosive Van Driver	20	√		
6.	Guard	09	√		
7.	Magazine Clerk	13	√		
8.	Vehicle/Tipper Operator	39	√		
9.	LPDT Operator	26	√		
10.	Electrician	06	√		
11.	Receiving Station Operator	07	√		
12.	Passenger Carrier Operator	13	√		
13.	Blasting Foreman	31		√	
14.	Mining Mate	04		√	
15.	Contractor Mech. Foreman	35		√	
16.	Geological Supervisor	07		√	
17.	Electrical Supervisor	10		√	
18.	Shift In-charge (General)	48		√	
19.	Surveyor	24		√	
20.	Assistant Manager	49			√
21.	Safety Officer	18			√
22.	Geotechnical Engineer	06			√
23.	Security Officer	02			√
24.	Contractor Asst. Manager (Drilling and Blasting)	18			√
25.	Contractor Shift In-charge	41			√

26.	Drilling and Blasting In-charge	30			√
27.	Contractor Asst. Manager	29			√
28.	Mechanical In-charge	11			√
29.	Contractor Proj. Manager	11			√
30.	Engineer In-charge	02			√
31.	VT In-charge	10			√
32.	Contractor Elect. Engineer	02			√
33.	Mine Geologist	13			√
34.	Contractor Mech. Engineer	07			√
35.	Mine Manager	64			√

c. Identify unsafe control actions.
d. Detect flawed implementation of controls.

A system has been implemented to examine the background of unsafe behaviour such as commands dispatched but not received or unsafe commands dispatched.

6. Mine Process Hazard Control Audit by AK Safe App

In line with regulatory requirements, DGMS guidelines[4-6] and stipulations of IS 14489:2018, developed guidelines for the review/audit of the SMP[8], which was used for carrying out the hazard control audit by AK Safe app, in Mine-A.

The audit team comprising auditors, with different specialised backgrounds (e.g., mining, electrical, mechanical, etc.) with requisite experience was constituted, led by an Occupational Safety and Health (OSH) expert of repute.

The Audit Information Questionnaire (AIQ) was completed in consultation with key mine officials, guided by the audit team. The interactive audit process involved verifying that identified controls were in place according to the prescribed protocols. This was achieved by interviewing lead operators, supervisors and managers/ workplace in-charges and by answering a series of yes/no questions on a task-by-task basis using the AK Safe App on a web-based platform. This process was followed by a field visit for verification.

The dedicated information questionnaire (IA) for Mine - A containing 600+ questions enabled examination of roles and functions of lead operators/cutting-edge personnel, supervisors and managers/workplace in-charges who routinely execute and verify those system controls and also identify the gaps/deviations in managing the controls.

The analysis of audit feedback in the mine through system dynamics models is recorded as positive feedback, or reinforcing loops, negative feedback or balancing loops and delays with suitable remarks in each case[1]. The process of hazard control in mines is dynamic as the geo-mining environment changes frequently, a component of field visits has been considered for the mine along with the basic building blocks of system dynamics models, which is a useful tool to assess the maturity of the developed socio-technical system.

Reinforcing loops, also known as positive feedback loops, are mechanisms that promote growth, amplify deviations, and solidify change within a system. An analysis of 78 Key Performance Criteria (KPCs) within the mine highlighted three primary lead performance indicators: (a) conducting refresher training/retraining, (b) maintaining electronic records/ registers, and (c) conducting periodic electronic reviews.

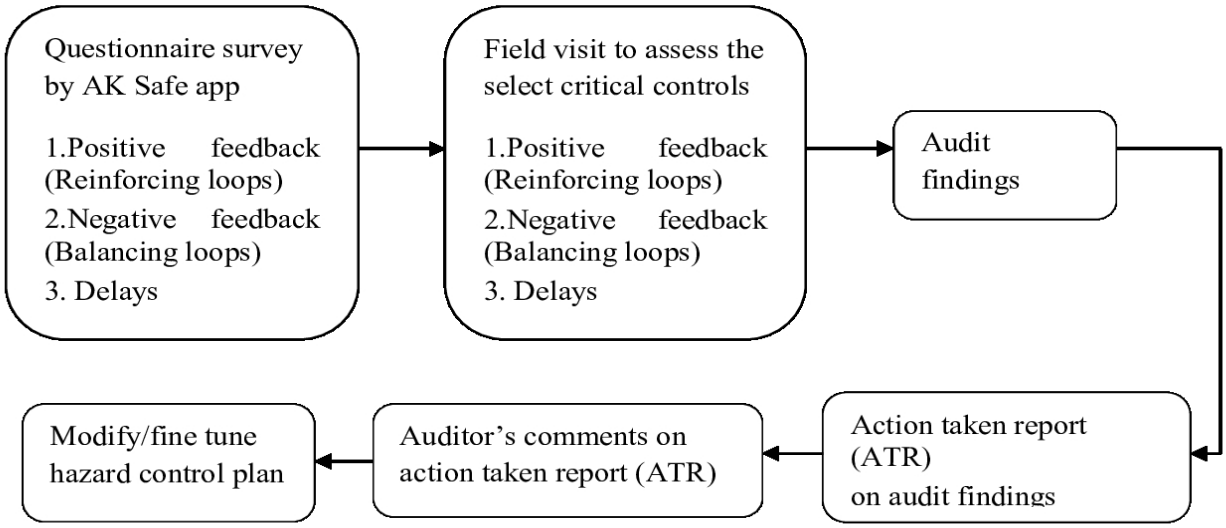


Figure 3. Flow chart for mine hazard control [modified after Howard and Kelley].

In contrast, a balancing loop (negative feedback) acts to adjust the current value of a system or reference variable. It addresses discrepancies between the current and desired values by perceiving the difference as an error. Actions proportional to the error are implemented to reduce it, gradually bringing the current value closer to the desired one. An analysis of 44 KPCs that demonstrated negative feedback within the mine necessitated improvement actions across seven critical areas.

The third fundamental element, delay, represents the time interval between cause and effect. Delays in a system complicate the correlation between cause and effect and can lead to unstable behaviours.

Field visits for on-the-spot verification have been considered for the mine along with the basic building blocks of system dynamics models, which is a tool to assess the maturity of the developed system.

The feedback facilitated a thorough mapping of Process Controls (PCs) and KPCs, organised according to their mitigation status and the degree of observed deviations. This mapping serves as a basis for initiating further management actions. Additionally, the feedback played a pivotal role in conducting a safety training needs analysis for essential personnel within the mine. Furthermore, it will support the evaluation and necessary revision of the PHMP, encompassing work protocols and guidelines. These revisions aim to enhance the system through added value and fine-tuning.

7.0 Results and Discussion

Key officials' feedback on the system control monitoring status, observation during field visits by the audit team for sample/test check, discussion and meeting on the execution of the PHMP along with procedures/process and demonstration of system control monitoring preparedness in respect of nine identified principal hazards, and auditor's observations, reflecting the status of conformity or otherwise were uploaded digitally through AK-Safe for mine process hazard control audit.

Decent practices and deviations in system control measures were mapped in detail, which empowered mine management to identify areas for improvement or corrective action.

The feedback of key officials indicated no deviations in the case of 81% of PC's, whereas varied degree of deviations was observed for 19% of PC's.

7.1 Audit Recommendations for No Deviations

Audit recommendations for qualitative improvement in the management of KPC where no deviations were recorded, are as under:

a. e-review to be conducted in 24% of cases.
b. Special refresher training to be conducted in 23% of cases.

c. e-record to be maintained in 19% of cases.
d. e-review to be conducted + e-record to be maintained in 10% of cases.
e. e-review + special refresher training to be conducted in 05% of cases.
f. System modification and management in 04% of cases.
g. e-record to be maintained + special refresher training to be conducted in 02% of cases.
h. Miscellaneous action in 13% of cases.

7.2 Audit Recommendations for Varied Degrees of Deviations

Audit recommendations for effective management of KPC where varied degree of deviations was recorded, can be summarised in the following areas:

a. System development, implementation and e-review.
b. Process preparation and e-record.
c. Conduct of training/re-training.
d. Variance with standards.
e. Assessment of vehicle operator's fatigue.
f. Conduct of noise and illumination survey.
g. Job Supervision.

7.3 Audit Observations Regarding Field Visits

Audit observations regarding field visits revealed that gap in control management reporting and the status of implementation. By fine-tuning the integrated approach by gaining more experience, the gap will tend to reduce.

8.0 Conclusions

In a pioneering application within the metalliferous mining sector, STPA was utilised at Mine-A to conduct a hazard analysis. This approach aimed to identify system-level hazards, determine causal factors and establish constraints to ensure safe operations.

The IT-enabled process control system AK Safe app emerged as a valuable tool in Mine-A, facilitating continuous monitoring and enabling timely interventions to address deviations in the management of PCs and KPCs. It played a pivotal role in successfully conducting the principal hazard control audit at Mine-A. Moreover, the AK Safe app was instrumental in structuring vocational training schedules for the mine based on a safety training needs analysis conducted as part of the PC/ KPC management initiative.

The executable STPA application developed for mine hazard analysis and control shows promise for broader applicability, albeit with adaptations to hazard control protocols and questionnaires tailored to various geological and mining contexts.

9.0 References

1. Howard. J, Kelley KA. Notation supporting systems-Theoretic hazard analysis technique; Safeware Engineering Corporation.
2. Sinha AK. An integrated approach to safety and health management in Indian mines. Copyright registration no: L-97924/2020 dated 23.12.2020; Extract from the register of Copyrights, Copyright Office, Government of India; 2020
3. Sinha AK. IT-enabled safety management framework in Indian mines. J Mines Met Fuels. 2021; 69 (12):439-44.
4. DGMS (Tech.) (S and T) Circular No. 05, dated 2nd April 2016, titled Integrated approach for development of safety management plan for coal and metalliferous mines; 2016.
5. DGMS (Tech.) Circular No. 03, dated 23rd December 2019, titled Guidelines for implementation of safety management plan in mines; 2019.
6. DGMS (Tech.) Circular (MAMID) No. 08, dated 29th April 2020, titled Recommendations of 12th national conference on safety in mines held on 28 and 29th January 2020 at New Delhi; 2020
7. Leveson NG, Thomas JP. STPA Handbook; 2018.
8. Sinha AK. Review/audit framework for Safety Management Plan (SMP) including a principal hazard management plan (PHMP) in coal and metal mines based on regulatory guidelines and (IS) 14489-2018. Copyright registration no: L-120079/2022 dated 22.12.2022; Extract from register of copyrights, copyright office, Government. of India; 2022.