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An investigation on emergency response system during Anjan hill coal mine disaster using control task analysis – a cognitive approach

The accidents due to gas and coal dust explosion are one of the most common and serious accidents in underground coal mines. A lot of different scientific and physical indications and signs alarms before any accidents. Disasters management is both reactive and proactive. The proactive management deals with various steps taken to prevent and eliminate any disaster. Whereas, reactive management, on the other hand, deals with the actions taken to reduce the damage caused by a disaster, mitigate sufferings, take up recovery measures, organize rehabilitation, bring normalcy of different operations in the mine, disseminate prompt information to relatives of the victims, civil authorities, print and electronic media and people living nearby. Therefore, in any emergency situation the emergency response system (ERS) plays the most crucial part. An efficient ERS can potentially save an emergency situation to turn into a disaster or serious accident. In this paper, a case study conducting control task analysis (CTA) to investigate into the emergency response system during Anjan hill coal mine disaster is presented. Inquiry reports of Anjan hill coal mine disaster has been used to identify the problem and know the current state of the system. Results of CTA are used to identify constraints in the system. The analysis has brought out recommendations to improve EMS.

Keywords: ERS, CTA, mine disaster, CWA.

1.0 Introduction

Coal plays an important role in the supply of energy worldwide for producing heat, electricity and other valuable industrial products over the past few centuries. To date, coal still represents approximately 27.6% of the total primary energy supply in the world (Zhao et al. 2019). According to statistics, in 2018, the total coal consumption in the world was 3.772 billion tonnes of oil equivalent. However, the discrepancy between its economic and environmental states has become increasingly prominent (Cattaneo et al. 2011). Coal resource endowments and long-term high demands have led to an increase in mining intensity and a decrease in the amount of shallow resources (Yuan 2016). Most mines are gradually entering a state of deep resource exploitation using underground mining technique. Many underground coal mines in India are gassy mine, and the coal dust in coal mine have explosion risk (LI and HU 2005). Study on analysis techniques of material evidence upon accident investigation of gas and coal dust explosion can verify the accident development process and the cause of the accident. The main work of accident investigation and analysis is to collect field trace, material evidences and determine the properties, locations and causes of accidents more accurately (Zhang and Chen 2009). Through the research of material evidence analysis measures and methods of accident investigation, it is helpful to further perfect the technical system of accident investigation and safety production standard system, form technical specifications providing technical support for coal mine safety production and national safety production supervision and monitoring (Durga and Swetha 2015).

In the process of mining and tunnelling, gas and coal dust universally exist in various workplaces (Si et al. 2012). Although safety awareness and supervision level of coal mine enterprise increased gradually and coal mine safety situation has much improvement, coal mine explosion accidents occur continuously still result from the complicated geological conditions, improper operation and inappropriate emergency response system (Dash et al. 2017).

Coal mining, under the guise of a system, is a complex socio-technical system characterized by large number of human and non-human interrelated components. The emergency management system of the mine is even more complex socio-technical sub-system with additional characteristic of dynamism, uncertainty and very high risk (He et al. 2019; Onifade 2021). In Indian context, the statutory body stipulates regarding emergency plan in which emphasis is given on general duties and responsibilities of mine officials. Regulations or circulars are generally silent on quality of decisions, methodology and support system for the decision makers (Kumar 2010).

Effectiveness of the emergency management system has

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been questioned time and again by inquiring authorities conducting public inquiry into disasters in coal mines. Some observations of public inquiries are mentioned below.

2.0 Observation of public enquiries of some similar disasters in past

Observations of public enquiries of some similar disaster as Anjan hills were discussed to relate the importance of ERP.

The observation of the Governor's independent investigation panel in upper big branch disaster (USA, 2010 claiming 29 lives) is as below:

"Life and death decisions – whether to send rescuers in or pull them back – are questioned, discussed and second-guessed, allowing the emotion of the moment to infringe upon the detached discipline and scientific approach that forms the basis of mine rescue. At its core, mine rescue is best served when decisions are based "on the numbers," the raw data as to the toxicity of the atmosphere and the potential for secondary explosions or fires. The emotion generated by media reports should not ever be a factor in those decisions. The mining community needs to address the rescue and recovery system in light of the new challenges presented by technology and the now ever-present media. Dilemma over the decision of deployment of rescuers under the unimaginable stressful condition which occurs after a disaster is a common phenomenon across the globe. The first priority and duty of officials in the command center (control room) must be safety of mine rescuers."

In its finding #8 the Panel made observation that "The emergency response to the upper big branch disaster raised concerns about how decision-making was conducted in the command centre and the manner in which mine rescue teams were deployed underground. Standard protocols were not followed, effective records were not kept and lives of rescuers were placed in jeopardy" (McAteer et al. 2011).

2.2 Observation in Moura No.2

The similar problem as the case was in upper big branch disaster was also mentioned in the Moura No.2 inquiry task group 4 (mines rescue strategy development) report stating; "Knowledge of conditions in a mine following an incident is essential in planning any rescue effort. Information systems must be provided to support implementation of the most appropriate rescue measures" (Moura No.2).

2.3 Raspadskaya mine explosion, Russia in 2010

20 rescuers lost their lives who were sent down the mine to carry out rescue work, due to second explosion that occurred within few hours following the first explosion. Very little information and data is available in public domain pertaining to Raspadskaya Disaster.

Report of Court of Inquiry into Anjan hill mine disaster (India, 2010, claiming 14 lives including 4 rescuers) recommended that:

2.4 Recommendation 10.8 Protocol/guidelines for rescue operations

"There does not seem to be clear cut guideline/instruction as to the circumstances under which even the rescue team should be withdrawn from underground mine and at what stage the rescue team could be sent to underground when mining operation is suspended. From the material which has come on record, it appears that entire discretion is left on the officer who is in-charge of the site. In the instant case, evidence indicates that late S.K. Goswami (one of the deceased in the disaster) took decision to send rescue teams to the underground mine and send persons to collect air samples from the underground mine on the morning of 6th May 2010. In this background, the Court of Inquiry is of the opinion that it is appropriate to recommend for developing well informed guidelines/instructions after thorough study regarding various aspects of mining operations and anticipated hazards." (Report of the Court of Inquiry constituted by Government of India (Ministry of Labour and Employment) by means of notification dated 28th February 2011).

From above discussion it can be concluded that emergency management system of a coal mine is very complex socio-technical system. When situation warrants to activate the system, it has performed below the expectations on many occasions, which is highlighted by public inquiry authorities of many countries in the inquiry reports. It has also been recommended by the inquiry authorities to develop a more effective emergency management system to help industry cope with emergent situations in more efficient way to save precious human lives.

The current system of emergency management is derived from the inquiry reports of Anjan hill mine disaster, by referring available literature and by interviewing subject matter experts (SMEs). The system is then analysed and evaluated with a phase of Cognitive Work Analysis (CWA) i.e. control task analysis for its efficiency in meeting the goals. Based on the analysis result recommendations are made for improving the system.

3.0 Case study of Anjan hill coal mine disaster

Situated at latitude and longitude of 23009'54" to 23011'00" (N) and at longitude 82011'40" to 82018'55" (W) respectively, Anjan hill mine of Chirimiri coalfields is close to a mining township of Chirimiri of Korea district in Chhattisgarh State. The coalfield is characterised by hilly terrain with scarps and is very densely forested as can be seen in the picture taken from google earth (Fig.1). The coalfield is under dense forest cover (Picture-A) and steep undulations in the surface. The central part has ground altitude varying from about 600 m to 870.00 m from eastern to central of the Anjan hill (Fig.2).

The topmost coal seam in the mine is '0' seam, which is split into three sections. These sections are named as bottom,

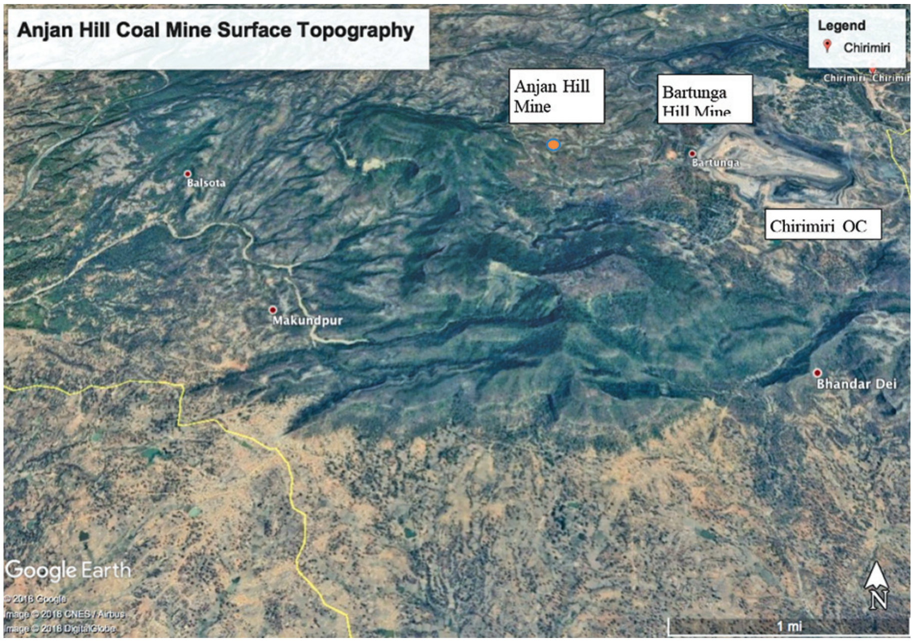

Fig.1: Bird's eye view of Chirimiri Coalfield (Source: Google Earth)

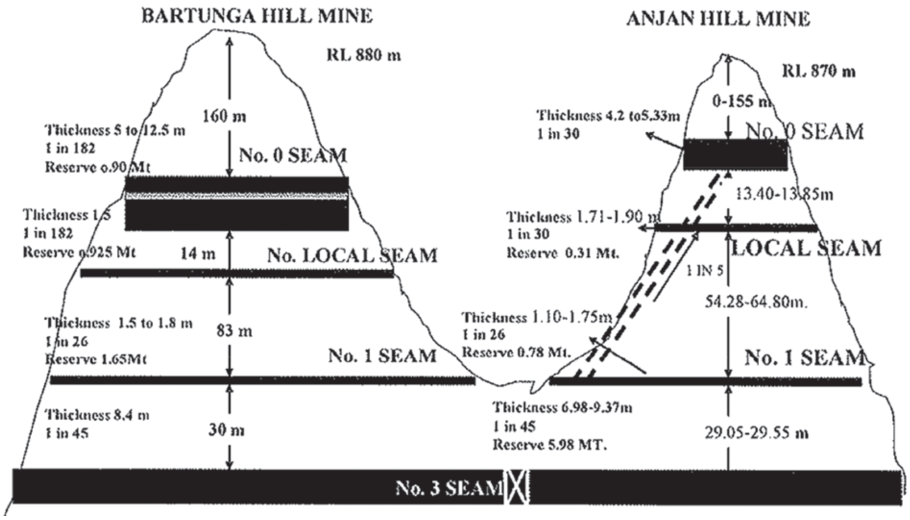

Fig.2: Section showing surface and seam profile (DGMS, 2010)

middle and top section. As top and middle sections are not exploitable due to low thickness they are not worked. Only bottom section was being exploited. No.II seam is worked simultaneously as it is very thin and combined with No. III seam in the mine boundary area of Anjan hill mine. Because of hilly terrain and scarp sides the thickness super incumbent strata above '0' seam varies between 0 to 160m. As other seams are almost parallel to each other hence exhibit similar characteristics. Neighbouring Bartunga hill coal mine and Anjan hill coal mine have common boundary.

3.1 The disaster

A massive explosion rocked Anjan hill mine approximately at 11:30 hours of 6th May 2010, resulting 14 casualties. Injuries of serious and minor nature was received by 31 other miners, five of them were serious.

3.2. Background events

Till afternoon of 3rd May normal operations were going on in the mine. Result of routine air sample exercise was received by mine in afternoon of 3rd May 2010, which showed presence of carbon monoxide (CO) outside old sealed panel A1 which was adjacent to the A2 panel in which coal winning operation was going on. All the key officials of coalfield and the mine assembled to meet which included line and staff functionaries. Incident management team (IMT) was formed including senior officials of area, in-charge of rescue services and mine officials.

3.3 Chronology of events

The chronology of events that took place along with decisions taken by the IMT is shown in the Table 1.

4.0 Methodology

The cognitive work analysis (CWA) was originally developed by Rasmussen et al. in 1994 (Rasmussen et al. 1994). The framework was used by RisÆ National Laboratory, in Denmark to consider suitability of nuclear power programmeme (Rasmussen et al. 1990). CWA is formative methodology which focusses on 'how work can be done' rather than 'how work should be done'. Hence the CWA provides solution in terms of a number of options for the workers to carry out the task rather than providing typical standard methodology for doing it. Thus it accommodates dynamism of the scenario giving more realistic solutions. The uncertainty in the real life work scenario is also taken care of by this method without compromising or deviating from overall goal of the system.

CWA is chosen for analysis in this study because it provides a structured process of analysing complex socio-technical system. Five phases of CWA offer opportunity to understand different constraints of the system, which in turn helps in better designing or redesigning of a system. As per vicente (1999) phases of CWA are as under (Vicente 1999):

- Work domain analysis

Table 1: Chronology of events at Anjan Hill mine with respect to disaster (Singh, Chandra Shekhar, 2018).

Date	Time	Location	Gas analysis report	Observations	Action taken/omission by IMT
2-May-10	1:00 PM	A1 Panel outside isolation stoppings.	CO-416 ppm, ethylene-43 ppm, hydrogen-.09%	Routine gas sample was taken. Report of GC received on 3rd May	
3-May-10	1:00 PM	A1 Panel outside isolation stoppings.	CO-1262 ppm, ethylene-138 ppm, hydrogen-0.27%, CH_4-0.24%	Report of GC received in the evening.	After receiving the report, a team was sent to validate the report by measuring again by handheld multi-gas detector.
	2:00 PM	A2 Panel Intake and return airway.	CO-5-15 ppm	A1 panel is on the intake side of A2 Panel readings were taken in intake and return airway of A2 panel	Normal production work continued.
	9:00 PM	A1 Panel Outside isolation stoppings.	CO>2000 ppm, CH4-0.34-0.7%	Readings of GC validated by the team using handheld multi-gas detector.	Strengthening of existing stoppings and erection of additional stoppings out-bye of existing stoppings under supervision and support of rescue team. Normal production work in A2 panel suspended.
4-May-10	1:00 PM	A1 Panel outside isolation stoppings.	CO-300-400 ppm	Plastering of existing stoppings reduced concentration of CO.	Production work in A2 Panel resumed. Work of erection of additional stopping continued.
5-May-10	9:00 AM	A1 Panel outside isolation stoppings.	CO->2000 ppm, CH_4-1.34%	Rescue team providing cover to groove cutting work for erection of stopping observed high concentration of CO and CH_4 out-bye of one isolation stopping of A1 Panel.	Normal operation continued.
	4:20 PM	Belowground		Belowground people felt sudden gust of air as a result cloud of dust formed in mine and was seen from all the mine entries	Mine officials present belowground visited A1&A2 Panel to see if there is any major roof fall causing this sudden gust of air. Found nothing unusual in both the locations.Investigation for reason of sudden gust of air not done and no specific conclusion was drawn.
	7:00 PM	Main return of the mine	CO-5521 ppm, CH_4-0.261%, CO_2-0.99%, Ethane-100 ppm, Ethylene-68 ppm		Comprehensible symptoms of blazing fire of advance stage in some location in the mine was overlooked and no specific action was taken.
	8:15 PM	Belowground and surface		Sudden gust of air felt belowground and surface with similar characteristics that of 4:20 PM. No burning or petrol like smell was felt.	Once again reason for sudden gust of air was not further investigated and no specific conclusion was drawn. Main focus was on seat of fire around working panel. Two officials were sent down the mine to collect samples form return airway of all the three individual seams.

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Date	Time	Location	Gas analysis report	Observations	Action taken/omission by IMT
	10:00 PM	Return airway seam III	CO-<2000ppm, Methane-1.25%, CO_2-2.3%, O_2-15.1%	Reading showed normal environment in Seam-I & Local Seam. Typical coal distillation smell was felt by officials. It is a clear symptom of blazing coal fire in advance stage in some part of Seam-III but not near Panel A1 or A2.	Further investigation was not done to identify the seat of fire.
	10:15 PM	Belowground and surface		Sudden gust of air felt for the third time belowground and at surface. People at surface and underground felt burning or petrol like smell.	Emergency evacuation of the mine was carried out. Normal production work was suspended in the mine (all three seams). At about 1:00 AM, team of rescue trained persons (RTP) sent to collect samples from main return airway of individual seams i.e. seam 0, seam I and seam III.
6-May-10	1:20 AM	Belowground		Sudden gust of air felt For the fourth time the sudden gust was felt belowground and at surface. RTPs encountered this and somehow came back to surface under almost zero visibility condition due to coal dust in the mine atmosphere.	Was not clear about the repeated occurrence of such sudden gust of air. Probability of explosion was not considered. Two teams were formed to visit one each to underground and surface locations to find out problem areas and the problem.
	3:00 AM	Return airway seam III	CO->2000ppm, CH_4-0.6%, CO_2-0.9%, O_2-18.8%	Indication of blazing fire reconfirmed in Seam-III. Other two seams were normal.	Team of officials sent to surface area over mine workings (forested hilly terrain) to report after sunrise.
	6:00 AM	Surface area of the mine		Potholes were observed away from area above Panel A1 and A2. Carbon Soots like black material observed on boulders near pothole.	Probability of explosion was not investigated. Two rescue teams with 6 RTPs in each team were sent down the mine to make inspection and take readings with hand held gas monitoring equipment.
	8:30 AM	A1& A2 Panel	CO-313 ppm, CH_4- Nil	Team members found that belt pieces (component of temporary ventilation stopping) knocked out of place, falling in the direction which suggested that gust of air was initiated further north of the A1 & A2 Panel.	Reason for dislodgement of temporary stoppings were not further explored. Probability of explosion was still not explored even though there were clear indications through repeated gust of air, potholing at surface, presence of soots on surface through potholes, dislodgement of temporary stoppings etc.One rescue team was called back to surface and other team was stationed near A1 & A2 Panel. Later, two persons from rescue team stationed belowground were asked to come out of the mine bringing self-rescuer breathing apparatuses provided to team. Two persons were deployed in Seam-III for collecting mine air samples from main return airway.

Date	Time	Location	Gas analysis report	Observations	Action taken/omission by IMT
	10:15AM	Surface area of the mine		Three potholes observed away from the area above A1 & A2 Panels. About 1m long open flame was coming out of the pothole.	Focal point of IMT's attention was seat of fire. Continually ignored the possibility of explosion. Could not identify the real hazard of explosion and its associated risk level. IMT decided to form two teams to inspect underground and surface sites of probable problem. The mine portals were not cordoned off and access to portal areas were not controlled. Huge number of work persons including Key personnel of IMT were assembled at the mine portal.
	11:30 AM	Belowground and surface		Massive explosion rocked the mine. Air under extremely high pressure containing burnibg coal dust at extremely high temperature ejected through mine entries to the surface. Four RTPs and two persons engaged sampling lost their lives belowground. Eight people, including key persons of IMT, standing near mine entry lost their lives. At surface, five persons received serious injuries and 26 persons received minor injuries.	

- Control task analysis
- Strategies analysis
- Social organisation and cooperation analysis
- Worker competencies analysis

The work domain analysis (WDA) reveals the purpose, values and priorities, functions, processes and physical objects of a system or work domain. Control task analysis (CTA) is used to analyse activity of a system in work domain term or decision making term and identifies control tasks. Strategies Analysis (SA) is used to identify different strategies or options available to carry out a task. This exercise gives opportunity to identify and choose best available strategy in a given situation. Social organisation and cooperation analysis (SOCA) deals with analysis of work distribution and allocation. This also deals with communication requirements. Worker competencies analysis (WCA) assesses perceptual and cognitive requirement of human components of the socio-technical system.

For the purpose of this study the WDA and CTA are used to analyse activity of a system in work domain term or decision making term and identifies control tasks. The questionnaire were prepared using critical decision method (CDM) and prompt questions were derived from for different steps. Input of SMEs a sought to define the 'should be' system by involving them in the Abstraction Hierarchy (AH) and decision ladder exercises.

5.0 Work domain analysis

To model purposive and physical context within which the system operates, WDA is used. The abstraction hierarchy diagram as given in Fig.3 is developed with input from synthesis of the accident inquiry reports and input from SMEs (Subject Matter Experts). The Functional Purpose of the system was derived as

- To prevent human casualty
- To prevent losses to the mine.

Former being primary purpose and later secondary goal. Only primary purpose has been considered for the analysis so as to focus the analysis on saving precious human life.

The relationships between different levels of abstraction in AH are means - ends relations (Naikar 2005). The relation is characterized by how-what-why triad. The purpose related function 'assessment of risk' (what) is to minimize risk to miners below ground (why). The risk can be assessed by collecting mine air data, analysing and interpret data and interpreting level of risk (how). The nodes of the AH are linked to above level node to describe 'why' it is there. The node linked to below level node describes 'how' to do it. The physical objects as shown in the diagram are used perform processes. Fig.3 describes how the EMS 'should be' to deliver optimum result.

Fig.4 describes the system 'as is'. Human life could not

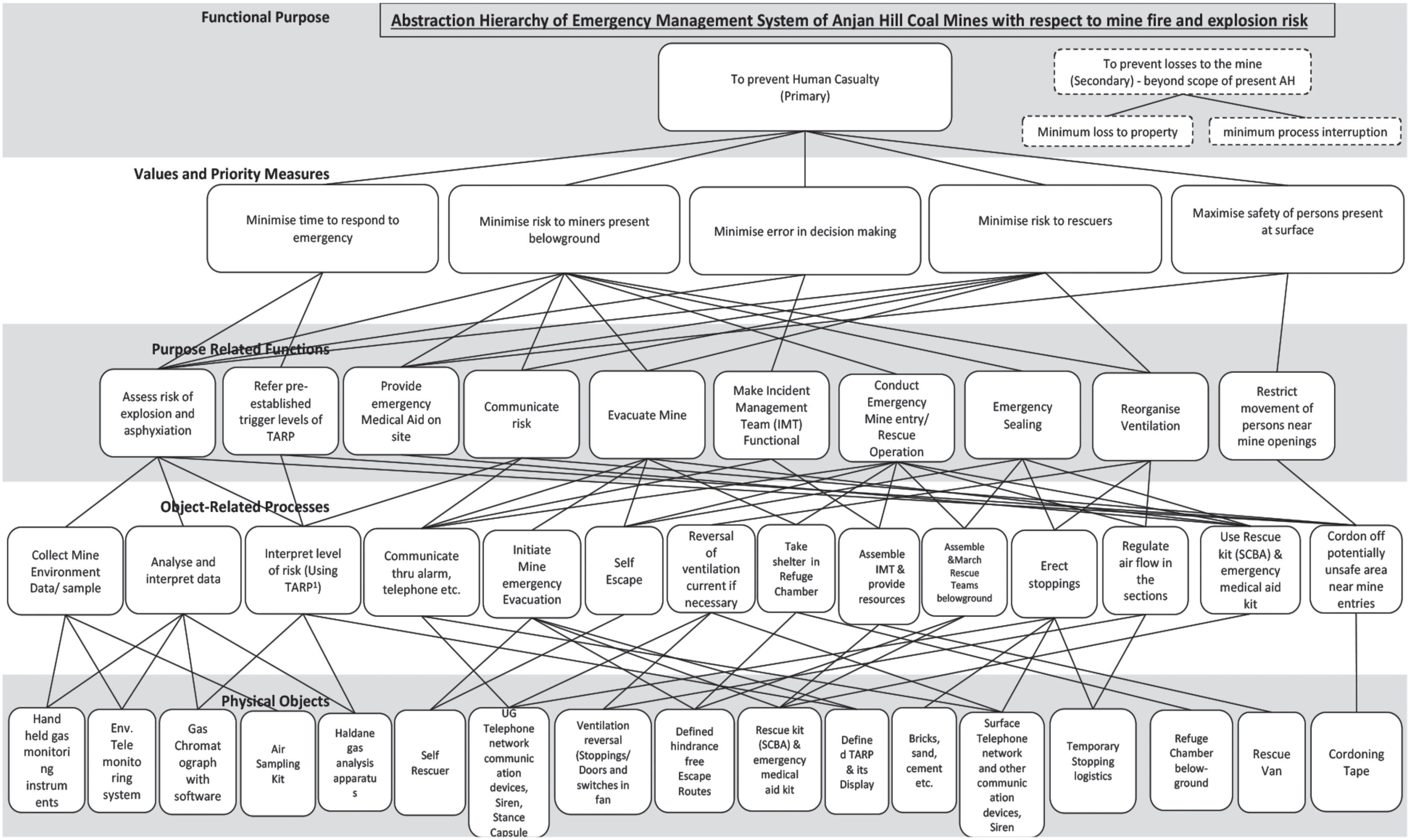

Fig.3: Abstraction Hierarchy for emergency management system ('should be')

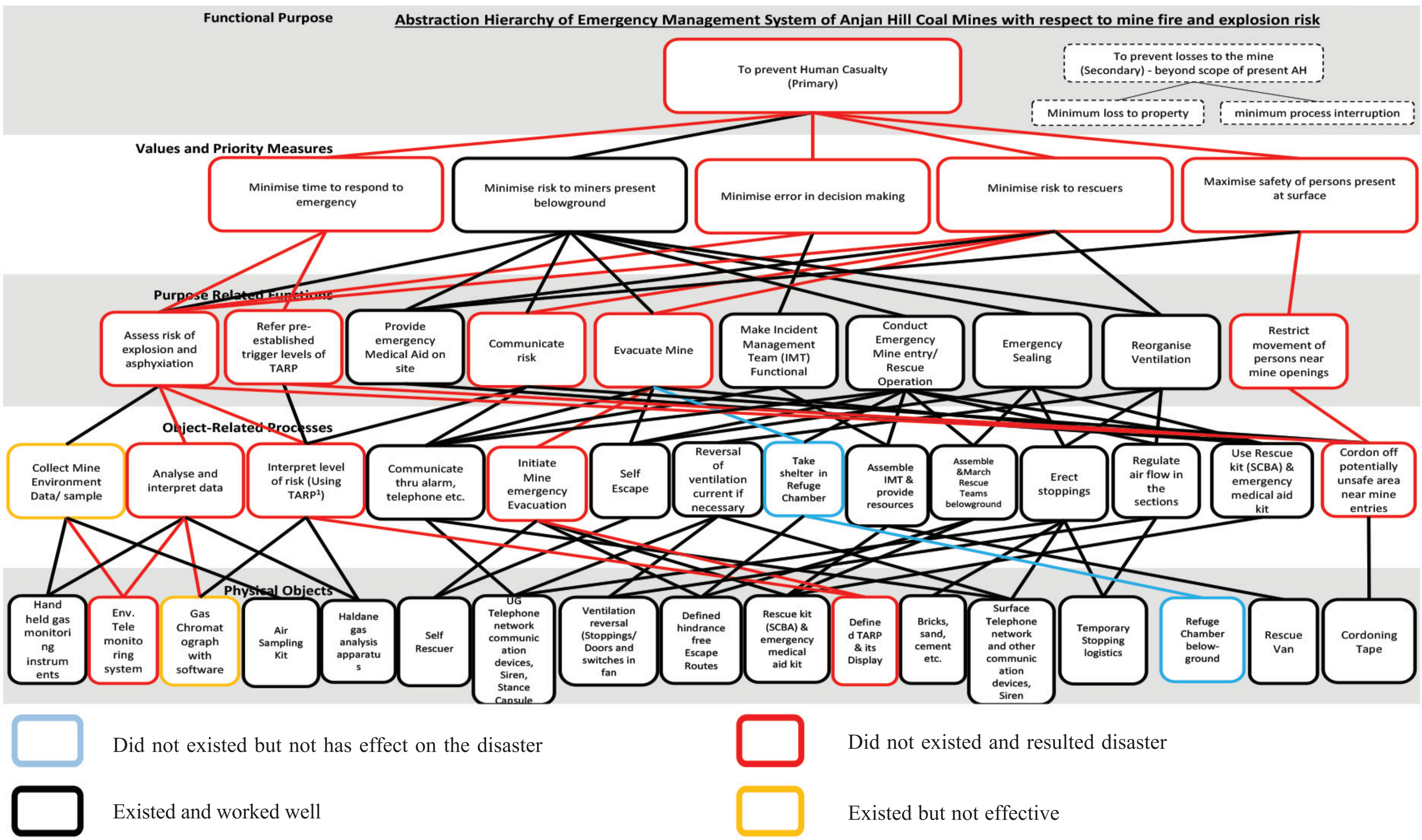

Fig.4: Abstraction Hierarchy for emergency management system ('as is')

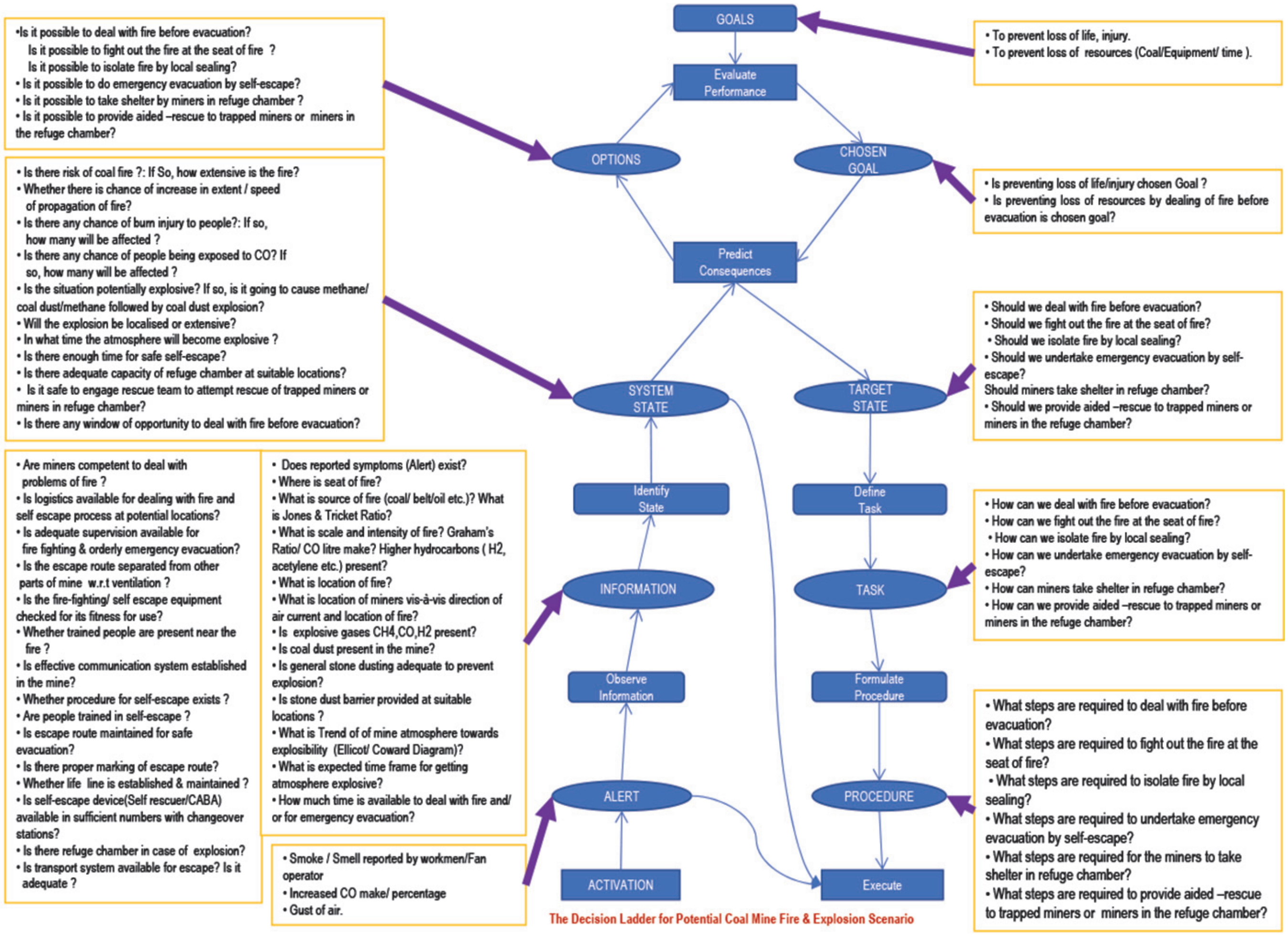

Fig.5: Decision ladder (should be)

be saved because risk to rescuers was not minimised and some wrong decisions, in terms of sending rescuers down the mine after emergency evacuation, were taken. Emergency was not timely and appropriately responded. As the IMT could not assess the risk it led to all above. Absence of tele monitoring system forced IMT to engage people down the mine to collect information for risk assessment. At the same time GC was installed in the mine but about 35 km from mine and sample collection required manual intervention. This resulted in presence of 6 miners and rescuers below ground. As risk of explosion was not assessed the entries to the mine were not cordoned off. Eight people were standing in front of mine entry (obvious path of explosion) and succumbed to explosion. In absence of defined trigger action response plan (TARP) in spite of high percentage of methane IMT was exposing people to unacceptable level of risk.

Interestingly, the AH reveals (blue node) that even if the miners could have survived to explosion and self-escape was not possible, there was no refuge camber in the mine for them to take shelter (refuge) to buy time and wait for the added rescue from the surface.

6.0 Control task analysis

The another phase of analysis control task analysis (CTA) works with recurring activities derived out of WDA and focusses on what has to be achieved independent of how or who takes it. For present study, Decision Ladder tool is used. As shown in the Fig.5, this uses two types of nodes, rectangular representing data processing activities and oval representing state of knowledge resulting from data processing activity (Jenkins et al. 2008). Short cuts may also be incorporated for expert users to use the information in terms of 'Alert' or 'System State' to execute a suitable procedure.

A decision ladder for potential coal mines fire and explosion scenario is shown in Figure 6 and it is a 'should be' system. The top of the ladder represents two most obvious and competing goals in case of coal mine fire firstly, to prevent loss of life and secondly to prevent loss to mine or loss of resources. Generally IMT or the mine officials base their decision to choose one of these goals based on the system state. To know the system state, a number of information are required. After processing the information and using perceptive and cognitive skill the system state is determined. In the instant case very crucial information in processed form was not coming to the IMT. For example, the intensity of fire (Graham's ratio) and explosibility (Ellicot/ Coward's diagram) of the underground environment requires processing of the mine air sample data, e.g. percentage of oxygen, carbon monoxide, air quantity, percentage of methane and other inflammable gases like hydrogen etc.

These data were not coming in constant and timely manner. At the same time, data were not processed for want of the data analysis tools such as GC with analysis software etc. Previous phases of CWA has also highlighted these issues. Consequently, in absence of knowledge of correct system state IMT chose wrong goal i.e. to prevent loss of resources. The EMS did not had the defined procedure for self-escape of rescuers and hence they were staying belowground and not responding to even gusts of air by misinterpreting it a result of roof fall in A2 panel.

7. Discussion

On literature survey it is observed that time and again it is reiterated by many academicians, regulators and public inquiries that emergency management system performs below expectations and results in huge loss of precious human lives. The application of CWA to the coal mine emergency scenario was aimed to analyse the current EMS to find shortcomings. The two phases of CWA were used for the analysis and many deficiencies emerged out of the study which has been discussed in this paper. Key recommendations based on the study can be summarized as below:

- The trigger action response plan which is most fundamental decision making guide in emergent situations should be essential part of any EMS and it should be displayed at suitable locations at surface and belowground so that people can readily refer them to make decisions.
- Tele monitoring system of mine environment and tube bundle system should be provided in the mine so as to get mine environment data without exposing miners and rescuers to unacceptable risks.
- Analytical capability of human being reduces drastically in emergency situation under influence of stress, time pressure, fatigue etc. It is therefore essential to provide mine environment analysis tools to provide important information depicting system state. This will enhance quality of decisions to choose right goal to save human life.
- Further, the standard protocol for mine evacuation, fighting fire, and emergency evacuation by rescuers should also be devised based on the CWA. An if-then check list based on CTA should also be part of the EMS.
- In case of mine fire chance of explosion can never be ruled out. It is therefore prudent to cordon off the mine entry in case on any mine fire. Only people dealing with fire should be allowed to go to mine if risk is low. All the other activities can be managed away from path of the explosion. In Anjan hill life of 8 people could have been saved simply by including cordoning off mine entry in EMS.

8.0 Conclusions

This study has highlighted the problem with emergency management system in respect of coal mine fire and explosion scenario. Due to complexity of the system, its performance while dealing with emergency remains below desired level and things go out of control resulting in loss of precious human life. The synthesis of public inquiry reports of Anjan hill mine disaster and input from SMEs was used to find out current EMS. The CWA, a comprehensive tool for analyzing complex sociotechnical system, has given insight to the EMS. Analysis has not been conducted comprehensively so as to limit the boundary for accommodating it within purpose of the dissertation. Still analysis has pin pointed important gaps in the system. As described earlier these gaps relate to physical objects, functions, strategies etc. The recommendations made in the study will definitely improve the EMS under study.

9.0 Disclaimer

Views expressed in the article are of the authors and not of the organisations they belong to.

Reference

1. Cattaneo C, Manera M, Scarpa E (2011): Industrial coal demand in China: A provincial analysis. *Resour Energy Econ* 33:12–35
2. Dash AK, Bhattacharjee RM, Singh CS, et al (2017): A decision can be a disaster: A descriptive analysis of a case study. *Int J Appl Environ Sci* 12:1803–1820
3. Durga S, Swetha R (2015): Disaster Prevention and Control Management. Procedia Earth Planet Sci 11:516–523. https://doi.org/10.1016/j.proeps.2015.06.052
4. He Z, Wu Q, Wen L, Fu G (2019): A process mining approach to improve emergency rescue processes of fatal gas explosion accidents in Chinese coal mines. *Saf Sci.* 111:154–166
5. Jenkins DP, Stanton NA, Salmon PM, et al (2008): Using cognitive work analysis to explore activity allocation within military domains. *Ergonomics* 51:798–815
6. Kumar D (2010): Emerging tools and techniques for mine safety and disaster management. Nat Anthropog Disasters Vulnerability, Prep Mitig 332–365. https://doi.org/10.1007/978-90-481-2498-5_15

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