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Analysis of soma mine disaster using causal analysis based on systems theory (CAST)

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ABSTRACT

Analyzing accidents of sociotechnical systems requires an understanding of the system safety structure. Among various methods proposed for accident analysis in complex sociotechnical systems the Systems-Theoretic Accident Model and Processes (STAMP) model is one of the most widely used model for predictive applications in the literature. The STAMP accident causality model with the accident analysis tool, called CAST (Causal Analysis based on Systems Theory) is an effective method for accident analysis. The Soma Mine Disaster (SMD), which occurred due to a fire in the underground coal mine and caused 301 fatalities in 2014, is one of the largest mine disasters in the last few decades. Although mine fires usually do not cause large number of casualties as compared to explosions in underground coal mines, the SMD has one of the highest number of deaths in the 21st century. In this paper, the CAST, which is based on STAMP is used for analyzing the SMD as it provides a system engineering perspective in accident analysis. Considering the complex nature of the SMD, a variety of factors were involved in the high number of casualties. Among them, socio-technical factors like unstructured organizational and human performance as well as inadequate safety culture, improper decision making and risk perception, which played a critical role in the SMD, are defined in an integrated system thinking framework. Finally, inadequate system control constraints are identified in each hierarchical level of the system and improvements are suggested, accordingly. It is also demonstrated that a CAST analysis is robust for the cases like the SMD, which involves high degree of uncertainty related to the occurrence of the accident. The analyses presented in this paper also show the design of prevention and mitigation measures against such disasters in different levels of the accident control hierarchy.

1. Introduction

The sociotechnical systems are complex in nature due to various levels of interactions between humans, technology and operating and organizational environments. Hence analyzing accidents of sociotechnical systems requires an understanding of the system safety structure. There are various methods proposed for analyzing accidents in complex sociotechnical systems. Grant et al. (2018) provides a comprehensive review of the existing methods and state that The Systems-Theoretic Accident Model and Processes (STAMP) model developed by Leveson (2011) is one of the most widely used model for predictive applications in the literature. The STAMP accident causality model and the accident analysis tool called CAST (Causal Analysis based on Systems Theory) are effective methods for accident analysis. The STAMP relies on systems theory. It considers safety as the interactions between the system components. Hence, control of safety is taken into account as constraints imposed on the component behavior and their interactions. Therefore, in STAMP, safety is expressed as a control problem in which enforcement of safety constraints is the main aim. The accidents are analyzed in terms of insufficient control that occur due to lack or inadequate safety constraints imposed on the design and operation of the system.

Based on the perspective of STAMP, CAST allows one to investigate the entire design and operational characteristics of the sociotechnical system to determine problems in the safety control structure as well as modification needs. Thus, in CAST, rather than focusing on the identification of responsible bodies that have role in the occurrence of the accident, the main aim is to determine reasons for accident occurrence and potential measures to prevent similar losses in the future. By this way, a system engineering perspective is incorporated into the accident analysis, where the whole system, with its physical, organizational and social components is taken into account. Moreover, in CAST, it is not only possible to understand the role of the system components in the accident, but also is possible to identify how their interaction in the system and their changing nature during the course of the accident affects the consequences. For this reason, even though there is insufficient data and a high level of uncertainty related to the accident, it is still possible to determine effective prevention measures by investigating the interactions in the system components.

The STAMP with CAST model has been successfully used for various accident analyses. For example Quyang et al. (2010) use it for analyzing China-Jiaoli railway accident for analyzing it and providing safety improvement measures. Pereira et al. (2015) and Kim et al. (2015) demonstrate successful use of it for analysis of the deep water blowout

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accident, and the Korean Sewol ferry accident, respectively. Lu et al. (2015) propose use of STAMP in reducing the number of trials and errors systematically for flight testing of a low-cost unmanned subscale blended-wing-body demonstrator. Kazaras et al. (2012) adopt STAMP in road tunnel safety assessment. Recently, Allison et al. (2017) utilized STAMP in understanding the rapid decompression scenario and determining actors that can influence a crew's response to a rapid decompression. They state that STAMP successfully determine factors played critical role in the accident's occurrence.

Salmon et al. (2012) compared various accident analysis models including STAMP with CAST using a case study. They state that STAMP's consideration for the context of decision making and mental model flaws are distinctive features however, STAMP exhibits difficulties during implementation by the practitioners, especially in locating human and organizational failures. Underwood et al. (2016) investigated the practitioner's evaluation of STAMP with CAST and its use by them for a live scenario. They state that practitioners mainly find application of STAMP with CAST challenging, particularly, understanding the method and defining event timeline in control structure diagram. These findings highlight that there is a need for more applications of STAMP with CAST in accident analysis with broad coverage of cases so that the practitioners can easily adopt it. Moreover, it is necessary to evaluate robustness of the STAMP and CAST in analyzing accidents with high degree of uncertainty due to information pollution and data gaps in complex sociotechnical systems. In order to meet these needs, In this paper, the STAMP model with the CAST tool is used for capturing the complex nature of a mine disaster, namely the Soma Mine Disaster (SMD) in the Soma-Eynez Mine (SEM), Turkey, which involves a high level of uncertainty and inadequate data related to the accident. The SMD was recorded as the largest mines disaster in the 21st Century with 301 fatalities due to a mine fire. Even though it is not possible to determine the exact cause of the fire in the SEM, the CAST tool provides identification of the reasons for the large number of fatalities due to mine fire, and it highlights required improvements, accordingly.

It is to be noted that to the auhors' knowledge use of STAMP with CAST has not been implemented for large mining hazards up to now. In the mining industry, it is almost a standard procedure to use event-based accident analysis models, EBAAM, specifically a root-cause accident analysis for investigating the accidents (e.g. Biswas and Zipf, 2003; Stanley, 2011; Papas and Mark, 2012). The EBAAM primarily concentrate on the events, where identification of causal links and the responsible actors are the main focus. However, EBAAM are not sufficient for explaining accidents related to complex sociotechnical systems like mines. The major weakness of EBAAM is that they lack adequate capabilities for representing accidents as complex processes involving structural weaknesses in the organization, management problems, and flaws in the safety culture in the coal mining industry. In fact, understanding accidents with severe consequences in the mining industry requires consideration of the case as a complex process operating in a convoluted mining system. In this way, all the causal factors along with guidance in determining these factors can be taken into account. Such a point of view also provides developing better accident prevention strategies as they allow actors to fully understand the purpose, goals, and decision criteria used to construct and operate systems (Leveson, 2011). Moreover, due to the large number of inadequate data and associated uncertainties, EBAAM becomes inadequate for identifying all the causes. This shortcoming further leads to insufficient design and implementation of the associated prevention measures.

The accident prevention strategies in mining mainly rely on hazard and risk assessment. Although there are various well-developed hazard assessment methodologies (e.g. Düzgün and Einstein, 2004; Sari et al., 2004; Coleman and Kerkerin, 2007; Margolis, 2010), as well as risk assessment methods (e.g. Düzgün and Einstein, 2004; Khanzode et al., 2014) for coal mines, their implementation requires continuous update and improvement. However, despite the well-developed methodologies for hazard and risk assessment, their update and revision based on disasters necessities better accident analyses that capture the complex system nature of the mining processes. As STAMP is capable of integrating quantitative risk assessment (QRA) methods (e.g. Kazaras et al., 2012; 2014), the presented accident analysis for the SMD in this paper provides a clear pathway for integrating STAMP with QRA.

2. Brief description of the SEM

The SEM is one of the underground mining operations in the Soma coalfield and the mining activities had three operational periods. The first one is the period of Turkish Coal Enterprises (TKİ), the state-owned mining company, which covers between 1990 and 2006. In this period the mining operations were conducted in seven underground mines, including the Eynez operation. The state-own period in the SEM ended in 2006 after the privatization of the mine for a period of 10 years with a planned production of 15 million tonnes (Union of Turkish Bar Associations, 2014). The private company, Park Teknik A.Ş., operated the SEM between 2006 and 2009 in the second period. After production of 0.852 million tonnes of lignite in three years, the company applied for the termination of the contract due to the technical problems and operational difficulties in the SEM. As a result, the third period in the SEM started in 2009 after signing the transfer agreement among the parties that are TKİ as the license owner, Park Teknik A.Ş., the company willing to end its operations in the SEM, and Soma Coal Enterprises A.Ş., the private company willing to take over SEM to produce the 14.1 million tonnes of lignite for seven years (Union of Turkish Bar Associations, 2014). In the third period, the production is performed by conventional, semi-mechanized and fully- mechanized systems. The conventional and semi-mechanized systems have mostly short face lengths, 40–70 m, and coal is extracted with pneumatic hand drills and explosives and hauled with the face conveyors. The main difference between the conventional and semi-mechanized systems is the type of support where hydraulic and timber supports are used in semi-mechanized and convectional systems, respectively. Coal is extracted by a drum shearer and loaded into armed face conveyor with longer face lengths in the mechanized system (Sari et al., 2004).

The coalfield has three seams namely, upper-KP1, lower-KM2 and middle-KM3 (Hokerek and Ozcelik, 2015) with thickness ranges of 7–8 m, 15–35 m and 6–10 m, respectively. As the coal seams are thick, longwall top coal caving (LTCC) is adopted. The simplified mine layout is given in Fig. 1.

In 2014 the production in the SEM, were based on five panels with nine production faces. The mining method, adopted in each face in the SEM, is given in Table 1.

Due to the spontaneous combustion propensity of coal, the ventilation rate was kept around 2300 m^3/min. Moreover, coal seams in Panel A contain considerable amount of methane (Erdoğan, 2015). The SEM worked in three shifts with approximately 800 workers/shift.

3. Proximate events in the SEM

The health and safety concerns related to mining sector in Turkey, especially after the privatization of large number of coal mines, had initiated investigation since 2009 due to dramatic increase in casualty statistics in coal mine accidents. Chamber of Mining Engineers of Turkey (TMMOB, Maden Mühendisleri Odası, TMMOB-MMO) published an investigation report (Web 3) and highlighted occupational health and safety problems and proposed solutions related to them. In 2010, Arslanhan and Cünedioğlu (2010) analyzed accident and casualty statistics in the Turkish hard coal mining sector in the report entitled Analysis of Mine Accidents and Their Consequences, which was prepared for The Economic Policy Research Foundation of Turkey (Turkiye Ekonomi Politikaları Araştırma Vakfı, TEPAV). It was stated in the TEPAV report that In 2008, the number of deaths per ton of coal production in Turkey was 7.22. an amount that is almost six times higher than China, which had 1.27. The problems related to the coal mines in

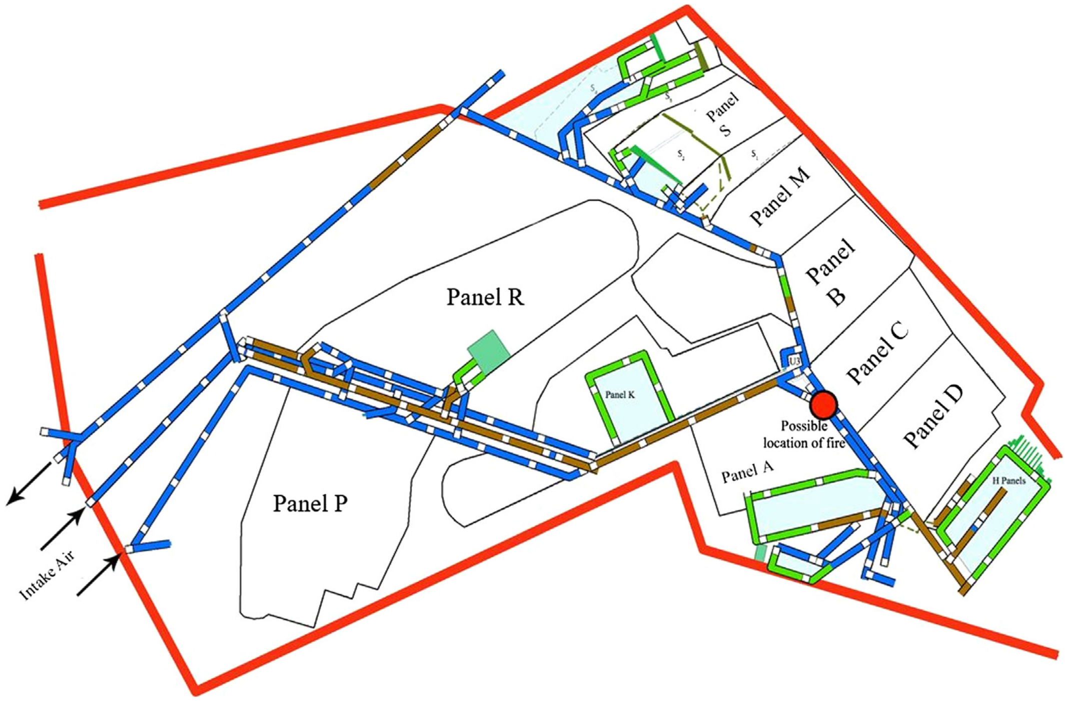

Fig. 1. The mine layout for the SEM.

Table 1
List of the mining method in each face in the SEM.

Panel	Face	Type
A	A1	Semi-mechanized
A	A2	Fully-mechanized
H	H1	Semi-mechanized
S	S2 upper	Semi-mechanized
S	S2 lower	Conventional
S	S3 upper	Semi-mechanized
S	S3 lower	Conventional
R	R7 (East)	Fully-mechanized
K	140	Conventional

the TMMOB-MMO and TEPAV reports were almost the same. In 2011, The State Supervisory Council of Presidency of Turkish Republic (T.C. Cumhurbaskanligi Devlet Denetleme Kurulu, DDK) published a comprehensive investigation report and similar type and number of problems indicated in the TMMOB-MMO and TEPAV reports. The DDK report also highlighted legislative problems and called for urgent changes. In 2012, Labor Inspection Board of Ministry of Labor and Social Security (MLSS-LIB) published the evaluation results of programmed annual inspections for coal mines in Turkey. The indicated safety problems related to the coal mining were almost the same as the ones indicated in the previous reports, which are:

- Ventilation problems
- Stress due to increased production
- Subcontracting the mining operations
- Insufficient personal safety equipment
- Auditing problems
- Inefficient inspection process
- No actual integration of risk assessment and management
- No consideration of lessons learned from the past accidents
- Insufficient precautions for methane explosion
- Inadequate mine monitoring systems
- Inadequate escape routes
- Unsatisfactory support systems
- Problems related to search and rescue
- Inadequate safety culture
- Inadequate training of the miners

Due to safety concerns in the coal mines, there were several demonstrations by the mine workers in the mining towns. One of the most striking was on November 2013, in which mine workers from Zonguldak barricaded themselves inside a coal mine in a protest at health and safety problems and poor working conditions (Web 4). There were also rising safety concerns related to the SEM. On 29 April 2014, the Republican People's Party demanded a parliamentary investigation regarding safety in the Soma mines. However, it was rejected by the Grand National Assembly.

In Table 2 the timeline of the events on May the 13th, 2014 in the SEM are summarized. It is to be noted that outlining timeline of the events for mine hazards is challenging due to associated uncertainties. However, in the SMD case, the case files contain more than 100 testimonies of witnesses, survived victims and suspects who consistently described the timeline similarly. As it can be seen from Table 2, on May the 13th, 2014, between 14:00 and 14:40 the ground control unit of the mine performed a blasting operation in order to level the heaved floor of the main road so that the road become suitable for belt conveyor operation. Shortly after this blasting, a roof fall occurred and a fire started between 14:40 and 14:45 in the roof of the same main road at a location close to the blasting location. The fire ignited the wooden pieces used for fixing steel sets. With the existence of methane, the upper part of the belt conveyor also ignited. The possible location of the mine fire (Fig. 1) is the point where the conveyor number 4 conveys materials to the conveyor number 3.

The outbursting smoke and the smoke from the open flaming fire that broke out in the roof of the main road combined, spread in a short time, expanded through all the main roads to the A and H panels and to the main road to the S panel in the main ventilation direction of the mine.

By the time the fire started (14:40–14:45) the electricity blackout in U3 area (Fig. 1), belts stopped, intense smoke covered the main road of the belt conveyor number 4 and search and rescue teams for the mine was requested to the accident scene.

At around 15:00, smoke appeared in the A panel and at

Table 2
The timeline of the events in the SEM on May the 13th, 2014.

Approximate time	Event	Location
14:00–14:40	Blasting by ground control unit	Main road close to the location of fire
14:40–14:45	Intense smoke, fallen rocks to the conveyor belt, ignition of wooden pieces between the roof and the steel sets, firing of conveyor belt	Roof of the main road
14:40–14:45	Power block out, stop of conveyor belts	U3 area close to fire location
14:45–15:00	Establishment of a short-circuit by SE1 in the ventilation system to protect workers from the smoke	Close to fire location near A0 face area
15:00	Arrival of smoke	A panel
15:10	Arrival of smoke	The main road of the H panel going to the S panel
15:20	Arrival of smoke	The first level of S panel
17:00	Decision of change in ventilation direction	The whole mine
17:30	Start of reverse ventilation	The whole mine
18:00	Start of fainting and deaths	A0 face area
20:20–20:30	Arrival of search and rescue teams	A0 face area

approximately 15:10 smoke first appeared in the main road of the H panel going to the S panel. Due to the precautions taken by the safety engineer in this area, 142 workers started waiting there safely. At around 15:10 an explosion in the U3 area (Fig. 1) was reported to the media and the news was given based on this information until the mid day of May the 15th.

At 15:20, when smoke arrived at the first floor of the faces in the S panel, fainting and death began. In the mean time, the executive mine management staff (EMMoSEM) entered into the mine with the executive mine managers of the neighboring mine (EMMoIMBAT). They tried to reach the location of the fire but couldn't get there due to intense smoke. At around 17:00, with the advice of EMMoIMBAT, the mine management (EMMoSEM) decided to change the direction of ventilation, which was completed at around 17:30. Due to this change, 142 workers, who accumulated at the A panel area, where smoke was not effective before, were affected. At around 18:00, fainting started and some died in the Panel A area. Between 20:20 and 20:30, search and rescue teams reached the A panel area.

The search and rescue operation took almost three days and the mine management was unable to announce the number of fatalities until the research and rescue operations were finalized. The Minister of Energy and Natural Resources reached to the site for coordinating the search and rescue operations, where more than 400 search and rescue staff were involved. At 00:10 am on May the 14th, The minister gave the fist official information about the scene but didn't provide the number of casualties. At 05:08 am, the minister declared 201 fatalities and 80 injuries. On the same day (May the 14th), three days national mourning was announced by The Office of the Prime Minister. The Prime Minister changed his schedule to visit Soma and his visit led to public outrage in the streets by the local residents protesting him. In May the 14th, there were various demonstrations related to the disaster in many Turkish cities. At around 22:22 on May the 14th' the Minister of Energy and Natural Resources updated the casualties as 274 fatalities and declared that it was the biggest mine disaster in Turkey's history. On May the 15th around 14:30 the numbers of fatalities were declared to be 282 by the Minister, and the street protests in the cities increased. In May the 16th, the mine management and the mine owner held a press conference as well as answering questions. They stated that they didn't know the major cause of the fire, they were well experienced with extinguishing fires in the mines but it was an extraordinary event that they had never come across and hence can not be predicted or prevented. The protest in the streets of the major cities as well as Soma increased, lawyers and the Journalist in Soma were arrested. The official number of casualties declared as 284. The minister stated that 18 miners were to be reached in the mine. The prosecutor investigating the case stated that they had started taking testimonies by releasing a press report. In May the 17th, the minister announced the total number of fatalities as 301 and the termination of the search and rescue operations as there was nobody left in the mine. The protests in the streets were also going on and the names of survivors were announced.

4. The uncertainties related to the analysis of the SMD

As this paper has a focus to evaluate the robustness of STAMP with CAST for high degree of uncertainty, a though determination of uncertainties would be beneficial. For this purpose, the associated uncertainties for the SMD are explained in this section.

In coal mining, the accidents due to explosions, which are sudden and onset, result in higher number of fatalities as compared to mine fires. For example, in the US coal mines, between 1900 and 2006, 10390 fatalities were recorded as a result of 420 explosion-related incidents, while 727 fatalities were recorded in 35 mine fires (CDC, 2009) for the same period. Similarly, between 1983 and 2013, 647 fatalities were recorded in Turkey as a result of 18 major mining incidents (i.e. incidents causing more than three fatalities). Among these incidents, only one was a mine fire in a copper mine, which caused 19 fatalities (Düzgün, 2015). While the number of fatalities due to fires has always been lower than that of explosions, in the SMD case it was the opposite, requiring further investigation. In fact, the SMD is considered to have one of the biggest casualties that ever happened in a coal mine worldwide since 1970 (Spada and Burgherr, 2016).

There are three published work on the SMD with varying views. Spada and Burgherr (2016) indicated the cause of fire as spontaneous combustion (SC) and state that the SC in an old panel turned into an open flame fire. Erkan et al. (2016) stated that media reported an explosion at 3:15 p.m, then, later, after investigations, a huge amount of CO and CH4 gasses accumulated in the old extracted C panel discharged into the area and quickly reached to A panel. Then fire rapidly spread due to the effect of a high level of oxygen and contact with flammable material and machinery. Farahani (2014) wrongly analyzed the SMD based on the assumption that the disaster was due to an explosion. The main reason for such a critical mistake was that the cause of the accident was initially announced to be an explosion in the media and appeared a long period of time as such.

There are three main reasons for these varying and even misleading descriptions of the cause of fire:

1. There is not healthy and sufficient data
2. The long duration of the fire and the dams created in extinguishing it destroyed the evidence that would assist in figuring out the cause of the fire
3. The existing data lost its reliability as a result of information pollution. Even the exact location of the fire was stated differently by various organizations (Düzgün, 2015).

In an effort to investigate the SMD, up to now, five expert reports during the course of investigations were produced, which are:

1. The report of the Ministry of Labor and Social Security, the Labor Inspection Board (MLSS report)
2. The expert report asked by the court dated September 18, 2014 (B1 report)
3. The report of the Parliamentary Research Commission, which was established to investigate mining accidents, particularly the one on May 13, 2014, in the Soma district of Manisa and to identify the labor security precautions to be taken in this sector (TBMM report)
4. The expert report requested by the court dated October 8, 2015 (B2.1 report)
5. The expert report requested by the court dated October 12, 2015 (B2.2 report)

The MLSS report was prepared at the end of the investigations conducted by the experts of the Labor Inspection Board. The B1 report was prepared by a team comprising mostly experts from University of Dokuz Eylul, and B2.1 and B2.2 reports were prepared by teams in which there were mostly experts from Istanbul Technical University. Two experts in the commission of experts who did not agree with the views in the B2.1 report presented the B2.2 report as the reason of the annotation they added to the B2.1 report and as their own notions. The TBMM report was prepared by the teamwork of a large expert group,

These five reports have two common aspects:

1. Trying to explain the cause of the fire
2. Determining the neglects, malpractices and deficiencies

On the other hand, these five reports diverge from one another in terms of the data they use. The MLSS, B1 and TBMM reports were prepared before the indictment was accepted and the case was opened, while the B2.1 and B2.2 reports were prepared after the lawsuit process began. In the reports that were prepared before the case was opened, investigation was carried out with a limited number of witnesses. The number of witnesses heard was much more than the MLSS and B1 reports. However, it was still not possible to access all the statements in the case file.

Due to high degree of uncertainties, five different expert groups, who are in charge of the accident investigation, introduced five different hypotheses. The detailed analysis of the hypotheses related to the occurrence of the fire described in these reports is given in Section 5. The hypotheses about the outbreak of the fire vary. Moreover, proving these hypotheses does not seem plausible because of the inadequacy of the required data. Hence the SMD case constitutes an appropriate case study for evaluating the robustness of the STAMP model and the CAST tool.

5. The hypothesis developed by the expert groups

Five different official reports were prepared for the SMD. The common factors indicated in these hypothesis highlights issues to be considered in the CAST analysis. Therefore, they are described briefly:

- Hypothesis I-The Definition of Accident Occurrence in the MLSS Report (H1-MLSS): It was concluded that the mine fire started because SC due to the coal left in the old production panels, which was oxidized from the mine ventilation and/or from fracture network connecting the old mine pannelss with surface due to subsidence. The SC increasingly continued in the old production panels leading to high temperature and pressure and met with methane in some way. The SC products also reached to the main road in which the belt conveyor number 4 was located by penetrating through weak parts in the formation with the help of the faults or cracks in the zone. The fire started in the roof of the main road and ignited the wooden pieces used for fixing the steel sets. With the existence of methane, the upper part of the belt conveyor also ignited. On the long side of the triangular pillar left in this area (the area between the point where the conveyor number 4 conveys materials to the belt number 3 in Fig. 1), the airflow was quite slow to the point of almost being stagnant. There were no methane detectors in this area. Therefore, it was not possible to find out whether there was an accumulation of methane here that would trigger or contribute to the fire before it broke out. The outbursting smoke and the smoke from the open flaming fire that broke out in the main road combined and spread in a short time, moving with high pressure through all the main roads to the A and H panels and in the main road to the S panel in the main ventilation direction of the mine. The methane levels that were measured at certain intervals immediately after the accident were an indication that methane had an impact on the outbreak and spreading of the fire. The detection of which old production panes/panels the mine fire started at will only be able to be evaluated at the end of detailed technical and scientific studies to be conducted in the field (drilling, measurements, etc.). Most of the 301 workers in those areas lost their lives from being poisoned by CO. 122 workers were injured.
- Hypothesis II- The Definition of Accident Occurrence in the B1 Report (H2-B1): The cause of the fire was explained as follows: According to the autopsy reports, most of the deaths resulted from COHb (carboxyhemoglobin) poisoning originating from CO. Considering the size of the underground mine, it does not seem likely that a CO concentration that will enable poisoning in such a scale is caused by a fire of belt, wooden support parts and PVC pipe alone. The main reason of the incident is the CO, which arose because of the uncontrolled spontaneous heating of coal, left as a pillar around the transformer U3 area (Fig. 1). Being in the clean air inlet, spontaneous combustion was turned into full combustion. Then the fire spreaded to the main road in which the belt conveyor number 4 was located and ignited the belt, wooden support parts between the roof and the steel sets, PVC pipes and electricity cables in this part and in the roadway where the belt conveyor number 3 was located. Finally the build-up of poisoning and choking gases as a result of cooling works with water (CO, CO2, HCl)" caused the massive fatalities.
- Hypothesis III- The Definition of Accident Occurrence in the TBMM Report (H3-TBMM): It occurrence of fire was summaried below:
  1. An uncollapsed opening that formed in the area of the C Panel because of the removal of coal was filled with CO and CH4 in time.
  2. The gases that formed in this opening first slowly and then suddenly entered the galleries at first in a slow manner and afterwards in an outburst as the layers above the opening settled
  3. Meanwhile, CH4 that accumulated in the A Panels spread to the mine penetrating from the cracks and faults.
  4. The high-concentration of methane, which spread to the environment, started to burn with faint flame due to a spark arising from the non-explosion-proof motors of the conveyor belts in the accident site
  5. As a consequence of methane fire, the conveyor belt and the wooden pieces between the roof and the steel sets also caught fire.
- Hypothesis IV-The Definition of Accident Occurrence in the B2.1 Report (H4-B2.1): The definition of the incident in this report totally supports the hypothesis in the TBMM report. Thus, no different hypothesis was put forward. However, the influence of emergency management following the incident on the losses was stated in this report, shortly addressing the factors below.
  1. The need for evacuating the mine as soon as the fire broke out, a lack of a central communication system to convey this decision to everybody within the mine and therefore delays in the evacuation of the mine,
  2. No planning dealing with emergency situations and evacuation procedures
  3. Lack of training for the use of escape routes and individual self

escape equipment
4. The fact that risks could not be anticipated because risk assessment was not performed accurately and effectively

- Hypothesis V- The Definition of Accident Occurrence in the B2.2 Report (H4-B2.2): This expert report was prepared by other experts who did not agree with certain factors addressed in the B2.1 report. These experts stated that they agreed with the evaluations about emergency management, but did not agree with some opinions about the mine conditions. For example, the geological structure was not considered adequately in the accident occurrence and the influence of active faults and explosions in the surface mine near the mine on the incidence of fire was not examined sufficiently. Moreover, these experts wrote that the deaths resulted from CO and other gases released because of the belt fire rather than poisoning because of CO, which was produced by SC, and stated that it was impossible to collect and evaluate evidence to determine this.

When these hypotheses are examined, it is observed that actually three of them give different sources about the cause of fire. H1-MLSS, suggests that the fire broke out due to the spontaneous heating of coal left in the old production zones near the starting point, H2-B1 suggests that the fire was caused by spontaneous combustion of the pillar coal at the starting point, and H3-TBMM suggests that the fire was caused because an uncollapsed opening in an old production panel (C Panel) closest to the starting point was filled with CO. The CO accumulated in this uncollapsed opening was produced by the spontaneous heating of coal left in this zone. Sudden collapse of this opening let the CO outburst to the main road where belt conveyor number 4 was located and in this area, there was also CH4, which found its way through faults and cracks from the A pannel. Hence high concentration of CO and some amount of CH4 ignited an open fire.

All three hypotheses mention the existence of methane in the environment and share the opinion that the fire quickly turned into a belt fire with the presence of methane. It is necessary that detailed data should be collected in the area where the accident happened in the mine (drill holes to understand the characteristics of the area of the incident and data output through geophysical methods) in order to assess the validity of the H1-MLSS and H2-B1 hypotheses. For the H3-TBMM hypothesis, however, subsidence measurements should be taken into account for the projection of the C Panel on the surface. Moreover, the H3-TBMM hypothesis did not take into consideration when the C Panel ended, did not calculate how long it would take the uncollapsed opening that might form because of the immediate roof above the panel to collapse. It also did not consider the data of a detailed subsidence measurements for the projection of the panel on the surface. It is another remarkable issue that this hypothesis is almost the same as the statement of the mine management. This hypothesis (H3-TBMM), which was explained well using alluring 3D visualizations, is impossible to be validated although it was acknowledged a lot in the public due to its presentation. For this reason, a set of costly data collection processes was recommended in the report, to validate the hypothesis. Similarly, such costly data collection like drilling and geophysical studies are also needed in order to validate the H1-MLSS and H2-B1 hypotheses. The H4-B.2.1 is already parallel with the H3-TBMM, and H3-B2.2, on the other hand, states that the hypothesis about the belt fire cannot be proved because of inadequate data.

All these hypotheses indicate the high degree of uncertainty associated with the SMD and hence the inadequacy of EBAAM in analyzing the accidents in such complex sociotechnical systems. However, the existing data still allows analyzing the SMD in figuring out reasons for the accident occurrence and potential measures to prevent similar losses in the future using STAMP with CAST.

6. STAMP with CAST analysis for the SMD

STAMP is a new, more inclusive model of accident causation. The tool built on this model and used to analyze a specific accident is called CAST (Causal Analysis based on Systems Theory). The STAMP with CAST analysis initially requires defining the following components:

1. the system hazards
2. the system safety constraints
3. the hierarchical control structure in place to enforce the constraints
4. the structural dynamics

The system hazards involve identification of the states with their consequences that lead to the losses. The system hazards are not only resultant from individual component failures but also from the interactions among system components and the external factors that disturb the system. Hence definition of system hazards includes accidents related to individual components, component interactions, external factors and their cascading impacts.

As the system's functionality depends on components, their interaction and external factors, system safety relies on constraints that are imposed for controlling them. Therefore, defining system safety constraints is essential in any CAST analysis. In this way, the system safety is expressed as a control problem where safety constraints are imposed in the design and operation of the system (Leveson, 2011).

The safety constraints are enforced in a hierarchical manner as the system is composed of hierarchical structures. Thus, analyzing the hierarchical control structure in place to enforce the constraints is necessary when using CAST in order to detect control problems in various hierarchical levels. The analysis of the hierarchical control structure serves for understanding the accident and hence development of effective prevention strategies. Inadequate controls in any one of the hierarchical structure, which may result from lack of constraints, unassigned responsibilities, inadequate communication, missing feedbacks, insufficient safety directives, can easily be identified.

Systems are not static but dynamic, which implies that safety state of the system evolves in time. For this reason, structural dynamics in CAST is essential for better understanding of evolution of the safety system according to the changes in the operational and environmental conditions. It is expected that resilient system control structures enforce appropriate constraints for maintaining safe operation and they sustain safe operation as changes and adaptations occur over time.

The CAST analysis mainly focuses on investigating the overall structure of the sociotechnical system rather than trying to identify the responsible person or group for the accident. As a result, each level's contribution to the consequences of the system failure can be better understood, which provides robustness under uncertainty. In this way, lessons learned from each accident can systematically be incorporated into the design of safer systems in terms of physical, social, institutional, and regulatory aspects. The following subsections demonstrate the use of CAST for the SMD.

6.1. The systems hazards

The system hazards for the SEM are the mine fire and exposure of mine employees to the fire products. The safety constraints basically involve the fact that the safety control structure should prevent the fire and exposure of the mine employee from the fire products (Fig. 2)

6.2. The system safety constraints

As the safety control structure for the overall mining system captures enforcement of the system safety constraints, each component of the safety control structure with their specific safety constraints serves for accomplishing its function in the overall system. Figs. 3 and 4 show the basic safety control structure of the mining system.

The Grand National Assembly of Turkey (Turkiye Buyuk Millet Meclisi, TBMM) establishes the mining and labor laws to ensure sustainable resource exploitation and safe and healthy working

System Hazard: A fire in the mine and exposure of the mine employees to fire products.
System Safety Constraints: Safety control structure must prevent a mine fire and exposure of mine employees to the fire products if it starts 1. Mine safety must not be compromised by a mine fire. 2. The ventilation system must always provide required air quality for all the working places in the SEM 3. Safety measures in the SEM must reduce the risk of exposure to fire products if the air quality is compromised 4. Adequate evacuation plans must be created and practiced

Fig. 2. System hazard and system safety constraints.

environment as well as making amendments when necessary. The major laws are the Constitution of the Turkish Republic, Mining Law and Occupational Health and Safety (OHS) Law. Article 168 of the Constitution (Chapter 2, Sec. 3,1982) defines the overarching principles of the mining and states that all the natural resources belongs to the nation. The mining law (Law 3213) allows the state to provide licenses to perform various mining activities (i.e., exploration, feasibility, production, closure) to private companies. If the mining company is licensed for production, it is responsible for overall mine safety by the Law 3213. The OHS law (Law 6331) defines the framework of a safe mining environment and gives workers the right to stop working in case they detect any danger. Hence according to Law 3213, for a mine fire, the mining company is responsible for taking all the precautions related to mine fires including emergency management when it starts. However, this law does not sufficiently specify how mine fire hazard and risk will be mitigated as well as its management during an emergency.

The Ministry of Labor and Social Security (MLSS) establishes rules and regulations as well as regulatory bodies related to OHS specific to coal mining activities. MLSS is also responsible for developing protocols, standards and guidelines for operational safety in coal mining as well as performing audits of the coal mines in terms of their compliance to standards, protocols and guidelines. Moreover, providing adequate resources (budget and human resources) to auditing bodies is the responsibility of MLSS. Ensuring the conduct of accurate risk assessment by the mining companies, establishment of effective risk management plans and enacting legislation to enhance coal mine safety are also critical safety requirements and constraints to be handled by MLSS. The protocols, standards and guidelines for mine fire risk reduction as well as emergency management was defined quite loosely, which did not require mining companies to take effective measures. Due to these loose protocols for mine fire prevention, the audits didn't have solid basis for blocking the companies from unsafe operations.

The Ministry of Energy and Natural Resources (MENR) with its directorate the General Directorate of Mining Affairs (Maden Isleri Genel Mudurulugu, MIGEM) regulates, controls and monitors the mining activities as well as safety. The MENR establishes energy policies and hence coal mining policies. Thus, it establishes rules and regulations related to the regulatory bodies for all mining activities starting from exploration, feasibility, design, exploitation and closure. The MENR assigns adequate resources to regulatory bodies to carry out their responsibilities. Based on the rules and regulations put forward by the MENR, the General Directorate of Mining Affairs (MIGEM) checks and approves the overall feasibility and mine design, and monitors the mine production, considering mine safety, optimum resource exploitation and sustainability. MIGEM takes precautions and provides financial opportunities for supporting mine exploration and production. It also develops measures and recommendations for promoting mining activities to satisfy the needs, benefits and security of the country, and ensure the mining activities are performed based on newly developed technologies. Hence rules and regulations as well as regulatory bodies specific to coal mining activities are also established and revised by the MİGEM. Although MENR and MIGEM has responsibility for enforcing mine fire risk reduction, their control mechanism was mainly focused on controlling the production reported by the companies and other production related aspects (e.g. approving feasibility reports, mine design and scheduling reports etc.)

In addition to small private mining companies, Turkish Coal Enterprises (Turkiye Komur Isletmeleri, TKI), Turkish Hardcoal Enterpreises (Turkiye Komur Isletmeleri, TTK) and The Electricity Generation Company (Elektrik Uretim A.S., EUAS) are the three public organizations that have the largest number of coal reserve licenses. TKI, EUAS and TTK also manage coal mining activities either through their own mines or a redevance system or subcontracting their mines to private companies. TKI has minimized mining operations performed by itself and used one of the redevance and subcontracting systems for exploiting the coal. In the redevance system, private companies pay for making a contract with TKI to share the produced coal with the state for a given part of the reserve. The license still belongs to TKI but the coal is exploited by the private company with the redevance system. In the subcontracting system, which is mainly started in 2005, for a certain part of the reserve, all rights for coal mining is given to the private company and the company pays for the contract.

The SEM was operated by the TKI until 2006 with a very low production amount. Sari et al. (2004) states that the average annual production in the SEM was 278 000 tonnes, where 193 000 and 91 000 tonnes were produced from mechanized and conventional systems, respectively. Then in 2006 the subcontracting system was adopted and the operation of 15 million tonnes of the reserve is given to Park Teknik A.Ş. for an annual production rate of 1.5 million tonnes (Union of Turkish Bar Associations, 2014). The Park Teknik A.S. the SEM between 2006 and 2009 and was able to produce 0.852 million tonnes in three years. It applied for the termination of the contract due to the technical problems and operational difficulties in the SEM. The main operational problems reported were frequent fires and safety concerns that were irreparable since the original design of the mine had serious flaws (Erkan et al., 2016). As a result, in 2009, a transfer agreement among the parties was made. The involved parties were TKİ as the license owner, Park Teknik A.Ş., the company willing to end its operations in the SEM, and Soma Komur A.S., the private company willing to take over the SEM to produce the 14.1 million tonnes of lignite for seven years (Union of Turkish Bar Associations, 2014). Since then, Soma Komur A.S. performed the coal production on the behalf of TKI by taking all the legal, financial and administrative responsibilities. However, this subcontracting system did not diminish the responsibility of TKI as it is still responsible for establishing sustainable and efficient coal production, controlling and monitoring operations and the mine design as well as approving annual production plans of the Soma Komur A.S. and check their implementation with respect to resource exploitation and the mine safety. It was known by TKI that the SEM has a high risk of mine fires, which caused serious operational problems during the operation of TKI and Park Teknik A.S. However, the mine design and related operational aspects of the SEM were not implemented for the fire risk reduction.

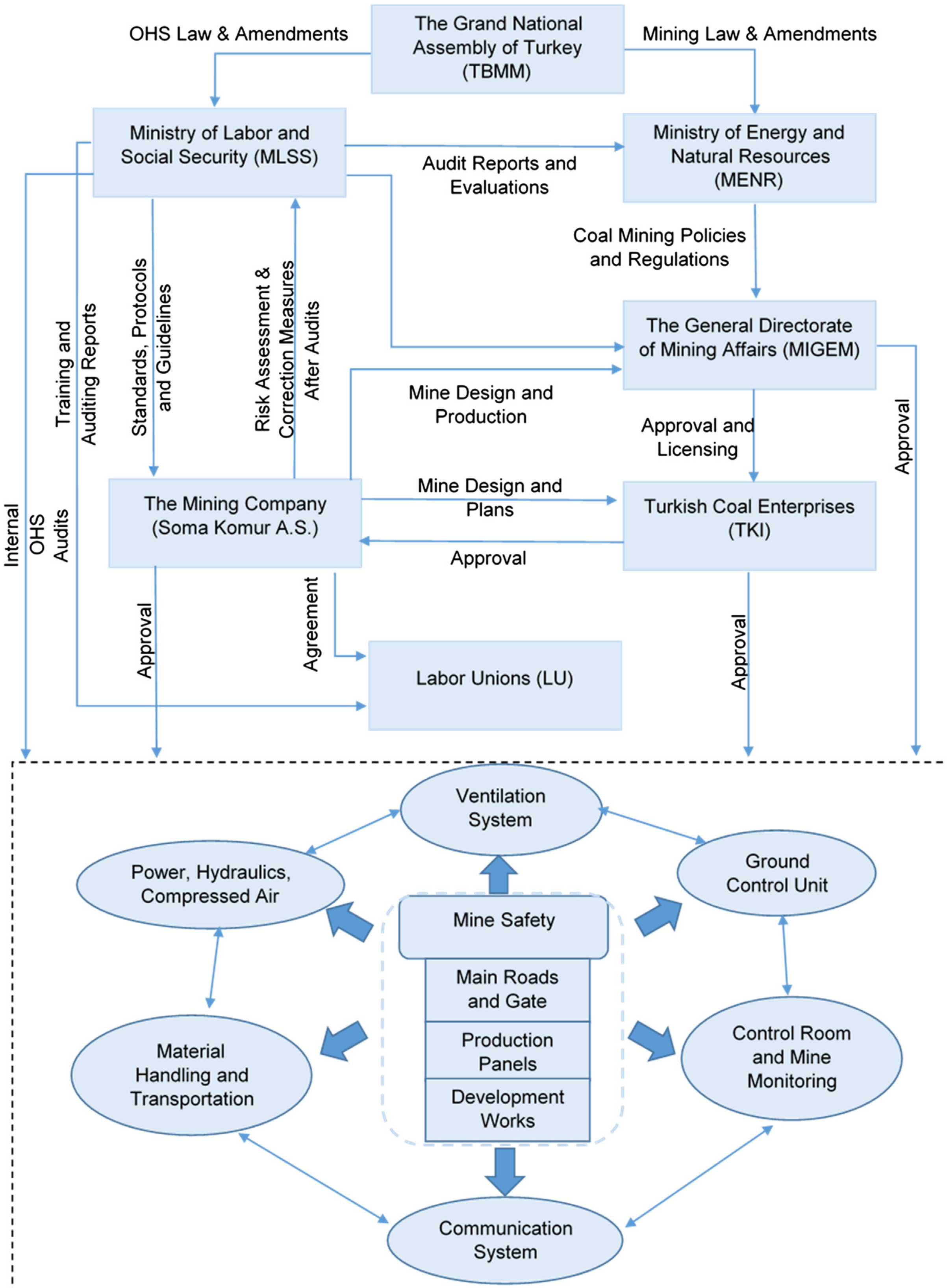

Fig. 3. Basic mine safety control structure.

Labor Unions serve for ensuring establishment of adequate procedures for health and safety of the mine workers. Monitoring the effectiveness of the measures for improving the health and safety conditions of the mine workers is also responsibility of the Labor Unions. The Labor Unions did not play an active role in ensuring mine safety, including the fire risk mitigation and emergency management drills.

The mining company (Soma Komur A.S.) has to establish a safe mining operation by constructing a safety culture that embraces the

The Mining Company (Soma Komur A.S.)

Overall Mining System

- Perform risk analysis by foreseeing potential hazards and their consequences as well as evaluating them to develop mitigation measures
- Revise and design the mine layout, ventilation, material handling and transportation, communication, water, power and compressed air systems before the production is increased so that all systems components support rise in production safely
- Install ex-proof/ATEX certified material in all part of the mine.
- Keep track of mine subsidence
- Establish a comprehensive database for monitoring all types of changes in the mine

Ventilation

- Provide efficient and satisfactory ventilation to the all working areas in the mine
- Install gas and temperature sensors to appropriate locations in the mine so that potential hazards can be detected earlier.
- Take necessary precautions when the gas, dust and temperature sensors record increased values and search for the potential causes.
- Keep updated and systematic records of gas, dust and temperature measurements
- Identify conditions of intentional ventilation changes and necessary measures to be taken before its implementation

Workers

- Equip all the workers with sufficient personal safety equipment and give adequate training related to their use
- Provide adequate education related to the safety issues and monitor the impact of education
- Track miners who are in the mine at all times according to their location in the mine
- Establish mechanisms for reporting unsafe operations
- Implement drills for self rescue and mine evacuation

Management

- Provide adequate communication system and coordination between the various decision makers in the mine.
- Develop codes and standards for safe mining practice and monitor its implementation
- Establish safety culture among all the hierarchical levels of the mine

Emergency management

- Develop emergency management plans and implement drills for envisaged emergencies including mine evacuation.
- Establish a trained and experienced team for search and rescue for emergencies and provide special training and equipment.
- Define cases that require mine evacuation and train all the operational and managerial staff
- Indicate mine evacuation routes in the mine
- Train control room staff in terms of coordination and communication for emergencies

Turkish Coal Enterprises (TKI)

- Establish sustainable and efficient coal production
- Control and monitor operations and the mine design
- Approve annual production plans and check their implementation with respect to resource exploitation and mine safety.

The General Directorate of Mining Affairs (MIGEM)

- Check and approve he overall feasibility and mine design and monitor mine production, considering mine safety, optimum resource exploitation and sustainability
- Take precautions and provide financial opportunities for supporting mine exploration and production
- Take measures and make recommendations for promoting mining activities to satisfy the needs, benefits and security of the country, and ensure the mining activities are performed based on newly developed technologies
- Establish rules and regulations as well as regulatory bodies specific to coal mining activities

Ministry of Energy and Natural Resources (MENR)

- Establish rules and regulations as well as regulatory bodies related to all mining activities starting from exploration, feasibility, design, exploitation and closure.
- Provide adequate resources to regulatory bodies to carry out their responsibilities.

Ministry of Labor and Social Security (MLSS)

- Establish rules and regulations as well as regulatory bodies related to occupational health and safety specific to coal mining activities
- Establish protocols, standards and guidelines for operational safety in coal mining.
- Audit coal mines in terms their compliance to standards, protocols and guidelines
- Ensure adequate risk assessment is conducted and effective risk management plan is in place.
- Enact legislation to enhance coal mine safety
- Provide adequate resources to auditing bodies to carry out their responsibilities.

Labor Unions (LU)

- Ensure adequate procedures are established for health and safety of the mine workers

The Grand National Assembly of Turkey (TBMM)

- Establish mining and labor laws to ensure sustainable resource exploitation and safe and healthy working environment

Fig. 4. Safety requirements and constraints of the control structure.

safety control structure of the overall system and its components (Fig. 3). For the overall system, the mining company must conduct risk analysis by foreseeing potential hazards and their consequences as well as evaluating them to develop mitigation measures, revise and the design, ventilation, material handling and transportation, communication, water, power and compressed air systems before the production is increased so that all system components support rise in production safely, install ex-proof/ATEX certified material in all part of the mine, keep track of mine subsidence, establish a comprehensive database for monitoring all types of changes in the mine.

Safety requirements and constraints for ventilation provide efficient and satisfactory ventilation to the all working areas in the mine, installing gas and temperature sensors to appropriate locations in the mine so that potential hazards can be detected earlier, taking necessary precautions when the gas, dust and temperature sensors record increased values and searching for the potential causes, keeping updated and systematic records of gas, dust and temperature measurements, identifying conditions of intentional ventilation changes and necessary measures to be taken before its implementation.

The company must equip all the workers and staff with sufficient personal safety equipment and give adequate training related to their use, give adequate education related to the safety issues and monitor the impact of education, track miners who are in the mine at all times according to their location in the mine, establish mechanisms for reporting unsafe operations, implementing drills for self rescue and mine evacuation. It is also responsible for providing adequate communication system and coordination between the various decision makers in the mine, developing codes and standards for safe mining practice and monitoring its implementation, establishing safety culture among all the hierarchical levels of the mine in terms of management aspects related to the safety requirements and constraints. For emergency management, the company must develop emergency management and evacuation plans and implement drills for envisaged emergencies including mine evacuation. It must also establish a trained and experienced team for search and rescue for emergencies and provide special training and equipment as well as raining control room staff in terms of coordination and communication for emergencies. Although past operations in the SEM had strong evidence for the high level of mine fire risk, the company's risk and emergency management plan as well as associated drills ignored a mine fire.

The safety of the overall sociotechnical mining system is dependent on adequacy of the safety constraints related to the individual system components and their interaction. Hence understanding the physical components of mine safety control structure is important. In Fig. 5 major physical components of the mining system and their interaction is given with regard to proximate events in the mine. A roof fall after the operation of the ground control unit triggered a fire in the roof which was expanded quickly due to existence of methane and wooden pieces between the steel support. The fire further developed through flammable materials like cables in the roof as well as conveyor belt which was ignited by the falling pieces from the roof. The fire control efforts was not enough and fire products distributed fast to almost all working areas in the mine through the ventilation system as the location was in one of the main roads, which let 301 fatalities.

6.3. The hierarchical control structure in place to enforce the constraints

The system's hierarchical control structure encompasses the overall safety. Hence each level of the hierarchical control structure and their role should be analyzed in order to identify their contribution to the occurrence of the accident. In CAST, this analysis is built upon four pillars, namely the goal, process or mental models, the actions, and the feedback. The goals represent the safety requirements and constraints to be put forward by each component of the hierarchical control structure. The process or mental models involve the context in which the behaviors took place or decisions are made. The actions cover inadequate control actions that were performed by each level of the hierarchical control structure. The feedback indicates the interaction between the components of safety control structure. The decisions made or actions put forward by the elements of the control structure always have a context. Thus, it is important to understand context and environmental factors that lead to an observed human behavior related to the accident.

The lower level in the hierarchical control structure in the SMD case

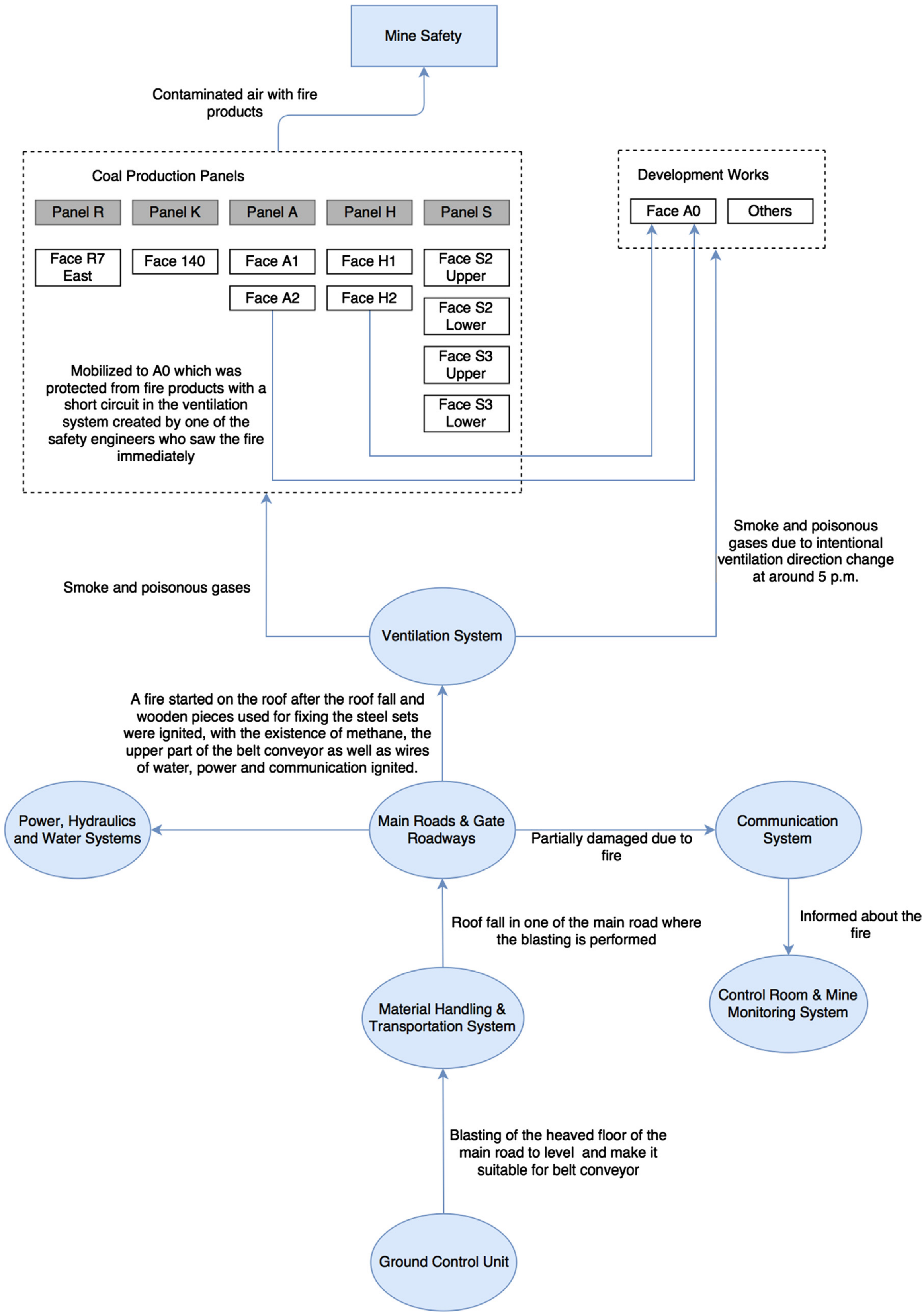

Fig. 5. Physical components of mine safety control structure.

is the mining company and TKI, which are the immediate operators. Then MIGEM is on the next level of TKI as an intermediate regulatory body. MENR, MLSS and LU are on the upper level, where they develop and impose regulations. Finally, TBMM is on the top level of the hierarchical control structure as the law making body. [But you drew it in the opposite manner,] The Mining Company (Soma Komur A.S.)

Safety Requirements and Constraints:

Overall Mining System

- Perform risk analysis by foreseeing potential hazards and their consequences as well as evaluating them to develop mitigation measures
- Revise and design the mine layout, ventilation, material handling and transportation, communication, water, power and compressed air systems before the production is increased so that all systems components support rise in production safely
- Install ex-proof/ATEX certified material in all part of the mine.
- Keep track of mine subsidence
- Establish a comprehensive database for monitoring all types of changes in the mine

Ventilation

- Provide efficient and satisfactory ventilation to the all working areas in the mine
- Install gas and temperature sensors to appropriate locations in the mine so that potential hazards can be detected earlier.
- Take necessary precautions when the gas, dust and temperature sensors record increased values and search for the potential causes.
- Keep updated and systematic records of gas, dust and temperature measurements
- Identify conditions of intentional ventilation changes and necessary measures to be taken before its implementation

Workers

- Equip all the workers with sufficient personal safety equipment and give adequate training related to their use
- Provide adequate education related to the safety issues and monitor the impact of education
- Track miners who are in the mine at all times according to their location in the mine
- Establish mechanisms for reporting unsafe operations
- Implement drills for self rescue and mine evacuation

Management

- Provide adequate communication system and coordination between the various decision makers in the mine.
- Develop codes and standards for safe mining practice and monitor its implementation
- Establish safety culture among all the hierarchical levels of the mine

Emergency management

- Develop emergency management plans and implement drills for envisaged emergencies including mine evacuation.
- Establish a trained and experienced team for search and rescue for emergencies and provide special training and equipment.
- Define cases that require mine evacuation and train all the operational and managerial staff
- Indicate mine evacuation routes in the mine
- Train control room staff in terms of coordination and communication for emergencies

Context in Which Decisions Made:

- The company is experienced in mine fires and able to control and extinguish it in any case
- Overall risk related to the hazards is low
- Serial ventilation is not a problem
- Keeping the workers in the mine is safer as the personal safety equipment my not be sufficient during evacuation and evacuating large number of workers (around 800) may create chaos
- Intentional ventilation change can be safely performed in case of emergency
- A total mine evacuation in case of emergency is not usually necessary and even can impose further safety problems

Fig. 6a. CAST analysis for the mining company-safety requirements and constraints, context in which decisions made.

6.3.1. *The first level operators (The mining company and TKI)*

The first level operators of the system are the mining company and TKI. The mining company operates the mine on the behalf of the TKI, which is the license owner. TKI approves mine design, production planning and other related operational issues. The results of CAST analysis for the mining company and TKI are given in Figs. 6 and 7. The CAST analysis for the mining company (Fig. 6) is conducted by considering the physical components of the mine safety control structure outlined in Fig. 5. Although the mining company performed a risk analysis, a fire that might occur in the main road was not among the anticipated risks. Therefore, an effective drill in which whole mine evacuation was not performed.

The mining company subcontracted the mine for an annual production rate of 1500000 tonnes in 2009. However, in 2012, TKI increased the annual production of the mine to 2500000 tonnes with a buying guarantee for all the produced coal in the mine (UTBA, 2014). The actual annual coal production in 2012 in the SEM was 3800000 tonnes. The annual coal production was planned to be 3000000 tonnes in the SEM. However, such a production rise was not reached by preparing the other systems components like ventilation, main roads etc. to be compatible with the increased production. In fact, the main system component that was not meeting the needs of the production increase was the ventilation system. The mine management was working on adding a new ventilation fan to the system before the disaster. Moreover In 2012 construction of a second ventilation gallery for the S panel was planned in order to convert existing serial ventilation system in this area to a parallel one. However, it was also not realized by the company. TKI also didn't enforce the opening of this gallery.

The production was planned mostly based on conventional mining system and hence increase in production led to rise in number of workers in every shift increasing the risk. This basically led large number of workers to cluster in the S panel as the production was mainly based on the conventional system in this panel. Considering the serial ventilation with large number of conventional production faces with high worker concentration, the risk in the S panel area had already increased. This increase in the risk level had not been evaluated and mitigated in the risk analysis of the company and TKI also didn't indicate the inadequacy of the risk assessment.

TKI basically promoted conventional production rather than mechanized mining. As mechanized mining requires a higher amount of investment capital, mining becomes feasible for larger coal reserves. However, TKI divided the large basin into smaller coal fields with reserves exploitable for a limited amount of years. This encouraged the company to increase the production based on conventional mining

The Mining Company (Soma Komur A.S.)
Inadequate Control Actions: In the Whole Mine • A fire that might occur in the main road was not among the anticipated risks and also an effective drill in which whole mine evacuation was not performed. • The production is doubled without improving the ventilation and there was a problem in the ventilation system. The mine management was working on adding a new ventilation fan to the system before the disaster. • In 2012 construction of a second ventilation gallery for the S panel was planned in order to convert ventilation in parallel. However, it was not realized • The production was planned mostly based on conventional mining system and hence increase in production led to rise in number of workers in every shift increasing the elements at risk • The decision to evacuate the mine was not taken for every part of the mine, rather, the working areas which have less number of workers are evacuated. Moreover, there was not systematic evacuation for these areas. The workers in the S, H and A panels, which are large in number, were ordered to stay and wait • The responsibility and related decisions for emergency management was distributed to safety engineers who were assigned to specific panels. An overall emergency management was not put into action. • The control room was also not informed about the nature and location of the fire. The staff there only noticed that some sensors in the A and H panels area were not sending data and called one staff in the mine to get there and check the sensors. The staff heading to this area was encountered his friends on his way and warned by his friend about intense smoke and fire in this area. He didn't contact to control room, In stead, he proceeded to the area of the fire despite the warnings of his friends. • All the top executive management entered the mine trying to reach the scene of the fire and did not organize the evacuation of the mine and check the implementation of it. In other words, instead of focusing on evacuating the mine safely, they tried to respond to the fire as they thought that controlling the fire is possible and this will provide safety. • As the accident started close to the time of shift change, measures for protecting workers from entering the mine were taken late and some entered and died on their way. • Search and rescue as well as emergency management was not adequate, the neighboring mine management with is search and rescue team was asked to come. • In efficient training program related to self-rescue was implemented • The number and location of workers in the mine was uncertain until the end of search and rescue, which took almost three days. • The search and rescue teams who were not equipped and trained were allowed to get into mine, where their lives were also put into danger. Even some fire trucks were asked to wait in front of the mine. • The information given to public and relatives of the victims were not so adequate, clear and transparent that it created public outrage. • The situation was put into media as if a natural hazard like an earthquake occurred and people from all over the country sent trucks of unnecessary material like, food, blankets, toys etc., to be stored in the town. In the S Panel Area • The communication between the management bodies as well as emergency management was not organized and decisions were made under inadequate information. • The safety engineers sent to the S panel were given inadequate information about the severity of the fire. They were only given responsibility by the top management for taking safety precautions. As the ventilation of the S panel was serial ventilation and the main road to the S panel carries return air of the other the working areas to the S panel, there was no other way the workers here could use in evacuation. • The safety engineers planned to limit exposure of the workers from the fire products in the return air by installing curtains at the entrance of working area and diluting air from the compressed air system. • The workers were not using masks properly even the safety engineers died while they were managing emergency. • The safety engineers responsible for the S panel were not aware of an old gallery which has intake air around the S panel and was constructed at the time of TKI (some wounded miners stayed here and were not affected by the smoke for a while, then they were affected by smoke when the direction of the ventilation changed but saved by the rescue teams) or they did not realize that this gallery could have been used since an evacuation plan for the mine was not organized. In the A and H Panel Area • When the fire started, the safety engineers responsible for the A and H panels saw the fire and made adjustments in the ventilation doors to form a short circuit of intake air in the A0 face area, thus prevented the fire from entering this area. The 142 workers from the A and H panels gathered in this area and was not affected from CO and other fire products. However, the decision to change the direction of the mine ventilation at around 5 p.m. let them exposed to CO. Though the workers moved towards the inner part of the face A0 in order to evade smoke, there were frequent exposures and fainting because of smoke between 6.30 and 7.30 p.m. • Due to lack of coordination and communication, the decision of ventilation direction change was made without considering the ventilation arrangement made in A0 areas. • The top management didn't collect all the information about the changes in the mining system made during the emergency management as well as not considering the number of workers in various parts of the mine and implemented ventilation change under inadequate information and improper assumptions. **Mental Model Flaws:** • Inadequate risk assessment, which led the mine management to have a perception of low risk operation despite the fact that the design and operation conditions were not adequate for the achieved productions. • Inadequate experience and competence in risk assessment • Risks can be tolerated in favor of doubled production. • Serial ventilation system is allowed by regulation and hence it does not impose high risks • Believed keeping large number of workers in the mine is safer as the fire can be controlled in a short period of time and chaos is more dangerous during the evacuation as the workers are not trained what to do in case of emergency and how to use personal safety equipment as a full mine evacuation had never experienced. • The workers entering the mine for the next shift will not be affected from the fire and fire products in the ventilation system. • Changing ventilation direction will save lives in the S panels and will not affect safety of the workers in the A and H panels

Fig. 6b. CAST analysis for the mining company- inadequate control actions and mental flaws.

system with intense worker needs. As TKI is the license owner of the Soma coal basin, its main concern was low cost coal production to meet the energy demand. Thus, according to TKI, subcontracting the production by dividing the reserve into various fields was the best way to obtain efficient coal production. Moreover, as contrary to the previous mining company (Park Teknik A.S.), the mining company (Soma Komur A.S.) was able reach the production levels demanded by TKI. Thus, it was believed that Soma Komur A.S. had great experience in coal mines

Turkish Coal Enterprises (TKI)

Safety Requirements and Constraints:

- Establish sustainable and efficient coal production
- Control and monitor operations and the mine design
- Approve annual production plans and check their implementation with respect to resource exploitation and mine safety.
- Context in Which Decisions Made:
- Instead of exploiting the reserves by TKI, subcontracting the production by dividing the reserve into various fields provide efficient coal production
- The Soma Komur A.S. has great experience in coal mines and can mitigate all the risks
- The mine didn't experience major accidents and handles safe operation.
- Mine mechanization is not suitable for this mine as it was tried in the past and was not successful
- The methane content in the mine is not so high and hence will not create serious safety risks
- Large number of workers in the underground mining operation decreases the production cost and does not impose safety related risks.

Inadequate Control Actions:

- Divided the large basin into smaller coal fields with reserves exploitable for limited amount of years, which made mechanized coal mining not so feasible in terms of investment as well as production planning.
- Allowed production increase with inadequate mine design.
- Promoted conventional mine production rather than mechanized mining
- Didn't enforced opening of a new main road in the S panel so that serial ventilation is converted to parallel.
- Allowed production in the A and H panels which have methane at the same time with the production in the S panel making a complex mine layout with increased amount and length of main roads
- Methane drainage was explored but not put into action.
- Ignored the use of flammable materials like conveyor belt, cables etc. in the mine
- Allowed the mining company to operate with inadequate risk and emergency management

Mental Model Flaws:

- Exploiting coal reserves by subcontracting the small coal fields in the basin provide efficient reserve exploitation
- The mine is one of the safest and the low cost mines in Turkey.
- Serial ventilation, use of flammable materials and other risk increasing factors are not a problem as the mining company had great experience and can control the risks
- Although soma coal basin has a propensity for spontaneous combustion, the companies in the basin are experienced in handling mine fires
- The possibility of a fire in the main road is near to zero

Fig. 7. CAST analysis for TKI.

Table 3
The distribution of bodies according to where they were collected before they were taken to the surface.

Panel	Number of victims
S panel and around	209
R panel and around	10
140 face	4
A and H panels and fire zone	78
Total	301

and can mitigate all the risks. In addition, the mine didn't experience major accidents, which is interpreted as a safe operation. In addition, TKI was convinced that mechanization is not suitable for the SEM as it was tried in the past and was not successful.

Similarly, despite the fact that the design and operation conditions were not adequate for the achieved productions, the mine management had a perception of low risk operation due to inadequate risk assessment, which was mainly due to the insufficient experience and competence in risk assessment. Hence high risk levels were accepted. Different socio-psychological factors, such as fear, culture, education, norms, value systems, society, experiences, type of hazard and knowledge, affect risk perception of individuals and in organizations (Zhao et al., 2016; Rohrmann, 2008). Furthermore, these factors are highly related with the risk acceptance and risk behavior (Rohrmann, 2008). Osei et al. (1997) and Renn (1998) lists factors influencing risk perception and acceptance like being voluntary vs. involuntary, controllability vs. uncontrollability, familiarity vs. unfamiliarity, short vs. long-term consequences, presence of existing alternatives, type and nature of consequences, derived benefits, presentation in the media, information availability, personal involvement, memory of consequences, degree of trust in regulatory bodies. In the SEM, having frequent mine fires and mitigating them successfully led to accepting higher fire risks due to personal involvement and controllability. For this reason, when the fire broke out, the mine management didn't make a decision to evacuate the whole mine as they believed that the fire was controllable. Rather, an evacuation decision was made for only some parts of the mine. Almost all of the survivors of the mine were those who received an order to evacuate the mine based on the news of the fire and who left the mine immediately. Those who did not leave the mine and stayed, lost their lives. Although there wasn't any record of the exact location of fatalities who were found by the rescue staff, based on the distribution of locations where the rescue teams accumulated the bodies for taking them to the surface, the distribution of the fatalities in the mine layout can be predicted (Table 3).

Because the S Panel is located remotely in the mine layout (Fig. 1) and clearly separated from other panels, it is obvious that most of the bodies kept here belonged to those who worked in this panel and its surroundings. Accordingly, 209 people lost their lives in this panel and its surroundings (Table 3). On the other hand, 78 people lost their lives around A and H panels. The low numbers of casualties in the R panel and around 140 Face was because fewer people worked in these panels and those who worked there could evacuate the mine immediately after the fire broke out.

The safety engineers responsible for the S Panel (SES1 and SES2), did not allow workers in these panels to leave the panel. The main reason for not evacuating the S panel is related to the risk perception factors of familiarity and controllability of the fire. As the mine experiences frequent fires due to the spontaneous combustion propensity of coal, the mine management considered this case like the ones familiar to the previous ones and they would be able to control it in a short period of time. However, they ignored the location of the fire in the mine, which started in one of the main roads handling ventilation air intake with probable methane in the environment. In contrast, the majority of the fires experienced in the past were in the production faces, which were easier to mitigate. As these fires are always controlled, the fire in this case was also considered to be the one that could be controlled easily. In addition, SES1 and SES2 were not given adequate information about the severity of the fire by the control center and the top management. SES1 even was not responsible for the shift when the fire broke out, and hence he was not in the mine but with the team of EMMoSEM. However, SES1 was sent to the S Panel to control the safety there but he was not given specific actions to be taken. The communication between the control room and the EMMoSEM was not properly established. The control room was unable to collect and distribute the relevant information. The EMMoSEM, who were responsible for emergency management and coordination, did not establish an appropriate coordination and efficient information exchange.

SES1 and SES2 were not experienced in handling such cases because drills related to emergencies were not practiced sufficiently in the SEM. For the given information and environmental conditions with the assumption of the controllability of the fire, the decision to keep workers in this area rather than evacuating the mine was considered to be the best option by SES1 and SES2. In this decision, it was assumed that the workers might be exposed to smoke while evacuating the mine and their CO masks would not function sufficiently during evacuation. As the ventilation of the S panel was serial ventilation and the main road to the S panel carried return air of the other working areas to the S panel, there was no other way the workers could use in evacuation. In this context, SES1 and SES2 fought against the smoke by blowing clean air to the faces in the S panel using the compressed air pipes so that the smoke would not affect the workers in the S panel faces. However, they all died during this action because their personal security devices like CO masks were not appropriate for protecting them from intense CO and other fire products. They were not monitoring the level of CO and duration of their masks, as they had not had sufficient emergency management experience.

When the fire was started, the control room was not informed about the nature and location of the fire. The staff there only noticed that some sensors in the A and H panels area were not sending data and called a safety superintendent (SS1) in the mine to get there and check the sensors. SS1 heading to this area had encountered his friends on his way and was warned by his friend about intense smoke and fire in this area. He didn't contact the control room. Instead, he proceeded to the area of the fire despite the warnings of his friends due to lack of coordination and emergency training.

A safety engineer (SE1) saw the fire when it started and made adjustments in the ventilation doors to form a short circuit of intake air in the A0 face area, thus preventing the fire from entering this area. The workers of the A panel gathered in this area. At around 3 p.m., smoke was seen in the H panel and the SE1 ordered evacuation of this panel. The workers evacuating the panel could not get out because of the smoke in the main road, thus, some tried the other way while some others entered into the A0 face area after the news they got from people they met on their way. A few people in the A0 face area sent to those who were stuck in the H panel and made it possible for them to gather in the A0 area. There were 142 workers from the A and H panels gathered in this area.

All the EMMoSEM, who had heard about the fire and entered the mine, were trying to reach the scene of the fire, which is related to increasing the level of information availability. However, this prohibited effective application of an organized emergency management and evacuation plan. Instead of focusing on evacuating the mine safely and implementing emergency management, they tried to respond to the fire. By the time the EMMoSEM were in the mine and got close the fire area, search and rescue teams were asked to go to the scene. However, it was found that the mine's search and rescue team were not able to control the fire as the fire was growing quickly and they were panicked. The neighboring mine (IMBAT Coal Mine) management (EMMoIMBAT) with its search and rescue team was asked to come. However, the EMMoSEM and MMoIMBAT were unable to reach the fire scene and decided to change the ventilation direction, as they believed that intentional ventilation change can be safely performed in this case and reaching the fire scene and controlling the fire would provide safety. This decision was made without considering the short circuit made by the SE1 to protect the workers of A and H panel. Therefore, the intentional change in ventilation direction caused smoke to reach the A0 face area, which was initially protected by the help of measures taken by SE1. When the smoke reached this area, fainting and deaths among the workers who had escaped to the A0 face area started.

The decision to evacuate the mine was taken for the working areas, which had fewer workers and were close to the exit. This decision was conveyed to the workers of these areas by the EMMoSEM when they met with workers while they were entering the mine. Although the workers of H and A panels were ordered to evacuate the mine, smoke was so intense that some of them were unable to evacuate but stayed in the A0 face area. Rather than putting an overall emergency management into action, the responsibility and related decisions for emergency management was distributed to safety engineers (SES1, SES2, SE1 and another two safety engineers who are the first responders), who were assigned to specific panels under the assumption that the fire was local and can be extinguished quickly with a limited degree of information. As the fire started close to the time of shift change, measures for protecting workers from entering the mine was not taken immediately and some entered and died on their way.

The long-term consequence of production increase without adequate mine design was ignored and trust by the regulatory bodies let TKI and the mining company to take a high level of risk. In addition, the statements of the government authorities that the mine was quite safe contributed to this risk perception. The most typical example was the statements made by Taner Yıldız, the Minister of Energy and Natural Resources, on July 9, 2013, which appeared on the media. In his talk in the mine, Minister Yıldız stated that the mine, which has exemplary qualities, puts the worker safety in the forefront and that they see that productivity increases as investments are made on safety-related systems and concerns of the workers are removed, adding that the share of domestic production is now on the increase along with the imported systems in mining, and they plan to extend this to other areas of mining as well (web 1).

The production increase in the SEM was achieved by developing new faces in the methane bearing zones like panels A and H at the same time with the production in the S panel. This brought about a complex mine layout with increased number and length of main roads, requiring adaptation in ventilation and transportation and material handling systems. TKI explored methane drainage but not put it into action, considering that the methane content in the mine is not so high. However, the location of the fire in the SEM was in the methane bearing part of the mine and existence of methane contributed the rapid development of the fire. Moreover, both TKI and the mining company allowed the use of flammable materials like conveyor belt, cables etc. in the SEM.

The search and rescue (S&R) teams were not only adequate in the mine but also in the neighboring mine. For this reason S&R of TTK from Zonguldak were requested. In the mean time, various S&R teams from local and national disaster relief organizations all over Turkey, who were not equipped and trained for mine S&R, were allowed to get into the mine, where their lives were also endangered. Even some fire trucks were asked to wait in front of the mine. The number and location of workers in the mine was uncertain until the end of the S&R, which took almost three days.

The information given to public and relatives of the victims was not adequate, clear and transparent, so it created public outrage. The situation was put into media as if a natural hazard like an earthquake occurred and people from all over the country sent trucks of

The General Directorate of Mining Affairs (MIGEM)

Safety Requirements and Constraints:

- Check the overall feasibility and mine design and monitor mine production, considering mine safety, optimum resource exploitation and sustainability
- Take precautions and provide financial opportunities for supporting mine exploration and production
- Take measures and make recommendations for promoting mining activities to satisfy the needs, benefits and security of the country, and ensure the mining activities are performed based on newly developed technologies
- Establish rules and regulations as well as regulatory bodies specific to coal mining activities

Context in Which Decisions Made:

- Antiregulatory culture.
- Efforts to increase investment to mines

Inadequate Control Actions:

- Allowed mining in the coal basin without considering the scale and sustainability issues
- Allowed production increase with inadequate mine design.
- Promoted conventional mine production rather than mechanized mining
- Didn't enforced opening of a new main road in the S panel so that serial ventilation is converted to parallel.
- Allowed production in the A and H panels which have methane at the same time with the production in the S panel making a complex mine layout with increased amount and length of main roads
- Ignored the use of flammable materials like conveyor belt, cables etc. in the mine
- Inadequate consideration of safety aspects in mine design during the approval process.

Feedback:

- No monitoring or feedback channels established to evaluate production increase with TKI and MLSS audits

Mental Model Flaws:

- Serial ventilation, ex-proof material use, conventional mining and other risk increasing factors are believed to be not exactly increasing the risk.
- The overall health and safety can be compromised in favor of production.
- Safety issues are implemented during the operation are not so critical in the mine design.

Fig. 8. CAST analysis for MIGEM.

unnecessary material like, food, blankets, toys etc., to be stored in the town.

6.3.2. The intermediate regulatory agency (MIGEM)

The CAST analysis conducted for MIGEM is given in Fig. 8. All the activities of the mining company and TKI was approved by MIGEM, which allowed mining in the coal basin without considering the scale and sustainability issues as well as production increase with inadequate mine design. Although, MIGEM was supposed to take measures and make recommendations for promoting mining activities to satisfy the needs, benefits and security of the country, and ensure the mining activities are performed based on newly developed technologies, it promoted conventional mine production rather than mechanized mining. Moreover, it didn't enforced opening of a new main road in the S panel so that serial ventilation is converted to parallel. In addition, it ignored the use of flammable materials like conveyor belt, cables etc. in the mine. The context in which these decisions made relies on MIGEM's effort to increase investments to the mines and inadequate consideration of safety aspects in mine design during the approval process. In addition, although MIGEM is responsible for developing mining standards, protocols and guidelines for every system component, it didn't establish them due to its antiregulatory culture.

MIGEM carries out some audits to control mining operations by checking if they are in line with the mining law, regulations, approved mine design as well as proposed plan of mine production. However, because the mining standards, protocols and guidelines are not well established, the audits were not performed based on clear and structured inspection criteria. Moreover, the inspectors as well as the experts in MIGEM, who conduct audits and provide approval, have limited training and experience related to coal mining.

6.3.3. The regulatory agencies (MENR, MLSS, LU)

The first regulatory body for the coal mines is MENR. The CAST Analysis for MENR is shown in Fig. 9. MENR did not specify well-established standards, protocols and guidelines specific to coal mining. For example, prohibition of serial ventilation of flammable materials were not clearly stated. The recent amendments in the mining legislation resulted in removal of specific safety issues related to coal mining, which caused high risks being taken so easily. In other words, it allowed the mining company to run high-risk operations provided that there were no serious accidents. MENR believed that existing regulations are flexible and therefore the companies had already satisfied any safety requirements. In addition, it was thought that developing standards and protocols specific to coal mining can limit the operations and decrease options for the companies to exploit the reserve.

The safety issues related to SC risks requires classification of reserves in terms of propensity of the coal to spontaneous combustion and regulation of the coal mine operations, accordingly. In this respect MENR didn't fully established spontaneous combustion characteristics of all the reserves.

Although MENR promoted exploitation of natural reserves by private companies, it didn't establish adequate and efficient ways of transferring the coal mining expertise of TKI to the private sector. Additionally, a comprehensive registry of practices of the private companies had not been established so that each company's capabilities are evaluated subjectively.

While MENR was stimulating increase in coal production, production efficiency is not taken into account. Instead, evaluation of production by using the metric of production only is considered to be the measure of performance. This made coal production mainly reliant on man-power, which was also announced to be an effective means of employment. In addition, the frequent visit of the Minister to the SEM and his declaration of highly safe conditions of the mine contributed to the development of a low risk perception.

As there were no feedback channels established to MLSS, the annual audit reports of MLSS which were indicating major safety problems in the coal mines were not seriously taken into consideration. Moreover, the reports of CMET, DDK and TEPAV, which were all underlining similar safety problems and highlighting the same concerns related to increased number of mine accidents, were ignored.

The MLSS is another critical regulatory body. The CAST analysis for MLSS is shown in Fig. 10. MLSS is the major regulatory body for conducting audits with respect to OHS. After the SMD, it was stated by MLSS that the SEM was inspected two months before the accident and

Ministry of Energy and Natural Resources (MENR)
Safety Requirements and Constraints: • Establish rules and regulations as well as regulatory bodies related to all mining activities starting from exploration, feasibility, design, exploitation and closure. • Provide adequate resources to regulatory bodies to carry out their responsibilities. **Context in Which Decisions Made:** • Energy demand through domestic resources should be promoted by increased coal production • The privatization of coal mines increase production and decrease the cost. • There is enough expertise and knowledge of coal mining in the private sector. **Inadequate Control Actions:** • Not well-established standards, protocols and guidelines specific to coal mining • Not fully established spontaneous combustion characteristics of all the reserves. • Inadequate transfer of coal mining expertise in TKI to the private sector. • No registry of company practices for the private companies • No consideration of production efficiency, rather evaluation of production by using the metric of production only. • False safety perception established by the frequent visit of the Minister to mine and his declaration of highly safe conditions of the mine **Mental Model Flaws:** • Existing regulations are flexible hence the companies have already satisfied any safety requirements. • Developing standards and protocols specific to coal mining can limit the operations and decrease options for the companies to exploit the reserve. **Feedback:** • No monitoring or feedback channels established to MLSS • Annual Audit reports are indicating major safety problems in the coal mines were not seriously taken into consideration

Fig. 9. CAST analysis for MENR.

no critical safety problems were noted. The main reasons for such an assessment was that there was inadequate standards, protocols and guidelines related to the coal mine safety, serial ventilation, explosive-proof material use, conventional mining and other risk increasing factors related to coal mining were allowed by regulation, no enforcement of quantitative risk assessment and risk management with well established acceptability and tolerability criteria, no regulatory requirements for establishing safety culture in the mines as well as monitoring it through indicators. Hence even if the experts performing the audit were able to detect safety problems they cannot be reported in the non-existence of regulatory basis.

Moreover, the number of experts for performing effective audits in the coal mines are not sufficient and protection of auditing bodies from political pressure is not fully established. A typical example was the statements by the Minister of Labor and Social Security, Faruk Çelik, which was made after the SMD. Faruk Celik stated that when a decision of closure for a mine due to safety concerns is made by our inspectors, they pull a few strings. Ministers make calls, deputies make calls; there are calls from Soma, just in order to allow the mine to operate and ignore the concerns. So, we opened the mines to give them a chance, and see what happened there (web 2).

In addition to MLSS audits, the SEM was monitored by a technical

Ministry of Labor and Social Security (MLSS)
Safety Requirements and Constraints: • Establish rules and regulations as well as regulatory bodies related to occupational health and safety specific to coal mining activities • Establish protocols, standards and guidelines for operational safety in coal mining. • Audit coal mines in terms their compliance to standards, protocols and guidelines • Ensure adequate risk assessment is conducted and effective risk management plan is in place. • Enact legislation to enhance coal mine safety • Provide adequate resources to auditing bodies to carry out their responsibilities. **Context in Which Decisions Made:** • Inadequate safety culture and systematic risk assessment expertise • Avoidance from political pressure applied by the mine owners though politicians **Inadequate Control Actions:** • Inadequate standards, protocols and guidelines related to the coal mine safety. • Serial ventilation, ex-proof material use, conventional mining and other risk increasing factors related to coal mining are allowed by regulation. • Relied on poor guidelines rather than legally enforceable regulations. • No enforcement of statistical data collection for establishment of quantitative risk assessment for coal mines and assessment of risk profile for each mine. • No enforcement of quantitative risk assessment and risk management with well established acceptability and tolerability criteria • No regulatory requirements for establishing safety culture in the mines as well as monitoring it through indicators • Frequent changes in the regulation • Inadequate number of experts for performing effective audits in the coal mines • Insufficient protection of auditing bodies from political pressure **Feedback:** • Inadequate monitoring or feedback channels established to evaluate impact of changes. **Mental Model Flaws:** • Serial ventilation, ex-proof material use, conventional mining and other risk increasing factors are believed to be not exactly increasing the risk. • The overall health and safety condition of many mines are so poor that the ones, which are better, can be tolerated.

Fig. 10. CAST analysis for MLSS.

supervisor who is responsible for reporting safety related issues to the EMMoSEM. When a safety issue is reported, the mine management has to deal with the issue. However, the employer of the technical supervisor is the mining company, which creates a conflict of interest. Hence majority of the technical supervisors do not want to put their jobs into danger by reporting all the safety issues, which would mean extra costs to the mining company. Even the minister directly declared that the external auditing mechanism (the inspectors of MLSS), which was expected to operate independently, was under pressure. It is clear that the internal auditors, who were working on the salary given by the owner of the mine, cannot perform effectively in such an ecosystem. Although this problem was reported many times in various government reports, a structured solution was not established.

Moreover, frequent changes in the regulation as well as poor guidelines instead of legally enforceable regulations, resulted in inadequate monitoring or feedback channels established for evaluating the impact of changes. Therefore, serial ventilation, explosion-proof material use, conventional mining and other risk increasing factors were believed to be not increasing the risk. Besides, the overall health and safety condition of many mines were so poor that the ones, which are better, were considered to be tolerable. MLSS also didn't established mechanisms for enforcing statistical data collection to be used in conducting quantitative risk assessment for coal mines and assessment of risk profiles for each mine.

The LU are responsible for imposing the regulations in order to ensure that adequate procedures are established for health and safety of the mine workers. The CAST analysis for the LU is illustrated in Fig. 11. In the SEM, mine management was recruiting the required labor through local human resources traders (dayisbasi) and work force in the mine was managed by these traders. Although this fact was known by the LU, it was ignored. The main reason for this was the lack of real democracy and bottom-up organization, which caused selection of labor union leaders to be manipulated by the employer. Moreover, the so-called "yellow unions" – unions under the direct influence of employers – were very strong in the SEM. This degraded the bargaining power of independent unions by signing weak collective agreements that fall short of meeting worker demands (Leverink, 2015). Therefore, the LU was not effective in ensuring the safe working environment for the SEM workers.

6.3.4. The Grand National Assembly of Turkey (TBMM)

The CAST analysis for TBMM is shown in Fig. 12. There was an excessive number of amendments made in the mining and OHS laws, which weaken the overall nature of the laws and decrease the complementary nature of these laws enforcing safety. Additionally, the amendments were not sufficiently supported by well-established standards, protocols and guidelines in the implementation. The amendments were made each time a safety concern emerged rather than considering an overall safety framework. During the process of law amendments, concerns of various stakeholders on the safety issues were overshadowed by dominance of a large number of small mining companies and their lobbying activities as they were trying to block safety measures that increase the cost of operational activities or requires additional investment.

6.4. Structural dynamics

The CAST approach takes the safety control system as its core and performs the analyses based on the structure of the safety control system, which is not static but dynamic. For this reason, accompanying the CAST with structural dynamics is essential for better understanding of evolution of the safety control system according to the changes in the operational and environmental conditions. It is expected that resilient system control structures enforce appropriate constraints for maintaining safe operation and they sustain safe operation as changes and adaptations occur over time.

In Turkey, until the beginning of 2000′s, most of the coal mines were state-owned and found to be inefficient and unproductive. The government started privatization of the mines since then. However, the private sector in fact didn't have enough experience in mining. More importantly, the mines were required to be mechanized to decrease safety risks and improve productivity, which requires large capital. The Turkish mining sector didn't have sufficient financial power either.

Hence the reserves were divided into small parts and subcontracted to these companies to be mined basically by using human power, which was not in line with production efficiency and the reserve economy. On the other hand, this allowed small mining companies to continue to mine and improve in capital over time. Moreover, mining based on human power decreased the unemployment rate in the local economies.

Allowing mining companies in this new atmosphere required changes in the legislation. Hence first the laws were changed in such a way that many specific safety aspects were removed so that many investors can be attracted to easy and simple mining regulations. These simplifications in the legislation weaken the safety control structure. Because most of the specific safety aspects were removed from the legislation by transferring all the responsibility to the companies, the inspections by the governmental organizations like MLSS and MIGEM didn't have any basis to impose the safety. Even though, inspectors noticed safety problems and have the right to stop unsafe mining operations, they cannot find any specific basis for doing so. Moreover, they were under the political pressure to let the mining companies operate continuously.

In the mean time, emergence of Yellow Unions contributed to reduced number of workers registered in the real ones because the employers wanted workers to register in yellow ones. Yellow Unions, with the collaboration of the employers, decreased the bargaining and enforcement power of the real unions. This also reduced the robustness of the safety control structure.

At the same time, the experienced engineers in the governmental organizations like TKI, retired or left and started working for the private

Labor Unions (LU)
Safety Requirements and Constraints: • Ensure adequate procedures are established for health and safety of the mine workers **Inadequate Control Actions:** • Willful blindness to the fact that mine management satisfies the required labor through local human resources traders (dayisbasi) and work force in the mine is managed by these traders. • The lack of real democracy and bottom-up organization made selection of labor union leaders who are manipulated by the employer • The strong power of the so-called "yellow unions" – unions under the direct influence of employers, which degrades the bargaining power of independent unions by signing weak collective agreements that fall short of meeting worker demands **Coordination:** • Neither MENR nor MLSS took responsibility for changing the situation. • [there are more explanations for the inadequate control actions in the text than here in the official analysis.]

Fig. 11. CAST analysis for LU.

The Grand National Assembly of Turkey (TBMM)

Safety Requirements and Constraints:

- Establish mining and labor laws to ensure sustainable resource exploitation and safe and healthy working environment

Context in Which Decisions Made:

- The amendments are made when necessary

Inadequate Control Actions:

- Excessive amount of amendments weakens the overall nature of the laws and decrease the complementary nature of these laws enforcing safety.
- The amendments were not sufficiently supported by well-established standards, protocols and guidelines in the implementation
- The amendments are made each time a safety concern was emerged rather than considering an overall safety framework.
- The concerns of various stakeholders on the safety issues were overshadowed by dominance of large number of small mining companies and their lobbying activities

Fig. 12. CAST analysis for TBMM.

companies. However, the amount of human capital was not enough to adopt appropriate mining systems in the private sector. Moreover, the experienced number of mining engineers in MIGEM and TKI, which were responsible for approving the mine design, safe operations etc. dramatically reduced. The replacements didn't have sufficient experience as the state closed most of the mines and hence the engineers who were doing the approvals also didn't have adequate knowledge of safety and experience. The experienced engineers, who started to work in the private sector, although they knew that mines were not safe, started accepting it due to the nature of the new system. When they were working for the state they had more freedom to identify safety problems due to work guarantees, which was not the case in the new system. New generation engineers, who developed experience in this unsafe working environment, also become accustomed to it. By this way, a critical pillar of safety control structure was damaged and unable to adapt the new system so that the safety control structure was sustained.

Under this fast and continuously changing environment, the increased number of accidents with large number of casualties in the coal mines attracted the attention of various hierarchical safety control structure elements as well as related stakeholders (e.g. reports of MICET, DDK, TEPAV). TBMM made a large number of amendments in the mining and OHS laws. However, these laws were unable to maintain overall integrity as the amendments were made on a case-by-case basis. Therefore, the complementary nature of the mining and OHS laws in enforcing safety was destroyed. More importantly, the new laws, the amendments and the regulations were not supported by a set of well-established standards, protocols and guidelines for their implementation. As a result, the nonexistence of standards, protocols and guidelines for the coal mines opened the doors for high risk operational conditions to the mining companies with decreased production costs. The lack of well-established standards, protocols and guidelines related to OHS made MLSS inspections ineffective in ensuring the safety of the mining environments. Moreover, the safety conditions of many mines operated by the private sector were so poor that the better ones were tolerated. Also, as MLSS didn't established mechanisms for enforcing statistical data collection to be used in conducting quantitative risk assessment for coal mines, it was unable to establish a risk profile for each mine.

Although exploitation of natural reserves by private companies has been promoted by MENR, adequate and efficient ways of transferring coal mining expertise of TKI to the private sector was not sufficiently achieved. While MENR was stimulating increase in coal production, production efficiency was not taken into account. Instead, evaluation of production by using only the metric of production was considered to be the measure of performance. This did not encourage coal production to be performed by the mechanized systems, which would provide safer mining systems with increased production efficiency. As there were no feedback channels established to MLSS, the annual audit reports of MLSS, which were indicating major safety problems in the coal mines, were not seriously taken into consideration, as well as the reports of MCET, DDK and TEPAV

The changing natural resource management policies, legislative framework, inspection practices, human resources and labor market and labor unions allow TKI and MIGEM to approve less safe mine operations and mine designs and develop a low risk perception for the SEM. As a result, in the SEM, a high increase in the production was achieved without improving the mine design and system, accordingly. Despite the fact that the design and operational conditions were not adequate for the achieved production, the mine management had a perception of low risk operation due to inadequate risk assessment, which was mainly due to the inadequate experience and competence in the concept of risk assessment. Hence high-risk levels were accepted by the mine management. Having frequent mine fires and mitigating them successfully led mine management to accept higher fire risks, as well. This led to making various unsafe decisions during emergency management.

The structural dynamics demonstrates that changes in the hierarchical control structure were not compensated well. This indicates that safety control structure for coal mines is not resilient and needs to be reinforced.

7. Suggested improvements for the safety control structure of coal mines in Turkey resulting from the CAST analysis

The CAST analysis highlights various weaknesses in safety control structure. The potential improvements related to the safety control structure are grouped and discussed based on three pillars:

- Sustainable resource management policies
- Laws and legislation
- Mining sector

The interactions between the system components for the safety control structures should be also redesigned to make the improvements effective. In this process establishment of a QRA based on STAMP would provide an effective methodological framework.

7.1. Sustainable resource management policies

The MENR's coal exploitation strategy is based on increased recovery with sustainable coal production. The MENR also aims at increased share of the domestic primary energy resources including coal in the primary energy resources of Turkey. It is obvious that these strategies will promote coal mining in future. However, the current safety control structure for coal mining is not adequate for achieving this aim. Dividing the state licensed coal reserves into smaller sections and subcontracting them to private sector for short time periods, prohibits mining companies from investing in mechanized systems as such systems require longer term production periods to recoup investments. Moreover, mining in the large coal fields with various private companies leads to decreased recovery, since neighboring mines need to leave large coal pillars for safe operations. On the other hand, the current structure of state organizations does not have conditions and resources for operating coal mines, which means that coal mining by private sector is expected to increase. Under these circumstances the government organizations, which have coal field licenses (TKI, TTK and EUAS) should develop new solutions that promote mechanized coal mining with increased production efficiency and decreased human power. In doing so the inadequate safety constraints defined for MENR, MIGEM AND TKI in Figs. 9, 8 and 7, respectively, should be taken into account. This implies the enforcement of the following constraints:

- Well-established standards, protocols and guidelines specific to coal mining. This implies development of well-defined roles for the government organizations so that they are capable of enforcing the standards
- Fully established spontaneous combustion characteristics of all the reserves. As TKI, TTK and EUAS still have large amount of coal reserve licenses, they should collaborate in assessing the coal reserve characteristics
- Transfer of coal mining expertise in TKI to the private sector. A consensus related to the required standards for mining engineering expertise in cola mining should be established between the mining companies, regulatory organizations, Turkish Chamber of Mining Engineers and Universities having Mining Engineering Education.
- Construction of a registry of company practices for the private companies. An automatic online accident reporting and analysis infrastructure should be established with agreed standards between the government organizations and the private companies.
- Evaluation of production efficiency, rather evaluation of production by using the metric of production only.
- Being distant and equal to all coal mines.
- Promoting mining by considering the scale and sustainability issues
- Enforcement of strict controls for compatibility of mine design and production increase as well as safety focused mine design.
- Encouraging mechanized coal mining
- Enforcement of methane control measures
- Prohibiting the use of serial ventilation, flammable material, conventional mining and other risk increasing factors related to coal mining

These government organizations should enhance their human resources by providing experts who have capability to evaluate safe, feasible and sustainable mine design and operations. This can be achieved by establishing close collaboration with the universities and MCET, as well as developing specific training and capacity building programs. Moreover, as indicated in Fig. 9, there should be monitoring and feedback channels between MENR and MLSS.

The development of a reserve classification based on spontaneous combustion propensity of coal reserves by MENR is critical as the standards and protocols related to operational aspects of coal mining depends on this classification. Moreover, MIGEM and TKI should be equipped with better exploration data and analysis tools so that new and existing mine designs can be evaluated based on principles of sustainability and safety.

7.2. Laws and legislation

The current integrity of mining and OHS laws are inadequate to support the safety control structure. Especially feedback loops between MENR and MLSS, MIGEM and MLSS and TKI and MLSS are urgently needed, which was one of common factors listed for TKI, MIGEM, MENR and MLSS in Figs. 7–10, respectively. Besides, mining and OHS laws should be accompanied by standards, protocols and guidelines specifically developed for coal mining, which is currently missing. In order to develop and update them, an independent organization, which is composed of experts on coal mining and performs and promotes research on improving coal mining safety, should be established so that protocols, standards and guidelines ensure the safety. This independent organization could also serve for protecting the safety control structure from the pressure of the sectorial lobbies.

The existing regulations for risk assessment and management are not enforced by the safety control structure, as it does not involve measures for incorporating them in the operational practice (Fig. 10). Hence it should be revised so that QRA is promoted, which allows objective comparisons of risks and monitoring risk mitigation. Additionally, risk acceptability criteria related to coal mining operations should be developed, which was one of the critical inadequate control actions listed for MLSS in Fig. 10.

The legislation related to internal and external safety investigations should be developed in such a way that they complement each other and ensure the identification of actual safety problems. In the current situation, the safety related inspections and controls are supposed to be made continuously by the technical supervisor who is responsible for reporting safety related issues to the mine management and paid by the company. The MLSS investigators and MIGEM staff make annual inspections. However, these inspection bodies are not supported by well defined standards and protocols and hence are subject to the pressures of the mining company (Figs. 9 and 10). Therefore, legislation that allows establishment of independent mine investigation should be developed. Moreover, as the mining systems are complex and dynamic, these external investigations are not solely sufficient to sustain safety. An internal safety culture should be adopted by the mining sector, which should be backed by legislations. As LUs are one of the key stakeholders for developing safety culture, legislation for making them independent from employers should be imposed (Fig. 11).

The current legislation still allows serial ventilation in coal mines. The use of mine trackers and monitoring systems are not compulsory by law. The critical emergency management aspect of coal mining like self-escape, mine evacuation, use of personal security devices are not enforced by the legislation which should be urgently revised (Fig. 10).

MLSS inspector staff should be increased so that annual inspections can be sufficiently handled. In addition, financial recourses related to detailed investigations should be allocated sufficiently. A central database for keeping the detailed accident and casualty data should be established. MLSS should evaluate each coal mine's safety performance and made the results open to the public (Fig. 10). The current automation trend in high-risk sectors like coal mining, allows each component of the safety control structure to have a data collection probe in the actual operation. The data from various sensors for the mine's environmental, geological and operational conditions has potential to support real time decision making for a mine fire management, which would be supported by the infrastructure of the central database.

TBMM should avoid excessive amount of amendments that weaken the overall nature of the laws and decrease the complementary nature of these laws enforcing safety (Fig. 12). The amendments should not be made each time a safety concern is identified by the occurrence of a hazard. The overall legal and regulatory structure should be established based on a safety-focused framework.

7.3. Mining companies

Although proposed improvements for the safety control structure will increase the cost of mining, in the long run mining companies should realize that only safe mining operation sustains the sector. For the sake of sustainability, in the mining sector, they should change their mining practice in such a way that safety should not be compromised. For this purpose, immediate measures for establishing a safety culture in every management and operational structure should be adopted by the companies. The mining companies should allow LUs to operate independently so that they play their critical role in the establishment of safety culture (Fig. 11).

The small mining companies' dominance in lobbying for cost-related issues should be avoided and safety-related concerns should be incorporated in the mining practice (Fig. 12).

In all levels of management hierarchy, safety culture should be adopted. The training, capacity building and implementation of safety culture should be imposed in technical, social and management components of the mining system.

8. Conclusions

The STAMP with CAST used for analyzing the SMD reveals that it allows analyzing the complex sociotechnical accidents involving high degree of uncertainty. As in the case of the SMD, even though it is not possible to determine exact cause of accident, CAST tool provide identification of reasons for consequences and dynamic nature of the events that cascades the consequences. It also provide an in depth understanding of role of each member of hierarchical safety control structure starting from legislative organizations to individuals. Accordingly, the required improvements in each hierarchical layer are easily identified.

The CAST analysis adopted in this study serves to identify flaws in the safety control structure that resulted in the SMD, which is one of the largest mine disasters in the recent decade. The legislative environment for promoting the development of mining industry in Turkey was not accompanied by required safety standards. This led to acceptability of high risk levels in every level of mining operation from mine design to operation. Even a false risk perception was developed for the mining operations in this legislative ecosystem. The societal checks and balances like labor unions had also lost their major role due to political changes. The existing social and legislative framework enabled mining companies adopting low financial risk operations, like production with large number of miners with unsafe mine design in stead of mechanized mine operations, with highly reduced in safety. Division of large coal reserves into smaller parts and subcontracting each part to several mining companies also did not allow the companies to have feasible investments to mechanized mines. In the case of the SMD, the mining company tried to achieve a high level coal production by employing large number of work force in the underground (approximately 800 worker/shift), with false risk perception, high probability hazards like fire omitted in risk assessment, ineffective emergency management training and implementation, production increase without making necessary technical improvements in the major mining systems like, ventilation, transportation, monitoring etc. All these factors and flaws indicated in the CAST analysis in fact resulted in decisions made during the emergency management, which elevated the number of fatalities.

The necessary changes in the overall system's safety structure are also identified based on inadequate safety constraints determined for each hierarchical level. Considering the involved level of uncertainties which lead to development of various hypotheses by different expert groups on the cause of the accident, STAMP with CAST is highly capable of handling uncertainties and hence robust for highlighting weaknesses in the safety constrains. For this reason, it enables identification of needs for safety enhancement in the mining system of Turkey,

Unfortunately, after the SMD, a conventional event-based approach was followed by not only the experts of the law suit but also other experts from the government organizations. This resulted in new amendments made in the legislation following the disaster that are not sufficient to improve the safety conditions in the current coal mines. In addition, any type of legislation enacted to improve safety cannot achieve the expected outcome without developing standards or protocols. Improvements carried out based on some general assumptions without examining the reasons for the casualties in the SDM have not made significant improvements to the sector. To sum up, high-risk production still continues in Turkey. On the other hand, specific findings from the CAST analysis given in this paper still provide opportunities for improvements.

Leveson (2011) indicated that CAST is not suitable for law suits as it does not focus on responsible groups or person for the socio-technological disasters like the SMD. However, it provides a systematic way of strengthening the system safety structure in order to prevent future disasters. The CAST analysis provided in this paper shed light on the SMD by investigating the system control structure in every hierarchical level, even though the exact cause of the accident is unknown. Hence systematic and tangible improvements are suggested for the establishment of resilient system safety controls for coal mines in Turkey, demonstrating the the added value of the STAMP with CAST and its robustness.

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