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A systems-theoretic approach for two-stage emergency risk analysis

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ABSTRACT

Coronavirus disease (COVID-19) is an infectious disease that has dramatically spread worldwide. Regarding the safety issues of industries, there is a requirement of dealing with the emergency risk in the period of urgent situations. In this work, we proposed a systems-theoretic approach of the two-stage emergency risk analysis (ERA) based on the systems theory, that is the System-Theoretic Accident Model and Processes (STAMP). The two-stage ERA includes the normal to emergency risk analysis (N2E-RA) and emergency to normal risk analysis (E2N-RA). Besides N2E-RA, we advocate that E2N-RA is also an important and indispensable part of ERA. We elaborated the characteristics of N2E-RA and E2N-RA, separately. Eventually, based on our analysis, we provided recommendations for decision makers in preventing and controlling industrial accidents in the period of COVID-19.

1. Introduction

At the time of writing these lines, Coronavirus disease (COVID-19) has led to 7, 410, 510 confirmed cases and 418, 294 confirmed deaths in 216 countries, areas or territories[1]. The world has spared no efforts to save lives and control the pandemic. From the viewpoint of researchers in safety science and engineering, it is important to ensure safety and health at work in the pandemic and in the work resumption (ILO, 2020).

In the domain of safety and reliability, several efforts related to COVID-19 have been conducted. Emmanouil et al. recommended to pay attention to the sero-prevalence studies, primary health care section, and the socially vulnerable communities (Emmanouil et al., 2020). Tran et al. discussed the health and economic vulnerabilities of workers to restrain the emergence of COVID-19 in an industrial zone in Vietnam (Tran et al., 2020b). Tran et al. studied the way to evaluate the capacity of the local government and community in the emergency response of COVID-19 (Tran et al., 2020a). Vordos et al. investigated how the additive technology and social media can be applied to deal with the shortage of the personal protective equipment (PPE) (Vordos et al., 2020). Sangiorgio and Parisi proposed a multi-criteria method for the infection risk analysis of COVID-19 in urban districts (Sangiorgio and Parisi, 2020). Saba and Elsheikh predicted the confirmed cases of COVID-19 in Egypt by using the nonlinear autoregressive artificial neural networks (Saba and Elsheikh, 2020). Duffey and Zio estimated the fluctuation of pandemic infections by applying the statistical physics and learning theory (Duffey and Zio, 2020). In a nutshell, aforementioned work can be very helpful for decision makers in fighting against the pandemic. Nevertheless, few works have been reported on dealing with the risk in the emergency situations, particularly those related to COVID-19.

The risk analysis of emergency processes is crucial for the effective emergency management (Qiao and Shi, 2019). A previous accident needs to be paid attention to is Tianjin port explosion accident (Chen et al., 2019; Wu and Huang, 2019). The accident, happened on August 12, 2015, finally led to 165 fatalities, 8 losses, and 798 injuries. Regarding the casualities in the accident, in the emergency process, 99 firefighters and 11 policemen died, 5 firefighters were missing.

There are several industrial accidents happened in the period of COVID-19 till now (i.e., June 12, 2020). There is risk for restarting factories. For example, on May 7, 2020, a polymer plant in Visakhapatnam, India reopened due to the COVID-19. Unfortunately, the styrene leakage happened, which finally led to 12 fatalities and over 1000 injures[2]. Another example is in Xinyang, Henan Province, China. On March 13, 2020, a flooding accident happened in a fluorite mine while preparing the resumption of work. The company were cleaning the

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[1] https://www.who.int/, accessed on 2020-6-12.
[2] https://news.un.org/en/story/2020/05/1064092, accessed on 2020-6-1.
[3] https://www.thepaper.cn/newsDetail_forward_6601941, accessed on 2020-6-1.

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tunnel and dredging the pipeline[3]. The accident eventually led to 7 fatalities.

Emergency risk is the undesirable hazard in the emergency operations. Such risk needs to be controlled throughout the emergency process. In the literature, risk during the normal conditions (including equipment, personnel, and environmental aspects) has been thoroughly studied. Deacon et al. proposed a methodology to select safety barriers and reduce risk in the individual muster procedures (Deacon et al., 2010). Taleghani et al. identified the failure modes and effects of the procedures of the emergency surgery department by the healthcare failure mode and effects analysis (FMEA) (Yasamin Molavi Taleghani, 2016). Ji et al. proposed to apply the cellular automata to conduct the risk analysis in emergency response activities (Ji et al., 2008). Qiao and Shi proposed to conduct the risk analysis of the emergency through fuzzy evidential reasoning (Qiao and Shi, 2019). Above work can be very useful for identifying and analyzing the risk in the emergency situations. Since the systems are becoming much more complex, corresponding interactions needs to be taken into account. In further steps, a simplified and systematic risk analysis approach method is highly expected in emergency scenarios.

As a systematic method, System-Theoretic Accident Model and Processes (STAMP) has been broadly applied for accident analysis and risk assessment. The theoretical basis of STAMP is the control theory and system theory. The managing structure can be built for analyzing corresponding responsibilities and drawbacks. The analysis of stakeholders in the managing structure of the system can thoroughly be conducted. Suggestions are subsequently provided to improve the performance of system safety.

To effectively prevent and control the risk in emergency situations, we proposed an approach for emergency risk analysis (ERA). In this paper, we illustrate ERA associated with emergency situations of COVID-19. The remainder of this paper is outlined as follows. Section 2 proposes the two-stage ERA. Section 3 illustrates the systems-theoretic approach, in the framework of STAMP. Section 4 illustrates the approach with a case study. Eventually, Section 5 provides recommendations and summaries this paper.

2. Two-stage emergency risk analysis

ERA is composed of two stages, that is, the normal to emergency (N2E) RA and emergency to normal (E2N) RA. Namely, the situations *from normal to abnormal* and *from abnormal to normal* need to be included.

2.1. Emergency systems

In an emergency situation, the local response resource is usually activated. Once the accident is controlled at this stage, the emergency process is terminated. Otherwise, the outer emergency personnel and resources are requested. Only if the accident situation is under control, a further outer force is required for continuing emergency operations.

Following factors in an emergency system are required to be considered:

- *Scale and severity of the accident*. As the core factor of the emergency system, the accident scale directly influences the change of the other related factors. The closely monitoring of the accident scale is beneficial for an emergency system.
- *Self-rescue ability of the facility* in accident, which includes the facility emergency response and evacuation abilities. The improvement of the self-rescue ability of the facility could control the accident escalation at an early stage with low cost.
- *Emergency personnel resources*. The professional emergency personnel (experienced specialists, technicians, and professional companies) could rapidly design and implement the effective emergency proposal and reduce accident consequences.
- *Harsh degree of the accident environment*. The increasing severity of the accident environment could induce the secondary accident risk to the emergency operation, thus can enlarge the accident scale. The increase of the severity degree could also worsen the emergency environment and increase the emergency risk.
- *The outer emergency resources ability*. The improvement of the outer assistance could effectively control the accident escalation.
- *The emergency commanding disposal ability*. This ability refers to the site operations and commanding center. The increase of the commanding disposal ability could enhance of the emergency resources, personnel and self-rescue abilities, which contribute to the control of the accident scale.

2.2. Normal to emergency risk analysis (N2E-RA)

After obtaining the knowledge of emergency systems, we need to characterize the two-stage ERA. With the COVID-19 as example, the characteristics of N2E-RA are:

(1) People can feel stress with increased anxiety, low mood, and low motivation in emergencies (ILO, 2020). The workers may stand *high pressure* in emergency situations. Therefore, necessary measures need to be taken to deal with the psychological pressure. Moreover, due to the possible reduction of wages, the workers may suffer psychological pressure.
(2) The workers may sustain *heavy work load or mission*. This is due to the insufficient human resources in emergency scenarios. For instance, factories for manufacturing masks or disinfectants obtained more orders than usual.
(3) The workers may become *fatigue* after the high working pressure and load. Therefore, it is essential to design activities to relax related workers.
(4) It is necessary to clearly issue *guidance* for workers in emergency situations. That is, it is crucial to determine and execute correct emergency plans.
(5) It is essential to *confirm machinery status* in the emergency environment. Necessary maintenance of crucial equipment is required.
(6) It is of necessity to *proactively respond* to environment changes.

2.3. Emergency to normal risk analysis (E2N-RA)

Besides the risk in the period from normal to emergency, risk also exists in the situation from emergency to normal. In the emergency to normal situations (e.g., the reopen activities in COVID-19), the characteristics of E2N-RA are:

(1) To avoid fatalities and injures, in case of meeting tight deadlines or grasp the progress, it is required to *monitor the working progress* of target enterprises.
(2) *Leadership* in the period of COVID-19 is vital to identify, assess and control the emergency risk.
(3) Machinery may undergo *restart failure* (e.g., the failure on demand for safety instrumented systems). Therefore companies need to carefully check machinery before the restart.
(4) People may suffer from *emotional relax or slacking*. In addition, workers may forget some working skills in the wake of the pandemic. Therefore the safety and emergency training is essential before their return to work.
(5) Risk identification, analysis, control, and prevention at different scenarios need to be conducted. Former risk analysis results can also be screened.
(6) Natural hazard triggered technological accidents (*Natechs*) need to be paid attention to. It requires the stakeholder to respond to the nature forecast proactively and promptly.
(7) *Responsibility* of each personnel or position should be declared.

(8) *Recovery work plan* (including the emergency plan) or safety checklist is required.
(9) PPE is required amid COVID-19. Goggles, gloves, masks are required, particularly for indoor workers.
(10) Fire and explosion hazards of *ethyl alcohol (for sterilization)* need to be considered.
(11) *Emergency drill* is essential before the resumption of companies.
(12) In the wake of the pandemic, *it is forbidden to discriminate the preinfected workers*. Simultaneously, these workers need to pass the nucleic acid testing and quarantine (e.g., normally 14 days before return to work).
(13) Prior to the resumption of work, it is necessary to *transport the workers directly* from home to factories in specially-chartered vehicles, rather than the public transportation.
(14) It is essential to provide the *safe workplace* before the assumption of work. In this way, the confidence and trust of workers can be established. Through the application of infrared thermometer, workers with fever (i.e., possible symptom of COVID-19) can be identified.
(15) It is necessary to put *safety* first. In the reopen of work, to reduce losses due to the pandemic, the shareholders tend to put *production* first. According to the estimation of International Labour Organization (ILO), the working hours in the second quarter of 2020 has decreased 10.7% when compared with the fourth quarter of 2019[4].
(16) Redundancy of crucial working positions is required.
(17) Remote distance training can be adopted in the pandemic. In this way, risk of infection can be reduced.
(18) According to the pandemic situation, dynamic management levels can be adopted. For instance, the operation with high risk (e.g., confined space operation) can be managed and monitored with strict management.

3. A systems-theoretic approach

3.1. STAMP

STAMP have been broadly utilized for the accident analysis of complex systems (Leveson, 2004). For instance, Düzgün and Leveson have analyzed the soma mine disaster via STAMP (Düzgün and Leveson, 2018). Yousefi and Hernandez have employed STAMP to conduct the hazard analysis in process industry (Yousefi and Hernandez, 2019). Meng et al. have applied STAMP for the safety analysis of deepwater well control (Meng et al., 2018). Xing et al. have utilized for the accident analysis of the urban pipeline (Xing et al., 2020). More specific of STAMP is referred to Leveson (2004, 2011).

In the framework of STAMP, accident is regarded as an inherent characteristic of complex systems. The accident is interpreted as the loss of constraints to system behaviors. The basic elements in STAMP are constraints, control loops and process models, and levels of control (Leveson, 2004). Therefore, in the analysis of stakeholders in the accident, their safety requirements and constraints, context in which decision made, inadequate control actions, as well as the mental model flaws can be systematically analyzed.

Safety requirements and constraints are specified to stop the hazards from happening (Leveson, 2011). Such constraints are applied to system design and tradeoff analysis (Leveson, 2011). That is, the safety requirements and constraints can be regarded as essential functions and responsibilities of involved stakeholders. For example, in the period of COVID-19, safety requirements and constraints of the government are to effectively establish and operate a resilient public health system.

Fig. 1 shows the methodology for analyzing the emergency risk (ER). We can conduct the two-stage ERA based on STAMP.

In an accident, main stakeholders can normally be classified as government and company parts. To prevent and control the emergency risk, the following illustration can regarded as suggestions for conducting ERA.

3.2. Companies

The emergency risk of companies can be investigated in following four aspects. Note that the companies here refer to both headquarters and branches.

3.2.1. Safety requirements and constraints

The safety requirements and constraints for companies are to:

(1) establish and maintain the responsibility regime of the operational safety.
(2) formulate and update the emergency plan.
(3) organize the emergency drill for employees.
(4) be responsible for the routine operation.
(5) identify, assess and control the emergency risk.

3.2.2. Context in which decision made

The context in which decision made by companies possibly include:

(1) failed to conduct the hazard inspection.
(2) failed to declare responsibilities about the work safety.
(3) inadequate drill and learning of the emergency plan.
(4) failed to report the accident information to related authorities.

3.2.3. Inadequate control actions

The inadequate control actions of companies possibly include:

(1) failed to adequately guide branches to thoroughly follow the contingency plan.
(2) failed to efficiently guide the emergency disposal.
(3) failed to trigger the emergency plan in time.
(4) failed to timely report the accident scenario.
(5) failed to carry out sufficient patrol and inspection.
(6) failed to promptly perform alarm and closure.
(7) failed to conduct detection of the toxic and inflammable gas.
(8) failed to utilize the non-explosion-proof device.

3.2.4. Mental model flaws

The mental model flaws for companies possibly consist of:

(1) lack of the emergency knowledge training to employees, including the patrol crew.
(2) failed to promptly detect and rectify incidents in emergency operations.
(3) inadequate education of the safety knowledge and skills.
(4) unacquainted with corresponding duties and contingency measures in the emergency scenario.

3.3. Governments

The emergency risk of governments can be studied in following dimensions. Note that the governments here include both superior and local ones.

[4] https://www.ilo.org/global/topics/coronavirus/impacts-and-responses/WCMS_745963/lang--en/index.htm, accessed on 2020-6-5.

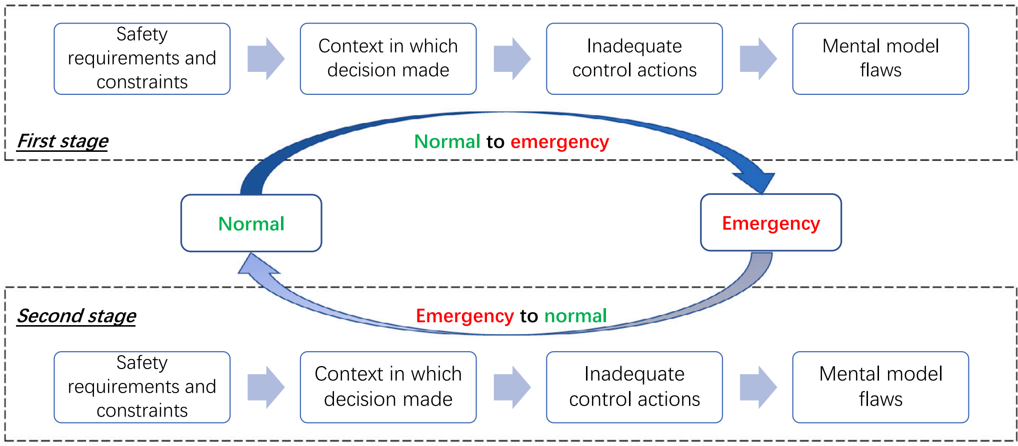

Fig. 1. The proposed approach.

3.3.1. *Safety requirements and constraints*

The safety requirements and constraints for governments are to:

(1) execute the policy and regulations related to the industrial safety.
(2) oversight of authority branches.
(3) scrutinize the safety operation of companies.
(4) join in the emergency rescue work.
(5) routine inspection of crucial facilities and operations.
(6) supervise the companies and government branches to conduct hazard rectification.
(7) oversight of companies to conduct the safety patrol and inspection.
(8) identify and control the emergency risk in accidents.

3.3.2. *Context in which decision made*

The context in which decision made by governments possibly include:

(1) insufficient communication with related companies.
(2) inappropriate urban planning, particularly the intersection of industrial plants, urban infrastructure, and residential areas.
(3) failed to pay attention to major risks in the safety inspection.
(4) inadequate supervision of the work safety of companies.
(5) insufficient to scrutinize companies to deal with identified risks.

3.3.3. *Inadequate control actions*

The inadequate control actions of governments possibly include:

(1) failed to forecast the evolution process of emergency incidents.
(2) inadequate to guide emergency operations.
(3) failed to correctly determine the degree of emergency response.
(4) failed to conduct alarm and closure in time.
(5) failed to evacuate the adjoining residents of industrial plants.
(6) postponed the report of emergency situation to public and superior governments.
(7) failed to scrutinize the companies to follow the emergency plan.
(8) failed to correctly estimate the emergency evolution.

3.3.4. *Mental model flaws*

The mental model flaws for governments possibly consist of:

(1) failed to identify risk in the emergency situation.
(2) failed to identify and supervise the violation in emergency operations.

3.4. *Suggestions*

Based on the discussion in Sections 3.2 and 3.3, by considering the aspects closely related to the pandemic, we provided the following suggestions.

The fear and the risk of infection exists in the pandemic. The focus of workers may be occupied by the pandemic evolution. Therefore, the protection of people from being infected should be paid high attention. In the workplace, essential measures should be undertaken to decrease the infection risk. Moreover, the quarantine can increase the risk of depression and anxiety, which can threaten work safety. Vaccination can be proactively considered with the support of enterprises and governments.

Since the long-time departure of the workplace, the workers may become unfamiliar with the facilities and operational procedures. This situation can increase the accidental risk. The lack of positions, due to losses in the pandemic, contributes to the increased risk of work safety.

The autonomous systems have been broadly applied in the pandemic. Therefore, the applicability, functionality, and safety of the autonomous systems require to be given more attention.

Telework cannot fully substitute the office work. For example, colleagues cannot fully communicate with each other online. The extent of affecting work safety by telework has to be kept in mind. Moreover, telework has been internet-dependent, thus the cybersecurity risk exists.

Besides, in the lockdown period (e.g., several months), the degradation of components and systems require to be considered in the resumption of the work. Corresponding maintenance can decrease the risk of abnormal incidents.

4. Case study

4.1. *Vizag gas leak*

The Vizag gas leak happened at a polymers chemical plant in Visakhapatnam, Andhra Pradesh, India. The leakage of styrene, which was occurred on May 7, 2020, has led to 13 deaths and over 1000 injured. The accident is happened in the process from emergency to normal situation. That is, the plant is under operation from the lockdown to production periods. Therefore, emergency to normal risk analysis has been conducted in the following systematic analysis. With the accessible information from the accident documents (Tammineni and Dakuri, 2020), companies and governments have been mainly discussed.

4.2. *Emergency to normal risk analysis of companies*

4.2.1. *Safety requirements and constraints*

(1) The company should conduct sufficient maintenance of the leaked tank.
(2) The cooling systems of the tank storing styrene should be kept working well.
(3) The pre-startup safety review (PSSR) should be carefully carried out.

4.2.2. *Context in which decision made*

(1) The plant was locked down due to COVID-19. The accident has occurred in the resumption of the work.
(2) The plant failed to organize risk assessment and control before the re-open of the plant.

4.2.3. *Inadequate control actions*

(1) The plant failed to efficiently guide the emergency response.
(2) The plant failed to follow standard procedures in re-open processes.

4.2.4. *Mental model flaws*

(1) The plant failed to conduct sufficient training and emergency drill for employers.
(2) Experienced staff has retired and left from the plant.

4.2.5. *Emergency to normal risk analysis of governments*

4.2.5.1. *Safety requirements and constraints.*

(1) The government should execute the policy and regulations of work safety.
(2) The government should closely inspect the facilities and operations of hazardous plants.
(3) The government should organize emergency drill and evacuation of local residents.

4.2.5.2. *Context in which decision made.*

(1) There exists inadequate supervision of the work safety of the chemical plant.
(2) There exists insufficient awareness of changes in the design and operations of the plant.

4.2.5.3. *Inadequate control actions.*

(1) The government failed to supervise the risk assessment conducted by the plant.

4.2.5.4. *Mental model flaws.*

(1) The government failed to timely identify the violation of safety regulations.
(2) The government should pay more attention to operations and equipment in the hazardous plant.

4.2.5.5. Suggestions. Based on the systematic analysis of the Vizag gas leak accident, we can provide the following recommendations to prevent similar accidents in the future.

(1) The company should fully comply with the safety rules issued by governments.
(2) The company needs to conduct a detailed risk assessment before the resumption of work.
(3) The government needs to closely monitor the changes in local hazardous companies.
(4) The government needs to conduct emergency drills for nearby residents in peacetime.
(5) The government needs to timely organize escape, evacuation and rescue (EER) of nearby residents.

5. Discussion and conclusion

Based on above analysis, we provide recommendations to assist the decision makers in preventing and controlling industrial accidents in the period of COVID-19.

- First, it is advocated to pay attention to *emergency risk* in the situation of COVID-19. The emergency activities are crucial to eventually defeat the pandemic. However, the risk in corresponding activities is also required to be identified, analyzed, assessed, and controlled.
- Second, it is suggested to apply the *systems theory* (e.g., STAMP) to analyze the emergency risk. That is, due to complicated situations in emergency, the risk during emergency situations should be treated from the systematic viewpoint.
- Third, it is suggested to control the *infectious risk* of workers, as well as to reduce the *psychological stress* of workers.
- Last but not the least, it is recommended to attach importance to *E2N risk*. Regarding a system (particularly a complex one), in the transition stage from one state to another, relevant risk is usually generated. People previously attached importance to *N2E risk*.

In this paper, we proposed a framework of two-stage ERA based on the systems theory. The characteristics of N2E-ERA and E2N-ERA have been discussed. In this paper, we advocate that E2N-RA is an indispensable part in ERA. Therefore, essential efforts need to be devoted to assess and control the E2N risk. Eventually, we provide recommendations for the decision makers in combating COVID-19. After the long-time lockdown, the companies will be reopened sooner or later. We hope that the proposed methodology and results can be helpful for the fighting of COVID-19, particularly in ensuring the safety operations in industrial plants.

The theoretical meaning of this research is that the systematic method can be used on the emergency risk in the pandemic, particularly COVID-19. The systematic methods are useful for complex systems in research and practical application. Only through analyzing the risk, we can take measures to prevent and control the corresponding risk. We need to not only analyze the N2E risk but also to consider the E2N risk. The characteristics of the risk from normal to emergency and rescue from emergency to normal are different. Hence the corresponding methods differ. This method cannot only be applied to analyze the emergency risk but also be applied to emergencies of other hazardous incidents and accidents. For example, the application domain can vary from onshore to offshore activities in the process industry.

Our research provided a general framework for preventing the accident risk. There are systematic risks in the pandemic. Potential practitioners can take such a framework and their specific situations into account. In a broader background, the systematic emergency risk analysis can not only be helpful in the period of COVID-19 but also public health emergencies, which have been regarded as one of the most possible ways to generate global hazards. The suggestions provided from the results would be useful to deal with the safety issues in COVID-19, as well as other possible pandemic situations.

Future work can extend the qualitative systematic research with other approaches. For example, game theory can be used in the research. And one example can be found in (Xing et al., 2020). Players in the game can be regarded as stakeholders in the system theory. The systematic approach considers the managing structure of complex systems. For example, the degradation of the components can be analyzed in the framework of prognostics and health management (PHM). The behaviors of workers in emergencies can be analyzed by using the methods of human reliability analysis (HRA). Another limitation of the research is based on the particular accident generated from the COVID-19 period. The accident has been analyzed from a microscale viewpoint. More broadly, from a macroscale perspective, society and international situations can also be investigated.

CRediT authorship contribution statement

Huixing Meng: Conceptualization, Visualization, Methodology, Writing - original draft. **Jinduo Xing:** Writing - review & editing, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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