JESK J Ergon Soc Korea 2017; 36(5): 485-498
http://dx.doi.org/10.5143/JESK.2017.36.5.485
http://jesk.or.kr eISSN:2093-8462

Comparison of Systemic Accident Investigation Techniques Based on the Sewol Ferry Capsizing

Dohyung Kee

Department of Industrial and Management Engineering, Keimyung University, Daegu, 42601

Corresponding Author
Dohyung Kee
Department of Industrial and Management Engineering, Keimyung University, Daegu, 42601
Mobile : +82-10-5656-1260
Email : dhkee@kmu.ac.kr

Received : August 22, 2017
Revised : September 01, 2017
Accepted : September 16, 2017

Objective: This study aims to survey and compare three systemic accident investigation techniques of Accimap, STAMP and FRAM, based on the application studies of the Sewol ferry accident.

Background: Traditional accident investigation methods such as domino models, FTA, etc. work well for losses caused by physical component failures or actions of human in relatively simple systems, but are unable to depict mechanisms generating errors and violations in the current complex socio-technical systems. For better understanding the structure and behavior of the socio-technical systems, systemic techniques have been developed and used.

Method: This study was mainly based on survey of literatures through surfing webpages of ScienceDirect and Google, and ergonomics relevant journals. The key words of Sewol, Sewol ferry, Sewol ferry accident, etc. were used in the survey.

Results: Three systemic accident investigation methods included similar actors in the Sewol ferry accident including government, Ministry of Ocean and Fisheries, Korean Coast Guard, Korean Register of Shipping, Korea Shipping Association, Chonghaejin Marine Company, crew members. The methods graphically represented each level's failures or performance variabilities of relevant functions and relationships between them. It was shown that the systemic methods consider the entire system, ranging from the environment in which the accident occurred, to the role of government in shaping the system of work. Each method has its own comparative pros and cons, but the Accimap has advantages in terms of time of analysis, data required, model complexity and degree of comprehensiveness.

Conclusion: This study reviewed and compared three systemic accident investigation methods, which showed that there are systemic characteristics and pros and cons in the methods.

Application: The results would be used as a guideline when selecting accident investigation methods.

Keywords: Accident investigation method, Accimap, STAMP, FRAM, Sewol ferry accident

Copyright@2017 by Ergonomics Society of Korea. All right reserved.

This is an open-access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (http://creativecommons.org/licenses/by-nc/3.0/), which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

1. Introduction

Accident investigations are critical to aid our understanding of the underlying causes as well as indicating where system safety may be improved, because accidents will continue to occur within complex socio-technical systems and occur due to the evolving, probabilistic complexity inherent in how they unfold (Hollnagel, 2004;

Salmon et al., 2012). For better understanding and analyzing accidents, several methods have been developed, which are classified into three categories: sequential, epidemiological and systemic techniques. The sequential methods describe accidents in a time-ordered sequences (cause-effect) of discrete events or a chain-of-event paradigm of causation (linear fashion), which include Domino models, Event Tree Analysis (ETA), Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), etc. (Kim et al., 2016; Underwood and Waterson, 2013b). These traditional approaches are inappropriate, as they are unable to sufficiently explain the non-linear complexity of modern-day socio-technical system accidents such as Three Miles Island, Chernobyl, Bhopal, Challenger. It can also lead to equipment or humans at the 'sharp end' of a system being incorrectly blamed for an accident. This represents a missed opportunity to learn important lessons about system safety and, therefore, develop more effective safety recommendations (Kee, 2016; Underwood and Waterson, 2013b).

Epidemiological techniques view accidents as a combination of latent and active failures within a system. Latent conditions such as management practices, organizational culture can lie dormant within a system for a long time like resident pathogens. The adverse consequences of latent failures only become evident when they combine with unsafe acts, i.e., active failures, to breach the defences of a system. The techniques include Swiss Cheese model, HFACS (Human Factors Analysis & Classification System), etc. (Underwood and Waterson, 2013a). These better represent the influence of organizational factors on accident causation, when compared with the sequential ones. However, many are still based on the cause-effect principles of the sequential models, as they describe a linear direction of accident causation (Hollnagel, 2004). So, these techniques were also not able to account for the increasingly complex nature of socio-technical system accidents (Underwood and Waterson, 2013a).

Systemic methods have their roots in control theory, in chaos theory and in the idea of stochastic resonance (Hollnagel, 2004). The techniques describe accidents as the unexpected behaviour of a system resulting from uncontrolled relationships between its constituent parts, rather than a sequence of cause-effect events. Here, accidents are not attributed to a combination of latent and active failures, and are the result of humans and technology operating in ways that seem rational at a local level but unknowingly create unsafe conditions within the system that remain uncorrected. Hence, focusing on simply removing individual errors or root causes from a system without improving the system design, new accidents arising from other root causes will continue to occur. A holistic approach is required whereby safety deficiencies throughout the entire system should be identified and addressed (Kim et al., 2016; Underwood and Waterson, 2013a). Three systemic techniques have been developed and applied: Accimap (Rasmussen, 1997), STAMP (Systems Theoretic Analysis Model and Processes) (Leveson, 2004) and FRAM (Functional Resonance Analysis Mehtod) (Hollnagel, 2004).

The systemic approaches briefly explained above are the dominant concept within accident analysis field (Underwood and Waterson, 2013b). The three systemic techniques are in general agreement in that describe accidents as a complex, systems phenomenon, but they are significantly different in viewpoint of their analysis methods from each other (Salmon et al., 2012). Salmon et al. (2012) compared three methods of the Accimap, HFACS and STAMP, based on a case study of the led outdoor activity accident in Australia. However, they did not include the systemic methods comprehensively with excluding the FRAM. Therefore, this study aims to compare the three popular systemic techniques of the Accimap, STAMP and FRAM, on the basis of the application studies to the Sewol ferry accident. It is expected that this study empirically reveals the pros and cons of the techniques.

2. Systemic Techniques

2.1 Accimap

Rasmussen (1997) suggested that accidents are typically 'waiting for release', the stage being set by the routine work practices of various actors working within the system. Normal variation in behavior then serves to release accidents. Thus, Rasmussen asserted that explaining accidents in terms of events, acts and errors has no utility for system redesign; rather, new approaches focusing on

the mechanisms generating behavior in the dynamic work context are required. For this purpose, Rasmussen (1997) introduced the Accimap approach. The Accimap is an accident analysis method that graphically represents the decision makers and decisions involved in producing the system in which an accident was permitted to occur. The Accimap method differs from typical accident analysis approaches in that it is used to identify and represent the causal flow of events upstream from the accident and also looks specifically at the planning, management and regulatory bodies that may have contributed to the accident (Salmon et al., 2010; Svedung and Rasmussen, 2002).

Although the number of levels is not rigid and varies according to domain, the model typically focuses on failures across the following six organizational levels: government policy and budgeting; regulatory bodies and associations; local area government planning and budgeting (including company management); technical and operational management; physical processes and actor activities; equipment and surroundings (see Figure 2). The Accimap describes failures, decisions and actions at each of the six levels through the construction of a causal diagram. In addition, this methodology maps the interrelationships of those levels. In general, the Accimap diagram is an integrated framework, which provides a big-picture to illustrate the context in which an accident occurred as well as the interactions between different levels of a socio-technical system that resulted in that event. Due to its generic nature, the Accimap is applicable in any domain and has previously been applied to a range of accidents and incidents occurring in various complex socio-technical systems (Branford, 2011; Salmon et al., 2010).

2.2 STAMP

STAMP is a constraints-based model which focuses on inadequate control or enforcement of safety-related constraints on the system design, development and operation (Leveson, 2004, 2011). The STAMP views systems as hierarchical structures with multiple control levels, with each level in the hierarchy imposing constraints on the level below. Conversely, information at the lower levels about the appropriateness and condition of the controls and constraints is communicated upwards in the hierarchy to inform the upper levels controls and constraints. This is called 'vertical integration' (Salmon et al., 2010). The STAMP has hierarchical structure very similar to that of Accimap, but has two basic hierarchical control structure: one for system development (on the left) and one for system operation (on the right) (see Figure 3). The STAMP views accidents as resulting from the inadequate control of safety-related constraints. In this framework, understanding why an accident occurred requires determining why the control structure was ineffective. Preventing future accidents requires designing a control structure that will enforce the necessary constraints (Leveson, 2004).

Leveson (2004) provided a taxonomy of control failures, including: inadequate control of actions; inadequate execution of control actions; and inadequate or missing feedback. Subsequent STAMP analyses have added 'mental model flaws' in order to cater better for human control structures in the system (see Figure 4) (Salmon et al., 2012). These are similar to taxonomies of HFACS across four levels: unsafe acts; pre-conditions for unsafe acts; unsafe supervision; and organizational influences. For systematic accident analysis, Leveson (2011) introduced Causal Analysis based on STAMP (CAST) with nine procedural steps, which is one of the dedicated techniques and processes for accident analysis that was constructed by using STAMP as theoretical foundation (Leveson, 2011; Salmon et al., 2012).

The STAMP analysis consisted of two phases. Firstly, the control structure as depicted in Figure 3 should be constructed. The key personnel from the control structure were then selected for further analysis such as field manager, training officer and instructor. Secondly, for these personnel, the safety requirements and constraints, context of decision making, mental model flaws, as well as inadequate enforcement of constraints, control actions and inadequate or missing feedback, which were taxonomies provided by Leveson (2004), were determined (Salmon et al., 2012).

2.3 FRAM

FRAM was developed by Hollnagel (2004), and is a non-linear accident model based on the assumption that accidents result from unexpected combinations (resonance) of normal performance variability (Victor and Carvalho, 2011). The model can be used both to account for complex accidents and to identify risks in dynamic systems. It graphically represents systems as a network of interrelated subsystems and functions which will exhibit varying degrees of performance variation (Hollnagel and Goteman, 2004). In other words, it provides a way to describe outcomes using the idea of resonance arising from the variability of everyday performance. According to this view, accidents are prevented by monitoring and damping variability among system functions, and safety requires the ability to constantly anticipate future events. Therefore, hazard-risks emerge from combinations of normal variability in the socio- technical system (Victor and Carvalho, 2011).

The FRAM focuses on how conditions leading to accidents may emerge. In practical terms, accident prediction requires the following steps (FRAM, 2017; Hollnagel, 2004):

- Identify and characterize essential system functions; the characterization can be based on the six connectors of the hexagonal representation (Figure 1).

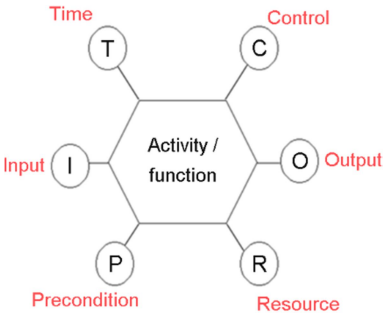

Figure 1. FRAM hexagonal function representation

- Characterize the (context dependent) potential for variability of the functions in the FRAM model, as well as the possible actual variability of the functions in one or more instances of the model (see Figure 5).
- Define functional resonance based on identified dependencies among functions.
- Identify barriers for variability (damping factors) and specify required performance monitoring.

3. Method

This study was conducted mainly based on survey of literatures through surfing webpages of ScienceDirect and Google, ergonomics and safety relevant journals including Applied Ergonomics, Ergonomics, Safety Science, etc., and personal communications. The key words of Sewol, Sewol ferry, Sewol ferry accident, etc. were used in the survey. Five academic papers or master and doctoral thesis were found: two for Accimap (Kee et al., 2017; Lee et al., 2017), two for STAMP (Kim et al., 2016; Kwon, 2016) and one for FRAM (Ka, 2017). Of these, two academic papers of Lee et al. (2017) for Accimap and Kim et al. (2016) for STAMP, and a master thesis of Ka (2017) for FRAM were selected and used in the following analysis and comparison, because they were on the basis of the same accident investigation report of Korean Maritime Safety Tribunal (2014).

4. Results

4.1 Sewol ferry accident

On April 15, 2014, the Korean ferry of the Sewol, carrying 476 people which included 325 high school students, left Incheon port for Jeju island. The ferry capsized in the sea 3.3km north Byungpoong island (narrow waterway called the Maenggol Strait) with treacherous currents about 13 hours after its departure. The accident claimed the lives of 299 passengers, the vast majority of whom were students of a high school on a four-day excursion trip to the island. Five passengers on board still remain missing as of August 8 2017, and marine search activity for the missing finally ended at November 11, 2014, 209 days after the accident. The ship was lifted and mounted on land of Mokpo port at April 11, 2017 (Kee et al., 2017).

4.2 Analysis by systemic accident investigation methods

4.2.1 Accimap

Following Accimap framework by Rasmussen and Svedung (2000) for the analysis of the Zeebrügge Ferry accident, Lee et al. (2017) included six layers, the first five layers of which are government and legislation, regulatory bodies and associations, company management and local area planning, technical and operational management involved, and accidental flow of events and acts. Finally, the sixth layer is the outcome of the Sewol Ferry accident. This layer consists of two separate outcomes: sinking of the Sewol Ferry and botched rescue attempt (Figure 2).

At the government and legislation level, three key factors of capsizing and one factor of poor rescue activities were included. Firstly, the maximum allowable age for a passenger ship went from 20 years to 30 years. This enabled Chonghaejin Marine Company to purchase the 18-year-old Japanese ship, which should have been on its way out of commission. Secondly, because of the advantages of paying less and having the ability to leverage termination of employment, Chonghaejin hired more irregular workers than regular ones. Thirdly, South Korea's not rigorous-enough ferry regulation system led to weak oversight and enforcement of government and industry regulations. Moreover, there was no commanding authority on-site to handle the rescuing process, which delayed action from the rescue team.

At the regulatory bodies and associations level, three actors such as Korea Shipping Association (KSA), Korean Register of Shipping (KRS) and Korean Coast Guard (KCG) were included. KSA ship inspectors admitted that they only conducted a cursory inspection by eyeballing the ship's water level in order to see whether or not it was overloaded with cargo. Close inspection would have revealed that on the fateful day, the Sewol had been transporting 2,142 tons of cargo, which is 1,155 tons over its limit. After the redesign to the ship was made, the KRS had inspected the Sewol and reduced the ship's carrying capacity significantly to 987 tons. However, this report was only given to Chonghaejin, and neither the KCG nor the KSA had any idea of the new capacity limits placed on the Sewol until after the incident. By expanding the size of the rooms, the maximum capacity of the ferry increased by 116 people. From the modification, the Sewol ferry's center of gravity moved upward by 51cm and the maximum storage weight decreased from 1,450 tons to 987 tons. However, this modification did not need any approval from the government, because the law did not require it. Beyond the lack of adequate regulation and oversight, the overarching problem within the industry is the alleged corruption and collusion between government officials and businesses in South Korea. Furthermore, there was an indication on the lack of a standard procedure for rescue communication by the KCG, which resulted in confusions in communications between relevant authorities. This further delayed the rescue process.

At company management and local area planning, Chonghaejin's serious problems and violations were revealed through the investigation of the sinking of the Sewol. Chonghaejin's questionable decision on grouping and scheduling two inexperienced

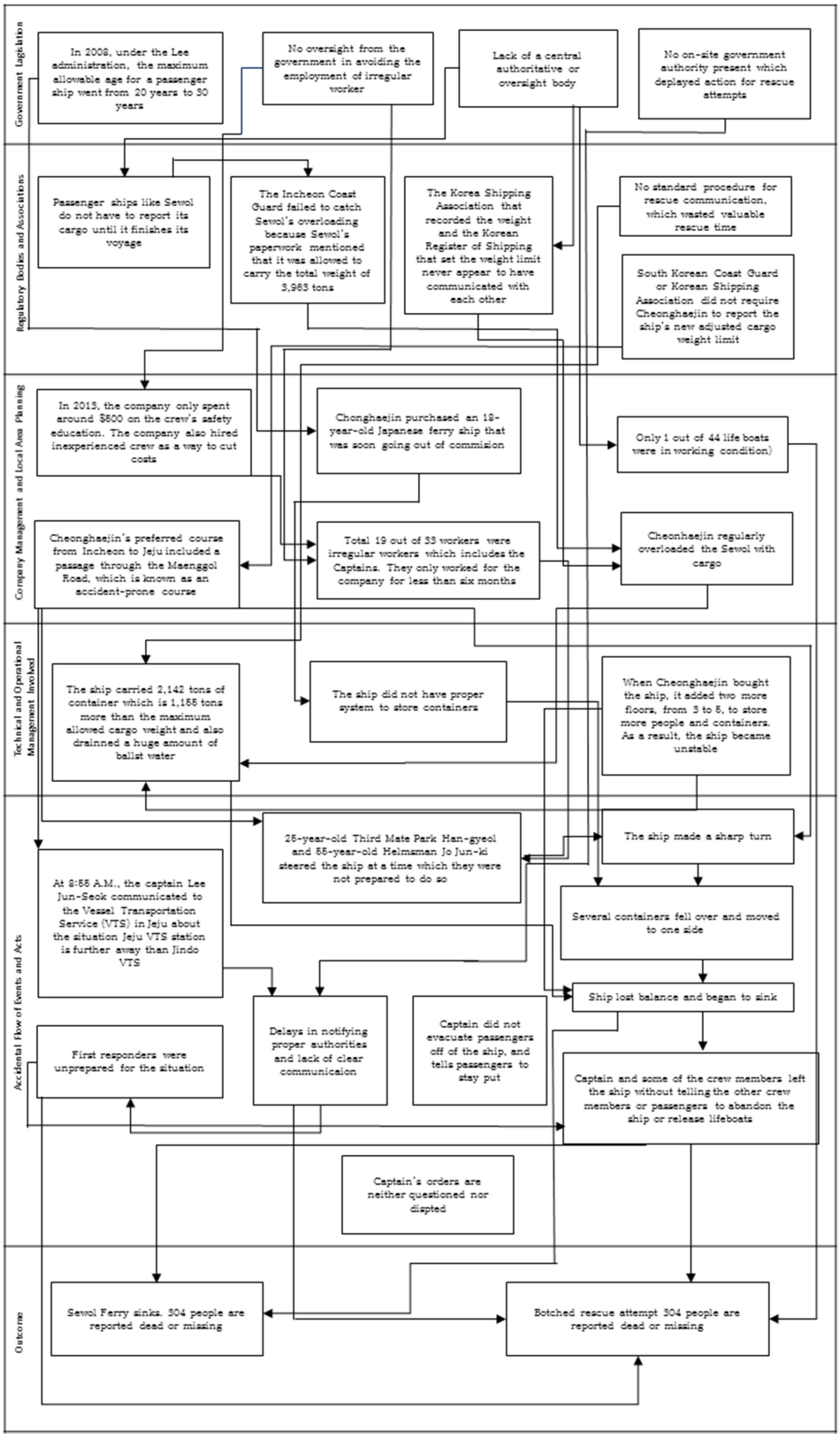

Figure 2. Accimap framework for analysis of Sewol ferry accident (Lee et al., 2017)

people at a certain time played a major role in causing the sharp turn. In just the 13 months preceding the accident, the ship exceeded its cargo limit an astounding 246 times out of 394 trips. In one of the more blatant displays of indifference for safety, Chonghaejin spent only $540 on the crew's safety in 2013, while they proceeded to spend $10,000 for entertainment purposes and another $230,000 on Public Relations. Only 1 out of 44 lifeboats was in working condition.

The level of technical and operational management showed how the fallacy of human performance can lead to painful tragedies. To begin with, the ship carried 2,142 tons of cargoes which is 1,155 tons more than the maximum permitted, and only carried 761 tons of ballast water which is 942 tons less than the minimum required to balance the maximum permitted weight. Therefore, the risky decisions of loading more than permitted cargo and less than required ballast water were two crucial contributing causes of the accident. In addition, the cargo and the containers on the ship were not properly secured, which led to the cargo falling when the ship made a sharp turn and caused the ship to lose its balance.

At the final level of accident flow of events and acts, three contributing factors were found. During the voyage, under the third mate command, an inexperienced helmsman made a 10-degree turn in one second, which caused the ship to list and tilt towards. Considering that large passenger ships like the Sewol would take 2min to make a 5-degree turn, the helmsman's decision to make the sharp turn was considered as a serious misjudgment. There were instances of ineffective communication between the VTS and the ship authorities, which caused the golden time of rescuing the passengers to be wasted. In addition, the captain and the crew did not communicate well with the passengers. As the ship was sinking, the captain repeatedly gave misleading announcements to calm people.

4.2.2 STAMP

Kim et al. (2016) defined the system hazard of the Sewol ferry accident as the vulnerable stability of the vessel that causes fatalities and injuries or property damage during sailing. Under this definition, three system safety constrains were assumed: 1) the vessel itself must have sufficient intact stability and steering ability for safe operation; 2) during operations, the safety control structure must ensure a satisfactory stability of the vessel to be allowed to sail out of port, and control any potential risks (e.g., overloading, inappropriate cargo stowage and securing, improper maneuvering) that might allow the vessel to exceed the safety stability constraints; 3) moreover, appropriate emergency preparedness and response must be ensured, rapid rescue operations must be initiated after the loss of stability by the master and crew on board in coordination with other emergency responders (e.g., KCG, vessels in the vicinity). Figure 3 shows the hierarchical control structure that ensures safe development and operation of passenger ships in Korea. The hierarchal control structure included several actors: government, Ministry of Ocean and Fisheries (MOF), KCG, KSA, KRS, ship-owning company of Chonghaejin Marine Company, ship inspector, crew members such as captain, third mate, helmsman, etc. The model of safety control structure (Figure 3) incorporate the development stage of the vessel (on the left) and those involving the physical control in the operational part of the system (on the right), as safety during operation not only depends on the design and construction of the vessel, but also on effective control during operations.

Secondly, Kim et al. (2016) selected the key components from the control structure of Figure 3 for further analysis, which included crew, ship-owning company, classification society, relevant government regulatory agencies and industry association. Then, the violated safety constraints, mental model flaws, as well as inadequate enforcement of safety constraints such as control actions or missing feedback were determined and analyzed by the components. An example of these analysis for the Sewol ferry operators appears in Figure 4. It is concluded from the analysis for crew members that inappropriate issue and execution of vessel command, poor awareness of hazards, failure to provide evacuation instructions on time, and failure to assist passengers by master and crew during rescue operation are considered the flawed control actions that trigger the accident to take place at the sharp-end level.

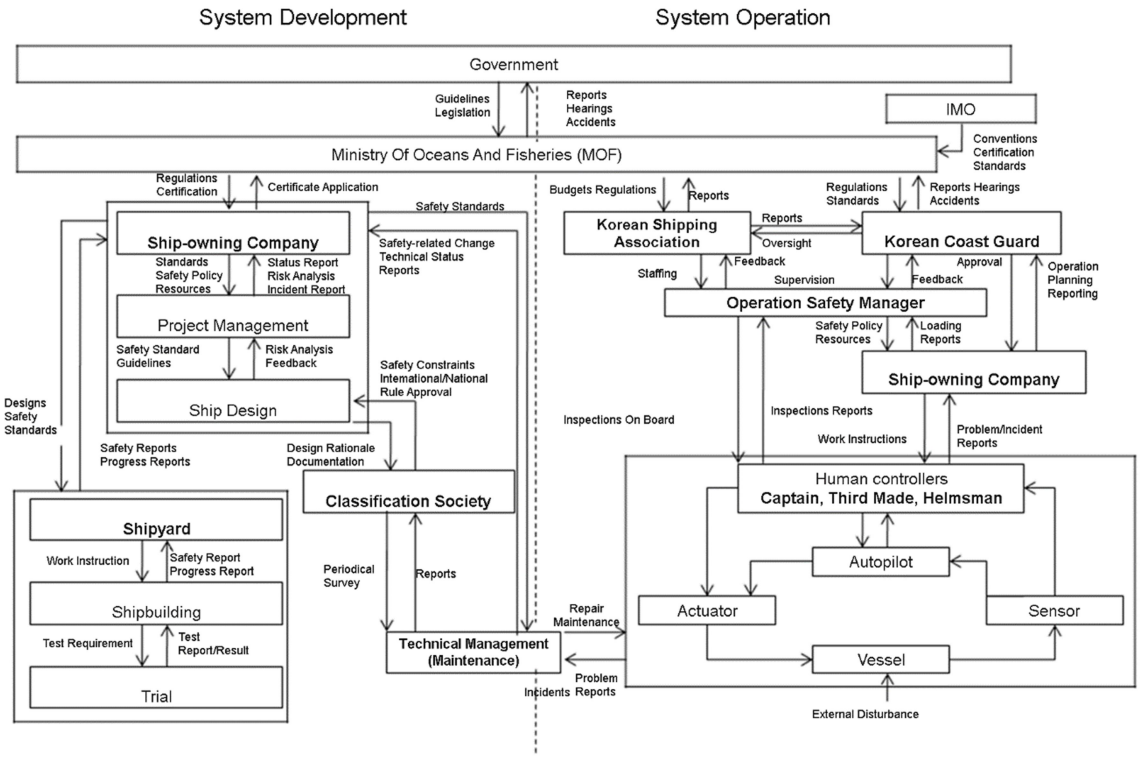

Figure 3. Hierarchical control structure of Sewol ferry accident (Kim et al., 2016)

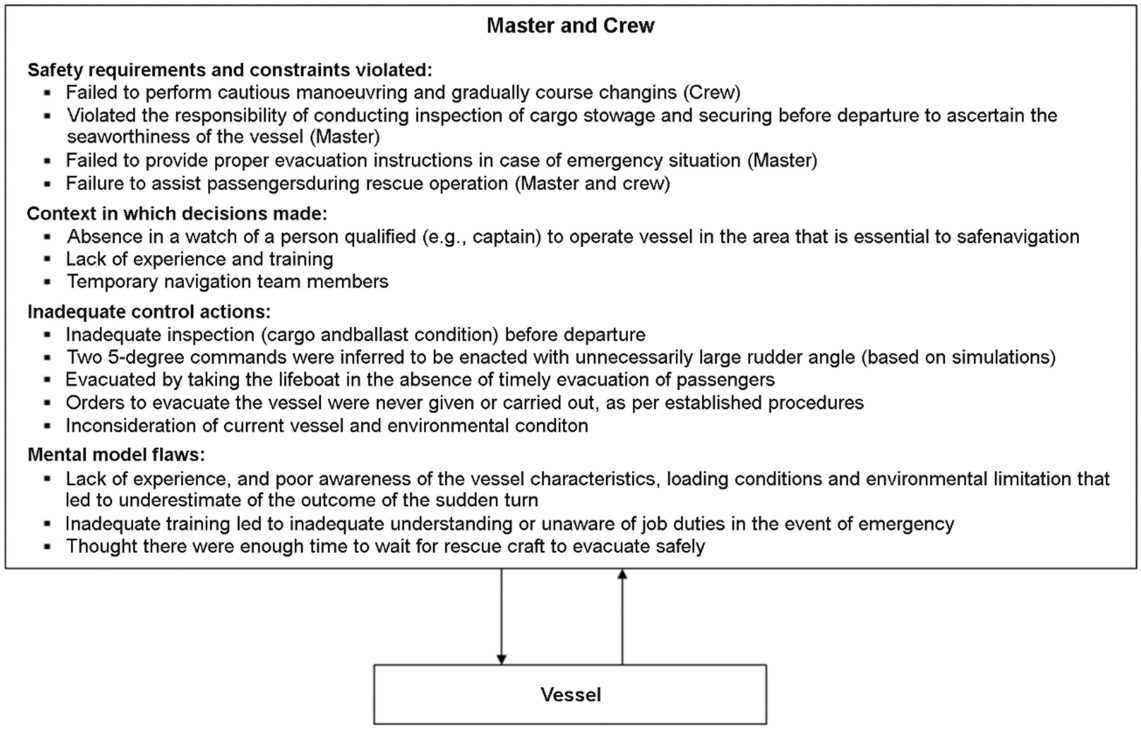

Figure 4. Analysis at the ship master and crew level (Kim et al., 2016)

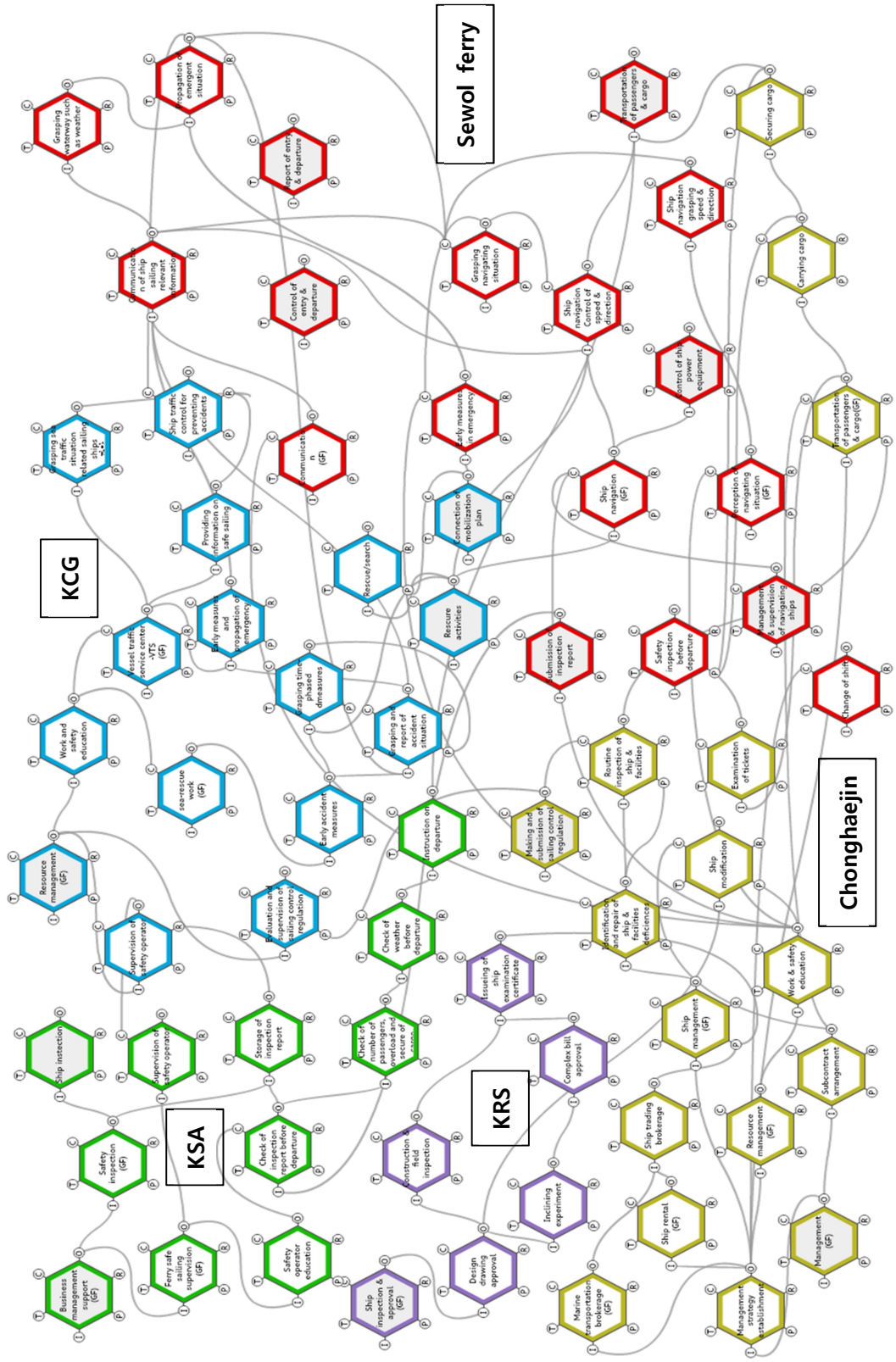

Figure 5. FRAM model for Sewol ferry accident (Ka, 2017)

4.2.3 FRAM

Ka (2017) analyzed the Sewol ferry accident by using the FRAM, the result of which is illustrated in Figure 5. A small change of performance variability of a system component, i.e., 'sudden turn of the ship due to helmsman's steering inexperience', was delivered to relevant functions of the remaining system elements such as KRS, KCG, KSA, Chonghaejin and Sewol ferry, and resonated with functions' variabilities of the elements, which finally resulted in the disaster. The variability of the single normal performance is rarely large enough to be the cause of an accident in itself or even to constitute a malfunction. But the variabilities from multiple functions such as lack of ballast water, overloaded cargo, lack of proper securing cargo, etc. may combine in unexpected ways, leading to the disaster. The author proposed potential causes that could be contributed to the actors' failures, which were classified by the actors such KCG, KSA, KRS and Chonghaejin and Sewol. For example, the ship inspector's negligence in inspecting the number of people on-board, quantity of cargoes, status of secured cargoes and life-saving appliances before every departure, could be attributed to performance variabilities including: 1) workload increase due to increase of the number of ferry passenger and decrease of inspectors; 2) non-qualified inspectors' work conduction due to negligence in supervising inspectors' qualification; and 3) missing penalties for breach of the inspectors' obligations in the legislation since 2012.

5. Discussion

The three systemic accident investigation methods dealt with in this study are all comprehensive in terms of coverage of the overall socio-technical systems. These methods enable safety practitioners and accident investigators to see or get a big-picture to illustrate the context in which an accident occurred as well as the interactions between different levels or functions of the studied system that resulted in that event, by incorporating associated socio-technical factors into an integrated framework (Lee et al., 2017). As shown in the above, the Accimap and STAMP include the same actors from top governing level to front line operators such as government, MOF, KCG, KRS, KSA, Chonghaejin, crew members. However, of these actors, government and MOF were excluded in the FRAM. This difference might be resulted from analysis by different analysts for the same accident, not from inherent characteristics of the methods. Other differences are: 1) The STAMP provides more varying failures of actors according to the inherent taxonomy of errors or failures modes than the Accimap; 2) Compared to the Accimap, each actor common in the three methods has been analyzed in more detail, i.e., has almost every its own functions or subsystems in the FRAM. In other words, although the Accimap represented actors' functions directly related to the accident, the FRAM included almost every functions or subsystems of the actors; and 3) While the frameworks of the Accimap and STAMP are hierarchical, that of the FRAM is not hierarchical, but rather horizontal. These differences are thought to be attributed to the inherent characteristics of the methods.

It is inferred from the above that the systemic methods consider the entire system, ranging from the environment in which the accident occurred, to the role of government in shaping the system of work. While the company and its crew members should be held accountable for the Sewol ferry accident in viewpoint of the traditional sequential techniques, the above showed that the government and its regulators were just as equally responsible for the tragedy. For example, one of the events that helped set the stage for the entire incident occurred back in 2008. The revision of relevant legislation for maximum allowable age for a passenger by government ship enabled Chonghaejin to purchase the 18-year-old Japanese ship (Lee et al., 2017). Subsequently, the ship was illegally modified, significantly overloaded on the day that the accident occurred, steered by inexperienced helmsman, and finally captured. This holistic approach is a big advantage and reason that the systemic techniques should be used when analyzing or investigating accidents in the socio-technical systems. On the contrary, the traditional sequential methods focus on finding out culprits for blaming who triggered root causes of accidents rather than improving the system design and constructing an effective safety control system. However, the systemic methods have some disadvantages: 1) they require significant training and skill for the methods, in-depth knowledge in specific domains such as control theory, system dynamics, etc. in STAMP and for system in question; 2) they are also very time-consuming in analyzing and investigating accidents, compared to the traditional techniques; 3) they demand extensive data associated with the overall system that may difficult to be fully obtained from

available resources.

Each method has its own comparative pros and cons. The Accimap provides analysts with essentially free reign to identify contributing factors across the varying levels specified. There is no taxonomy of errors or failure modes to guide the analysis. Unlike the STAMP and FRAM which focus on operators and functions, respectively, the Accimap explicitly consider environmental conditions such as equipment & surroundings in the original Accimap (Salmon et al., 2012), accident flow of events & acts in Figure 2. These makes Accimap potentially highly comprehensive in terms of its ability to identify all of the contributory factors involved in a particular accident, ranging from operator failures on the day of the incident to failures in government and local authority decision making and policy even many years before the accident. Provided sufficient data is available and the analyst is skilled enough, the Accimap method can potentially describe the entire accident trajectory in terms of failures across the system and the relationships between them. The linkage of failures within and between levels is also an important feature of the Accimap, since this ensures that failures are considered in the context of the factors influencing them, and also supports the development of appropriate system wide countermeasures, as opposed to the traditional ones (Salmon et al., 2012).

In the Accimap structure, the physical processes and actor activities level do not specifically deal with failures in cognition of behalf of those involved; rather, flawed decisions are normally represented at this level without necessarily identifying the factors influencing them, such as poor situation awareness or operator mindset. The lack of taxonomies for failures at each level is its disadvantage and advantage at the same time. Since the analysis is entirely dependent upon analyst subjective judgement, the reliability of the method is likely to be limited. Differences in the actual failures identified, the way in which the failures are described, and the level at which they are placed, are likely to emerge across different analysts. This also makes inexperienced analysist feel difficult when investigating accidents. In addition, the absence of taxonomic support renders the Accimap more suitable to single case study analyses rather than to multiple case analyses. Without taxonomies of specific failure modes, it is difficult to aggregate the Accimap analyses in order to derive a useful summary of multiple accident cases. On the contrary, this can give analysts greater flexibility in investigating accidents occurring in varying fields or having different characteristics, because the analysists are not restricted by taxonomies of failure modes (Salmon et al., 2012).

STAMP has two basic hierarchical control structure with interaction between them: one for system development (on the left) and one for system operation (on the right). This can give a broader representation of the varying factors influencing behavior and safety (Kim et al., 2016; Leveson, 2004). This separate analysis and coupling according to system development and operation would be very helpful in the situation that systems are becoming more complex and larger. Unlike the Accimap, the STAMP provides a taxonomy of control failures. However, since it is generic in nature, the STAMP is not restricted to a particular domain (see Figure 4). The STAMP is equipped with an application process of CAST, which helps accident investigator systematically apply to real situations.

Compared to the Accimap, the STAMP requires an additional data and analysis requirement involved due to the need to construct the control structure diagram representing the safety control loops present in the domain in question. This involves going beyond merely collecting and analyzing data regarding the accident itself, and requires that data on the domain in question be collected. This much resource usage is likely to be beneficial in enabling the analyst to develop a deeper understanding of the system under analysis and subsequently to derive recommendations. The language used, borne out of its control theory and system dynamics origins, often makes it difficult to discriminate between control failure types (Salmon et al., 2012). Another disadvantage is that although failures or events of actors included in analysis explicitly appear in the Accimap, they are implicit in the STAMP. In the STAMP analysis, failures or events of actors are shown only in another taxonomy analysis by actors (Figure 4), not in the hierarchical control structure (Figure 3). The control structure shows just hierarchical levels of controls and constraints for the given system, i.e., vertical integration (Cassano-Piche et al., 2009; Salmon et al., 2012). On the other hand, this in-depth analysis for the failures makes it easier to find out what caused them, which would be helpful in establishing recommendations.

FRAM is also comprehensive and generic in nature, and can be used to model any kind of performance or activity without restricting its application, because it does not provide any domain-specific taxonomy like the STAMP. The FRAM provides a useful tool/software of 'FRAM model visualizer' graphically representing its model, which can be freely downloaded. The FRAM makes the given system be analysed in the most detailed, because 1) it identifies essential system functions, and characterise each function using the six basic characteristics including input, output, precondition, resources, time and control; and 2) grasp the potential variabilities of the functions in the FRAM model (FRAM, 2017). Contributing factors to an accident or variabilities can be easily traced from front-liner's failure or root-cause of the accident by following connections between functions represented based on the six characteristics. This way is better for extracting recommendations for improving the system. However, it may take the longest time to do a FRAM analysis, and may also be the most difficult of the systemic methods. The FRAM obviously requires the largest amount of data for a given system analysed. Graphical representation of the FRAM model is so complex and not expressed in hierarchical structure that it is not easy to grasp the relations between functions or to trace variabilities related to an accident at a glance, especially in large systems such as the Sewol ferry accident (Figure 5).

6. Conclusions

This study surveyed and compared the three systemic accident investigation techniques including Accimap, STAM and FRAM, based on the application studies of the Sewol ferry accident. The three methods are comprehensive in terms of their application, and adopts holistic approach to consider all actors related to an accident and their interrelations. The methods also have their advantages and disadvantages in terms of analysis time and data required, complexity or difficulty, ease of alternative establishment, degree of comprehensiveness, and applicability of cognitive tasks, which are summarized in Table 1. The Accimap was used as reference method for comparison in Table 1. It is concluded that the Accimap requires less analysis time and data, less complex, easy to use and more comprehensive than other ones. However, the results of Table 1 should be taken with caution, because they were based on the author's knowledge and subjective judgement as well as the findings of the existing research.

Table 1. Comparison results of systemic methods

	Accimap	STAMP	FRAM
Time	–	Longer	Longest
Data	–	More	Most
Complexity	–	More	Most
Difficulty of use	–	More	Most
Ease of alternative establishment	–	Easier	Easiest
Degree of comprehensiveness	–	Less	–
Applicability of cognitive tasks	–	Possible	–
Hierarchical structure	Yes	Yes	No

It should be noted that although the three systemic methods were based on the same investigation report for the Sewol ferry accident, the analysts are so different from each other that analysis results may also different depending upon their viewpoints. In addition, it is not easy to directly compare the three systemic methods, because each method has its own inherent characteristics discussed in the above.

Acknowledgment

This research was supported by the Keimyung University Research Grant of 2016.

References

Branford, K., Seeing the big picture of mishaps: applying the AcciMap approach to analyze system accidents, *Aviation Psychology and Applied Human Factors*, 1(1), 31-33, 2011.

Cassano-Piche, A.L., Vicente, K.J. and Jamieson, G.A., A test of Rasmussen's risk management framework in the food safety domain: BSE in the UK, *Theoretical Issues in Ergonomics Science*, 10(4), 283-304, 2009.

FRAM, A brief instruction to the FRAM, http://functionalresonance.com/brief-introduction-to-fram/index.html (retrieved August 15, 2017).

Hollnagel, E., Barriers and Accident Prevention, Ashgate, Aldershot, UK, 2004.

Hollnagel, E. and Goteman, O., The functional resonance accident model. In Cognitive System Engineering in Process Control 2004, CSEPC, 155-161, 2004.

Ka, D.H., Application of functional resonance analysis method for analyzing combined system accidents, unpublished master thesis, KAIST, 2017.

Kee, D., Needs for changing accident investigation from blaming to systems approach, *Journal of the Ergonomics Society of Korea*, 34(1), 45-62, 2106.

Kee, D., Jun, G.T., Waterson, P. and Haslam, R., A systemic analysis of South Korea Sewol ferry accident: Striking a balance between learning and accountability, *Applied Ergonomics*, 59, 504-516, 2017.

Kim, T-E., Nazir, S. and Øvergård, K.I., A STAMP-based causal analysis of the Korean Sewol ferry accident, *Safety Science*, 83, 93-101, 2016.

Korean Maritime Safety Tribunal (KMST), Safety Investigation Report, Korean Maritime Safety Tribunal, 2014.

Kwon, Y., System theoretic safety analysis of the Sewol-Ho ferry accident in South Korea, unpublished doctoral thesis, MIT, 2016.

Lee, S., Moh, Y.B., Tabizadeh, M. and Meshkati, N., Applying the AcciMap methodology to investigate the tragic Sewol Ferry accident in South Korea, *Applied Ergoonmics*, 59, 517-525, 2017.

Leveson, N., A new accident model for engineering safer systems, *Safety Science*, 42(4), 237-270, 2004.

Leveson, N.G., Engineering a Safer World: Systems Thinking Applied to Safety, MIT Press, USA, 2011.

Rasmussen, J., Risk management in a dynamic society: a modelling problem, *Safety Science*, 27(2-3), 183-213, 1997.

Rasmussen, J. and Svedung, I., Proactive Risk Management in a Dynamic Society, first ed. Raddningsverket, Risk and Environmental Department. Swedish Rescue Services Agency, Karlstad, Sweden, 2000.

Salmon, P.N., Cornelissen, M. and Trotter, M.J., Systems-based accident analysis methods: a comparison of Accimap, HFACS, and STAMP, *Safety Science*, 50, 1158-1170, 2012.

Salmon, P.N., Lenné, W.M., Mitsopoulos-Rubens, E. and Rudin-Brown, C.M., Systems-based analysis in the led outdoor activity domain: application of a risk management framework, *Ergonomics*, 53(8), 927-939, 2010.

Svedung, I. and Rasmussen, J., Graphic representation of accident scenarios: mapping system structure and the causation of accidents, *Safety Science*, 40, 397-417, 2002.

Underwood, P. and Waterson, P., Accident analysis models and methods: Guidance for safety professionals, Loughborough University, 2013a.

Underwood, P. and Waterson, P., Systemic accident analysis: Examining the gap between research and practice, *Accident Analysis and Prevention*, 55, 154-164, 2013b.

Victor, P. and Carvalho, R.D., The use of Functional Resonance Analysis Method (FRAM) in a mid-air collision to understand some characteristics of the air traffic management system resilience, *Reliability Engineering and System Safety*, 96, 1482-1498, 2011.

Author listings

Dohyung Kee: dhkee@kmu.ac.kr
Highest degree: Ph.D., Department of Industrial Engineering, POSTECH
Position title: Professor, Department of Industrial and Management Engineering, Keimyung University
Areas of interest: Systems ergonomics, Population stereotype, Product design, Posture classification scheme, Industrial safety, Musculoskeletal disorders