A New Approach to Analysing Human-Related Accidents by Combined Use of HFACS and Activity Theory-Based Method

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ABSTRACT

This study proposes a new method for modelling and analysing human-related accidents. It integrates HFACS (Human Factors Analysis and Classification System), which addresses most of the socio-technical system levels and offers a comprehensive failure taxonomy for analysing human errors, and AT (Activity Theory)-based approach, which provides an effective way for considering various contextual factors systematically in accident investigation. By combining them, the proposed method makes it more efficient to use the concepts and principles of AT. Additionally, it can help analysts use HFACS taxonomy more coherently to identify meaningful causal factors with a sound theoretical basis of human activities. Therefore, the proposed method can be effectively used to mitigate the limitations of traditional approaches to accident analysis, such as over-relying on a causality model and sticking to a root-cause, by making analysts look at an accident from a range of perspectives. To demonstrate the usefulness of the proposed method, we conducted a case study in nuclear power plants. Through the case study, we could confirm that it would be a useful method for modelling and analysing human-related accidents, enabling analysts to identify a plausible set of causal factors efficiently in a methodical consideration of contextual backgrounds surrounding human activities.

Keywords: Human error; Activity theory; HFACS; Accident analysis; Accident model

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1. Introduction

An accident in a complex system can be defined as an undesired and unplanned (but not necessarily unexpected) event that leads to a specified level of loss (Leveson 1995). Thus, it is essential to prevent and manage accidents in a system effectively in order to enhance the safety of a system, which is the freedom from accidents or losses. However, it has been reported that human error is a key factor to the occurrence and progression of most of the significant accidents in complex and high-risk systems, such as nuclear power plants (NPPs) and air traffic control systems (Perrow 1999; Reason 2008; Shin 2014). Here it is meaningful to consider two different views of human error. One old view of human error regards human error as a cause of failure. Accordingly, in this view, human error is the cause of most accidents and the main threat to safety comes from the inherent unreliability of people in a system (Dekker 2002a). The other new view of human error regards human error not as a cause, but as a symptom of failure (Hollnagel 1998; Dekker 2002a). This view claims that human error is a symptom of trouble deeper inside a system, and that human error is systematically connected to the features of people, tools, tasks, and operating environment. The view on human error or human (error)-related accidents in this study is in line with this new view. We can say that a thorough and valid analysis of human-related accidents is needed to prevent and reduce them, thereby enhancing system safety. However, unlike the analysis of an accident due to technical failures, human-related accident analysis has some difficulty in understanding the accident situation and extracting useful lessons-learned from the accident (Akyuz and Celik 2015; Dekker 2002b; Woods et al. 2010; Haslam et al., 2005). For example, the data on human-related accidents are typically elusive and qualitative. Moreover, problematic conditions and relevant causal factors cannot be directly observable in many cases, but they can be identified only through the analyst's effortful reconstruction on the accident situation (Niwa 2009).

Accident analysis methods have been developed to support analysts in conducting the four critical steps during accident investigation: (1) gathering information on an accident and documenting what actually happened based on different techniques, such as STEP (Sequentially Timed Events Plotting) (Hendrick and Benner 1986), (2) identifying contextual factors to be considered for characterizing a human-related accident, (3) understanding the accident situation by the use of identified contextual factors, and (4) determining a plausible causes of an accident through establishing reasonable cause-effect relationships based on the identified contextual factors and the understanding. In order to enhance the efficiency of accident investigation, most of the accident analysis methods offer a set of predetermined causal factors or a taxonomy of failure types. With these features, accident analysis methods have been effectively used for investigating a human-related accident (e.g. INPO 1990; Kjellen 2000; Wiegmann and Shappell 2003; Svenson 2001; Woodcock et al. 2005). However, if a model of human activities in a system can be methodically used throughout the four steps in order to offer diverse perspectives on contextual backgrounds surrounding an accident, analysts would make the better use of accident analysis methods. As a set of predetermined causal factors are generally used in association with a linear, simplified causality model presumed in an accident analysis method, it is likely that analysts look at an accident only with causal factors and a causality model provided by a method, without considering other meaningful contextual factors (Shorrock et al. 2014). This limitation would be supplemented by using a model of human activities. Additionally, if we can establish a theoretical basis for explaining why and how pre-specified causal factors in accident analysis methods are derived and for understanding their interrelationships systematically, it would be used as another effective leverage for modelling and analysing a human-related accident.

Recently, a new approach to modelling and analysing human-related accidents based on activity theory (AT) has been developed to address those issues described above in our previous work (Yoon et al. 2016). The usefulness of this approach has been demonstrated in several case studies in the domain of NPPs. These case studies showed that the new approach was helpful for analysts to produce a more comprehensive, meaningful set of contextual factors systematically, which cannot easily be obtained by using existing methods, in consideration of holistic backgrounds of human activity based on the concepts of AT. It was also found that it could be more advantageous than other analysis methods that offer predefined set of causal factors or none of them, in the process of identifying plausible causal factors for a human-related accident under investigation. Additionally, AT could be effectively served as a theoretical basis for explaining why a set of causal factors need to be considered and for specifying how those factors and their interrelationships should be interpreted.

Although the AT-based method has several advantages for analysing human-related accidents in comparison with existing methods, it has also some limitations. Particularly, there is a limitation in the scope of contextual factors that can be considered by the use of the method. An accident analysis method needs to address all of the hierarchical levels of socio-technical systems (Leveson 2011; Salmon et al. 2011; Stanton et al. 2013). However, it is not easy to identify some kinds of contextual factors such as physical environment or external factors of macro-level such as the effects of a regulatory body by the use of the method. As understood from a disastrous accident such as the Chernobyl accident, those factors and their relationships with other factors (e.g. the design of hardware) are significant in the examination of an accident in a complex system. Thus it is necessary to broaden the scope of contextual factors that can be considered by using the method. And it is also necessary to improve the usability of the method, especially in the process of identifying a set of causal factors. It is surely a good advantage that the AT-based method forces analysts to look for a range of contextual factors comprehensively, not only relying on a predetermined set of causal factors. However, if a predetermined set of causal factors can be provided, analysts can examine an accident initially with these factors and then more easily expand the scope of causal factors to be considered with the concepts and principles of AT. This would enhance the practicality of the AT-based approach.

There exist some analysis methods that are effective in looking for contextual factors and offer a pre-specified set of causal factors. Thus, it is a viable approach to integrate the AT-based method and an existing method. Of those existing methods, which can supplement the limitations of the AT-based method, Human Factors Analysis and Classification System (HFACS) would be a good choice as it is currently one of the most popular methods for analysing human errors and addresses comprehensive contextual factors. HFACS is a systems-based accident analysis method, which enables a comprehensive analysis on most of the levels of socio-technical systems. Furthermore, it is highly usable because it is simple to learn and simple to use (Salmon et al. 2011; Baysari et al. 2009). This aspect may be the most attractive feature from the perspective of safety practitioners working in the industry (Underwood and Waterson 2013, 2014). Therefore, a cross-fertilization between the two methods (HFACS and the AT-based method) seems to be a good way for developing a more useful approach to analysing human-related accidents.

In order to address this issue, this study aims to propose a new method for modelling and analysing human-related accidents, which integrates two methods (HFACS and the AT-based method) by embedding the concepts and principles of AT into HFACS. AT can be served as a useful theoretical framework for understanding and modelling human activities and their performance in successful system conditions as well as accidental situations. For this reason, the proposed method has a potential to surmount the limitations of traditional approaches to accident investigation as well.

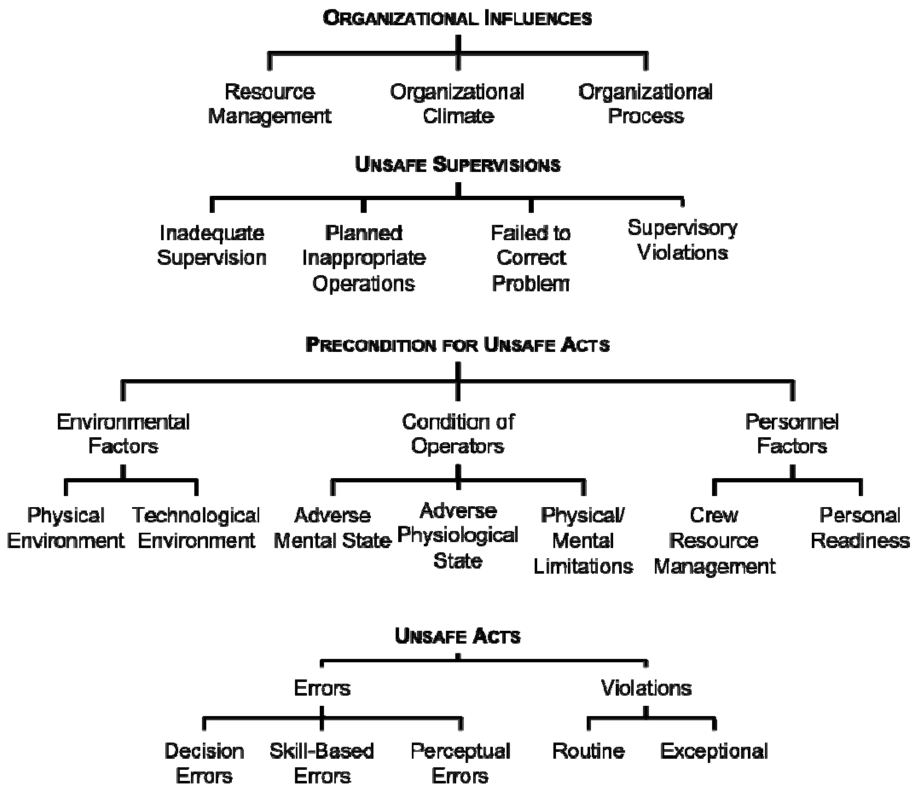
This paper is organized as follows. Section 2 describes research backgrounds on HFACS, AT, and the AT-based method. Section 3 describes the proposed method, by focusing on the process of accident modelling and investigation and the integration of the failure taxonomy provided by HFACS and contextual factors identified by using the AT-based method. Section 4 demonstrates the usefulness of the proposed method through a case study in the domain of NPPs. Section 5 describes a set of requirements to be addressed in a method for analysing accidents and discusses the benefits of using the proposed approach in relation to those requirements. Finally, section 6 summarizes this study and suggests future research topics.

2. Research background

2.1 HFACS (Human Factors Analysis and Classification System)

HFACS is one of the well-known methods for human-related accident analysis, which was developed based on Reason's framework of human-related accident causation (or Swiss cheese model). As shown in Fig. 1, HFACS provides a consistent structure (i.e. taxonomy) to describe human erroneous activities and relevant causal factors at the four hierarchical levels in a system, such as unsafe acts, preconditions for unsafe acts, unsafe supervision, and organizational influences (Wiegmann and Shappell 2003). HFACS has been applied to multiple domains including aviation, rail transport, maritime, healthcare, and discussed in numerous studies on accident analysis (Shappell and Wiegmann 2000, 2006, 2007; ElBardissi et al. 2007; Patterson and Shappell 2010; O'Connor and Walker 2011; Chauvin et al. 2013; Mitchell et al. 2016)). Following the concept of Swiss cheese model, HFACS leads accident analysts to investigate an accident in consideration of two types of failures: active failures at the level of unsafe acts and latent failures at the other three levels. A causation model assumed in HFACS is as follows: an active failure at the level of unsafe acts is influenced by a latent failure at the next level-preconditions for unsafe acts, a latent failure at the level of preconditions for unsafe acts is caused by a latent failure at the next level-unsafe supervision, and so on. Especially, as intra- or inter-analyst reliability has been validated repeatedly through several studies (Li and Harris 2006; O'Connor 2008; Olsen 2011; Cohen et al. 2015; Ergai et al. 2016), it is expected that HFACS will be reliably used for analysing human-related accidents in a range of work domains.

However, HFACS has also some limitations for thorough and valid accident analysis (Olsen and Shorrock 2010; Salmon et al. 2011). First, HFACS analysis can be constrained by the taxonomy. The analysis is just fitting of the collected data into the categories within the taxonomy rather than exploring the contextual data on the accident as a whole. Thus, some problems and relevant causal factors may not be addressed during accident analysis. Furthermore, when the identified problems or causal factors do not fit neatly into one of the categories provided by HFACS taxonomy, analysts often force the identified data to fit into one of the options in the taxonomy (Salmon et al. 2012). Second, the taxonomy was developed based on analysing a set of accident data, but it was not based on theoretically sound model on human activity in a work system. In addition to this, it was reported that some causal factor categories cause confusion among analysts when conducting causal factor mapping during accident analysis (Baysari et al. 2008; Olsen 2011). Thus, it is needed that the taxonomy should be defined more specifically to avoid misinterpretation among analysts. Furthermore, it is necessary to improve the way of selecting and mapping causal factor categories by providing a theoretical basis on the derivation of a set of causal factors and their interrelationships (Yoon et al. 2016).



<Fig. 1. The Human Factors Analysis and Classification System (HFACS) framework (Wiegmann and Shappell 2003)>

Some researchers have tried to extend the original HFACS framework to overcome some limitations described above (Reinach and Viale 2006; Harris and Li 2011; Chen et al. 2013). For example, Rienach and Viale (2006) developed HFACS-RR by adding a new top-most level 'outside factors' into the framework. They extended the HFACE framework to address regulatory environment as a meaningful causal factor category in a railroad industry. Harris and Li (2011) proposed HFACS-STAMP to deal with open system characteristics such as errors promulgating across organizational boundaries in civil aviation industry. Chen et al. (2013) developed HFACS-MA as follows: First, it integrated Reason's Generic Error Modelling System (GEMS) to define the contents of errors within 'unsafe act' level. Second, it adopted Hawkins's SHEL model to define the categories within 'precondition for unsafe acts' level. Third, it also added a new top-most level 'external factor' into the framework.

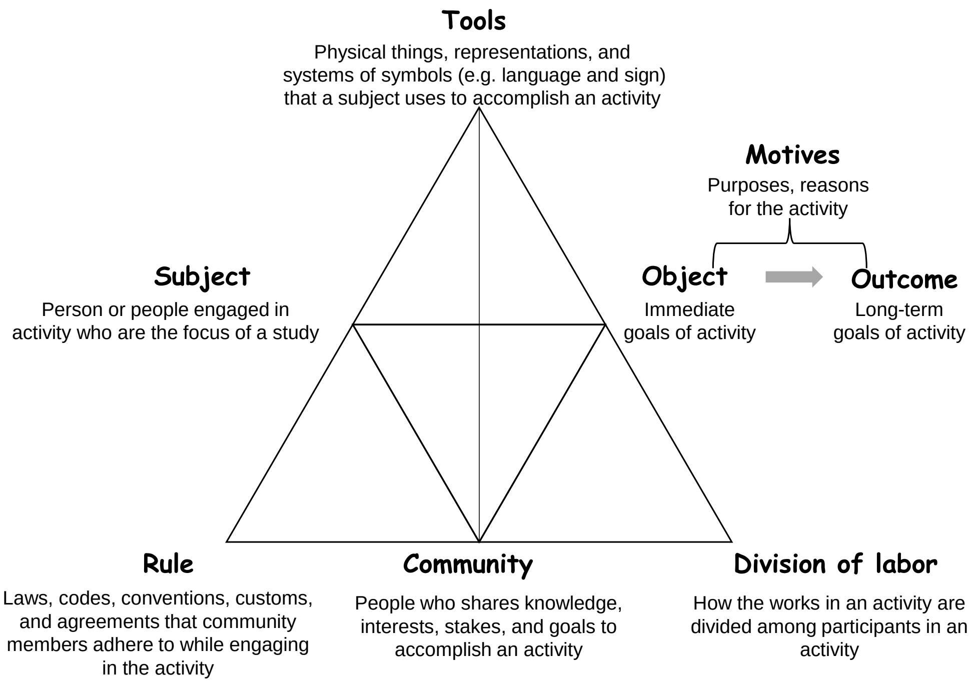
2.2 Activity Theory (AT)

Activity theory (AT), which is also known as cultural historical activity theory (CHAT), provides a broad theoretical framework for describing the structure, development, and context of human activity (Bertelsen and Bødker 2003; Rogers 2004). AT is rooted in the works of the Russian psychologist Vygotsky (Vygotsky 1978; Engeström 1987) and has been applied mainly for the design framework for computer supported cooperative work (CSCW) (Nardi 1996; Kaptelinin et al. 1999). Although its main application area was the design of CSCW, it has also been used for diverse problems, including elicitation of software requirements (Martins and Daltrini 1999), evaluation of system dependability (Sujan et al. 2000), design and evaluation of IT systems in terms of usability (Gay and Hembrooke 2004), evaluation of user experience in an educational game (Law and Sun 2012), evaluation of interaction in virtual environment (Roussou et al. 2008), development of a framework for interaction design (Kaptelinin and Nardi 2006), and development of a framework for information systems research (Crawford and Hasan 2006).

AT was also used as a theoretical basis for improving the safety of system. Bedny and Harris (2013) introduced a safety and reliability analysis method based on systemic-structural activity theory, which is derived from general activity theory. It is useful to identify design deficiencies in terms of safety in the early stages of a design process; however, it is not a method for analysing human-related accidents. AT has been used for characterizing human activities in an organizational context in accident investigation as well (Nuutinen and Norros 2009; Holt and Morris 1993). Particularly, the study of Holt and Morris (1993) indicated the possibility of AT as a useful tool for modelling and analysing human-related accidents. However, little attention has been given to the development of a practical and procedural approach for modelling human-related accidents and for investigating the plausible causes of accidents, on the basis of AT.

One thing to note is that AT should be mainly used for describing or explaining human behaviour in a context, rather than for predicting the process or outcome of human behaviour. AT points out that an isolated human being is not appropriate for the unit of human behaviour analysis (Nardi 1996). Instead it aims at understanding human behaviour in a broader context. It offers a broad conceptual basis for considering contextual factors influencing human behaviour as well (Kaptelinin et al. 1999). AT suggests that a minimal meaningful context for human behaviour should be included in the unit of analysis. For this purpose, AT introduces a new term called 'activity' (Bertelsen and Bødker 2003); that is, an activity should be the basic unit of human behaviour analysis.

The original model of human activity states that every human activity can be described by triadic relationship between a subject and an object (or purpose) mediated by tools or artefacts. AT claims that we cannot pull these three elements (subject, object, and tool) apart without violating the core essence of human activity (Leont'ev 1978). The studies on AT have realized that human behaviour should be understood in a more comprehensive context; thus three more elements (community, division of labour, and rule) were incorporated in order to expand the original model (Bertelsen and Bødker 2003; Engeström 1987). The expanded model of human activity is called an activity system and is represented as an activity triangle shown in Fig. 2. The meaning of the six elements of activity system are described in Fig. 2. The upper part of activity system composed of subject, tools, and object represents an individualized and goal-oriented action involved in an activity. The lower part of activity system consisting of rules, community, and division of labour represents the collective and social nature of an activity.



<Fig. 2. Elements of activity system model (adapted from Kain and Wardle 2014, p. 277)>

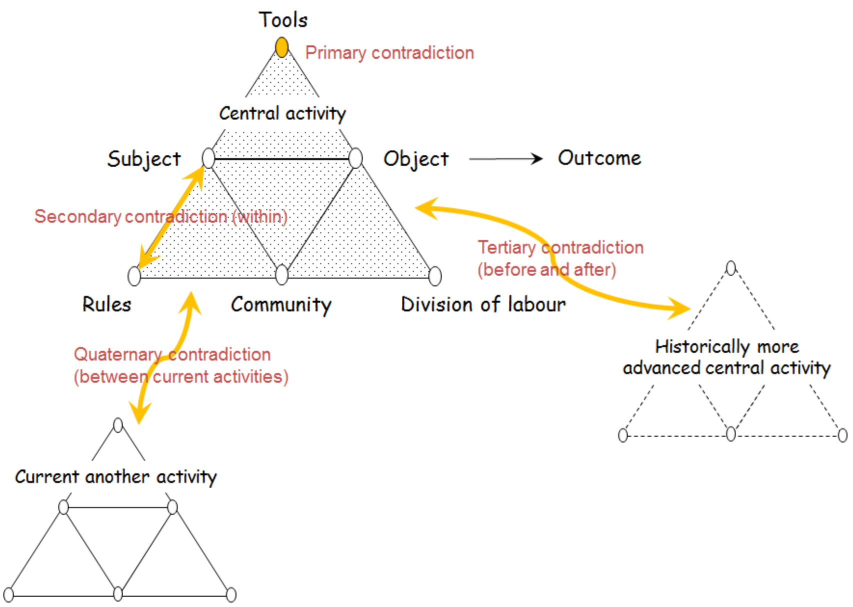
It is interesting to consider activity system in terms of three aspects: interacting elements, types of interaction (interrelationship), and mediating elements. The three main interacting elements are: subject, object, and community. The interaction between the two of these three elements results in the three main types of interaction: subject-object, subject-community, and community-object. These three types of interaction are mediated by the three elements: tools for interaction between subject and object, rules for interaction between subject and community, and division of labour for interaction between community and object.

The theoretical bases of AT are framed by five basic principles for understanding human activities: (1) object-orientedness, (2) hierarchical structure of activity, (3) internalization and externalization, (4) tool mediation, and (5) historical development (Kaptelinin et al. 1999).

- First, the principle of object-orientedness states that every human activity is purposeful and directed toward something (object). For example, a new house can be an object of an architect's activity. As described above, an object could be physical things in real world or ideal concepts in human mind. Thus, a newly established knowledge structure of students can be an object of a teacher's activity.
- Second, the principle of hierarchical structure of human activity emphasizes that human activities can be described at various abstraction levels. An activity is carried out through actions, accomplishing objective results. Actions are governed by the conscious goals of the subject. Goals reflect the objective results of actions. Actions can be regarded as the similar concept to tasks in the literature of human-computer interaction (HCI) (Kaptelinin et al. 1999; Khosla et al. 2003). Actions are realized through series of operations that are conducted without conscious thinking. Operations refer to an unconscious, automatic process, and it depends on the conditions under which an action is carried out. It can be said that the nature of hierarchical structure is not a whole-part relationship but a behavioural goal-means relationship. When an action is repeatedly conducted and thus routinized, it can be transformed into an operation because it can be performed in an unconscious way. In contrast, it is also possible that an operation can become an action when there is a change in activity system and thus a previous unconscious operation cannot be done any more (e.g. introduction of new tools). In this case, the operation should be performed with a conscious goal, which becomes an action.
- Third, AT makes a distinction between internal and external activities. Internal activities refer to cognitive activities happening inside the head (e.g. counting numbers in the head), whereas external activities mean cognitive activities conducted

outside the head (e.g. counting numbers with fingers). The principle of internalization and externalization points out that each of them cannot be understood if it is analysed separately from the other one, because there is a constant transformation between internal and external activities in carrying out an activity. Such a constant transformation forms a basis for human cognition and activity.

- Fourth, the principle of tool mediation explains how cultural factors and the interaction between human and environment can be reflected in the use of tools. In general, a tool reflects the previous experience of other people who have already attempted to solve similar problems or have devised more efficient methods for using it. The reflection of such an experience can be considered in two ways: (1) the structural properties of a tool, which can be developed into its affordance, and (2) the knowledge about when and how a tool should be used.
- Fifth, the principle of historical development claims that human activities are all reformed and reshaped through historical development, and are open to further development as well. If an element or an interaction in an activity system changes, the activity system becomes unstable and accordingly makes adjustments in order to return to stable states. This principle is also related to the understanding of how tools are used as usage unfolds over time. This principle emphasizes that it is necessary to focus on how the purpose of the use of tools changes along with changes in actual objects and in ways of using tools (why, what, and how).



<Fig. 3. The classification of contradiction in activity theory (adapted from Turner and Turner 2001, p. 3)>

Regarding the dynamics described above, AT uses the concept of disturbance and contradiction to describe and analyse the in-depth problems related to human activities (Gedera and Williams 2013). Contradiction is historically accumulated structural tensions within and between activity systems (Engeström 1987), and manifests itself as disturbances, such as problems, ruptures, and breakdowns. As shown in Fig. 3, contradictions are categorized into four types: primary, secondary, tertiary, and quaternary (Turner and Turner 2001). Each of them indicates the misfit within an element of an activity system, the misfit between two elements, the misfit between different developmental phases of an activity, and the misfit between different concurrent activities (Engeström 1987). The primary contradiction happens when there is a mismatch within an element of an activity system. In practice, this contradiction can be understood in terms of tension between the best possible states of an element and what may be actually implemented or employed with time and resources available. An example of this contradiction is that a novice operator is allocated to work situations because of certain constraints where an expert operator should be allocated in principle (contradiction at subject). The primary contradiction is sometimes latent and manifests itself in the secondary contradictions taking the form of concrete tensions between elements of an activity system. The secondary contradiction occurs when two interacting elements mismatch. For example, this contradiction can happen between a human operator's understanding of how a device works and the actual workings of the device (contradiction between subject and tool). Usually, tensions related to the secondary contradiction can be resolved by introducing new elements into activity system in order to reconfigure it. This new introduction can result in the tertiary contradiction. The tertiary contradiction can be found when an activity is reformulated to take account of new motives or ways of working. It happens when there are misfits between different developmental phases of an activity system. For example, when a new task procedure is introduced to achieve works more efficiently, it is possible that they have difficulty following the newly introduced task procedure, because human operators are accustomed to work with old task procedures, (contradiction between two phases of the same activity for conducting something by the use of task procedure). Lastly, the quaternary contradiction takes place in the interaction between two coexisting or concurrent activities. An example of the quaternary contradiction may be found in the interaction between the two activity systems: an activity system that human operators would like to manage their mental stress level, and another activity system that instructors would like to deliver as much knowledge and skills as possible to human operators within a specified time period.

2.3 AT-based accident analysis

Recently, a new method for modelling and analysing human-related accidents based on AT has been developed in our previous work (Yoon et al. 2016). The AT-based method is composed of four stages: data collection, preliminary analysis, in-depth analysis, and recommendations of corrective actions. The two core analysis activities are preliminary analysis and in-depth analysis. In the preliminary analysis, analysts need to model human-related accident situations by the use of activity system model. In this stage, analysts identify surface problems, which mean the problematic elements of an accident as well as human errors involved in an accident. For this, the collective consideration of the six perspectives of activity system model helps analysts understand an accident in the comprehensive contextual backgrounds of a human activity. In the in-depth analysis, analysts attempt to identify in-depth problems, which refer to the causal factors resulting in human errors or problematic situations involved in the sequence of events, by using the four types of contradictions in AT. In terms of activity system model, in-depth problems are related to the contradictions.

As described in the introduction, the usefulness of this method has been demonstrated in several case studies in the domain of NPPs. From the case studies, it was found that the new method supported analysts in producing a more comprehensive, meaningful set of contextual factors systematically, which cannot easily be obtained by using existing methods. Additionally, it was confirmed that AT could be effectively used as a theoretical basis for explaining why a set of causal factors need to be considered and for specifying how those factors and their interrelationships should be interpreted.

It was also found that it could be more advantageous than other analysis methods that offer predefined set of causal factors or none of them, in the process of identifying plausible causal factors for a human-related accident under investigation. When analysts too much depend on a predefined set of contextual factors, it is likely that they make a premature judgement on causal factors without a deep consideration of a range of contextual backgrounds surrounding a human-related accident. In contrast, when analysts identify plausible causal factors without any predefined set of contextual factors, they can take account of various contextual factors. However, in this case, it is likely that the process of discerning contextual factors may be unsystematic and inefficient, and there may be no meaningful relationships among the identified contextual factors. The AT-based method can be an effective alternative to overcome the limitations of the two different approaches to identifying a set of contextual factors. It does not put any restrictions on looking for a set of contextual factors because it does not force analysts to stick to a predefined set of contextual factors. However, it leads analysts to consider a range of contextual factors and their interrelationships systematically on the basis of human activity system models related to the accident, which can be developed by the use of concepts and principles of AT. As a result, a set of contextual factors and their interrelationships identified by using the AT-based method can be interpreted with a theoretically sound model of human activities.

2.4 Research motivation

As shown in the study of Yoon et al. (2016), AT can be usefully used as a theoretical framework for modelling and analysing human-related accidents. In spite of several relative advantages of the AT-based method in comparison to existing methods, it has some drawbacks to be considered. As described previously, there is a limitation in the scope of contextual factors that can be considered by using the method. For example, it can be difficult for analysts to take account of some kinds of factors (e.g. physical environmental factors and the effects of a regulatory body) when they look at an accident based on human activity system model. Considering that an accident analysis method should deal with all of the hierarchical levels of socio-technical systems (Leveson 2011; Salmon et al. 2011), this limitation should be supplemented to improve the usefulness of the method. Another limitation to overcome lies in the usability of the method in the process of identifying a set of causal factors. When determining plausible causes for an accident in the use of the method, analysts can look for a range of contextual factors comprehensively and systematically by considering human activity system models and their related contradictions, without only depending on a predetermined set of causal factors. However, if a preliminary set of causal factors can be provided, which are linked to the elements and relations within or between activity system models, the process of using the method would be more efficient. In this case, analysts can investigate an accident initially with the pre-specified causal factors and then more easily look for other causal factors to be considered with the concepts and principles of AT. As a result, this would enhance the practicality of the AT-based method.

In order to supplement those limitations, this study aims to integrate HFACS and the AT-based method, by embedding the concepts and principles of AT into HFACS. This integration is a viable approach because HFACS provides a set of causal factors (the taxonomy of failure types) at each four levels and addresses most of the hierarchical levels of a socio-technical system. Another good point is the fact that HFACS is currently one of the most popular methods for analysing human errors. Additionally, it has been reported that HFACS is highly usable because it is simple to learn and simple to use (Salmon et al. 2011; Baysari et al. 2009), and this aspect may be the most attractive feature from the perspective of safety practitioners working in the industry (Underwood and Waterson 2013). Therefore, a cross-fertilization between the two methods (HFACS and the AT-based method) seems to be a good way for developing a more useful approach to analysing human-related accidents.

As stated above, embedding the concepts and principles of AT into HFACS would complement the limitations of the AT-based method, making the most of the advantages of HFACS. However, we can expect more benefits of this integration in relation to the shortcomings of traditional approaches to accident analysis, which have been strongly pointed out in the introduction of a new paradigm of system safety called Safety-II (Hollnagel et al. 2013). Some of those drawbacks include: (1) an oversimplified approach that identifies linear, simple cause-effect relationships, (2) looking for plausible causal factors only based on a causation model assumed in a method for analysing accidents, and (3) neglecting other possible causes by over-relying on a root cause (Hollnagel 2014; Shorrock et al. 2014). As the interaction between human and system is increasingly complex and dynamic, it is more likely that we can experience human-related accidents that cannot be sufficiently investigated with traditional approaches, thereby exposing those drawbacks. Therefore, traditional accident analysis methods need to be complemented to mitigate them, and new accident analysis methods reflecting the concepts of Safety-II need to be developed as well (Hollnagel 2014).

In this regard, it is interesting to look at how the FRAM (Functional Resonance Analysis Method) (Hollnagel 2012; Patriarca and Bergström 2017), which is a system modelling tool for reflecting the concepts of Safety-II, addresses those shortcomings. In particular, of those three weak points, the first two drawbacks are well addressed in the FRAM. The FRAM mitigates the first drawback by introducing the concept of functional resonance and by stipulating that an accident happens in an emergent manner (results from the dynamic interactions between contextual factors and performance variability of work functions). In addition, the FRAM does not assume any accident causation model; it is just a method for modelling a socio-technical system that explains how a system works. Thus it does not enforce accident analysts to depend on a causation model blindly to identify a plausible set of causal factors. This is how it mitigates the second drawback above.

However, it is expected that the integration of AT and HFACS (particularly the AT-based method) can also be a promising approach to overcome the limitations of traditional approaches. The three drawbacks above can be supplemented as follows. Firstly, the AT-based method claims that an accident needs to be examined from the perspectives of six elements constituting an activity system and their dynamic interactions (contradictions). This means that the AT-based method encourages accident analyst to reject the view that an accident can be reasonably understood in terms of a linear cause-effect relationship, thereby mitigating the first drawback above. Secondly, the AT-based method does not assume any accident causation model, like the FRAM; it can be used as a method for describing human activities with their contextual backgrounds in a system. This point would be helpful to overcome the second drawback. Thirdly, the AT-based approach encourages analysts to look at human-related accident situations with broad perspectives in order to consider as many different possible causal factors as possible, which can be meaningful to an accident under investigation. Thus we can say that the AT-based method would be useful for analysts to overcome the third shortcoming.

One should not think that traditional approaches are useless due to their weak points. In spite of those shortcomings, traditional approaches are still useful in accident modelling and investigation. However, we should also note that there is a growing number of accidents in modern complex systems where traditional approaches cannot be effectively used (Hollnagel 2016). For this reason, accident analysts should always keep in mind the limitations of traditional approaches and make an attempt to overcome them. Thus, we can say that it is desirable to develop a method that can support the use of traditional approaches to accident investigation as well as help analysts avoid their drawbacks. We will examine whether or not the new method proposed in this study can be an answer to this research issue.

To sum up, the purpose of this study is to propose a new method that integrates HFACS and the AT-based method, thereby enhancing the practicality of AT-based approach to modelling and analysing human-related accidents. Moreover, the proposed method is expected to have a potential to overcome some drawbacks of traditional approaches. This potential of the proposed method will be examined as well.

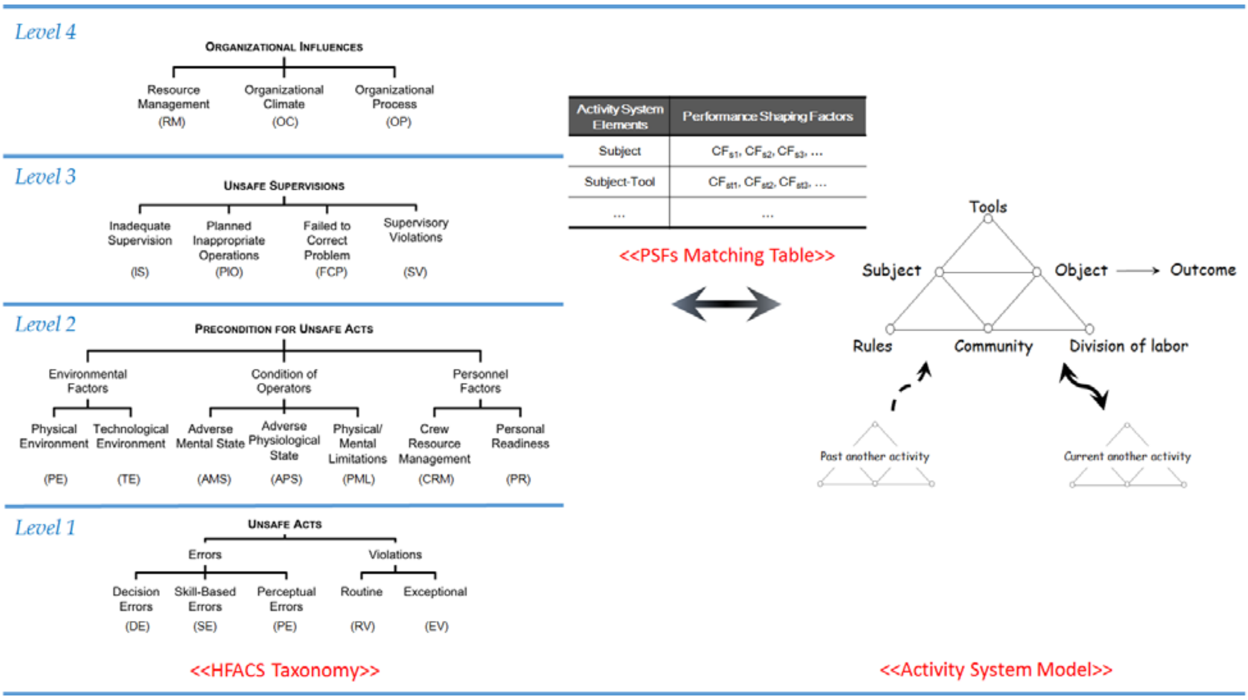
3. The proposed method

The proposed method presents a methodological framework to describe various contextual factors of human-related accidents by combining HFACS (particularly, the failure taxonomy) and the AT-based method (particularly, AT-based modelling and analysis of activities). As shown in Fig. 4, the basic approach is to describe activities and their interrelationships before determining plausible causes of a human-related accident. The relationships among activities within the same time zone are represented with solid lines, but the relationships among activities located in different time zones are represented with dotted lines. Moreover, the four types of contradictions embedded within and between activities become a basis for identifying a set of plausible causes of an accident. The contradictions are color-coded orange in this paper (Fig. 3 & Fig. 7).

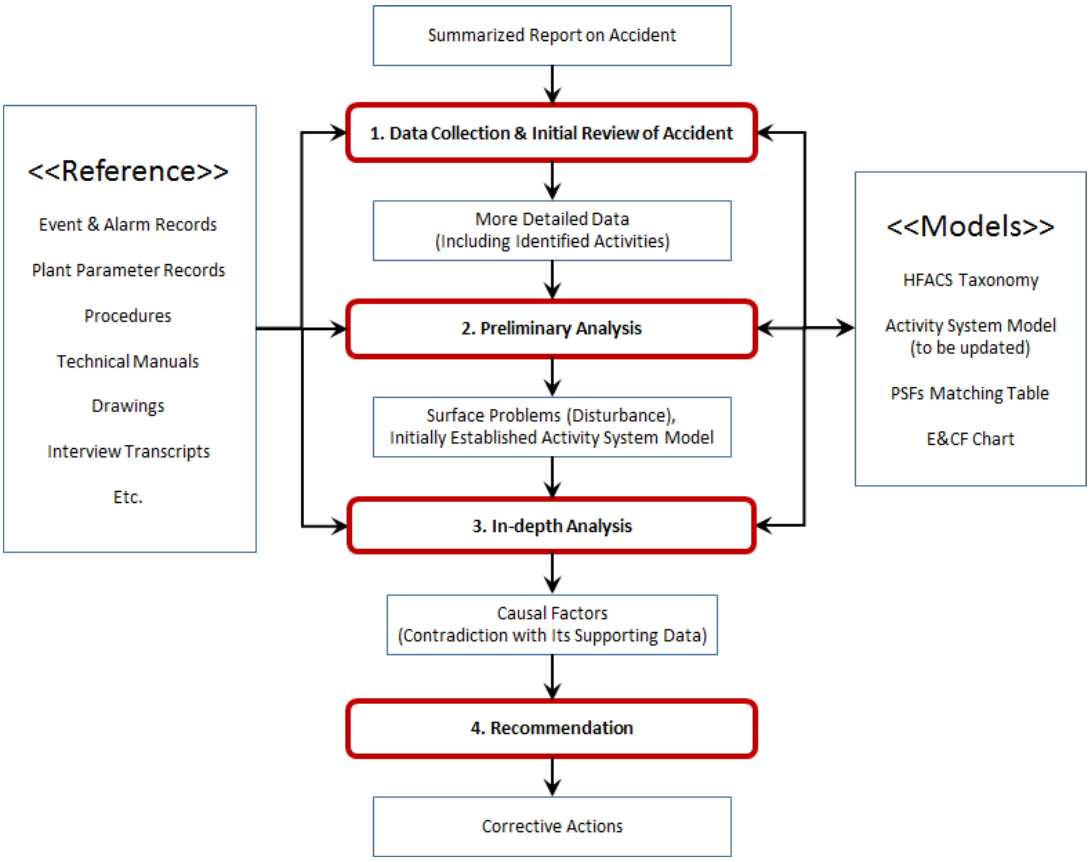
In order to help accident analysts more efficiently derive a set of problematic contextual factors for understanding a human-related accident and determine a set of plausible causal factors for the accident, the proposed method recommends them to use the failure taxonomy of HFACS and the performance shaping factors (PSFs) matching table shown in Appendix A. The PSFs matching table provides the links between the elements of activity system model and their corresponding PSFs (i.e. probable causal factors for an accident). The PSFs matching table can be used to help analysts to examine another candidate of causal factors which are not included in HFACS taxonomy as well. The PSFs matching table in Appendix A offers some examples of PSFs for the elements of activity system model. However, it should be noted that they are not a complete set; instead they need to be regarded as typical examples of PSFs for the elements of activity system model.

Performance shaping factors (PSFs) refer to the factors that affect human performance in a system (Swain and Guttman 1983). It seems that PSF is a term more frequently used in human reliability analysis (HRA) rather than human-related accident analysis. Considering the meaning of PSFs, we can say that the concept of PSFs is similar to the concept of contextual factors. However, although PSFs can also include any factors increasing human reliability (decreasing the likelihood of human errors), the more widely accepted meaning of PSFs in accident investigation seems to be closer to the factors affecting human performance in a way that caused the error of interest (Salmon et al. 2011; Shorrock and Kirwan 2002). This is the reason why we used the term the PSFs matching table, rather than the term the contextual factors matching table. Obviously, there can be a range of PSFs that influence human performance in a variable manner, thereby affecting the likelihood of human error (Hollnagel 1998). Nonetheless, it is necessary to consider PSFs that have the most effect on performance in the accident analysis and risk assessment. In general, if a PSF is believed to contribute to the occurrence of a human-related accident under investigation, it can be regarded as a plausible causal factor for the accident.

The overall process of the proposed approach consists of the four stages: data collection and initial review of accident, preliminary analysis, in-depth analysis, and recommendation (Fig. 5). The more detailed description of these four stages are as follows.



<Fig. 4. Accident analysis framework of the proposed method>



<Fig. 5. The overall process of the proposed method>

Step 1: Data Collection and Initial Review of Accident

As with most of the existing methods, data collection is the first and most important step for analysing a human-related accident. It is necessary to collect suitable data on an accident comprehensively for understanding the whole picture of the accident situation. Analysts usually start with some initial data such as summarized report on accident, and try to collect additional data to reconstruct the situation around an accident using some reference information such as event & alarm records. In addition, analysts should identify human activities shown in the initial representation of the accident scenario. Although the data should be collected as abundantly as possible at the initial trial, additional data also need to be collected continuously throughout the entire process of accident analysis. The data collection process can be supported with activity system models. An activity system model is used as a template with the six perspectives for collecting comprehensive data on the situation of an accident.

Step 2: Preliminary Analysis

The second step is to conduct preliminary analysis with the data gathered in the previous step. First of all, analysts identify surface problems (or disturbances), which refer to problematic elements (e.g. technological aspects, environmental aspects, etc.) involved in an accident as well as unsafe acts or unsafe supervisions. A popular practice in accident analysis is to use the event and causal factor (E&CF) chart in order to identify and describe these surface problems. The E&CF chart can aggregate the data on accident situation in a simple manner, and provide an intuitive explanation on linear sequence of events and causal factors (i.e. linear cause-effect relationships) involved in the progression of an accident. However, the E&CF chart can be ineffective for identifying surface problems from multiple perspectives as well as further looking for more specific types of problems. Thus, we recommend the use of activity system model and HFACS taxonomy for identifying and describing surface problems. As shown in Table 1, a surface problem should be described on activity itself that needs to be analysed. In addition, more specific surface problems of an accident can be identified from the six different perspectives, each of which respectively corresponds to the six main elements of activity system model. Although outcome and motive are represented in the description of an activity system, they are not the main elements of an activity system model that need to be considered to understand human activities in a context. Thus they are not further considered in the analysis of human-related accidents based on the AT-based method. Here the probable causal factors shown in the PSFs matching table in Appendix A can be effectively used for identifying surface problems. Furthermore, the failure taxonomy of HFACS, which provides a detailed classification on the types of unsafe acts or unsafe supervisions, can be useful referential information for this process as well. For example, let's suppose that an operator made a mistake which manipulated a wrong valve during a maintenance work (disturbance: activity). In this situation, the operator could be a worker with weak mental states (disturbance: subject). Besides, the step of the valve line-up for the maintenance could be described ambiguously in the maintenance procedure (disturbance: tool). Referring to this information, analysts can determine this erroneous action as 'decision error' with HFACS taxonomy. When analysts make the best use of HFACS taxonomy and the PSFs matching table in this step 2, they can efficiently establish a set of rough, initial contextual factors and then conceive a likely tentative accident mechanism or scenario with those established factors. The application of HFACS taxonomy can give a more detailed information to surface problems identified by the use of activity system model as well, which helps analysts characterize surface problems more specifically.

<Table 1. Multiple perspectives on surface problems (or disturbances)>

Disturbance Types	Definition
Activity	Unsafe acts or unsafe supervisions (consequence) involved in the sequence of events
Subject	Subjects involved in the activity and their unsafe actions; Personal background related to the unsafe actions
Tool	Problems of the tool used by the subject when performing the unsafe action
Object	Problems related to the object of the activity
Rule	Problems of the explicit or implicit norms, code of conduct used in the community
Community	Problems related to the group or participants of the activity
Division of Labour	Problems related to division of responsibility, communication and coordination among members of the community

<Table 2. Classification of in-depth problems (or contradictions)>

Contradiction Types	Definition
Primary contradiction	Misfit within the elements of an activity system (e.g. subject, tool, rule, etc.)
Secondary contradiction	Misfit between the elements of an activity system (e.g. subject-tool, etc.)
Tertiary contradiction	Misfit between different developmental phase of an activity system (e.g. activity A (time-1) - activity A (time-2), etc.)
Quaternary contradiction	Misfit between coexisting or concurrent different activity system (e.g. activity A – activity B, etc.)

Step 3: In-depth Analysis

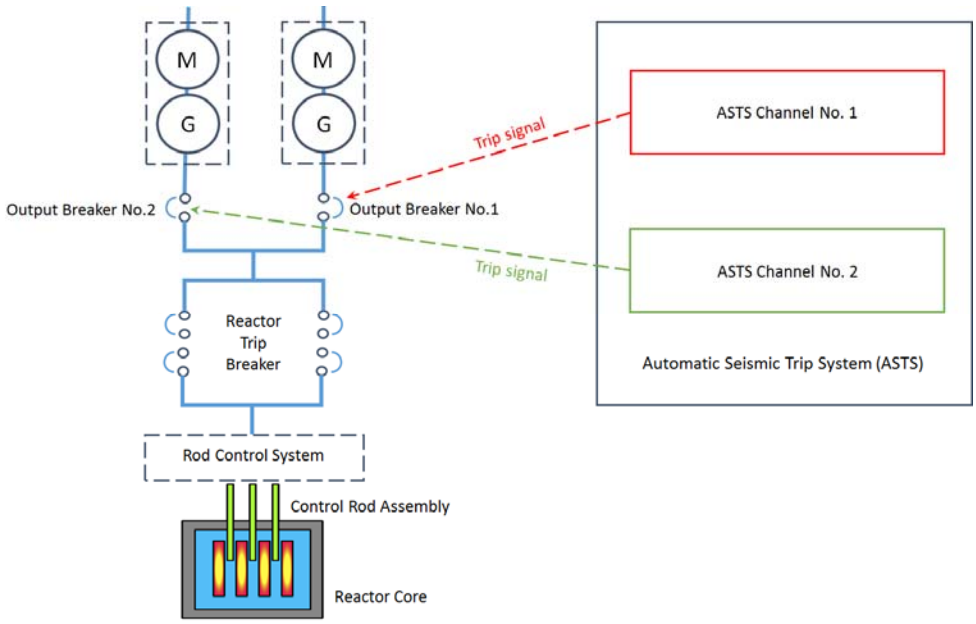
In this step, analysts conduct in-depth analysis to examine and uncover more in-depth problems (or contradictions), which result in unsafe acts or unsafe supervisions as well as problematic situations involved in accident progression. As shown in Table 2, in-depth problems are embedded within and between activity systems and classified into four types: primary, secondary, tertiary, and quaternary contradictions. Before identifying in-depth problems, it is necessary to build more extended activity system models which cover the whole hierarchical structure of HFACS. Activity system models are built by updating the initial activity system models established in the previous step. After that, analysts identify in-depth problems based on the extended activity system models which were described on the layers of the hierarchical structure of HFACS. Finally, analysts select relevant causal factors from HFACS taxonomy by considering identified in-depth problems. In this step, accident analysts can also effectively refer to the probable causal factors shown in the PSFs matching table to determine a set of causal factors, by associating the elements of activity system model with HFACS taxonomy. Some examples of probable causal factors related to the contractions in Table 2 are also offered in the PSFs matching table. For example, let's suppose that analysts identified some subject-related contradictions as in-depth problems (e.g. primary contradiction on subject, secondary contraction between subject and other elements, etc.) for unsafe acts. For these contradictions, analysts can select some causal factors such as personality (subject), job satisfaction level (subject-object), knowledge and skills of using tools, equipment and procedures (subject-tool) from the PSFs matching table. However, it should be again noted that the causal factors shown in the PSFs matching table in Appendix A are not complete; they are just the examples of the probable causal factors corresponding to the elements of the activity system. They can serve only as a referential basis for identifying a set of causal factors. Thus they need to be expanded and refined continuously.

Step 4: Recommendation

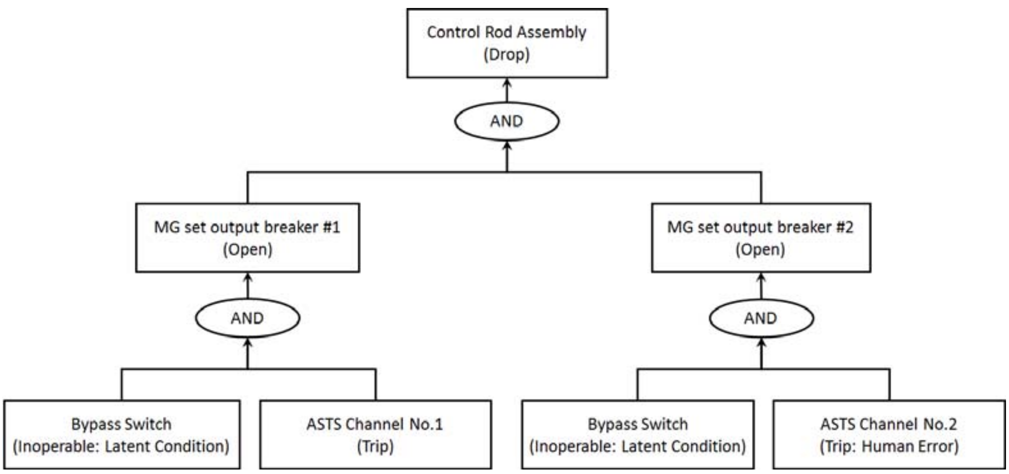
Lastly, corrective actions are recommended based on the results of the previous analyses. When developing corrective actions, analysts should consider the problems and relevant causal factors as well as the whole picture of the interrelationships among activity systems. In addition, analysts should take account of a set of identified causes and their cost-benefit trade-offs together. Furthermore, analysts need to acknowledge the possibility of unexpected side effects that may result from implementing corrective actions. These potential problems can be addressed with the help of activity system model (i.e. tertiary contradiction). For example, when a mandatory job rotation in key areas of an organization is considered as a corrective action against the problem of corruption, the potential effect can be examined roughly based on the tertiary contradiction between current activity systems and more advanced activity systems after applying the corrective action. Based on the tertiary contradiction, analysts can anticipate another issues (e.g. staffing and qualification, workload, professionalism, etc.) in the new activity system.

4. Case study

To demonstrate the applicability of the proposed method, we conducted a case study of analysing a human-related accident that occurred in Korean NPPs. This case is the re-examination of a human-related accident that was investigated previously (KINS, 2014). During the investigation of the accident, we collected the relevant information by reviewing some documents and interviewing four plant personnel who conducted the surveillance test of the automatic seismic trip system (ASTS) and four personnel working in the sub-contractors who developed the ASTS. Four plant personnel include two operators (one shift supervisor and one reactor operator) who had worked more than ten years as the operator and two test personnel who had more than five years' experience as the instrumentation and control (I&C) engineer. All of the four personnel working in the sub-contractors had more than ten years' experience in the field of I&C system development. For the re-analysis of the accident, we interviewed another three plant personnel (i.e., one engineer who installed the ASTS at the NPP where the unplanned reactor trip occurred, and two another engineers who installed the ASTS at another two NPPs around the same time), who were not interviewed at that time. They had worked around four years as the I&C engineer. We used unstructured interview method, and spent one or two hours for each of the interviews. The interviews were recorded by using a voice recorder, and then the interview transcripts were made. These interview data were analysed by using the concept underlying the proposed method. This means that the six elements constituting an activity system and four types of contradictions were used as analysis grid in the analysis of the interview data. Moreover, the result of the accident analysis was compared with those examined by other methods such as HFACS (Wiegmann and Shappell 2003) and the AT-based method (Yoon et al. 2016) used in the previous study.



(a) A functional relationship between ASTS and relevant components in NPP



(b) The sequence of events

<Fig. 6. A simplified reconstruction of the unplanned reactor trip event>

4.1 Event description

The abnormal event occurred during a 6-month surveillance test of the ASTS. The ASTS was installed in the NPPs in Korea as one of the post-Fukushima action items. The ASTS is the supplemental system that scram the reactor swiftly to cope with potential risks after extreme earthquake. The ASTS consists of two redundant trip channels. Each channel of the ASTS determines the trip (i.e. open) of each output breaker of the Motor-Generator (M-G) sets, which supply electrical power to the rod control system. Removing the electrical power from the rod control system makes the control rod assembly drop into the reactor core (Figure 6 (a)).

The surveillance test was started with placing the bypass switch on the maintenance and test panel (MTP) into the bypass position to block the inadequate trip signal during the test. After finishing the test for the channel No. 1 of the ASTS, and while performing the test for the channel No. 2 of the ASTS, the control rods suddenly dropped, and as a result, the reactor was scrammed automatically. The drop of the control rods was due to the inadvertent open of all M-G set output breakers. The M-G set output breakers were opened due to human errors by the operators and test personnel, combined with a technical design defect, which is the inoperability of the bypass switch on the MTP of the ASTS. Moreover, while performing the test on the channel No. 1 of the ASTS, the channel No. 1 trip signal was indicated on the alarm windows in main control room, and on the information display of the MTP. However, the operators and test personnel could not acknowledge the abnormal situation (i.e. the trip of channel No. 1) and continuously carry out the next stage on the channel No. 2. As a result, both of the M-G set output breakers were opened unintentionally during the test (Fig. 6 (b)).

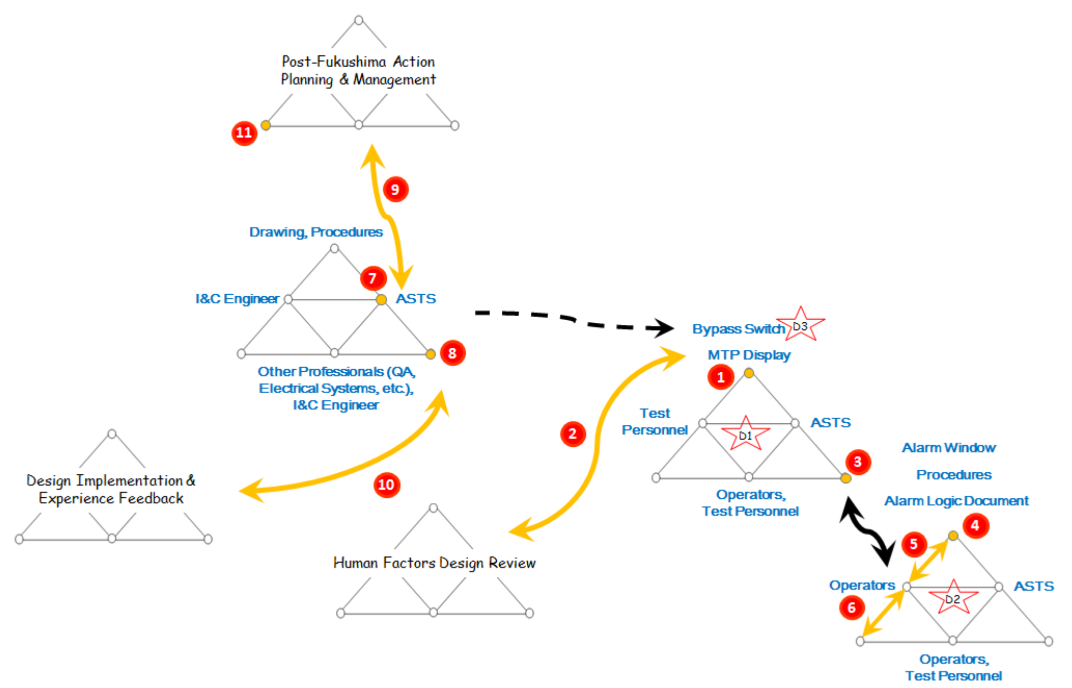
4.2 The analysis results using the proposed method

4.2.1 Results of preliminary analysis

We identified three surface problems (or disturbances) such as two human errors (D1 and D2) and one latent condition (D3). These surface problems were described with star-marks and activity system models (Fig. 7). As an initial building of activity system model, we made two activity system models which represent the activities of test personnel and operators. After that, we assigned specific failure categories onto each surface problems with HFACS taxonomy. In summary, the surface problems were identified and described with HFACS taxonomy as shown in Table 3.

<Table 3. The surface problems identified using the proposed method>

	Failure types	Relevant information & activity system model
D1	Perceptual errors	Test personnel failed to detect the abnormal situation (activity) - The status of channel trip was indicated on MTP display, but it disappeared within 1 second (tool)
D2	Decision errors	Operators saw the alarm occurrence, but failed to recognise it as an abnormal situation and to share the information with test personnel (activity) - The alarm was cleared when an operator pushed the button of 'acknowledge' and 'reset' (tool)
D3	Technological failures	The bypass switch on the MTP has been inoperable due to design deficiency (tool)



<Fig. 7. Accident analysis using the proposed method>

4.2.2 Results of in-depth analysis

For the surface problems described above, we built more extended activity system models and conducted in-depth analysis to identify specific causal factors (Fig. 7). First, we identified that the test personnel's human error (D1) was resulted from two primary contradictions, such as the design deficiency of MTP display (tool) and inadequate cooperation with operators (div. of labour). In addition, we identified a quaternary contradiction; that is the scope of human factors design review (tool-another activity). The

MTP display had the function of indicating the status of channel trip of the ASTS. However, this design feature did not contribute to acknowledge the channel trip of ASTS. The reason was that the indication of channel trip was displayed, but suddenly disappeared from the MTP display within less than 1 second. Thus, the test personnel could not acknowledge the abnormal situation during the test. This problem is also related to the quaternary contradiction that is the scope of human factors design review. Until recent years, the scope of human factors design review was restricted to main control room of the nuclear power plant. The MTP display was installed in the electrical equipment room (EER) outside of main control room, thus human factors principle was not integrated into the design of MTP display. Besides, the test personnel could be supported to recognize the abnormal situation by the operators who continuously monitored whether or not the alarm occurred. However, the operators did not stop the test process or share the information of alarm occurrence with the test personnel. This is another primary contradiction.

Second, we identified that operators' human error (D2) was influenced from one primary contradiction such as procedure or document deficiency related to alarm logic (tool), and two secondary contradictions such as knowledge deficiency related to alarm logic and response (subject-tool) and a sense of responsibility to cooperate with test personnel (subject-rule). In this case, the operator understood that an alarm would be displayed on alarm window when triggering the channel trip of ASTS. However, he confused which alarm would be displayed, so he focused on another alarm window irrelevant to the channel trip of ASTS. Furthermore, he directed attention to another alarm occurrence in an abnormal situation, so he failed to recognize the alarm of channel trip of ASTS as a real situation. When he pushed the button of 'acknowledge' and 'reset', the alarm was cleared. As the result, the operator believed that the alarm was a false signal. Thus, the operator did not perform any action and also did not share the situation with test personnel. We identified that the operator's knowledge deficiency was due to some confusable description of alarm response procedure.

Third, we identified that the latent inoperability of the bypass switch on the MTP (D3) could be traced back to the installation stage of the ASTS about three years ago. Although the installation of the ASTS was completed, the ASTS was not connected to the M-G set to verify whether or not the functionality of the ASTS is stable until recent time. Thus, the design problem remained unnoticed for long time. Although the NPP-A (i.e. the NPP in which the unplanned reactor trip occurred) was the first case to design and install the ASTS, the installation of the ASTS was also carried out at another two NPPs (i.e. NPP-B and NPP-C) around the same time. Unfortunately, the NPP-A failed to identify and correct the design deficiency of the bypass switch, but NPP-B and NPP-C successfully identified and corrected the latent design problem. Ironically, the I&C engineers in the NPP-A were more qualified persons with more job experience in the technical area in comparison with the I&C engineers in the NPP-B and NPP-C. We identified that the failure of design review and correction was influenced from two primary contradictions such as relatively tight schedule for installation of the ASTS (object) and insufficient support from other professionals (div. of labour) and two quaternary contradiction such as forcing to meet the tight schedule from the upper levels of the organization (object-another activity) and design implementation and experience feedback related to the prior installation of the ASTS (div. of labour-another activity). The I&C engineers, who were responsible for installing the ASTS at NPP-A, had not enough time to review and test the ASTS during the installation stage. Furthermore, they were busy due to another more important project such as power uprate which increases the licensed thermal power limit, but they could not be supported to relieve their workload by other professionals in the NPP. Moreover, the design deficiency was successfully identified and corrected by the I&C engineers in NPP-B and NPP-C. Especially, the I&C engineers in NPP-B swiftly shared their experience of identifying the design deficiency of the ASTS with other I&C engineers in other NPPs using an unofficial channel such as email. However, the I&C engineers in NPP-A moved to another job positions after installing the ASTS, and the successful experience of dealing with the design deficiency of the ASTS was not transferred to the I&C engineers' successors in NPP-A. In summary, we could identify the in-depth problems shown in Table 4, referring to HFACS taxonomy and the PSFs matching table.

<Table 4. The in-depth problems identified using the proposed method>

	No	Plausible causal factors	Relevant information & activity system model
D1	1	(Some part of) usability of tools or equipment	- The MTP display had a human factors design deficiency (tool)
	2	Design control of tools or equipment	- The MTP display was not included in the scope of human factors design review (tool-another activity)
	3	Adequacy of coordination and communication	- There was not suitable cooperation between operators and test personnel (div. of labour)
D2	4	Technical correctness of procedures/documents	- There was some deficiency related alarm logic among technical documents (tool)
	5	Knowledge and skills of using tools/equipment/ procedures	- The operator had inadequate knowledge on alarm logic (subject-tool)

	No	Plausible causal factors	Relevant information & activity system model
	6	Sense of responsibility	- There was not sufficient sense of responsibility to cooperate between operators and test personnel (subject-rule)
D3	7	Task characteristics	- The installation of the ASTS was conducted with a relatively tight schedule (object)
	8	Adequacy of coordination and communication	- The cooperation between the I&C engineer and other professionals was not effective for the design review of the ASTS (div. of labour)
	9	Adequacy of work planning or control	- The post-Fukushima action plan was announced with the relatively tight schedule (object-another activity)
	10	Adequacy of protocols or methods for communication and instruction	- The communication between the I&C engineer at NPP-B and the I&C engineers at other NPPs was not effective to reflect the prior experience of identifying and correcting the design problem (div. of labour-another activity)
	11	Adequacy of policy and guidance	- The progress of implementing post-Fukushima action plan was considered as important criteria for rating the performance of the company (rule)
			- It was forced the NPP workers to meet the schedule established by headquarter office (rule)

4.3 Comparison with the individual use of HFACS and AT-based approach

An accident analysis was previously conducted to the same case by using the AT-based approach and HFACS individually (Yoon et al. 2016). The analysis results were summarised in Table 5. The analysis results using HFACS show similar results with those obtained from AT-based approach. However, HFACS and the AT-based approach had some relative advantages or limitations for accident analysis. HFACS was useful to characterize error types and causal factors more specifically and reliably than the AT-based approach. However, some causal factors could not be addressed by the use of HFACS when compared with those obtained with the AT-based approach. For example, as shown in Table 5, work management of implementing post-Fukushima action items was not considered as a causal factor during HFACS analysis. Moreover, some causal factors such as procedure or knowledge-related aspects were not predefined in HFACS taxonomy, thus they could not be identified as causal factors during HFACS analysis. In contrast to this, some causal factors (e.g. inadequate training to operators) were forced to be identified when conducting HFACS analysis. These supervisory-related factors can be picked up from the analysts' hindsight views as with other analysis methods. However, we could not find any clear evidences to support this judgement when conducting AT-based analysis.

The comparison between Table 4 and Table 5 indicated that the proposed method identified additional in-depth problems more coherently, which were not addressed as causal factors in the previous analysis. Especially, there were some contributing factors from the upper levels of the organizational structure. These influences were related to the levels of corporate leadership and NPP management. For example, the headquarter office established the fixed schedule of post-Fukushima action plan without enough review and communication with the NPP managers. Moreover, it was announced that the progress of implementing post-Fukushima action plan would be evaluated as one of important rating criteria for the company. Thus, this quick and easy decision-making led to the unexpected excessive demand for the installation activity of the ASTS in the first NPP (i.e. NPP-A) which was prescribed in the schedule.

<Table 5. The analysis results using HFACS and AT-based approach (Yoon et al. 2016)>

	HFACS analysis & relevant information	AT-based analysis & relevant information
D1	<Level 2> ■ Technological environment - Design deficiency of MTP display and alarm logic	■ Design deficiency of MTP display □ The scope of human factors design review □ Inadequate cooperation with operators
	<Level 1> ■ Perceptual errors - Test personnel's failure of detecting the abnormal situation from MTP display	■ Test personnel failed to detect the abnormal situation
D2	<Level 3> √ Inadequate supervision - Inadequate training to operators	-
	<Level 2> √ Adverse mental states - Operator's inattention or situation awareness failure ■ Crew resource management - Communication deficiency between operators and test personnel on the abnormal situation	□ Knowledge deficiency related to alarm logic and response ■ Cooperation with test personnel □ Procedure or document deficiency related to alarm logic
	<Level 1> ■ Decision errors - Operator's failure of recognising the alarm occurrence as abnormal situation and sharing the information to test personnel	■ Operating shift personnel saw the alarm occurrence, but failed to recognise it as an abnormal situation and to share the information with test personnel

	HFACS analysis & relevant information	AT-based analysis & relevant information
D3	<Level 4> ■ Organizational process - Inadequate design review and experience feedback about design deficiency	■ Experience feedback related to the prior installation of the ASTS □ Work management of implementing post-Fukushima action items
	<Level 3> -	□ Work management of implementing post-Fukushima action items
	<Level 2> -	□ The bypass switch on the MTP has been inoperable due to design deficiency

(Notes) ■: matched between HFACS analysis and AT-based analysis, □: not-matched between HFACS analysis and AT-based analysis, √: not-matched and wrong results

The results of this case study showed that the use of the proposed method could have unique advantages in comparison with the individual use of HFACS or the AT-based approach. First, the AT-based approach described the interaction among activities with just one dimension of 'relevance'. However, the proposed approach represents the relations among activities with three kinds of dimensions such as vertical relationship between activities across the layers of HFACS, horizontal relationship between activities within a layer of HFACS, and temporally influencing relationship between activities. Thus, analysts can understand the relationships between activities involved in an accident situation more comprehensively. Especially, historical and organizational background of an accident can be clearly represented and used for accident analysis. Second, HFACS assumes the top-down causality in the hierarchical structure of an organization. Thus, it constrains that accident analysis should be conducted through a bottom-up process by starting the lowest level such as unsafe acts. However, the proposed approach does not put any constraint to the flow of causality in the hierarchical structure; it does not enforce analysts to investigate an accident by using only the causality relationship. Although the proposed approach adopts the process of starting with surface problems and moving to in-depth problems, the surfaces problems do not necessarily have to be unsafe acts (i.e. HFACS Level 1). It is allowed that the surface problems can be also preconditions of unsafe acts (i.e. HFACS Level 2) or unsafe supervision (i.e. HFACS Level 3).

5. Discussion

We have found that HFACS could be effectively used for supplementing the AT-based approach to accident analysis with its failure taxonomy and broad coverage of hierarchical levels of a system. As the failure taxonomy of HFACS serves as an initial set of candidate causal factors, analysts can relatively easily diagnose an accident and conceive the most probable causes on the basis of the failure categories. This is surely a good point in terms of the efficiency of accident investigation. HFACS addresses most of the hierarchical levels of a system, excepting only the highest level (i.e. government and local authorities). This is also a good point in that HFACS makes analysts look at an accident from the perspectives of the three levels (a single human worker, a group of workers, and an organization) and their interactions in a balanced way. HFACS can be effectively used for supplementing the limitations of the AT-based method with those features described above.

However, it should be noted that the mechanical use of HFACS without considering its shortcomings can make it difficult for analysts to escape from the limitations of traditional approaches to accident investigation. As described in section 2.4, the critical limitations of traditional approaches include: (1) an oversimplified approach that identifies linear, simple cause-effect relationships, (2) looking for plausible causal factors only based on a causation model assumed in a method for analysing accidents, and (3) neglecting other possible causes by over-relying on a root cause (Hollnagel 2014; Shorrock et al. 2014). As HFACS was developed based on the concept of Swiss cheese model, it enforces analysts to diagnose an accident in consideration of two types of failures: active failures and latent failures. In relation to this, a causation model is assumed in HFACS. The causation model is as follows: an active failure at the level of unsafe acts is affected by latent failures of the next higher level, and these latent failures are again influenced by latent failures of the next higher level, and so on. Thus, if analysts look for a probable set of causal factors by rote by the use of the causation model and its related failure classifications in HFACS, it is likely that they fall into the drawbacks of traditional approaches to accident investigation.

While HFACS can supplement the weak points of the AT-based approach, the concepts and principles of AT can also be usefully used for complementing those drawbacks described above. We should note that AT is not a causation model for accident analysis, but can be used as a method for describing human activities with their contextual backgrounds in a system. The AT-based approach encourages analysts to look at human-related accident situations with diverse perspectives and to consider as many different probable causal factors as possible, which can be meaningful to an accident under investigation. For that reason, AT can be effectively used as a theoretical framework for overcoming (or at least lessening) the drawbacks of traditional approaches to accident investigation. As Hollnagel (2012) pointed out, the limitations of traditional accident analysis methods come from their underlying causation models, even though a causation model can enhance the efficiency of accident investigation. He emphasizes the importance of developing a method that does not presume a causation model. Thus, we can find a good advantage of the AT-based method in that it does not rely on an accident causation model but can be used as a method for modelling human activities in every situation, as explained above.

As we discussed above, the integration of HFACS and the AT-based method is meaningful in that each of them can be effectively used for supplementing the drawbacks of the other. As a result, in comparison to the individual use of each method, the method proposed in this study can be more effectively used for accident investigation. Considering the features of the proposed method and the findings of the case study, we can say that it can make analysts enjoy the benefits of traditional approaches to accident investigation as well as help them avoid the drawbacks of traditional approaches.

However, we can discuss other benefits of using the proposed method in relation to the introduction of a new paradigm on system safety (Safety-II) and the comparison between it and traditional approaches. In the currently dominating safety paradigm (Safety-I), safety is defined as the condition where the number of adverse outcomes (accidents and incidents) is as low as possible. Thus, the main goal of traditional approaches to accident investigation is to determine a set of plausible causes and to fix them (find and fix approach) (Hollnagel 2014). As described above, the new safety paradigm indicated that traditional approaches suffer from the following three shortcomings, in spite of their usefulness in many accident investigations: (1) they attempt to diagnose an accident with a linear, simple cause-effect relationships, (2) they generally assume a causation model and attempt to explain an accident investigation based on the model, and (3) they strive to look for a root cause and tend to neglect other possible causes once a root cause is found. In addition, the following three more points can also be regarded as the limitations of traditional approaches: (4) they try to understand an accident with a pre-specified set of causal factors linked to a presumed causation model, (5) they have a stance that all adverse outcomes have their unique, respective causes, and (6) they are inclined to seek human errors and regard them as root causes (Hollnagel 2012; 2014; Hollnagel et al. 2013; Shorrock et al. 2014).

In spite of those drawbacks, it is sure that traditional approaches can still be effectively used for accident investigation in many cases. However, the new safety paradigm pointed out that there are increasing number of accidents in modern complex systems, which cannot be effectively investigated by the use of traditional approaches because of their shortcomings (Shirali et al. 2016). Therefore, in order to supplement the shortcomings, it presents a different way of looking at safety and accidents. It defines safety as the condition where the number of successful outcomes is as high as possible. With this viewpoint in mind, the new safety paradigm emphasizes the following alternative viewpoints: (1) an accident analysis method should admit that an accident cannot be explained by linear, simple cause-effect relationships, (2) an accident needs to be investigated without too much relying on an accident causation model, (3) an accident is not so simple that it can be sufficiently explained only with a root-cause, (4) it should be acknowledged that the currently assumed set of causal factors may not be actual causes of the accident and that other contextual factors assumed not to be problematic may be actual causes, (5) the causes of successful outcomes and adverse outcomes are not different but the same, and (6) an accident analysis method should focus on the performance variability in terms of resource demands and resources available in the situation of an accident, instead of human errors (Leonhardt et al. 2009; Hollnagel 2012; 2014; Hollnagel et al. 2013; Shorrock et al. 2014). These six alternative viewpoints correspond, in order, to the six drawbacks of traditional approaches above.

However, the last two points need to be explained in more detail. It is natural that people perceive current work demands and adjust their performance to meet the demands by actively looking for and using currently available resources (e.g. procedures, their knowledge and skills, and collaborators' knowledge and skills, etc.). This phenomenon is called performance adjustment or performance variability. It is inevitable and necessary for the safe operation of modern complex socio-technical systems (Besnard and Greathead 2003). An interesting point is that the result of such a performance adjustment can be successful or unsuccessful, depending on the given condition. It is thus reasonable to think that successful outcomes and adverse outcomes have the same origin. These two points are well reflected in FRAM that was developed in order to realize the concepts and principles of the new safety paradigm.

Here, we should keep in mind that the traditional approaches to accident investigation as well as the new safety paradigm are all needed to enhance system safety. An accident analysis method needs to make the most of advantages of both of them. It is therefore necessary to develop a method that can support the use of traditional approaches as well as help analysts escape from the limitations of traditional approaches. For this, based on the review of literatures, we summarized the twelve requirements that should be addressed in accident analysis methods (Table 6). Of those requirements, seven requirements (the sixth to the twelfth requirements) are based on the alternative viewpoints of the new safety paradigm, which are explained above. More specifically, the sixth to the eleventh requirements are in order related to the first to the sixth alternative viewpoints of the new safety paradigms, and the twelfth requirement is connected to the sixth alternative viewpoint.

However, the requirements of Table 6 can be regarded as evaluation criteria for accident analysis methods as well. We can discuss the characteristics and advantages of using the method proposed in this study, by taking account of these requirements. The rightmost column of Table 6 describes how and how well the proposed method dealt with these requirements. Although the proposed method does not fully address all of the requirements, we can claim that it has several good points and gives insights for developing a more advanced accident analysis method.

<Table 6. Requirements to be addressed in a method, and the way and the degree that the proposed method addressed>

No	Requirements to be addressed (in a method for accident analysis)	The way and the degree that the proposed method addressed
1	As an accident model or causation model underpinning a method makes accident analysis more efficient, a method should have a model that specifies a set of causal relations (Hollnagel 2012).	It employs a causation model underpinning HFACS. (Fully addressed)
2	In order to exhaustively describe accidents, the unit of analysis should be the entire complex sociotechnical systems (Svedung and Rasmussen 2002; Salmon et al. 2011).	Its scope of analysis is the same as that of HFACS, which covers most of the levels, excepting the higher levels beyond organization. (Partially addressed)
3	If a method offers a range of failure classifications, analysts can easily associate plausible causes for an accident being investigated with a set of causal factors (it would be beneficial in terms of efficiency of analysis) (Wiegmann and Shapell 2001; Hollnagel 2012).	It makes the most of failure classifications specified in HFACS. (Fully addressed)
4	A set of failure classifications (or causal factors) of a method should be defined on the basis of a sound theory or framework on human activities or human-related accidents (Ferjencik 2011; Yoon et al. 2016).	There is no grounded theory for the failure taxonomy of HFACS; AT may be served as a theoretical basis for this. However, this point was not studied well in this study. (Partially addressed)
5	A method should be scale invariant in order that it can be used for any scale of accidents, no matter what they are low-	The concepts and principles of AT can be used in the same way for each level of HFACS.

No	Requirements to be addressed (in a method for accident analysis)	The way and the degree that the proposed method addressed
	level failures or high-level failures (Hollnagel 2012).	(Fully addressed)
6	A method should allow accident analysts to admit that some accidents cannot be explained in terms of causality relationships between decomposed functions or components of a system in consideration (i.e. they are emergent, not resultant from causality) (Hollnagel et al. 2013; Shorrock et al. 2014).	Although it does not explicitly address the process of how an accident emerges, it fully admits that some accidents cannot be explained by cause-effect relationships. (Fully addressed)
7	As a causality model underlying a method generally restricts the use of a method, a method always looks at all accidents with a set of predefined assumptions and causality relationships of the model. To overcome this limitation, a method should not depend on a causality model too much (Leonhardt et al. 2009; Hollnagel 2014; 2016).	It uses the causation model of HFACS (the relationships between active failures and latent failures); however, it does not follow the causation model blindly. It assists analysts to identify other ways (not the causation model) for understanding an accident particularly through in-depth analysis based on AT. (Fully addressed)
8	A method should encourage accident analysts not to take a single root-cause approach and thus to identify as many likely causes as possible thoroughly (Lundberg et al. 2010; Ferjencik 2011; Hollnagel 2014).	HFACS and the AT-based method all do not follow a single root-cause approach; they encourage analysts to look for as many probable causes as possible. (Fully addressed)
9	The same manifested failures can happen with different causes and mechanisms. Thus a method should not make accident analysts to think by rote that the same manifested failures have the same causes and mechanisms (Lundbert et al. 2010).	This requirement is addressed in it; the AT-based approach claims that the same surface problems in preliminary analysis can be associated with different causal factors in in-depth analysis. (Fully addressed)
10	A method should reflect the idea that successful outcomes and unacceptable outcomes have the same origin; This means that a method should help accident analysts avoid their hindsight bias (Hollnagel 2014; Shorrock 2014; Patterson and Deutsch 2015).	In order to help analysts avoid hindsight, it enforces them to look for other probable causes by using AT. (Partially addressed)
11	A method should reflect the phenomenon that human workers always attempt to adjust their performance to meet current working demands by the use of available resources. In order to reflect this, a method should enable accident analysts to consider a meaningful set of contextual factors when examining an	Although it does not address the performance variability in a detailed manner, it enables analysts to consider a meaningful set of contextual factors systematically on the basis of human activity system models and their relevant contradictions. (Not addressed)

No	Requirements to be addressed (in a method for accident analysis)	The way and the degree that the proposed method addressed
	accident situation (Dekker 2002a; Hollnagel 2009; 2012; 2016; Woltjer et al. 2015).	
12	There may be other types of causes rather than human errors for explaining human-related accidents. Thus a method should not make accident analysts to think that identifying plausible human errors for an accident is the ultimate goal of accident analysis (Reason 1997; Hollnagel 2014).	HFACS and the AT-based method all have a stance that there are other types of failures, rather than human errors, which can be regarded as actual causes of an accident. (Fully addressed)

6. Concluding remarks

This study proposed a new approach for modelling and analysing human-related accidents by integrating HFACS and the AT-based approach. In this proposed method, the failure taxonomy and the scope of analysis in HFACS are usefully used for supplementing the limitations of the AT-based approach. Thus, the proposed method addressed most of the hierarchical levels of complex sociotechnical systems as a unit of analysis and provided a set of causal factors, enabling analysts to identify a plausible set of causal factors efficiently. However, the mechanical use of HFACS taxonomy without a systematic consideration of human activities and their contextual backgrounds makes it suffer from the drawbacks of traditional approaches to accident investigation. The concepts and principles of AT, which form the basis of the AT-based approach, can be usefully used for complementing the drawbacks. We can therefore say that the proposed method has the following advantages in accident investigation: (1) it encourages accident analysts to think that an accident can happen in various ways and thus to consider a human-related accident from multiple perspectives, (2) it helps accident analysts to look for as many different causal factors as possible without too much depending on a causality model and a predetermined set of causal factors, and (3) it encourages accident analysts to avoid sticking to the identified root cause and instead to look for other probable causes actively in consideration of human activities in a context. In this regard, it can be said that the proposed method shows the synergistic effects of HFACS and the AT-based approach, and that it has several promising features for realizing the concepts and principles of the new safety paradigm. With the features described above, the proposed method would be a useful method for safety practitioners working in the industry.

However, there are some points to consider in order to enhance the practicality of the proposed method. Firstly, it is worth considering the reliability and the validity of the proposed method, which are not well addressed in this paper. Reliability is concerned with random error; thus it refers to the consistency or dependability of a measurement and is concerned with the consistency of the results obtained from the measurement (Higgins and Starub 2004; Marczyk et al. 2005). Validity is related to systematic error; thus it refers to what the measurement measures and how well it does so (Higgins and Starub 2004; Marczyk et al. 2005). It seeks to answer the question: ‘‘does the measurement measure what is supposed to measure?’’ Accordingly, when an accident analysis method or model is developed, its reliability and validity need to be systematically examined. However, it is known that assessing them (particularly validity) can be a very difficult and overwhelming task (Wiegmann and Shappell 2003). For this reason, not too much work has been done to investigate them for accident analysis methods (Salmon et al. 2011). Nonetheless, checking the reliability and the validity of the proposed method can be an important process for securing its theoretical soundness and practicality.

There are different types of reliability and validity. However, interrater reliability and two types of validity (content validity and construct validity) would be the most meaningful to the method proposed in this study. Interrater reliability is used to determine the agreement between different judges when they observe or evaluate the performance of others. Therefore, for accident analysis methods, interrater reliability is used to assess the level of agreement between different analysts when they examine the same accident by using the method. Content validity generally evaluates the extent to which a measuring instrument covers a representative sample of the domain of behaviours to be measured (Jackson 2009). In the case of accident analysis methods, we can say that content validity refers to whether a method adequately covers the human-related accident domain to be measured. In other words, it measures how well a method captures a range of ways that a human-related accident can happen. Construct validity assesses the degree to which a measuring instrument accurately measures a theoretical construct or trait that it is designed to measure (Jackson 2009). When it is applied to accident analysis methods, it can refer to how well a method characterizes a human-related accident and identifies a plausible set of causes for the accident. There are several approaches for determining construct validity. However, these approaches focus on the extent to which the measurement of a certain construct converges or diverges with the measurement of similar or different constructs (Marczyk et al. 2005).

In the case of HFACS, there are several studies reporting its acceptable and high interrater reliability (Wiegmann and Shappell 2003). The proposed method recommends analysts to use the PSFs matching table when they investigate a human-related accident; this can be useful for reducing the disagreement between the causal factors discerned by analysts. However, the proposed method integrating HFACS and the AT-based method has not been yet tested empirically in terms of interrater reliability; thus it remains as an issue to be further studied. Regarding the content validity of the proposed method, we cannot say with a full confidence that the proposed method covers all of the ways that a human-related accident can happen. In addition, as HFACS taxonomy does not address the highest level (i.e. government and local authorities) in a socio-technical system hierarchy, it can be said that it does not have a full coverage for examining an accident in terms of a socio-technical system hierarchy. Nevertheless, it can be said that its content validity is not so low that its practicality is significantly threatened. This is because it helps accident analysts look for as many different plausible causal factors and their relationships as possible for an accident based on the comprehensive set of probable causal factors offered from HFACS, the PSFs matching table, and the models of activities related to the accident. Assessing the content validity of the proposed method empirically will be also a future research issue. When it comes to the construct validity, its assessment would be the most difficult at this time. Accident investigations using the proposed method that will be accumulated for a long time would give a reasonable indicator for the construct validity. However, HFACS was developed on a Reason's framework of accident causation and has been a popular method for accident analysis in several work domains; the AT-based method was also developed on a sound theoretical model about human activities in a context. In addition, the proposed method has several characteristics for supplementing the drawbacks of traditional approaches. Considering these points, we can cautiously say that the construct validity of the proposed method would not be so problematic.

Besides the issue of the reliability and validity, this study has some weak points to be noted and further studied. It is sure that the effective use of the proposed method requires analysts to understand several theoretical frameworks and concepts. In addition, one may think that it is not efficient for accident investigation because its use is too complex. However, considering the purposes of investigating accidents, we can say that accident investigation should be thorough at any cost, even if it takes much effort and time. Nonetheless, the development of more detailed procedure and guidance for using the proposed method would be a meaningful work for enhancing its practicality. The proposed method was not developed for a particular work domain, and its use does not need any work domain characteristics. Because the conceptual underpinnings of the proposed method can be applied to any work domain, it is expected that it would be used for any human-related accident in a complex system. However, HFACS was originally developed in aviation industry and most of the causal factors were developed to reflect the accident characteristics of aviation industry, and the probable causal factors of the PSFs matching table for using the AT-based method are not a complete set. Accordingly, it would be necessary to modify the causal factors of HFACS and supplement the PSFs matching table when applying the proposed method to a specific work domain. In association with this, it will be meaningful to develop more case studies in a range of work domains.

Appendix A. Linking between the elements of activity system model and performance shaping factors

This appendix describes the PSFs matching table which links the elements of activity system model and performance shaping factors to facilitate the effective use of the AT-based method. However, it should be noted that this is not a complete listing, rather an example of using the concepts of the AT-based method when identifying plausible causal factors.

Activity System Elements	Performance Shaping Factors (Examples)
Subject	▪ Personality (e.g., under-confidence, complacency, self-esteem) ▪ Mental states (e.g., mental fatigue, stress, inattention) ▪ Physical states (e.g., physical fatigue, illness)
Object	▪ Number of simultaneous goals ▪ Task characteristics (e.g., urgency, risk level, the time available) ▪ Systems or components to be handled for a task
Subject-Object	▪ Risk perception ▪ Domain expertise level (e.g., knowledge and skills for a job) ▪ Negative transfer of prior knowledge or skills
Tool	▪ (Some part of) usability of tools/equipment (e.g. visibility) ▪ Technical failures of tools/equipment ▪ Level of detail of procedures/documents ▪ Technical correctness of procedures/documents
Subject - Tool	▪ Knowledge and skills of using tools/equipment/procedures ▪ (Some part of) usability of tools/equipment (e.g. compatibility with user's expectation) ▪ Usability of procedures (e.g, readability, clarity)
Tool - Object	▪ Availability of tools/equipment/procedures ▪ (Some part of) usability of tools/equipment (e.g. task difficulty)
Community	▪ Leadership of supervisors ▪ Team composition
Subject - Community	▪ Delegation of authority ▪ Rewards and punishments
Community - Object	▪ The level of staffing and qualification ▪ Teamwork for a task ▪ Clearness in roles and responsibilities

Activity System Elements	Performance Shaping Factors (Examples)
Rule	▪ Work practices ▪ Adequacy of policy and guidance ▪ Organisational customs
Div. of labour	▪ Adequacy of coordination or communication ▪ Level of supervision
Subject - Rule	▪ Sense of responsibility ▪ Commitment to leadership
Community - Rule	▪ Team cohesiveness and collaboration ▪ Team or organizational climate
Object - Div. of labour	▪ Adequacy of distributed workload ▪ Gap between roles and capabilities
Community - Div. of labour	▪ Role awareness ▪ Gap between roles and preference (or motivation)
Subject - Another activity	▪ (Some part of) selection and placement ▪ Management of fitness-for-duty (e.g., drug, alcohol, fatigue) ▪ Adequacy of training
Tool - Another activity	▪ Design control of tools/equipment (e.g., requirement, V&V) ▪ Provision of required tools/equipment ▪ Management of technical documents
Object - Another activity	▪ Adequacy of work planning or control ▪ Adequacy of risk assessment
Community - Another activity	▪ (Some part of) selection and placement ▪ Crew resource management ▪ (Some part of) organizational change management (e.g., job rotation)
Rule - Another activity	▪ Adequacy of organisational culture assessment ▪ Adequacy of policy making process
Div. of labour - Another activity	▪ Adequacy of protocols or methods for communication and instruction ▪ (Some part of) organizational change management (e.g., division of responsibility)

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References

Akyuz E, Celik M (2015) Application of CREAM human reliability model to cargo loading process of LPG tankers. Journal of Loss Prevention in the Process Industries 34:39-48

Baysari MT, McIntosh AS, Wilson JR (2008) Understanding the human factors contribution to railway accidents and incidents in Australia. Accident Analysis & Prevention 40(5):1750-1757

Baysari MT, Caponecchia C, McIntosh AS, Wilson JR (2009) Classification of errors contributing to rail incidents and accidents: a comparison of two human error identification techniques. Safety Science 47(7):948-957

Bedny GZ, Harrix SR (2013) Safety and reliability analysis methods based on systemic-structural activity theory. In: Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, pp 549-556

Bertelsen OW, Bødker S (2003) Activity theory. In: Carroll JM (ed) HCI models, theories, and frameworks. Morgan Kaufmann Publishers, San Francisco, CA, pp 291-324

Besnard D, Greathead D (2003) A cognitive approach to safety violations. Cognition, Technology & Work 5(4):272-282

Chauvin C, Lardjane S, Morel G, Clostermann J-P, Langard B (2013) Human and organizational factors in maritime accidents: analysis of collisions at sea using the HFACS. Accident Analysis and Prevention 59:26-37

Chen S, Wall A, Davies P, Yang Z, Wang J, Chou Y (2013) A human and organizational factors (HOFs) analysis method for marine casualties using HFACS-Maritime Accidents (HFACS-MA). Safety Science 60:105–114

Cohen T, Wiegmann D, Shappell S (2015) Evaluating the reliability of the human factors analysis and classification system. Aviation, Space, and Environmental Medicine 86(8):728–735

Crawford K, Hasan H (2006) Demonstrations of the activity theory framework for research in information systems. Australian Journal of Information Systems 13(2):49-68

Dekker S (2002a) Reconstructing human contributions to accidents: the new view on error and performance. Journal of Safety Research 33(3):371-385

Dekker S (2002b) Field guide to human error investigations. Ashgate, Aldershot, UK

ElBardissi AW, Wiegmann DA, Dearani JA, Daley RC, Sundt TM (2007) Application of the human factors analysis and classification system methodology to the cardiovascular surgery operating room. The Annals of Thoracic Surgery 83(4): 1412–1419

Engeström Y (1987) Learning by expanding: an activity-theoretical approach to developmental research. Orienta-Konsultit, Helsinki

Ergai A, Cohen T, Sharp J, Wiegmann D, Gramopadhye A, Shappell S (2016) Assessment of the Human Factors Analysis and Classification System (HFACS): intra-rater and inter-rater reliability. Safety Science 82:393-398

Ferjencik M (2011) An integrated approach to the analysis of incident causes. Safety Science 49(6): 886-905

Gay G, Hembrooke H (2004) Activity-centred design: an ecological approach to designing smart tools and usable systems. The MIT Press, Cambridge, MA

Gedera DSP, Williams PJ (2013) Using activity theory to understand contradictions in an online university course facilitated by Moodle. International Journal of Information Technology and Computer Science 10(1):32-40

Harris D, Li WC (2011) An extension of the Human Factors Analysis and Classification System for use in open systems. Theoretical Issues in Ergonomics Science 12(2):108-128

Haslam RA, Hide SA, Gibb AGF, Gyi DE, Pavitt T, Atkinson S, Duff AR (2005) Contributing factors in construction accidents. Applied Ergonomics 36(4):401-415

Higgins PA, Starub AJ (2004) Understanding the error of our ways: mapping the concepts of validity and reliability. Nursing Outlook 54(1):23-29

Hendrick K, Benner L (1986) Investigating accidents with STEP. Marcel Dekker, New York, NY

Hollnagel E (1998) Cognitive reliability and error analysis method. Elsevier, Oxford, UK

Hollnagel E (2009) The ETTO principle: efficiency-thoroughness trade-off. Ashgate, Farnham, UK

Hollnagel E (2012) FRAM: the functional resonance analysis method, Ashgate, Farnham, UK

Hollnagel E, Leonhardt J, Licu T, Shorrock S (2013) From Safety-I to Safety-II: a white paper. european organization for the safety of air navigation (EUROCONTROL), Brussels, Belgium

Hollnagel E (2014) Safety-I and Safety-II: the past and future of safety management. Ashgate, Farnham, UK

Hollnagel E (2016) From Safety-I to Safety-II: a brief introduction to resilience engineering. http://safetysynthesis.com/onewebmedia/Introduction%20to%20S-I%20and%20S-II.pdf .Accessed 30 May 2016

Holt GR, Morris AW (1993) Activity theory and the analysis of organizations. Human Organization 52(1):97-109

INPO (1990) Human performance enhancement system (INPO 90-005). Institute of Nuclear Power Operations, Atlanta

Jackson SL (2009) Research methods and statistics: a critical thinking approach (3rd ed.). Wadsworth, Belmont, CA

Kain D, Wardle E (2014) Activity theory: an introduction for the writing classroom. In: Wardle E, Downs D (eds) Writing about writing: a college reader. 2nd edn. Bedford/St. Martin's, Boston, pp 273-283

Kaptelinin V, Nardi B, Macaulay C (1999) The activity checklist: a tool for representing the "space" of context. Interactions 6(4):27-39

Kaptelinin V, Nardi B (2006) Acting with technology: activity theory and interaction design. The MIT Press, Cambridge, MA

Khosla R, Damiani E, Grosky W (2003) Human-centred e-business. Kluwer Academic Publishers, Boston, MA

KINS (2014) Reactor trip and SI actuation by inadequate opening of M-G set breaker (No. PRI-14-03). Korea Institute of Nuclear Safety, Daejon, Korea

Kjellen U (2000) Prevention of accidents through experience feedback. Taylor & Francis, London, UK

Law EL-C, Sun X (2012) Evaluating user experience of adaptive digital educational games with activity theory. International Journal of Human-Computer Studies 70(7):478-497

Leonhardt J, Hollnagel E, Macchi L, Kirwan B (2009) A white paper on resilience engineering for ATM. european organization for the safety of air navigation (EUROCONTROL), Brussels, Belgium

Leont'ev AN (1978) Activity, consciousness, and personality. Prentice Hall, Englewood Cliffs, NJ

Leveson N (1995) Safeware: system safety and computers. Addison Wesley, Boston, MA.

Leveson N (2011) Engineering a safer world: systems thinking applied to safety. The MIT Press, Cambridge, MA.

Li WC, Harris D (2006) Pilot error and its relationship with higher organizational levels: HFACS analysis of 523 accidents. Aviation, Space, and Environmental Medicine 77(10):1056-1061

Lundberg J, Rollenhagen C, Hollnagel E (2010) What you find is not always what you fix-how other aspects than causes of accidents decide recommendations for remedial actions. Accident Analysis and Prevention 42(6):2132-2139

Marczyk G, DeMatteo D, Festinger D (2005) Essentials of research design and methodology. John Wiley & Sons, Hoboken, NJ
Martins LEG, Daltrini BM (1999) An approach to software requirements elicitation using precepts from activity theory. In: Proceedings of the 14th IEEE Conference on Automated Software Engineering, pp 15-23
Matthews T, Rattenbury T, Carter S (2007) Defining, designing, and evaluating peripheral displays: an analysis using activity theory. Human-Computer Interaction 22(1):221-261
Mitchell RJ, Williamson A, Molesworth B (2016) Application of a human factors classification framework for patient safety to identify precursor and contributing factors to adverse clinical incidents in hospital. Applied Ergonomics 52:185-195
Nardi BA (1996) Context and consciousness: activity theory and human-computer interaction. The MIT Press, Cambridge, MA
Niwa Y (2009) A proposal for a new accident analysis method and its application to a catastrophic railway accident in Japan. Cognition, Technology & Work 11(3):187-204
Nuutinen M, Norros L (2009) Core task analysis in accident investigation: analysis of maritime accidents in piloting situations. Cognition, Technology & Work 11(2):129-150
O'Connor P (2008) HFACS with an additional layer of granularity: validity and utility in accident analysis. Aviation, Space, and Environmental Medicine 79(6):599–606
O'Connor P, Walker P (2011) Evaluation of a human factors analysis and classification system as used by simulated mishap boards. Aviation, Space, and Environmental Medicine 82(1):44–48
Olsen NS, Shorrock ST (2010) Evaluation of the HFACS-ADF safety classification system: inter-coder consensus and intra-coder consistency. Accident Analysis and Prevention 42(2):437–444
Olsen NS (2011) Coding ATC incident data using HFACS: Inter-coder consensus. Safety Science 49(10):1365-1370
Patriarca R, Bergström J (2017) Modelling complexity in everyday operations: functional resonance in maritime mooring at quay. Cognition, Technology & Work (To appear)
Patterson JM, Shappell SA (2010) Operator error and system efficiencies: analysis of 508 mining incidents and accidents from Queensland, Australia using HFACS. Accident Analysis and Prevention 42:1379–1385
Patterson M, Deutsch ES (2015) Safety-I, safety-II and resilience engineering. Current Problems in Pediatric and Adolescent Health Care 45(12):382-389
Perrow C (1999) Normal accidents – living with high risk technologies. Princeton University Press, Princeton
Reason J (1997) Managing the risks of organizational accidents. Ashgate, Farnham, UK
Reason J (2008) The human contribution: unsafe acts, accidents and heroic recoveries. Ashgate, Farnham, UK
Reinach S, Viale A (2006) Application of a human error framework to conduct train accident/incident investigations. Accident Analysis and Prevention 38:396–406
Rogers Y (2004) New theoretical approaches for human-computer interaction. Annual Review of Information, Science and Technology 38:87-143
Roussou M, Oliver M, Slater M (2008) Exploring activity theory as a tool for evaluating interactivity and learning in virtual environments for children. Cognition, Technology & Work 10(2):141-153
Salmon PM, Stanton NA, Lenne M, Jenkins DP, Rafferty LA, Walker GH (2011) Human factors methods and accident analysis: practical guidance and case study applications. Ashgate, Farnham, UK
Salmon PM, Cornelissen M, Trotter MJ (2012) Systems-based accident analysis methods: a comparison of Accimap, HFACS, and STAMP. Safety Science 50(4):1158-1170

Shappell SA, Wiegmann DA (2000) The Human Factors Analysis and Classification System-HFACS (Technical Report No. DOT/FAA/AM-00/7). Office of Aerospace Medicine, Washington, DC

Shappell SA, Wiegmann DA (2006) Developing a methodology for assessing safety programs targeting human error in aviation (Technical Report No. DOT/FAA/AM-06-24). Office of Aerospace Medicine, Washington, DC

Shappell S, Detwiler C, Holcomb K, Hackworth C, Boquet A, Wiegmann D (2007) Human error and commercial aviation accidents: an analysis using the Human Factors Analysis and Classification System. Hum. Factors 49(2):227–242

Shin IJ (2014) Loss prevention at the startup stage in process safety management: From distributed cognition perspective with an accident case study. Journal of Loss Prevention in the Process Industries 27:99-113

Shirali GA, Motamedzade M, Mohammadfam I., Ebrahimipour V, Moghimbeigi A (2016) Assessment of resilience engineering factors based on system properties in a process industry 18(1):19-31

Shorrock S (2014) What Safety-II isn't. http://humanisticsystems.com/2014/06/08/what-safety-ii-isnt/ Accessed 20 May 2016

Shorrock S, Kirwan B (2002) Development and application of a human error identification tool for air traffic control. Applied Ergonomics 33:319-36

Shorrock S, Leonhardt J, Licu T, Peters C (2014) Systems thinking for safety: ten principles a white paper. European Organization for the Safety of Air Navigation (EUROCONTROL), Brussels, Belgium

Stanton NA, Salmon PM, Rafferty LA, Walker GH, Baber C, Jenkins DP (2013) Human factors methods: a practical guide for engineering and design. Ashgate, Farnham, UK

Sujan M-A, Rizzo A, Pasquini A (2000) Dependability evaluation: model and method based on activity theory. Lecture Notes in Computer Science 2000:406-419

Svedung I, Rasmussen J (2002) Graphic representation of accident scenarios: mapping system structure and the causation of accidents. Safety Science 40(5):397-417

Svenson O (2001) Accident and incident analysis based on the accident evolution and barrier function (AEB) model. Cognition, Technology & Work 3(1):42-52

Swain AD, Guttman HE (1983) Handbook of human reliability analysis with emphasis on nuclear power plant applications (NUREG/CR-1278). U.S. Nuclear Regulatory Commission, Washington, DC

Turner P, Turner S (2001) A web of contradictions. Interacting with Computers 14(1):1-14

Underwood P, Waterson P (2013) Systematic accident analysis: examining the gap between research and practice. Accident Analysis and Prevention 55:154-164

Underwood P, Waterson P (2014) Systems thinking, the Swiss cheese model and accident analysis: a comparative systemic analysis of the Grayrigg train derailment using the ATSB, Accimap and STAMP models. Accident Analysis and Prevention 68:75-94

Vygotsky L (1978) Mind in society: the development of higher psychological processes. Harvard University Press, Cambridge, MA.

Wiegmann DA, Shappell SA (2001) Human error analysis of commercial aviation accidents: application of the Human Factors Analysis and Classification System (HFACS). Aviation, Space, and Environmental Medicine 72:1006–1017

Wiegmann DA, Shappell SA (2003) A human error approach to aviation accident analysis: the Human Factors Analysis and Classification System. Ashgate, Farnham, UK

Woltjer R, Pinska-Chauvin E, Laursen T, Josefsson B (2015) Towards understanding work-as-done in air traffic management safety assessment and design. Reliability Engineering and System Safety 141:115-130

Woodcock K, Drury CG, Smiley A, Ma J (2005) Using simulated investigations for accident investigation studies. Applied Ergonomics 36(1):1-12

Woods DD, Dekker S, Cook R, Johannesen L, Sarter N (2010) Behind human error. 2nd ed. Ashgate, Aldershot, UK

Yoon YS, Ham D-H, Yoon, WC (2016) Application of activity theory to analysis of human-related accidents: method and case studies. Reliability Engineering and System Safety 150:22-34