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A new methodology for accident analysis with human and system interaction based on FRAM: Case studies in maritime domain

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ABSTRACT

In the maritime domain, a crew network is characterized by complex collaborative interactions for distributed decision making and rapid transactions of correct information to ensure maritime safety within a limited area and with limited resources. The interaction within the crew network determines the system performance, and the loss of interaction leads to maritime accidents with significant human, economic, and environmental losses. The interactions that occur within the collaborative crew network need to be reflected for system safety. Among systematic safety analysis methods, the safety-II-based functional resonance analysis method (FRAM) is very effective at evaluating the interaction of system functions under normal conditions. We propose a new methodology for accident analysis with human-system interaction (HSI) based on FRAM. To improve the resolution of interaction with crew network level, we defined the relationship between the system function analyzed by FRAM and the crew network as the link type between the function node and the crew node. HSI is analyzed descriptively using the defined HSI link type and graphically expressed. Through semi-quantification of the analysis, we tried to quantify the effect of HSI variability. As a result, this methodology enables to analyze the HSI variability that arises from the relationship between system and human, and to suggest critical part at the HSI level to support the discussion of strategy to manage variability. Two case studies were conducted to illuminate the importance of HSI analysis in the maritime domain.

1. Introduction

There are many latent human and organizational interactions behind technical causes of maritime accidents. For example, in the capsizing of the MV *Herald of Free Enterprise*, the technically apparent cause was the bow door being open. This caused the deck to be filled with water a few minutes after the voyage started, and the stability of the ship collapsed. However, there were multiple human and system interactions related to the technical cause (Department of Transport, 1987). In addition to this accident case, other maritime accidents cannot be simply explained by technological factors; technical, human, and organizational factors dynamically interact in a sociotechnical system. According to shipping accident data analysis, the rate of accidents due to human error was significantly reduced after 1998 ISM code enforcement (Tzannatos and Kokotos, 2009; Kokotos and Linardatos, 2011). However, in spite of regulation to manage the human error, we can still find that the number of accidents related to human is still present and interaction related to human need to be studied (Tzannatos and Kokotos, 2009; Kokotos and Linardatos, 2011; Batalden and Sydnes (2014); Berg, 2013).

In order to analyze the human and organizational factors related to maritime accidents, it is necessary to understand the characteristics of a crew network in the maritime domain. According to the European Maritime Safety Agency (EMSA), 67% of maritime accidents occur during onboard operations, where communication and teamwork are traditionally considered to be critical (EMSA, 2014; Grech et al., 2008). A crew network related to the operation is characterized by strict collaboration within the team to ensure safety during maritime operation with limited space, time, and resources (Grech et al., 2008). The operation also needs the rapid transaction and interaction of correct information. This can be considered a complex collaborative system that interacts with other agents (Stanton et al., 2006). The flow of information within interactions in collaborative system determines the performance of the system, and a loss of interaction can instantly lead to significant human, economic, and environmental losses in maritime domain.

To reflect the collaborative characteristics of the crew network in a maritime domain, maritime accidents and systems need to be addressed

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with the distributed situation awareness (DSA) concept in relation to the transactions and compatibility of information within complex collaborative systems. Stanton et al. (2006) introduced this concept to the maritime domain. Grech et al. (2002, 2008) showed in their analysis that 71% of human errors in marine accidents are related to situation awareness (SA) errors. In other words, the figure is based on Endsley's three-stage model of individual SA, it has limited applicability to dealing with the complex and collaborative nature of a crew network in a maritime domain (Endsley, 1995). Yoo (2016) pointed out the need to apply the DSA concept to marine systems and showed that, in accidents, not only individual SA errors but also DSA errors are associated with interactions between system functions.

Because a maritime system is sociotechnical in nature, the interactions of the crew network are closely related to the interactions with system functions. Thus, each interaction between human and system functions needs be considered together, not separately. Hollnagel (2012) proposed the functional resonance analysis method (FRAM), which is a systematic approach to analyze the interactions between functions in normal situations based on the concept of Safety-II. Unlike Safety-I, which focuses on eliminating errors or errors in the system, Safety-II takes the view that performance variability in system functions is inevitable and that the system should adapt to changing circumstances. According to FRAM, an accident occurs when the variability exceeds the acceptable range and resonates due to interactions between functions. Studies have also applied FRAM to maritime industry and accidents as one of the safety critical system, such as collision analysis (Yoo, 2016), the Blowout of Deepwater Horizon (Pereira et al., 2014), and the capsizing of the MV *Herald of Free Enterprise* (Praetorius et al., 2011). And, other studies have considered vessel traffic systems (Praetorius et al., 2015; Åhman, 2013). However, existing studies mainly focused only on the interactions of system functions.

In this study, we considered perspectives of system function and human to enhance safety in the maritime domain. The dynamic interaction between the system function and human was defined as HSI link types in the suggested method. Basically, this study based on philosophy of FRAM, and FRAM was used to explain the interaction of system functions and concept of variability. The method was extended to analyze collaborative interaction with human in more detail.

The paper is constructed as follows. The theoretical background and related researched of the proposed method is explained in Section 2. The proposed method is presented in Section 3. Section 4 presents the application of this method in two maritime accidents to consider HSI.

2. Theoretical concept and related researches

In the proposed HSI analysis method, the interaction analysis of the system functions is based on FRAM, and HSI are defined according to heterogeneous network theory. These underpinning theories are introduced here.

2.1. FRAM and related researches

2.1.1. Concept of FRAM

While existing safety assessment methods focus on what goes wrong, FRAM focuses on what goes right. It is based on the following principles. Because failure and success are equivalent, it is unreasonable to analyze safety by only focusing on failure. Because performance variability always exists in a sociotechnical system, approximate adjustment of the system is necessary. However, an emergent outcome may arise from a combination of interactions that exist for a short time in the system. The instantaneous interaction is explained by functional resonance, and FRAM is a way to describe the transition from a normal situation to functional resonance (Hollnagel, 2012). FRAM analyzes the system functions according to six aspects: input, output, precondition, resources, time, and control (Hollnagel, 2012).

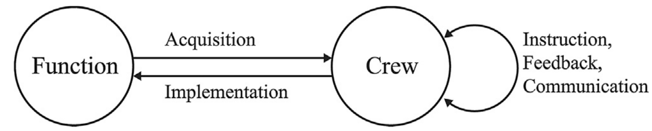

Fig. 1. Schema of HSI network.

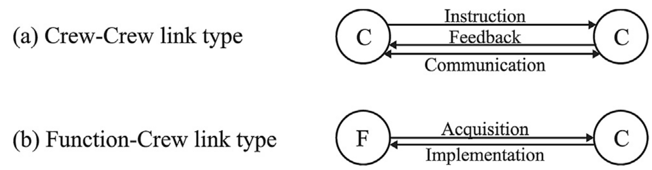

Fig. 2. Link types HSI network.

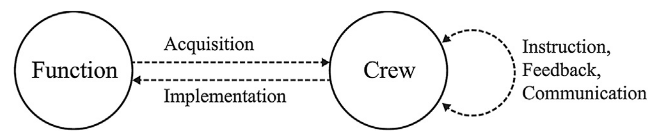

Fig. 3. Variability in links in HSI network.

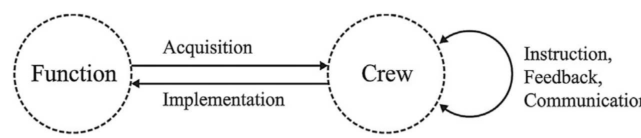

Fig. 4. Variability in nodes in HSI network.

Table 1
Table template to analyze HSI.

Function index	HSI link type	Related node	Description	HSI variability score
–	–	–	–	–

Table 2
Events during the capsizing of the MV *Herald of Free Enterprise*.

Time	Event
17:40	The *Herald* was trimmed by the head in order to load the E deck
17:40	That deck was completed before the G deck, and stripping of the No. 14 deep tank commenced
18:05	The *Herald* was manned by a crew of 80 hands
18:20	The *Herald* passed the inner breaker
18:23–18:24	The *Herald* passed the outer mole
18:24	Water entered through the bow door and flooded the G deck
18:28	The *Herald* capsized.

2.1.2. Related researches

There were researches to increase the analysis resolution of the interaction between human or organizational agent, which is the actual subject of system function interaction. Patriarca et al. (2017a) suggested an abstraction/agency hierarchy with FRAM to increase the resolution of the analysis according to different levels of abstraction among agents. Through a hierarchical analysis of the functions, the complexity of the system and relations with agents are expressed. However, from the viewpoint of more practical tasks and functions, it is necessary to analyze the interactions in crew network to reflect the organizational and complex collaborative characteristics of the interactions between functions and human. This is resolved through the suggested method.

There are studies to find critical interaction by quantifying the variability in FRAM analysis. Patriarca et al. (2017b, 2017c) identified a critical path in functional interactions by quantifying the variability

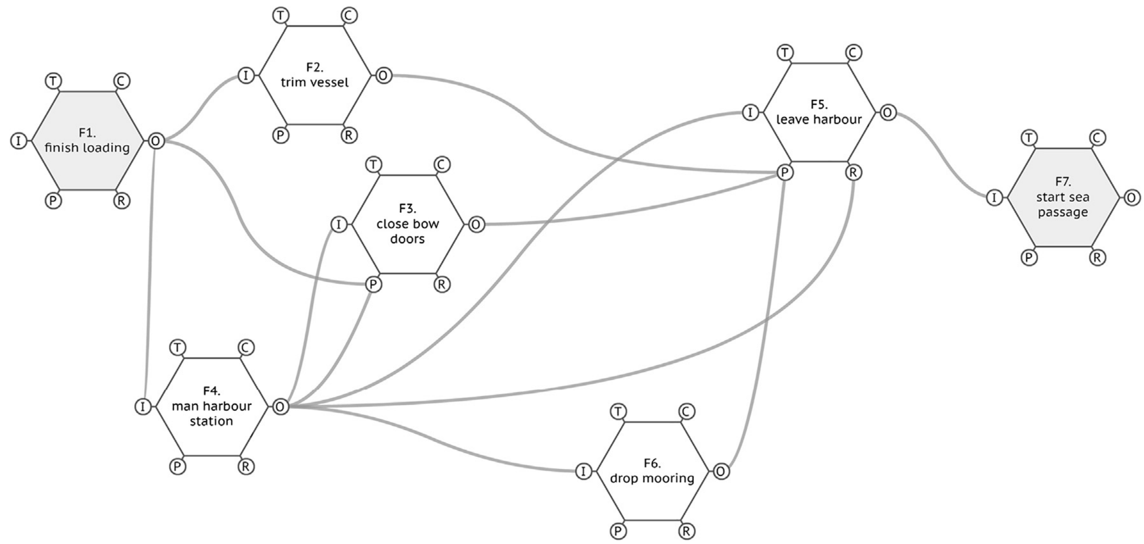

Fig. 5. FRAM model of case study 1 (Hollnagel, 2012).

Table 3
Analysis of HSI variability related to case study 1.

Function index (F_i)	HSI link type	Related node	Description	HSI variability score	Normalized HSI variability score of Function
F1	Implementation	F-C4	Boatswain (C4) implemented F1 completely	0	0.57
	Feedback	C4-C1	No feedback from boatswain (C4) to Master (C1) about overloading state	1	
	Acquisition	F-C2	Master (C1) did not acquire the data about the state of F1. Master (C1) completely trusted the implementation of boatswain (C4)	1	
	Implementation	C1-C2, C1-C3, C1-C4, C1-C5	Master (C1) gives “man harbor station” by announcement without confirm of the state	0.5 × 4	
F2	–	–	–	0	0
F3	Acquisition	F-C2	Chief officer (C2) vacated his work place.	1	1
	Implementation	F-C5	Assistant boatswain (C5) vacated his work place.	1	
	Feedback	C5-C2	Assistant boatswain (C5) did not report the state of the bow door.	1	
F4	Acquisition	F-C2	Chief officer (C2) did not supervise the state of loading crews.	1	0.5
	Implementation	F-C5	Assistant boatswain (C5) did not follow the announcement	1	
	Feedback	C5-C2	Assistant boatswain (C5) did not report his state.	1	
	Implementation	F-C2, F-C3, F-C4	Each Crew follow the announcement.	0 × 3	
F5	–	–	–	0	0
F6	Feedback	C2-C1	Chief officer (C2) did not report to Master (C1)	1	1
F7	–	–	–	0	0

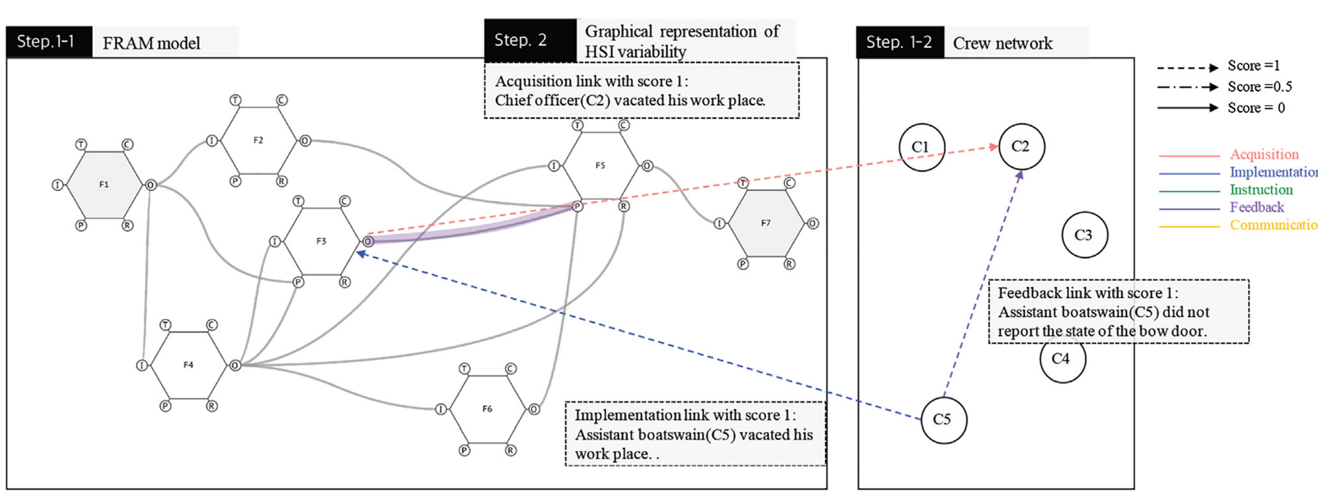

Fig. 6. Graphical representation of HSI variability related to F3.

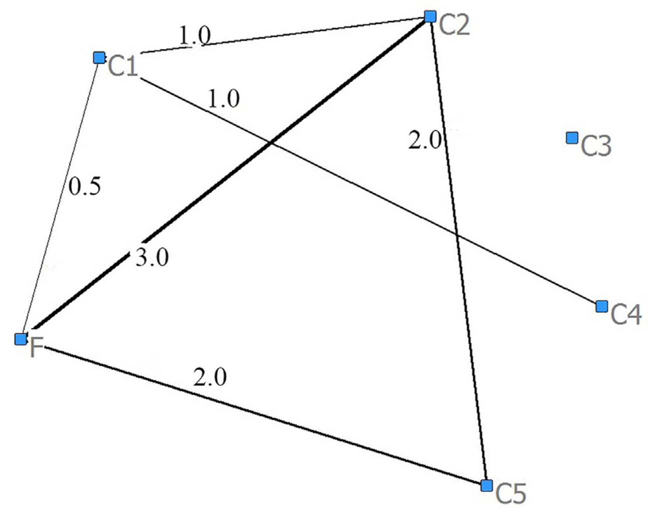

Fig. 7. Weighted graph with the accumulated score between nodes related to case study 1.

and changing the conditions in a Monte Carlo simulation. Those researches suggested the method to quantify output variability from the function and coupling variability between functions. These studies are related to the semi-quantification of the HSI criticality proposed in this study.

2.2. Concept of social network

The human and organizational interrelationships with the greatest performance variability as subjects of system functions appear to be similar to a social network. A social network comprises nodes, which are persons or groups, and links, which are the social interactions between nodes (Newman, 2010). An online social network service that expresses a user as a node and a friendship as a link is an example of a homogeneous network. In other words, a homogeneous network comprises one node type and one link type.

However, most of realistic problems have heterogeneity that are difficult to represent as a single type of node and link and if the system is assumed as a homogeneous network, important information may be lost (Sun and Han, 2012). For example, a bibliography network consists of 4 types of node, which are paper, author, terms, and venue. And, the network contains write/written by, mention/mentioned by, publish/published by, and cite/cited by. The heterogeneous networks have a particularly strong advantage in expressing real-world interactions between entities in different domains (Sun et al., 2012). The proposed HSI network in this paper can be defined as heterogeneous because the network need to represent the interactions between system and related human.

Heterogeneous networks are mathematically based on graph theory and are defined as follows.

> G = (V, E), where V is the node set and E is link set. The network schema is a meta-structure of the network and is denoted as TG = (A, R); this is a meta-template of network G with the type mapping function φ: $V \rightarrow A$ and link mapping function ψ: $E \rightarrow R$. Each object $v \in V$ belongs to one particular type $\varphi(v) \in A$, and each link $e \in E$ belongs to a particular link type or relation $\psi(e) \in R$ (Sun and Han, 2012).

3. Suggested method

3.1. Definition of HSI network

First, HSI is analyzed based on a model using FRAM, and the concept of HSI and analysis process are described in the following sections.

3.1.1. Node types in the network

Function nodes from FRAM model and crew nodes are connected by HSI links. There are two node types: system functions and crew. Generally, G = {V, E} denotes a network, where V is the set of nodes and E is the set of links. In the interaction network, V in G is denoted by $V = F \cup C$. When the total number of function nodes is denoted by *n* and the number of related human is denoted by *m*, F is the set of function nodes $F = \{F_1, F_2, \ldots, F_n\}$, and C is the set of crew nodes $C = \{C_1, C_2, \ldots, C_n\}$. E in G is denoted by $E = E_{ff} \cup E_{cc} \cup E_{fc}$, which indicates links within F, within C, and between F and C. Fig. 1 shows the schema of HSI network, which is denoted by SG = (T, R). T is the set of node types in G, where T = {Function, Crew}, and R is the set of link types in G.

3.1.2. Link types in the network

Fig. 2 shows the types of links between nodes, which are defined as R = {acquisition, implementation, instruction, feedback, communication}. Link types are classified into three major types considering collaboration between node types: interactions between functions, between crewmembers, and between functions and crewmembers. Interaction between function nodes are already analyzed by FRAM. And, between crewmembers, the link types of “instruction” and “feedback” reflects a one-sided relationship between crew and crew, while “communication” is a bidirectional link type. And the interaction between the specific function and the crew is defined as “acquisition”

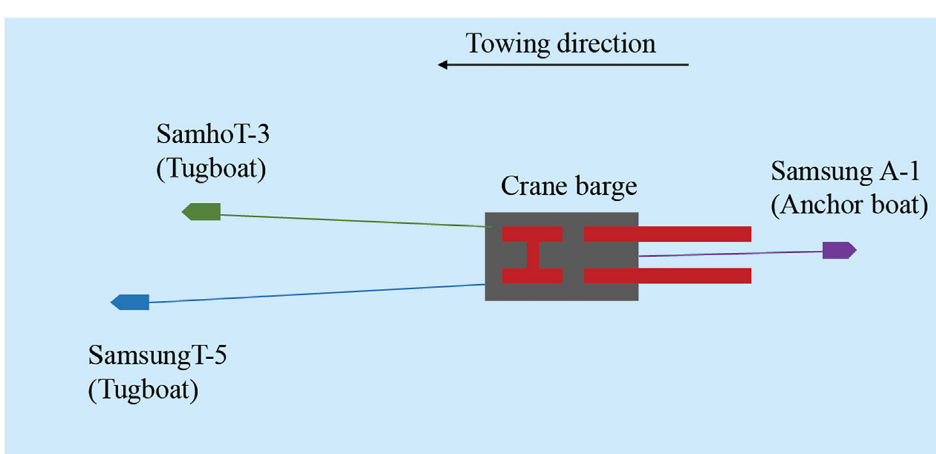

Fig. 8. Arrangement of the towing convoy (The Korean Maritime Safety Tribunal, 2008; The Hong Kong Special Administrative Region Marine Department, 2007).

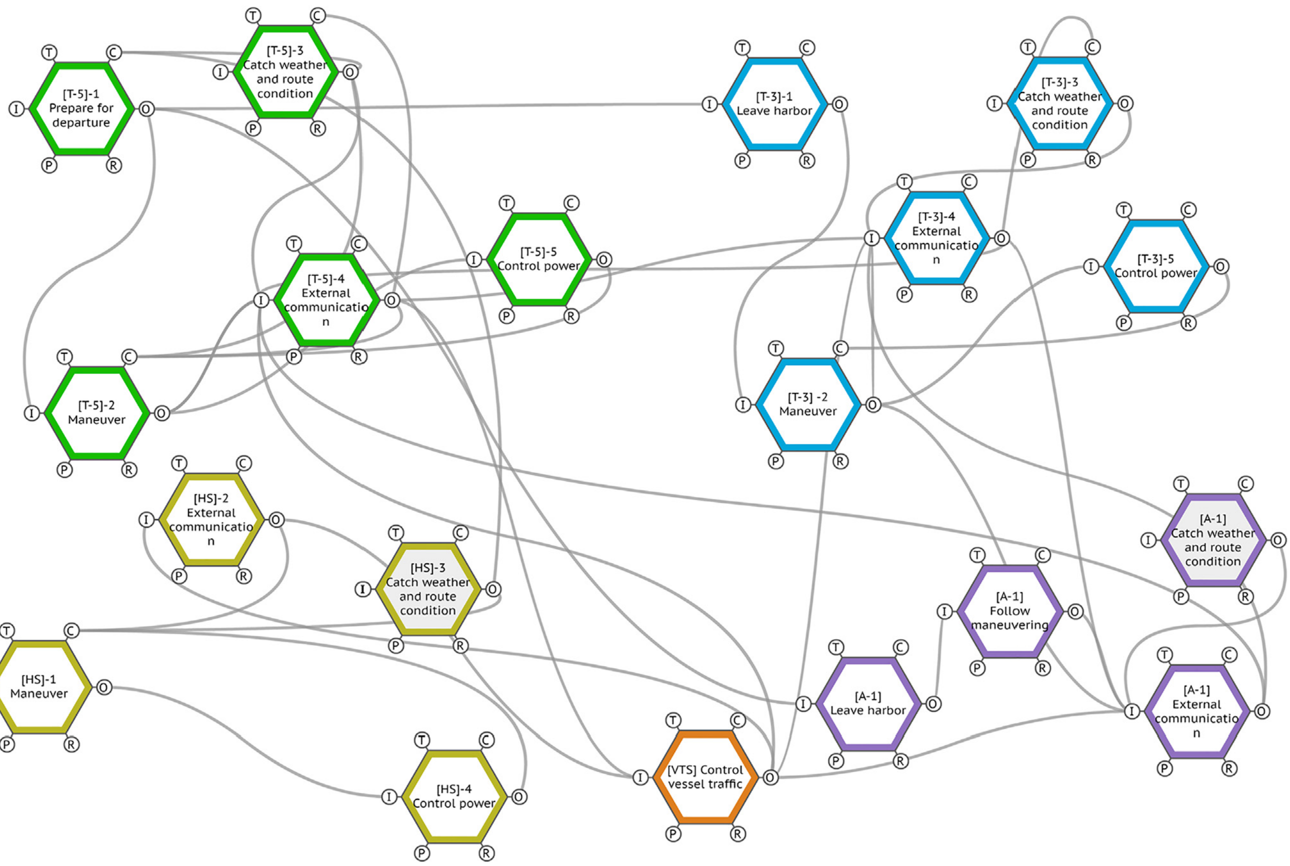

Fig. 9. FRAM model related to case study 2.

Table 4
List of functions related to T-5 and HS.

Function index	Function name	Function index	Function name
[T-5]-1	Prepare for departure	[HS]-1	Maneuver
[T-5]-2	Maneuver	[HS]-2	External communication
[T-5]-3	Catch weather and route condition	[HS]-3	Catch weather and route condition
[T-5]-4	External communication	[HS]-4	Control power
[T-5]-5	Control power		

which means check and supervising its performance status and "Implementation" which means that performing the function node.

The taxonomy of each link type is based on the DSA theory and we suggest link types as representative behaviors that are necessary for the transaction and compatibility of information. The DSA theory originated in the maritime domain and reflects the interaction between human agents and the characteristics of the target domain (Salmon et al., 2009).

3.2. Analysis of variability in HSI network

In the network, HSI variability is defined by the state of node and links. Fig. 3 shows the absence of a link in the network schema defined above. The variability of HSI link types in Fig. 3 can be taken into account when there is a variability in the performance of the link due to the absence of the node as shown in Fig. 4 and when there is a variability in the performance of the link even though the node is present. Also, the variability of the links associated with the crew node is directly related to the variability and absence of links between functional nodes. In other words, the variability of function nodes and the propagation in FRAM are related to the collaboration of the human composed of crew nodes and HSI links. In this paper, the variability associated with the HSI link type is defined as HSI variability. In addition, the HSI variability can be graphically represented with FRAM model and HSI links.

3.2.1. Descriptive analysis of HSI variability

The concept of HSI variability is analyzed according to the following table template (see Table 1). Function index refers to the *i*th function node from FRAM analysis. The HSI associated with the function is described and analyzed by HSI link type, related person, and description. The related node denotes the collaborative crews associated with the aspect of the forward function that is coupled with the output of that particular function as well as the resource aspect in FRAM.

3.2.2. Semi-quantification of HSI variability

The semi-quantification process for the HSI variability score in the above table is used to find the critical function and the HSI relationship that need improvement. The value of HSI variability score is expressed as a value between 0 and 1 depending on the degree of variability. A value of 1 means the absence of a link and includes the absence of the link because of the absence of the node and the case where the node was present but the link was absent. And, if the link exists but the variability was occurred in the aspect of timing and accuracy, 0.5 is defined as the intermediate value between 0 and 1.

3.2.3. Discussion for strategy to manage variability

These values are a measure of criticality in terms of HSI variability and it can be used for the strategy to manage variability. In order to derive a critical function node, we use the normalized HSI variability score of the specific function with mean value of HSI variability scores

Table 5
Analysis of HSI variability in [T-5]-3.

Function index	HSI link type	Related node	Description	HSI Variability score
[T-5]-2. Maneuver	Instruction	[T-5]Master-[T-5]Chief officer	Instruction about navigational watch from master under weather deterioration	1
	Feedback	[T-5]Chief officer-[T-5]Master	The chief officer reported late	0.5
	Implementation	[T-5]F-[T-5]Chief officer	The chief officer performed the navigating watch, but the officer did not aware danger	0.5
	Implementation	[T-5]Master	The master did not aware danger	0.5
[T-5]-3. Catch weather and route condition	Implementation	[T-5]F-[T-5]Master	Master did not check weather information	1
	Instruction	[T-5]Master-[T-5]Chief officer	Master did not give the instruction about weather consideration during the navigational watch	1
	Implementation	[T-5]F-[T-5]Chief officer	No weather consideration	1
	Feedback	[T-5]Chief officer-[T-5]Master	No report to the master about weather condition	1
	Communication	[T-5]Master-[T-3] Master	The master of T-3 did not share information about weather condition or give suggestion as one of the convoy.	1
	Communication	[T-5]Master-[A-1] Master	The fleet manager of A-1 did not share information about weather condition or give suggestion as one of the convoy	1

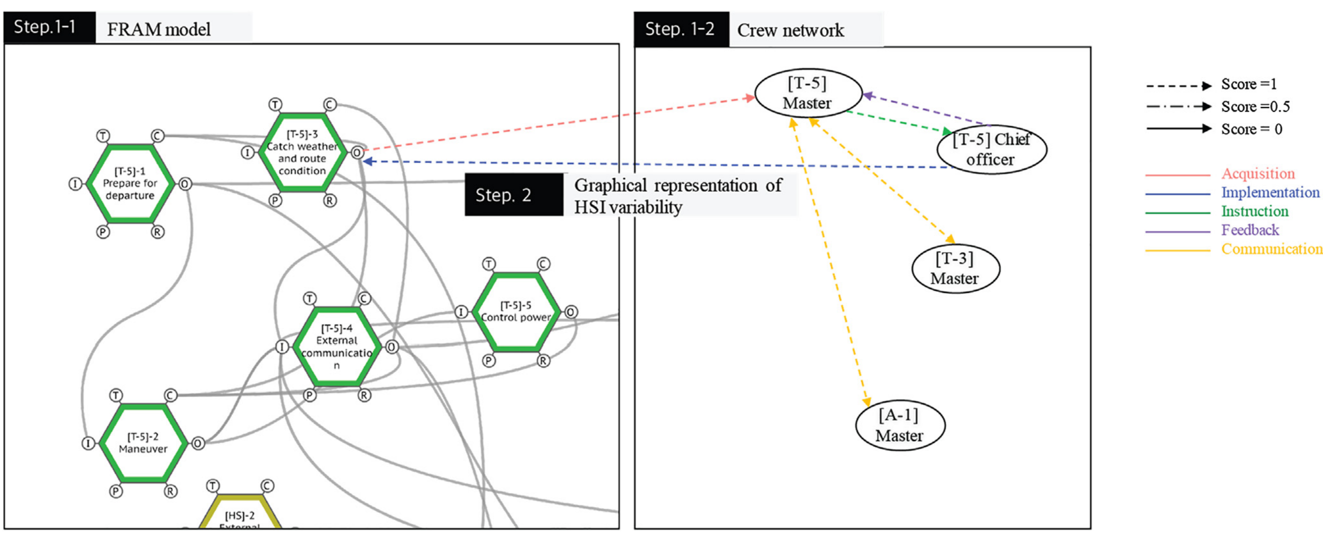

Fig. 10. Graphical representation of HSI variability related to [T-5]-3.

in a function. Moreover, the critical relation between nodes is derived by weighted graph with an accumulated HSI variability score between specific nodes. Based on the result of analysis, we will discuss strategies to manage variability.

4. Case studies

4.1. Case study1: Capsizing of the MV herald of free enterprise

On March 6, 1987, the Ro-Ro ferry departed from Port Zeeburge and capsized after a few minutes; this resulted in 193 casualties among the 495 passengers and 80 crewmembers. Table 2 presents the progress from departure to capsizing (Department of Transport, 1987). The vessel reached 18.9 kn in 90 s with an opened bow door through which seawater entered the deck. The ship tilted to the port side as it destabilized. According to Table 2, each step appears to occur in sequence. However, the accident investigation report describes the behavior of crewmembers related to the opened bow door. This allows us to recognize that the accident was not sequentially caused by the process described by Table 2 and can be explained by HSI.

4.1.1. Defining functions related to case study 1

Hollnagel (2012) used FRAM to evaluate the normal condition of the Ro-Ro ferry, which is visualized by FRAM Model visualizer (FMV) in Fig. 5.

4.1.2. Analysis of case study 1 using the suggested methodology

The mainly related human for performing functions are the master, chief officer, second officer, boatswain, assistant boatswain, and ship owner. They are referred to in turn as c1, c2, c3, c4, and c5.

The HSI variability related to FRAM model in Fig. 5 was analyzed in Table 3 using the table template. For example, three HSI links were related to F3, “Close bow door.” Among three links, node types F and C2 were related to “acquisition”, because C2 supervises and acquire data about F3 in normal condition. “implementation” between node types F and C5 and “feedback” from C5 to C2 was assigned to F3. However, there was HSI variability with missing of all links when the accident occurred. The “acquisition” link related to the C2 were missing because of his vacancy at bow door. Because of the absence of C5, the links corresponding to implementation and acquisition were missing. The HSI variability scores related to three missing are 1. And, the normalized HSI variability score of the function is 1 as the mean value of the three links.

The HSI variability related to F3 is graphically represented in Fig. 6, which includes steps to represent. First, the FRAM model and the crew network were set for represent HSI network in step 1-1 and step 1-2.

Table 6
Analysis of HSI variability related to HS-3.

Function index	HSI link type	Related node	Description	HSI variability score
[HS]-3. Catch weather and route condition	Acquisition	[HS]F-[HS]Master	Even under forecast warning, the master did not aware the weather and did not supervise	1
	Implementation	[HS]F-[HS]Chief officer	As the chief officer did not perform his anchor watch, the officer also did not aware the forecast warning	1
	Implementation	[HS]F-[HS]Apprentice officer	The apprentice was unqualified and unfamiliar to anchor watch. The officer worked, but could not the weather information or light indication from the convoy	0.5
	Feedback	[HS]Apprentice officer- [HS]Chief officer	The apprentice officer did not report the warning	1
	Feedback	[HS]Chief officer- [HS]Master	As the chief officer awarded the waring late and reported late	0.5

Next, if there exist specific HSI link between related nodes, the nodes are connected using specific type of line which is sorted by color and line style. Finally, the three missing HSI links are represented with colored and dashed lines which mean the score of 1.

From the value of normalized scores in Table 3 HSI variability is noticeable in F1, F3, and F4. In addition, the accumulated score between nodes are represented by the weighted graph as shown in the Fig. 7 using Unicet Netdraw ver.6.642 (Borgatti et al., 2002). From this result, it can be derived that the variability related to C2 and C5 is relatively high.

4.1.3. Discussion related to case study 1

From the analysis, it is pointed out that the cause of the accident is only by the opened bow door. In the FRAM analysis, we can see that the interaction with other functions is already related. Especially, through the proposed method, HSI related to human can be analyzed based on FRAM analysis. There were missing or incomplete HSI links related to the depart with the door being opened. Nevertheless, at that time, we could find situations in which the performance of the function seemed to be performed well without variability, because of the act of believing that someone should have done it instead without clear instruction.

We can discuss ways to improve the variability in terms of HSI. First, we can suggest the improvement of the crew network to back up the situation where the variability occurs, such as adding human nodes or creating links to dampen the HSI variability. For example, in the case of missing link of “acquisition” in F3, adding a HSI link with other crew can be discussed as a strategy to manage variability. For example, “Instruction” which directs from the chief officer (C2) to the second officer (C3) before C2 vacate his place, “implementation” of the second officer (C3), and “Feedback” from the second officer (C3) to the chief officer (C2) after the execution can be suggested.

It can be derived from the Fig. 7 that the relationship with C2 and C5 is relatively weak, and that the relationship has a strong influence on the propagation of the variability related to the accident situation. Therefore, it is possible to consider strategies to complement current human relations by arranging personal relationships that can back up C2 and C5 in terms of human network.

4.2. Case study 2: Collision of MT Hebei spirit

On December 7, 2007 at 07:00 local time, the collision between Korean crane barge and Hong Kong registered very large crude oil carrier (VLCC) resulting in about 10,900 tons of oil spill Accident was occurred (The Korean Maritime Safety Tribunal, 2008; The Hong Kong Special Administrative Region Marine Department, 2007). As shown in Fig. 8, the crane barge was towed by Tugs Samsung T-5 and Samho T-3, and anchor boat Samsung A-1 followed by the end of barge. The merchant tank (MT) Hebei Spirit (HS) was anchored in Daesan, about 10 km from the Korean coast line at that time (The Korean Maritime Safety Tribunal, 2008; The Hong Kong Special Administrative Region Marine Department, 2007). This accident, which is recorded as the worst oil spill in Korea, is divided into collision and oil spill. In this study, we analyze the collision before oil spill as the scope of analysis.

4.2.1. Defining functions related to case study 2

Prior to analyzing the HSI using the method proposed in this study, we define the functions in normal situation of each ship using FRAM as shown in Fig. 9. In the case of maritime accidents, there are cases of accidents in a single system of ship like case study 1, and there are also many cases in which multiple systems are involved in a complex manner, as in case study 2.

When each ship systems are approaching within a certain distance, they may collaborate through temporary direct communication or through intermediary system such as Vessel Traffic System (VTS). Case Study 2 analyzes the main towing vessels T-5 and HS, and its functions are listed in Table 4. Some functions of each ship refer to FRAM analysis

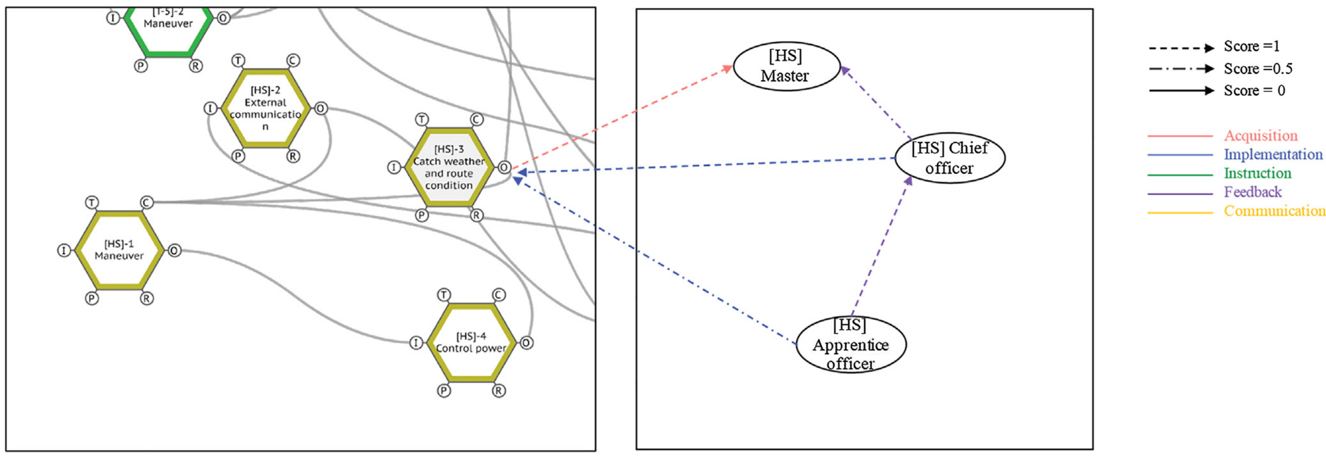

Fig. 11. Graphical representation of HSI variability related to [HS]-3.

Table 7
Normalized HSI variability score of functions related to T-5 and HS.

Function index	Function name	Normalized HSI variability score of Function	Function index	Function name	Normalized HSI variability score of Function
[T-5]-1	Prepare for departure	0.75	[HS]-1	Prepare for departure	0.5
[T-5]-2	Maneuver	0.63	[HS]-2	Maneuver	0.83
[T-5]-3	Catch weather and route condition	1	[HS]-3	Catch weather and route condition	0.8
[T-5]-4	External communication	0.94	[HS]-4	External communication	0.5
[T-5]-5	Control power	0			

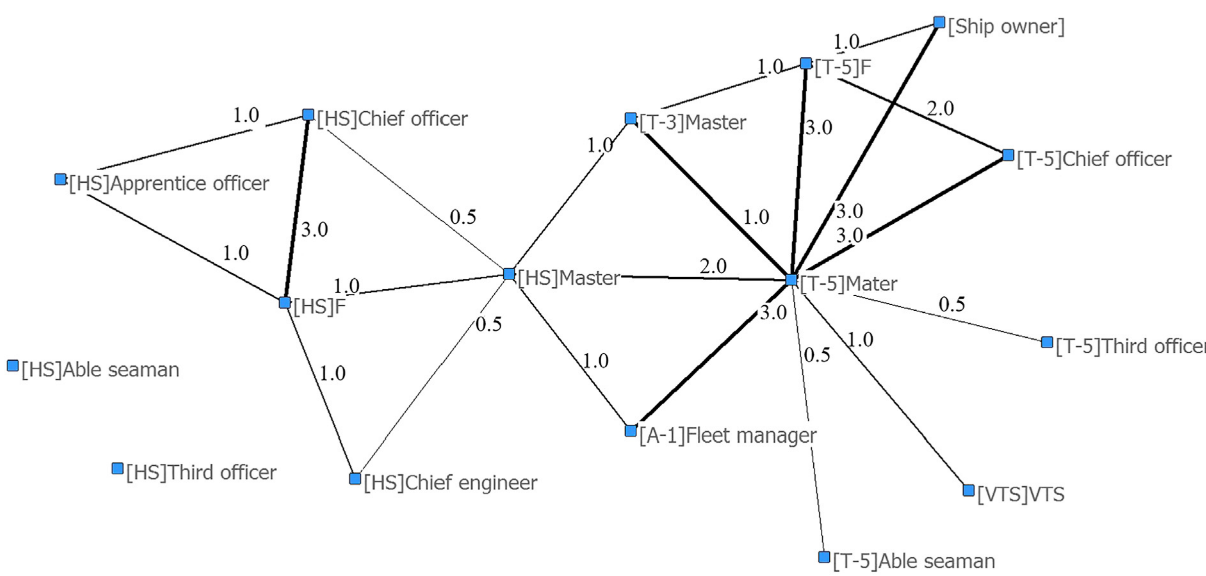

Fig. 12. Graph with variability weight among nodes related to case study 2.

of Yoo (2016)'s ship system in normal operating condition. The HSI analysis for T-5 and HS is given in the next section.

4.2.2. Analysis of case study 2 using the suggested methodology

In this section, examples of HSI analysis is described in Table 5. For example, the function with index [T-5]-3 includes six HSI links. The master of T-5 and the chief officer of T-5 have "Implementation" link because they need to know weather information during normal condition. Due to the nature of the maritime operation that takes place 24 h a day, the chief officer was allocated for night shift, so the "Instruction" link for the operation and the "Feedback" link to report the abnormal situation are defined. A fleet manager of A-1 and the master of T-3 of the convoy have "communication" link with the master of T-3 and they can be communicated about weather condition at any time.

Table 5 contains HSI variability such as the absence of the link and the incomplete existence of link occurred. Related to [T-5]-3, each HSI variability is related to the absence of link, and the variability has a value of 1. In [T-5]-2, the incomplete link occurred by late "feedback", and the value of variability score is 0.5. Then, in order to intuitively understand the HSI variability of [T-5]-3, it is graphically represented in Fig. 10 with step indication.

The example of HSI variability related to HS is analyzed in Table 6. The HSI links with the master of HS, chief officer of HS and apprentice officer of HS were associated [HS]-3. The chief officer of HS and the apprentice officer of HS had duties to perform function, which was defined as “Implementation”. However, there was no “implementation” by leaving of the chief officer, and the “feedback” from chief officer to the master was done late. Although the apprentice officer kept his place and performed the duty, there was a variability in terms of accuracy due to lack of practical experience. In other words, the apprentice officer could not recognize the degree of danger even when the officer observed the situation. The HSI variability is graphically represented in Fig. 11

In Table 7, it is possible to judge the critical function in terms of HSI quantitatively. In the case of T-5, the normalized score of HSI variability is relatively high in [T-5]-4, [T-5]-1 and [T-5]-3. In the case of HS, HS had significant HSI variability in the [HS]-2 and [HS]-3.

In addition, the accumulated variability scores between nodes related to T-5 and HS are represented with a weighted graph in Fig. 12 using Unicet Netdraw ver.6.642 (Borgatti et al., 2002).

4.2.3. Discussion related to case study 2

From the analysis, it can be found out that a number of HSI are involved in the severed tow wiring due to weather deterioration and collision. For example, in the function of [T-5]-1, the process of examining the wire in preparation for departure had variability in terms of HSI at that time, but the test results were passed without pointing out any controversial issues. Although there seems to be no direct temporal and spatial connection to severed wire and collision, the analysis shows that there is significant impact on HSI before departure. In addition to that, there was noticeable HSI relation among systems including not only internal towing convoy but also HS.

From Fig. 12, we can find the critical relationships where the variability is relatively high. It is weak in relation to multiple systems as well as the relationship within a ship system, such as the relationship between T-5, T-3, A-1 and HS. Also, on the node side, it can be derived that a particular node tends to be connected in multiple directions to another node. It means that the crew node corresponds to the significant position where variability can be amplified or damped. Thus, in terms of human networks, it is possible to consider strategies in which an expert should be assigned to the position of the node or an expert should accompany the node.

5. Conclusion

Based on FRAM, we proposed a methodology to analyze collaboration by using link types. In addition, the variability in FRAM is analyzed in terms of HSI related to functions. Analysis results considering HSI could contribute to discuss the damping strategies to improve collaborative links that are absent or improperly performed on the HSI. For example, plans to improve through adding nodes or adding links can be considered as a strategy. Through the two case studies of marine accidents, it was found that not only the HSI in the shipboard system but also the HSI between the multiple systems are important.

In addition, this study proposed a method to simply quantify HSI variability and analysis of criticality. Through the semi-quantification process, we found weak relationships and critical crew nodes or hub nodes which have significant position for variability amplification and damping. The criticality means that the current system and the human network are not sufficiently supporting the collaboration, so the system or the human network need to be improved to manage the variability. If the large scale of data collection about HSI is accumulated, it is possible to combine the suggested concept of HSI variability score with Patriarca (2017b)’s quantification and simulation of variability.

This method was suggested to address the need for analyzing the HSI in the maritime domain. Among FRAM's previous studies, there have been a number of cases where the theory has been applied to industries such as aviation, nuclear, and railway as safety critical systems such as Maritime domain (Sawaragi et al., 2006; Nouvel et al., 2007; Hollnagel et al., 2008; De Carvalho, 2011; Herrera and Woltjer, 2010; Lundblad et al., 2008; Hollnagel and Fujita, 2013; Patriarca et al., 2017a; Belmonte et al., 2011; Clay-Williams et al., 2015; Sujan and Felici, 2012). Therefore, this method has the potential to apply to other industries with reflecting their own complex collaborative interaction related to human network of particular industry.

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