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CONVERGENCE OF THE EPIDEMIOLOGICAL AND SYSTEMIC ACCIDENT MODELS

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ABSTRACT

Accident models are divided into three types: sequential, epidemiological, and systemic. The latter two are applicable to modern socio-technical systems, and can be identified based upon the how the idea of the model arose—either the existence of a cause-effect link, or systemic thinking. The Swiss cheese model (SCM), which represents the epidemiological accident model, has several disputable questions and has limited applicability in socio-technical systems. The purpose of this study is to find the similarities and differences between analytical methods by using two models to study a recent marine accident. The first is the risk management and quality management process approach (RMQMP) accident model, which solves the disputed SCM questions; the second is the Systems-Theoretic Accident Model and Processes (STAMP) model, which represents the systemic accident model. The findings show that the RMQMP model has the same analytical method concepts as the STAMP model; this indicates convergence of the epidemiological and systemic accident models, and paves the way for the model's application to fields where only the systemic accident model is currently used.

Keywords: Swiss cheese model, systemic accident model, STAMP, marine accidents, risk management

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1. **INTRODUCTION**

1.1 Background of the Accident Model

Hollnagel (2004) states that accident models are divided into three types: sequential, epidemiological, and systemic. The latter two models are applicable to accidents occurring in modern socio-technical systems. The Swiss cheese model (SCM), which represents the epidemiological accident models, was developed to explain every organisational accident (Reason 1997); however, several disputable questions existed: the characteristics of holes; the relationship between holes and latent conditions; and the reasons for the accident trajectory passing through aligned holes in layers of defences, barriers, and safeguards (Wiegmann and Shappell 2003, Dekker 2006, Reason, Hollnagel and Paries 2006). The author and co-author of this paper clarified the characteristics of holes and the relationship between holes and latent conditions by using a risk management and process approach established in quality management systems. This solved the questions relating to the SCM model, and allowed for the development of the accident model using the risk management and quality management process approach (RMQMP model) (Fukuoka 2016a, 2016b, Fukuoka and Furusho 2016). The Systems-Theoretic Accident Model and Processes (STAMP) model, which represents the systemic accident model developed in missile safety systems, can be applied to loss of satellites, friendly fire accidents, and bacterial contamination of a public water supply (Leveson 2011). The epidemiological accident model is applicable to accidents in the first classification quadrant; this category relates to marine transport, airways, rail transport, power grids, and dams. The systemic accident model is applicable to accidents in the second classification quadrant, which includes nuclear plants, nuclear weapon accidents, chemical plants, space missions, and aircraft. The epidemiological accident model can only be applied to the first quadrant, whereas the systemic accident model can be applied to both the first and second quadrants (Perrow 1999, Hollnagel and Speziali 2008).

A significant difference between the models is the existence of a cause-effect link. The epidemiological accident model has a link, but the systemic accident model does not, and accidents occur when coordination among the components comprising the system changes over time (Leveson 2011, Hollnagel 2004).

This paper aims to find the similarities and differences between the two types of accident models by applying them to a marine accident published by the United Kingdom Marine Accident Investigation Branch (MAIB). A sample report was selected that outlined the investigation into the capsizing and sinking of the cement carrier *Cemfjord* in the Pentland Firth, Scotland with the loss of all eight crew on 2nd and 3rd January 2015 (MAIB 2016). The choice was made at random from recent, very serious marine accidents in which local workplace and organisational factors needed to be included in the marine accident investigation reports; this was by provision of the Casualty Investigation Code (The International Maritime Organization 2008).

Although accident preventive measures or recommendations drawn from the analysis of each model are included in the analytical method as shown below in Sect. 2.1, this paper does not list them from the accident investigation report; this is because the purpose of this study is to clarify the similarities and differences in analytical methods between two types of accident models.

1.2 Synopsis of the Sample Accident

The accident investigation report concludes that the *Cemfjord* capsized in extraordinarily adverse sea and weather conditions; it also concludes that the conditions were predictable and could have been avoided by passage planning, and that the rapid nature of the capsize prevented the crew from sending a distress message or abandoning the vessel. It also determined that the *Cemfjord* proceeded to sea with significant safety regulation deficiencies, as a result of safety regulation exemptions approved by the flag state. The accident went unnoticed for twenty-five hours, when a passing ferry found the upturned hull of the *Cemfjord*; the delay occurred because the Shetland Coastguard, of the Maritime and Coastguard Agency, did not require an exit report when the vessel left the voluntary reporting scheme area in the Pentland Firth.

2. METHOD

2.1 Analytical Method

The accident investigation report into the capsizing and sinking of the cement carrier *Cemfjord* was analysed using processes in both the RMQMP and STAMP models.

The analysis process in the RMQMP model is as follows: (1) The definition of a hole is determined. This means that an unacceptable risk, as stated by ISO/IEC Guide 51 (ISO/IEC 1999), exists in an organisation or a local workplace. In this case, the vessel capsized; therefore, the hole opened when the vessel's stability was reduced to the extent that led to the capsize. (2) Locations of holes at a local workplace or an organisation are identified, using the risk management process or the plan-do-check-act (PDCA) cycle, respectively. To determine the locations of holes at a local workplace, the procedures for passage planning defined by Swift (1993) and IMO (2000) are used. (3) Latent conditions that caused the opening of holes and led to the accident are classified into 10 groups, in accordance with their definitions. The ten latent conditions are: passage planning, procedures, rules, human-machine interface, condition of equipment, environment, condition of operators, communication, teamwork, and management. Analyses of the locations of holes and latent conditions are conducted with all organisations related to the accident; for each organisation, latent conditions are written in a textual form in a table. (4) The locations of holes and related latent conditions are shown graphically. (5) Accident preventative measures are used to shut the holes. Each latent condition that caused the holes to open is rectified by implementing the methods of risk reduction stated in ISO/IEC Guide 51, and risk reduction is prioritised as follows: inherently safe design, protective devices, information for safety, additional protective devices, training, personal protective equipment and organisation (Fukuoka 2016a, 2016b, Fukuoka and Furusho 2016).

For the STAMP model, the analysis process is as follows: (1) The systems and hazards involved in the loss are identified. (2) The system safety constraints and system requirements relating to the hazards in the safety control structure are determined. (3) The loss at a physical system level is analysed. Factors contributing to ineffective physical and operational controls, physical failures, dysfunctional interactions, communication and coordination flaws, and unhandled disturbances are all considered. (4) At higher levels of the safety control structure, the inadequate control that led to the contributing factors is determined. Assignment of responsibilities and inadequate enforcement of assigned responsibilities, context and influences on the decision-making process, and flaws in the mental models of those making the decisions are all considered. (5) Coordination and communication related to the loss are examined, and dynamics and changes in the system and the safety control structure over time are determined. (6) Safety requirements and constraints, the context in which decisions are made, inadequate control actions, and mental model flaws are each described in textual form in a table of each component. Control channels and communication channels are described by arrows between the components that constitute the system. (7) Recommendations are generated. There is no algorithm for identifying the relative importance of recommendations (Leveson 2011).

In this case, the accident investigation report determined that, even if a distress alert from an emergency position indicating radio beacon (EPIRB) or a distress radio call from *Cemfjord* had been raised at the time of the capsize, the rapid nature of the capsize and ferocious sea conditions meant the outcome for the vessel and crew would almost certainly have been the same. Therefore, in this study, the analysis focused on factors that led to the capsize, and in both models, other factors were written in parentheses.

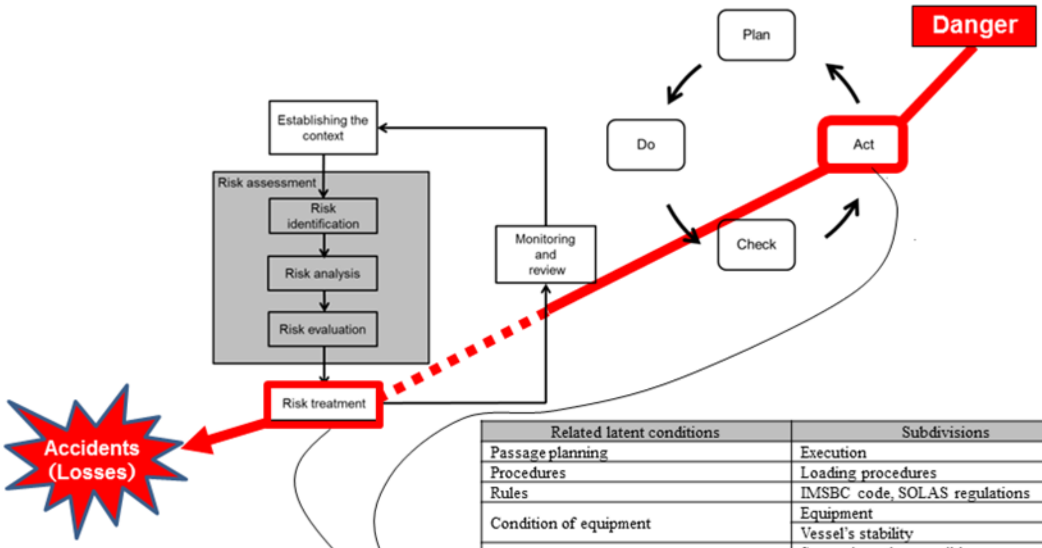
2.2 Limitations of Analysis

While the accident investigation report did not contain any organisational factors or local workplace factors, the study could not analyse holes or latent conditions in the RMQMP model; in the STAMP model, the study could not analyse safety requirements and constraints, the context in which decisions were made, inadequate control actions, or mental model flaws.

3. RESULTS

3.1 Analysis using the RMQMP model

Figure 1 illustrates the latent conditions derived from Table 1, and the locations of holes that opened at the local workplace, the *Cemfjord*, and the organisation (Brise Bereederungs GmbH). An operator or the master decided to proceed to the Pentland



Related latent conditions	Subdivisions
Passage planning	Execution
Procedures	Loading procedures
Rules	IMSBC code, SOLAS regulations
Condition of equipment	Equipment
	Vessel's stability
Environment	Sea and weather conditions
	Geographical features
Condition of operators	Physiological conditions
	Psychological limitations
	Individual workload management
	Experience
Communication	Communication among the crew
Management	Functional requirements of the ISM Code
	Maintenance management
	Resource management
	Communication with other organisations
	Organisation's environment
	Safety culture

Fig. 1 The RMQMP model for the *Cemfjord* and Brise Bereederungs GmbH, showing holes and latent conditions

Firth despite very poor conditions arising from a maximum westerly current being opposed by westerly gale force winds. Therefore, a hole opened either during the execution of the passage planning or the risk treatment during the risk management process. Brise Bereederungs GmbH did not take corrective action regarding passage planning, loading operations, or the vessel's stability after the investigation into a separate cargo shift incident occurred on 7th October 2014; they also failed to rectify the cargo hold bilge-pumping system. Instead, they repeatedly sought safety regulation exemptions from the flag state. A hole therefore opened during the 'act' process of the PDCA cycle. The hole that opened at the ship management company, Brise Bereederungs GmbH, was influenced by the way that the vessel's flag state, the Department of Merchant Shipping for the Republic of Cyprus (DMS Cyprus), approved the exemptions. Approvals were granted without understanding the nature of the work undertaken and the new level of risk caused by the work on board the *Cemfjord*. Because the accident investigation report did not describe in detail who at DMS Cyprus was responsible for conducting exemption risk assessments, the location of a hole on the part of an operator was not analysed; thus, the RMQMP model for DMS Cyprus, which could connect with the 'act' process of the RMQMP model for the *Cemfjord* and Brise Bereederungs GmbH, is not shown in Figure 1.

Table 1 Analysis using the RMQMP model for the *Cemfjord*, and Brise Bereederungs GmbH

	10 latent conditions	Subdivisions	Details of latent conditions which led to the accident
Local workplace	Passage planning	Stages of appraisal, planning, execution, and monitoring	Regarding the stage of execution, the Cemfjord approached the Pentland Firth at the worst possible time, with the maximum westerly current being opposed by westerly gale force winds. In this case, an alternative plan such as seeking shelter, slowing down, or diverting via the English Channel should be executed.
	Procedures	Procedures, manuals, checklists, station bills, standing orders, company rules, and others	The cargo was settled unevenly, deviating from the loading procedures because of list to port by about 5 degrees, which subsequently increased the risk of the cargo shifting in heavy sea.
	Rules	The convention on the international regulations for preventing collisions at sea, 1972, International convention on standards of training, certification and watchkeeping for seafarers, International convention for the safety of life at sea (SOLAS), local navigation rules, and others	The density of the cargo was not considered properly, resulting in parameters outside the international maritime solid bulk cargoes code (IMSBC code). Safety related shortcomings such as modification of life saving appliances (LSA) and defective bilge pumping system were exempted by the flag state. (Abandon ship procedures were not practiced.)
	Human-machine interface	Design of work stations, displays, controls and other factors that constitute a human-machine interface	
	Condition of equipment	Structure/machinery/equipment	Cargo hold bilge pumping system was defective. (A rescue boat could not be launched due to long lifting slings.) (Emergency position indicating radio beacon horizontally mounted on the bridge wing was not a float-free arrangement, resulting in it being trapped in the upturned hull.)
		Vessel's stability	The density value of the white cement was 1100 kg/m^3, and the vertical center of gravity was higher than the one in the loading manual; as a result, the IMO's minimum stability criteria were not satisfied.
	Environment	Sea and weather conditions	The Cemfjord approached the Pentland Firth with the maximum westerly current being opposed by westerly gale force winds, resulting in a shift in the cement cargo as she heeled beyond 30 degrees.
		Conditions people are working in	
		Traffic density	
		Geographical features	The Pentland Firth is a channel where mariners can encounter extensive and dangerous conditions.
		Berth facilities and other factors	
	Condition of operators	Physical or sensory limitations	
		Physiological conditions	Master and crew suffered fatigue or tiredness resulting from by cargo loading problems and deteriorating sea conditions.
		Psychological limitations	Master was under pressure due to the delayed departure from Rordal and further delays due to the weather in the North Sea.
		Individual workload management	Tight charterer's schedule prevented master and crew from taking time for routine maintenance.
		Knowledge, skill, experience, education/training	Recent master's experience of a near miss when the cargo shifted during a turn in heavy sea, led to his unwillingness to alter course.
	Communication	Communication among the bridge team, between a pilot and the bridge team, or between the bridge and vessel traffic services	There was no challenge against the master's operational decisions because of lack of experience of chief officer and crew.
	Teamwork	Roles and responsibilities of the crew, pilot, and other people involved in an accident	
Organisation	Management	Functional requirements of ISM Code regarding safe operation	Corrective actions regarding passage planning, loading operations and vessel's stability were not taken after the investigation into the cargo shift incident on 7th October 2014.
		Maintenance management	Rectifications of the LSA and cargo hold bilge pumping system were not taken; instead, safety regulation exemptions were repeatedly sought to the flag state.
		Emergency preparedness	(Specific abandon ship procedures were not established.)
		Resource management	A stability computer was absent. Lack of resource management was dominant because of the policy of running equipment until it failed.
		Communication with ship or within the organisation	
		Communication with other organisations (Flag states, recognized organisations, manning companies, etc.)	Misleading messages were given to the flag state and the recognized organisation regarding safety regulation exemptions by phone call or email.
		Organisation's environment	Commercial pressure existed, leading top management to seek safety regulation exemptions repeatedly.
		Safety culture (informed culture)	Lessons learned were not used.

Table 2 Analysis using the RMQMP model for the DMS Cyprus

10 latent conditions	Subdivisions	Details of latent conditions which related to the accident
Rules	SOLAS regulations	Cemfjord with safety regulation exemptions was allowed to proceed to sea with safety deficiencies relating to rescue boat launching arrangements and cargo hold bilge pumping system.
Management	Requirements of safety management system based on the quality management system	An effective mechanism to identify different opinions in the inspections between its surveyors and PSC officers was not established. Managing the exemptions was not established.
	Communication with Brise Bereederungs GmbH and Det Norske Veritas-Germanischer Lloyd	All communication was done by phone call or email, and the information passed was ambiguous and misleading concerning safety regulation exemptions.
	Organisation's environment	Global industry pressure existed, leading management to approve the safety regulation exemptions without a real understanding of the situation onboard.

Table 3 Analysis using the RMQMP model for the Shetland Coastguard

10 latent conditions	Subdivisions	Details of latent conditions which related to the accident
Procedures	Local procedures at Shetland Coastguard	(Exit reports from vessels were not required for the purpose of reducing levels of very high frequency (VHF) radio traffic.) (No alert system was established when the automatic identification system (AIS) transmission from a vessel ceased.)
Rules	SOLAS regulations, IMO resolutions	(The purpose of the voluntary reporting scheme was not defined.) (Distinctions between mandatory or voluntary reporting schemes were not offered.)
Condition of equipment	Maintenance of equipment	(The operation room data distribution system was faulty, and the AIS information was not displayed on the screen.)
Teamwork	Roles and responsibilities of the crew, pilot, and other people involved in an accident	(Watch officer was assigned the task of monitoring VHF radio traffic and responding to vessel's maritime reports, not monitoring vessel's progress.)
Management	Requirements of safety management system based on the quality management system	(It was not prepared for emergency situations, because no measures of identifying AIS transmission failures existed.)
	Organisation's environment	(IMO did not offer any distinction between 'mandatory' or 'voluntary' regarding ship reporting systems.)

Table 1 shows the latent conditions that led to the accident regarding *Cemfjord* and Brise Bereederungs GmbH. Tables 2 and 3 show latent conditions relating to the DMS Cyprus, and the Shetland Coastguard of the Maritime and Coastguard Agency. Holes and latent conditions for the organisations, Det Norske Veritas-Germanischer Lloyd, and Lloyd's Register were not analysed because these were not described in the accident investigation report.

3.2 Analysis using the STAMP model

For the *Cemfjord* accident, Table 4 shows each component that constitutes the system. The components were IMO, the DMS Cyprus, the Shetland Coastguard of the Maritime and Coastguard Agency, Det Norske Veritas-Germanischer Lloyd, Lloyd's Register, Brise Bereederungs GmbH, and the *Cemfjord*. The safety requirements and constraints violated, the context in which decisions were made, inadequate decisions and inadequate control actions, and mental model flaws in each component are described; some components are interrelated. The IMO establishes safety regulations, which are enforced by the flag states; the flag states ensure that the flagged vessels and ship management companies are following the regulations, both by themselves and through recognised organisations.

Table 4 Analysis using the STAMP model

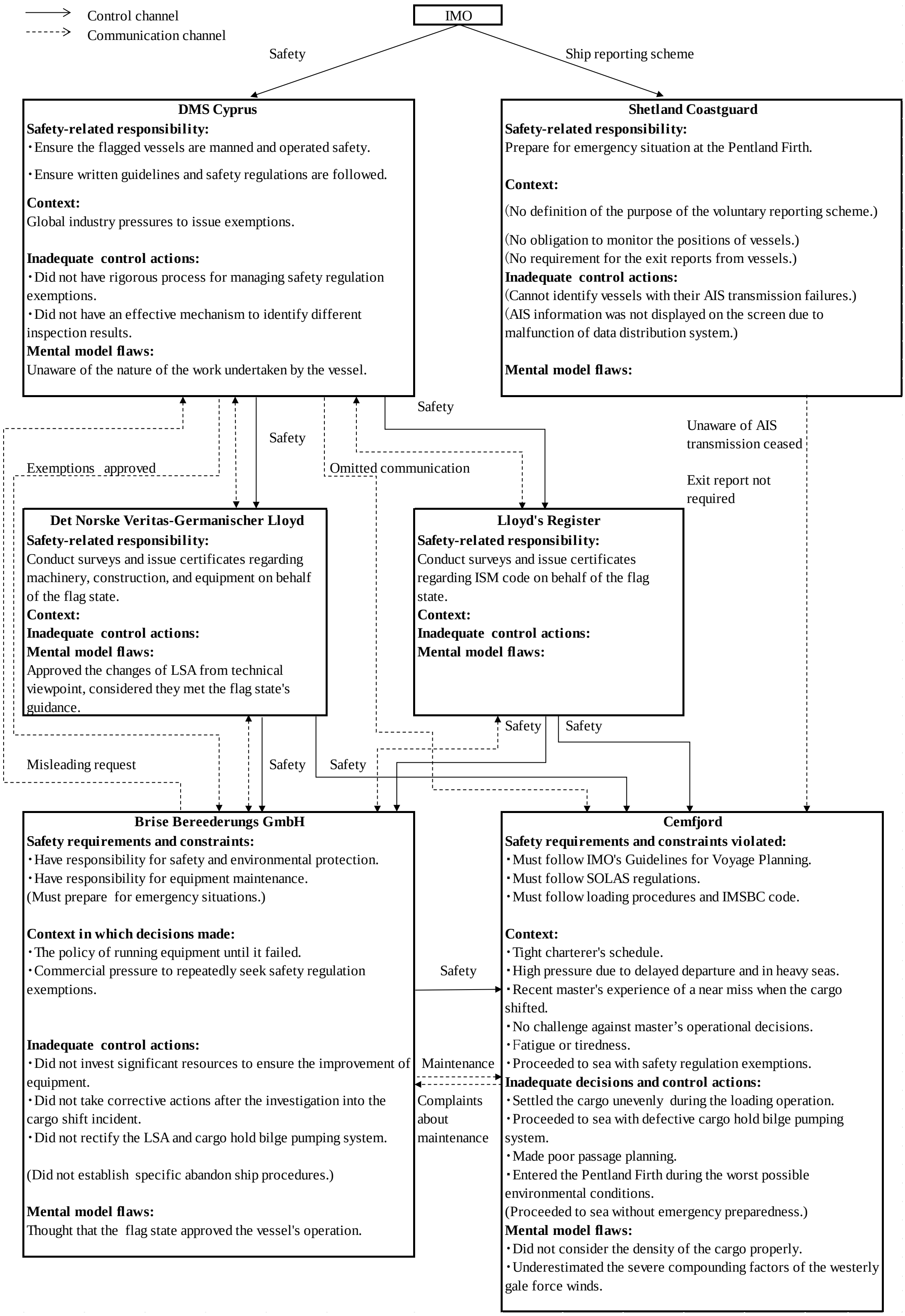


Table 4 illustrates that misleading requests for safety regulation exemptions on the *Cemfjord*, sought from Brise Bereederungs GmbH, were sent to the DMS Cyprus; those requests were not scrutinized within the DMS Cyprus and Det Norske Veritas-Germanischer Lloyd organisations. Furthermore, communication between the DMS Cyprus and the *Cemfjord* did not take place, and safety regulation exemptions were approved by the flag state without clarifying their ramifications. It also illustrates that the Shetland Coastguard did not require an exit report; therefore, the communication channel was unilateral, implying that it could not detect that the AIS transmission from the *Cemfjord* ceased while passing through the Pentland Firth.

4. DISCUSSION

The contents of Tables 1-3 are equivalent to those in Table 4, although the representation of the analysis is different. This means that results of the accident analyses by the two different types of accident models are the same. This finding is further supported when the analytical methods of the RMQMP and STAMP models are compared. Comparison of the analytical methods is as follows: (1) A hole on the RMQMP model is equal to the hazard involved in the loss on the STAMP model. (2) Local workplaces and organisations are identical in the components that constitute the system. (3) Risk management embedded at local workplaces, as well as the PDCA cycle embedded in organisations comprise the system safety constraints or controls in the STAMP model. (4) The safety management system or quality management system is the safety control structure in the STAMP model. (5) Ten latent conditions are equivalent to contributing factors to ineffective physical and operational controls, physical failures, dysfunctional interactions, communication and coordination flaws, unhandled disturbances, and so forth on the STAMP. The reason for this equivalency is that ten latent conditions are mostly drawn from the concept of the SHEL model (Hawkins 1987), which explains the interrelationship among five factors: software, hardware, environment, central liveware, and peripheral liveware. (6) The latent conditions of passage planning, procedures, and rules at local workplaces or those in organisation management structures mean that dynamics change in the system and in the safety control structures in the STAMP model over time.

Regarding representation of the system and the failure of system control, each model takes on a different style. (1) The RMQMP model can depict the whole system both in textual and graphic form by adding the risk management and safety management system defences of the organisations involved in the accident. In contrast, the STAMP model can depict the whole system, with control channels and communication channels in a single table. (2) The RMQMP model indicates the locations of unacceptable risk in the risk management and safety management system defences in graphic form. In the STAMP model, the location of risk is described within the inadequate decision and control action description in textual form.

Underwoods and Waterson (2013) stress the importance of the system-thinking approach in accident analysis in modern socio-technical systems. This approach includes the system structure, system component relationship, and system behaviour, which can be described as follows: the hierarchical level of the system and its boundaries are indicated in the system structure; all components and their interrelationship are considered in the system component relationship; the way that goals, resources and environmental conditions influence human behaviours are determined in the system behaviour. According to the comparison discussed above, both accident models include the system-thinking approach.

Accident models are divided into three categories, and each accident model has applicable fields based on the two dimensions of coupling and tractability (Hollnagel 2004, Hollnagel and Speziali 2008). The study found that the RMQMP model, which solved the disputable SCM questions, has the same analytical methods as the STAMP model, which is classified as a systemic accident model. This finding indicates the convergence of the epidemiological and systemic accident models, and paves the way for the practical application of the RMQMP model to fields where only the systemic accident model is currently applicable.

5. CONCLUSION

National marine accident investigation authorities collect evidence in accordance with the SHEL model, and analyse accidents by utilizing the SCM concept (Marine Accident Investigators' International Forum 2014). After studying 41 marine accident investigation reports, Schröder-Hinrichs et al. (2011) found that the reports did not provide sufficient analysis of organisational factors. Underwoods and Waterson (2013) concluded after comparison of the epidemiological and systemic accident models that the systemic accident model is not used by investigators or practitioners; the reason is that investigators have limited time for publishing reports, and it requires considerable time to investigate all aspects of past and current situations, for each component and contributing factor.

The paper describes the convergence of the epidemiological and systemic accident models. The RMQMP model, which was developed for marine accidents, includes organisational factors based on ISO 9001 and 9004, and can graphically present weaknesses of a system. It can assist investigators and practitioners with limited time by providing the areas in which they should investigate, analyse, and establish preventive measures. When the definition of latent conditions is modified to fit other fields—for example, the first and second quadrant defined by Perrow (1999)—it can also help those working in these fields. It can do this by providing guidance as to which directions should be followed, as long as risk management and safety management systems based on quality management systems are implemented in those fields.

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