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INFLUENCE OF HUMAN FACTORS ON THE OCCURRENCE OF ACCIDENTS

—Quantification of the influence of SHEL elements and latent conditions—

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ABSTRACT

National accident investigation authorities conducted an analysis of causal factors by using the Swiss cheese model as theoretical background after collecting evidence with the software-hardware-environment-liveware (SHEL) model in accordance with the Casualty Investigation Code adopted by the IMO. The Swiss cheese model posits that if latent conditions in a system are identified in advance it may be possible to take preventive measures before accidents take place. This research quantified the degree of influence of each element of SHEL or its latent conditions on the occurrence of accidents by conducting a multivariate analysis on statistical data attained from 89 cases of serious marine accidents.

Keywords: SHEL model, human factors, Swiss cheese model, accident prevention, marine accidents

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1. INTRODUCTION

Takemoto (2009) has argued that human factors are at work in about 90% of the causes of marine accidents, and Kuroda (1988) estimates that human factors account for more than 70% of the causes of aviation accidents. The importance of human factors has been stressed, but studies seldom consider the specific aspects of human factors that influence the occurrence of accidents.

The International Civil Aviation Organization (ICAO) (1993) created guidelines for the use of the software-hardware-environment-liveware (SHEL) model of accident investigation and analysis in response to the fact that human factors as causal agents in aviation incidents and accidents have increased in importance since the 1940s. The International Maritime Organization (IMO) (2000) made the same guidelines as ICAO did. National investigation authorities like the Japan Transport Safety Board (JTSB), the National Transportation Safety Board (NTSB) and others responsible for preventing accidents and mitigating damages use the SHEL model to collect all evidence of causal factors during investigation processes. From the exhaustive evidence collected, elements associated with the accidents are selected during the process of analysis of causal factors, which uses the Swiss cheese model as the theoretical background. Therefore, latent conditions in the Swiss cheese model are drawn up by using the SHEL model in marine accidents and aviation accidents.

Wiegmann and Shappell (2003) as well as Decker (2006) note that the location of the holes and the relationships between holes and latent conditions in the Swiss cheese model have not been well clarified, and as a result, the model cannot provide systemic measures for conducting accident analysis or prevention. To determine the locations of holes and their relationship with latent conditions toward the objective of reducing the number of marine accidents, the author and co-author (2016) visualized the location of holes on the Swiss cheese model, and then clarified the relationship between latent conditions and holes by analyzing 84 cases of serious marine accidents from accident investigation reports published by the JTSB. Ten latent conditions were defined based on the SHEL model and IMO/ILO processes in order to investigate human factors (IMO 2000) and other variables.

In this research to determine the influences of each element of the SHEL that underlie the occurrence of marine accidents, the authors conducted multivariate analysis of statistical data from 89 cases of serious marine accidents. The data were released by the JTSB from 2008 to 2015, which added 5 cases to the previous study.

2. METHOD

2.1 Selection of Samples

Organizational accidents have many causes involving many people at different levels, and the Swiss cheese model aims to provide a better understanding of these accidents (Reason 1997). All of the 89 serious marine accidents examined in this research are characterized as organizational accidents involving organizations such as a ship management company, a pilot association, a manufacturer of equipment, or a cargo-handling company.

This research addresses accidents that are defined as serious marine casualties by the Casualty Investigation Code and that result in the total loss of the vessel, death, or severe damage to the environment. The investigation report into a serious marine accident must contain detailed circumstances of the accident, analysis, and comments on the causal factors including mechanical, human and organizational factors (IMO 2008). To identify each element of the SHEL, the investigation reports must include all of these factors.

This study does not address marine incidents, which are events other than a marine accident that endanger the safety of the vessel, people or the environment if not corrected (IMO 2008). An incident differs from an accident with regard to the causal mechanism. In an accident, the defenses do not work, and loss or damage ensues, whereas in an incident, they do work (Underwood and Waterson 2013).

From 2008 to 2014, there were 6,974 marine accidents and 1,089 marine incidents involving 10,759 vessels, of which 5,083 were classified as other than fishing vessels, recreational fishing vessels, angler tender boats, pleasure boats, or personal water craft. Approximately 10% (508) of these 5,083 vessels were involved in marine incidents, according to JTSB (2015). Therefore, the remaining 4,575 vessels were considered to have been involved in organizational accidents. The 89 cases included in this study are regarded as a representative sample of such accidents with regard to the causal mechanism.

2.2Analytical Method

The causal factors of serious marine accidents were classified according to each element of the SHEL. Table 1 shows the relationship between each element of the SHEL and 10 latent conditions. The occurrence of accidents and each element of the SHEL have a cause and effect relationship; therefore, the number of vessels involved in a serious marine accident is regarded as the dependent or y variable, and each element of the SHEL as an independent or x variable.

In this research, x_1 represents software that addresses passage planning, procedures and rules; x_2 is hardware, which includes human-machine interfaces and conditions of equipment; x_3 is environment; x_4 is central liveware or L1; and x_5 is peripheral liveware or L2, which includes communication, teamwork, and management. Variable y represents the number of vessels involved in each type of accident. Variable n represents the number of each type of accident: collisions, contacts, grounding, occupational casualties, fires, explosions, sinking, and capsizing.

Multiple regression analysis was conducted on these statistical data using Excel Toukei 2015 for Windows.

Table 1 Elements of the SHEL and their mapping onto the 10 latent conditions

Element of the SHEL	10 latent conditions	Definitions
Software (S)	Passage planning	Stages of appraisal, planning, execution, and monitoring.
	Procedures	Manuals, checklists, station bills, standing orders of captains, and company rules.
	Rules	The Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREGs), International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, International Convention for the Safety of Life at Sea, and local navigation rules.
Hardware (H)	Human-machine interface	Design of work stations, displays, controls and other factors that constitute human-machine interface.
	Condition of equipment	Maintenance of ship and equipment.
Environment (E)	Environment	Sea and weather conditions, traffic density, geographical features of waters such as narrow channels, berth facilities and other factors that constitute conditions in which people are working.
Central Liveware (L1)	Condition of operators	Physical limitations, physiological conditions, psychological limitations, and individual workload management, as well as knowledge, skill, experience, education, and training.
Peripheral Liveware (L2)	Communication	Communication among the bridge team, between a pilot and the bridge team, or between the bridge and vessel traffic services.
	Teamwork	Roles and responsibilities of the crew, pilot, and other people involved in an accident.
	Management	Functional requirements related to accident prevention as prescribed in the ISM Code, resource management, and safety culture.

3. RESULTS

3.1 Multiple Regression Equation

Table 2 shows latent conditions by each type of accident, taken from the analysis of 89 cases of serious marine accidents.

Table 3 shows statistics on the number of vessels involved in accidents (as dependent variables) and elements of the SHEL (as independent variables). Table 4 shows the result of multiple regression analysis. The multiple regression equation, which was calculated using the data shown in Table 3, was as follows:

$$y = 0.428 + 0.514x_1 + 0.250x_2 + 0.051x_3 + 0.014x_4 + 0.125x_5$$

R^2 was 0.999 and adjusted R^2 was 0.999.

Table 2 Latent conditions by type of accident

Latent conditions	Collisions	Contact	Grounding	Occupational casualties	Fires	Explosions	Sinking	Capsizing	Total
Passage planning	15	8	9	4	0	0	1	2	39
Procedures	13	1	0	26	5	2	2	0	49
Rules	64	0	1	4	1	1	0	0	71
Human-machine interface	7	0	0	1	0	0	0	0	8
Conditions of equipment	3	1	4	7	3	1	3	0	22
Environment	46	7	10	15	1	2	2	2	85
Conditions of operators	64	6	8	13	2	2	1	1	97
Communication	28	3	7	7	1	0	0	1	47
Teamwork	19	2	4	10	0	0	0	0	35
Management	28	5	3	24	3	1	1	0	65
Total number of latent conditions by type of accident	287	33	46	111	16	9	10	6	518

Table 3 The number of vessels and elements of the SHEL

Types of accident	y	$S(x_1)$	$H(x_2)$	$E(x_3)$	$L1(x_4)$	$L2(x_5)$
Collisions	63	92	10	46	64	75
Contacts	7	9	1	7	6	10
Grounding	9	10	4	10	8	14
Occupational casualties	26	34	8	15	13	41
Fires	5	6	3	1	2	4
Explosions	2	3	1	2	2	1
Sinking	3	3	3	2	1	1
Capsizing	2	2	0	2	1	1

3.2 Hypothesis Testing of Multiple Regression Equation

The degrees of freedom were 5, and the multiple regression equation was significant at $p < 0.001$.

3.3 Influence of Elements of the SHEL on the Number of Vessels Involved in Accidents

The influence of independent variable on dependent variable is measured by the standardized partial regression coefficient. The most influential elements of the SHEL, in descending order, were: software (β = 0.755), peripheral liveware (β = 0.158), hardware (β = 0.042), environment (β = 0.036) and central liveware (β = 0.015).

Table 4 The result of multiple regression analysis

Independent variables	Partial regression coefficient	Standard error	Standardized partial regression coefficient
x_1	0.514	0.196	0.755
x_2	0.250	0.140	0.042
x_3	0.051	0.325	0.036
x_4	0.014	0.301	0.015
x_5	0.125	0.172	0.158
Intercept	0.428	0.556	

4. DISCUSSION

The most influential element of the SHEL on the number of vessels involved in accidents was software, and then peripheral liveware. The standardized partial regression coefficients of hardware, environment and central liveware were orders of magnitude smaller than those of software and peripheral liveware.

Chauvin et al. (2013) studied 39 vessels involved in cases of collisions and classified causal factors in accordance with the human factors analysis and classification system (HFACS), which was based on the Swiss cheese model. They concluded that decision errors and perceptual errors of operators accounted for 97% of operators' unsafe acts, and that the most frequent causal factors were communication with approaching vessels, bridge resource management (BRM), safety management systems and audits. Although the research of Chauvin et al. dealt with the cases of collisions only and the classification system of causal factors differed from those of our research, the observed importance of operators' decision errors and perceptual errors for collisions in their study meant that operators deviated from the rules or COLREGs defined in our research. Therefore, their results were consistent with ours in that software and peripheral liveware had a strong influence on the number of vessels involved in accidents.

Swift (2000) and Adam (2006) have stressed the importance of passage planning and BRM as causal factors in cases involving collisions and groundings, but they did not consider causal factors other than software and peripheral liveware. The present study objectively confirms the degree of importance of not only software and peripheral liveware but also hardware, environment, and central liveware in the number of vessels involved in accidents.

5. LIMITATIONS OF THE STUDY

There are two limitations of this study. First, some of the marine accident investigation reports did not include organizational factors. This research used the contents of the reports to classify the elements of the SHEL; therefore the findings, especially in relation to organizational factors, were not comprehensive, and the importance of peripheral liveware might have been underestimated. Chauvin et al. (2013) and Schroder-Hinrichs et al. (2011) pointed out that such organizational factors as safety culture and organizational climate were not included in accident investigation reports issued by national marine investigation authorities. This is an issue that national investigation authorities across the world face today.

Second, few cases involving fire, explosion, sinking, or capsizing were analyzed in this research, and the sample size in these cases was small. This might have had an effect on the results in relation to the elements of the SHEL and the accuracy of analysis.

6. CONCLUSION

The most influential elements of the SHEL on the number of vessels involved in accidents were, in descending order: software, peripheral liveware, hardware, environment and central liveware. Reason, Hollnagel, and Paries (2006) have noted that if the Swiss cheese model can identify latent conditions in a system in advance it may be possible to take preventive measures before the accidents take place. This research quantified the elements of the SHEL or latent conditions to which organizations and operators should devote attention and effort, and the insights gained should prove useful for the prevention of accidents.

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