Effective Measure for Accident Prevention Onboard Sea Vessels—Improvements on 4M4E Analysis

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Abstract: The 4M4E analysis is a type of root-cause analysis that can multilaterally pinpoint the trigger factors of an accident or disaster using its analytic capabilities and can clarify various countermeasures against each trigger factor. This study aims to reduce the number of vessel accidents and disasters involving seafarers by improving the practical use of 4M4E analysis. Vessel accidents or disasters involving seafarers, related to a mooring line, sometimes result in a fatality; therefore, this research area has attracted international attention. In consideration of this, we devised an analysis method for accidents involving a mooring line by adding prediction to the 4Ms of 4M4E, having first extracted the potential causes of an accident through brainstorming. The 4M4E+P analysis could obtain additional trigger factors that were not revealed in the 4M4E analysis. Thus, a measure of adopting these newly acquired trigger factors was evaluated. In addition, it is thought that 4M4E+P analysis can reduce the risk of vessel accidents and disasters involving seafarers.

Key words: Root-cause analysis, 4M4E analysis, 4M4E+P analysis, mooring line accident, trigger factor.

1. Introduction

According to the Japan Coast Guard, in 2019, there were 1,895 marine accidents, resulting in 63 people being declared dead or missing. Although the number of vessel accidents is decreasing every year, there were still ~2,000 of these accidents in the abovementioned year [1]. The rate of incidence of fatalities and injuries is also decreasing, although the rate of decrease has slowed down and appeared to level off in recent years [2]. Furthermore, marine workers are highly valued and outnumber land workers (in all industries) by approximately four times [3]. An accident involving a seafarer is problematic in that it results in the loss of both human resources and the regular operation of a vessel; vessels and their crew are mutually indispensable. Additionally, one of the reasons that the young do not choose a seafaring occupation is that it is considered much more dangerous than a land-based occupation.

Since an environment in which a seafarer feels comfortable and committed to is not fully ready, the unemployment rate is high [4]. The 4M4E analysis can multilaterally extract the trigger factors of an accident or disaster, using its analytic capabilities, and can clarify various countermeasures against each trigger factor. This study aims to reduce the number of vessel accidents and disasters involving seafarers, by improving the practical use of the 4M4E analysis.

2. 4M4E Analysis

The fundamental trigger factors or causes of an accident have been discovered and many methods for counteracting these have been devised. These techniques are called root-cause analyses (RCAs), and include 4M4E analysis, SHEL analysis, and why-why analysis. The 4M4E analysis can multilaterally pinpoint the trigger factors of human error and accident, and its analytical capabilities can consider countermeasures from a broad perspective. Furthermore, it is an easily-understood technique compared to other RCAs. Therefore, in this study, we

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applied 4M4E analysis to disasters involving seafarers and onboard-vessel accidents and decided to investigate how best to use this analytical technique effectively.

4M4E analysis is a technique used for analyzing accidents; it was devised by the U.S. National Transportation Safety Board. It has been adopted as an accident analysis technique even in the U.S. State National Aeronautics and Space Administration (NASA), as well as extensively in risk management worldwide [5]. Particularly, in Japan, the Japanese Railway (JR) East Japan has been able to improve its safety using 4M4E analysis [6]. Furthermore, 4M4E is used in medical institutions to analyze medical workers' errors and medical accidents during procedures [7].

With regard to accidents, when two or more errors occur and overlap, 4M4E analysis generates many scenarios. To extract the trigger factors of an error, the analysis is conducted from four viewpoints (the 4Ms): Man (person), Machine (equipment and machine), Media (environment), and Management (organization and management). Then, a countermeasure is considered for the trigger factors acquired from these four viewpoints (the 4Es): Education (education and

training), Engineering (technology), Enforcement (strengthening), and Example (model and example). Table 1 can be used to summarize these factors in the form of a matrix sheet.

Although what is set to Environment instead of Example (a model and an example) in 4E exists, in this study, the countermeasures relevant to Environment are assigned to Enforcement (strengthening) and Engineering (technology). Furthermore, there is a method of classifying communication into Man or Management. In this study, Media is defined as information or environment, and the trigger factors concerned with communication are also classified as Media. The flow of 4M4E analysis is shown in Fig. 1.

Man relates to factors involving people. As a concrete example, when an accident occurs, it can be due to insufficient knowledge, experience or skill, poor health, or inattention. **Machine** relates to factors involving machinery or equipment and defects thereof, or where an interface is not optimal, or it is hard to operate. **Media** relates to factors involving connection, information, and the related environment, and includes the weather, oceanographic phenomena, workplace environment, restriction of view, surrounding noise, and communication between involved persons.

Table 1   4M4E matrix sheet.

|	Trigger factor	Education	Engineering	Enforcement	Example
Man	The trigger factor in connection with man	Education and training in connection with man	The engineering countermeasures in connection with man	The strengthening measure in connection with man	The good example and the bad example in connection with man
Machine	The trigger factor in connection with a machine	Education and training in connection with a machine and equipment	The engineering countermeasures in connection with a machine and equipment	The strengthening measure in connection with a machine and equipment	The good example and the bad example in connection with a machine and equipment
Media	The trigger factor in connection with environment and information	Education and training in connection with environment and information	The engineering countermeasures in connection with environment and information	The strengthening measure in connection with environment and information	The good example and the bad example in connection with environment and information
Management	The trigger factor in connection with an organization and management	Education and training in connection with an organization and management	The engineering countermeasures in connection with an organization and management	The strengthening measure in connection with an organization and management	The good example and the bad example in connection with an organization and management
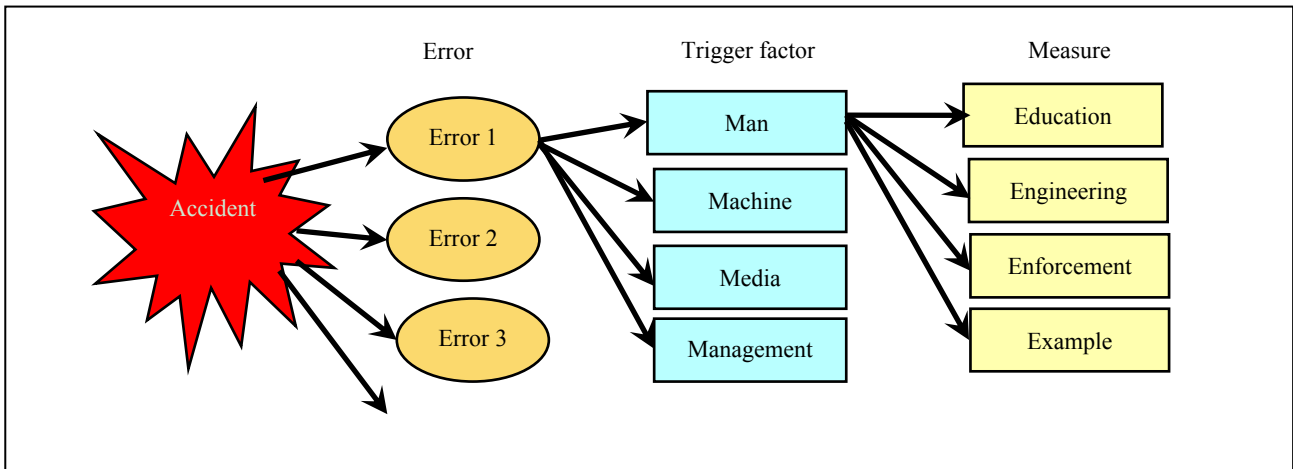
Fig. 1   The flow of 4M4E analysis.

Management relates to factors involving organization and management, whether instructions or signals are sufficient, defects in cooperation between organizations or workplaces, and an insufficient or unsuitable work manual.

Measures for the prevention of accidents caused by these 4M trigger factors are considered from the viewpoints of the 4Es. **Education** is the factor related to education and training, including the workers' safety awareness, mastery of technique, and procedural education and training. **Engineering** is the factor related to the use of technology and equipment, and is a countermeasure that involves improving the function of a vessel's equipment or machinery, as well as the introduction of new apparatus and equipment. **Enforcements** are measures related to strengthening, diligence, and management; for example, the tightening-up of a manual or rule, and reexamination of the work organization and assignment methods. Finally, **Example** relates to measures involving the demonstration of a model or an example, such as measures that are being implemented in other companies or those that demonstrate dangerous examples of similar scenarios that have happened in the past.

Although there are factors that overlap across categories, analyzing from a broad viewpoint, 4M4E analysis can pinpoint many trigger factors of an accident and consider countermeasures from many perspectives. Examples of the viewpoints of 4Ms are shown in Table 2, and those of 4Es are shown in Table 3.

3. Mooring Line Accident

Among the accidents relating to vessels or seafarers, accidents involving a mooring line can sometimes be fatal, and therefore, have attracted much attention

Table 2   Examples of the trigger factors from the viewpoints of 4M.

Man (people)
· A shortage of knowledge and experience.
· Poor health.
· Physiological phenomenon.
· Etc.

Machine (machinery-equipment)
· The defect of a machine or equipment.
· The difficulty of operation.
· Hard to see a signal and a sign.
· Etc.

Media (environment)
· The weather and oceanographic phenomena.
· Workplace.
· View and sound.
· Communication.
· Etc.

Management (organization-management)
· An insufficient manual.
· Working hours.
· Staff assignment.
· Cooperation between organizations.
· Etc.

Table 3   Examples of the countermeasure from the viewpoints of 4E.

Education (education-training)
· The upsurge of safety consciousness.
· Mastery of skill.
· Education and training in work procedure.
· Etc.

Engineering (technology-equipment)
· The functional improvement of apparatus and equipment.
· Introduction of new apparatus and equipment.
· Etc.

Enforcement (strengthening-management)
· Tightening-up of a manual or a rule.
· Reexamination of work organization and assignment.
· Etc.

Example (model-example)
· Presentation of a model example.
· Presentation of a dangerous example.
· Cooperation between organizations.
· A case study from another company.
· Etc.

internationally. From February 13 to 17, 2017, in the International Maritime Organization (IMO), the 4th Sub-Committee on Associated Design and Construction was held to deliberate on safety measures involving mooring work. In this sub-committee, since a reliable implementation of checking and maintenance is important for the prevention of accidents involving the breaking of mooring lines, Japan proposed that a guideline on the checking and maintenance of mooring lines should be created. Support for this proposal was given by every country and consideration and creation of the necessary guideline was conducted. In the 6th Sub-Committee on associated Design and Construction of the IMO, in February 2019, this was taken up as the agenda for discussion as "revised SOLAS regulation II-1/3-8 and associated guidelines (MSC.1/Circ.1175), and new guidelines for sale mooring operations for all ships (OW31)" [8]. In response to this, the Oil Companies International Marine Forum (OCIMF) published a new guideline on handling of a mooring line [9]. To reduce the risk of

onboard accidents, we decided to focus on accidents and disasters involving a mooring line and to use 4M4E analysis.

The Japan Transport Safety Board investigated 10 accidents related to a mooring line from 2008 to 2018. As a result of these accidents, three people were killed: two quay workers were killed in a fatal accident that occurred in the Port of Kobe, and the chief officer was killed in the Port of Tsuruga.

4. Improvement in the Analysis Method

4.1 Trigger Factor Extraction for a Mooring Line Accident

The following analysis was conducted in relation to the 10 accidents involving a mooring line, investigated by the Japan Transport Safety Board. We decided to consider and analyze the trigger factors of each of these accidents involving a mooring line, by instigating brainstorming among four students and a teacher from the School of Marine Technology at Tokyo University of Marine Science and Technology. As a result of attempting to extract the trigger factors of the accidents through brainstorming, it was thought that the weather and oceanographic phenomena, i.e., the presence of wind and swell, and the human error lead to many examples of the trigger factor. A human error causes trigger factor and there is an example which the mooring line fractured. In the former, a worker was mistaken as to where to attach the mooring line. In the latter, the wind was involved, and the mooring lines tended to fracture in five or more winds of force.

Trigger factors for accidents include a mistake in ship-handling; a mistake, or failure, in predicting weather conditions; a mistake or failure in hull-movement prediction; a mistake in mooring-line operation; a mistake in operating mooring equipment; a mooring line being worn; lack of maintenance of a mooring line; and a mistake or failure in checking a mooring line. Many trigger factors were extracted.
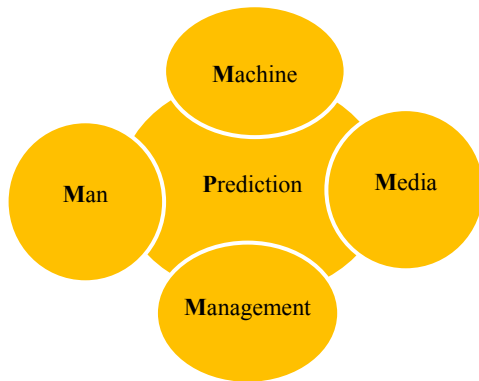
Fig. 2   The mimetic diagram of 4M4E+P analysis.

4.2 Improvement in the Analysis Method

As a result of extracting the trigger factors of accidents by brainstorming, many failures or mistakes in various predictions, were revealed: prediction became clear—prediction of the weather and oceanographic phenomena, such as a wind and a swell, prediction of hull movement, prediction of mooring line breaking force, prediction of the behavior of the fractured mooring line. Any one of these predictions, taken alone, was considered to be insufficient; therefore, the 4M4E analysis method was considered. By adding P (Prediction) to the 4M4E analysis, we considered that it would be easy to extract the accident's trigger factors that were relevant to its prediction. We called this analysis 4M4E+P analysis.

Fig. 2 shows a mimetic diagram of the 4M4E+P analysis. Although it is thought that the viewpoint of Prediction is already contained in those of Man, Machine, Media, and Management, the trigger factors relevant to Prediction are made easier to derive by adding P.

5. Verification of the Analysis Method

5.1 Verification Method

To verify the effect of 4M+P (Prediction) analysis, 32 students considered the trigger factors of the accident in which the navigation officer was injured in the cargo vessel in June 2014. One group (of 24 students) considered the trigger factors using only 4M,

and another group (of eight students) considered them using 4M+P. All the above students are from the School of Marine Technology at Tokyo University of Marine Science and Technology.

5.2 Contents of the Example Used for Verification

A summary of the example that was verified by this analytical method is as follows. The mooring line was broken during the unberthing work, hitting and injuring the navigation officer. To examine the trigger factors, the content shown to the students is presented in Fig. 3. The students considered the trigger factors of this accident based on this content.

5.3 Verification Result

We compared the replies of the group that considered the trigger factors only by 4M (hereinafter the 4M group) with those that considered the trigger factors by 4M+P (hereinafter the 4M+P group). As a result, the 4M+P group produced the following replies in addition to those obtained from the 4M (only) group.

• Prediction of ability to leave port independently under the influence of the wind and swell was insufficient.

• The action of the rope at the time of cutting was not predicted.

• Information required for the safety according to a situation was not predicted. Prediction of the hull action was neglected.

• Prediction of the fracture position of the mooring line was not sufficient.

• Prediction of the location for evacuation was not carried out.

• The prediction of the tension added to the mooring line was not sufficient.

Table 4 shows an extract of the 4M4E+P analysis matrix related to an accident involving injury of a navigation officer. In the Prediction column, many replies other than the abovementioned trigger factors were obtained. Prediction referred to many things concerning the weather and oceanographic phenomena.
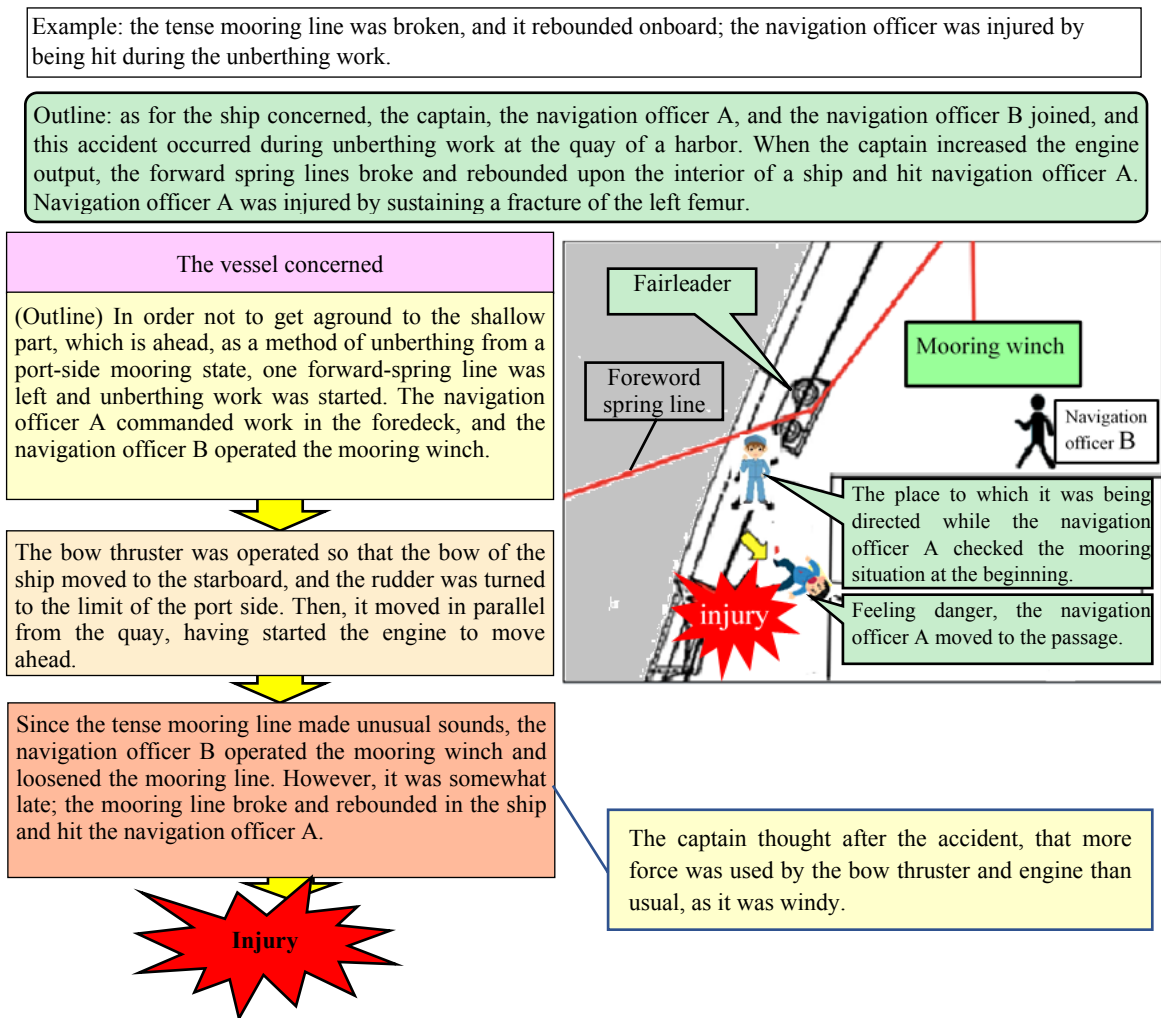
Example: the tense mooring line was broken, and it rebounded onboard; the navigation officer was injured by being hit during the unberthing work.

Outline: as for the ship concerned, the captain, the navigation officer A, and the navigation officer B joined, and this accident occurred during unberthing work at the quay of a harbor. When the captain increased the engine output, the forward spring lines broke and rebounded upon the interior of a ship and hit navigation officer A. Navigation officer A was injured by sustaining a fracture of the left femur.

The vessel concerned

(Outline) In order not to get aground to the shallow part, which is ahead, as a method of unberthing from a port-side mooring state, one forward-spring line was left and unberthing work was started. The navigation officer A commanded work in the foredeck, and the navigation officer B operated the mooring winch.

The bow thruster was operated so that the bow of the ship moved to the starboard, and the rudder was turned to the limit of the port side. Then, it moved in parallel from the quay, having started the engine to move ahead.

Since the tense mooring line made unusual sounds, the navigation officer B operated the mooring winch and loosened the mooring line. However, it was somewhat late; the mooring line broke and rebounded in the ship and hit the navigation officer A.

Injury

Fairleader

Mooring winch

Foreword spring line

Navigation officer B

The place to which it was being directed while the navigation officer A checked the mooring situation at the beginning.

injury

Feeling danger, the navigation officer A moved to the passage.

The captain thought after the accident, that more force was used by the bow thruster and engine than usual, as it was windy.

Fig. 3   Outline of the cargo vessel accident involving injury of the navigation officer.

Table 4   4M4E+P analysis of a navigation officer injury accident (extract).

	Trigger factor	Education	Engineering	Enforcement	Example
Man	The position in which a navigation officer stands	Knowledge of the mooring work and training	Installation of the safe platform	Emphasis of the snap-back zone	Illustration of the position that is safe
Machine	Allowable load of the mooring line	Education about the allowable load of a mooring line	Installation of a tension gauge	Examination of the quality of the material of the mooring line and the diameter	The example of the mooring line of a high-intensity fiber
Media	Strong wind	Education about wind pressure	Installation of an alarm system that informs about strong wind more than a certain wind force	Improvement of ship-handling skill according to a wind force	Manual preparation according to wind forces
Management	Departure standard	Education about a departure standard	Establishment of a related standard and acquisition of ISO	Keeping stricter a departure standard	It refers to the departure standard of the other companies
Prediction	Prediction of action of the mooring line	Education about the action of a mooring line and about the snap-back zone	Installation of the cover that predicted the action of the mooring line	Creation and use of a prediction check list	The example of an accident in which neglected prediction is shown

For example, "navigation officer B should have predicted that it was windy, and he should have let out the mooring line appropriately." "The captain should have predicted the weather situation appropriately." The 4M group also mentioned prediction of the weather and oceanographic phenomena. In the 4M (only) group and the 4M+P group, much of the content of Media and Prediction overlapped. However, the content, which is propriety prediction of an independent departure, not using a tugboat from the situation of a wind and a swell, was able to be pointed out in only the 4M+P group. In addition, "the action of the rope at the time of a fracture is not predicted", "after a mooring line fracture, the response is not assumed", and "the acquisition place of required information is not assumed in advance" were obtained from the 4M+P group as trigger factors of the accidental injury to the navigation officer. The decision regarding the addition of a new measure from "mooring line action prediction" to the column of Prediction the bottom of the table was made. As mentioned above, since the trigger factors of the target accident and the countermeasures could be drawn from several viewpoints, it can be said that adding of Prediction to the 4M4E analysis is effective.

6. Consideration and Result

The 4M4E analysis, which is one form of cause analysis of an accident, was carried out to analyze an accident on a vessel. The trigger factors of the accident can be considered from the four M perspectives, and the countermeasures against each trigger factor can be considered from the four E perspectives. We have recognized that many trigger factors and countermeasures can easily be considered by this approach. Furthermore, there are contents related to many predictions in the stage that consider a trigger factor from the 4Ms, and it was considered an important trigger factor of an accident. Then, the idea was put forward to adopt this factor, Prediction, as a new viewpoint. Prediction is related to all four types

of Ms. By focusing on Prediction, the important trigger factors of an accident can be easily considered. We devised the 4M4E+P analysis, which added Prediction to the former 4M4E analysis, and investigated the resulting effect.

Regarding the onboard accident involving the fracture of the mooring line, the following investigations were conducted. The students were divided into the 4M4E analysis group and 4M4E+P analysis group, and each group conducted accident analysis accordingly. As a result, in the 4M4E+P analysis group, many trigger factors were obtained, and there were many more trigger factors than those acquired by the 4M4E (only) analysis group. The countermeasures could be considered in relation to each of the acquired trigger factors. By adding Prediction to the existing 4M4E, the trigger factors of the accident could be discovered from yet another viewpoint, i.e., more than those for 4M, and it became possible to easily identify the accident trigger factors that would not have emerged using only 4M. It is thought that by adding P to 4M, as in this example, it becomes easy to specify the trigger factors of an accident that result from neglected or insufficient predictions. In addition, in the operation of a vessel, there are many essential things related to prediction, such as weather prediction and hull-movement prediction, which can be trigger factors for an accident. By considering countermeasures to these trigger factors, we think that more accidents can be prevented. To reduce the risk of an onboard accident, we proposed an analysis method that adds Prediction to the already existing 4M4E analysis. We would like to verify the effectiveness of this 4M4E+P analysis in various accidents and disasters in the future.

By contrast, although the trigger factors and countermeasures for many accidents can be derived by conducting 4M4E+P analysis, it is not realistic to perform all of the many countermeasures obtained. It is necessary to implement the most effective countermeasure. In Japan, research on the

condition-monitoring system of a mooring line is now being carried out [10]. Furthermore, in Europe, research on how to lay up a vessel using an electromagnet, without need of a mooring line, is also advancing [11]. Such methods are being investigated in an attempt to devise realistic countermeasures for the trigger factors. When implementing countermeasures, we have to consider the frequency and importance of accidents, as well as to validate these countermeasures. In the future, we would like to verify the validity of the considered countermeasures.

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