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HAZARD IDENTIFICATION METHODS

Summary. This article presents the main hazards that occur in the context of inland navigation and their impact on the vessel. First, characteristics are extracted from the following methods with regard to identifying threats: involving steering gear damage to an inland vessel moving on a straight waterway. Next, a hazard identification model is presented, which is appropriate to a situation involving steering gear damage to an inland vessel moving on a straight fairway.
Keywords: hazards identification; inland shipping; HAZOP; FTA; ETA; FMEA; SWIFT; risk analysis.

1. INTRODUCTION

Inland waterway transport is considered as one of the safest and most cost-effective modes of transport. Still, the operation of inland units is associated with a risk of, e.g., damage to the cargo and the ship, a threat of human life and environment pollution. Hazard identification is the first step in any formal safety assessment, whose purpose is to identify all the factors that may affect the operational safety of the vessel. Understanding the actual threats allows for the development of appropriate procedures, aimed at the elimination of the threats' source.

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2. INLAND WATERWAYS HAZARDS

Risks occurring in inland transport can be classified according to the factors that cause them. These are:

- Hazards resulting from the transport of cargo
- Hazards resulting from human error
- Hazards resulting from the failure of navigation devices, steering or other equipment
- Area-specific hazards

2.1. Hazards resulting from the transport of cargo

Inland shipping is a type of transportation, which deals with the carriage of all kinds of cargo, including oversized cargo and containers. In the case of river units, especially sea-to-river vessels, it is important to load the vessel correctly, as the uneven distribution of a load in the cargo spaces or on deck can affect the heel or trim of the vessel. Too much trimming, especially at higher speeds, results in an increase in the subsidence of the vessel. This phenomenon is particularly dangerous on shallow waters, such that the under-keel clearance is limited. The lack of monitoring and control of the value of the current draught and its relation to the depth can lead to grounding. Regarding the carriage of containers, as their subsequent layers increase the supply surface, it can be difficult to manoeuvre a vessel on open waters and with a strong wind. A special type of cargo is dangerous goods, the carriage of which is associated with risks, such as explosions. It is necessary for such cargo to be properly distributed and kept under appropriate conditions during transportation [6].

2.2. Hazards resulting from human error

A major factor behind accidents caused in inland areas is human error. In shipping, the 80:20 rule is typically asserted: this states that 80% of accidents are human-caused, while 20% are due to other reasons. Regardless of whether human error is intentional or unintentional, it can lead to an accident. Fig. 1 presents the classification of human errors [7].

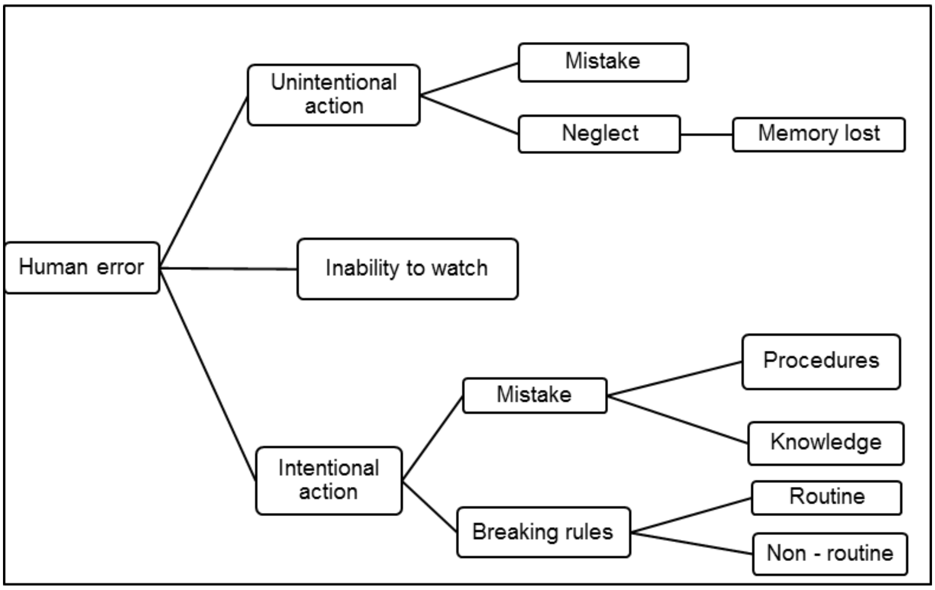


Fig. 1. Classification of human errors [7]

If the descent of the unit from the axis of the fairway is observed early enough, and the person on the bridge behaves in accordance with the given procedures (putting the unit back on the right course), the event will not generate any losses. Meanwhile, the lack of an adequate response to the descent of the unit from the axis of the fairway may result in:

- collision with another vessel, especially while overtaking or passing
- collision with another moored vessel
- collision with the jetty
- collision with a fixed object
- grounding

The consequence of each event is different and depends on many factors, including the speed of the ship, the kinetic energy of a collision or impact, and the place of contact with the ship's bottom. In the case of a collision, crash or grounding, demurrage, towing or necessary repairs could be among the consequences.

2.3. Hazards resulting from the failure of navigation devices, steering or other equipment

Each item of navigation or steering equipment is characterized by the intensity of damage. This means that, within a specified time period (hours or years), the vessel may crash. To determine the reliability of the technical support unit, it is necessary to qualify the reliability of each of its components. In the case of a ship, this represents a complex challenge, given that its construction comprises various pieces of equipment, such as radar, a main engine, aggregates and generators. To determine the intensity of damage to individual devices, the number of failures within a fixed period of time must be specified [6], while the intensity is dependent on the use of data elements, e.g., in the case of the rudder, its moves are important, while hydrometeorological conditions can affect the engine.

2.4. Area-specific hazards

By appreciating the characteristics of the analysed area, it is possible to identify risks such as: grounding, restrictions in the vertical plane, insufficient clearances under bridges and the conformation of a navigation route. Knowledge about navigation hazards helps to avoid risks. From a safety point of view, it is critical to have access to data on visibility, currents and wind. Other factors to be taken into consideration include the presence of RIS and the movement of other vessels [6].

3. METHODS USED TO IDENTIFY HAZARDS

The main ideology behind hazard identification is to identify all the possible strings of events leading up to an event threatening the safety of the unit. According to the literature, early detection and determination methods are available for the effective prevention of threats. These methods are as follows: HAZOP, FTA, ETA, FMEA and SWIFT.

3.1. HAZOP technique

This is one of the most commonly used analytical methods, otherwise known as the guide words technique, which is conducted in order to indicate deviation from acceptable levels on the basis of being too high, too low, too little, too much etc. HAZOP is mainly employed in order to determine a ship's systems, while analysis using this method is carried out by experts (engineers, technologists, designers, control and test facility experts) under the direction of a leader [3, 4, 5]. Table 1 presents an example set of words used in hazard identification based on the HAZOP technique.

Table 1. An example sets of words used in hazard identification, based on the HAZOP technique [9]

NO or NOT
MORE
LESS
PART OF
OTHER THAN
EARLY
LATE
BEFORE
AFTER

The HAZOP technique, which can be applied to each stage in the construction or operation of the relevant technology [9], mainly generates qualitative results. HAZOP technology is based on a systematic review of the design intent and the technological process concerning deviations from the accepted parameters. Typically, it is employed in order to determine any possible incident that may endanger health and human life or the environment, as well as cause damage to equipment and create technological problems. Fig. 2 shows the main steps in the proceedings when applying the HAZOP technique.

The form used when applying the HAZOP technique consists of the following elements [2,5]:
- Guide words for identifying potential deviations from the design intent
- Variations, i.e., changes in the actual operating system
- Real causes behind these deviations during a “brainstorm”, i.e., what are the consequences of the incorrect functioning of the system?
- Security measures to prevent deviation
- Recommendations to improve security

Sample form for hazard identification by HAZOP method presents table 2.

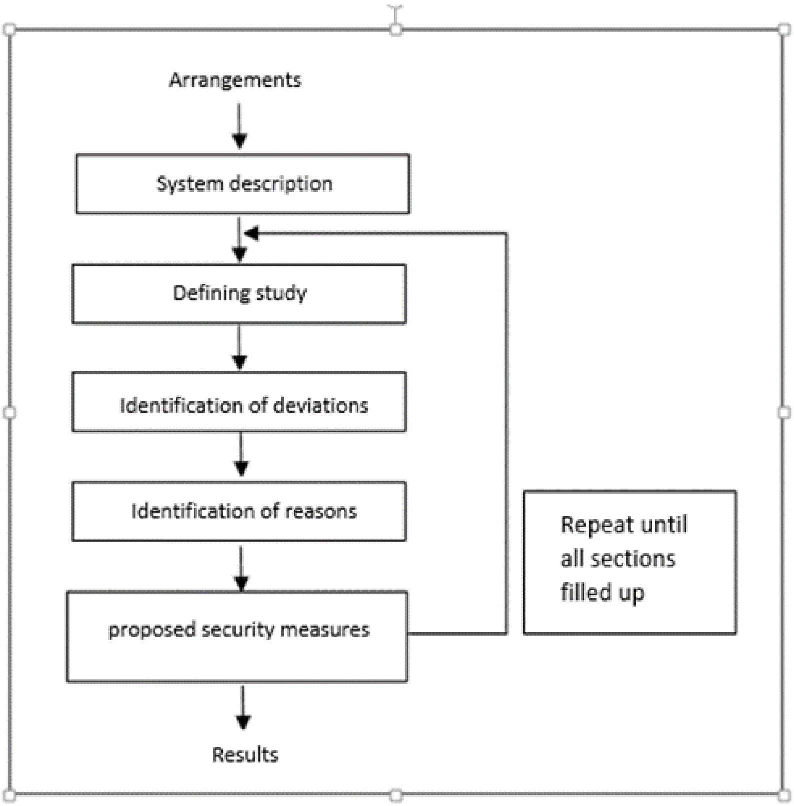


Fig. 2. The main stages in the HAZOP procedure [4]

Table 2. Sample worksheet for HAZOP analysis [4]

<table>
<tr><td colspan="7">HAZOP</td><td colspan="2">Project:
Object:
Page: Date:</td></tr>
<tr><td>No.</td><td>Guide word</td><td>Deviations</td><td>No.</td><td>Causes</td><td>No.</td><td>Effects</td><td>Safety measures</td><td>Recommenda-tions</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

3.2. FTA technique: the construction of an incapacity/fault tree

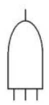
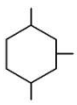
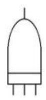
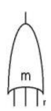
The model built using FTA techniques aims to identify the relationship between damaged equipment on ships and errors resulting from human or external factors. The construction of a fault tree starts with the identification of the effects of an event, as well as considers the course of previous events. In the process, a range of possible combinations of events is specified. The event tree is used for qualitative and quantitative analysis [2], while FTA employs Boolean logic. The main steps in FTA are:

- Determination of the initial events
- Determination of the events/indirect damage
- Construction of the tree damage, using event-binding logical gates
- Identification of the fundamental event leading up to the main event

- Specification of the probability of occurrence of the initial event
- Calculation of the probability of occurrence of the final event
- Analysis of the results, along with the fixing of the dominant events
- Sensitivity analysis to check how changes in the probability of the damage to one item from a set of influences affect the likelihood of the occurrence of peak events

The purpose of this method is to identify the cause of failure instance, determine the frequency of the occurrence of dangerous states, and identify critical components of the system. The basic elements of the event (or fault) trees are gates and events [3, 4, 5]. Table 3 shows the gateway used for FTA.

Table 3. Gate symbols used in FTA [4]

Gate symbol	**Gate name**	**Symbol meaning**
	AND	The output event occurs if all input events occur simultaneously
	OR	The output event occurs even if there is only event input
	Inhibit gate	The input-output product is followed by a conditional event
	Priority AND gate	Precedence over the conjunction of events from left to right
	Exclusive OR gate	The output event occurs if followed by one (but not more than one) input event
	m out of n gate	The output event occurs if and m exit/n enter event occurs

Hazard identification involving FTA is used in risk analysis and the determination of reliability to specify the relationship between the peak events and the underlying events. Fault tree construction uses a gateway connecting the event via a logical relationship. With reference to the fault tree, it can be determined exactly which errors were committed, which actions have not been observed and which actions have been performed to prevent accidents.

3.3. ETA technique: building an event tree

ETA technology is based on a graphical model depicting the relationship between cause and effect in an event. Hazard identification begins by determining the initialization event and considering all possible strings of events, which are consequences of the initialization event. The probability of the effect is determined by multiplying the probability of all the events. The ETA technique analyses the situation from beginning to end, taking into account partial events that may have decisively impacted on the status of the analysis process. In many cases, a single event can result in different consequences, depending on the performance or failure of equipment, systems or operator activities. ETA is a method used to build an object model of probability for risk analysis. There are two approaches to this technique: before an accident and after an accident. The technique used before an accident is applicable when there is a need to determine possible events and the likelihood of their occurrence. The technique used after an accident seeks to analyse and identify the functional safety system failures.

The ETA procedure consists of six major stages:

- Identifying the initiating event that can lead to a specific failure
- Identifying the safety features that are applied to mitigate the effects of the initiating events
- Constructing an event tree
- Describing the findings in light of the construction of the tree sequence
- Specifying the minimum cross sections of the tree
- Developing the documentation

Fig. 3 presents the method for conducting an analysis of the data using the event tree.

Each event has two branches that determine the success (positive) or the lack of success (negative), while the probability of events contains between ‘0’ and ‘1’. The sum of the probabilities of the event and its lack thereof is equal to ‘1’. Hence, if the entire event is described, a collection of this success can be described as P (A), while the failure is an event to the contrary:

$$1- \mathrm{P}\ (A) = \mathrm{P}\ (\overline{A})$$

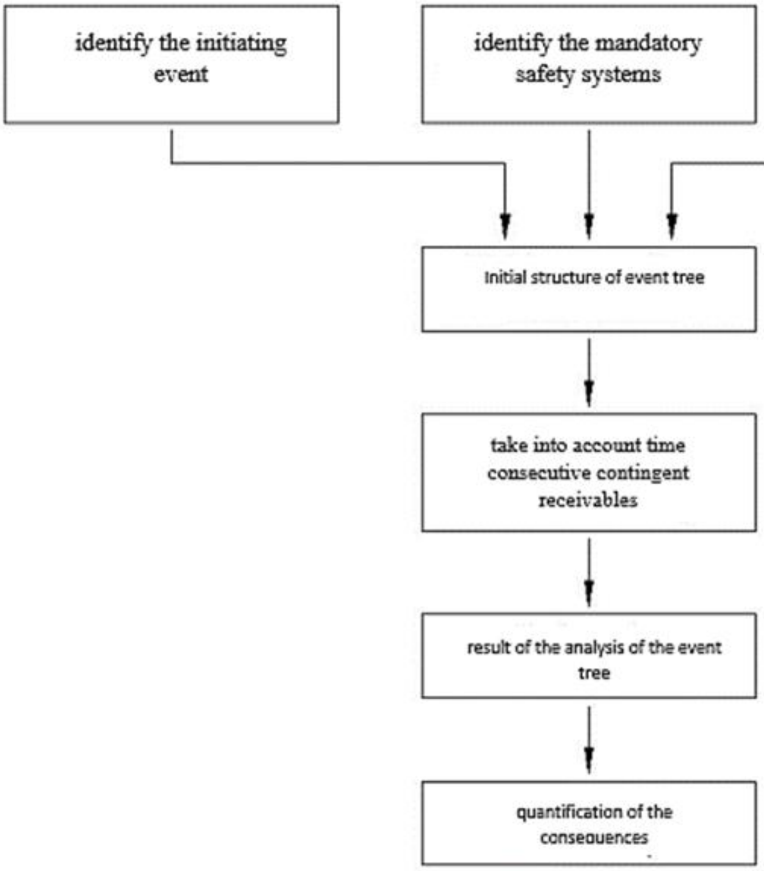


Fig. 3. ETA stages [4]

3.4. FMEA technique

This technique is used to determine the damage, which significantly impacts the operation of the entire system (mainly its efficiency), and evaluate the reliability of individual components of the system. In FMEA, the types and effects of damage are considered in relation to elements of the systems and other equipment, as well as the possible damage and effects on other components, systems or the state. The purpose of the FMEA is to identify specific shortcomings in the process and how to exclude or minimize their effects. This is achieved by determining the cause and effect relationships, depending on the potential creation process, with the defects, while taking into account the risk factors. Thanks to this process, continuous improvements are possible by carrying out in-depth analyses and introducing amendments, which are aimed at eliminating the sources of defects and enhancing the performance capabilities of the product. The FMEA method, which is described in standard PN-IEC 812 [7], is divided into two types:

- Product FMEA – This is a technology-oriented approach, which optimizes the reliability of the product. On the basis of the assessment, the product can be made stronger by addressing its weak points.
- Process FMEA – This consists of determining the disorganizing factors in the production process.

FMEA consists of five main steps:
- Identification of the characteristics of the system and its basic functions, as well as the minimum requirements that determine its operation
- Identification of possible malfunctions and system failure
- Identification of the consequences of each system failure
- Determination and evaluation of methods to detect system failure
- Description of the reduction and elimination of adverse effects

The quantitative analysis of defects is used to describe the cause-defect-effect relation, while the assessment of this relationship is determined on a scale from one to 10, divided into three categories:
- Risk of defects/causes - R
- Ability to detect the emergence of causes before any defects occur - W
- Importance of disadvantages to the user - Z.

Based on the determination of these values, the level of priority, which takes a numerical value between one and 1,000, can be established. As the value increases, so does the risk of defects. The formula for calculating priorities as a numerical value is as follows:

$$P = R \times W \times Z$$

FMEA documentation should take the form of an at-a-glance a report describing the effects of any damage to the equipment/system, as well as other devices/components of the system. Table 4 sets out the FMEA documentation.

Table 4. FMEA documentation [6]

<table>
<tr><td colspan="3">System:</td><td colspan="10">Drafted by:</td></tr>
<tr><td colspan="3">Table no.:</td><td colspan="6">Date:</td><td colspan="4">Page:</td></tr>
<tr><td colspan="3">System description</td><td colspan="3">Damage description</td><td colspan="3">Damage effect</td><td rowspan="2">Failure rate</td><td rowspan="2">Ranking of seriousness</td><td rowspan="2">Risk reduction measure</td><td rowspan="2">Comments</td></tr>
<tr><td>No.</td><td>Function</td><td>Operating mode</td><td>Damage mode</td><td>Damage cause or mechanism</td><td>Detection of damage</td><td>Subsystem</td><td>System function</td><td>Resulting state</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

3.5. SWIFT method

This technique involves team “brainstorming”, in which experts ask each other questions and identify potential risks. The SWIFT method aims to:
- identify risks

- determine the effects of the occurrence of each event
- designate possible measures/methods of reducing risks

The SWIFT is divided into three stages:

- Stage 1. Preparation – This involves the analysis of the current situation, as well as examining with the applicable rules and procedures. During this stage, specific questions will be put to a team of experts.
- Stage 2. Review – This involves the presentation of the problem and asking the right questions in order to identify risks and develop remedial procedures.
- Stage 3. Documentation – This involves the compilation of a report based on the outcomes from using the SWIFT, including the identified hazards and their effects.

To document the outcomes from using the SWIFT technique, a worksheet similar to that presented in Table 5 can be used.

Table 5. Example of a SWIFT worksheet [5]

NAME…………………………………………………..		DATE…………………	
DOCUMENTATION NO…………………………………...			
MEMBERS OF THE TEAM……………………………...			
WHAT-IF	CONSEQUENCES/HAZARD	REMEDIES	RECOMMENDATIONS

4. HAZARD IDENTIFICATION MODEL USING THE EXAMPLE OF STEERING GEAR DAMAGE

The analysed event involves an inland vessel passing through a straight fairway. During the passage, the vessel's steering gear is damaged (initialization event).

This type of event, which is independent of any human factor, can lead to the corruption of the navigation device and steering gear on the ship. The immediate threat concerns whether control can be maintained over the movement of the vessel, while longer-term consequences include the costs of repairing and servicing equipment. Rudder damage can also lead to the loss of a ship's control.

The initiating event concerns damage to the steering gear. Table 5 shows the hazard identification model developed on the worksheet used in the HAZOP analysis.

Deviation (the state that deviates from the proper operation of the unit) is represented by the loss of control over the ship. This may be caused by damage to the rudder, which can affect the units of the axes along the navigation route or cause a blackout. In the event of damage to the rudder, security measures in the form of frequent checks are required in order to detect any irregularities in the functioning of the steering gear. It is also recommended to check the rudder before the output units, as damage to the rudder during transition along the shipping route can endanger the safety of the units and other users of the fairway. As a result of a blackout, the vessel may stop responding to movement, which could lead to the ship colliding with another unit, object or jetty. To prevent such a situation, installing sensors and alarms to monitor the energy facilities is advisable. Security measures should again involve frequent checks and a review of the devices. Table 7 presents the hazard identification model developed with the aid of the FMEA worksheet.

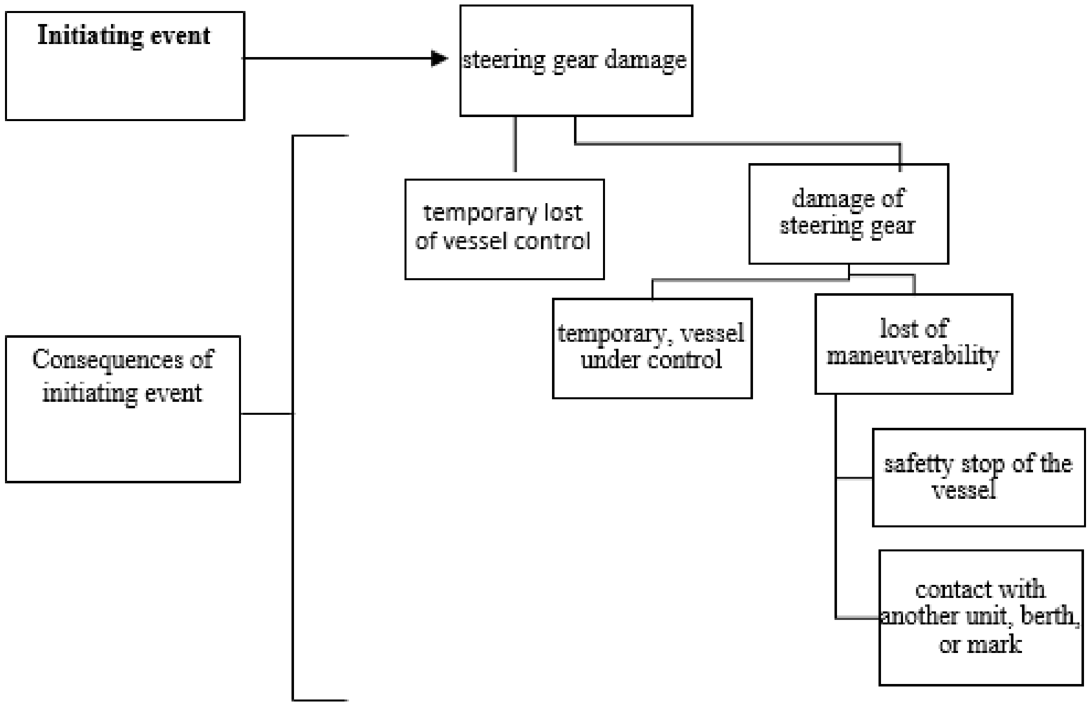


Fig. 4. Hazard identification model constructed using ETA techniques

Table 6. Example of a HAZOP worksheet [4]

HAZOP							**Project:** **Object:** **Page:**	**Date:**
No.	**Guide word**	**Deviations**	**No.**	**Causes**	**No.**	**Consequences**	**Safety measures**	**Recommenda-tions**
1.	Lack	Loss of manoeuvra bility	1.	Rudder damage	1.	Descent from the axis of the fairway	Frequent checks	Rudder control before leaving the port
			2.	Blackout	2.	Vessel not under command	Frequent mainte-nance of whole energetic system	Sensors, alarms

Table 7. Example of an FMEA worksheet [8]

System:		**Drafted by:**									
Table no:		**Date:**						**Page:**			
System description		**Damage description**			**Damage effect**			Fail- ure rate	Serio usn- ess ran- king	Risk reduc tion meas ures	Amen dment s
Fun- ction	Work mode	Dama- ge mode	Dama- ge cause or mecha nism	Dama ge dete- ction	Sub- system	Funct ion of the syste m	Resul- ting state				
Stee- ring gear damage	Nor- mal	Sudden	Rudder break- down	Alarm sound	Stee- ring pump	No effect	Descen t from the axis of the fairway	Rare	Serio us	Tur- ning off	Re- pair

The analysis carried out by FMEA is a method that allows for a precise description of the both the test system, which is experiencing failure, and the effects of the damage. The considered damage is divided into components, which are analysed separately in order to determine the full impact of the damage on the function of the system.

Table 8 presents the hazard identification model, as developed on the worksheet used in SWIFT analysis.

Table 8. Example of a SWIFT worksheet

NAME……………………………………………………….. DATE…………………			
DOCUMENTATION NO……………………………………....			
TEAM MEMBERS………………………………....			
WHAT-IF	CONSEQUENCES/HAZARDS	REMEDIES	RECOMMENDATIONS
Steering gear damage during passage on a straight fairway	Descent from the axis of the fairway/collision with the jetty/another vessel/object	Steering gear controls/checklists	Tests of the steering gear before departure/sensors/alarms

The SWIFT method is one of the most straightforward ways to identify risks, as it is based on posing simple questions. Typically, a SWIFT worksheet consists of four questions:

- If a threat occurs, what kind of threat is it?
- What can be the effect?
- What measures should be taken?
- What recommendations should be made?

In this case, the threat involves damage to the steering gear. The effect is considered to be on the unit's descent along the axis of the fairway, which generates another threat in the form of the possibility of collision with another unit, a jetty or an object. In order to ensure safety, the introduction of checks of the controls of the steering gear and the rudder before departure is recommended. Additional threat indicators are sensors and alarms, as their use allows for the earlier detection of a problem and its quick elimination

5. CONCLUSIONS

Hazard identification is an important element in the risk estimation procedure. Its main advantage is the ability to determine possible problems and events, which can impact the vessel and other users on the fairway. A commonly used method in the analysis of risks is HAZOP, which is characterized by a thorough review of the assumptions of the entire technological process, as well as designed to specify all possible deviations from the accepted standards. A HAZOP worksheet takes into account deviations, and their causes and effects, safety measures, and recommendations for use. Meanwhile, the SWIFT method is based on questions that can help to define potential problems and find appropriate solutions. This is one of the more creative methods because it is based on the so-called “brainstorming” approach. As with HAZOP and FMEA methods, the outcomes when employing the SWIFT method should be documented on worksheets, which define the risks in words. Methods such as ETA or FTA identify hazards by visualizing the problem using gates depicted as a set of appropriate symbols. The estimation of the impact of damage on the process allows for remedies and recommendations to be specified, which in turn can ensure safety and minimize the risk of hazards.

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