Towards the Development of a Risk Model for Unmanned Vessels Design and Operations

K. Wróbel & P. Krata
Gdynia Maritime University, Gdynia, Poland

J. Montewka
Gdynia Maritime University, Gdynia, Poland
Research Group on Maritime Risk and Safety, Aalto University, Finland
Finnish Geospatial Research Institute, Finland

T. Hinz
Waterborne Transport Innovation Foundation, Poland

ABSTRACT: An unmanned merchant vessel seems to be escaping from the stage of idea exploration. Once the concept proofs its safety, it may become a part of maritime reality. Although the safety aspect of such a ship has been addressed by a handful of scholars, the problem remains open. This is mainly due to lack of knowledge regarding actual operational circumstances and design of unmanned ships, which are yet to be developed. In the attempt of bridging this gap, the risk analysis associated with unmanned ships needs to be carried out, where all relevant hazards and consequences are assessed and quantified in systematic manner. In this paper we present the results of a first step of such analysis, namely the hazard analysis associated with the unmanned ships. The list of hazards covers various aspects of unmanned shipping originating from both design and operational phases of vessel's life. Subsequently the hazards and related consequences are organized in a casual manner, resulting in the development of a structure of a risk model.

1 INTRODUCTION

Autonomous and remotely controlled vehicles have been successfully implemented in various industries, e.g. automotive, subsea and airborne as well as in military applications. Also the safety issues of those have been addressed by various authors (Gerigk 2015) (Özgüner et al. 2007) (Stokey et al. 1999). However, since unmanned merchant vessels are still in conceptual and design phase (Burmeister et al. 2014), any elaboration on their safety levels must inevitably be incomplete by simply not including historical and empirical data. Operational issues of unmanned ships are elaborated in (Rødseth et al. 2013), and summarized in Figure 1. In (Kretschmann & Rødseth, et al. 2015)(Kretschmann & Mcdowell, et al. 2015) authors optimistically claim that autonomous ship proposed by them will be in general safer to operate than conventional vessels operating

nowadays. In (Kretschmann, Mcdowell, et al. 2015), it is said that the results of risk analysis are 'encouraging' despite acknowledging that there are some uncertainties regarding future systems' design. Authors claim that human errors' contribution to maritime accidents' occurence will be to large extent limited. However, the study does not seem to take into account that, should the accident occur, there will be nobody on board the unmanned vessel to undertake immediate corrective action in unfavourable circumstances and restrict the consequences of hypothetical maritime disaster. Thus, vessel's survivability of the accident will depend solely on her designers' ability to anticipate potential accidents' scenarios and possibly on the operational performance of any remotely controlled system installed on board and operated by qualified crew based ashore.
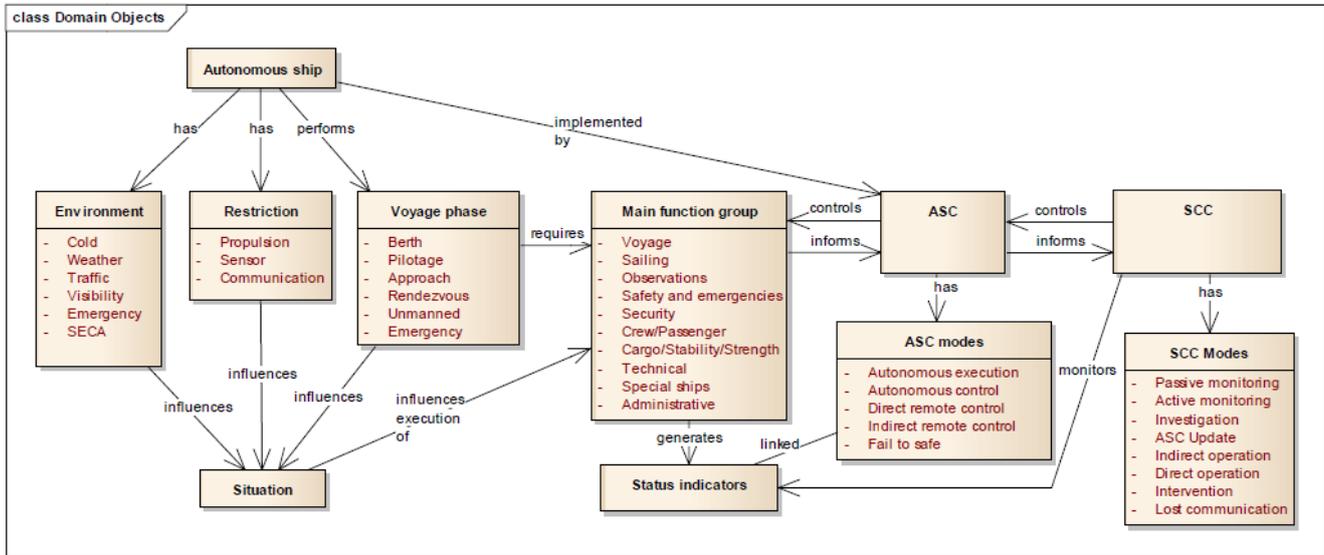
Figure 1. Unmanned ships operational context relationship diagram (Rødseth et al. 2013)

Meanwhile, in (Rødseth et al. 2013), authors presented identification of major risks associated with introduction of unmanned vessels and then assigned them with estimated frequency and severity indices divided into three categories to indicate that a particular hazard can be of either human, material or environmental nature (Kretschmann & Rødseth et al. 2015). However, each and every accident is caused by a series of casual factors, which can be assigned to various categories. Moreover, malfunctions tend to propagate and, for instance, what initially seems to be harmless mechanical breakdown can easily turn into fire and, eventually, ship's sinking. Those issues do not appear to be addressed to date.

Thus, in our study we made an attempt to combine the past experience, encapsulated in the vast literature on maritime accident causes (Allianz 2015)(Mazaheri et al. 2015), with the insight into the future, as elicited from the experts, in order to develop a list of potential hazards that pertain to the design and operation of a unmanned ships (Gerigk and Skorupski 2012). Subsequently those are organized in a casual manner and linked with their potential consequences, providing a structure of a risk model. The latter, when fully developed can be seen as a useful tool measuring the effect of various factors on the safety of unmanned ships.

Due to high uncertainty of the potential risk model, a suitable modelling techniques shall be adopted, allowing for the uncertainty assessment, representation and quantification, if possible, if not some qualitative evaluation needs to be performed, (Flage & Aven 2009). Therefore, the structure of the model presented here is developed with the use of Bayesian Networks, which seems to be suitable for the given purpose (Weber et al. 2012). At this stage the network lacks the parameters (probabilities, in other words), since the intention of the authors is to demonstrate the structure only. The parameters shall be elaborated in future works to come.

The remainder of the paper is organized as follows: firstly, data sources are presented together with methodology. Then, Bayesian network structure as elaborated is given and its details described. Brief discussion and suggestion for further study is followed by conclusions.

2 MATERIALS AND METHODS

2.1 Materials

In order to investigate factors concerning unmanned vessel's safety, we used the available description of system concepts as presented in (Burmeister et al. 2014)(Rødseth and Burmeister 2015). Therein the authors suggest that future ships shall be capable of operating in either fully autonomous mode (in open sea), remotely-controlled (e.g. in case they encounter a situation that control system cannot handle for some reason) or manned by so-called flying or conning crews (in approaches to ports similarly to pilot service nowadays and during mooring operations for instance). To provide them with sufficient level of operational safety, they will be equipped with redundant propulsion systems, secure communication links and additional environmental sensors among other purpose-designed features (Burmeister et al. 2014).

Similar approach is taken by consortium members involved in currently pursued projects Advanced Autonomous Waterborne Applications Initiative (AAWA)(Jokioinen 2016), and US-based Defense Advanced Research Projects Agency's (DARPA) Anti-Submarine Warfare Continuous Trail Unmanned Vessel (Rogoway 2015) project. As can be seen, despite the fact that unmanned merchant vessels are yet to be introduced to international shipping, their future anticipated design and performance are decently described in many sources, both scientific and popular (Burmeister et al. 2014)(Rødseth and Burmeister 2015)(Man et al. 2014). We have used those to create a model describing their expected safety features.

2.2 Methods

Having experience in both academia and industry in various disciplines relevant to unmanned shipping (naval architecture, safety science, marine navigation, ship stability etc.) we applied brainstorming as a method of eliciting and systematizing professional knowledge regarding expected outcome of processes. Brainstorming is widely accepted in numerous disciplines and valued inter alia for its simplicity, tendency to magnify one's creativity and sort of fun that comes with it (Isaksen 1998). We used basic brainstorming guidelines as given in (Rossiter & Lilien 1994), namely:

1 Create strict brainstorming rules and follow them
Brainstorming best practices have been used, just to mention free-wheeling and refraining from criticism;

2 Set a specific and difficult target
Our goal was to create a structure of a risk model describing best the anticipated relationships between safety features of unmanned merchant vessel;

3 Initial ideas should be created by individuals rather than groups
Ideas on including particular risk and its relations to remaining ones were presented by individuals;

4 Use group interaction to amalgamate and refine ideas
If found appropriate or necessary, those were clarified or developed by entire group;

5 Use individual voting to select final ideas
Results of brainstorming were put under democratic vote;

6 Keep timing as short as possible
We have applied a limit of one hour for creating ideas about the network and some additional time for resolving arising problems.

The technique was applied among the group of experts, comprising of ship designers and naval architects, master mariner, ship stability expert, risk analyst, all of them having research and industrial background. The group is deliberately diversified, containing six people from two countries representing various field of shipping.

2.3 Results

As a result of the brainstorming sessions, we created a structure of Bayesian network describing relationships between safety issues pertaining to unmanned vessels. We debated on causes and effects of some unfortunate events affecting ships' safety without considering their actual probabilities and consequences as in a classic definition of risk being a product of those. Instead, we focused on accidents' potential causes and failures' development within the system. Nevertheless, importance of estimating likelihood and consequences of such events is acknowledged and will be addressed in future work. In a course of brainstorming, it has been noted that seemingly very different types of accidents tend to originate from similar root causes. Those can be attributed to malfunctioned sensors or improper maintenance regime for instance. For presentations' simplicity reasons, those were grouped together as most of them could potentially lead to numerous types of accidents. The obtained structure of the risk model is presented in Figure 2. We divided the safety features of unmanned vessels into three levels as follows:

– Level 3 focuses on potential root causes of accidents as given in Level 2;
– Level 2 describes potential accidents to which the unmanned ship can be susceptible and the way the damage might escalate thus causing secondary accidents;
– Level 1 constitutes a set of unwelcome events, their development paths and likelihoods (the latter to be addressed in future work) as considered in hereby paper that put a vessel into a risk of foundering or otherwise directly endangering maritime safety including the natural environment.

2.3.1 Level 3

Each of potential accidents has its direct and root causes. Those have been listed in Level 3 of analysis since they have an influence on most of Level 2 elements:

– maintenance regime - basis on which various ship's systems and mechanisms would be supervised will have a great influence on their reliability;
– sensors' performance - quantity, quality and arrangement of e.g. environmental or machinery sensors will affect vessel's ability to detect navigational hazards or abnormal operational conditions;
– control algorithms - vessel's response to environmental and navigational conditions she would meet will to great extent depend on quality of the software and its developers' ability to predict all circumstances the ship can potentially encounter;
– alerting - command to call for shore operator's assistance must be implemented in software in proper place for such operator to take over the vessel in ample time, before malfunctions or other conditions develop to a point after which nothing can be done remotely - such points shall be defined;
– external information quality - unmanned vessel's safety will also depend on quality of data provided by external actors including weather forecasts, passage plans, stowage plans and, which is particularly important, shore-based operator's situational awareness and ability to react properly when prompted;
– operational regime - whether ship is operating in fully-manned, remote or autonomous mode would have great consequences for its safety, particularly for its capability of dealing with uncertainties and magnitude of human error likelihood;
– area of operation - it is widely accepted among shipping industry that some regions of the world are more dangerous for vessels due to e.g. dense traffic, long periods of heavy weather or other factors.

2.3.2 Level 2

Unfortunate events as listed at Level 3 can potentially initiate a chain of events that can

eventually lead to an accident. We divided accidents, to which unmanned vessels can be exposed into four main categories:

- navigation-related;
  From navigational point of view, there are two major hazards, namely collision and grounding which can both result from the third one, which is loss of position fix. Should the latter occur due to e.g. satellite navigation system being not available, a secondary mode of establishing vessel's position can be applied – some other radio navigation system or contemporary dead reckoning based on accelerometers and gyrocompasses. Long-term accuracy of the latter, due to inherent bias, can be, however, questionable which may eventually lead to a vessel running aground or colliding with another object (not necessarily a vessel), especially when in littoral waters.

- engineering-related;
  Problems with proper functioning of variety of engines on board the ship can be both cause and result of navigational accident. Grounding, for instance, can be caused by abnormalities in functioning of steering devices. On the other hand, if a vessel runs aground it can cause a serious damage to the rudder. Similar relationships can be attributed to propulsion and collision. Furthermore, loss of electric power can disable most of ship's systems including propulsion, steering, communication and ballasting.

- originating from stability or buoyancy issues;
  Stability and buoyancy issues can greatly impact ship's overall safety. Consequences of stability loss can be particularly devastating for ship as well as for her crew and cargo. On the other hand the excessive stability of a ship causes the undue rolling resulting in high values of accelerations acting on ship equipment and cargo. Especially, the dynamic phenomena that do not cause the vessel to sink can damage the cargo. Goods carried themselves can also be a reason for which the loss of stability may occur, e.g. in case of liquefaction or containment loss. Meeting intact stability criteria will also depend on proper functioning of ballast system since ballast operation will most likely need to be carried out at sea in order to compensate for fuel spent and follow ballast water management regulations.

- others
  Last but not least, there are many more hazards to include in safety analysis, which do not fit into any specific category. Unlawful acts can potentially lead to many kinds of accidents including fire and explosion. Those in turn (regardless their origin) can badly influence other subsystems, just to mention propulsion, cargo or structural integrity. Vessel's ability to communicate with shore-based operator can also be reduced which would in turn have critical consequences to further ship's functions, e.g. collision avoidance or ability to take part in Search and Rescue operation. This aspect shall be addressed with particular attention as unmanned vessels might at some point find themselves somehow involved in a situation, which threatens other ship's crew's life. Distress signal might be received by unmanned vessel or she can be the only ship in area capable of picking up survivors (she would therefore need to be equipped with proper appliances and provisions to accommodate those unfortunate seafarers). On the other hand, sufficient solutions aiming in establishing that Search and Rescue is taking place shall be provided so that the unmanned ship proactively participates in it or at least does not interrupt it. This aspect of decrewing of shipping industry does not influence safety of unmanned vessels themselves, but can have a significant impact on safety of marine transportation as a whole.

Another issue that affects unmanned ships' safety to a limited extent but can potentially have great influence on their perception by shippers and P&I clubs and - eventually - on their economic results is safety of cargo, hereby referred also to as 'cargo damage'. Shipper or cargo owner expects his/her goods to be delivered in ample time and good condition. Any deviation from those contractual conditions is unwelcome. Situation in which cargo gets wet or odorized has no effect on ship's safety but a great one on shipowner's wallet size. Some cases, however, include hazards to both of them, like self-heating or self-ignition of cargo for instance.

Each and every accident as listed in Level 2 is by itself an unwelcome event that can potentially cause a major maritime disaster and create either financial or environmental losses. However, it can also constitute just another link in the chain of events leading to even more devastating consequences.

On the other hand, some minor unwelcome events constituting Levels 3 and 2 do not necessarily endanger the ship's safety as a whole, e.g. sensor's failure can be of little importance should proper redundancy arrangement be in place.

2.3.3 *Level 1*

Assessing and ensuring safety of unmanned vessels is a difficult task but must be carried out in order to prove that those can create some added value to global community. As can be deduced from various papers on this subject (Burmeister et al. 2014)(Rødseth & Burmeister 2015)(Man et al. 2014), ships in question will be complex and to some point revolutionary. Regardless their design, they shall be exposed to most of the same hazards as today's conventional ships, and many more - most likely. Those are given in Level 2.

Another issue in designing safety is its influence on cost-effectiveness of the system in focus. In unmanned vessels' case, that would express in both investment and operational costs. For instance, avoiding heavy weather areas can improve vessel's safety, but will increase time required for sea passage and by that - fuel costs and likelihood of being off schedule. Passing through such area might be risky for the ship not only because weather damage can be expected, but also for the likely necessity to reduce speed and create even greater delays and fuel consumption. On the other hand, weather conditions in the area can prove better than expected and the risk taken might prove beneficial (Krata & Szłapczyńska 2012). Satisfactory compromise must therefore be found between vessel's overall safety and cost-effectiveness (Rødseth & Burmeister 2015).
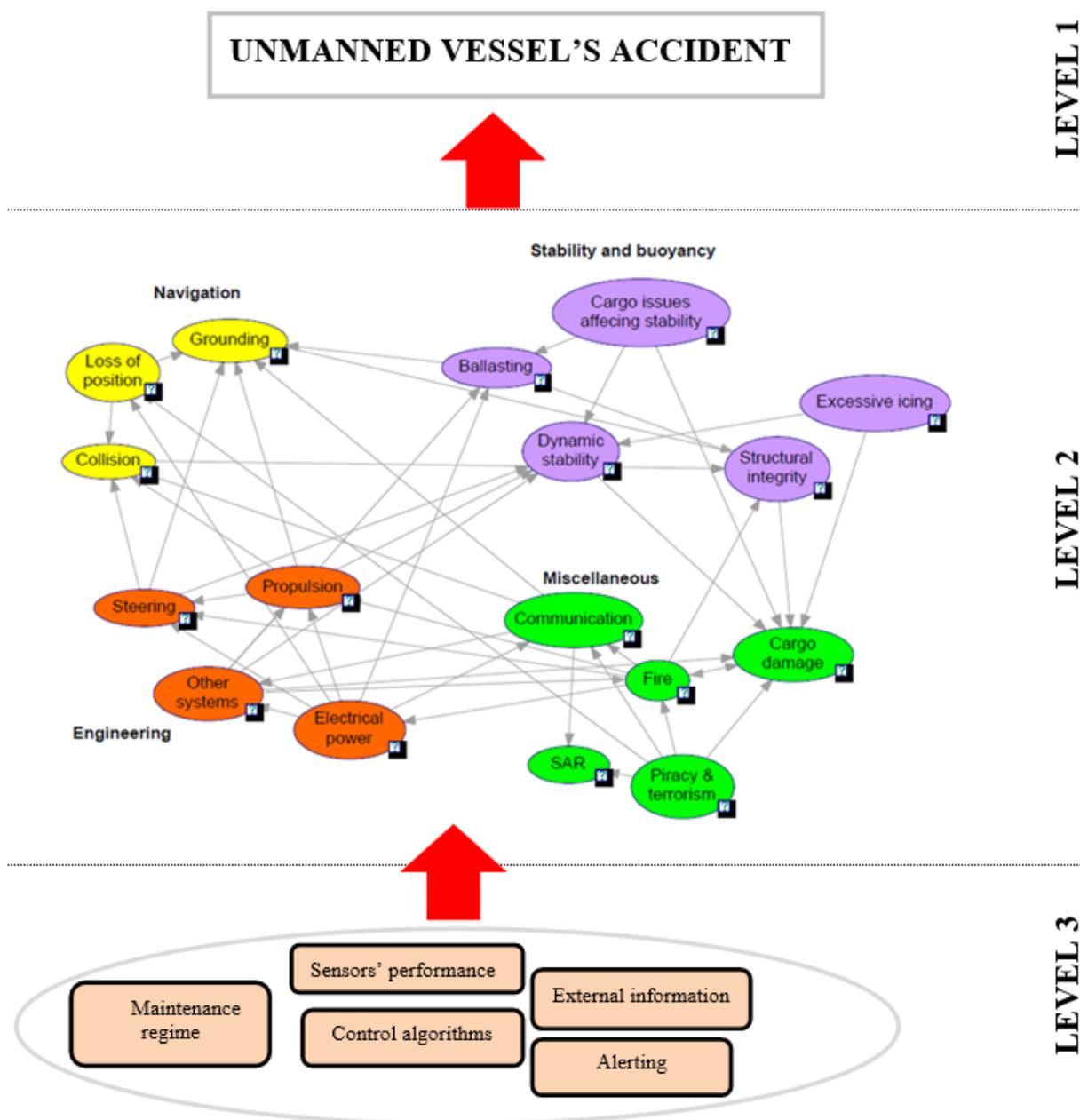
Figure 2. Model structure depicting relationships between three levels of unmanned merchant vessel's safety.

Therefore, by studying the ways and likelihoods of unfavorable situation's development from e.g. sensor's malfunction into a serious maritime disaster, one shall be capable of estimating risks to which an unmanned merchant vessel shall be exposed. Utilizing risks estimation as a measure of assessing object's safety conforms to International Maritime Organization's guidelines for Formal Safety Assessment (IMO 2002). As a result, output of a model (Level 1) as given in Figure 2 consists of a likelihood of specific maritime accident (fire, loss of stability, grounding etc.) to which some less consequence-abundant events could have contributed. Notably, the model itself does not specify which of events affects accidents' consequences the most – such feature can only be deduced by studying a chain of events for each individual case of accident's scenario. We therefore deliberately omit considering disaster's consequences and focus on its likelihood

instead. By learning the latter, we shall be capable of estimating how safe the vessel in question is.

2.3.4 Model validation

In order to verify correctness of model's structure, we applied it to a maritime accident of fire which occurred on board a fully-manned m/v 'Maersk Doha' on 2nd October 2006 in Chesapeake Bay.

Its root cause is attributed to a malfunction of boiler's automatic controls which led to operation with low water level and deposition of soot in exhaust gas economizer, which was not removed during routine maintenance (Level 3). Although the engine crew was aware of the problem, vessel was allowed to proceed with reduced speed. Rapid rise in boiler's temperature caused nearby equipment to ignite (Level 2). Carbon dioxide extinguishing system did

not function properly due to one of pilot cylinders being inoperative and fire has been extinguished by crew using fire hoses despite problems with emergency power generator and emergency fire pump. Those were also found inoperative. Fire had also caused issues with power generators starting air supplies which in turn made the generators themselves impossible to start. Major temporary repairs had to be completed including main engine turbochargers' cleaning before vessel could be declared ready to proceed for permanent repairs(MAIB 2007). Fact that the accident occurred in restricted waters of Chesapeake Bay caused the vessel likely to run aground should the main engine fail – fortunately, that was not the case, see Figure 3 (Level 1 has not been reached).

As per validation performed basing on real accident, we were able to confirm that a model's structure is valid for describing risks associated with today's vessels' operation. Future unmanned ships shall be subject to majority of hazards that are encountered by today's merchant vessels. That makes the herein developed model suitable for describing their safety.

3 DISCUSSION

In the course of presented research we aimed at a general overview of relationships between safety features of unmanned vessels. As can be seen, major subsystems of such vessels are dependent on each other. For instance, performance and reliability of main and auxiliary engines will affect vessel's navigational capabilities, but will be depend on performance of fire protection systems and equipment (Gawdzińska et al. 2015).
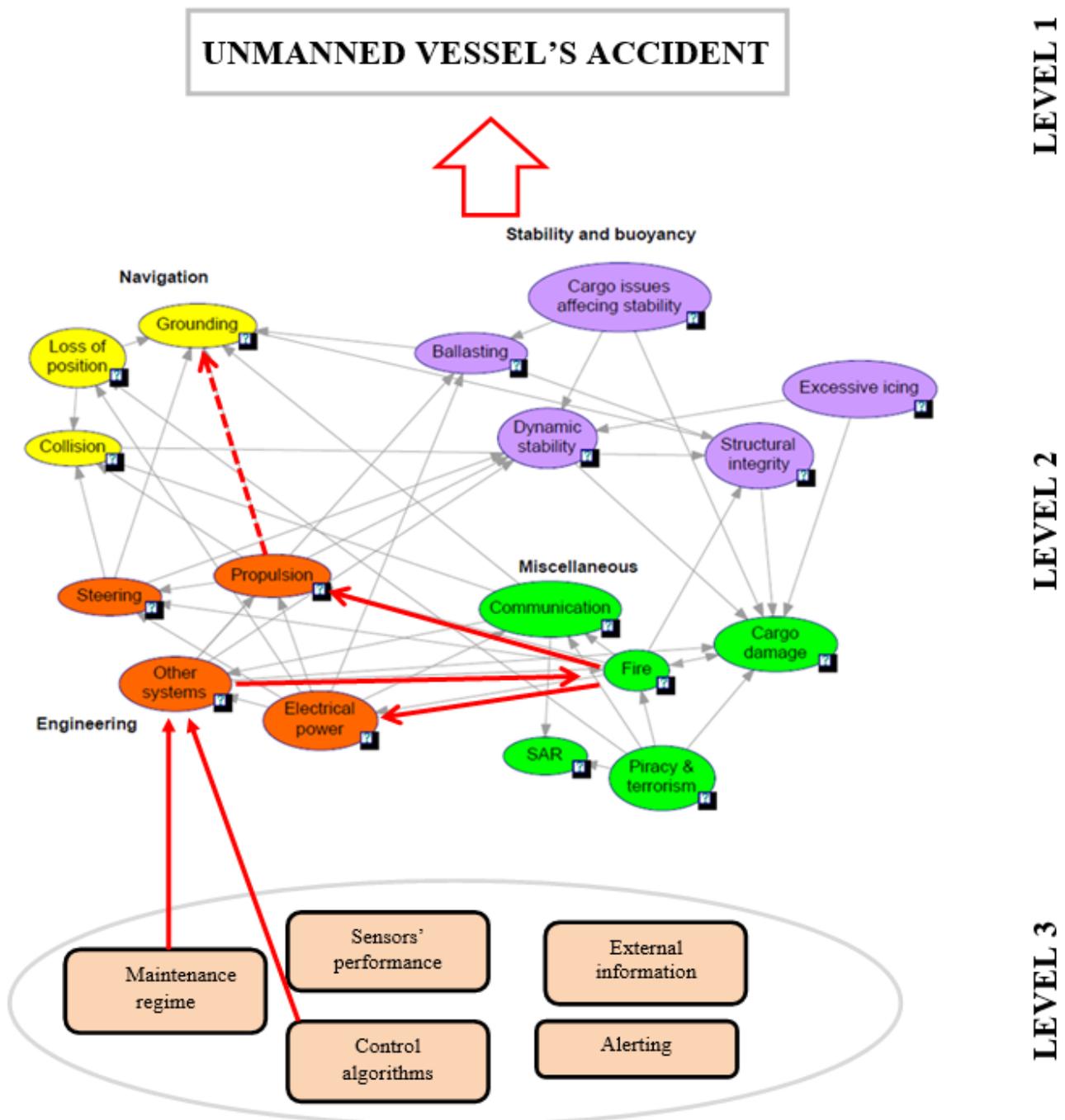

Figure 3. Validation of model's structure as applied to m/v 'Maersk Doha' accident

Most of safety features will also rely on secondary issues just to name maintenance regime, sensors and external information.

Uncertainties of the model are the result of future unmanned vessels' design, which remains to large extent unknown. On the other hand, this very paper is aimed in assisting future designers of such systems in their work by allowing them to trace some basic relationships between safety features.

Further uncertainties can be related to imperfections of brainstorming itself as a scientific method. Those are listed in (Isaksen 1998) and include issues regarding choice of experts, their productivity and potential lack of understanding.

4 FURTHER STEPS

Future work should include eliciting Bayesian network's parameters (probabilities). This will be achieved by involving wider group of stakeholders taking part in the process of planning unmanned ship design and operations. This will help to get insight into the design of a ship, allowing for the quantification of the technical reliability of the ship, along with the probabilities describing the occurrence and the negative effects of the anticipated hazards. Due to lack of historical data pertaining to unmanned ship operations, the experts' knowledge elicitation techniques will most likely be the only solution for the risk model parameterization.

Another issue relates to the definition of the acceptable risk level, which will be used as criteria for the safety assessment of the unmanned ships. However this issue remains in the responsibility of relevant maritime authorities rather than researchers, (Vanem 2012)(Rødseth & Burmeister 2015).

5 CONCLUSIONS

In this paper we present the results of the hazard analysis associated with the unmanned ships adopting brainstorming as a method of compiling experts' opinions on their safety features.

Hazards to which they will be exposed had been listed and structure of risk model developed in course of the study. The latter's parameters (probabilities or frequencies) are yet to be determined and shall be a subject of future work.

Results of our work suggest that safety of an unmanned ship as a system is made up of several features, most of which must not be considered separately from others. Basic incidents like sensors' malfunctions or flaws in mechanisms' maintenance regime can not only cause one of ships' subsystems to fail but can also propagate and trigger a chain of events that could eventually make a whole system collapse with catastrophic consequences. This underlines importance of not only using best-suited materials and equipment in construction of such vessels but also paying special attention to how subsystems' operation will affect others, particularly in extraordinary circumstances.

Our model is intended to be applied in unmanned vessels' design process from its early stages. After its parameters are determined, it can serve as useful tool for naval architects in identifying potential risks to unmanned ships and analyzing cost-effectiveness of solutions considered. We expect it to be improved in years to come when vessels under consideration are finally implemented thus making empirical data available.

REFERENCES

Allianz. 2015. Safety and shipping review 2015. Munich.

Burmeister, H.C. & Bruhn, W.C. & Rødseth, Ø.J. & Porathe, T. 2014. Can unmanned ships improve navigational safety ? In *Proceedings of the Transport Research Arena*, 14-17 April 2014. Paris.

Flage, R. & Aven, T. 2009. On treatment of uncertainty in system planning. *Reliability Engineering & System Safety 94(4): 884–90.*

Gawdzińska, K. & Kwiecińska, B. & Przetakiewicz, W. & Pelczar, M. 2015. Przyczyny wypadków i pożarów na statkach morskich. *Zeszyty Naukowe Akademii Morskiej w Gdyni* (91): 21–29.

Gerigk, M. 2015. Innowacyjne rozwiązania w zakresie okrętów i obiektów oływających. *Logistyka* 3: 1431–1438.

Gerigk, M. & Skorupski, J. 2012. Safety management of complex airborne and seaborne technical objects. *Archives of Transport* 24(3): 285–296.

IMO. 2002. Guidelines for Formal Safety Assessment (FSA) for use in the IMO rule-making process.

Isaksen, S.G. 1998. A review of brainstorming research: six critical issues for inquiry.

Jokioinen, E. 2016. Remote and autonomous ships - the next steps.

Krata, P. & Szłapczyńska, J. 2012. Weather hazard avoidance in modeling safety of motor-driven ship for multicriteria weather routing. *TransNav* 6(1): 71–78.

Kretschmann, L. & Rødseth, Ø. et al. 2015. *Maritime Unmanned Navigation through Intelligence in Networks final report - Qualitative Assessment.*

Kretschmann, L. & Mcdowell, H. et al. 2015. *Maritime Unmanned Navigation through Intelligence in Networks final report - Quantitative Assessment.*

Yemao, M. & Lundh, M. & Porathe, T. 2014. Seeking harmony in shore-based unmanned ship handling-from the perspective of human factors, what is the difference we need to focus on from being onboard to onshore? *Advances in Human Aspects of Transportation.* Part I: 231-239.

Marine Accident Investigation Branch (MAIB). 2007. *Report on the investigation of the machinery breakdown and subsequent fire onboard Maersk Doha.* Southampton.

Mazaheri, A. & Montewka, J. & Nisula, J. & Kujala, P. 2015. Usability of accident and incident reports for evidence-based risk modeling - a case study on ship grounding reports. *Safety Science* 76: 202–14.

Özgüner, Ü. & Stiller, C. & Redmill, K. 2007. Systems for safety and autonomous behavior in cars: The DARPA grand challenge experience. *Proceedings of the IEEE* 95(2): 397–412.

Rødseth, Ø.J. & Burmeister, H.C. 2015. Risk assessment for an unmanned merchant ship. *TransNav* 9(3): 357–64.

Rødseth, Ø.J. & Tjora, Å. & Baltzersen, P. 2013. *Maritime Unmanned Navigation through Intelligence in Networks final report - Architecture Specification.*

Rogoway, T. 2015. DARPA's unmanned submarine stalker could change naval warfare forever. http://foxtrotalpha.jalopnik.com/darpas-unmanned-submarine-stalker-could-change-naval-wa-1695566032 (retrieved July 1, 2016).

Rossiter, J.R. & Lilien, G.L. 1994. New 'brainstorming' principles. *Australian Journal of Management*. 19(1): 61-72.

Stokey, R. et al. 1999. AUV bloopers or why Murphy must have been an optimist: a practical look at achieving mission level reliability in an Autonomous Underwater Vehicle. *11th International Symposium on Unmanned, Untethered, Submersible Technology (UUST '99)*: 32–40.

Vanem, E. 2012. Principles for setting risk acceptance criteria for safety critical activities. In: *Advances in Safety and Risk Management:* 1741–1751. London.

Weber, P.G. & Medina-Oliva, G. & Simon, C. & Iung, B. 2012. Overview on Bayesian networks applications for dependability, risk analysis and maintenance areas. *Engineering Applications of Artificial Intelligence 25*(4): 671-682.