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Risk Assessment of a Battery-Powered High-Speed Ferry Using Formal Safety Assessment

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ABSTRACT

Full electric vessel has been under development to fulfil the restrict emission control strategy set up by International Maritime Organization requiring marine industry to reduce 40% of carbon dioxide emission by 2030 and 50% of greenhouse gases by 2050. This paper provides an risk assessment for a selected battery powered full electric vessel. Through identifying hazards and estimation of frequency and consequence, the most severe hazards will be determined so the top events will be analyzed by conducting event-tree analysis to evaluate the reliability. The results indicate the battery powered ship has a lower risk impact than traditional cruise ships.

KEY WORDS: Full electric; Battery power system; Risk; Hazard Identification; Event tree.

NOMENCLATURE

Symbols	**Full names**
€	euro
AC	Alternating Current
CAF	Cost of Averting Fatality
CAPEX	Capital Expenditures
CBA	Cost-benefit Analysis
CI	Consequence Indices
CO2	Carbon Dioxide
DC	Direct Current
DG	Diesel Generator
EMSA	European Maritime Safety Agency
ETA	Event Tree Analysis
FAR	Fatality Accident Rate
FIRESAFE	Study investigating cost effective measures for reducing the risk from fires on ro-ro passenger ships
FSA	Formal Safety Assessment
FTA	Fault Tree Analysis
FW	Fresh Water
GHG	Greenhouse Gas
GISIS	Global Integrated Shipping Information System
GOALDS	Goal Based Damage Ship Stability
GrossCAF	Gross Cost to Avert a Fatality
h	hour
HAZID	Hazard Identification
IMO	International Maritime Organization
K	thousand
LCA	Life Cycle Assessment
LOA	Length Overall
M	Million
MSC	Maritime Safety Committee
NetCAF	Net Cost to Avert a Fatality
NMA	Norwegian Maritime Authority
OPEX	Operating Expenses
P	Probability
PI	Probability Indices
PLL	Potential Loss of Life
PoB	Passengers on board
PV	Photo Voltaic
RCOs	Risk Control Options
RI	Risk Indices
RoPax	Ro-Ro Passenger Ship
SAFEDOR	Design, Operation and Regulation for Safety
STABALID	Stationary Batteries Li-ion safe Deployment
SW	Sea Water
TrAM	Transport: Advanced and Modular
VCG	Vertical Centre of Gravity
ZEBRA	Zero Emissions Batteries Research Activity

INTRODUCTION

Nowadays, sustaining for a green world has rapidly become an increasingly hot topic. International shipping has made a huge contribution to achieve a sustainable world and provides world's most transportation services while generating least emissions released to atmosphere. According to IMO's third GHG study, 80% of global transportation by volume is delivered by international shipping and the carbon dioxide emission generated from shipping activity only occupies 2.2% of global emissions (Smith et al. 2015). However to meet the ultimate goal of eliminating GHGs and constructing a zero GHG emission world, IMO has set up its timetable to deliver the emission control step by step. By the year of 2030, it targets to reduce 40% of carbon dioxide emission from the marine sector and by the year of 2050,

at least 50% of total GHG emissions from marine industry must be mitigated which is about 85% of CO_2 reduction per ship. Owing to this challenge, many technologies are emerging and under development in order to not only reduce the emission generation but also strive to eliminate them permanently. One of the technologies popularly under consideration is the full electric ship which is a concept using energy storage system as the power source of marine vessels, such as battery and supercapacitors.
Battery power system has been investigated by many researchers: Galloway and Hustmann have investigated the material cost and recycling of battery in automotive industry (Galloway and Dustmann 2003). Dai's research has analyzed Lithium-ion battery for automotive application using life cycle approach which indicates the impact of battery are coming from manufacturing phase but depending on the production location and the material sources from the perspective of emission control (Dai et al. 2019). It proved the research results from Dunn etc. in 2016 who have presented summary for li-ion battery production and recycling (Dunn et al. 2016). It is further investigated by Raugei and Windfield in 2019 (Raugei and Winfield 2019). Zhao and You have carried out a comparative study on Li-ion battery through process based and integrated hybrid LCA approach. In their research, it compared the greenhouse gas emission and energy consumption of two types of batteries ($LiMn_2O_4$ (LMO) and $Li(Ni_xCo_yMn_z)O_2$ (NCM) battery) and difference in the aspect of LCA is focused on the recycle part (Zhao and You 2019). Hiremath etc. have investigated and compared different battery storage system applied for stationary applications using LCA approach (Hiremath, Derendorf, and Vogt 2015) and Matheys etc. have evaluated the environmental impacts of 5 electric vehicle battery system to find out the preferred one for automotive industry (Matheys et al. 2009).

In the maritime transportations, most research are about hybrid system combining battery with marine diesel engines: Back to 1999, Kluiters etc. have started to consider battery system for marine vessels and the sodium/nickel chloride ZEBRA battery has been tested investigated for navy vessels by simulating the charge and discharge processes based on practical operation (Kluiters et al. 1999). Lan etc. have conducted an optimization of a hybrid system for ship power system including photovoltaic, diesel engine and battery which illustrated the optimal sizing of three components for a ship with route from China to Yemen by minimizing exhaust CO_2, investment and fuel costs (Lan et al. 2015). Concerning environmental and financial impacts, Misyris etc. also investigated the use of battery on marine vessels (including hybrid and full electric ships) and developed a parameter identification method and an evaluation and validation method for battery state estimation which will be supporting the battery performance evaluation during the on board operation (Misyris et al. 2017). Yu etc. have investigated the potential of combining PV/battery/generator for short route ferries operated in inland water of China and the assessment has taken into account of the electric charged while in port (Yu, Zhou, and Wang 2018). Another assessment on full-electric ships was carried out by Zahedi etc. which investigated a system includes diesel engines, synchronous generator-rectifier units, a full-bridge bidirectional converter, and a Li-Ion battery bank as energy storage. The potential fuel saving of this application was estimated for an offshore support vessel (Zahedi, Norum, and Ludvigsen 2014).

Although the benefits of battery power system application has been broadly evaluated specifically from the perspectives of fuel cost saving and environmental protection, the recommendations of this application can hardly be realistic due to the lack of reliability checking about the adopted system. Currently the battery related risk assessment is not so sufficient that while operating the battery system on marine vehicles accidents usually come alone due to lack of risk assessment and prevention methods. Some existing risk assessment on battery systems are focusing on automotive or stationary applications:

Wang etc. have carried out a review on li-ion battery on its failure mode and fire prevention strategies for electric vehicles and energy storage system (Wang et al. 2019). In STABALID project, risk assessment was carried out for stationary li-ion batteries to show the possibility to reduce the probability of frequency/consequence of all the risks related to the battery life cycle to acceptable or tolerable levels (Soares et al. 2015). Another research work is to investigate the application of battery system in PV applications to estimate the performance of the system from the perspective of CO_2 emission reduction in order to meet the requirement from Paris Climate Change Agreement (Jones et al. 2017). However, there is now a few researches carrying out maritime risk assessment on battery power plants. Some exiting research works have mentioned some points in this subject but still limited to a confined objective. Jeong etc. have developed a multi-criteria decision making approach for hybrid battery-engine system and focused on cost-environment-risk issues (Jeong et al. 2018). The risk assessment carried out could be further expanded to more detailed hazard identification and risk assessment. There have been many classification providing guideline for battery application on board ships and one of the most important issue is the risk assessment (Andersson et al. 2017; DNV GL 2019). Therefore, to investigate the reliability of the battery system applied in marine sector, this paper will utilize HAZID and ETA methods to identify the possible hazards and top event during the life span of battery power vessel and to quantitatively estimate their risk impacts (including frequency, consequence and risk levels).

METHODOLOGY

This paper will apply a series of method to quantitatively assess the safety and reliability of full electric ferry. A general FSA will be carried out supported with HAZID, fault tree and event tree analysis.

Formal Safety Assessment (FSA) is a risk assessment approach approved by IMO to evaluate the risk issues associated with shipping industry and to determine the cost and benefits of RCOs to reduce the potential risks (IMO 2018). It comprises 6 steps as shown in Figure 1. In this study, Step 1 will be supported by HAZID; Step 2 will be provided in FT and ET; the approach of cost-benefit assessment will be presented in the last step.

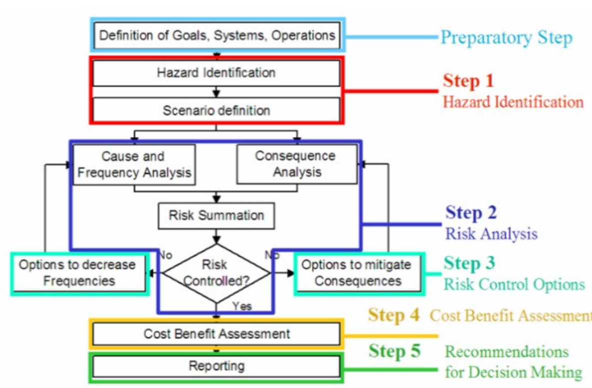

Figure 1 General approach of FSA

Hazard Identification (HAZID) is an essential part of the risk assessment where participants, including ship operators, technology inventors, manufacturers, assessment investigators and regulation makers, sit down and brainstorm all the possible hazards during the ship's holistic life span. It also need to consider the existing database, reports, latest regulations and guidance. The HAZID will confirm the most concerned hazards for the ferry and provide frequencies and consequence levels for each hazards so that a quantitative risk assessment could determine the risk levels from risk matrix. A risk matrix could be developed using defined consequence and probability indices by a logarithmic scale. A risk index can be established by adding the probability/frequency and consequence indices. The logarithmic scale of the Risk Index for ranking purposes of an event can be presented in 1:

$$\begin{aligned} &\text{Risk} = \text{Probability} \times \text{Consequence}, \\ &\log(\text{Risk}) = \log(\text{Probability}) + \log(\text{Consequence}), \qquad (1) \\ &RI = PI + CI, \end{aligned}$$

The frequency and consequence are defined and categorized as shown in Table 1 and Table 2. The possibility index ranges from 1 to 7 presenting the likelihood of hazard happening in one ship year. The consequence index ranges from 1 to 5 showing the severity of the consequence based on the impact of hazards such as cost or fatality. In this step, the experience and judgement from the participant of shipping industry will be adapted. All the indices will be filled in to the risk analysis table and then the risk impacts/results will be calculated directly (see Table 3). With the definition of risk levels, the levels of hazards will be determined. There are many different hazard impacts justifying the consequence level, such as effects on ship and effects on potential loss of human life. However, in one study, one appropriate effect should be selected. In this study, effects on ships will be firstly considered and in the following steps, the impacts on assets, fatality and environment will be considered.

Table 1. Definition of probability index

PI	Probability	Definition	P (per ship year)
7	Frequent	Likely to occur once per month on one ship	10
5	Reasonably probable	Likely to occur once per year in a fleet of 10 ships, i.e. likely to occur a few times during a ship's life	0.1
3	Remote	Likely to occur once per year in a fleet of 1000 ships, i.e. likely to occur in the total life of several similar ships	1E-03
1	Extremely remote	Likely to occur once in the lifetime (20 years) of a world fleet of 5000 ships	1E-05

Table 2. Definition of consequence index

SI	Severity	Ship safety & technology	Equivalent fatalities
1	Minor	Local equipment damage (repair on board possible, downtime negligible)	0.01
2	Significant	Non-severe ship damage - (port stay required, downtime 1 day)	0.1
3	Severe	Severe damage - (yard repair required, downtime < 1 week)	1
4	Catastrophic	Total loss (of, e.g. a medium size merchant ship)	10

Table 3. Risk matrix

PI Probability		SI Severity			
		1	2	3	4
		Minor	Significant	Severe	Catastrophic
7	Frequent	8	9	10	11
5	Reasonably probable	6	7	8	9
3	Remote	4	5	6	7
1	Extremely remote	2	3	4	5

Fault tree analysis is applied to determine the probabilities of top events in order to identify the most concerned events. A FTA will be based on the hazard identified in the HAZID and applying Bayes' Theorem to determine the final probabilities of top events (Kristiansen 2013). The Bayes' Theorem is stated in 2:

$$P(A|B) = P(A)\, P(B|A)/P(B) \qquad (2)$$

Where,
A, B are events under consideration;
P(A), P(B) presents the independent probabilities of A and B;
P(A|B) presents the probability of A given B is true;
P(B|A) presents the probability of B given A is true.

All the identified hazards will be sorted based on the consequences in order to categorize them into different top events which will help to build the event tree and carry our event tree analysis afterward. Event tree analysis is an inductive way to show all possible outcomes from an initiating event which could be sub system failure, external event (like flood, fire, and earthquake) or operator error. Event tree can be used to model the sequences including the relationships among initiating event, subsequent responses and final states. Various accident sequences will be identified and probability of occurrence of each sequence will be further quantified in an event tree analysis. The procedures for event development are shown in Figure 2.

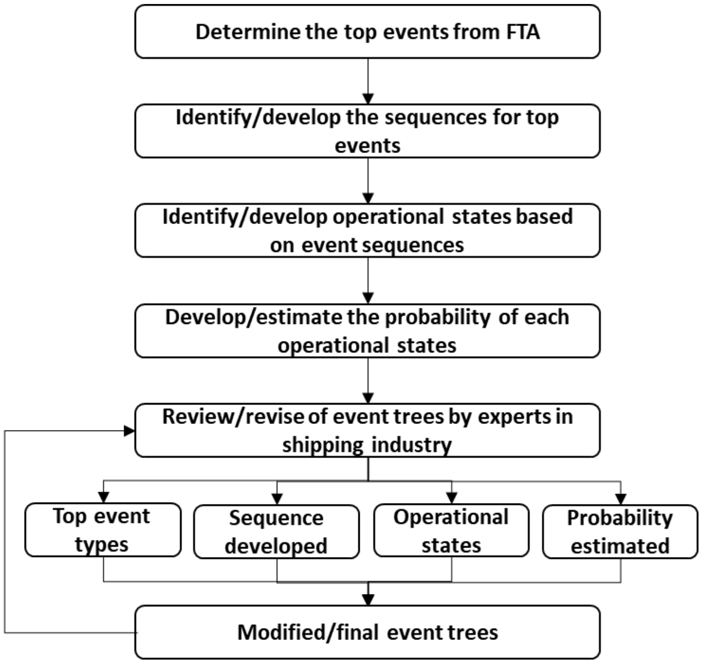

Figure 2. Event tree assessment approach

To carry out an ETA, based on the FSA report for cruise ship and data from GOALDS, event trees are established first. With the sequences, event trees for the case ferry could be developed. Although the findings of quantitative risk assessment can be determined using above mentioned approaches, it is necessary to investigate measures which could improve the design further. According to the methodology used, a Cost-Benefit Assessment (CBA) is required in order to rank the appropriateness of the proposed Risk Control Options (RCOs). The Gross Cost to Avert a Fatality and the Net Cost to avert a fatality are used as indicators. The definitions of GrossCAF and NetCAF are given here below in 3 and 4:

$$\text{GrossCAF} = \Delta C / \Delta R \quad (3)$$
$$\text{NetCAF} = (\Delta C - \Delta B) / \Delta R \quad (4)$$

Where:
GrossCAF: The cost of RCOs per fatality reduced.
NetCAF: The net cost (cost minus the economic benefit of RCOs) per fatality reduced.
ΔC is the cost per ship of the risk control option during the lifetime of the vessel.
ΔB is the economic benefit per ship resulting from the implementation of the risk control option during the lifetime of the vessel.
ΔR is the risk reduction per ship, in terms of the number of fatalities averted, implied by the risk control option during the lifetime of the vessel.

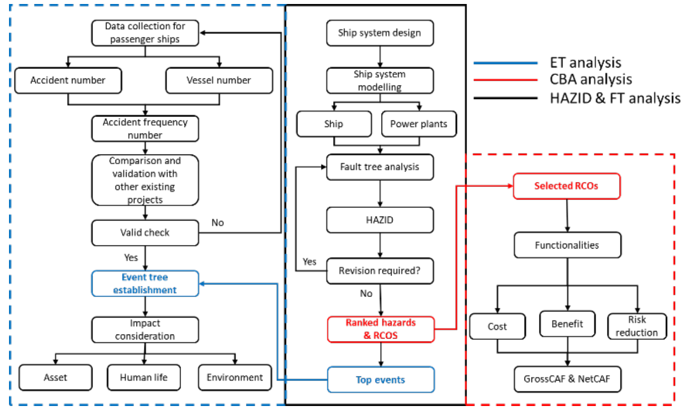

Figure 3 Overview of approaches relationships: HAZID, FTA, ETA and CBA

This paper will follow the procedure of FSA to evaluate the risk impact of full electric ferry. HAZID will identify potential hazards during the design, construction and operation of the ferry and the installation and usage of the battery power system. A schematic diagram was shown in Figure 3 to present the overall and collaboration of approaches in this study. Within the identification processes, the frequency and consequence levels will be estimated based on experts' experience and judgement in order to determine the risk impacts of the hazards. It will also help to identify a list of most concerned top events which will be analyzed using ETA to determine the frequencies of a series of accident scenarios. The impacts under different scenarios will be further evaluated from the perspective of asset financial cost, fatality cost and environmental recycle cost. To make sure the data collected providing reasonable and acceptable results, a validation process will be used to test the data collected for passenger ships before applying to high-speed inland waterway ferries. The validation will be conducted by comparing the determined accident frequencies with other projects: GOALDS, SAFEDOR and FIRESAFE (EMSA 2016; Grønstøl 2006; Hamann, Olufsen, and Zaraphonitis 2017; Nilsen 2006). Until the model is valid, the same approach will be carried out for ferries in order to determine the accident frequencies for this type of ship. A list of risk control options with cost and their potential to reduce the accident frequencies will be provided based on the recommendations of HAZID members (experts from shipyard, ship operators, technology providers and research institutes). Eventually, the risk assessment will be quantified from risk levels to financial costs which provides a straightforward approach to shipping industry to evaluate the performance of full electric vessels from the perspective of risk.

CASE STUDY

To investigate the safety and reliability of battery power plants on marine vessels, one case ship study was carried out on a high-speed battery powered ferry operated in Norwegian Sea which area covers many small islands and requires frequent passenger transportation between islands and mainland. The specification of the case ship has been presented in Table 4.

Table 4. Case ship specifications and general arrangement

Main dimensions			
LOA	35 m	Number of stops	up to 12
Breadth	10 m	Passengers	147
Height	23 m	Crew	3

Draft	2.5 m	Motor	2 x 400 KW
Lightship	200 tones	Battery capacity	1 MWh
Operational speed	23 knots	Route length	23 nm
Service time per day	Up to 20.5 hours	Route serviced per day	14 times

The battery power system includes two packs of batteries, located on port and starboard sides of the case study ferry. The layout of the battery power plant on the vessel is presented in Figure 4. It shows two identical battery packs are connected to the DC hubs and through power module (DC/AC convertors) they can provide energy to motors, driving propellers and thrusters, and hotel loads. The battery packs will be charged while in port from local grid power or existing auxiliary power supply in the shore changing station. The capacity of the Wartsila approved battery packs is 653 kWh and the output voltage ranges from 672 to 896 V. To identify the hazards among the battery system, the systems of innovative battery and conventional engine power plant are simplified as shown in Figure 5 and Figure 6. Inside the dash line area, the deviations between two power plants are highlighted so that the risk assessment will be focused in these components.

RISK ASSESSMENT RESULTS AND DISCUSSION

According to the methodology, the risk assessment has been carried out and results were determined and presented in the following sections including hazard identification, accident statistic, event tree analysis and cost-benefit assessment of identified RCOs.

A risk register was developed during the HAZID meeting (shown in Appendix A. Risk Register) and the consequent follow-up work and discussions on estimating probabilities and consequences of the identified hazards and their ranking were carried out to determine the most concerned top events: collision, contact, grounding and fire. The risk register containing a total of 55 hazards whose frequencies and consequences were evaluated. The following number of hazards was identified:

- Design, construction, installation (21 hazards)
- Operation (25 hazards)
- Emergency (9 hazards)

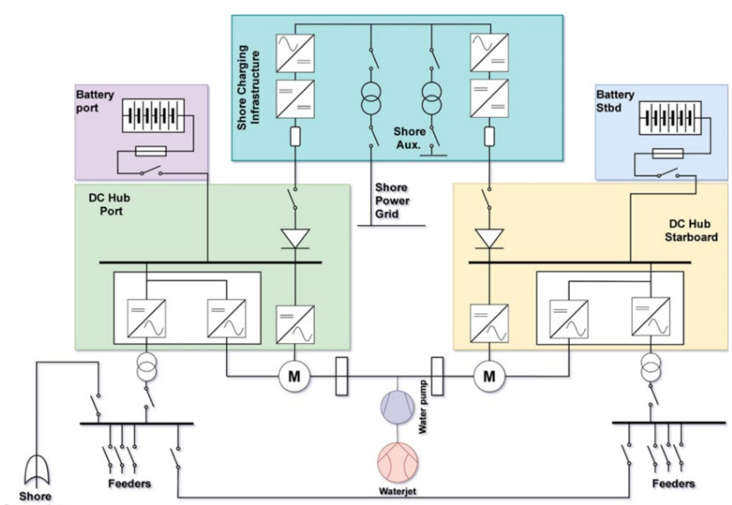

Figure 4. Single line layout of battery power plant on the case study ferry

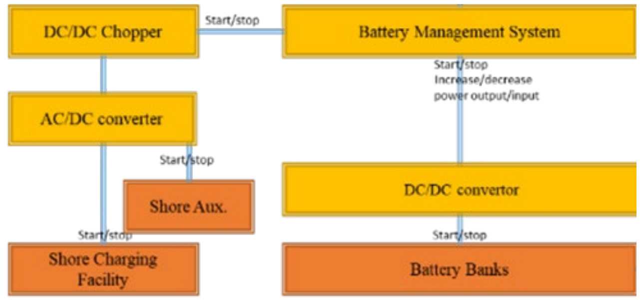

Figure 5. System diagram of battery power plant

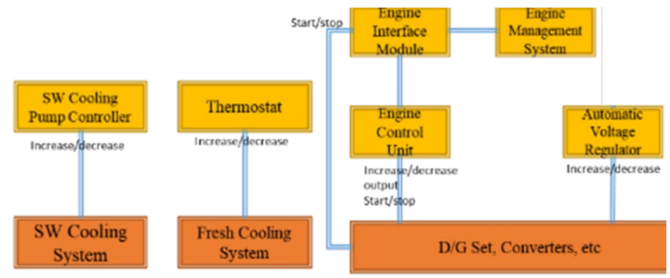

Figure 6. System diagram of engine power plant

One of the challenges with the Qualitative Risk assessment is the collection of reliable data regarding past accidents. The challenge in this case is that the previous FSAs have not addressed inland/protected water and high-speed vessels similar to our designs. In this respect, new data had to be collected. The accident data derived from GISIS: Marine Casualties and Incidents (IMO). Passenger ship accident data were collected and there are 337 accidents in the database, and the numbers of accidents in different categories were determined and listed (IMO 2020). According to data provided by Sea-web (IHS Markit 2020), the number of passenger vessels in the world merchant fleet in a yearly base were derived and the ship-year of global passenger ship is 4872. The accident frequencies for global passenger ship fleet are derived and presented in Figure 7.

The newly collected data are compared for verification purposes with the frequencies found in previous projects, namely GOALDS and SAFEDOR. GOALDS reported the accident frequencies (collision and grounding) for cruise ship and RoPax from 1994 to 2010; SAFEDOR reported the accident frequencies (collision, contact, grounding and fire) for cruise ships and RoPax respectively from 1994 to 2004. It is obvious that the result from this study, are at the same exponential level with the previously reported figures.

For the fire accident frequency, the results from FIRESAFE project were used which indicates that the fires on ro-ro vessels have a frequency (per ship year) of 5.79E-03. In this report, it mentioned the fire accident frequencies from DNV GL are 5.83E-4 (year 1990-2003) and 2.00E-3 (year 2005-2016). According to SAFEDOR, it is about 1.02E-3. Therefore, the fire accident frequency is expected to be in the order of 10^{-3}.

Following the same approach, the number of accidents for the global ferry fleet is derived based on the accident database (GISIS) and the number of inland waterways ferries in the world from 2006 to 2018 are determined from Sea-web database which in total has 1178 existing. The incident frequencies are determined and shown in Table 5.

It is reasonable to have much lower accident frequencies for all the categories since ferries are usually operation close to shore which has shallower water comparing to offshore condition.

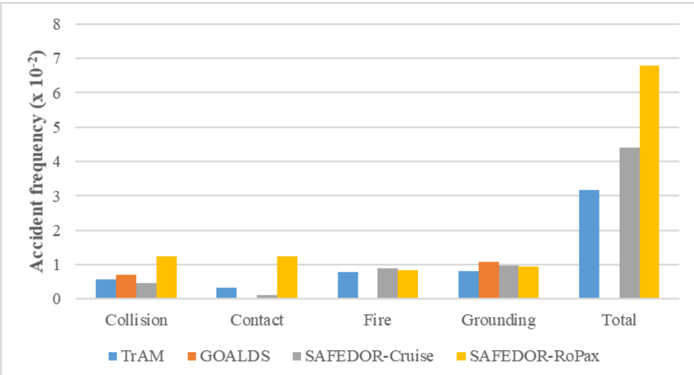

Figure 7. Comparison of Accident frequency results between this study and existing projects

Table 5. Number of incidents and frequencies for global ferry fleet

Accident	No of accidents	Percentage	Accident frequency
Capsizing / listing	9	19.15%	1.24E-03
Collision	8	17.02%	1.10E-03
Contact	7	14.89%	9.64E-04
Fire	10	21.28%	1.38E-03
Stranding / grounding	11	23.40%	1.52E-03
Flooding	0	0.00%	0.00E+00
Injury & fatality	1	2.13%	1.38E-04
Machinery damage	1	2.13%	1.38E-04
Total	47	100%	6.47E-03

After determining these data, an event tree analysis has been conducted to determine the impact of the different accident scenarios. Based on the results from the HAZID session and the analysis of available accident statistics, the following top events were selected for event tree analysis and the sequences are described and presented in the following section:

1. Collision

Struck/Striking => Operational state =>Water Ingress => Sinking => Consequences

2. Contact

Contact =>Water Ingress => Sinking => Fatalities => Consequences

3. Fire

Escalation => Extinguishing speed => Damage degree => Consequences

4. Grounding

Navigation => Sea Bed => Water Ingress => Staying Aground => Afloat => Consequences

The risk reductions, costs and benefits brought by the different RCOs were estimated based on the feedback from the experts in the consortium so that the cost-benefit impacts can be determined after applying the RCOs. Their values will be updated when more details about the design are available and market prices are confirmed. There are 7 potential RCOs identified after HAZID indicating the most severe hazards:

1. Move the battery room on the main deck

Moving the battery room of the case study vessel on the main deck will reduce the risks associated with potential fire in that room. This is in line with NMA's recommendations. This measure will also have the benefit of reducing the allowable minimum breadth of the demihulls, resulting to potential total resistance reductions (-15%) which will produce CAPEX (battery costs) and OPEX (recharging costs). On the other hand, it will raise the vertical center of gravity (VCG) and affect the stability, but due to the catamaran design, this will not affect adversely its collision, contact and grounding risks.

2. Select proper firefighting system

A firefighting system will be coupled with the ferry which requires new ship design and construction and the operation and maintenance cost of the system shall be considered.

3. Add alarm system

An alarm system will be coupled with the ferry which requires new ship design and construction and the operation and maintenance cost of the system shall be considered.

4. Pre-test system/equipment

Pre-test any new system and equipment before the installation will avoid to have incidents/accidents while operating. It will require system/equipment inspection and checking where labors and testing equipment will be necessary.

5. Supply protection for crew

Protections such as goggles, gloves and jackets should be provided to crews while working on board and repairing faulty systems. The associated costs are investment of these protections and might be replacing them every a few years to keep the quality to be well functioning.

6. Regular inspection and maintenance

This is necessary to prevent accident and incident from happening. This requires labor investment as well as replacement of aging spare parts.

7. Crew training

Crew training should be included in all phases, i.e. construction, operation and maintenance phases, in order to avoid unskilled persons who might mis-operate and cause accidents.

The costs, benefits and risks associated to the application of RCOs are estimated and presented in Table 6. The cost data based on experts' recommendation, judgment and experience. The costs of the RCOs include the investment (CAPEX) and operational cost (OPEX). The potential reduction rate on accident frequencies (collision, contact, grounding and fire) of each RCO was estimated. With an assumption of 20 years ferry life span and 5% interest rate, the gross and net cost-benefits were determined. It indicates RCO 1 (relocation of the battery room on the main deck), bring the highest benefits. For RCO 1 this corresponds to €112.3K savings while averting a fatality but other RCOs require capital investment to help to reduce the potential loss of life.

Table 6. Cost and benefit assessment of RCOs

RCOs	1	2	3	4	5	6	7
PLL (fatalities/shipyear)	1.61						
Reduction	10%	10%	5%	5%	5%	7.5 %	7.5 %

ΔPLL (fatalities/shipyear)	0.161	0.161	0.080	0.080	0.080	0.120	0.120
Cost (€)	-30000	20000	10000	20000	5000	0	10000
Annual Maintenance Cost (€)	0	5000	2500	0	1000	5000	1000
ΔC (€)	-30000	82311	41156	20000	17462	62311	22462
Gross CAF (€)	-9339	25624	25624	12452	10872	25864	9323
Annual Benefit (€)	26544*	0	0	0	0	0	0
ΔB (€)	330802	0	0	0	0	0	0
NetCAF (€)	-112319	25624	25624	12452	10872	25864	9323

*Energy saving due to moving battery room on the main deck which brings improvement of ship hull form and reduces the resistance.

CONCLUSION AND RECOMMENDATIONS

From this paper, it presented an approach to assess the risk and safety level for a battery-driven high-speed catamaran ferry using HAZID, fault tree, event tree and cost-benefit assessment. The HAZID meeting provided experts' judgement and experience on identified hazards to determine the levels of frequency and consequence of these hazards. A supplement is made to the hazard register to include more concerned risk incidents in the register. Also based on the expertise of the HAZID members, some hazards have been eliminated and are not necessary to be included. Based on the HAZID results, four most severe top events were identified: collision, contact, grounding and fire. With data collected from IMO and Sea-Web database, the accident frequencies of these top events were determined for both passenger ships and ferries. Referring to GOALDS project and the FSA report for cruise ships (IMO), event trees were established for all types of passenger ships. During the HAZID meeting, the event trees were modified based on experts' suggestion to fit for HSC ferries. With consideration of financial, potential loss of life and environmental impacts, eventually the total risk and its impact were determined for the selected ferry and were compared to large passenger ships as well as other types of ferries.
The findings of the risk and safety assessment suggest that:

- The accident frequencies for vessels, high-speed battery-driven ferries, are not significantly different from the ones for larger passenger ships;
- The system architecture, especially the battery management system, doesn't give rise to any concerns regarding higher accident frequencies. This of course will have to be confirmed with the final BMS design and the more detailed analysis the manufacturer will perform as the ship design progresses;
- The quantitative risk assessment show that the vessel's design is as safe as existing ships.
- Risk control options for further reduction of the risk have been examined. Among all the proposed risk control options, option 1, namely the relocation of the battery room on the main deck is the most cost-effective RCOs.

Furthermore, the results from this paper could be updated along with a more complete battery system and ferry design. With further detail information about the system and the ferry, a more accurate assessment will be achieved.

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APPENDIXES

Appendix A: Risk Register

Hazards				RCOs	P	C	R
No.	**Initial accidental event**	**Cause**	**Consequence**				
Design, construction, installation							
1	Ferry overheight	Designed battery pack didn't comply with the height requirement for ferries operated in Thames River	Contact	Check design to fulfil the requirement	1.27	4.10	5.37
2	Too big battery	Too large battery in size and weight	Failed the classification check	Design optimization	1.00	4.20	5.20
3	Steel overweight	Change of ferry structure and design due to battery system	Failed the classification check	Design optimization	1.10	4.60	5.70
4	Battery breach	Physical damage: cut, shock, vibrations, metal projection	Fire, Corrosion, Asphyxia	Pre-test system/equipment when arrived and after installation	1.40	4.60	6.00
5	Battery fail to start	Component damaged due to harsh installation environment	Power unavailability	Check and test system when arrived and after installation; follow the installation manual	1.64	4.10	5.74
6	Thermal runaway	Occur flame or heat source	Fire	Install firefighting system	1.33	4.66	5.99
7	Battery room damaged	Didn't comply the ship hull design rule: keep certain distance between battery room wall and outer hull during collision contact and grounding	Flooding, ship power loss	Check design to fulfil the requirement	1.09	2.10	3.19
8	Loss of propulsion or steering	Battery room contains other systems supporting essential vessel services	Ship power loss	Remove unnecessary systems in battery room	1.17	3.34	4.51
9	Battery room damaged	Battery room is positioned before the collision bulkhead	Flooding	Follow DNV GL's regulation on battery room arrangement	1.09	2.10	3.19
10	Loss of essential services	Battery room contains other systems supporting essential vessel services	Other essential services failed	Follow DNV GL's regulation to avoid other systems in battery room	1.64	2.64	4.28
11	Fire and explosion in battery room	Heat sources or high fire risk objects in battery room	Fire and explosion	Follow DNV GL's regulation on battery room arrangement	1.18	3.00	4.18

12	Gas development (toxic, flammable, corrosive)	No system equipped; not start automatically; low capacity; no local start-stop system; lack of monitoring; no alarm system; sensor malfunctioning	Asphyxia; fire	Follow DNV GL's regulation on ventilation requirement	1.09	4.64	5.73
13	Release of flammable/toxic gases	Failure/damage of the battery system; lack of detection	Fire and explosion	Follow DNV GL's regulation on Hazardous area design	1.09	4.82	5.91
14	Fire and explosion in battery room	No fire assessment; no detection methods; improper fire extinguishing	Fire and explosion	Design follow DNV GL's regulation on Fire integrity	1.09	6.10	7.19
15	Short circuit in battery or power system	Fail to shut the battery: 1 No circuit breaker available; 2 no fuses available; 3 wrong breaker selected.	Power loss	Equip with switchgear	1.42	4.50	5.92
16	Overvoltage and undervoltage	Bad converter design	Potentially fire	Test of converters and regular inspection; add alarm	1.25	3.34	4.59
17	Battery system unavailable	Insufficient testing: interface, converter, system and its auxiliaries, and the installation space (possible ventilation, liquid cooling, gas detection, fire detection, leakage detection)	Battery damaged	Test of the whole system and regular inspection; add alarm; and add condition monitoring system	1.67	3.00	4.67
18	Battery out of power	Selected battery capacity insufficient	Other essential services failed	Design to fulfil the power requirement	1.50	3.00	4.50
19	Battery fall	Collision; too high battery (improper design)	Battery damaged; injury	Reduce stack height; batteries shall be properly attached to the ship hull.	1.17	3.00	4.17
20	Low battery power	Low capacity of battery; low charging rate of charging system	Power unavailability	Understand and match the system to the operational profile	1.08	2.34	3.42
21	Evacuation obstructed	Evacuation station too close to battery room	Fail to evacuate	Evacuation plan simulation; risk based ship design.	1.00	3.00	4.00
Operation							
a. Voyage							
1	Battery breach	Cut, shock, vibrations, metal projection on battery	Fire, Corrosion, Asphyxia	Restrict access to and objects in battery rooms	1.00	5.00	6.00
2	Thermal runaway	Heat sources or high fire risk objects in battery rooms	Fire, Corrosion, Asphyxia	Comply with the rule of no heat source in battery rooms and install alarming and firefighting system	1.20	5.20	6.40
3	Battery on fire	No communication between EMS and the packs	Fire	Keeping the packs powered up; Ensure ESS parameters are showing on the interface; and install alarming and firefighting system;	1.64	5.18	6.82
4	External short circuit	Wire aging, bad insulation	System failed; injuries	Wear protection gloves and check & replace aging wire	1.55	3.36	4.91
5	Gas off the battery (toxic, flammable, corrosive)	Failure/damage of the battery system	Fire, Corrosion, Asphyxia	Ventilation system	1.09	4.28	5.37
6	Battery fail to disconnect	Battery management system failed; no emergency disconnections	Fire	Regularly maintenance the BMS; Disconnection switch installed	1.10	3.90	5.00
7	Internal thermal incident	No emergency instruction; aging wire	Battery damaged	Include instructions and avoid heat or sparks	1.60	2.80	4.40
8	External fire	No emergency instruction; heat source nearby	Fire and explosion	Prepare emergency document; keep battery from heat, spark and fire; firefighting system	1.27	4.28	5.55
9	System failed	Lack of systematic maintenance and function testing and observation	Battery damaged	Advance inspection and testing; maintenance and change regularly; condition based monitoring system	1.55	2.64	4.19
10	Fire and explosion	Overtemperature	Fire and explosion	Ventilation system; avoid heat source in BM and install alarming and firefighting system;	1.30	5.80	7.10
11	Battery fall	Collision; too high battery (improper design)	Battery damaged; injury	Reduce stack height; strength and maintain battery shelves	1.00	3.20	4.20
12	No cooling of battery	Failures of fans; loss of coolant	Battery damaged	Include monitoring and inspection	1.73	2.26	3.99
13	Passenger get in the battery room	Lack of sign and warning	Battery damaged; injury	Add warning sign; lock the battery room	1.09	1.18	2.27
14	Terrorism	Enormous media attention	Loss of ship, fatalities	Apply ISPS Code, anti-piracy procedures to be in place and ship security	1.00	5.90	6.90
15	Cyber-attack/connect to wrong system	Enormous media attention; lack of cyber security protection	Loss of ship	Include security system; cautions of spam emails and regulating the remote access	1.27	3.90	5.17
16	Damage to the hull	Electrical-chemical corrosion due to high DC from shore charging to ship	Corrosion	Supply protection for crew; regular inspection and maintenance	1.00	5.00	6.00
17	Battery life span shortened	Battery working at adverse SOC	Battery damaged	Detection; alarm systems	1.00	3.00	4.00
b. Arrival/departure to/from port							

1	Battery overcharging/overheating	No automatic disconnection or lack of monitoring; failure of temperature sensors	Battery damaged	Charging/discharging failure shall give alarm at a manned control station.	1.30	2.40	3.70
2	Battery fail to start	Component damaged due to bad battery operation and harsh operation conditions	Battery damaged	Check and test system before servicing; follow the operation manual	1.70	2.00	3.70
3	Battery management system failed	Overvoltage and undervoltage without protection	Fire	Converter designed following regulation	1.64	3.18	4.82
4	Human error	Lack of crew training on maneuvering	Collision, contact, grounding	Train crew before onboard and provide guide for operation.	2.55	3.36	5.91
5	Collision	Operation failure, Struck by other ship	Total loss	Enhance navigation system; crew training	1.00	7.00	8.00
6	Contact	Bad maneuvering	Hull damaged	Train crews; include anti-contact equipment	2.00	1.00	3.00
7	Grounding	Mooring ropes broke; An insufficient or improper information of the port or the navigational water ways	Hull damaged	Navigation system/plan; berthing system	2.00	3.00	5.00
8	Charging station damaged	Lack of protection: hit by objects (cable, plug etc.); electrical hazard; overheating	System/equipment damaged	Pre-test system/equipment; standard electrical safeguarding (fuses, breakers, overvoltage protection, power control etc.)	1.00	5.00	6.00
Emergency operation							
1	Fire propagation	Improper firefighting system; fire door failure; no detection or alarm	Total loss	Apply proper firefighting and alarming system; regular inspection and maintenance on fire door;	1.10	5.40	6.50
2	Evacuation failed	Lack of ladders, rope, lifebuoy and life jacket; evacuation blocked	Fatalities	Evacuation equipment check; arrangement of evacuation route	1.00	5.60	6.60
3	Collision	Operation failure, Struck by other ship	Total loss	Enhance navigation system; crew training	1.50	6.60	8.10
4	Contact	Bad maneuvering	Hull damaged	Train crews; include anti-contact equipment	2.40	2.40	4.80
5	Thermal runaway	Battery power down during events; no other packs running	Fire	Keep battery power on; run other battery systems	1.10	3.80	4.90
6	Crew unsafe when entering the room	Lack of ventilation, protection, initial assessment and check	Asphyxia	Keep the ventilation system running, Supply protection for crew; inspection before entering the site	1.10	5.20	6.30
7	Crew unsafe when removing damaged equipment	Lack of ventilation; system still working while removing; lack of training, assessment, monitoring, inspection of other module in same column	Asphyxia	Keep the ventilation system running; crew training; assessing and monitoring before crew entering to remove	1.10	5.00	6.10
8	Grounding	Mooring ropes broke; An insufficient or improper information of the port or the navigational water ways	Hull damaged	Navigation system/plan; berthing system	2.00	3.00	5.00
9	Flooding	Contact, collision, grounding.	Capsizing	Regular inspection and maintenance on ship hull and watertight doors	1.00	5.00	6.00

Appendix B: HAZID Participants: Short CVs

Professor Evangelos Boulougouris

Evangelos is RCCL Professor of Safety of Marine Operations at the University of Strathclyde, His main research interests are focused on safety of ships and marine design optimization participating in many EU and UK research projects. He is a member of RINA's IMO Correspondence Group and IMarEST's Alternative Fuels for Shipping Special Interest Group.

Professor Gerasimos Theotokatos

Gerasimos Theotokatos is the DNV GL Professor of Safety of Marine Systems and the Deputy Head at the Department of Naval Architecture, Ocean & Marine Engineering of the University of Strathclyde. He has an extensive experience of around 20 years on teaching and researching in the scientific area of marine systems engineering. His research focuses on the development of scientific approaches to holistically capture the safety, energy and sustainability interplay of the complex marine systems including cyber-physical and autonomous systems by employing advanced model-based methods and tools for their design and optimisation pursuing life-cycle risk and energy management, efficiency improvement, and safety and sustainability enhancement.

Dr Alex Priftis

Alexandros Priftis works as a Research Associate at the Maritime Safety Research Centre of the University of Strathclyde. His research interest focuses on ship design optimisation under uncertainty. He has been involved in research projects dealing with holistic ship design methodologies and modular ship design concepts.

Dr Haibin Wang

Haibin Wang is a researcher at Department of Naval Architecture, Ocean and Marine Engineering of the University of Strathclyde. From 2016, he started participating research projects, with the tasks of developing and conducting socio-economic assessment approach for shipping industry, including risk assessment for hybrid and battery power systems. He is a member of Institute of Marine Engineering, Science & Technology (IMarEST) and UK Carbon Capture & Storage Research Centre (UKCCSRC).

Professor Apostolos Papanikolaou
Prof. Dr.-Ing. Habil. Apostolos D. Papanikolaou is Senior Scientific Advisor of the Hamburg Ship Model Basin, Professor Emeritus NTUA and Visiting Professor of the University of Strathclyde. He headed more than 75 funded research projects and was author/co-author of over 630 scientific publications dealing with the design and optimization of conventional and unconventional vessels, the hydrodynamics analysis of ships in calm water and in seaways, the logistics-based ship design, the stability and safety of ships and regulatory developments regarding maritime safety at IMO. He was recipient of numerous national and international prizes, awards and commendations. He is Fellow of the Society of Naval Architects and Marine Engineers (SNAME), the Royal Institution of Naval Architects (RINA), the German Soc. of Naval Architecture (STG), Distinguished Foreign Fellow of the Japanese Society and Naval Architects and Ocean Engineers (JASNAOE) and International Vice President of SNAME.

Mikal Dahle
Mikal Dahle is a Project Manager with Kolumbus for the TrAM project. He has worked in various engineering and management positions in JP Kenny, ABB Offshore Systems and Technip, before joining Kolumbus in 2018. His work has covered detailed engineering, project engineering and technical lead positions within marine operations projects, primarily offshore construction and subsea installation work. Since 2008, Mikal has held management roles within engineering, including responsibilities of up to 110 engineers within marine operations and subsea installation engineering.

Patrick Bollaert
Patrick Bollaert is working for the Flemish Waterway (de Vlaamse Waterweg nv) – government, as extern transport expert for inland waterways, barges and innovation. He received Insurance bachelor degree in specialty of ships. He has experience in in inland storage of liquid products and barge navigation.

Lars Erik Tveit
Lars Erik Tveit is a Marine Operations Manager in Kolumbus, Rogaland, Norway. During his employment in Kolumbus, he has been contributing to several project, such as, Ryfylkeferjen, TrAM and Vannbus. Before he joined Kolumbus, he has substantial experiences on board ships as Captain and Chief Officer, Second Officer and Deck Officer since 2003.

Dr. Eleftheria Eliopoulou
Dr. Eleftheria Eliopoulou is senior researcher and special teaching staff at the Ship Design Laboratory of NTUA. Her PhD is focused on the harmonisation of ships' damage stability regulations (SLF47/3/2). Her research fields are related to ship design, intact-damage stability, marine accident investigations and risk-based design. She has participated on Formal Safety Assessment studies, especially on risk analysis of large tankers (submission to IMO), large passenger ships and fully cellular containerships.

Tobias Seidenberg
Tobias Seidenberg works as research associate at the Fraunhofer Institute for Mechatronic Systems Design IEM in Paderborn, Germany. He received his B.Eng. degree in mechanical engineering at the University of Applied Science Bielefeld with a focus on production. This was followed by a MEng in Production and Management at the Technical University Ostwestfalen-Lippe. During this time he gained experience in industrial projects at Bosch and Miele, including production quality methods and the implementation of new technologies. Since 2018 he works at Fraunhofer and is involved in several industrial and research projects in the fields of Systems Engineering and production technology.

Morten Berhovde
Morten Berhovde is the CTO at Fjellstrand shipyard from 2016, responsible for all technical disciplines, project management and production planning, for newbuilding, major conversions. He participates in development projects, sales and contract negotiations. He also prepares building specifications for the shipyard's own vessels and is the technical responsible decision-maker for projects. He also works as a responsible person for a Registered Electrical Contractor for electrical engineering and installations for Maritim Elektro AS since 1993, within electrical power distribution, automation, navigation and communication, mainly for ship installations. He has various experiences in electrical installations in agriculture, housing, industry, fishing vessels and passenger vessels. He has participated in shipbuilding projects all over the world, such as Poland, Netherland, China, Azerbaijan, Tahiti, Denmark, Germany, France, Malta, Faroe Islands, Singapore, the USA etc. He obtained the electrician licence in (1984) and the certification as a responsible person for a Registered Electrical Contractor for engineering and installations, in Norway in 1993. He graduated from Technical College Electrical Engineering, Bergen Technical College in 1989 and worked as an electrical engineer from 1989 to 1993, from then on as responsible person for a Registered Electrical Contractor for engineering and installations, moving gradually over to shipyard technical department, with involvement in all disciplines from 2008 to 2016, until he was given the role as CTO of shipyard including the registered electrical contractor, now merged with shipyard, in 2016.