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Development Of Framework For Systems Based Risk Analysis: Offshore Wind Industry

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Abstract

This study explores the application of a systems-based risk analysis of the offshore wind industry using the STPA (System-Theoretic Process Analysis) methodology. Offshore wind is an emerging, rapidly growing, and high-risk industry. Studies have shown that safety performance lags comparable offshore industries. STPA has been successfully implemented across many industries but its application in the renewable energy sector to date has been very limited. This study sets out the framework for an industry level STPA analysis, this involved identification of system goals, loss events, system requirements and mapping of the industry safety control structures. The paper then describes the next steps required to validate the control structure, complete a detailed hazard analysis and develop industry specific leading indicators of risk. System level goals, hazards, loss events and requirements are presented and show the potential for application of STPA to the indistry. The safety control structure of the industry is mapped out and a process for validation discussed. The application of STPA can provide new insights to help manage safety in the offshore wind industry. As the industry is at an early stage of development STPA could help the industry shape its control structures with the aim of improving safety outcomes. The next stage of this research will involve industry engagement to validate the initial findings and complete a full mapping of the control structures, detailed hazard analysis, risk indicator selection and development of a dynamic risk model.

Keywords: STAMP, STPA, risk indicators, safety indicators, offshore wind

1. Introduction

The offshore wind industry is an emerging, high growth and high risk industry (Rowell, McMillan et al. 2024). As the offshore wind industry develops it is important to understand the safety performance of the industry and the risk levels associated with it. Across many industries there has been significant amounts of research in the development of risk indicators or leading indicators of safety. These indicators are intended to provide industry leaders with an understanding of risk or safety levels in the industry or organization before accidents occur. To date there has been little research on this area specific to offshore wind and it has been shown that the industry relies on lagging indicators to measure risk and safety performance (Gonzalez, Nanos et al. 2017). Zhen identified that there are three main methods of leading indicator of risk development, these are event chain methods, systems engineering methods and resilience engineering methods (Zhen, Vinnem et al. 2022). Seyr proposed a set of safety leading indicators for offshore wind based on an event chain methodology, this used an analysis of accident data and drew on oil & gas research and proposed a sat of safety indicators focused on occupational accidents for the development of offshore wind farms (Seyr and Muskulus 2016). Kopke has applied a resilience engineering methodology (FRAM) to develop *“safety and security”* goals for an offshore wind farm. This study sets out to complete an industry level systems-based risk analysis and develop industry level risk indicators. As offshore wind is a relatively young industry, it does not have significant experience of major incidents from which it can learn. While the industry has a relatively high recordable injury rate the number of major accidents is thankfully small (Rowell, McMillan et al. 2024). Major safety organizations in the industry have reported no fatal accidents to date, however there have been some serious accidents reported in the media (Rowell, McMillan et al. 2024). Industry level risk indicators have been successfully implemented in the oil and gas industry and these could also be of benefit to the offshore wind industry and can help shape the safety control structures as the industry grows (Vinnem, Huseb et al. 2006, Vinnem, Aven et al. 2006, Vinnem 2010). Leveson set out a systems-based approach to the development of risk indicators and has applied these methods to the US pharmaceutical industry (Leveson, Couturier et al. 2012, Leveson 2015). Dulac has used a similar methodology to complete an organizational level analysis of the NASA engineering organization (Dulac 2007, Dulac, Owens et al. 2007). This study demonstrates the application of this approach to the offshore wind industry and makes an initial analysis of the industry system goals, hazards, safety control structures and industry requirements and considers the potential for further application to the industry to allow for a full industry level STPA analysis and identification of industry specific risk indicators.

2. Systems risk analysis framework development

2.1. STAMP background

STAMP (Systems-Theoretic Accident Model and Processes) is a relatively new accident causation model introduced by Leveson in 2004, and builds on work by Rasmussen et al which developed a hierarchical model of safety control (Rasmussen and Svedung 2000) (Leveson 2004). STAMP takes a differing approach to accident causation and treats safety as a control problem, it proposes that accidents occur due to a lack of control and considers factors beyond the usual event chains. STAMP was developed to analyze complex systems and takes into consideration technical, social and organizational factors in its analysis. Whereas traditional accident causation models focus on component failures, STAMP also considers component interactions and external disturbances (Leveson 2015). Within STAMP theory, STPA has been developed as a hazard analysis technique. While STAMP and STPA were originally developed for technical engineering systems, they have also been applied to management and organizational analysis (Dulac 2007, Leveson, Couturier et al. 2012). Recent literature reviews provide an extensive history of the development and applications of STAMP, these have shown while STAMP has grown in popularity and has recently been applied to the aviation, process, medical and maritime sectors, it has seen little application in the renewable energy sector (Patriarca, Chatzimichailidou et al. 2022) (Zhang, Dong et al. 2022). Leveson set out a process for the development of risk indicators using the STAMP methodology and the potential for application to the offshore wind industry is explored in this study (Leveson 2015). Leveson has argued that most approaches to finding indicators of risk have used event chain methodologies, while in reality most accidents have multiple causes which often include social, technical, and organizational factors. The offshore wind industry can be considered as a complex system, it includes many stakeholders which interact in different ways, these stakeholders cooperate to design, build, operate and maintain the offshore wind infrastructure. In order to improve the operation of this system to make it safer for those who work in it, all parts of the system and their interactions need to be considered. For this reason, a systems approach analyzing the operations of the industry and developing risk indicators may be beneficial. The process of applying the STAMP methodology to an organization or industry has been mapped out by Dulac and is summarized in Fig. 1. Research process map (Dulac 2007). This study sets out the findings of steps 1 to 3, and presents results of the preliminary hazard analysis, control structure modeling and system requirements development. It also discusses the next steps in the research to complete an industry level STPA hazard analysis, gap analysis, risk indicator development and dynamic modelling.

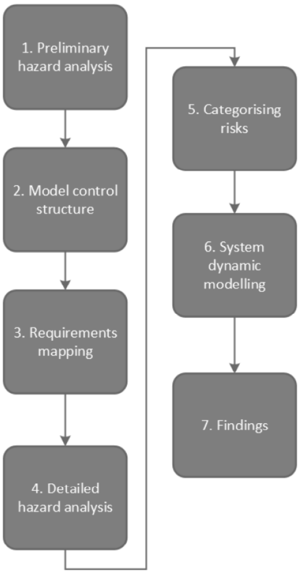

Fig. 1. Research process map.

To conduct the preliminary hazard analysis the initial steps of an STPA (Preliminary Hazard Analysis) are completed, these define the system limits, goals and loss events and then identify system level hazards. The results of these steps are set out in sections 2.2 to 2.4. A model of the OWI safety control structure is then presented, and industry level safety constraints and functional requirements are proposed in sections 2.5 to 2.7.

2.2. System limits

For this analysis the offshore wind industry organization is considered as a complex system, a system can be defined as *"a set of components that act together as a whole to achieve some common goal"* (Leveson and Thomas 2018). For this analysis the system is considered as the offshore wind energy infrastructure and the organizations and structures that construct, operate and maintain it. Related onshore infrastructure is considered to be out of scope.

2.3. System goals and loss events

The system goals of the offshore wind industry for the purposes of this safety risk-based analysis can be defined as:

- SG-1: Offshore wind infrastructure is designed to provide a safe workplace for persons involved in installing, operating, and maintaining it.
- SG-2: The offshore wind industry develops an open and transparent safety culture where all persons feel able to raise concerns and report incidents.

The goal of this analysis is to improve safety outcomes for personnel working in the industry, so losses are restricted to those involving harm to people. A loss event is defined as:

- A person is injured or killed during the installation, operation, or maintenance of offshore wind infrastructure.

2.4. System level hazards

System level hazards are framed differently to hazards in traditional risk assessment methods and are defined as "a system state or set of conditions that, together with a particular set of worst-case environmental conditions, will lead to a loss" (Leveson and Thomas 2018). System level hazards can be considered from the point of view of the organisational control structures of the offshore wind industry and the technical systems of the offshore wind industry infrastructure. Using this definition system level hazards and associated sub-hazards were identified for both systems, these are listed in Table 1 and Table 2.

2.4.1. Organizational system level hazards

Table 1. OWI Organizational system hazards.

Hazard ID	Hazard
[OH-1]	Inadequate engineering decision making leads to loss or injury of persons involved in offshore wind operations and maintenance.
[OH-2]	Inadequate management decision making leads to loss or injury of persons involved in offshore wind operations and maintenance.
[OH-3]	Lack of industry regulation or oversight leads to loss or injury of persons involved in offshore wind operations and maintenance.

2.4.2. Operational system level hazards

Table 2. OWI operational system hazards.

Hazard ID	Hazard	Sub-hazard
[SH-1]	Person in uncontrolled contact with wind turbine equipment	-
[SH-1.1]	-	Person exposed to falling material or dropped objects.
[SH-1.2]	-	Person exposed to live, unprotected electrical equipment.
[SH-1.3]	-	Person exposed to unprotected rotating machinery.
[SH-1.4]	-	Person exposed to crushing hazard
[SH-2]	Person medical emergency on wind farm	
[SH-3]	Person overboard	
[SH-3.1]	-	Person falls from vessel during travel to and from wind farm
[SH-3.2]	-	Person falls from vessel during transfer to turbine or other structure
[SH-3.3]	-	Person falls overboard from a vessel or turbine during activities offshore
[SH-4]	Person fall from height	
[SH-5]	Fire in turbine, vessel or other infrastructure offshore	
[SH-5.1]	-	Fire in the turbine nacelle
[SH-5.2]	-	Fire in turbine structure
[SH-5.3]	-	Fire onboard a wind farm support of construction vessel
[SH-6]	Person stranded on turbine or other infrastructure offshore	
[SH-7]	Ship or aircraft in uncontrolled contact with turbine	Ship in uncontrolled contact with turbine

For each of these hazards' safety constraints must be applied to control the hazard. The development of the safety constraints can then be used to develop safety requirements for the offshore wind farm. Safety constraints are essentially the inverse of the system hazard ***(Leveson and Thomas 2018)***. So, for example, a safety constraint for SH-1 Person in uncontrolled contact with wind turbine equipment could be - Turbine design must prevent human contact with rotating equipment in the nacelle. Development of these constraints at a system design stage can help ensure the system is designed with the provision of a safe system as a first principle.

2.5. Industry level functional requirements

Industry level functional requirements were developed in consideration of the defined system level hazards and through analysis of existing industry level safety requirements and the published safety goals of offshore wind industry developers and operators (Oceanwinds 2022), (Orsted 2020), (Vattenfall 2021), (G+ Global Offshore Wind 2022). Functional requirements are usually set out at the beginning of the design of the system. The requirements are set out in Table 3. These requirements in addition to constraints generated from the system hazards can be used to develop a full set of industry safety requirements.

Table 3 - Industry functional requirements.

Hazard ID	Hazard
FR-1	Implement safety into the design of the system.
FR-2	Implement best practices.
FR-3	Audit and measure performance.
FR-4	Investigate all incidents.
FR-5	Define clear roles and responsibilities.
FR-6	Develop robust emergency plans.
FR-7	Foster cross industry safety collaboration and communication.
FR-8	Promote a positive safety culture.
FR-9	Provide safe and healthy working conditions.
FR-10	Eliminate or reduce safety risks to ALARP.
FR-11	Communicate and consult with workers.
FR-12	Comply with legal requirements.
FR-13	Foster a culture of continuous improvement.

2.6. Safety control structures development

Fig. 1**Błąd! Nie można odnaleźć źródła odwołania.** shows the mapping of the offshore wind industry control structures. This structure is developed from the authors personal experience and available industry reports and documentation (G+ Global Offshore Wind 2022), (The Energy Institute 2021), (renewableUK 2014).

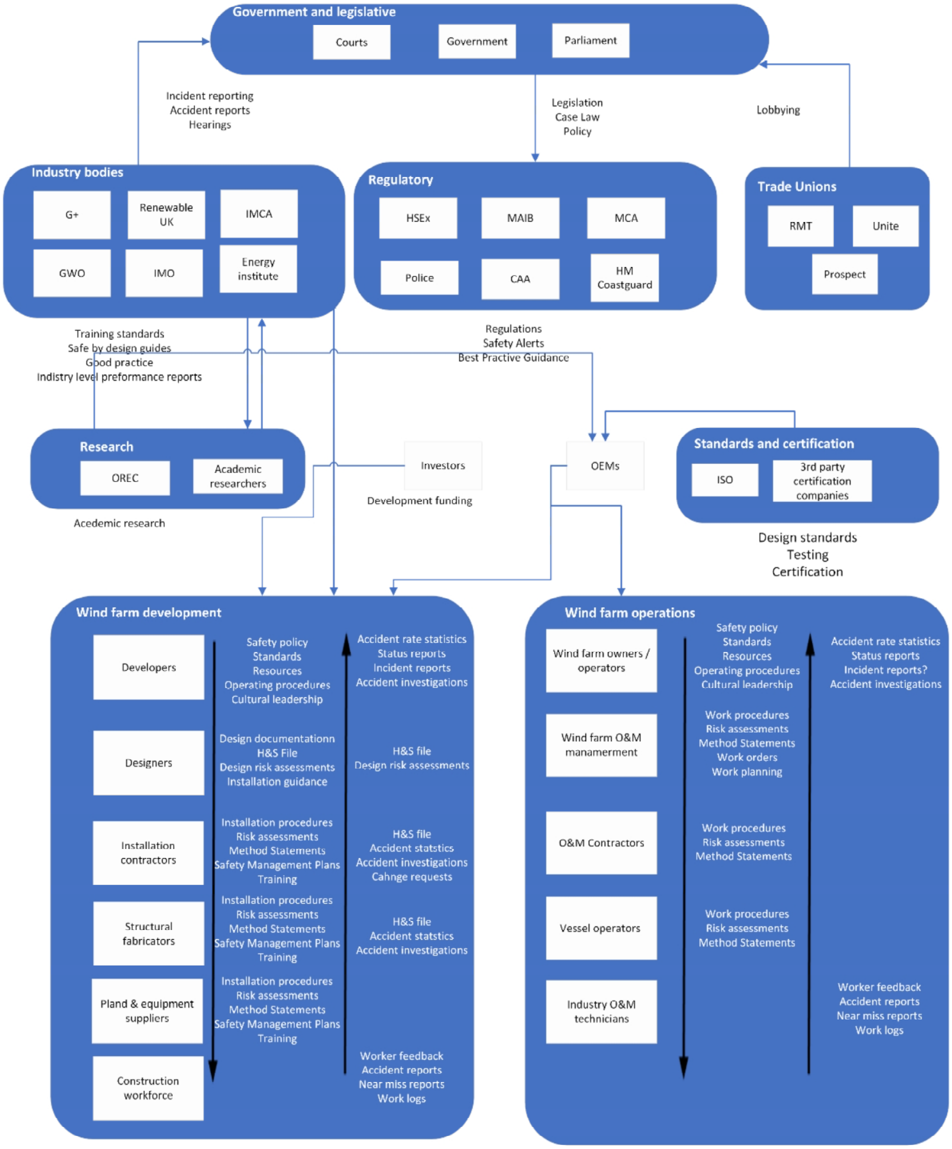

Fig. 2. OWI Safety control structure.

The safety control structure diagram shows the layers of hierarchy which combine and interact to control safety in the offshore wind industry. STAMP theory considers safety to be a control problem, each layer of hierarchy places constraints on those below it. STPA proposes that accidents occur when the control system is not functioning due to improper control, improper feedback or unexpected interactions between components of the system (Leveson and Thomas 2018). Entities are grouped together by categories such as government, regulation, trade unions and regulatory. Arrows indicate information flows between entities, and these are labeled with specific types of control signal and feedback type. Full validation of the control structure will be done through interviews with industry members involved in each of the stakeholders, this will be the subject of future research.

2.7. Requirements analysis

The next stage of the STAMP process involves a gap analysis of requirements against the existing industry control structure. Industry functional requirements and constraints based on the system hazards can be mapped to each entity in the control structure, gaps where requirements or constraints are not adequately addressed by the control structure can therefore be identified. Through this initial analysis one of the first gaps identified is one of inadequate feedback from industry safety performance or risk levels that allows safety regulators sufficient information about the industry risk levels without waiting for accidents to occur. For example, the Norwegian oil industry uses an industry wide risk level report to provide feedback to industry leaders and regulators (Petroleum Safety Authority Norway 2020). No such measure or risk levels for offshore wind exists. A full gap analysis will be completed as part of the STPA analysis following expert validation of the control structure and requirements.

2.8. Indicator based assumptions development

Leveson proposed that risk indicators can be developed through an assumptions based method (Leveson 2015). Levesons argues that to find more effective leading indicators of risk the assumptions around why accidents occur should be analyzed. This is based on the idea that accidents occur when assumptions made in design or development stage no longer hold due to a migration in the way the system operates. These are split into three categories, listed here with examples (Leveson 2015):

- Development and implementation - assumptions about the system hazards are not correct. i.e hazards were missed in design development.
- Operations - Changes to the system over time mean that controls are no longer adequate.
- Management - The safety management system is not operating the way it was intended.

Leveson proposed that reducing these types of causes will reduce accidents and that leading indicators can be developed to detect these kinds of changes before accidents occur. These types of changes to assumptions are relevant to the offshore wind industry due to the rapid changes the industry has seen since its inception. Early offshore wind farms were situated close to shore and use small crew transfer vessels (CTVs) for access. Rapid changes to the industry mean that future wind farms could be up to 100km offshore with floating wind turbines using large service operations vessels (SOVs) and walk to work access systems (Rowell, Jenkins et al. 2022). For the assessment of the risk of adverse events Leveson proposes using the concept of vulnerability rather than likelihood. Using vulnerability only considers whether an event could occur but does not try to calculate a probability of it. Considering that the system is vulnerable to an event does not mean that controls will be implemented, but it means that the event cannot be disregarded from the outset and must be considered (Leveson 2015).

2.8.1. Framework for 3 levels of indicators

This study proposes the development of three tiers of risk indicators for the offshore wind industry.

Level 1 – Industry wide
Level 2 – Wind farm wide
Level 3 – Activity or operations-based indicators

Level 1 would include industry-wide risk indicators which would help inform industry regulators and policy decision makers about risk level and safety performance in the industry. Level 2 would be developed for a specific wind farm and would vary depending on the nature for example, fixed bottom vs floating wind, methods of transportation used, helicopter vs CTV vs SOV and finally Level 3 activity specific indicators that could be tailored to specific high-risk activities such as heavy lifting for major component exchange. A full STPA analysis of the offshore wind industry control structure and interviews with industry members will be used to aid in the identification of safety critical assumptions and propose indicators for each level.

2.9. Dynamic model development

The final stage of the risk analysis project for the offshore wind industry involves the development of a dynamic risk model. This will be complete through steps 3 to 6 as set out in Fig. 1. Forrester has discussed that the development of the model can create as many insights as the model itself (Forrester 2006). The goals of dynamic risk modelling per Dulac (Dulac 2007):

- Improve the quality of mental models used to make safety related decisions,
- Analyze risks identified by system analysts and stakeholders,

- Improve the robustness of systems against time dependent risk increase,
- Improve risk monitoring to detect and correct potential migration towards higher risk levels.

Dynamic model development will be explored in a further stage of this research.

3. Discussion

Section 2 has set out the framework of a systems-based analysis of the offshore wind industry and presented results of the first phase of the analysis. This has demonstrated that a systems-based approach to risk analysis could have positive benefits for the industry. A systems-based analysis takes a different approach to risk analysis and therefore has the potential to find hazards and risk mitigation measures that may not have been considered by traditional risk assessment methodologies. The systems goals and loss events definition show the importance of considering the provision of a safe workplace and the development of an open and transparent safety culture as intrinsic parts of the system and not as an additional item that is though about after engineering decisions have been made. Three organizational system hazards and seven operational system level hazards were identified, and these will be applied to the STPA analysis in phase two of the research study. Section 2.5 set out a proposed set of functional requirements based on the initial systems level hazard analysis and a study of existing industry documentation. The functional requirements are normally developed prior to system design but consideration of these can help guide the hazard analysis of the industry and identify where improvements could be made. The safety control structure map identified eight operating groups and at least 35 stakeholders which interact to manage safety of the industry. Initial control mechanisms and feedback types were also identified, and these will be further validated through industrial interviews in phase two of this research. The mapping of the control structure helps to illustrate the complexity of the industry and the many channels for flow of information and control that can impact the safety of the industry. A full STPA analysis of this structure can help identify new failure mechanisms or hazards that may not have previously been considered.

4. Conclusions

This study has set out the framework for a full systems theory-based risk analysis of the offshore wind industry. Offshore wind is a technically complex, high-risk industry which has little existing safety specific research and which can benefit from further analysis. The analysis has been completed with a focus on personnel safety and the prevention of harm to workers or other parties involved in the construction, operations or maintenance of the industry. The paper has presented results from the initial part of the analysis including the identification of systems level hazards for both the organizational and technical aspects of the industry, the proposal of industry level functional requirements and the mapping of the safety control structures of the industry. The completion of the first phase of this research demonstrates that the application of this methodology to the offshore wind industry could have benefits and allows for a full industry level STPA analysis and gap analysis to be completed. These steps will be completed as phase two of this research through use of expert interviews.

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