ANALYSIS AND IMPROVEMENT OF RISK ASSESSMENT METHODOLOGY FOR OFFSHORE ENERGY INSTALLATIONS

ASPECTS OF ENVIRONMENTAL IMPACT ASSESSMENT AND AS-BUILT SUBSEA CABLE VERIFICATION

Andreas Olsson

Blekinge Institute of Technology
Licentiate Dissertation Series No. 2023:02

Department of Mathematics and Natural Sciences

Analysis and Improvement of Risk Assessment Methodology for Offshore Energy Installations

Aspects of Environmental Impact Assessment and As-Built Subsea Cable Verification

Andreas Olsson

Blekinge Institute of Technology Licentiate Dissertation Series
No 2023:02

Analysis and Improvement of Risk Assessment Methodology for Offshore Energy Installations

Aspects of Environmental Impact Assessment and As-Built Subsea Cable Verification

Andreas Olsson

Licentiate Dissertation in Systems Engineering

Department of Mathematics and Natural Sciences
Blekinge Institute of Technology
SWEDEN

Department of Mathematics and Natural Sciences
Publisher: Blekinge Institute of Technology
SE-371 79 Karlskrona, Sweden
Printed by Media-Tryck, Lund, Sweden, 2023
ISBN: 978-91-7295-450-2
ISSN: 1650-2140
urn:nbn:se:bth-24264

Fear can hold you prisoner. Hope can set you free.

–Stephen King

ABSTRACT

In the expansion of offshore sustainable energy systems, there is growing pressure on the environment and permit processes and the accumulation results in much higher total risk for accidents of future assets. Anticipating the problems at the design stage and improving verification is likely to increase energy development and reduce costs. This thesis explores offshore DST (Decision Support Tools) and risk verification of subsea cable assets.

For subsea cables, a statistical method is proposed utilizing measurement data together with shipping traffic data (AIS) to estimate the environmental risk and risk of accidents of installed cable assets. This should partially solve issues of improving design using more data and surveys and utilizing mechanical and sensor-specific characteristics to improve the confidence and burial estimation, contrary to today's methodology. The implication of the two studies of cable burial risk assessment techniques and verification shows how a developed methodology can solve issues for verifying the integrity of an installed asset. Putting our methodology into practice involves many challenges.

For the marine Decision Support Tool (DST) and sustainable energy development, to estimate potential savings if permit processes would be shorter and less burdensome without degrading the quality of the EIA (Environmental Impact Assessment). A method is proposed to model various scenarios of *effective* savings from the development of a DST to reduce costs spent on EIA permitting by the offshore energy developers. The study of the implication of the marine EIA DST shows a quantifiable estimate of the savings potential for permit processes for sustainable offshore development, and results indicate a need for optimization of DST development, which can be an essential factor in its implementation and success.

In memory of my father

ACKNOWLEDGEMENT

I want to start by thanking my three supervisors, Wlodek Kulesza, Oskar Frånberg, and Ida-Maja Hasselöv. Professor Wlodek K., part of the Department of Mathematics and Natural Sciences at the Blekinge Institute of Technology has been an invaluable supervisor and examiner, dedicating extraordinary time for advice, encouragement, critical reviewing, and comments on co-authored papers and the thesis. Our discussions have been meaningful for my work. Docent and Ph.D. Oskar Frånberg, also part of the Department of Mathematics and Natural Sciences at the Blekinge Institute of Technology, I would like to thank for his infinite inspiration during *fikas*, and his advice as co-author and support during my research and insight into the role of the Ph.D. process and research funding, and special thanks for dedication to finding research funding for my studies. Associate Professor Ida-Maja from the Department of Mechanics and Maritime Sciences, Division of Maritime Studies at the Chalmers University of Technology has been an incalculable source of optimism and encouragement for which my Ph.D. studies, which would have otherwise ended abruptly sooner, and further, as a co-author to manuscripts with incredible expert knife sharp contributions, very critical comments, and suggestions in the form of quick feedback.

I would also like to give a special thanks to the staff at NKT for the help and support, and encouragement of my research. I spent many hours in the factory at Verkö and visits at the office in Rotterdam and the cable laying vessel NKT Victoria where I could meet and ask questions from staff and subcontractors on multiple occasions, acquire data and get feedback on my research. A special thanks to Kent Cronholm at NKT and fellow Ph.D. candidate for uncountable hours of discussion, a source of know-how of the subsea cable industry, and inspiration for my research questions.

I would like to thank my colleagues at Blekinge Insitute of Technology in the department of mathematics and natural sciences and the department of mechanical engineering for their help and support. I especially like to thank the following: Ph.D. candidate Mårten Silvanius for his encouragement, helping me improving my teaching and interesting discussions during many fika breaks. Ph.D. Shafiqul Islam, for his advice and discussion being a researcher. Ph.D. Bruna Palm for her encouragement and inspiration. Ph.D. Saleh Javadi for his support and optimism. Ph.D. Yevhen Ivanenko for helpful encouraging advice. Further, I like to thank the adjuncts and Ph.D. candidates Johan Hjortsberg and Martin Gredehall for their company during fika discussions and advice in the field of marine technology. Lastly, I would like to thank colleague and department head Vanja Lindberg for her remarkable dedication and guidance in making my thesis finalization possible.

Finally, I would like to thank my family for their support, especially my grandmother Inez Olsson, for her unwavering support and encouragement for higher education throughout my life.

LIST OF APPENDED PAPERS & AUTHORS CONTRIBUTION

Paper A

Published conference article with the title: ***A New Method for As-built Burial Risk Assessment for Subsea Cables*** at the *"2nd International Conference on Energy Transition in the Mediterranean Area (SyNERGY MED 2022)"*
Author contribution: Andreas Olsson: Methodology, Methods, Data curation, Original draft.: Oskar Frånberg: Funding acquisition, Supervision.: Wlodek J. Kulesza: Supervision, Methodology, Writing - Review & Editing.

Paper B

Published conference article with the title: ***An Improvement of Assessing As-built Burial Risk for Subsea Cables*** at the *"2nd International Conference on Energy Transition in the Mediterranean Area (SyNERGY MED 2022)"*
Author contribution: Andreas Olsson: Methodology, Methods, Data curation, Original draft.: Oskar Frånberg: Funding acquisition, Supervision.: Wlodek J. Kulesza: Supervision, Methodology, Writing - Review & Editing.

Paper C

Submitted manuscript with the title: ***Strategic development of environmental impact assessment decision support tool for offshore energy enables decreased costs, increased utilization, and quality***
Author contribution: Andreas Olsson: Conceptualization, Methodology, Software, Investigation, Data curation, Writing - Original Draft.: Oskar Frånberg: Supervision, Resource, Funding acquisition.: Ida-Maja Hassellöv: Supervision, Writing - Review & Editing, Visualization.

Supporting Material

Processed data and methods for Strategic development of environmental impact assessment decision support tool for offshore energy enables decreased costs, increased utilization and quality Author contribution: Andreas Olsson: Conceptualization, Methodology, Software, Investigation, Data curation, Writing - Original Draft.: Oskar Frånberg: Supervision, Resource, Funding acquisition.: Ida-Maja Hassellöv: Supervision, Writing - Review & Editing, Visualization. Submitted together with Paper C

NOMENCLATURE

Abbreviations

AIS	Automated Identification System
BPI	Burial Protection Index
CBRA	Cable Burial Risk Assessment
DNV	Det Norske Veritas
DoB	Depth of Burial
DST	Decision Support Tools
DWT	Deadweight tonnage
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
EU	European Union
GNSS	Global navigation satellite system
GPS	Global Position System
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
MBES	Multi Beam Echo Sounder
MMSI	Maritime Mobile Service Identity
MSP	Maritime spatial planning
ROV	Remotely Operated Vehicle
RP	Recommended Practices

SEA Swedish Energy Agency

SwAM Swedish Agency for Marine and Water Management

UHC Ultimate Holding Force

USBL Ultra-Short BaseLine

UTM Universal Transverse Mercator

Symbols

$\mu^{z}_{\overline{D}_{\text{DoB}}}(L)$ Measured depth of burial sample mean value

$\sigma^{z}_{\overline{D}_{\text{DoB}}}(L)$ Measured depth of burial sample standard deviation

μ Ecosystem vulnerability to a Pressure (impact weight)

$s_{\text{tool}}(t)$ DST savings potential

$U_{\text{computational component}}(t)$ Utilization of computational component of environmental impact pair

$c_{\text{DST development}}$ Total development cost DST

$f_{\text{application}}$ Fraction of offshore project costs being EIA process

f_{offshore} Fraction of EIA process being offshore versus onshore

I_{rate} DST investment rate

$N_{PE\mu}$ Number of computational components, $PE\mu$s

$t_{\text{DST development}}$ Time to develop all of the DST's computational components

t_{left} Time left after a computational component is developed

σ^{org}_{m} Sample standard deviation

a Standard deviation coefficient

B^{old}_{i} Boolean vector to exclude already utilize measurement in the path approximation

C Line segment crossing boolean equation

c_n Noise coefficient

c_T Model approximation coefficient

$c_{\text{computational component}}(t)$ Development cost of computational component

c_{MWh} Cost per yearly MWh of offshore wind energy

D_{DoB} Depth of Burial estimation

D_{DoP} Depth of Penetration

$f_{\text{line}}(..)$ Help equation line segment crossing identification

F_{UHC} Ultimate holding strength of an anchor

$H(..)$ Heaviside function

k_i slope of each line-segment

L Generated 2D line segmented of the cable path length

L_i Generated 2D line segmented of the cable path length per index i

M_x Measurement position in x-direction

M_y Measurement position in y-direction

P_{incident} Risk for anchor deployment as function per time

r DST efficiency

$r_e xtent$ Effective radius extended to the furthest included measurements within the radius r_L

r_L Radius to include measurements excluding already used measurements

R_M Cable tracker range data

S_i^x x poisition of line segments point i

S_i^y y poisition of line segments point i

S_{length} Ship anchor dragging length

S_M polynomial function for sensor standard deviation

$t_{\text{lead-time}}^{\text{EIA}}$ Project lead-time EIA process

$t_{\text{lead-time}}^{\text{other}}$ Project lead-time other apsects, e.g. build time

$T_{\text{new basis}}$ The basis in the direction of the newest generated line segment of the cable path

$t_{\text{available}}$ Available time window

t_{total} Scenario time window

V_{drag} Ship's speed during dragging anchor

V_{ship} Ship's average speed during o normal operations

W Offshore wind in yearly MWh capacity

W_{anchor} Ship's anchor weight

W_{DWT} Ship's deadweight tonnage

ν t-distribution degrees of freedom

c_r Radius coefficient

c_X Sampling per meter coefficient

c_{EIA} EIA costs

$c^{ij}_{PE\mu}$ EIA cost per pressure-ecosystem impact pair

D_{ship} Distance ship travel during anchor dragging

F^{-1} t-Student's inverse cumulative distribution

$f_{\text{failure rate}}$ Permit failure rate per MWh

N Number of measurements

P_{strike} Anchor collision cable risk

P_{traffic} Probability modifier

P_{wd} Probability modifier for nature and water depth

$PE\mu$ Impact pair

r Radius window

r_0 Reference window size

t_F Time to failure

X Measurement sampling per meter

X_0 Reference sampling per meter

CONTENTS

Chapter 1
INTRODUCTION

The main theme of this thesis focuses on the handling of uncertainties for cable measurements for risk assessment and design considerations for environmental impact assessment decision support tools (EIA DST). These uncertainties were explored separately, where below in Section 1.1 the cable burial problem implies increased risks and costs for high voltage installment through conservative design choices and additional burial works or rock placement. And in Section 1.2 the problem of EIA DSTs concerns permit lead-time, failure rate, and future utilization as factors influencing costs and savings potential for offshore installations as they are built from a national or international perspective.

1.1 Cable risk assessment and verification for high voltage cable installations

The research themes build upon the idea that improved risk assessment results in decreased cost and operational uncertainty on how to handle problematic situations. This includes goals of the creation of risk assessment methods to improve the determination of effective burial depths through automation and optimization of the processes. Other goals are to create analog or similar methods and methodologies to the existing cable burial design risk methods and methodologies. Such new method and methodology can be used to assess cable installment integrity of installed and measured assets. Additionally, under certain conditions, verify integrity without no measurements needed. Further goals are to improve or create methods for assessment of risk which can estimate future costs and be able to compare with cable design choices and cable routing to optimize the cable design. Additionally goals include to improve validation and verification, making proposed methods and methodologies rigorously tested through experimental data.

To reach these goals, a possible avenue is to improve existing and to build new trust-able design methods. An approach considered is the extension of cable risks assessment methods and methodologies for anchor burial risk design, anchor penetration methods and models to include the assessment of measurement data in a more holistic statistical manner. Additionally, this cable burial assessment of anchors should incorporate other risk factors dependent on the depth in a unified model. Primarily other risk factors such as fishing gear penetration and electro-thermal degradation.

My research contribution for offshore asset risk includes analysis of methods used to assess subsea cable burial design and measurements, leading to improve understanding of uncertain elements and risk factors. Another element is to improve and propose new methods to estimate risks for assets which will help in accurately estimating future costs for maintenance. And lastly show how the proposed method is affected by variation and limitations, which is an element that can be of great consequence in deciding survey requirement and design parameters.

The following research questions will be answered:

- How do the risk model parameters affect the cable design risk?
- How could the measurement uncertainty of cable burial depth be implemented into risk management analysis?
- What possible implementation scenarios enable evaluation of differences between the risk estimates for a large-scale project of the design risk and the as-built cable measured risk?
- What is a conservative estimate for the upper limit difference between the design risk and as-built cable measured risk?

1.2 Offshore Environmental Impact Assessment Decision Support Tools - EIA DST

In order to achieve the objectives outlined in this thesis, there is an imperative to address two key issues. Firstly, it is essential to prioritize the use of appropriate quantitative models for assessing ecosystems and economic assets, with an emphasis on absolute impact. Furthermore, it is necessary to develop new type of support for these DSTs. Secondly, the development of marine EIA DSTs must be facilitated, and their analysis must take into account efficiency gains and other sources of value. This can be accomplished by creating a development model that can be optimized or skewed towards value-adding aspects, even if they are not the primary driving forces behind the funding or development of these tools by the relevant agencies. The goals of this research are to work with the following subset, to present Sweden's situation and potential future scenarios of potential savings for offshore sustainable energy development based on reduced or automated permitting processes and lead times.

The following research questions will be answered:

- What mechanisms are most influential when considering DST's savings potential?
- How are influencing parameters motivated in their estimation?
- How is the savings potential of the DSTs impacted by estimated parameters and uncertainties or variability?
- How large is the expected costs and savings of the DST using the proposed savings model?

Chapter 2
THEORETICAL BACKGROUND

Reliability of risk assessment has been a vital component of risk analysis. It is especially relevant in today's world with exponential growth of offshore sustainable energy production [1, 2, 3]. Additionally, adverse actions against critical subsea infrastructure become crucial in the current situation[4, 5, 6]. The accuracy of risk assessment may not only result in costs for repairation but it may have significant impacts on the economy, socioeconomic and environmental aspects as we are moving towards less dependency on hydrocarbons [7].

Since this thesis focuses on quantitative risk assessment of offshore assets, two theoretical approaches need to be explored. The first is the quantitative risk assessment of offshore high voltage cables, where improvements to methodologies for the management of assessment using measured as-built data results in issues [paper A and B]. Secondly, the risk assessment of marine Decision Support Tools for Environmental Impact Assessment, where in the EIA qualitative assessment dominates over quantitative assessment, and DSTs move the assessment into the quantitative direction [paper C]. This chapters introduces the theoretical background regarding risk management and assessment framework in Section 2.1, additionally risk management for high voltage subsea cables and risk management for marine environmental status. Furthermore in Section 2.2, cable burial depth design and validation is introduced, and the methodology for cable burial depth assessment is introduced. In Section 2.3 the regulatory issues and the challenges and opportunities surrounding DSTs are introduced. Lastly, in Section 2.5, methodologies and standards for shallow subsea power cables projects is introduced.

2.1 Risk management frameworks

The risk management framework is a systematic methodology for assessing and managing risk in a structured manner. This includes risk identification, assessment, prioritization, mitigation, monitoring, and review [8]. Preferable quantitative risk assessment necessitates a significant amount of data, which can be time-consuming and expensive. Additionally, the approach cannot be relevant in case of high data uncertainty or scarcity of data, and it has to be reduced to a qualitative approach [9].

2.1.1 Risk management for high voltage subsea cables

The risk management and assessment of burial depth for subsea power cables is derived from the ISO 31000 [10] and IEC 31010 [11] standards. The risk assessment includes risk identification, analysis, and evaluation. The final stage of the risk assessment is risk treatment and *Monitoring and Review* requiring external communications. To enable a risk-based approach for designing shallow subsea power cables, *DNV's Recommended Practice 360 'Subsea power cables in shallow water'* [12] serves as an industry document that contains guidance on every step of cable projects and applicable industry best practice.

One of the main risks for subsea power cables come from fishing gear and dragging ship anchors that may catch the cables on top or in the sediments. Anchors generally have a greater penetration depth than fishing equipment. The cable burial design must ensure the avoidance of anchors penetrate the sediments, primarily from the extended flukes. Additionally, in areas with low shear strength, there is a risk that a heavy anchor may sink deeper into the sediment than the flukes extend. In sandy environments, where cables are typically buried, the bottom behaves similarly to a desert environment, with dunes of various sizes that shift and move over time.

In project development shown in Figure 2.1, risk assessments are conducted by different stakeholders. In the early design stages, project developers take the main responsibility, while the ownership group takes on this task toward the end of the project. Additionally, midway through the project, governmental agencies issue permits, which include risk assessments, and this prior risk assessment information is usually integrated as a part of the Environmental Impact Assessment (EIA) process [12]. A general project plan, analysis, and the input of external experts and stakeholders shape this process.

Through the design of the EIA, the project owner aims to select an operational alternative that will have the most negligible impact on the ecosystems. This underscores the importance of carefully considering the feedback provided by external experts and stakeholders throughout the EIA process to be potentially be granted permits.

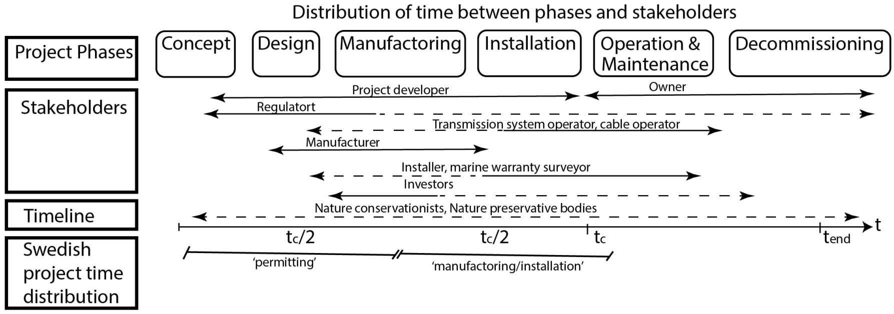

Figure 2.1: *A typical timeline of an offshore cable project[12].*

2.1.2 Risk assessment for marine EIA

For marine environmental phenomena, a risk assessment framework D(A)PSIR [13] or its derivatives (Driver-(Activites)-Pressures-State-Impacts-Responses) is commonly utilized where OSPAR[14] (Convention for the Protection of the Marine Environment of the North-East Atlantic) supports the use of this framework (See Figure 2.2). It helps to identify and categorize key factors that contribute to a problem, identify gaps, and identify policy responses to address the these issues. DAPSIR consists of the following categories:

- *Drivers* referring to the underlying causes of the environmental issue, such as human activities or natural phenomena.
- *Activities* identifying the specific actions or behaviors contributing to the issue.
- *Pressures* assessing the impact of these activities on the environment.
- *State* evaluating the current condition of the environment.
- *Impacts* looking at the consequences of the environmental issue, such as harm to wildlife or damage to ecosystems.
- *Response* considering the various measures that can be taken to mitigate the risks and address the issue.

The DAPSIR is primarily a 6-step qualitative approach, which includes a *semi-quantitative* assessment of the pressures (Expert opinion-driven significance of the Pressures change to the State).

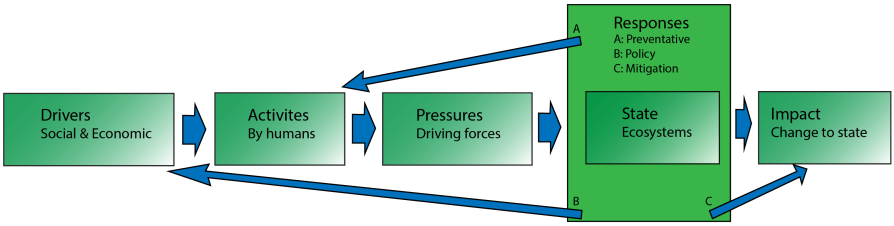

Figure 2.2: *A typical flow of usage of DAPSIR framwork[14].*

2.2 Cable burial depth design and validation

For a cable project, there are typically two boundaries for the cable to stay in between. The lower boundary is dependent on resulting cable temperature impacted by thermally resistant sediment layers. The upper boundary is related to protection from fishing gear and dragging anchors that ships drop down during accidents. These penetrate into the sea bottom sediments, and depending on the burial depth and the anchors' size may be likely hit the cable, which result in some mechanical damage.

When offshore cable assets are buried deep in sediments for protection for fishing gear and anchors dragging from ships, but designed a maximum depth due to maximum limited active temperature from heat generation and the thermally insulation layers of sediment, illustrated in Figure 2.3.

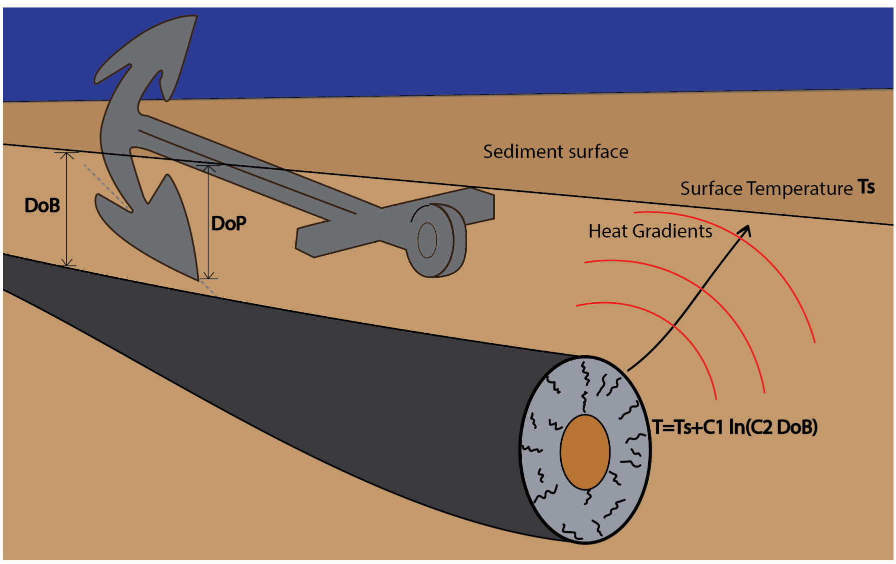

Figure 2.3: *Illustration of an anchor deployment near a cable drag on and in the sediments.*

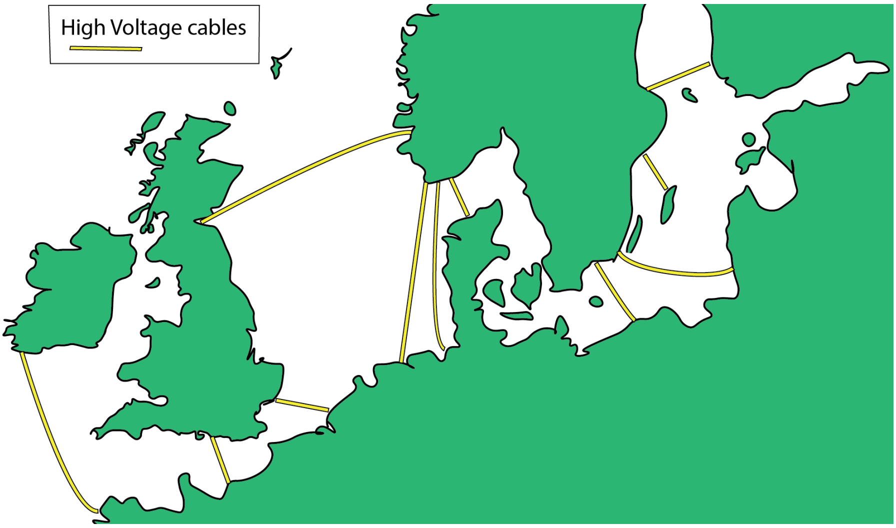

Figure 2.4: *Mapping of a few of the longest high voltage inter-connectors in Europe[15].*

The burial equipment is used to install hundreds of kilometers of cable, as illustrated in Figure 2.4. When a burial installation has been completed, a survey of the buried cable must be carried out to verify the Depth of Burial (DoB). The designed burial depth is verified by measurement, performed using a Remotely Operated Vehicle (ROV). It can be done using an active magnetic sensor, acoustic sensor, or passive magnetic flux-gate, last of which requires a signal emitting from the cable, see Figure 2.5. DoB is defined as the distance between the seabed surface and the cable's top.

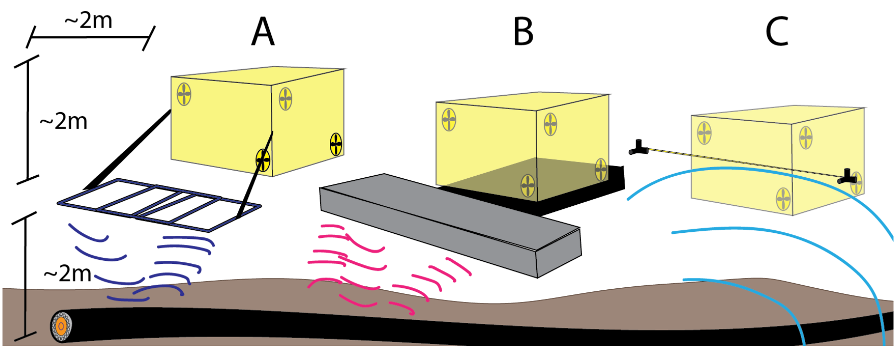

Figure 2.5: *Illustration of the burial depth measurement methods (A - active magnetic sensing, B - sonar, C - passive magnetic sensor, and in yellow underwater vehicles, ROV).*

The verification may face a problem if there are large variations and uncertainty in the burial measurements. The cable's measurements requires spatial synchronization of the *cable tracker sensor* mounted on an ROV with an *acoustic positioning system* placed on the survey ship (E.g., an Ultra-Short Baseline USBL). The survey ship is positioned using a GNSS, a satellite positioning system. The need for synchronization induces additional uncertainty in estimating the DoB, Figure 2.6.

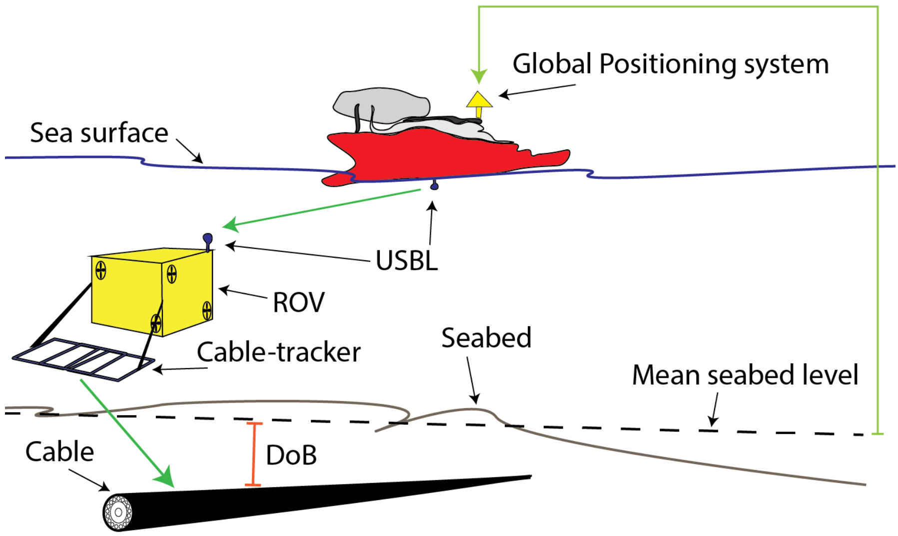

Figure 2.6: *Simplified exemplification of a Depth of Burial, DoB, definition, and its measurement method.*

The problem has been that cable sensors have a few-meter range and poor repeatability, and they work in highly complex surroundings. The physics of an irregularly moving antenna, coil, or acoustic hydrophone configuration to estimate the depth or distance to a nearby cable is difficult in modeling all contaminations. One of the challenges to measuring burial depth is the need for a signal to penetrate the conductive sea water and the dense and opaque sediments covering the cable or cables. This typically limits available sensors to ranging cables at a few meters impacted by noisy data, Figure 2.7.

Additionally, to complicate matters in managing deviations of the cable position, the required deliverable of the designed burial depth results in requirements being defined in the design constraints. If a validation proves deviations in the data from design constraints, this could lead to additional surveys, reburial operations, and rock dumping operations. Furthermore, surveyors request more precise survey requirements, which can improve the operations' efficiency.

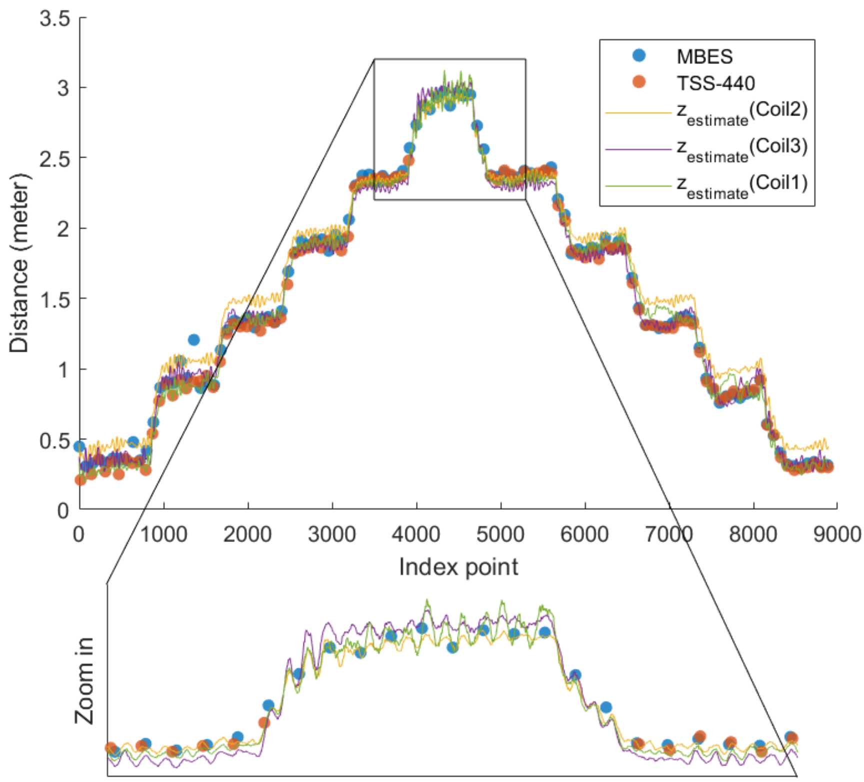

Figure 2.7: *Comparing MBES and TSS-440 measurement data for three coils.*

2.2.1 Cable Risk Assessment

Historically the most commonly used approach is the BPI (Burial protection index) developed by P.Mole [16] and improved by Allan [17]. BPI methodology considers sediment shear strength, anchor penetration strength, and sand wave movement to establish a burial depth that protects the cable from a scale of one to three, where one is protected from fishing gear, and three is for large anchors.

The most modern methodology CBRA [18] (Cable Burial Risk Assessment) is primarily used during the design stage to optimize burial depth boundaries for an acceptable anchor risk. Note that the method is not designed to be used for measurement data verification. Heat and other aspects are optimized separately. CBRA takes into account certain types of anchor accidents and fishing-gear seabed penetration. The methodology was developed by 'S. Gooding P., Allan P., Errington J. Hunt ' compiled into the open document known as CBRA [18], of which statistical analysis of historical shipping crossings to come up with estimations for the probability of impact along sections of the cable route resulting in an estimate of risk. However, a fish gear is considered the baseline for burial depth, and anchors are considered for how often they have accidents or similar, for which anchors will likely be deployed. Using CBRA results in estimating the annual probability of damage to sections of a cable where soil conditions and properties are assumed to be constant over large sections. The annual probability of a section P_{strike} is described by:

$$P_{\text{strike}} = \sum_{n=1}^{N_0} \frac{D_{\text{ship}}}{8760 V_{\text{ship}}} P_{\text{traffic}} P_{\text{wd}} P_{\text{incident}} \tag{2.1}$$

where
- $\frac{D_{\text{ship}}}{8760 V_{\text{ship}}}$ expresses the fraction of exposure at the cable during a year.
- V_{ship} the estimated average speed of the vessel over the cable is used (m/hr).
- D_{ship} describes the estimated distance the anchor is dragged in meters.
- P_{wd} modifies the probability as anchoring during an incident is more unlikely at deeper water in the presents of fewer obstacles. Example tables give this modifier zero value for depths >50 m, otherwise one.
- P_{incident} is the probability of an engine incident such as loss of propulsion or steering.

A recommended approach is to use the conservative estimate of the energy absorbed by the anchor:

$$D_{\text{ship}} = \frac{m V_{\text{ship}}^2}{F_{\text{UHC}}}, \tag{2.2}$$

where
- m is the mass of the ship.

- F_{UHC} is the anchor's holding force, estimated from size and soil characteristics.
- UHC states for Ultimate Holding Force.

When risk or depth are estimated using CBRA, there is a reference to Factor of Safety, F_{FoS} defined in relation to Depth of Burial B_{DoB} related by $B_{\text{DoB}} = D_{\text{DoB}} F_{\text{FoS}} + D_{\text{SM}}$, where D_{SM} is the sediment mobility. However, the Factor of Safety is not defined within CBRA and it is up to the engineers to include the uncertainty. There are six factors that contribute to FoS:

- Inherent uncertainty in the soil profile, the limited or sparse distancing of samples, the soil profile's impact, and its stability over time.
- Positioning and resolution of shallow geophysical surveys.
- Limitations of using historical shipping data, as future shipping routes may change.
- The approximate manner of anchor size and anchor behavior.
- Inaccuracy of measuring of DoB.

Nevertheless, there are no methods to estimate any of these factors, especially concerning an arbitrary factor F_{FoS}. The two main factors of heat and anchor risks are burial depth-dependent and result in cable failures, where expected collisions stay relatively constant over time, while the expected electro-thermal failures are expected to grow exponentially over time as shown in (Figure 2.8). However, the risk factor related to thermal and electrical stresses is not in the scope of the thesis.

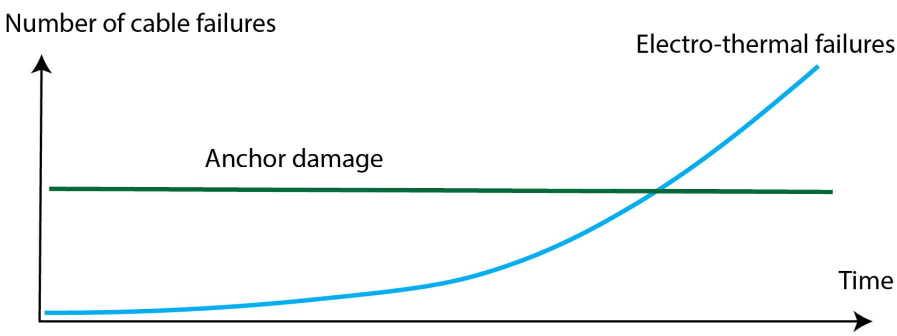

Figure 2.8: *Illustration of expected failures over time from shipping anchors and electro-thermal failures.*

2.3 Regulatory issues for subsea and offshore sustainable development

The *Environmental Impact Assessment* processes are a standard internationally recognized risk assessment method for permitting projects with potentially significant environmental impact [19]. Most western nations have developed similar processes enshrined in environmental acts [20]. When new large projects are planned that potentially affect the environment, an EIA is performed. However, as depicted in Figure 2.9, it is unclear if design options for lessening the impact from *pressure* are efficiently powerful [21]. There are three distinct possible outcomes:

- the response results in significantly improves conditions;
- the response results in very little changes from the prior expected poor conditions outcome;
- the prior conditions are good, and the response changes very little.

However, the EIA process lacks quantitative assessment of risks, even minor supervision, and follow-up of pressure impacts. These issues are partly due

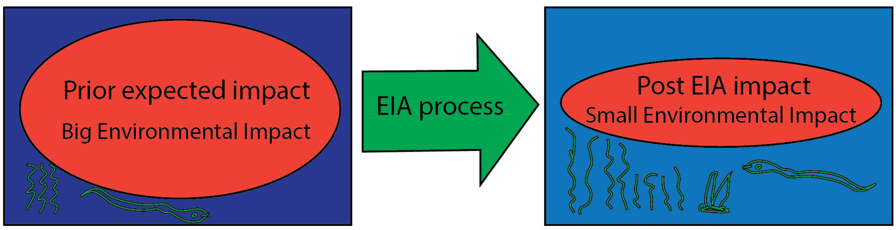

Figure 2.9: *The illustration of an EIA process and its impact.*

to the challenge of inferring a change in pressure to the cumulative change in the environment. It is a multi-variable problem that is also coupled with not enough measurement data to verify the results. A lack of access to sea measurement data is partly due to the more immense challenges in collection, conventional sensors do not function and access the seawater, the collection could be very costly, and funding for marine research is limited [22, 23].

Therefore, there is a challenging need for developing and verifying quantitative models for marine ecosystems (*State*) and their interactions (*Impact*) with (*Pressures*) and especially long-term effects with accordance to a DAPSIR methodology [13, 14] .

For those who are not familiar with the standard practices of EIA, for instance, scientists and engineers), it is common practice to categorize different environmental pressures on a scale from 0 to 1 to conduct impact assessments.

These pressures are then assigned to a natural number representing their impact, ranging from 0 to 5. The cumulative impact on the state of ecosystems is determined by taking the summation of the impact values multiplied by their corresponding pressure presence, which results in a relative value [24].

2.4 Marine Decision Support Tools - DST

In the case of the trade-off between quantitative and qualitative risk assessments, the former is the preferred method. This is particularly visible when seeking a quantifiable estimate of the effectiveness of mitigation, preventative measures, and policy changes. To obtain this level of precision and detail, a quantitative method is required to support decision-making and inform the design of effective risk management strategies. However, it is often impossible to conduct a comprehensive quantitative assessment due to limited resources, including time and data analysis capabilities. Nevertheless, there have been efforts to improve access to increase the use of quantitative methods and data for more effective assessments, which are now converging into marine EIA DSTs [25, 26].

The last few decades have seen a rise in offshore development, particularly in nearshore wind energy. However, the traditional EIA permit processes have been deemed to be *too slow* for the necessary development of renewable energy goals [27]. The purpose of the DSTs is to enhance the EIA process for better environmental protection, and these tools are designed to automate and streamline analysis. The DSTs utilize methods and analysis to estimate the presence and behavior of ecosystems based on the pressures applied [28, 29].

A challenge in the development and maintenance of effective DSTs can be both difficult and expensive. This challenge is being addressed through a structured approach by the Swedish Agency for Marine and Water Management (SwAM) in the development of early DSTs named Mosaic and Symphony [24, 30]. In this case, it is unclear if these development efforts will be or are ongoing developments or are developed at a pace where the DSTs have a significant impact on improving environmental impact assessment as the future use of the seas, current marine environmental challenges and lowering the lead times for projects.

2.5 DNV-GL RP-360

The DNVGL RP-360 is a recommended practice[12] detailing all aspects of cable projects, and Figure 2.10 depicts its different project phases, sub-phases, and stakeholder involvements. Cable considerations, which are typically in the early *Concept* stage, and the *Design* stage, both during *Tendering* and *Detailed* design, involve optimization of the cable and cable burial design. DNV-GL RP360 details the risk assessment process for optimizing the design

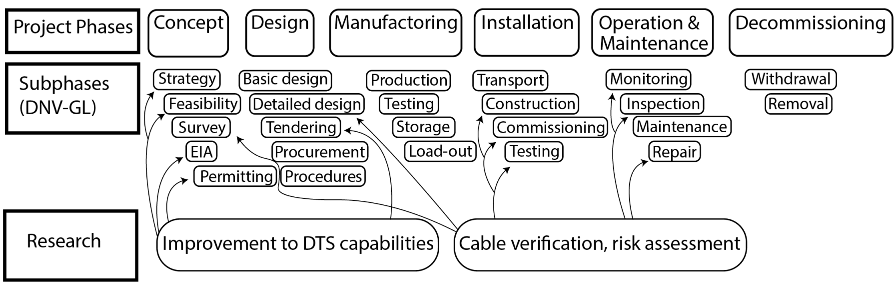

Figure 2.10: *Cable design and risk assessment related to different phases of a project detailed by the DNV-GL recommended practice[12].*

of the cable design, the planned route, or burial depth in relation to the cable risk factors, which include, but are not limited to, mechanical damage such as over-bending, axial elongation, shear as a result of the installation, or dragging anchors and fishing equipment getting stuck to the cable. The damages led to breaks in water tightness and compromised electrical insulation. Mitigation efforts to improve protection led to deeper cable burial, which helps protect the cables from anchors and fishing equipment. The Depth of Penetration, DoP, depends primarily on the object's/anchor's weight and sediment shear strength.

Electrical insulation degradation occurs naturally under high-voltage power transfer, and thermal damage can happen as heat increases the electrical insulation's aging rate [31, 32], resulting in an eventual insulation breakdown. Since a cost-effective cable has high power output and long life compared to cable insulation, electrical core, and installation costs, electrical longevity can be improved by designing with additional electrical insulation or by increased conductor size for fewer losses and generated heat. The thermal resistivity of sediments is much higher than that of the convection effects of seawater. Hence, deeper burial will increase the temperature of the cable or an equivalent lowering of the rated power output of the cable to maintain the expected time to failure. [33] This led to increased repair, capital, and installation costs for the overall project.

The EIA are a integral part of a project from initial concept to decommissioning. For marine EIA DST the effect is automated processes that may impact these kind of projects positively in the reduction of manual and time consuming work, during the concept, design phases, Figure 2.10.

Chapter 3

METHODOLOGY

The research field of the thesis is System Engineering relevant to marine applications, specifically in the area of energy installations. On the one hand, it deals with the measurement data and models uncertainties[34] and their impacts on risk assessment of buried subsea high voltage cables. On the other hand, it concerns the complexity, cost- and time-effectiveness of permit processes, including EIA for offshore installations. The applied methodology is relevant for the engineering approaches rooted in uncertainty and/or ambiguity in the risk assessment and methods used.

In this section the described methodological connections between the two aspects of this thesis are illustrated in Figure 3.1. It is shown that the cable burial assessment part focuses on the verification and validation of cable assets. While the marine DST aspect focuses on risk management and its integration with a potential co-benefit of developing marine DST with a particular focus on offshore energy applications.

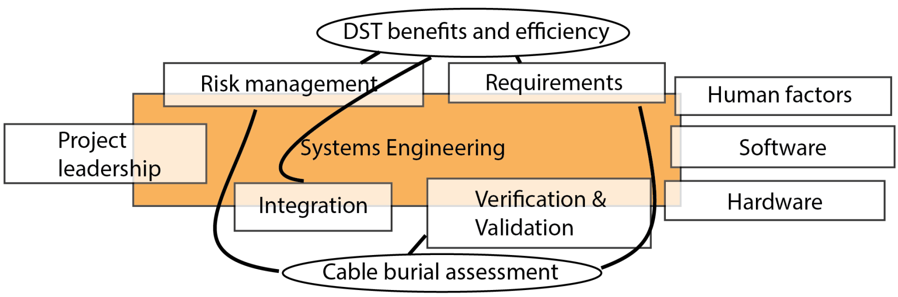

Figure 3.1: *Methodological connections between the two aspects of this thesis: DST and cable burial assessment.*

Both main thesis aspects deal with risk management and assessment along with verification and validation methods, as shown in Figure 3.1. Those two aspects are applied to marine technology, mainly from an engineering approach considering engineering components, as illustrated in Figure 3.2. However, the main issues relate to traditionally viewed impenetrable obstacles as human factors or complex ecosystems. Both aspects are based on the same principal research methodology, but each is customized for different purposes. The first relates to risk management and design validation of submarine cable assets regarding measurement data integration. The second relates to marine EIA DST in how development and design choices may be integrated to result in cost-effective deployment.

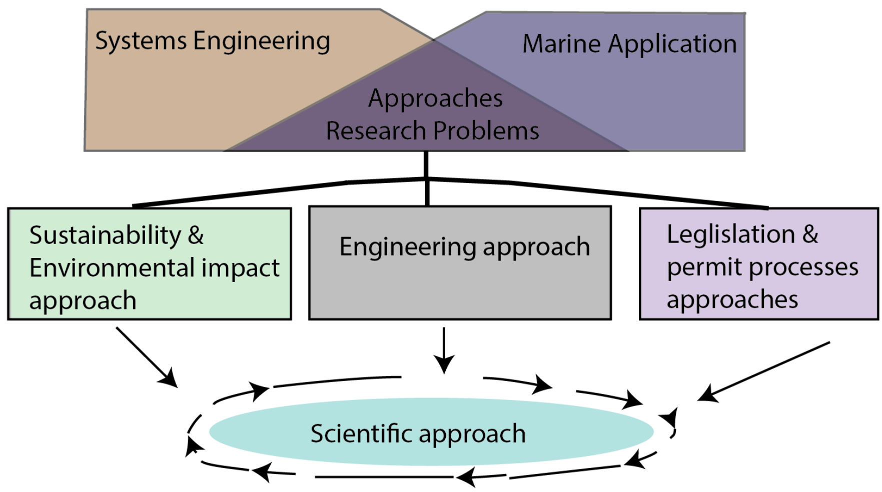

Figure 3.2: *A view of relationships among thesis research fields/applications and three main applied approaches.*

The cable risk assessment aspect follows a traditional scientific method presented in Figure 3.3 [35], where a problem of cable measurement is initially identified and research questions followed by relevant hypotheses have been evolving to assess the cable risk anew. The thesis research goal is to solve the problem of how measurement data contaminated by different types of noises and uncertainties can be implemented into a robust assessment model of cable burial risk of installed assets. The limitation of the approach is accessibility to the data from reliable sources and how to verify results. This research applies a multidimensional approach, which can limit the model's overall accuracy but, on the other hand, shows comprehensively how the proposed model works. This is in contrast to isolating a single assessing variable, which is typically preferred.

Extending from a classical paradigm towards a field with less tangible secondary processes such as human or multi-ecological impacts and with fewer well-defined goals, which are related to marine EIA DST, a new methodological approach is needed, more design orientated and focusing on tool devel-

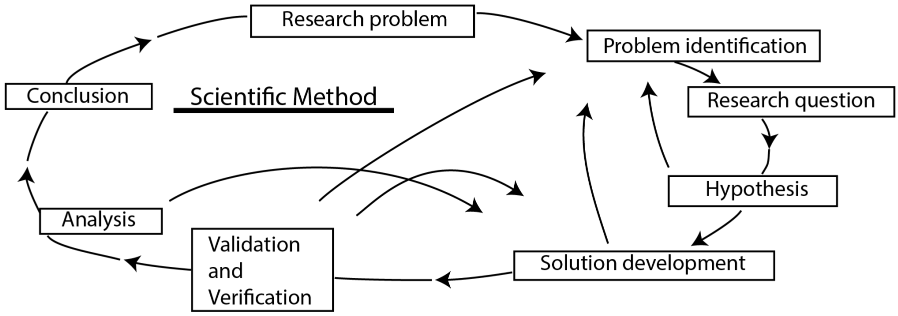

Figure 3.3: *A classic scientific method and the main steps relevant for the research.*

opment. Legislation and related processes are essential in designing the DST model as it sets limitations. The current and future permit system is the baseline in the model. The market is assessed in terms of its growth and the time aspect that impacts the effectiveness and efficiency of the design. However, aspects of tools, users, and social factors are not deeply investigated. They are considered constant or not change over time and may implicitly be incorporated in some processes as a constant factor in efficiency for human design outcomes. The initial rationale is to model a simplified DST working with one of the aspects of the subsea environment, processes, and users. But the scope of this thesis is limited to a simplified representation of the tool with goals to assess and evaluate different designs of efficiency and effectiveness during development. The analysis focuses on DST in relation to costs, benefits, and time constraints.

Chapter 4

SOLUTIONS

Section 4.1 explores the marine EIA DST aspects. A number of methods which were developed are summarised in the section. For the EIA DST assessment, the method and models are presented in Section 4.2. Section 4.3 explores aspects of verification methods for cable assets. The cable burial measurement analysis and methods are included in five sections. The main method for statistical assessment of data is presented in Section 4.4. The risk estimation is a topic of Section 4.5 and supplementary methods for processing the cable measurements are included in Section 4.6. The processing of collisions of AIS data is summarized in Section 4.7, and finally, the method for defining a path from the cable measurement data is included in Section 4.8.

4.1 Analysis basis of EIA DST aspect

As it was established, it would be favorable to assess further development of offshore DSTs in relationship to goals and savings potential of new sustainable offshore energy development. Finding applicable data to estimate the potential expenditure of EIA processes, is limited to a case study of offshore wind development in Sweden. Multiple parameters necessary to approach potential savings potential, which is potential EIA expenditure, are defined as multiple scenarios. One of the main assumptions relate to energy goals in both Sweden and the EU in 2030 or 2050 implicates time limits to the goals to be reached (Figure 4.1), making the problems time-dependent, with cumulative improvement as an essential factor to consider.

The cost function considers multiple factors that are roughly estimated, there were multiple possible choices/sources, and an assessment of multiple scenarios was necessary to get the wide range of possible outcomes. The time interval for national goals and the goal to effect permit lead times, led to implementing a possible mechanism in the model using simple linear relationships. Linear relationships are chosen in the model of mechanism in the absence of other identified theories. Further, multiple scenarios were defined for various

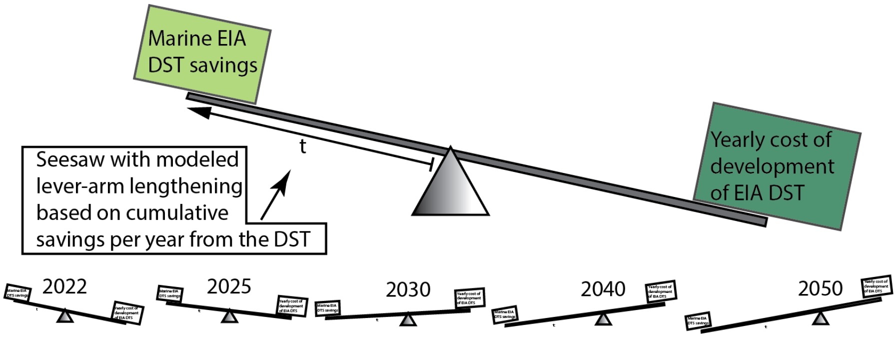

Figure 4.1: *A marine EIA DST timing to reduce costs of future offshore renewable energy assets in terms of reduced permit costs.*

efficiencies to represent different possible outcomes. Hypothetical variables had to be considered to complete the analysis where no proper estimation or model is available, such as for the DST efficiency, i.e. how efficient the developed DST will be in lowering the EIA permit lead times.

4.2 Proposed method to estimate EIA offshore DST development costs and benefits

A method is presented to roughly estimate the savings potential of the development of EIA DST tools by the automation of EIA permit-related assessment. Factors such as DST usage (utilization), development cost, and EIA costs can potentially be reduced by the EIA permit processes. By using Sweden as a case study, it was possible to roughly estimate different scenarios for the expansion of offshore energy projects and their costs and the percentage spent on permits & applications resulting in a total cost for permits and EIA defined by the model. The initial point was not to generate an exact analysis for all affected parameters but to limit to one approximate for offshore wind, and the one available component to study easily. Also, the efficiency and cost of the development of the offshore EIA DST are assumed, and the combination of these two assumptions casts uncertainty of exact behavior. However, the wide range of scenarios captures many possible outcomes.
There are many impacts and mechanisms that are assumed linear when time constraints and DST efficiency are to be considered. However, at this early and rough stage, it is not so essential to model the model's behavior, but time-limiting effects and design-dependent aspects, which require some approximation. E.g. the DST development may result in different progress efficiencies over time, while the assessed scenario considers only constant parameters over time.

To estimate the permit-related costs c_{EIA} for the future time scenario the following constants were estimated:

$$c_{\text{EIA}} = \frac{1}{1 - f_{\text{failure rate}}} c_{\text{MWh}} W f_{\text{application}} f_{\text{offshore}} \tag{4.1}$$

where W are the estimated cost per yearly MWh of offshore wind energy, and $f_{\text{application}}$ is the fraction of project costs related to the application process, the fraction f_{offshore} is the application process contributed to projects offshore-part assumed a linear relationship between page count and value of EIA and was estimated of what amount of the EIA reports are concerning onshore vs. offshore. Further, the cost per yearly MWh in capacity is c_{MWh}, and the model assumed that the EIA assessment quality improvement from the DST was the main contributing factor to permit failure rate $f_{\text{failure rate}}$.
This future EIA cost is presented in figure 4.2.

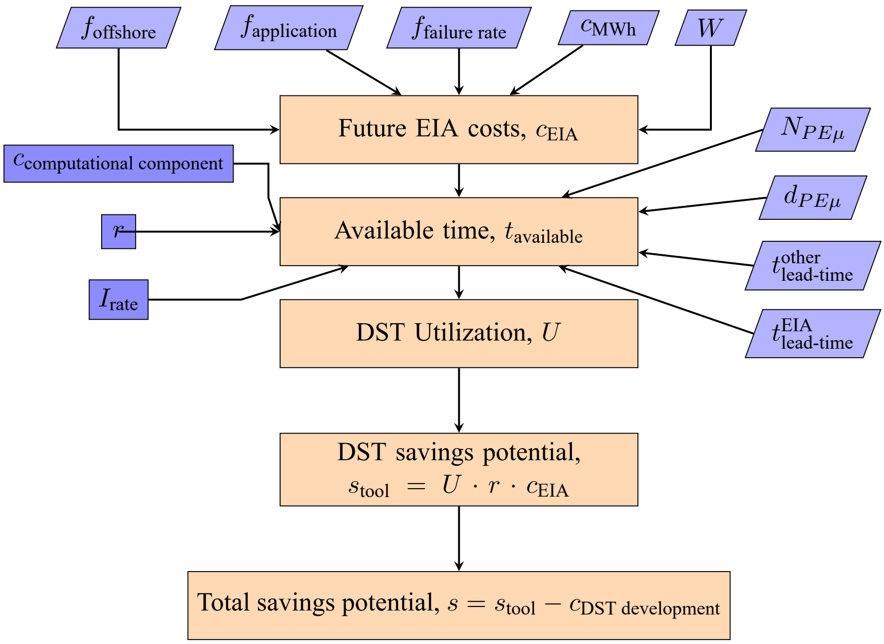

Figure 4.2: *Flowchart of the five steps of the analysis with parameters and estimates definitions. Dark blue represents scenario variables, light blue represents estimated parameters, and light orange represents the methods.*

Following, the available time $t_{\text{available}}$ is modified based on the efficiency of the DST tool.

$$t_{\text{available}} = t_{\text{total}} - t^{\text{other}}_{\text{lead-time}} - t^{\text{EIA}}_{\text{lead-time}} \frac{1}{f} \tag{4.2}$$

$$f = \frac{c_{\text{EIA}}}{c_{\text{EIA}} - \sum_{x=1}^{N} c_{\text{EIA}} r H(t - t_{\text{DST development}} \frac{x}{N})} \tag{4.3}$$

$$U(t) = min(1, \sum_{x=1}^{N_{PE\mu}} H(t - t_{\text{DST development}} \frac{x}{N_{PE\mu}}) \cdot (t - t_{\text{DST development}} \frac{x}{N_{PE\mu}}) \cdot \begin{cases} \frac{d^x_{\text{EIA}}}{t_{\text{available}}} & \text{for optimized development} \\ \frac{1}{N_{PE\mu}} & \text{for unoptimized development} \end{cases} \tag{4.4}$$

$$c_{\text{DST development}}(t) = \begin{cases} \frac{nc_{\text{computational component}} N_{PE\mu}}{t_{\text{DST development}}} t & : t < t_{\text{DST development}} \\ nc_{\text{computational component}} N_{PE\mu} & : \text{Otherwise} \end{cases} \tag{4.5}$$

$$s_{\text{tool}} = U \cdot r \cdot c_{\text{EIA}} \tag{4.6}$$

The last step is the savings potential model. Based on DST tool utilization and cost of development resulting in equation (4.7).

$$s(t) = s_{\text{tool}}(t) - c_{\text{development}}(t) \tag{4.7}$$

4.3 Analysis basis of risk assessment verification aspect

The cable assets verification problem has established that there is a need to determine the position of subsea cable installations to verify the risk assessment i.e. the future lifetime and repair costs for the cable installations. Further, using burial limits when there are large variations and uncertainties in the measurement data makes it not ideal to make a rudimentary check if data is above a boundary for burial depth. We propose a statistical averaging function to take multiple data points into consideration when determining the position along the cable. There are two main aspects to be taken into account. The first is data availability i.e. if data is missing, which increases uncertainty, or if there are more or duplicate data sets along the cable, then the model and analysis should result in a better estimation. The second aspect is data variability for burial depth, such that more noisy data generates a worse estimate and the other way around, how variability in data could result in more accurate positioning of the cable.

A buried steel reinforced subsea high voltage cable position is limited by forces bending the cable during burial and sensors used may receive a signal

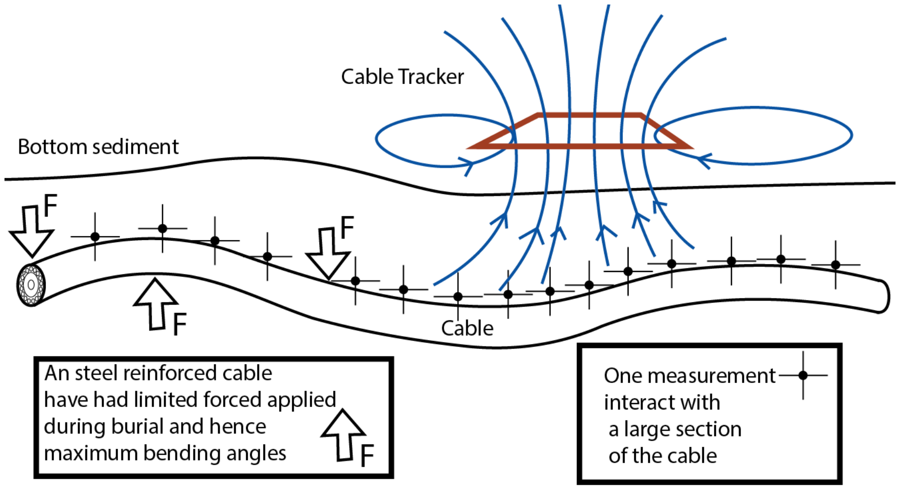

Figure 4.3: *An illustration of the position of buried steel reinforced subsea high voltage cable and its effect on the measurement result.*

from a larger section of cable, which also can help to identify the cable position from multiple measurements. Then two phenomena affecting the cable measurements are to be considered: 1.The interactive surface of the sensor (Figure 4.3); 2.The indirect positioning of the cable if the positioning of the cable in front or behind the cable is typically very stiff. Considering that only limited forces act on the cable during burial such that not every shape is possible, and for the largest subsea high voltage cables, the bending possible deviations are very limited. This aspect primarily motivates to introduce a window of data to be used to estimate cable position, as there are physical limitations of how much the actual position is likely to vary for a high-voltage cable even if there are more variations in the data.

4.4 Proposed method to approximate Depth of Burial using multiple measurement points

To assess cable measurements a data averaging method was inspired by the statistical average of measurement data into account to define confidence [36], an factor of variance should result in a more accurate representation the more data is available. As the mean $\mu^z_{\overline{D}_{\text{DoB}}}(L)$ and standard deviation of the mean $\sigma^z_{\overline{D}_{\text{DoB}}}(L)$ are unknown in general for the measured population, the sample means, and sample standard deviation has to be used. Then it changes the standard deviation into t-Student's inverse cumulative distribution function,

F^{-1} :

$$D_{\text{DoB}} = \mu^{z}_{\overline{D}_{\text{DoB}}}(L) + F^{-1}(a,\nu) \cdot \sigma^{z}_{\overline{D}_{\text{DoB}}}(L), \tag{4.8}$$

where $\nu = N - 1$. The function takes into consideration the variability of the data, and the burial depth decreases depth based on the variability of the mean value. The data used along the cable route is designed by a square window centered around the coordinate. This approach works well if the error is assumed to be white noise and centered around the true position. Any offsets may generate a linear offset error and are unavoidable, multiple surveys from different times and sensors or sensor types, if combined in this fashion may be a practical way to assess and limit the impact of systematic errors.
The motivation for the windows can be exemplified in two ways, sensor and cable aspects. Sensors can have a large footprint, i.e. data point in three dimensions is not just a representation by a point but is a signal of interacting with a larger area of the cable. In this case, the cable measurement is the cable position of the cable and the contribution of the signal is probably some kind of bell curve centered right below the cable (i.e. some part of the signal comes behind and in front of the midpoint of the cable estimation).

In terms of the measured high voltage cable, it is very stiff, this mechanically limits where the cable can be positioned from one measurement to another. Consider having a trampoline it bends from standing on the edge and knowing the maximum applied force its behavior is predictable. Now it is similar to a cable to some extent, the practical difference is the plastic and elastic deformation characteristics of a cable. For a large armored high voltage subsea cable, it is buried under tension (~1000 kg), and ideally this with the forces acting during lowering operation limits the bending that the cable may have. It should be possible to construct a physical representation of how to define an approximate probability distribution of the likely position of the cable that takes into consideration the sensor and cable characteristics. However, this has not been explored and the proposed method defines the simplest square window. Further, to verify the model behaviors an approximation of the linear response of the incoming measurement parameters was derived.

The coefficients c_r and c_X are defined as the linear scale of the window radius and data sampling per meter and a near constant X_0 samplings per meter is assumed to result in the sampled standard deviation of the mean being defined as:

$$\sigma^{\text{org}}_{m} = \sqrt{\frac{\sum_{i=1}^{N}(M^{i}_{n} - \mu)}{N(N-1)}} \tag{4.9}$$

where the mean is defined as $m = \mu = \frac{1}{N}\sum_{i=1}^{N} M^{z}_{i}$ for N burial depth measurements M^z. Where the number of measurements N is defined as:

$$N = \lfloor 2r \cdot X \rfloor = \lfloor 2r_0 c_r X_0 c_X \rfloor, \tag{4.10}$$

where $r = r_0 c_r$ and $X = X_0 c_X = X_0 c_X(z_{\text{DoB}})$. resulting in

$$\sigma_m^{\text{org}} = \sqrt{\frac{\sum_{i=1}^{2r_0X_0}(M_n^i - \frac{1}{2r_0X_0}\sum_{j-1}^{2r_0X_0} M_n^j)^2}{2r_0X_0(2r_0X_0-1)}} \tag{4.11}$$

The standard deviation of the mean σ_m together with the level of confidence define the difference in position compared to the mean $\mu^z_{\overline{D_{\text{DoB}}}}$ as $F^{-1}(a, N-1)\sigma^z_{\overline{D_{\text{DoB}}}}(L)$ and approximated as:

$$F^{-1}(a, N-1)\sigma^z_{\overline{D_{\text{DoB}}}}(L) \approx a\frac{c_n}{\sqrt{c_r c_X}}\sigma_m^{\text{org}}(L) \tag{4.12}$$

If $N \gg 1$ then $a \approx F^{-1}(a)$ and $N \approx N-1$ and $\mu(N) = \mu(N^*)$ where N^* is any large N. Coefficient $c_T = a\frac{c_n}{\sqrt{c_r c_X}}$ defines a relationship between the variables and parameters uncertainty and variability.

Equation (4.12) is to give a general direction of how parameters influence the model behavior of accuracy and how to compensate for changes in design between projects.
As an example, consider an assessment of a much larger 3-phase high voltage cable than a single DC cable. The three-phase cable is much stiffer resulting in the possible use of a wider window as data further behind and in front will imply the position of the cable. And in general, a wider window will improve the estimation of the position, and hence the burial depth estimation.

4.5 Proposed statistical method assessing subsea buried cable data

The proposed model to assess the measurement data of the subsea cable is defined to represent a near analog to the established CBRA methodology risk evaluation for the design of cables. The modified expression is presented in equation (4.13). Where the estimated position of the cable in the bottom surface plane of the cable from the measurements by fragmentation of the sections into smaller pieces of length Δx to consider smaller changes in the risk. Additionally, we define the section width $D_{\text{section}}(j) = L_j - L_{j-1}$ and a step size $\Delta x_j = \frac{D_{\text{section}}(j)}{N_{\Delta x}}$, where $N_{\Delta x}$ is the number of steps in each section. This led to the definition used of a continuous function for the variable x, where the cable length is integrated using equation (4.8).

$$
\begin{aligned}
P_{\text{strike}}^{\text{All sections}} = \sum_{j=1}^{N_s} \sum_{i=1}^{N_p(j)} \int_{L_{j-1}}^{L_j} dx P_{\text{wd}} \\
H[D_{\text{DoB}}(x) - D_{\text{DoP}}(i)] \frac{D_{\text{ship}}}{V_{\text{ship}} \cdot 8760} P_{\text{incident}} \frac{1}{D_{\text{section}}(j)}.
\end{aligned}
\tag{4.13}
$$

To model a verified risk it was necessary to be able to split the risk into smaller sections, and hence the choice of a continuous integration equation was chosen.

The ideal test would be a survey of cable burial of a cable with exact knowledge of its burial depth and compare the measurement with a known burial depth risk assessment. That is however not available or possible in a real scenario, and all burials of cables are at unknown depths to some degree. Some options that might be more feasible are some burial equipment have an arm that moves the cable to a certain position, or multiple surveys of a cable have been conducted to improve confidence or put certain limits on burial.

The analysis requires traffic data (AIS data) over the nearby area of the cable installation. The data should preferably be annualized over at least one year to null seasonal variations in traffic.

When only a single survey data set of a cable is available, it makes sense just to consider white noise in the model, as there is no reference to being able to consider offsets in the data produced by either burial or the sensor.

4.6 Cable sensor data model

Assessing the risk model when the cable survey data set is available is straightforward, however, when it is not available an inferior approach is to model the sensor and its data using a calibration data series (Cable tracker data and sonar data as an indication of ideal reference data). The proposed method to fit the expected 'white' noise standard deviation of the sensors dependent on depth through equation (4.14).

$$
S_M = b_0 + b_1 R_M + b_2 R_M^2 + b_3 R_M^3 + b_4 R_M^4 \tag{4.14}
$$

Where S_M is the standard deviation, and R_M is the cable tracker's distance to the cable measurements, scaled through the reference depth. Equation (4.14) is presented as a 4th order polynomial as it was a good fit for the data used in this study, but other choices of models for the uncertainties can be used too.

4.7 AIS method

With available historical AIS data from the Danish Maritime Authority that is used in accordance with the conditions for the use of Danish public data from year 2019 [37], it is possible to assess the crossings of ships over a cable path. Using annualized AIS data is assumed to be a good approximation of future traffic and hence future accidents. In the proposed method AIS data is processed in the local Cartesian plane of the cable, so AIS data have to be converted from the longitude and latitude coordinate system UTM (Universal Transverse Mercator). To assess crossings of the raw AIS data, it has to be sorted by ships (MMSI number) and by the time such that the data represent the path of the ships over time.

A crossing is defined if two consecutive points of the ship's path are defined as a line segment crossing one of the line segments of the cable route.

The following help equation (4.15) for establishing a crossing defines a point $[x, y]$ is above (positive) or below (negative) the line defined by the two points P_h^{point} =$[x_{L_h}, y_{L_h}]$ and P_{h+1}^{point} =$[x_{L_{h+1}}, y_{L_{h+1}}]$:

$$\begin{aligned} f_{line}(P_h^{\text{point}}, P_{h+1}^{\text{point}}, x, y) = (y_{L_{h+1}} - y_{L_h})x+ \\ +(x_{L_{h+1}} - x_{L_h})y + (x_{L_h} y_{L_{h+1}} - x_{L_{h+1}} y_{L_h}). \end{aligned} \tag{4.15}$$

Putting together four expressions of equation (4.15) returns in the detection of two line segments crossing each other. The crossing can be defined by the Boolean value C for the two points defining a cable section: P_h^{point} =$[x_{L_h}, y_{L_h}]$ and P_{h+1}^{point} =$[x_{L_{h+1}}, y_{L_{h+1}}]$.
And two points defining ship's path: P_{AISg}^{point} =$[x_{AISg}, y_{AISg}]$ and $P_{AISg+1}^{\text{point}}$ =$[x_{AISg+1}, y_{AISg+1}]$. Then the Boolean value C define the crossing by equation (4.16):

$$\begin{aligned} C = H\Big[- f_{line}(P_h^{\text{point}}, P_{h+1}^{\text{point}}, P_{AIS1}^{\text{point}}) \cdot \\ f_{line}(P_h^{\text{point}}, P_{h+1}^{\text{point}}, P_{AIS2}^{\text{point}})\Big] \wedge \\ H\Big[- f_{line}(P_{AISg}^{\text{point}}, P_{AISg+1}^{\text{point}}, P_h^{\text{point}}) \cdot \\ f_{line}(P_{AISg}^{\text{point}}, P_{AISg+1}^{\text{point}}, P_{h+1}^{\text{point}})\Big] \end{aligned} \tag{4.16}$$

4.8 Measurement data path generation method

Cable measurement data is scattered around the designed cable path in the spatial plane aligned with the sediment surface. Assessing the real position of the

cable is may require not just assessing measurements nearby the design cable, as if there are larger deviations the analysis will be limited. So the following method defines a new cable path based on the measurement data-plane coordinates. It is important later in the assessment of which measurement to include in the window deployed.
The lengthwise position of the cable is defined by the length L of curved data of a survey in the 2D dimensional plane. L is the 2D path along the sequence of line segments defined below. The method starts in one endpoint on the 2D dimensional coordinates Easting, Northing (UTM), the measurements within a circle with a radius r_L excluding points assessed in previous steps B_i^{old}, their center of mass defines a linear line from the start point with the extent of the furthest measurements r_{extent} to handle data gaps(where data is missing, either a cable missing can be assumed or the cable is approximated as a single line segment of the gap.). The line is defined by a coordinate system rotation such that the x-axis becomes the distance along L for each point, where the previous lengths of the segments need to be added. For each step, L for all measurements B_i within the circle is defined as:

$$\begin{aligned} L_{\text{measurements}}(B_i) = +\sum_{i}^{N_i} r_{extent}(i) \\ +T_{\text{new basis}} \cdot (M(B_i) - T_{\text{new basis}} \cdot L_i^{\text{start point}}) \end{aligned} \tag{4.17}$$

where previous generated steps N_i lengths are added, $T_{\text{new basis}} = [\frac{\nu}{||\nu||}, \frac{\nu^{\perp}}{||\nu||}]$ is the new basis, directional basis vector is $\nu = -S_i + \overline{M(B_i))}$, where Boolean for measurements in the step is defined as $B_i = ((M_y - S_i^y)^2 + (M_x - S_i^x)^2 < r_L^2) \wedge \neg B_i^{old}$, where $B_{i+1}^{\text{old}} = B_i^{\text{old}} + B_i$, S are the end-points of each line segment defined as $S_{i+1} = S_i + T_{\text{new basis}}(i, 1) \cdot r_{\text{extent}(i)}$.

Moreover, the *x* and *y* coordinates on linear line segments along the cable of L are defined as:

$$\begin{aligned} [x, y] = [x_i + sgn(x_{i+1} - x_i)\frac{L - L_i}{\sqrt{1 + k_i^2}} y_i + \\ +sgn(y_{i+1} - y_i)\frac{L - L_i}{\sqrt{1 + k_i^{-2}}}]. \end{aligned} \tag{4.18}$$

where index $i = \sum_i (L > L_i)$, line segment $L_i = \sum_{j=2}^{i} ||S_{j+1} - S_j||$ and the slope k_i is between L_{i+1} and L_i.

Chapter 5

CONTRIBUTIONS, CONCLUSIONS AND FUTURE WORK

This thesis's published and submitted contributions add to the knowledge and insight of subsets of cable burial risk assessment and verification in relation to offshore renewable energy development, as illustrated in Figure 5.1. Below, each contribution is summarized by claims, results, conclusion, and future research ideas. Section 5.1 is related to the published conference papers, Paper A *'A New Method for As-built Burial Risk Assessment for Subsea Cables'* while Paper B *'An Improvement of Assessing As-built Burial Risk for Subsea Cables'* is a subject of Section 5.2. Additionally, Section 5.3 is dedicated to contributions to EIA DST development impact on permit lead-times included in a submitted Paper C *'Strategic development of environmental impact assessment decision support tool for offshore energy enables decreased costs, increased utilization, and quality'*. Future work is proposed in Section

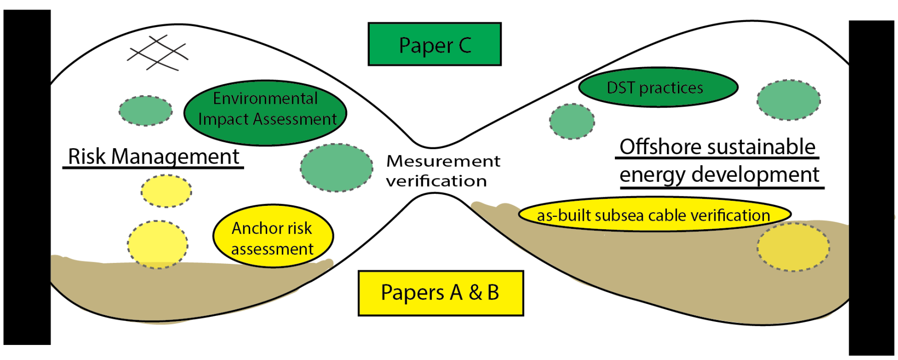

Figure 5.1: *Hourglass of the papers' contributions to application areas and research subjects*

5.1 A New Method for As-built Burial Risk Assessment for Subsea Cables

An improved methodology for verification of cable burial risk assessment will protect assets and lower maintenance. A method was proposed to assess cable burial. The method opens up new viewpoints of verification and other more dynamic options and possible requirements for burial and following measurements. The proposed verification method, with the addition of confidence intervals, makes it possible to consider systems more comprehensively.

The methodology is a re-design of the burial depth methodology CBRA to assess cable burial measurement data to verify installations. Development and testing was conducted in *Matlab* resulting in data calibration, and collision analysis summarized in Figure 5.2, and Figure 5.3.

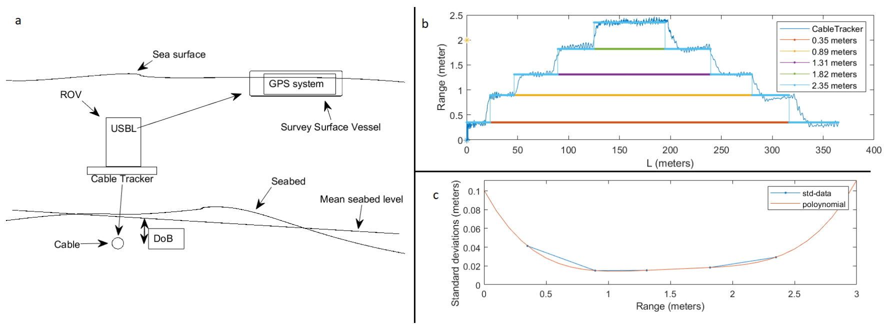

Figure 5.2: *Data calibrations and analysis (a) Illustration of measurement method; (b) The cable tracker data; (c) fourth-order polynomial fit of sampled standard deviations of the cable noise.*

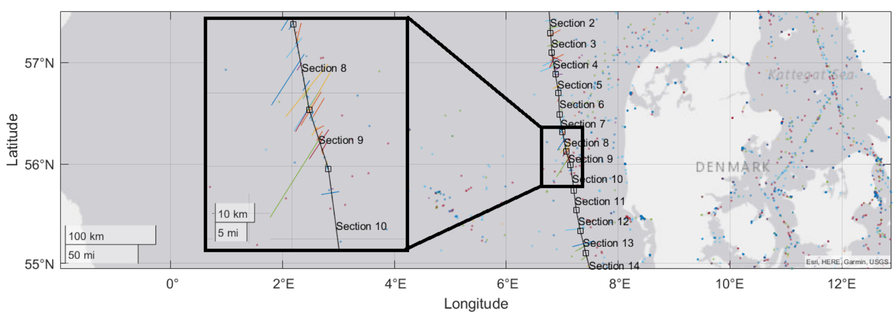

Figure 5.3: *Collision analysis of AIS data coverage of traffic data[37], samples of the data as colored dots. Crossing line segments for the vessel AIS positions with the sections numbered 1-14.*

5.2 An Improvement of Assessing As-built Burial Risk for Subsea Cables

Estimation of anchor risk for a hypothetical conservatively high-risk project, assuming that systematic measurement errors are negligible for the analysis, is a study that, in the first step, will define the magnitude of the issue. A value for the generated maximum risk was determined using actual AIS data for the cable route shown in Figure 5.4. Deviations from the noisy measurement data were compared to an equivalent design depth, and the maximum possible risk deviations were estimated by varying the design depth. This enables estimating deviations in risk to expect or verify it during a subsea cable project's design or in the verification phase. The results indicate that the deviations in verifiable risk can be significant to be considered during cable burial depth design, and the choice of cable sensors may be of importance.

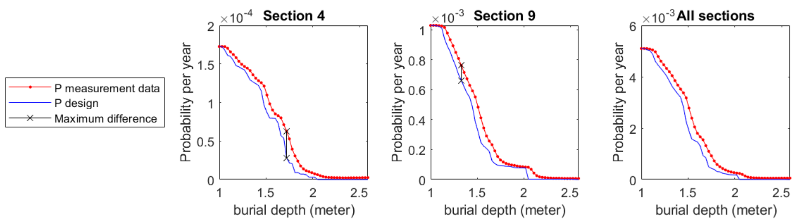

Figure 5.4: *The generated maximum risk of a number of burial depths in Sections 4 and Section 9, and the average risk for the same depths for each section.*

5.3 Strategic development of marine EIA decision support tools for offshore energy enabling decreased costs, increased utilization, and quality

A design improvement during DST development and deployment may affect future cost savings for sustainable offshore energy growths. A model was proposed to assess savings potential, and parameters were estimated and data collected to assess future offshore wind development. A Myriad of forecast scenarios was used to assess DST savings potential based on a wide range of estimated parameters, resulting in both negative and positive savings potential, as shown in Figure 5.5.

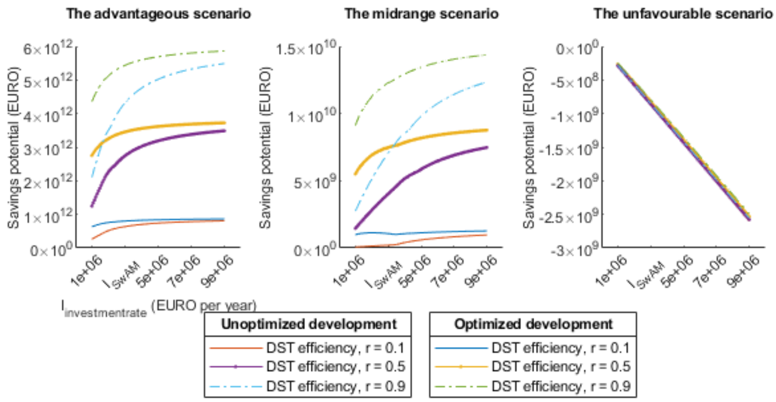

Figure 5.5: *The resulting savings potential of the model at the end of the scenario time window $t_0 + t_{total}$, with varying investment rates I_{rate}.The subplots are for the advantageous, midrange, and unfavorable scenarios where different DST efficiencies and levels of optimization exist.*

5.4 Future research

Ideas for future research for cable risk management following Paper A and Paper B could be summarized as follow:

- To assess systematic errors by assessing data from multiple re-surveys and using different sensors.
- To use the methodology to optimize burial depth during the design phase where measurement capabilities and limitations are taken into consideration.
- To apply methodologies including CBRA to assess anchor risk of recently surveyed projects that have been in operation for many years and have been assessed to verify the model or model parameters.
- To assess cable data using different confidence intervals and compare it to the designed risk from the Burial Assessment.
- To improve an anchor model to a statistical model as dragging length and depth vary dependent on anchor type, sediment, but also as a function of time, such that anchor depth varies along the drag and may resurface.
- To apply a more complex anchor model using e.g., a distribution of penetration depths which may lead to optimization of burial depth that will have fewer step-wise characteristics.

Ideas for future research for marine EIA DSTs from Paper C could be summarized as:

- To address model aspects for efficiency and development options, and to generate a modular model and to perform some experiments or studies to result in a model for development efficiency and dependency on various parameters.
- To improve the development model where another layer of development is introduced, which defines the functionality to be developed and to figure out how aspects of a platform interact or generate scenarios or EIA assessments.
- To verify partial systems and case studies to improve the model or verify assumptions for fewer variables.

BIBLIOGRAPHY

[1] International Energy Agency, "Offshore wind outlook 2019," tech. rep., IEA, 2019.

[2] P. Ehlers, "Blue growth and ocean governance—how to balance the use and the protection of the seas," *WMU journal of maritime affairs*, vol. 15, no. 2, pp. 187–203, 2016.

[3] EU commission, "on a new approach for a sustainable blue economy in the eu transforming the eu's blue economy for a sustainable future," 2021.
https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0240&from=EN.

[4] Nord Stream AG, "Incident on the nord stream pipeline." https://www.nord-stream.com/press-info/press-releases/incident-on-the-nord-stream-pipeline-updated-14112022-529/, 2022. Accessed on February 20, 2023.

[5] L. A. Kóczy, D. Csercsik, and B. R. Sziklai, "Nord stream 2: A prelude to war," *Energy Strategy Reviews*, vol. 44, p. 100982, 2022.

[6] L. Burdette, "Leveraging submarine cables for political gain: Us responses to chinese strategy.," *Journal of Public & International Affairs*, 2021.

[7] International Energy Agency, "Net zero by 2050: A roadmap for the global energy sector," tech. rep., IEA, 2021.

[8] J. Lam, *Enterprise Risk Management: From Incentives to Controls*. Wiley Finance, John Wiley & Sons, 2003.

[9] M. Abrahamsson, *Uncertainty in Quantitative Risk Analysis - Characterisation and Methods of Treatment*. PhD thesis, Division of Fire Safety Engineering, 2002.

[10] ISO Central Secretary, “Risk management — guidelines,” Standard ISO 31000:2018, International Organization for Standardization, Geneva, CH, 2018.

[11] ISO Central Secretary, “Risk management — risk assessment techniques,” Standard ISO 31010:2019, International Organization for Standardization, Geneva, CH, 2019.

[12] DNV GL AS, “Subsea power cables in shallow water.” https://www.powerandcables.com/wp-content/uploads/2021/08/Subsea-Power-Cables-in-Shallow-Water-DNVGL-RP-0360.pdf, 2016. Accessed: 2022-07-26.

[13] European Environment Agency, “Environmental indicators: Typology and overview,” Tech. Rep. Technical report No.25, European Environmental Agency, Kongens Nytorv 6, DK-1050, Copenhagen K, Denmark, 1999.

[14] OSPAR, “Ospar special session on the dapsir framework.” https://www.ospar.org/news/ospar-special-session-on-the-dapsir-framework, 2021. [Accessed: February 19, 2023].

[15] M. Ardelean and P. Minnebo, “Jrc technical reports; hvdc submarine power cables in the world,” 2015.

[16] P. Mole, I. Featherstone, and S. Winter, “Cable protection: solutions through new installation and burial approaches: Les liaisons optiques sous-marines,” *REE. Revue de l’électricité et de l’électronique*, no. 5, pp. 34–39, 1997.

[17] P. Allan, “Selecting appropriate cable burial depths a methodology,” in *A Methodology IBC conference on Submarine Communication. The Future of Network Infrastructure, France*, pp. 1–12, Citeseer, 1998.

[18] Carbon Trust, “Cable burial risk assessment methodology.” https://prod-drupal-files.storage.googleapis.com/documents/resource/public/cable-burial-risk-assessment-guidance.pdf, 2015. Accessed: 2022-07-26.

[19] N. Craik and K. Gu, “Strategic environmental assessment in marine areas beyond national jurisdiction: Implementing integration,” *The International Journal of Marine and Coastal Law*, vol. 37, no. 2, pp. 189 – 216, 2022.

[20] F. D. Guerra, C. Grilo, N. M. Pedroso, and H. N. Cabral, “Environmental impact assessment in the marine environment: A comparison of

legal frameworks," *Environmental Impact Assessment Review*, vol. 55, pp. 182–194, 2015.

[21] A. Barker and C. Wood, "An evaluation of eia system performance in eight eu countries," *Environmental Impact Assessment Review*, vol. 19, no. 4, pp. 387–404, 1999.

[22] G. B. Deane, J. C. Preisig, and A. C. Singer, "Making the most of field data to support underwater acoustic communications r&d," *2018 Fourth Underwater Communications and Networking Conference (UComms)*, pp. 1–5, 2018.

[23] J. A. Adam, "Probing beneath the sea: Sending vessels into environments too harsh for humans poses challenges in communications, artificial intelligence, and power-supply technology," *IEEE Spectrum*, vol. 22, pp. 55–64, 1985.

[24] L. Hammar, J. Schmidtbauer Crona, G. Kågesten, D. Hume, J. Pålsson, M. Aarsrud, D. Mattsson, F. Åberg, M. Hallberg, and T. Johansson, "Symphony: Integrerat planeringsstöd för statlig havsplanering utifrån en ekosystemansats." https://www.havochvatten.se/download/18.52d593d41624ea1d549cfe1d/1523361761104/rapport-symphony-integrerat-planeringsstod-for-statlig-havsplanering-utifran-en-ekosystemansats.pdf, 2018.

[25] K. Pınarbaşı, I. Galparsoro, Ángel Borja, V. Stelzenmüller, C. N. Ehler, and A. Gimpel, "Decision support tools in marine spatial planning: Present applications, gaps and future perspectives," *Marine Policy*, vol. 83, pp. 83–91, 2017.

[26] D. Depellegrin, H. S. Hansen, L. Schrøder, L. Bergström, G. Romagnoni, J. Steenbeek, M. Gonçalves, G. Carneiro, L. Hammar, J. Pålsson, *et al.*, "Current status, advancements and development needs of geospatial decision support tools for marine spatial planning in european seas," *Ocean & Coastal Management*, vol. 209, p. 105644, 2021.

[27] R. H. Leeney, D. M. Greaves, D. C. Conley, and A. M. O'Hagan, "Environmental impact assessments for wave energy developments – learning from existing activities and informing future research priorities," *Ocean & Coastal Management*, vol. 99, pp. 14–22, 2014.

[28] M. Dahl, D. Deyanova, L. D. Lyimo, J. Näslund, G. S. Samuelsson, M. S. Mtolera, M. Björk, and M. Gullström, "Effects of shading and simulated grazing on carbon sequestration in a tropical seagrass meadow," *Journal of Ecology*, vol. 104, no. 3, pp. 654–664, 2016.

[29] T. Bekkby, E. Rinde, L. Erikstad, V. Bakkestuen, O. Longva, O. Christensen, M. Isæus, and P. E. Isachsen, "Spatial probability modelling of eelgrass (zostera marina) distribution on the west coast of norway," *ICES Journal of Marine Science*, vol. 65, no. 7, pp. 1093–1101, 2008.

[30] H. och vattenmyndigheten, "Rapport 2020:13 - mosaic: En resa genom arktis och över tid." https://www.havochvatten.se/download/18.1bd43926172bdc4d648d4f7e/1593701389470/rapport-2020-13-mosaic.pdf, 2020. [Accessed: February 19, 2023].

[31] C. C. Reddy and T. S. Ramu, "Estimation of thermal breakdown voltage of hvdc cables - a theoretical framework," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 14, 2007.

[32] J. Zhang, J. Li, Y. Wang, L. Bao, and X. Zhang, "Electrical breakdown properties of low density polyethylene under dc voltage," *2014 ICHVE International Conference on High Voltage Engineering and Application*, pp. 1–4, 2014.

[33] T. Worzyk, *Submarine power cables: design, installation, repair, environmental aspects*. Springer Science & Business Media, 2009.

[34] I. Iso and B. OIML, "Guide to the expression of uncertainty in measurement," *Geneva, Switzerland*, vol. 122, pp. 16–17, 1995.

[35] H. G. Gauch Jr, H. G. Gauch, and H. G. Gauch Jr, *Scientific method in practice*. Cambridge University Press, 2003.

[36] J. McGhee, I. A Henderson, M. J. Korczynski, and W. Kulesza, *Scientific metrology*. Lodart SA, 1998.

[37] D. M. Authority, "Historical ais data." http://web.ais.dk/aisdata/. Accessed: 2022-06-06.

PAPER A

A New Method for As-built Burial Risk Assessment for Subsea Cables

Andreas Olsson
Blekinge Institute of Technology
371 79 Karlskrona, Sweden
andreas.olsson@bth.se

Oskar Frånberg
Blekinge Institute of Technology
371 79 Karlskrona, Sweden
oskar.franberg@bth.se

Wlodek J. Kulesza
Blekinge Institute of Technology
371 79 Karlskrona, Sweden
wlodek.kulesza@bth.se

***Abstract*—A new method using burial measurements for risk assessment of subsea cable installations is proposed. Only methods comparing the design boundaries have previously been used to verify subsea cable installments. The disadvantage of utilizing design boundaries is the possibility of not fulfilling the risk requirements since the assumed burial depth of the cable and its measurement data can differ, leading to the challenge of assessing how the difference and its uncertainty affect burial risk. We proposed and tested the method for a scenario using sea-going vessel traffic data and sensor characteristics. The analysis is limited to white measurement noise but shows a deviation in risk estimation between the design- and measurement-based assessments. The presented result enables the approximation of the risk assessment for projects of varying specifications. The proposed statistical method is a less conservative way to assess the correct installment of a cable and possibly to evaluate verification specifications.**

***Index Terms*—AIS, Cable Burial, CBRA, Depth of Burial, Risk Assessment, Subsea Anchor Protection Assessment, Subsea cable measurement data analysis, Subsea High Voltage Cables.**

I. Introduction

Today, a survey of the cable burial depth relates cable depth data to upper and lower design depth boundaries to verify the integrity of the risk assessment of a high-voltage cable. If measurements indicate that the cable is out of bounds, a remedial burial operation can be used to lower the cable further. Alternatively, rock dumps can be utilized where layers of large rocks are placed on top of the cable or seabed for protection. Therefore, the methodological drawback in assessing the completion and verification of subsea high voltage cables is the assumption that burial measurement data are between the design boundaries from the design risk assessment or additional protective measures must be taken. The variation of the cable burial depth measurement can either be caused by uncertainty in the actual cable position or uncertainty in the measurements of two distances between the cable and the surface.

This paper proposes a new method for assessing as-built cable burials by reassessing the cable risk instead of the design depth to the design boundaries. This method assesses deviations to expected risk due to cable measurement uncertainty modeled as white noise. It is applied for a relatively large and traffic-intensive area with the presents of large sub-sea cable installations, which constitutes a relative anchor collision-prone project. The idea is to give a relatively high-risk cable project to be used to assess the design and measurement risks for anchor collisions. The significance of such research relates to whether an assessment of the final as-built survey can verify or estimate the future breakage risk of a subsea cable project. In this study, we present an analysis of how risk assessment is affected by the model's input parameters. We model measurement depth data with additive noise based on a relatively high anchor collision risk project. The study evaluates the proposed method and shows a simplified relationship between the included parameters.

II. Theoretical background

Among the significant cable risk factors, the pre-burial risk factors come from handling the cable from the factory to the sea bottom in two critical steps: lowering to the sea floor and lowering procedure into the sea bottom sediments.

There are also two post burial risk factors: thermal degradation of cable and its joints and collision risks from anchors or fishing gear [1], [2]. Thermal degradation increases the risk of cable failure over time. The improved cable design, like lower resistance, thicker insulation, or a lesser designed transfer power, and the cooling capacity, such as sediment thermal resistivity or thickness of the thermal insulator sediment to the moving cooling seawater, contribute to a longer lifetime of a cable. Collision risk from fishing equipment cuts into the top layer, which is the primary risk to protect the cable against due to the high frequency of fishing ships and high probability of fishing close to cables. However, the fishing equipment does not cut very deep, so a baseline penetration depth is typically deployed when fishing activities are frequent [1].

Another common risk factor to focus on is a risk from anchors, which are assumed to be deployed during distress such as engine or rudder failure, deployed by mistake, for instance, anchor wind-lass failure, or being hung below the ship for stabilizing during bad weather and which may be accidentally cut into the sea bottom.

Continuing, thermal degradation contributes to industrial practice's lower burial depth boundary. The fishing gear is usually seen as giving a constant minimum value to the upper boundary of the burial depth to be avoided due to its high frequency. Finally, ship anchors are assessed as contributing to the upper burial boundary through a methodology such as BPI (Burial Protection Index) [3], [4] and CBRA (Cable Burial

Risk Assessment) [5]. Lastly, a more oversized cable design increases cost but, on the other hand, contributes to an increase in the width between these boundary layers.

A. CBRA - Cable Burial Risk Assessment Methodology

CBRA document titled 'Guidance for the Preparation of Cable Burial Depth of Lowering Specification' [5] aims to be an open-source cable burial risk assessment method advancement from BPI - Burial Protection Index [3]. The goal is that if less cautious measures can be used, it can result in less risk during installation and cost of projects without compromising the requirements from the risk analysis or, as it is referred to as acceptable risk.

CBRA defines a probabilistic function to determine the risk of ship anchors hitting the cable depending on shipping in the area (using historical AIS - Automated Identification System data) and designed burial depth. The basic equation following an iterative arrives at a burial depth at the desired anchor collision cable risk P_{strike} for the specific section is:

$$P_{\text{strike}} = P_{\text{traffic}} P_{\text{wd}} \sum_{j=1}^{\text{No.Passings (J)}} \frac{D_{\text{ship}}}{V_{\text{ship}} \cdot 8760} P_{\text{incident}}, \quad (1)$$

where: P_{traffic} is a probability modifier based on the tolerable level of risk, P_{wd} is a probability modifier for nature and depth of seabed, V_{ship} [meters/hour] is ship speed during anchor deployment, D_{ship} [meters] is the distance traveled by ship under consideration, P_{incident} is the probability of an incident occurring for that vessel size and type. The parameters for D_{ship}, V_{ship}, P_{incident}, P_{wd} are defined in CBRA [5].

Each Section represents steady traffic and seabed conditions along the cable route. The calculations follow an iterative approach to calculate risk at depths of interest and to halt at a probability of anchor risk of interest. The risk is the summation of annualized representations of the number of ships passing within the sections based on historical AIS data. An increasing or decreasing burial limits the size of the ships that can strike the anchor, assuming that the vessels' sizes relate to their anchor sizes, where heavier anchors penetrate deeper into the seabed. Probability modifier P_{traffic} is the feedback to calculate burial. However, it can be used to determine the P_{strike} based on a given burial depth.

B. AIS - Automated Identification System

For a cable project, to calculate the risk of collision with a specific cable design, historical AIS data of ships crossing the cable route sections are assumed to be a good approximation of the future number of ships and distribution of ship sizes and their shipping speeds. All larger ships are supposed to have an AIS transmitter and collecting data from ships within an area, from shore stations, and satellites can result in near-global coverage. Many parameters are broadcast, where the relevant information for assessing burial depth are ship length, position, speed, and ship type. Though it is typical for ships to have a problem broadcasting certain variables, particularly ship speed, equivalent 'null' value ships cannot be analyzed and discarded. The AIS data be annualized as there may be seasonal variations in traffic patterns and intensity over the year.

C. Converting ship length to anchor dragging depth

The choice to convert ship length S_{length} to a ship anchor dragging length D_{ship} and anchor Depth of Penetration D_{DoP} should be close to the worst case. The method detailed in CBRA converts length S_{length} to ship DWT (Deadweight tonnage) W_{DWT} and from ship DWT to anchor weight W_{anchor} and from anchor weight W_{anchor} to ship anchor dragging length D_{ship} and anchor Depth of Penetration D_{DoP}. Expressions cited in CBRA and used in 'Intertek CBRA analysis,' [6], such as *cargo ship* and anchor size equation, are also used in this paper. The anchor size conversion to vessel weight is defined as: $W_{\text{DWT}} = 32.2 \cdot S_{\text{length}}^{2.6119}$. The drag distance when anchors are deployed can be found from:

$$D_{\text{ship}} = W_{\text{DWT}} \frac{0.2642 \cdot V_{\text{drag}}}{4 \cdot F_{\text{UHC}}}, \quad (2)$$

where V_{drag} is the ship's speed beginning to drag, it is recommended to be 2 m/s (4 knots), and Ultimate Holding Capacity F_{UHC} is defined as the ultimate holding strength of the anchor. The VRYHOF manual [7] is a cited source for anchor holding strength:

$$F_{\text{UHC}} = A_s W_{\text{anchor}}^{0.92}. \quad (3)$$

The anchor weight W_{anchor} in tons can be calculated from:

$$W_{\text{anchor}} = 7 \cdot 10^{-22} W_{\text{DWT}}^3 - 6 \cdot 10^{-13} W_{\text{DWT}}^2 + \\ +1.636 \cdot 10^{-4} W_{\text{DWT}} + 2162, \quad (4)$$

where A_s=[0.0272 for mud; 0.0391 for medium clay; 0.0527 for sand].

And anchor Depth of Penetration D_{DoP} is:

$$D_{\text{DoP}} = B_s W_{\text{DWT}}^{\frac{1}{3}}, \quad (5)$$

where B_s= [1.1 for mud; 0.4 for medium clay; 0.08 for sand]. Note, with F_{UHC} in the denominator; it does not contribute to a cautious outcome but rather the contrary, when placed in (1), as D_{ship}, is in the nominator.

III. RESEARCH PROBLEMS AND MODELING OF THE PROPOSED METHODS

As stated, there are two types of uncertainties in the cable burial data. One from the actual cable position to the design depth and the other from the burial depth measurements. Its data combines ROV (Remotely Operated Vehicle) positioning systems, a cable tracker sensor, and bottom scanning equipment. In this analysis, we limit the study to the measurement uncertainty of the non-systematic type (i.e., a simulated scenario applying white noise modeled from the measurement without offset errors).

The purpose of the study is to assess the method performance and determine a conservative estimate of the impact of cable anchor risk coming from the measurement uncertainty. The research questions we would like to answer in this paper concern the parameters used or could be used for cable risk evaluation. And then, we would investigate the usefulness of as-built cable measurements for risk management. The following two questions frame the research problem of the paper:

- How do the risk model parameters affect the cable design risk?
- How could the measurement uncertainty of cable burial depth be implemented into risk management analysis?

TABLE I
CONTAINS SPECIFIED COORDINATES FOR THE CORRESPONDING SCENARIO SECTIONS ONE THROUGH FOURTEEN.

Section numbers	**Coordinate**	
	Latitude	***Longitude***
1	57.7	6.74
1,2	57.5	6.79
2,3	57.28	6.79
3,4	57.09	6.81
4,5	56.88	6.87
5,6	56.70	6.93
6,7	56.49	6.94
7,8	56.32	7.0
8,9	56.12	7.06
9,10	55.99	7.14
10,11	55.73	7.20
11,12	55.54	7.25
12,13	55.32	7.32
13,14	55.1	7.42
14	54.86	7.52

To assess the impact of the risk model parameters, a large dataset is necessary for smoothness. At our disposal, we have public AIS data from the Danish EEZ (Exclusive Economic Zone) from the Danish Maritime Authority[1]from 2019 [8]. With this data and aiming at the disposal, we apply a scenario of a project with 14 sections positioned along the Danish west coast, see Table I. The scenario uses the start and end coordinates of sections to determine crossings. Coordinates are placed in a long line on the Danish West coast. The seabed sediments are considered to be *sand-like*. Further, a calibration survey's measurement and sampling resolution distribution are used to generate random samples in each scenario. The calibration survey means measurements of a surface laid cable in the North Sea, using a cable sensor (TSS440 [10]) measuring the distance to a cable at various distances by flying the cable sensor mounted on the ROV at various distances to the cable. Next, we propose how to calculate P_{strike} using cable measurements and motivations for its design choices, followed by a derivation of an approximate relationship between the model parameters.

A. Proposed method for evaluation of P_{strike} using cable measurements

Equation (6) defines the probability of anchor strike for a given burial depth by using a Heaviside function $H(D_{\text{DoB}} - D_{\text{DoP}})$ to exclude anchors not hitting cable at Depth of Burial D_{DoB}, where ships of a specific size do not penetrate the seabed sediments and Depth of Penetration is D_{DoP}. Additionally, No.Section (Number of Sections) was changed to N_s and No.Passings (Number of Passings over a section *j*) to $N_p(j)$ where:

$$P_{\text{strike}}^{\text{All sections}} = \sum_{j=1}^{N_s} \sum_{i=1}^{N_p(j)} P_{\text{wd}} H[D_{\text{DoB}}(j) - D_{\text{DoP}}(i,j)] \cdot \cdot \frac{D_{\text{ship}}(i,j)}{V_{\text{ship}}(i,j) \cdot 8760} P_{incident}(i,j). \tag{6}$$

Differentiating from the CBRA method of a Depth of Burial in the whole section, the proposed method uses measurements $M(x)$ to estimate a probability of anchor strike P_{strike} at a given confidence level for a completed cable installation. Measurements describe the position of a cable along a path L. Sections' start and end positions are defined by the length along the line segments L_i. A continuous cautious estimate of the cable position is defined by us as the measurements M mean of a cable's depth of burial $\mu_{D_{\text{DoB}}}(L)$ and adding standard deviations of the mean $\sigma_{D_{\text{DoB}}}(L)$ following a suggestion for management of random errors in Scientific Metrology [9]. The vertical component describes the worst-case position of the cable (as it is perpendicular to anchor movement) for a factor dependent on the confidence level, is given by:

$$\mu^z_{D_{DoB}}(L) + a \cdot \sigma^z_{D_{\text{DoB}}}(L). \tag{7}$$

As the mean $\mu^z_{D_{\text{DoB}}}(L)$ and standard deviation of the mean $\sigma^z_{D_{\text{DoB}}}(L)$ are unknown in general for the measured population, the sample means, and sample standard deviation has to be used. Then it changes the (7) by adding t-Student's inverse cumulative distribution function, F^{-1} :

$$D_{\text{DoB}} = \mu^z_{D_{\text{DoB}}}(L) + F^{-1}(a,\nu) \cdot \sigma^z_{D_{\text{DoB}}}(L), \tag{8}$$

where $\nu = N - 1$. The first step is utilizing an estimated position of the cable in the bottom surface plane of the cable from the measurements by fragmentation of the sections into smaller pieces of length Δx. Additionally, we define the section width $D_{\text{section}}(j) = L_j - L_{j-1}$ and a step size $\Delta x_j = \frac{D_{\text{section}}(j)}{N_{\Delta x}}$, where $N_{\Delta x}$ is the number of steps in each section. Then, it is possible to define the continuous function for the variable x, where the cable length is integrated using (8), resulting in:

$$P_{\text{strike}}^{\text{All sections}} = \sum_{j=1}^{N_s} \sum_{i=1}^{N_p(j)} \int_{L_{j-1}}^{L_j} dx P_{\text{wd}} H[D_{\text{DoB}}(x) - D_{\text{DoP}}(i)] \frac{D_{\text{ship}}}{V_{\text{ship}} \cdot 8760} P_{\text{incident}} \frac{1}{D_{\text{section}}(j)}. \tag{9}$$

IV. APPROXIMATE RELATIONSHIP OF MODEL PARAMETERS

For the analysis, the measurement $M_0(d)$ is based on the design depth d and the calibration data set's noise scaled at 2.35 m depth. M_n is used to assess the noise in the data

[1]When using the AIS dataset in this study, the following must be stated: Contains data from the Danish Maritime Authority that is used in accordance with the conditions for the use of Danish public data.

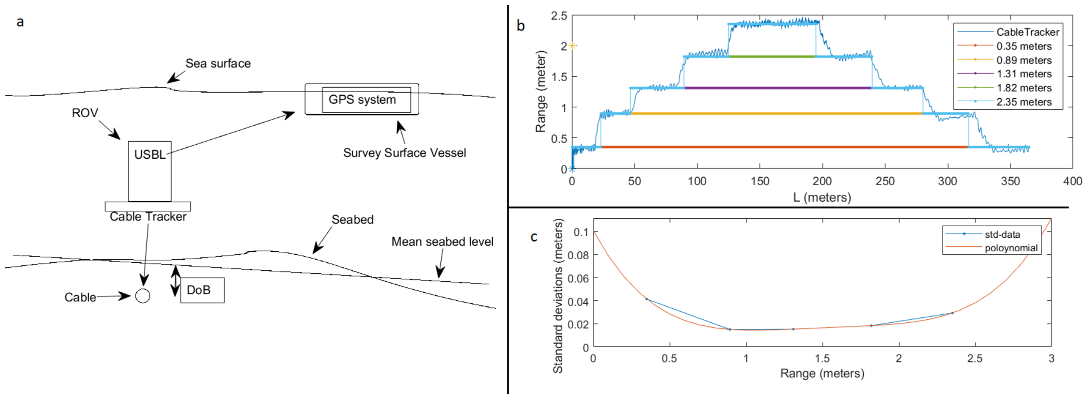

Fig. 1. (a) Illustration of measurement method; measurement uncertainty depends on cable tracking and the positioning of the ROV. The mean seabed level is a predetermined depth. The position of the Vessel and the ROV with the cable-tracker are used to determine a Depth of Burial (DoB); (b) The raw measurement data from the cable tracker and categorized constant depths. The data within the categorized depths are used with the overall cable position data (cable lying flat on the seabed) to extract noise at different depths; (c) fourth order polynomial fit of sampled standard deviations of the cable noise.

(offset errors are not analyzed in this study) such as the cable burial data is defined as $M = M_0 + c_n M_n$, where $c_n(d)$ is a coefficient to scale the original noise data, based on a fourth-order polynomial between the designated depths and its standard deviation of the calibration data. Additional samples are collected for a point along L using a circle in the plane, then the approximate number of measurements is defined as:

$$N = \lfloor 2r \cdot X \rfloor = \lfloor 2r_0 c_r X_0 c_X \rfloor, \tag{10}$$

where $r = r_0 c_r$ and $X = X_0 c_X = X_0 c_X(z_{\text{DoB}})$.

If the coefficients c_r and c_X define the linear scale of the window radius and data sampling per meter and assume a near constant X_0 samplings per meter, the sampled standard deviation of the mean can be defined as:

$$\sigma_m^{\text{org}} = \sqrt{\frac{\sum_{i=1}^{2r_0X_0}(M_n^i - \frac{1}{2r_0X_0}\sum_{j-1}^{2r_0X_0} M_n^j)^2}{2r_0X_0(2r_0X_0 - 1)}} \tag{11}$$

where the mean $m = \mu = \frac{1}{N}\sum_{i=1}^{N} M_i^z$ for N burial depth measurements M^z.

The standard deviation of the mean σ_m together with the level of confidence define the difference in position compared to the mean $\mu^z_{\overline{D_{\text{DoB}}}}$ as $F^{-1}(a, N-1)\sigma^z_{\overline{D_{\text{DoB}}}}(L)$ and hence in this analysis, the design depth is approximated as:

$$F^{-1}(a, N-1)\sigma^z_{\overline{D_{\text{DoB}}}}(L) \approx a\frac{c_n}{\sqrt{c_r c_X}}\sigma_m^{\text{org}}(L) \tag{12}$$

When $N \gg 1$ then $a \approx F^{-1}(a)$ and $N \approx N-1$ and $\mu(N) = \mu(N^*)$ where N^* is any large N. Coefficient $c_T = a\frac{c_n}{\sqrt{c_r c_X}}$ defines a relationship between the variables and parameters of the model. To test this relationship, several parameters are run that modify c_T to [1, 1.4142, 1.7321, 2] alternating the variables c_r, c_n, c_X, respectively as seen in Table II.

TABLE II
VALUES OF COEFFICIENTS
c_T= [1, 1.4142, 1.7321, 2], AND $r = r_0 c_r$

Variable name	*Variable*	*Values*
Standard deviation confidence factor	a	[1, 1.4142, 1.73, 2]
Window radius factor	c_r	[1, 0.5, 0.33, 0.25]
Noise factor	c_n	[1.31, 1.5, 1.8, 2.4]
Sample per meter factor	c_X	[1, 0.5, 0.333, 0.25]
Unit radius	r_0	1 m

A. *Definition of cable measurements, generating M_n, and its dependency on cable distance*

One standard burial depth is defined in the DNV-GL RP360 [1] using three terms that may apply, *depth of trench* is the depth of the cut trench to the mean seabed level, *depth of cover* is the sediment covering from the top of the cable, and *depth of lowering* is the distance from the top of the cable to the mean seabed level.

Many types of sensors are used to measure buried high voltage subsea cables, which rely on being mounted on an ROV. In Fig.1(a), three sources contribute to the uncertainty of the measured cable position; the 1st is the cable tracker; the 2nd is the positioning and direction of the ROV, primarily through a USBL system with additional sensory concerning the survey vessel; and the 3rd is the positioning of the vessel in global coordinates which the mean seabed level has been determined at.

The cable burial depth measurements are a calibration data set of an ROV with MBES bottom scanning and a cable sensor (TSS440 [10]) of a bottom surface laid cable. The noise level is represented in the data from ~0.3 m to ~2.5 m, around 400 m of surveyed cable (ca 8000 measurement points), see Fig. 1(b). The global Pipe Depth data coordinates take the form of a staircase down, up, and down. Noise data is subtracted from a polynomial fit of 19th order; it is assumed to cancel the variability due to flight altitude variation above the cable. We define an average depth for a cable with a distribution of the measurements related to the measured distance. The distribution is approximated by a polynomial of 19th order from hundreds of samples from cable lengths of over 400 m. The smooth distribution variation is due to the cancellation of the uncertainty of cable positioning and calibration offset by the polynomial fit. A 4th-order polynomial fits the sampled standard deviation of the noise at different distances between the sensor and the cable, see Fig. 1(c).

As stated for the analysis, we have measurement data of approximately 400 m, while a typical high voltage cable installation is on the order of (1,000 m - 100,000 m). For this analysis, we chose to generate additive measurement noise based on the calibration data. The first step is to scale the data based on the polynomial for a depth to get the desired noise. Furthermore, from the transformed calibration data set, a random sample is generated for the length of the section. This represents the measurements in the simulation. In the calibration data set, L is calculated for each measurement. This vector's lengthwise step length distribution $f_\delta L$ is utilized to generate the L values for each random measurement sample.

B. Count of vessels crossing cable section

Each crossing of a ship over a cable is considered a potential anchor event. Historical crossings are utilized to estimate possible future events. Each historical crossing could be calculated using the AIS data converted into the UTM (Universal Transverse Mercator) coordinate system. First, the data should be sorted by each unique ship by its MMSI (Maritime Mobile Service Identity) number, then by their timestamps and position converted into UTM coordinates into a single projection. The following function helps to define position of a point $[x, y]$ in relation to the line given by the points $P_h^{\text{point}} = [x_{L_h}, y_{L_h}]$ and $P_{h+1}^{\text{point}} = [x_{L_{h+1}}, y_{L_{h+1}}]$:

$$f_{line}(P_h^{\text{point}}, P_{h+1}^{\text{point}}, x, y) = (y_{L_{h+1}} - y_{L_h})x + \\ +(x_{L_{h+1}} - x_{L_h})y + (x_{L_h} y_{L_{h+1}} - x_{L_{h+1}} y_{L_h}). \quad (13)$$

If a point $[x, y]$ is above the line, the function results in a positive value and in a negative one when the point is placed below the line. The function can be used to find if two arbitrary line segments are based on two points (four coordinates), where one is of a hypothetical cable section, and the other one is between two AIS data positions for a moving vessel, crossing each other. Putting together four expressions of (13) should return in the detection of two line segments crossing each other. The crossing can be defined by the Boolean value C for the two points defining a cable section: $P_h^{\text{point}} = [x_{L_h}, y_{L_h}]$ and $P_{h+1}^{\text{point}} = [x_{L_{h+1}}, y_{L_{h+1}}]$. And two points defining ship's path: $P_{AIS1}^{\text{point}} = [x_{AIS1}, y_{AIS1}]$ and $P_{AIS2}^{\text{point}} = [x_{AIS2}, y_{AIS2}]$. Then the Boolean value C is:

$$C = H\Big[-f_{line}(P_h^{\text{point}}, P_{h+1}^{\text{point}}, P_{AIS1}^{\text{point}}) \cdot \\ f_{line}(P_h^{\text{point}}, P_{h+1}^{\text{point}}, P_{AIS2}^{\text{point}})\Big] \wedge \\ H\Big[-f_{line}(P_{AIS1}^{\text{point}}, P_{AIS2}^{\text{point}}, P_h^{\text{point}}) \cdot \\ f_{line}(P_{AIS1}^{\text{point}}, P_{AIS2}^{\text{point}}, P_{h+1}^{\text{point}})\Big] \quad (14)$$

C. Approximate length along the cable L from cable measurements

The lengthwise position of the cable is defined by the length L of curved data of a survey in the 2D dimensional plane. L is the 2D path along the sequence of line segments defined below. The method starts in one endpoint on the 2D dimensional coordinates Easting, Northing (UTM), the measurements within a circle with a radius r_L excluding points assessed in previous steps B_i^{old}, their center of mass defines a linear line from the start point with the extent of the furthest measurements r_{extent} to handle data jumps The line is defined by a coordinate system rotation such that the x-axis becomes the distance along L for each point, where the previous lengths of the segments need to be added. For each step, L for all measurements B_i within the circle is defined as:

$$L_{\text{measurements}}(B_i) = +\sum_i^{N_i} r_{extent}(i) \\ +T_{\text{new basis}} \cdot (M(B_i) - T_{\text{new basis}} \cdot L_i^{\text{start point}}) \quad (15)$$

where previous generated steps N_i lengths are added, $T_{\text{new basis}} = [\frac{\nu}{||\nu||}, \frac{\nu^\perp}{||\nu||}]$ is the new basis, directional basis vector is $\nu = -S_i + \overline{M(B_i))}$, where Boolean for measurements in the step is defined as $B_i = ((M_y - S_i^y)^2 + (M_x - S_i^x)^2 < r_L^2) \wedge \neg B_i^{old}$, where $B_{i+1}^{\text{old}} = B_i^{\text{old}} + B_i$, S are the end-points of each line segment defined as $S_{i+1} = S_i + T_{\text{new basis}}(i, 1) \cdot r_{\text{extent}(i)}$.

Moreover, the x and y coordinates on linear line segments along the cable of L are defined as:

$$[x, y] = [x_i + sgn(x_{i+1} - x_i)\frac{L - L_i}{\sqrt{1 + k_i^2}} y_i + \\ +sgn(y_{i+1} - y_i)\frac{L - L_i}{\sqrt{1 + k_i^{-2}}}]. \quad (16)$$

where index $i = \sum_i (L > L_i)$, line segment $L_i = \sum_{j=2}^{i} ||S_{j+1} - S_j||$ and the slope k_i is between L_{i+1} and L_i.

V. Results discussion and conclusions

The filtered spatial data coverage and the crossing line segments with sections 1-14 resulted in 40,989 crossings used for our scenario, a sample of positions is shown in Fig. 2. There are two reasons for filtering the data: corruption of data and error in the method. The data could be corrupted in a specific way; for instance, the vessel's positioning point could jump up to 100° in a single day. In our approach, we filter the

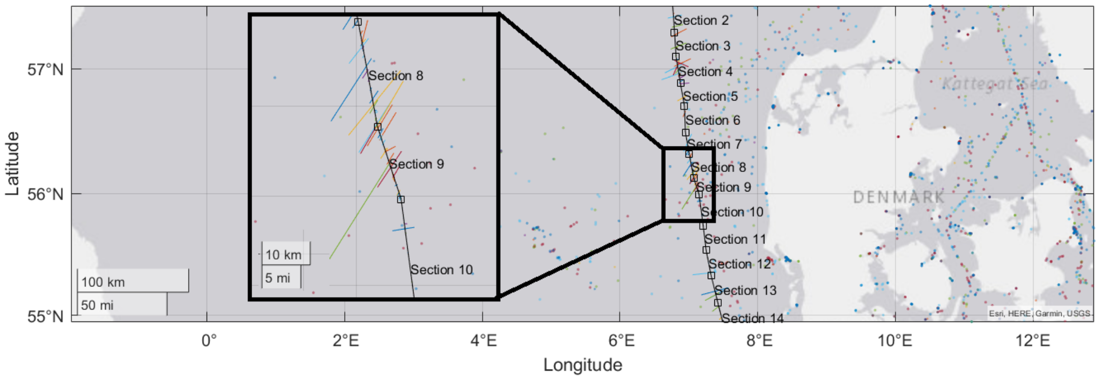

Fig. 2. AIS data coverage of traffic data, samples of the data as colored dots. Crossing line segments for the vessel AIS positions with the sections numbered 1-14. In total, 40,989 crossings were used in the analysis to estimate the design risk and the measurement risk of anchor collisions.

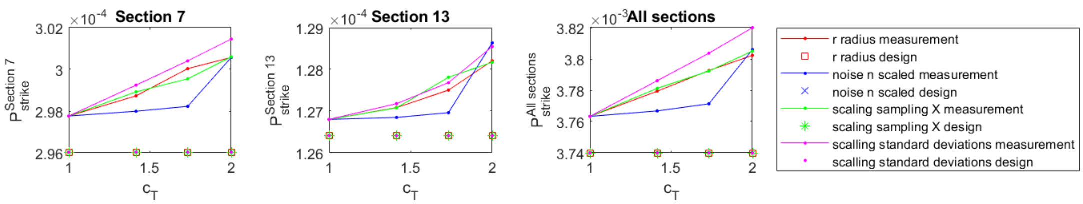

Fig. 3. Each variable is modified one at a time, according to Table II such as c_T goes from 1 to 2 in four steps.

data points to the area of interest and realistic speeds, between more than null and 45 knots.

The effect of varying c_T on the variables c_r, c_n, c_X and a is shown in Table II. An increase in risk in different sections differs slightly; see Fig. 3. The standard deviation defined by (11) causes the variation in risk. The scenario with 14 sections, while c_T varying from 1 to 2 results in a constant design risk of $3.74 \cdot 10^{-3}$/year while a measured risk increases in 1.6% from $3.76 \cdot 10^{-3}$/year to $3.82 \cdot 10^{-3}$/year.

The proposed approach enables customizing the model parameters for another project or alternative design choices. It can be relevant for assessing projects during a survey or design phase. Then the customization could be done to the measurement conditions, or it can be applied to figure out how a change in one parameter may compensate for another.

We presented a new way to assess as-built subsea cable installments related to the risk assessment. It could result in a more realistic estimation of the risk. Our findings show a possible usage of the method to customize projects in terms of an impact on the verification of the following as-built survey.

Acknowledgment

The authors would like to thank mathematicians and colleagues J. Richter and J. Öinert for their meaningful discussion to define the function to identify crossings of line segments. And lastly, colleges S. Javadi and B. Palm for their insights.

References

[1] DNV GL AS, “Subsea power cables in shallow water,” https://www.powerandcables.com/wp-content/uploads/2021/08/Subsea-Power-Cables-in-Shallow-Water-DNVGL-RP-0360.pdf, 2016, accessed: 2022-07-26.
[2] T. Worzyk, Submarine power cables: design, installation, repair, environmental aspects. Springer Science & Business Media, 2009.
[3] P. Allan, ”Selecting appropriate cable burial depths a methodology,” in A Methodology IBC conference on Submarine Communication. The Future of Network Infrastructure, France. Citeseer, 1998, pp. 1–12.
[4] P. Mole, I. Featherstone, and S. Winter, ”Cable protection: solutions through new installation and burial approaches: Les liaisons optiques sous-marines,” REE. Revue de l’ électricit é etde l’ électronique, no. 5, pp. 34–39, 1997.
[5] Carbon Trust, “Cable burial risk assessment methodology,” https://prod-drupal-files.storage.googleapis.com/documents/resource/public/cable-burial-risk-assessment-guidance.pdf, 2015,accessed: 2022-07-26.
[6] AECOM, “Bijlage 8 cbra report,” https://www.jbic.go.jp/ja/business-areas/environment/projects/pdf/62940 10.pdf, 2021, accessed: 2022-07-26.
[7] VRYHOF, ”Vryhof manual, the guide to anchoring,” https://insights.vryhof.com/download-the-vryhof-manual, 2018, accessed: 2022-07-26.
[8] Danish Maritime Authority, ”Historical AIS data.” http://web.ais.dk/aisdata/, accessed: 2022-06-06.
[9] J. McGhee, I. A Henderson, M. J. Korczynski, and W. Kulesza, Scientific metrology. LodartSA, 1998.
[10] VT TSS Limited, ”440 Pipe and Cable Survey System System Manual,” https://www.oceanscan.net/gallery/PDFs/402196_440_System_Manual_Iss_1.1.pdf, 2003, accessed:2022-09-14.

PAPER B

An Improvement of Assessing As-built Burial Risk for Subsea Cables

Andreas Olsson
Blekinge Institute of Technology
371 79 Karlskrona, Sweden
andreas.olsson@bth.se

Oskar Frånberg
Blekinge Institute of Technology
371 79 Karlskrona, Sweden
oskar.franberg@bth.se

Wlodek J. Kulesza
Blekinge Institute of Technology
371 79 Karlskrona, Sweden
wlodek.kulesza@bth.se

***Abstract*—Available methods using the burial measurements to assess the subsea cable installations risks compare measurements to the design boundaries. The disadvantage of using this is that the assumed cable burial depths and their measurements can differ. However, it is unclear how the uncertainty in depth affects burial risk; hence, there is a need to verify the burial operations using a proper method to handle this aspect of risk reliability. We proposed a conservative cable burial scenario test, which evaluates the highest deviation between the measured risk and the design risk to indicate differences in risk based on the measurements. The result shows that the most significant deviation could be up to 55%. It proves that measurement uncertainty significantly affects the final risk evaluation. Moreover, this deviation in verifiable risk is not considered in today's boundary-level verification methodology.**

***Index Terms*—AIS, Cable Burial, CBRA, Depth of Burial, Risk Assessment, Subsea Anchor Protection Assessment, Subsea cable measurement data analysis, Subsea High Voltage Cables**

I. Introduction

Today, a survey of the cable burial depth relates cable depth data to upper and lower design depth boundaries to verify the integrity of the risk assessment of a high-voltage cable. If measurements indicate that the cable is out of bounds, a remedial burial operation can be used to lower the cable further [1]. Alternatively, rock dumps can be utilized where layers of large rocks are placed on top of the cable or seabed for protection. Therefore, the methodological drawback in assessing the completion and verification of subsea high voltage cables is the ambivalence whether burial depth is between the risk assessment's design boundaries or additional protective measures must be taken.

However, the confidence of the cable burial depth measurement can either be caused by uncertainty in the actual cable position or uncertainty in the measurements of two distances between the cable and the surface. In the previous work [2], a new method was proposed to assess as-built cable burials by customization of the cable design risk. The proposed solution assesses deviations to expected risk due to cable measurement uncertainty, which was modeled as white noise. It was applied for a test scenario in a relatively large and traffic-intensive area with the presence of sizeable subsea cable installations, see Fig. 1. This paper aims to apply the same relatively high-risk cable project scenario to assess the maximum anchor collision risk difference between the design and measurement risks for anchor collisions. The significance of such research relates to whether an assessment of the final as-built survey can verify or estimate the future breakage risk of a subsea cable project. An improved method will decrease the cost of offshore grid projects. It is vital for the industry, which is going through a transformation where grid infrastructure connecting nations and offshore installation is growing fast and is expected to continue to grow exponentially for decades to come, as is evident from strategies for the blue economy coming out of the European Commission [3], [4]. In this study, we present cautious results for what difference in risk to expect using ideal measurement depth data with additive noise from a relatively high anchor collision risk project and modified lowered sampling and high confidence requirements. The study analyzes the expected impact of the normal variations in the measurement on the final estimated risk, independent of actual burial depth deviations.

II. Theoretical background

The method to assess risk in the previous work, which [2], proceeded from CBRA (Cable Burial Risk Assessment) methodology, proposes a change in how to assess cable measurement of an installed cable burial at sea. An analog function to determine risk was proposed using functions and referenced sub-functions from the methodology.

Equation (1) defines the probability of anchor strike for a given burial depth by using a Heaviside function $H(D_{\text{DoB}} - D_{\text{DoP}})$ to exclude anchors not hitting cable at Depth of Burial D_{DoB}, where ships of a certain size do not penetrate the seabed sediments and Depth of Penetration is D_{DoP} [2]:

$$P_{\text{strike}}^{\text{All sections}} = \sum_{j=1}^{N_s} \sum_{i=1}^{N_p(j)} \int_{L_{j-1}}^{L_j} dx P_{\text{wd}} \cdot \\ \cdot H[D_{\text{DoB}}(x) - D_{\text{DoP}}(i)] \frac{D_{\text{ship}}}{V_{\text{ship}} \cdot 8760} P_{\text{incident}} \frac{1}{D_{\text{section}}(j)}, \quad (1)$$

where ship speeds $V_{\text{ship}}(i,j)$, dragging distance $D_{\text{ship}}(i,j)$ and probability of incidence $P_{incident}(i,j)$ are defined in [2] and in utilizing CBRA [5], [6].

The variable Depth of Burial D_{DOB} is described for this methodology by a windowed mean in combination with its standard deviation [9]:

$$D_{\text{DoB}} = \mu_{D_{\text{DoB}}}^{z}(L) + F^{-1}(a,\nu) \cdot \sigma_{D_{\text{DoB}}}^{z}(L), \quad (2)$$

where L is the length along the cable, $\mu^z_{\overline{D}_{\text{DoB}}}$ and $\sigma^z_{\overline{D}_{\text{DoB}}}$ are the windowed average and standard deviation in the burial z direction respectively. F^{-1} is the t-Student's inverse cumulative distribution function. And ν is the number of measurements in the window minus one. The standard deviation confidence factor a is the number of deviations included.

For this approach, a selection of points is needed. The sampled data is in a curved line, so it considers data in a window along the cable. The motivation for using windowing is related to the stiffness of high voltage cables being under consideration. The stiffness and the limited forces acting on the cable during burial impact the cable position and indirectly affect the measurements behind and in front of a position along the cable.

III. Research problems and questions

Including measurement and its uncertainty into risk management already at the design, phase would help to customize the design process. It applies the uncertainty in the actual cable position due to burial operation and the uncertainty of the burial depth measurements acquired during the cable as-built survey, which is the combination of ROV (Remotely Operated Vehicle) positioning and cable sensor and bottom scanning and cable sensor data. In this analysis of a simulated scenario, we limit the study to the measurement inaccuracy of the random type using a white noise model with a filtered offset component.

This study aims to assess the performance of the measurement data risk assessment method presented [2] and to determine a conservative estimate of the impact of cable anchor risk coming from the measurement uncertainty. The research questions to be answered in this paper concern the parameters used or could be used for cable risk evaluation. Then we would like to investigate the significance of implementing as-built cable measurements for risk management. Therefore, the following two questions frame the research problem:

- What possible implementation scenarios enable evaluation of differences between the risk estimates for a large-scale project of the design risk and the as-built cable measured risk?
- What is a conservative estimate for the upper limit difference between the design risk and as-built cable measured risk?

Non-biased white noise sensor data from the cable sensors are used to assess the conservative estimate. To assess the impact, a large project is necessary. At our disposal, we use public AIS (Automated Identification System) data from the Danish EEZ (Exclusive Economic Zone) from the Danish Maritime Authority[1] [8]. With this data and aiming at the disposal, we apply a scenario of a hypothetical project with 14 sections positioned along the Danish west coast, using the AIS data utilized from the year 2019, and the seabed sediments

[1]When using the AIS dataset in this study, the following must be stated: Contains data from the Danish Maritime Authority that is used in accordance with the conditions for the use of Danish public data.

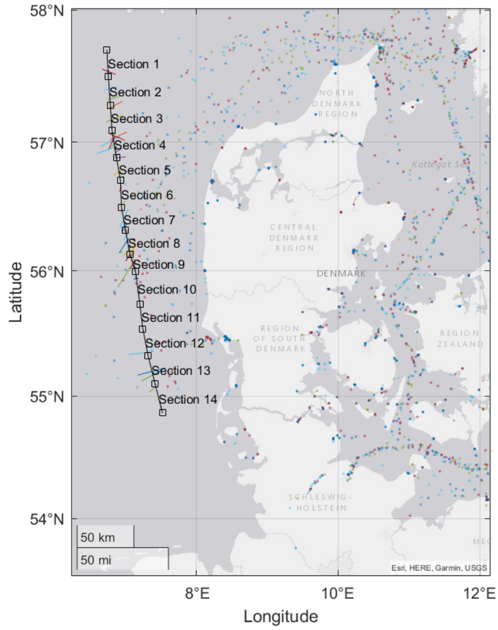

Fig. 1. Position the sections off the Danish west coast and a small sample of the raw data used for vessel positioning using AIS and crossings over the sections by line segments.

are considered to be sand. See Table I for sections and their coordinates. Data samples are shown in Fig. 1, and histograms of the collision simulations presented [2], are depicted in Fig. 2.

Further, a calibration survey's measurement and sampling resolution distribution are used to generate random samples in each scenario. The measurements of a surface-laid cable in the North Sea are performed using a cable sensor (TSS440 [10]), measuring the distance to a cable at various distances by flying the cable sensor mounted on the ROV at various distances to the cable.

IV. Implementation Scenario

For the implementation scenario of the worst case with a high confidence requirement, the following parameters are used: radius $r = 1$ m, sample per meter factor $c_X = 0.125$ and standard deviation confidence factor $a = 4$. The values can be considered to be of the order of magnitude lower and equate to artificial modification to the data $c_T = a\frac{c_n}{\sqrt{c_r c_X}}$ from the previous work [2] to alternate data from its original state, with the assumed window radius of 1 m. A confidence level of 95% (a=2), which can be considered as normal, then the *quality* is approximately scaled-down by a factor $\frac{2}{\sqrt{0.125}} = 16$ times.

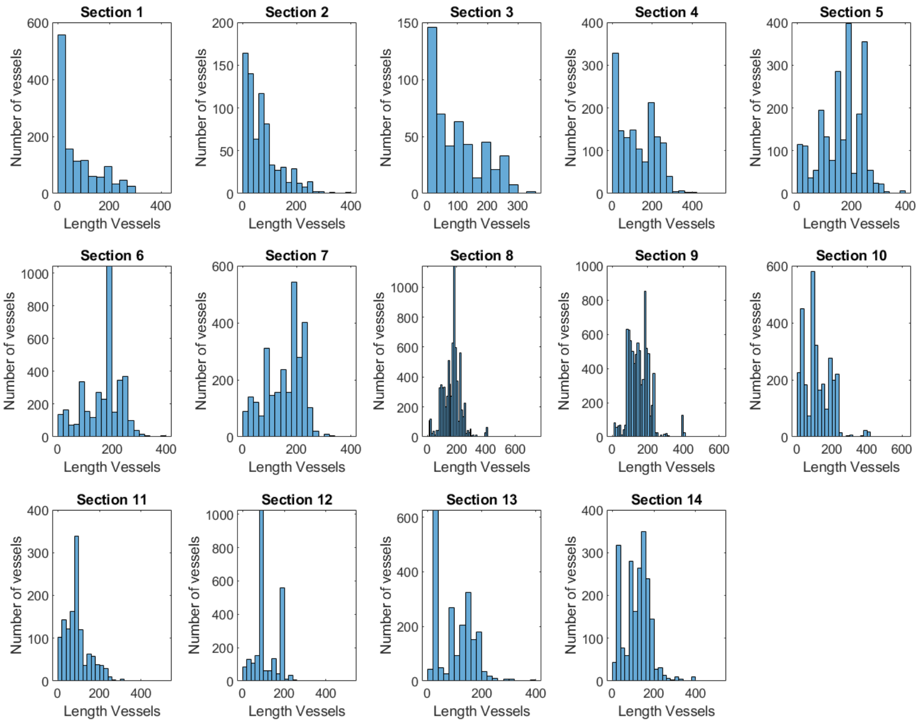

Fig. 2. Histograms of vessel crossings by length for crossing sections 1 to 14 during the year 2019 in the North Sea.

TABLE I
SECTIONS AND THEIR COORDINATES

Section numbers	Coordinate	
	Latitude	***Longitude***
1	57.7	6.74
1,2	57.5	6.79
2,3	57.28	6.79
3,4	57.09	6.81
4,5	56.88	6.87
5,6	56.70	6.93
6,7	56.49	6.94
7,8	56.32	7.0
8,9	56.12	7.06
9,10	55.99	7.14
10,11	55.73	7.20
11,12	55.54	7.25
12,13	55.32	7.32
13,14	55.1	7.42
14	54.86	7.52

Following, to determine the maximum deviation between design risk and measured as-built cable risk, burial is discretized between 1.00 m and 2.60 m with 0.03 m step. Choice of the range stems from the (3) for anchor weight W_{anchor} used in the scenario, [6], it puts a lower limit of anchor weight W_{anchor}=2162 kg approximately equating to 1 m depth of penetration.

$$W_{\text{anchor}} = 7 \cdot 10^{-22} W_{\text{DWT}}^3 - 6 \cdot 10^{-13} W_{\text{DWT}}^2 + \\ +1.636 \cdot 10^{-4} W_{\text{DWT}} + 2162, \quad (3)$$

The anchor penetration depth source [7] used in the scenario is limited as in (4) and (5) by the very few largest ships longer than 400 m, which do not penetrate much more than 2 m in the scenario, but since there can be such, a chosen depth of 2.60 m as an upper limit is reasonable.

$$D_{\text{DoP}} = B_s W_{\text{DWT}}^{\frac{1}{3}}, \quad (4)$$

$$W_{\text{DWT}} = 32.2 \cdot S_{\text{length}}^{2.6119} \quad (5)$$

Further, in the exemplified equation of anchor dragging length used in our scenario

$$D_{\text{ship}} = W_{\text{DWT}} \frac{0.2642 \cdot V_{\text{drag}}}{4 \cdot F_{\text{UHC}}} \quad (6)$$

where speed during initial lowering of anchor V_{drag} is assumed to be not more than 4 knots, which is a common practice, while Ultimate Holding Force of an anchor F_{UHC} is the maximum holding strength to expect from an anchor, and since it is in the denominator, it will not affect an upper limit but the lower estimate. Though for maximum penetration such holding strength could be expected. While for lower holding strength, resulting in longer dragging length, its depth of penetration should not be as deep. This would make an impact in two ways, more exposure but lower penetration, equates to less risk for deeper burial in general, but more for shallower burials.

V. Results and Discussion

In this section, we present the analysis of the results, including both potential impacts of measurement variability and possible limits to today's assessment cable installments for the data and project scenario positioning shown in Fig. 1.

A. Maximum risk scenario, sections and total calculations return period

The lower and upper range of risk for the design was estimated from $1.0 \cdot 10^{-5}$ up to $5.8 \cdot 10^{-4}$ yearly and for measurement it ranged from $3.2 \cdot 10^{-5}$ up to $8.3 \cdot 10^{-4}$ yearly, see Table II. The risks as a function of depth for Section 4 and Section 9, and average of all sections are presented in Fig. 3. The worst case risk differences for the two sections are at 1.72 m and 1.48 m respectively.

The maximum risk deviation between the design risk model and the measurement risk model for the applied scenario equals 54.8%. In this scenario, the assumed parameters were more cautious than would likely be. A risk assessment of a real project could answer what choice of confidence would be *normal* to have, where differences in cost between confidence levels would be the primary factor in making a choice.Hence, we used the *worse* measurement quality than the data was based upon, indicating an approximate factor and the uncertainty for a similar project could be significantly smaller, at the same time it might be realistic for a deeper burials or less-careful survey, which could result in similar conditions as the scenario used. Additionally, in a real scenario, there could appear systematic errors, which could affect the risk assessment. Our observations prove that enough sources motivate the need for cumulative assessment of cable burial projects.

Considering the simplifications and assumptions of the model and functions chosen for this study, e.g., the anchor and sediment models, which are straightforward, and the lowest anchor possible penetration around 1 m, an use of better model could improve the accuracy of the results of a project. However, for this study, the accuracy is good enough to make a general conclusion about the method, for instance, how to solve the challenges of using as-built data. It can be exemplified by the fact that the white noise in the simulation is centered around the design depth, and hence 50% of measurements are above this design depth. The results shown in Fig. 3, depict that from a depth of 2 m for all sections there is not a significant impact on the risk deviation between the design and measurement risk. However, if a more traditional approach to assess the cable installment is used, the varying burial measurement would surely be of great concern.

TABLE II
The design and measured based risk per year at burial depth at the maximal deviation of risk

Section numbers	Risk [1/y]		Burial Depth [m]
	P design	*P measurement data*	
1	$5.2 \cdot 10^{-5}$	$6.9 \cdot 10^{-5}$	1.48
2	$3.2 \cdot 10^{-5}$	$4.0 \cdot 10^{-5}$	1.15
3	$1.0 \cdot 10^{-5}$	$3.2 \cdot 10^{-5}$	1.78
4	$2.8 \cdot 10^{-5}$	$6.3 \cdot 10^{-5}$	1.72
5	$4.7 \cdot 10^{-5}$	$1.5 \cdot 10^{-4}$	1.72
6	$3.1 \cdot 10^{-4}$	$4.8 \cdot 10^{-4}$	1.48
7	$1.8 \cdot 10^{-4}$	$2.6 \cdot 10^{-4}$	1.48
8	$5.8 \cdot 10^{-4}$	$8.3 \cdot 10^{-4}$	1.48
9	$3.8 \cdot 10^{-4}$	$5.5 \cdot 10^{-4}$	1.48
10	$9.0 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	1.54
11	$7.5 \cdot 10^{-5}$	$9.9 \cdot 10^{-5}$	1.15
12	$2.7 \cdot 10^{-5}$	$1.1 \cdot 10^{-4}$	1.51
13	$2.8 \cdot 10^{-5}$	$7.2 \cdot 10^{-5}$	1.51
14	$1.6 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$	1.33

Another point of the results in Fig. 3, is that when the deviation for the simulated results is maximal, the deviation in design risk and measurement risk can be 55%. However, in a real-world scenario, burial depths are optimized for cable design cost, lower burials are more likely compared to a safer 2 m, but significant deviations in risk should impact the risk assessment.

B. Suggestions for future work

The holding strength of the anchor during dragging can be assumed to relate to its penetration depth if a sediment type and shear strength are constants. The anchor digs down into the sediment and resurfaces due to forces acting on the anchor resulting in varying holding forces throughout anchoring the vessels. A model, which can take these phenomena into account could result in significant contributions in terms of risk impact of burial depth. For any type of sediment, even looser sediment types such as mud, which previously would have a very deep anchor penetration would result in a more continuous changing risk with depth. Moreover, varied anchor penetration depth should generally result in less exposure for deeper burials, but more for lower burials due to the variation and as the dragging length should increase if the anchor penetration decreases (less anchor chain contact drag or not fully extended anchor flukes decrease drag).

Further investigation of how to handle systematic errors should be investigated. We propose using data from an actual project, with multiple surveys of the cable burial. Then they can be analyzed separately and combined by the proposed method. If there is a sizable systematic difference between the surveys, it will result in worse confidence or worse boundaries. This can be an indication of systematic errors presence.

The chosen square truncation window is used to avoid an extra complexity to the results. A stiff high voltage cable does not bend easily by the acting forces during burial. Hence, there

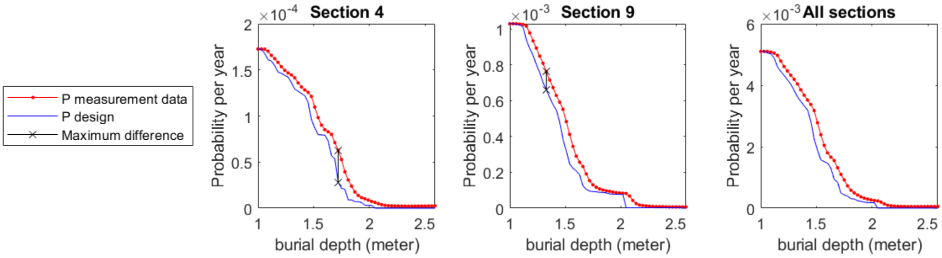

Fig. 3. Burial depths of the maximum deviations between the design risk and the measurement risk in Sections 4 and Section 9, and the average risk for the same depths for each section. To note, there are the parameter settings, with high confidence and assumed four times lower sampling than the measurement data.

is a considerable probability that measurements in front and behind follow cable position. Further investigation could focus on truncation window, and instead of using the simple one, one approach could be to look at the bending radius of the cable by the maximum forces applied and producing a distribution of where the cable must have been previously. Additionally, multiple windows can be applied, e.g., one for cable bending characteristics and one for the cable depth of the burial sensor.

ACKNOWLEDGMENT

The authors would like to thank J. Flinke, K. Cronholm, U. Andersson, M. Wahlbom, K. Johannesson, C. Trosgard, D. Kerkhoff, S. Leggett, A. Wolowicz from NKT and P. Grodzicki from iSURVEY for insights and survey data. We would also like to thank mathematicians and colleges J. Richter and J. Öinert for their meaningful discussion to define the function to identify crossings of line segments. And lastly colleges S. Javadi and B. Palm for their insights.

REFERENCES

[1] DNV GL AS, "Subsea power cables in shallow water," https://www.powerandcables.com/wp-content/uploads/2021/08/Subsea-Power-Cables-in-Shallow-Water-DNVGL-RP-0360.pdf, 2016, accessed: 2022-07-26.

[2] A. Olsson, O. Frånberg, W.J. Kulesza, "A New Method for As-built Burial Risk Assessment for Subsea Cables," in The 2nd International Conference on Energy Transition in the Mediterranean Area (SyNERGY MED), 2022.

[3] EU commission, 'on a new approach for a sustainable blue economy in the EU Transforming the EU's Blue Economy for a Sustainable Future'. 2021.

[4] EU commision, 'An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future'. 2020.

[5] Carbon Trust, "Cable burial risk assessment methodology," https://prod-drupal-files.storage.googleapis.com/documents/resource/public/cable-burial-risk-assessment-guidance.pdf, 2015,accessed: 2022-07-26.

[6] AECOM, "Bijlage 8 cbra report," https://www.jbic.go.jp/ja/business-areas/environment/projects/pdf/62940 10.pdf, 2021, accessed: 2022-07-26.

[7] VRYHOF, "Vryhof manual, the guide to anchoring," https://insights.vryhof.com/download-the-vryhof-manual, 2018, accessed: 2022-07-26.

[8] Danish Maritime Authority, "Historical AIS data." http://web.ais.dk/aisdata/, accessed: 2022-06-06.

[9] J. McGhee, I. A Henderson, M. J. Korczynski, and W. Kulesza, Scientific Metrology. LodartSA, 1998.

[10] VT TSS Limited, "440 Pipe and Cable Survey System System Manual," https://www.oceanscan.net/gallery/PDFs/402196_440_System_Manual_Iss_1.1.pdf, 2003, accessed:2022-09-14.

PAPER C

Strategic development of environmental impact assessment decision support tool for offshore energy enables decreased costs, increased utilization, and quality

Andreas Olsson[b,1], Ida-Maja Hassellöv[a], Oskar Frånberg[b]

[a]*Department of Mechanics and Maritime Sciences, Chalmers University of Technology, 412 96, Gothenburg, Sweden*
[b]*Department of Mathematics and Natural Sciences, Blekinge Institute of Technology, 371 79, Karlskrona, Sweden*

Abstract

In the transition to a sustainable energy system, there is an urgent need for expansion of offshore renewable energy installations. To ensure sustainable development also with respect to the marine environment, a variety of decision support tools (DSTs) are currently under development, aiming at potentially increased quality and efficiency for environmental risk assessment (EIA) of planned offshore energy installations. However, the savings potential of a DSTs is to a large extent governed by the timing of the DST development, which in turn is directly dependent on the investment rate over time. A set of development scenarios were evaluated, simulating different degrees of strategic implementation and successful utilization of the DST for offshore energy. Using the situation in Sweden as a case study, we demonstrate that an optimized investment can lead to considerably lower total costs for the EIA at a national level, at the same time allowing for improved quality of the EIA in line with the ambitions in both marine spatial planning and existing goals within marine environmental management.

Keywords: Decision Support Tool, Environmental Impact Assessment, DST development savings potential, DST utilization analysis

Email addresses: `Andreas.Olsson@BTH.se` (Andreas Olsson), `Ida-Maja@Chalmers.se` (Ida-Maja Hassellöv), `Oskar.Franberg@BTH.se` (Oskar Frånberg)
[1]Corresponding author.

1. Introduction

Offshore energy is an integral part of the Blue Economy and is identified as key in the transition to sustainable energy production [1] and is forecasted to continue to multiply in the near future [2, 3]. In terms of offshore wind energy, within the European Union, the plan is to go from today's 20 GW to reach a capacity of ca 300 GW before 2050 [4]. This will require multi-billion Euro investments, of which permit-related expenses in terms of environmental impact assessment will be substantial. Project planning and implementation of offshore energy installation projects are complex and involve multiple time-consuming permit application processes, where the evaluation of environmental impact is a significant contributor in terms of time and cost. Environmental Impact Assessment (EIA), i.e. to assess environmental pressures (P) on an ecosystem (E), can be labour-intensive and long-drawn [5, 6]. Yet, EIA is essential to minimize the risk of deterioration of environmental status [7, 8, 9, 10], and there is an urgent need to improve and speed up the EIA process, without compromising quality and reliability of the assessment. At the same time, Decision Support Tools (DST) for Marine Spatial Planning (MSP) are being developed and deployed [11, 12]. Current DST implementations have individual functionalities and are often based on individual case studies. Some DSTs include ideas on how to facilitate the application process for governmental permits, for public authorities responsible for MSP on the one hand and the offshore industry on the other, and forecasting long-term and cumulative impacts on the marine environment. DSTs have high ambitions for future improved functionalities and are predicted to allow automated accelerated and enhanced analysis, particularly capabilities to assess long-term and cumulative impacts on the marine environment. Developing this kind of advanced DST is an extensive endeavor, both in terms of development time and costs, which can be illustrated by a comparison of part of the costs directly related to data collection and mapping aspects needed to develop and verify DSTs development, e.g., of the Norwegian program MARE-

ANO [13]. MAREANO has been continuously been progressing since 2005, and until 2021 the program has achieved governmental funding corresponding to 127 M€ for mapping and gathering of subsea sediments and biotopes. However, a well-functioning DST has the potential to increase the quality and efficiency of the EIA and offshore energy planning processes in general and, subsequently, a substantial cost-saving potential. Considering the expected growth of offshore energy to meet renewable energy demands and still ensure sustainable use of the marine environment, it will become increasingly vital to effectively balance challenges in reaching renewable energy goals and protecting and restoring the environment when allocating resources. Therefore, it is important to investigate this matter further, and from a DST development point of view further look into and identify the break-even between the cost savings of EIA and the cost of further development of a DST to assess the financial incentives of advanced DST development.

As the offshore wind sector is planned to extend rapidly in the coming years, it will result in financial incentives for taking advantage of savings in utilizing a DST, but within a limited time window of opportunity before set goals such as carbon neutral by 2050. As a consequence, fast development of the DST is required to utilize the savings potential fully. Further, a DST in development will take time to become operational and develop. Moreover, the EU and Sweden are planning to build much offshore renewable energy in the near term. Consequently, the DST's fast development is required to utilize the savings potential fully. This development is a global problem most larger economies will have to handle for their national goals and energy needs.

This study explores the potential strategic importance of the timing of investment and the resulting usefulness and utilization in developing a DST in offshore project planning costs and lead times. The development progress of the DST over time will affect the possible increased efficiency of permit application processes, and it is, therefore, essential to optimize the development process of the DST.

This study connects to broader research themes of the improvement and facilitated development of offshore EIA DTSs in terms of protection assessment and management of the environment and efficiency improvements of secondary effects, e.g., permit costs for offshore sustainable energy development. One step towards achieving DTS effectiveness comes from improvement of understanding, analysis of costs and benefits and analysis of how and what need to be developed.

To evaluate the resource efficiency of different DST-development and investment scenarios, detailed data on both offshore energy installation related EIAs and MSP DSTs is needed. The Swedish failure to reach the desired offshore energy capacity until 2020, in combination with extensive ongoing work led by the Swedish Agency for Marine and Water Management (SwAM) to develop DSTs (*Symphony*[14] and *Mosaic*[15], makes Sweden a suitable case study, with easy access to publicly available data.

The DST in Sweden's main goals are spatial identification presence of Ecosystems (E) and Pressures (P), and pairwise combinations with their impact weight μ generate their relative individual $PE\mu$s and cumulative impacts $\sum PE\mu$ [16] to be used in the MSP. However, there is a complete lack of evaluation of the dependence of the timing of investment in the development of the DST and the resulting usefulness and utilization of the DST. If these effects are unknown, there is a significant risk that any potential savings potential will be unexploited. Future EIA costs in Sweden relate to the planned capacity, offshore wind project EIA costs, and the number of failed permit processes. Today in Sweden, the expansion of the offshore wind industry is claimed to be unpredictable, and the extensive permitting processes lead to a high degree of 'failed projects' [17]. Additionally, offshore wind energy installations have historically been costly compared to onshore wind installations[18, 19]. It is estimated that a typical offshore wind farm project spends, on average, 7.4 years in the EIA process and up to 14 years in some cases [20, 21, 22, 23, 24, 25]. The remaining project lead times are, on average, 4.4 years before the projects become operational, i.e., the time for the EIA process corresponds to, on average more than 60% of the total project lead time. In 2009 the Swedish Parliament passed an action plan with the intention of 10 TWh yearly offshore wind capacity by 2020 [26]. In reality, from 2009 to 2020, roughly a total of 0.3 TWh per year capacity came from new offshore wind installations [27],and analysis in Supplementary Material section 4). In a statement in 2018 regarding the development of the Marine Spatial Plans (MSP), the Swedish Energy Agency (SEA) assessed a need for 50 TWh of offshore wind capacity by 2045 [28]. The following year, 2019, the ambition was modified to 23-30 TWh by 2045, which was included in the latest proposed national Marine Spatial Planning work [29] by SwAM and SEA. To conclude, there is a major discrepancy between the desired and forecasted capacity versus recent development [27],and analysis in Supplementary Material section 4). Between 2009 and 2020, less than 1% of the applied energy capacity was built, despite that 32 TWh of yearly capacity had been seriously planned through EIA processes [27],and analysis in Supplementary Material section 4) and 4.5 TWh had been fully permitted but delayed and referred to as not being cost-effective to continue with at current state [20]. Beyond the scope of this study, there are also non-EIA-related possible reasons for delays, e.g., the Swedish Armed Forces have objected to many offshore installations [30, 31]. The EIA-part of the permit application process, however, is identified as a general bottleneck [32, 33]. Therefore, the focus of this study is to use hypothetical future scenarios of DST development, where the potential for increased investment and optimization of DST development are highlighted, to assess the savings potential for the future cost of EIA.

2. Materials and Methods

The methods proposed to estimate savings potential for EIA is divided up in five steps illustrated in Figure 1. In the first step **1.** the fiuture EIA costs are estimated for offshore wind energy production. For second step **2.** the available time is estimated, using scenario and estimated variables. Thereafter follows calculations of DST utilization, DST savings potential and total savings potential in steps **3.**, **4.** and **5.** respectively.

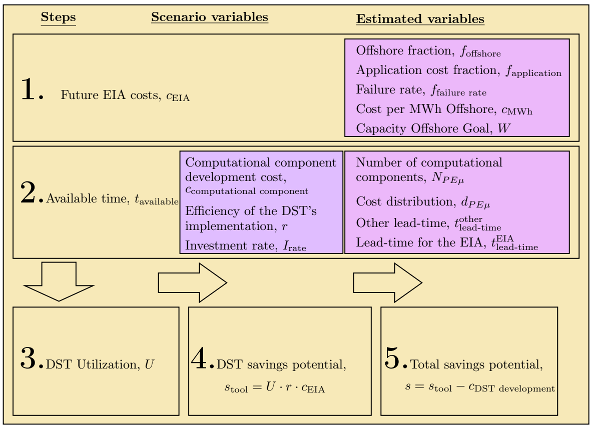

Figure 1: The flowchart illustrates the five steps of analysis comprised of parameters and estimates definitions. The purple represents scenario variables, the light purple represents estimated parameters, and light orange represents the methods. The first step is to calculate the future permit-related environmental impact assessment (EIA) costs c_{EIA} for the offshore (wind) energy industry. It uses a method where development in MWh/year and a fraction of project cost going into permitting is the most crucial factor. The time window for much of the expected offshore wind energy will be shortly, and this time window is estimated. Furthermore, a Decision Support Tool (DST) is developed slowly over time. Therefore the time window will affect the utilization of the DST in a limited time frame and will be estimated using a component-based DST development model. The two last steps use the presented equations first to estimate the savings potential of the DST and, secondly, the overall savings potential considering a DST development cost.

2.1. Scenarios for EIA costs and DST development

In evaluation of the step **5.** total savings potential, six future scenarios were developed (Figure 2). Scenarios was based on different assumptions calculating EIA costs, c_{EIA} in step **1.**, and cost of DST development $c_{\text{DST development}}$ in step **5.**.

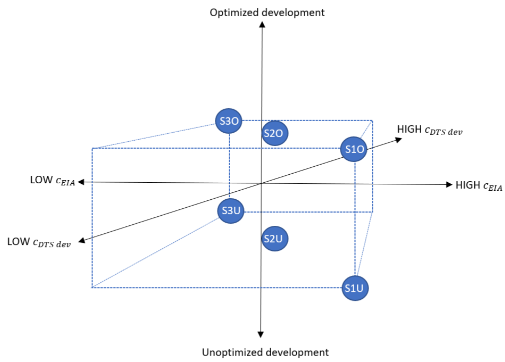

Figure 2: Scenario 1 Optimized (S1O) is considered the most advantageous scenario, while Scenario 3 Unoptimized (S3U) is the most unfavorable and shall result in the most versus the least value of development of a DTS (Decision Support Tool). Each scenario's parameters are set into a simple linear model to analyze the savings potential over time. Optimized development represents the optimized ordering of the defined tool components for development, while unoptimized is the average statistical outcome. This 'optimization' is to straightforwardly consider for what or whom the DST is developed.

The most advantageous scenario (S1O) was defined as the high cost of EIA and low cost of development of a DST in combination with an optimized DST development. On the other end, a more unfavorable scenario (S3U) was defined by a low-cost EIA and high cost of DST development in combination with unoptimized DST development. Midrange alternatives for optimized vs. unoptimized DST development defined scenarios for the mid estimate for EIA costs and a mid-value for EIA development costs (S2O vs. S2U).

2.2. Considerations and assumptions assessing the future Offshore Energy Development

Modeling hypothetical future scenarios to calculate the EIA cost savings potential requires many assumptions for the modeling, variables, and parameters, both with respect to the offshore industry development and with respect to EIA and DST development and performance. Sweden was chosen as a case study to delimit data collection and analysis as there are clear energy goals and ongoing efforts in, and goals for, development of DST capabilities.

Information from relevant national strategies and publicly available from all digitized historic offshore energy permit applications were collected to determine the current state of EIA in Sweden. This background was used to provide estimates and motivation for variables, parameters, and method choices, further described in Supplementary Material in section 4 .

Practical limitations, such as EIA costs, are assumed to be spent linear over the time window, and therefore potential savings of EIA costs are calculated as a function of the state of DST over time. The simplifying assumption of the future progress of offshore wind energy development for Swedish waters will follow the linear expenditure (constant rate) derived from the total TWh in offshore energy applications during the period 2009-2020. If these assumptions are over relatively small time windows linear, the future expenditure may evolve more dynamically, but for the conclusions in this study, a simpler assumptions of behaviour from year to year or decade to decade are close enough, additionally it simplifies the analysis for the reader and at the same time we haven't found evidence for any other relations-ship with time that are more appropriate to use. Therefore, was the total savings potential, s, in step **5.** defined as subtracting a future EIA or permit cost (Figure 1). The total savings potential s was defined as the EIA cost mitigated by the DST s_{tool} subtracted by the cost to develop the DST $c_{\text{DST development}}$.

2.3. Utilization for optimized versus unoptimized DST Development

The total utilization U represents the hypothetical utilization of a fully developed DST. It is calculated through the incremental development of individual, so-called 'computational components' that make up the DST. The computational components are the solutions to the problems the DST solves for its users performing an EIA. The computational problems are the environmental impact that must be assessed for each pair of environmental pressure, P and ecosystem, E.

For the analysis, two distinct development paths are defined, where the first defines an *unoptimized development.* The unoptimized development of the computational components can be seen as having no pre-knowledge about which is the most cost-efficient component to be developed, hence represented by assuming the average statistical outcome of random development of the DST is an appropriate method/behaviour to expect. The second development path is called *optimized development*, i.e., it is assumed that the most cost-efficient computational component for the DST will be developed first, and then the rest in descending order with respect to cost-efficiency.

2.4. Future EIA Costs

The future expenditure for EIA by the offshore energy industry in their permit application processes was defined as the future EIA cost in step **1.** (Figure 1). The future EIA cost was estimated based on, e.g., projects in Sweden, the national offshore development goals, historical built data, and failure rate. Ideally, the EIA permit cost estimation could be based on bookkeeping from historical projects, but data were not available. Hence, the cost estimate was based on available data from cost estimates originating from project application estimations. The model assumes a minimum constant installation rate, i.e. c_{EIA} was assumed to be incurred linearly over the time interval ,$t_{\text{available}}$.

The following linear equation (1) can estimate offshore EIA application costs for a given time frame. It required several assumptions and parameter estimations, outlined in Supplementary Material, section 4.

$$c_{\text{EIA}} = \frac{1}{1 - f_{\text{failure rate}}} c_{\text{MWh}} W f_{\text{application}} f_{\text{offshore}} \tag{1}$$

In equation (1), the estimated cost per yearly MWh of offshore wind energy W was assumed to correlate with national energy goals and planning; hence input was sourced from three places; the working document for MSP (Marine Spatial Plans), where 23 TWh yearly capacity planed with lowest total utilization of the space; the higher value was set to 89 TWh is the maximal realizable available by SEA report [34] when projects with permits are excluded; the lower bound was set to 10 TWh, being the Swedish Riksdag's 2020 goal [26].

The fraction of project costs related to the application process $f_{\text{application}}$ (environmental surveys, consent, compliance and etc) the three estimates 1.5% [35], 3% [36] and 11% [37] comes from studies of project costs for offshore wind. Further, the fraction f_{offshore} of the application process contributed to projects offshore-part assumed a linear relationship between page count and value of EIA and was estimated of what amount of the EIA reports are concerning onshore vs. offshore see Supplementary Material section 4 named subsection *Fraction of offshore project costs being EIA process.*

The cost per yearly MWh in capacity c_{MWh} was established from the low, average, and high value of surveyed Swedish applications, containing cost estimates, see section 4 Supplementary Material's subsection *Cost per yearly MWh of offshore wind energy* for sourced data. The model assumed that the EIA assessment quality improvement from the DST was the main contributing factor to permit failure rate $f_{\text{failure rate}}$, less uncertainty in the process should lead to acceptable projects (non failed applications) and is indirectly included in any cost reductions. For the determined failure rate per MWh, $f_{\text{failure rate}}$, the analysis differentiates between 1) failure rate due to projects not completing the application step and 2) projects getting a permit but not being completed. The second aspect is referred to as the failure of projects due to lead-time where,

Table 1: Parameters are chosen based on national goals, direct estimates, or calculated from a combination of sources. The lowest median or average and the highest possible value are presented per parameter. In order to limit unnecessary complexity for the cost of the EIA costs c_{EIA} which is calculated of the other parameters as defined in equation (1), three values (lowest, median and highest combination of above parameters) were chosen for the further analysis of the respective scenario.

Parameter	Low	Median/Average	High
Cost per MWh Offshore c_{MWh} (EURO/MWh)	238	512	667
Capacity Offshore Goal W (TWh)	10	24	89
Application cost fraction $f_{\text{application}}$	0.015	0.03	0.11
Offshore fraction f_{offshore}	0.44	0.66	0.8911
Time window t_{total} (Years)	19	24	29
Failure rate $f_{\text{failure rate}}$	0	0.8457	0.9905
EIA cost $c_{\text{EIA}}(t_{\text{total}})$ (MEURO)	15.7	1,577	555,606

i.e., old technologies make the project nonviable. These two high and medium values and the idealized case with no failure rate as the low value were used for the advantageous, midrange, and unfavorable scenarios, respectively (Table 1). Together with assumed cost of development $c_{\text{DST development}}$ ranging from values 50, 100 and 500 M€. The cost to develop the DST is represented by $c_{\text{DST development}}(t) = \sum c_{\text{computational component}}(t)$ and is the sum of equal cost to develop the computational components.

2.5. Available time window

In the step **2.** (Figure 1) the available time window $t_{\text{available}}$ is calculated using the following method, where it is based on the total time window t_{total}, which was set to the 2040 goal [38], the 2045 goal [28], and the 2050 goal [39], of which 2050 will primarily be used in the following analysis. The available time window $t_{\text{available}}$ is defined as the available time to complete projects, while after $t_{\text{available}}$ projects will not complete in time for set energy goals at the end of the scenario time window, t_{total}. Hence there is a cutoff point where future energy developments have to be initialized. The available time window from the total time window was numerically calculated by equation (2).

$$t_{\text{available}} = t_{\text{total}} - t^{\text{other}}_{\text{lead-time}} - t^{\text{EIA}}_{\text{lead-time}} \frac{1}{f} \tag{2}$$

Where the EIA lead-time fraction of reduction f is defined by (equation (3)).

$$f = \frac{c_{\text{EIA}}}{c_{\text{EIA}} - \sum_{x=1}^{N} c_{\text{EIA}} r H(t - t_{\text{DST development}} \frac{x}{N})} \tag{3}$$

The total lead-time for a offshore energy project used the average of previous Swedish offshore energy projects $t^{\text{other}}_{\text{lead-time}} + t^{\text{EIA}}_{\text{lead-time}} = 11.8$ years. And similarly, the lead-time for the EIA/consent process average is $t^{\text{EIA}}_{\text{lead-time}} = 7.4$ years. Further information can be found in Supplementary Material section 4 subsection *Estimated Project lead-time EIA process and Project lead time other aspects,*. In the analysis, a lead-time reduction was assumed to scale linearly with cost savings, thereby prolonging how long offshore energy buildup may continue to reach future energy goals. Hence, if the permit lead-time can be significantly decreased, it may significantly impact cost savings.

2.6. Cost Distribution $d_{PE\mu}$ of Pressure P and Ecosystem E Pairs

The offshore wind energy industry projects' EIA focus may vary from project to project. Hence, their permit costs will also vary. Development of DST in the analysis assumed EIA computational components to be divided into different environmental impact problems $PE\mu$s. The DST implemented computational component was assumed to improve future EIA costs from implemented time and forward into the future. The estimated total utilization over time $U_{\text{utilization}}$ as DST are being developed considered compositions of workload with various outcomes. Each computational component was assumed to be of equal development cost $c_{\text{computational component}}$. Hence, the savings enabled by using a developed DST computational components was described by the efficiency of the implemented components, r, affecting the EIA costs but on the component level. The efficiency r of each DST's implemented computational component was assumed to represent improvements in time and cost for the developed DST. In practice, r concerns DST usability and reusability by the final users. Furthermore, the efficiency improvements represent the DST predictability of environmental outcome projects or MSP strategies. Hence, DST savings $s_{\text{tool}}(t)$ are defined as the sum of developed computational components j developed for a DST that improve the DST efficiency r_k of the existing estimated base EIA cost c_{EIA}. Each project consent process pertains to considering environmental impact aspects, i.e., the ecosystem's E_i vulnerability μ_{ij} to each pressure P_j. Our study divides the DST's EIA costs and development costs by their impact components, each assigned to a corresponding impact. A cost reduction by the DST over time was defined as the expenses expected to be spent on the applications/EIA process $s_{\text{tool}}(t)$, subdivided into environmental impact component costs. Each environmental impact component $P_i E_j \mu_{ij}$ was represented by an impact component cost $c_{PE\mu}$.

Estimation of EIA cost per EIA component $PE\mu$ was conducted by word analysis of the EIA process per ecosystem's E_i vulnerability μ_{ij} to a pressure P_j to represent the cost distribution $d^{ij}_{PE\mu}$. Through word analysis of Swedish EIA offshore energy applications, the distribution $d^{ij}_{PE\mu}$ was estimated (figure 3). The cost per impact $c_{PE\mu}$ was defined as a function of the total EIA costs c_{EIA} as in equation (4). Where the total costs is $c_{\text{EIA}} = \sum c^{ij}_{PE\mu}$. Further insight into data and analysis can be found in section 4 Supplementary Material's section *EIA Cost Distribution for Computational Components.*

$$c^{ij}_{PE\mu} = d^{ij}_{PE\mu} c_{\text{EIA}} \tag{4}$$

2.7. DST Utilization

Following the definition of available time in step **2** a function for the DST utilization over time is defined as the step **3** (Figure 1).

Modeled savings estimation of the DST should be viewed as the reduced permit cost and its total utilization U over time. An early-developed computational component will be utilized for a longer time. To determine the utilization

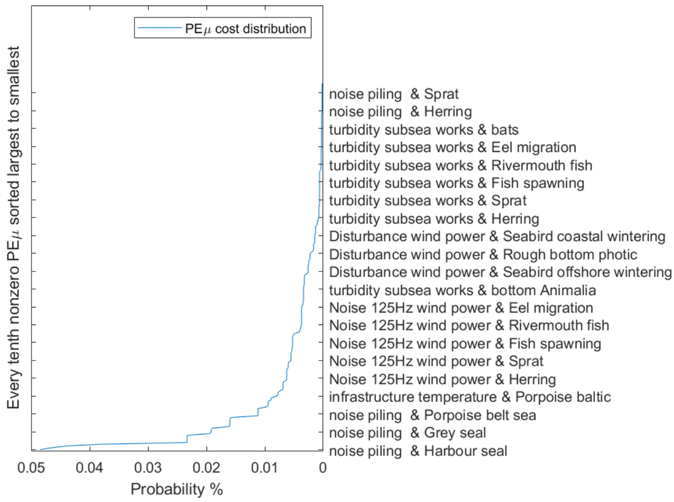

Figure 3: The estimated cost distribution of each non-zero impact pair $PE\mu$ is on the x-axis, where every 10th pair is displayed and sorted by probability. Ecosystems and Pressures start with capital letters as if defined by Symphony, while lowercase is introduced definitions by us. Each pair is represented by the presents of the pair in reviewed EIA reports found in the Supplementary Material's subsection *Analyzed Project Applications for Word Count Analysis.* This data is then assumed to correlate with EIA costs per pair, resulting in a Pressure-Ecosystem distribution for the study.

of the DST U, the development of each computational component results in utilization by equation (5).

$$U^i_{\text{computational component}}(t) = \begin{cases} 0 & : t < t^i_{\text{left}} \\ \frac{c_{PE\mu}}{c_{\text{EIA}}} \frac{t^i_{\text{left}}}{t_{\text{available}}} \frac{t - t^i_{\text{left}}}{t_{\text{available}} - t^i_{\text{left}}} & : \text{Otherwise} \end{cases} \tag{5}$$

and t is time, t^i_{left} is time left after computational component i is developed, $c_{PE\mu}$ is total EIA cost for that $PE\mu$, r is the efficiency of the DST's implemented computational components and $t_{\text{available}}$ is the available time window. The available time $t_{\text{available}}$ depends on the DST efficiency to lower permit lead times, and hence, if this factor is important, it may significantly impact the time window the DST effectively can be utilized. The time after a computational component of the DST was completed constitutes the usable time, i.e., the time the component can be used. In this study, the implementation order of the cost distribution was used to differentiate between the optimized implementation versus the unoptimized implementation (expected outcome of random implementation).

It was assumed that time and cost-effectiveness in computational component development scale linear with the investment rate I_{rate}. As the cost distribution $d^{ij}_{PE\mu}$ is the only variable in the model, it results in the most cost-effective implementation order to be sequential.

To consider savings for an uncorrelated implementation order of $d^{ij}_{PE\mu}$, i.e. costs are not considered, but will be represented by an expected cost $c_{PE\mu} = E(d^{ij}_{PE\mu} c_{\text{EIA}}) = \frac{c_{\text{EIA}}}{N_{PE\mu}}$.

Utilization is defined by equation (6).

$$U(t) = min(1, \sum_{x=1}^{N_{PE\mu}} H(t - t_{\text{DST development}} \frac{x}{N_{PE\mu}}) \cdot (t - t_{\text{DST development}} \frac{x}{N_{PE\mu}}) \cdot \begin{cases} \frac{d^x_{\text{EIA}}}{t_{\text{available}}} & \text{for optimized development} \\ \frac{1}{N_{PE\mu}} & \text{for unoptimized development} \end{cases} \tag{6}$$

The time to develop the DST $t_{\text{DST development}}$ with a constant investment rate I_{rate} can be written as $t_{\text{DST development}} = \frac{n c_{\text{computational component}} N_{PE\mu}}{I_{\text{rate}}}$. Which

Table 2: Assumed parameter ranges used for the scenarios, r are efficiencies of implemented computational components, $c_{\text{DST development}}$ are the total costs to develop the DST, I_{rate} are estimated investment rates and $N_{PE\mu}$ are the number of computational components of non-zero impact pairs. A smaller set of parameters are used to limit the scope of the analysis but at the same time enough visualize interesting behavior. Each parameter chose is further motivated in Supplementary Material.

Parameter	Ranges
r	$[0.1 \quad 0.5 \quad 0.9]$
$c_{\text{DST development}}(t)$(EURO)	$[\ 50 \cdot 10^6 \quad 100 \cdot 10^6 \quad 500 \cdot 10^6\ ]$
I_{rate} (Year)	$[\ 1 \cdot 10^6\ ..\ 9 \cdot 10^6\ ]$
$N_{PE\mu}$	231

further leads to cost of development of DST (equation (7)).

$$c_{\text{DST development}}(t) = \begin{cases} \frac{nc_{\text{computational component}} N_{PE\mu}}{t_{\text{DST development}}} t & : t < t_{\text{DST development}} \\ nc_{\text{computational component}} N_{PE\mu} & : \text{Otherwise} \end{cases} \tag{7}$$

Investment rate I_{rate} was assumed to be constant and span from 1'000'000 EURO per year to 9'000'000, 3 times the investment rate of current SwAM overall IT development budget I_{SwAM} at 3'000'000 EURO per year. The model parameters utilized in this study are presented in Table 2.

2.8. DST savings potential

The DST savings potential is defined as the mitigated EIA costs by using a DST as the step **4** (Figure 1). The function for the DST savings (8) was derived from equation (5)

$$s_{\text{tool}} = U \cdot r \cdot c_{\text{EIA}} \tag{8}$$

The efficiency of the DST r is defined as a constant factor of the mitigated cost; three different model parameters for the DST efficiency r will be used, assuming that 10%, 50%, and 90%, respectively, of the subsequent EIA cost, will be mitigated.

2.9. DST savings

The DST savings s in the last step **5** (Figure 1) is defined as the alternative future EIA process costs s_{tool} over time by equation (9):

$$s(t) = s_{\text{tool}}(t) - c_{\text{development}}(t) \tag{9}$$

The total utilization U and hence total savings potential, s, is dependent on how fast the DST is developed. A higher investment rate, I_{rate}, leads in general to higher savings potential, if total utilization U times cost of EIA c_{EIA} is larger than cost of development $c_{\text{DST development}}$ at the end of available time window $t_{\text{available}}$. Potential savings were estimated for six scenarios (Figure 2) at different DST efficiencies.

2.10. Break-even

The break-even is defined as when savings over time, mitigated by the DST minus the development cost $c_{\text{DST development}}$, becomes positive. Over time it follows that a DST's computational components will start to mitigate EIA costs for the impact pairs $PE\mu$. Additionally, the unoptimized and optimized development order of computational components differ, it is expected to lead to different outcomes for the savings and the break-even point.

3. Results and Discussion

3.1. Total Utilization

The future total savings potential of DST development is defined in six scenarios, of which three have an optimized and three an unoptimized development. The core differentiation determining savings potential between optimized vs. unoptimized development is the degree of utilization of the DST over the time window of interest, i.e., total time window. Each scenario results in a considerable difference in the total utilization. The midrange scenarios (S2O, S2U) result in a 42.8% percentage points maximal difference between the optimized vs. unoptimized development (Figure 4). The unfavorable scenarios (S3O, S3U) result in the maximal relative difference at 547%, but the optimized and unoptimized development have low utilization, with the optimized at 33.2% and 5.1%, respectively. These results indicate that optimized development is vital to consider realizable utilization and not only the savings potential. In other words, it will be relevant to consider how the DST is to be developed, which likely will impact its performance.

However, several of the considered assumptions directly impact the behavior of the model outcome. The most critical aspects regard the limited industry and academic foresight in the cost, performance, options, and composition of development of a DST's computational components. Firstly, the assumption that the cost of development $c_{\text{DST development}}$ for each of the computational components was evenly distributed is a simplification. In reality, the computational components have indeed radically different design requirements. Additionally, there will be a workload associated with completion done by engineers and programmers, which will not scale linearly with the number of developers on a specific component. These together will impact both potential development costs, and the optimized development could be more parallel in nature for a realistic scenario.

Secondly, more realistically, the estimations and validation of cost are uncommon, as is the case for the computational component's efficiency, where the future of these cost estimations should be considered highly uncertain.

Thirdly, both the optimized and unoptimized cases only develop the components found relevant to offshore wind energy, implying that 14% of non-zero value components are excluded. Naturally, most interactions are irrelevant, but some additional aspects are likely to be developed in the unoptimized case, which would not contribute to any savings potential.

Lastly, essential functionality components, such as the platform and user interface, will be required to deploy other components. Likely there is an increase in dependencies between ecosystems and pressures if higher functionality and DST efficiency are to be reached, which need to be considered. These challenges

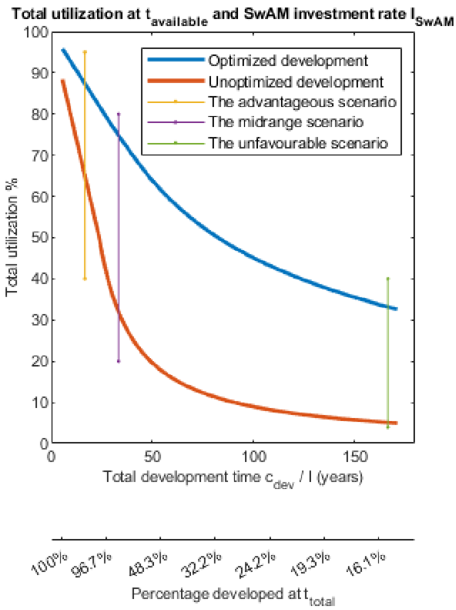

Figure 4: Impact on Total utilization at what speed of DST implementation under the available time window ($t_{\text{available}}$) where utilization is scaled to mitigated cost, i.e., when an impact contributes 10% of the overall permit costs. A computational component (solution to this impact) is developed halfway through, the multiple of fraction time left and cost fraction leads to a DST utilization of 5%, then cumulative add savings from other developed computational components to get the total utilization. The optimized curve is where the most cost-efficient computational components are developed first, and the statistical average(random) development is unoptimized. Each scenario is represented at the defined investment rate I_{SwAM}, which is the assumed/estimated investment rate of DSTs by the Swedish SwAM agency. The blue and red line is the resulting upper. It lowers the bound of the total utilization model where the parameters for the three vertical lines' advantageous, midrange, and unfavorable scenarios intersect with the type of development for our model.

typically would result in early developments being more straightforward but limited to efficiency but at a reduced cost; on the other hand, higher complexity scales with the number of growing dependencies and hence higher development costs would generally result in more costly high efficient solutions.

Given the limited data available, the assumptions made in this work were necessary,however, we argue that it is sufficient for our broad and general analysis, e.g., the significance of a high investment rate. Hence, the results indicate essential aspects to consider to enable cost-efficient development and implementation of a DST. We have also identified aspects that need to be further explored to develop future DSTs efficiently.

3.2. Savings over Time & Available Time Window

If the goal is to develop a DST that can transform maritime management, it would likely be a costly endeavor. However, considering the large number of offshore energy projects that are being planned in the near future, there may be a substantial savings potential in terms of reduced permit costs for future projects if there is a readily available analysis by a DST capable of offering the industry efficient and harmonized EIAs.

In each scenario is either the savings potential or development costs the dominant variable. In the midrange scenario, the optimized development reaches a positive savings potential of 106,9 MEURO, ca 0.7% of the EIA costs, and 20.8 MEURO for the unoptimized scenario at DST efficiency at 10% (Figure 5). This scenario is based on the cost of a recently developed IT platform in Sweden with expenses above 100 MEURO and the Norwegian program MAREANO for sediment and biodata collection, at around 127 M€. While the midrange development cost is set to 100 MEURO, the other scenarios use half and five times this development cost to span a wide range of outcomes. These different development cost estimates resulted in three primary patterns, where the midrange case cost and savings potential are of similar size, while for the other two, these diverge drastically.

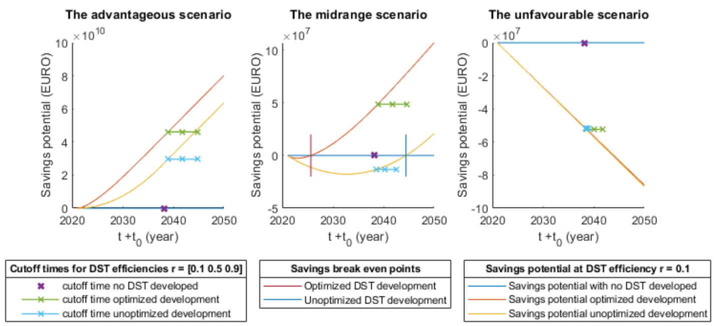

Figure 5: Results of savings potential over time for the advantageous (S1O, S1U), the midrange (S2O, S2U), and the unfavorable scenarios (S3O, S3U) for future offshore energy savings potential respectively at I_{SwAM} investment rate and efficiency of the DST at 10%. The available time is modified based on the finishing project before the cut-off time calculated using equation(2), and the development of the DST modifies this value based on its assumed efficiency and completion. The different extended available times $t_{\mathrm{available}}$ are presented for each DST efficiency for optimized and unoptimized development. The midrange scenario exhibits break-even for the DST savings and development costs for optimized and unoptimized DST development. The three scenarios present the three primary different savings outcomes of development, advantageous, break-even, and unfavorable.

The primary factor contributing to savings, apart from utilization, is the estimated cost of EIA, c_{EIA}. The advantageous scenario's savings potential reached 79.9 and 63.7 BEURO, 14.4 % and 11.5%, respectively, of EIA costs, while there was only a tiny difference between the optimized and unoptimized development (for tool efficiency at 10%). There was a negative, approximately -85.6 MEURO or 545% of EIA costs for both optimized and unoptimized development in the unfavorable scenario.

The definition of future EIA costs results in a wide span of possible outcomes for the available estimators. It was hard to argue that one combination of estimators is more reliable or probable than another at this point in the study. Therefore three scenarios for a low, mid, and high value have and should have the most impact on the results (Figure 5). Further research should focus on narrowing down and defining probable outcomes. It would lead to reduced uncertainty choices made during development to take maximum advantage of the savings potential.

3.2.1. Lead-Time

The lead-time of the development of offshore wind energy has been described as a significant obstacle, with project installation and permit processes taking more than a decade in some cases, inferring indirect costs and project failure rate [22, 20] A robust and capable DST is argued to be the central solution that consistently could lower lead-time without compromising environmental protection. The available time window is extended for the optimized midrange scenario (S2O) by 0.68, 3.58, and 6.48 years for respective DST efficiency, r (Figure 5). The shorter lead-time could result in a long time to complete projects to meet set energy goals. In the analysis, lead-time for an impact $PE\mu$ is assumed linear to the cost reduction for the impact, implying that if the cost for EIA is reduced by 50%, the lead-time for the EIA will also be reduced correspondingly. The available time to reach the energy goals is thus increased by the reduction in time to complete the project, i.e., an improvement in the available time increases the effective window of the DST. Lead-time reduction for each

DST efficiency is nearly the same as for the advantageous scenario as each tool has similar utilization(Figure 5). Hence, it results in the midrange scenario getting the most significant difference between optimized and unoptimized development. For the unfavorable scenario, the reduction would be minimal due to the assumption that only a tiny percentage of the tool is fully developed. The lead-time of permits affects the cost in terms of delayed projects. It is usually due to preset technical specifications set many years earlier in the permit applications that differ too much from the current state-of-the-art wind energy technology. For example, a project can turn inefficient if too small a tower size and height specifications limit what can be built later [20]. This effect will induce more failed projects by new applications that need to be revised and sent in again following the same procedures, inducing additional EIA/permit costs. As mentioned, EIA's cost and its lead time are likely correlated and constitute a significant factor in possible cost reductions. Further, it would also impact how the DST should be developed to maximize savings concerning energy goals set in the near future.

3.3. Analysis of Efficiency of the DST's Implemented Computational Components r and Investment Rate I_{rate}

In addition to building an efficient DST is the question of funding, especially for large and costly projects. Concurrently with our case study, a publicly funded Swedish DST is being developed. The coordination of current and coming development efforts, and its funding, will ultimately dictate if a DST can be built and if the DST will be ready in time to be utilized (Figure 4), to hopefully be indirectly break even or produce some savings potential (Figure 6).

A reference investment rate was used to assess development, this being the SwAMs budget for IT development. Our assessment is that this budget is used for many other projects apart from Symphony. It is unclear if their budget includes, e.g., engineering costs, but it is nevertheless likely a gross overestimation of expenditures in the near term and the past couple of years. How the three scenario's savings potential changes using a different investment rate depends

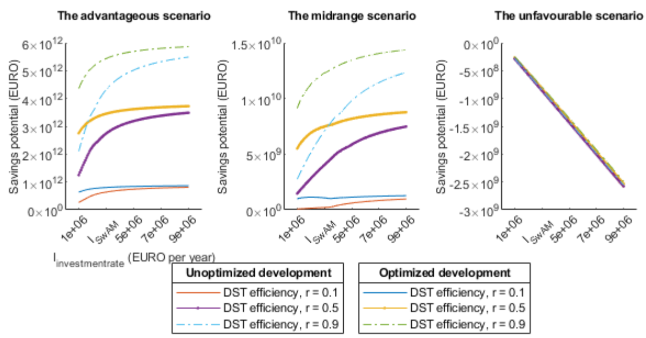

Figure 6: The resulting savings potential of the model at the end of the scenario time window $t_0 + t_{\text{total}}$, with varying investment rates I_{rate}.The subplots are for the advantageous, midrange, and unfavorable scenarios with different DST efficiencies and optimization levels. In the first two subplots, there is a weakening improvement over time due to a lessening change in of utilization of the DST development components. For the third subplot, the unfavorable scenario is that the potential is smaller than the DST development costs over time, resulting in a near-linear negative savings potential.

on whether potential savings $r \cdot c_{\text{EIA}} \cdot U$ or $c_{\text{DST development}}$ is dominant. The fast rise in savings potential for the advantageous and midrange scenarios at the low range of investment rate, and the steep loss for the unfavorable scenario, indicate how important analysis of the development of DSTs for marine EIA may become. The largest uncertainties for a successful financial DST development are DST efficiency r and potential EIA costs. Further investigation into these factors should be necessary for future investment decisions.

4. Conclusions

In this work, multiple factors consequential when considering offshore renewable energy expansion and offshore decision support management have been identified and initially assessed. First, identifying a relationship between the cost of developing and operating a DST compared with savings potential. Secondly, identifying a relationship with a limited time window to build DSTs results in realistic settings impacts savings potential for the offshore wind economic sector. Thirdly, exemplified through a simple model, multiple scenarios impact the usefulness of the DST if there is a limited time frame.

Supplementary Material

Supplementary data to this article can be found online at 'http:/....'

Acknowledgement

The authors thank Kent Cronholm for his discussions and his support. The project 'Standardisering av undervattensteknik' (2018-04665) has financially assisted this research.

CRediT author statement

Andreas Olsson: Conceptualization, Methodology, Software, Investigation Data curation, Writing- Original Draft.: Oskar Frånberg: Supervision, Resource, Funding acquisition.: Ida-Maja Hassellöv: Supervision, Writing - Review & Editing, Visualization.

References

[1] EU commission, on a new approach for a sustainable blue economy in the eu transforming the eu's blue economy for a sustainable future, 2021. `https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0240&from=EN`.

[2] P. Ehlers, Blue growth and ocean governance—how to balance the use and the protection of the seas, WMU journal of maritime affairs 15 (2016) 187–203.

[3] T. Børresen, Blue growth opportunities in sustainable marine and maritime sectors, Journal of Aquatic Food Product Technology 22 (2013) 217–218.

[4] EU commission, An eu strategy to harness the potential of offshore renewable energy for a climate neutral future, 2020. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:741:FIN.

[5] A.-K. Govindji, R. James, A. Carvallo, Appraisal of the offshore wind industry in japan, Carbon Trust: London, UK (2014).

[6] G. Middle, I. Middle, The inefficiency of environmental impact assessment: reality or myth?, Impact Assessment and Project Appraisal 28 (2010) 159–168.

[7] EU commission, Council directive of 27 june 1985 on the assessment of the effects of certain public and private projects on the environment, 1985. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31985L0337&from=EN.

[8] EU commission, Directive 2014/52/eu of the european parliament and of the council of 16 april 2014 amending directive 2011/92/eu on the assessment of the effects of certain public and private projects on the environment, 2014. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0052&from=EN.

[9] E. ten Heuvelhof, C. Nauta, The effects of environmental impact assessment in the netherlands, Project Appraisal 12 (1997) 25–30.

[10] A. Barker, C. Wood, An evaluation of eia system performance in eight eu countries, Environmental Impact Assessment Review 19 (1999) 387–404.

[11] K. Pınarbaşı, I. Galparsoro, Ángel Borja, V. Stelzenmüller, C. N. Ehler, A. Gimpel, Decision support tools in marine spatial planning: Present applications, gaps and future perspectives, Marine Policy 83 (2017) 83–91.

[12] D. Depellegrin, H. S. Hansen, L. Schrøder, L. Bergström, G. Romagnoni, J. Steenbeek, M. Gonçalves, G. Carneiro, L. Hammar, J. Pålsson, et al., Current status, advancements and development needs of geospatial decision support tools for marine spatial planning in european seas, Ocean & Coastal Management 209 (2021) 105644.

[13] Mareano, About mareano; mareano maps depth and topography, sediment composition, biodiversity, habitats and biotopes, and pollution in the seabed in norwegian offshore areas., 2021. https://web.archive.org/web/20210603070130/https://www.mareano.no/om_mareano.

[14] Swedish Agency for Marine and Water Management, Symphony integrerat planeringsstöd för statlig havsplanering utifrån en ekosystemansats, 2018. https://www.havochvatten.se/download/18.52d593d41624ea1d549cfe1d/1523361761104/rapport-symphony-integrerat-planeringsstod-for-statlig-havsplanering-utifran-en-ekosystemansats.pdf.

[15] Swedish Agency for Marine and Water Management, Mosaic – verktyg för ekosystembaserad rumslig förvaltning av marina naturvärden, 2020. https://www.havochvatten.se/download/18.1bd43926172bdc4d648d4f7e/1593701389470/rapport-2020-13-mosaic.pdf.

[16] B. Halpern, S. Walbridge, K. Selkoe, C. Kappel, F. Micheli, C. D'Agrosa, J. Bruno, K. Casey, C. Ebert, H. Fox, R. Fujita, D. Heinemann, H. Lenihan, E. Madin, M. Perry, E. Selig, M. Spalding, R. Steneck, R. Watson, A global map of human impact on marine ecosystems, Science (New York, N.Y.) 319 (2008) 948–52.

[17] Swedish Energy Agency, Delrapport 2: 100 procent förnybar el - scenarier, vägval och utmaningar, 2019. https://energimyndigheten.a-w2m.se/Home.mvc?ResourceId=5787.

[18] S. Tegen, M. Hand, B. Maples, E. Lantz, P. Schwabe, A. Smith, 2010

cost of wind energy review, Technical Report, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2012.

[19] T. Stehly, P. Beiter, P. Duffy, 2019 Cost of Wind Energy Review, Technical Report, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2020.

[20] Vattenfall AB, Vindkraftsprojekt kriegers flak, 2021. https://web.archive.org/web/20210415121220/https://group.vattenfall.com/se/var-verksamhet/vindprojekt/kriegers-flak.

[21] Vattenfall AB, Offshore wind project lillgrund, 2013. https://web.archive.org/web/20130331092857/http://www.vattenfall.se/sv/fakta-om-lillgrund.htm.

[22] RWE, Offshore wind project kårehamn, 2022. https://se.rwe.com/en/locations/wind-farm-karehamn.

[23] Sweden Offshore wind ab, Eia offshore wind project kriegers flak, 2007.

[24] Vattenfall AB, Consultation material offshore wind project kattegatt syd, 2021.

[25] Wpd, Eia offshore wind project finngrundet, 2009.

[26] Swedish Parliament, 2009. https://data.riksdagen.se/fil/A24C92CC-0491-4A96-AB6B-E1BD4CC1E46B.

[27] Swedish Energy Agency, Havsbaserad vindkraft, 2015. https://www.energimyndigheten.se/globalassets/nyheter/2015/rapport-havsbaserad-vindkraft.pdf.

[28] Swedish Energy Agency, Yttrande angående samråd om havsplaner, 2018. https://www.havochvatten.se/download/18.6090324b1691dd5349ebb8dc/1551790524218/Energimyndigheten.pdf.

[29] Swedish Agency for Marine and Water Management, Havsplaner för bottniska viken, Östersjön och västerhavet förslag till regeringen, 2019. https://www.havochvatten.se/download/18.4705beb516f0bcf57ce1b184/1604327609565/forslag-till-havsplaner.pdf.

[30] Ministry of the Environment, Ansökan om tillstånd enligt miljöbalken till uppförande och drift av gruppstation för vindkraft i hanöbukten i sölvesborgs och karlshamns kommuner, 2016. https://www.regeringen.se/contentassets/5a5304ce813441b4b4bafe37d48300a4/beslut---ansokan-om-tillstand-enligt-miljobalken-till-uppforande-och-drift-av-gruppstation-for-vindkraft-i-hanobukten-i-slovesborgs-och-karlshamns-kommuner.pdf.

[31] Vattenfall AB, Vindkraftsprojekt taggen, 2021. https://group.vattenfall.com/se/nyheter-och-press/pressmeddelanden/2019/vattenfall-avbryter-vindkraftsprojektet-taggen.

[32] Ministry of Infrastructure, Moderna tillståndsprocesser för elnät, 2021. https://www.regeringen.se/497631/contentassets/22365d8e3dca4849aea08a185f52f893/moderna-tillstandsprocesser.

[33] Ministry of the Environment, En modern och effektiv miljöprövning, 2021. https://www.regeringen.se/4a4bbe/contentassets/ea3a4b77147140b8b853761f61f42d1c/en-modern-och-effektiv-miljoprovning-dir.-202086.

[34] Swedish Energy Agency, Havsbaserad vindkraft - en analys av samhällsekonomi och marknadspotential, 2017. https://www.regeringen.se/contentassets/609980e5801242e8b62765c0ef32eaec/statens-energimyndighets-rapport---havsbaserad-vindkraft.pdf.

[35] M. Noonan, T. Stehly, D. F. Mora Alvarez, L. Kitzing, G. Smart, V. Berkhout, Y. Kikuch, Iea wind tcp task 26: Offshore wind energy in-

ternational comparative analysis, National Renewable Energy Laboratory (2018).

[36] R. A. Board, Value breakdown for the offshore wind sector, Report RAB (2010) 365 (2010).

[37] S. Alsubal, W. S. Alaloul, E. L. Shawn, M. S. Liew, P. Palaniappan, M. A. Musarat, Life cycle cost assessment of offshore wind farm: Kudat malaysia case, Sustainability 13 (2021).

[38] Ministry of the Environment, Överenskommelse om den svenska energipolitiken, 2016. https://www.regeringen.se/49cc5b/contentassets/b88f0d28eb0e48e39eb4411de2aabe76/energioverenskommelse-20160610.pdf.

[39] UN, Paris agreement, 2019. URL: https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en.

Nomenclature

μ	Ecosystem vulnerability to a Pressure (impact weight)
$s_{\text{tool}}(t)$	DST savings potential
$U_{\text{computational component}}(t)$	Utilization of computational component of environmental impact pair
$c_{\text{DST development}}$	Total development cost DST
$f_{\text{application}}$	Fraction of offshore project costs being EIA process
f_{offshore}	Fraction of EIA process being offshore versus onshore
I_{rate}	DST investment rate
$N_{PE\mu}$	Number of computational components, $PE\mu$s
$t_{\text{DST development}}$	Time to develop all of the DST's computational components
t_{left}	Time left after a computational component is developed
$c_{\text{computational component}}(t)$	Development cost of computational component
c_{MWh}	Cost per yearly MWh of offshore wind energy
r	DST efficiency
$t^{\text{EIA}}_{\text{lead-time}}$	Project lead-time EIA process
$t^{\text{other}}_{\text{lead-time}}$	Project lead-time other aspects, e.g. build time
$t_{\text{available}}$	Available time window
t_{total}	Scenario time window
W	Offshore wind in yearly MWh capacity
c_{EIA}	EIA costs
$c^{ij}_{PE\mu}$	EIA cost per pressure-ecosystem impact pair
$f_{\text{failure rate}}$	Permit failure rate per MWh
$PE\mu$	Impact pair
DST	Decision Support Tools
EIA	Environmental Impact Assessment
MSP	Marine Spatial Plans
SEA	Swedish Energy Agency
SwAM	Swedish Agency for Marine and Water Management

Processed data and methods for

Strategic development of environmental impact assessment decision support tool for offshore energy enables decreased costs, increased utilization and quality

Andreas Olsson,[*,†] Ida-Maja Hassellöv,[*,‡] and Oskar Frånberg[*,†]

†*Department of Mathematics and Natural Sciences, Blekinge Institute of Technology, 371 79 Karlskrona, Sweden*

‡*Department of Mechanics and Maritime Sciences, Chalmers University of Technology, SE-412 96 Göteborg, Sweden*

E-mail: andreas.olsson@bth.se; ida-maja@chalmers.se; oskar.franberg@bth.se

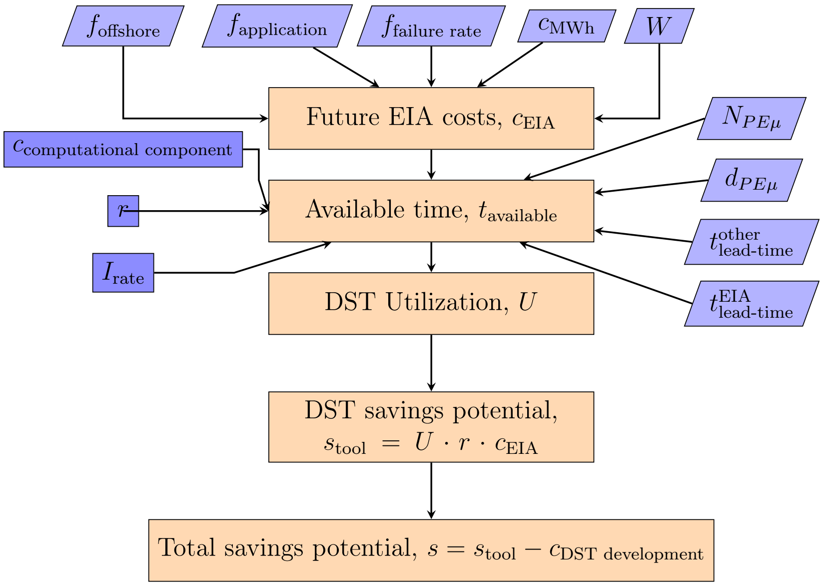

Figure 1: Flowchart of parameters and estimates. Dark blue represents scenario variables, light blue represents estimated parameters, and light orange represents the method.

Future EIA Costs

Ideally, the estimated costs for Environmental Impact Assessment (EIA) within offshore wind energy installations could be found in the previously accomplished project documentation. Unfortunately, such data is not publicly available, leading to EIA costs being estimated from different factors, such as the Yearly Cost per MWh, Average Permit and Build Project Lead-Time, Fraction Onshore vs. Offshore Estimate, Fraction of project costs in the permit process, as well as the National Capacity Goal and the historic Failure Rate. Estimates found in literature and from other sources are presented below.

Cost per yearly MWh of offshore wind energy

The nationally forecasted total cost for offshore projects was used to estimate the EIA costs for the Swedish case study. The permit application EIA reports from the Swedish projects Kriegers Flak, Storgrundet, Midsjö, Stora Middelgrund, Lillgrund, and Taggen include estimates for the cost of projects, summarized in Table 1 and was retrieved from the national registry. These secondary estimates were used for the forecasted cost estimates, as first-hand sources or more precise estimates or post-project costs analysis were unavailable.

Another potential source could have been using the Levelized Cost Of Energy (LCOE), e.g.(IEA WINd TCP task 26 (Noonan et al. (2018)) of which, depending on the type of fundament type, rotor size, and year, it tends to be on the lower end compared to the above.

A problem could arise if future cost estimations were paired with older proportional esti-

Table 1: Average cost per MWh produced per year table (*lower bound used).

EIA report	Total Cost project	Yearly production	Cost per MWh per year
Kriegers Flak park	10.3 GSEK	2'010'000 MWh / year	5124 SEK year /MWh
Storgrundet	4 GSEK	700'000 MWh / year	5'714 SEK year /MWh
Midsjö	>20 GSEK *	8'400'000 MWh / year	>2'381 SEK year /MWh
Stora Middelgrund	12-15 GSEK	3'000'000 MWh / year	4'000-5'000 SEK year /MWh
Lillgrund	2.167 GSEK	348'000 MWh / year	6'227 SEK year /MWh
Taggen	6-7 GSEK	1'050'000 MWh / year	5'714-6'667 SEK year / MWh
Average	c_{MWh}		5'121 SEK year / MWh

mates of EIA as project costs. The continuation of status quo EIA would most likely cost the same, while the cost of construction, e.t.c. could be making use of technological advances and economies of scale for construction.

Estimated Project lead-time EIA process and Project lead time other aspects

In this study the total project lead-time was subdivided into Project lead-time EIA process $t^{\text{EIA}}_{\text{lead-time}}$ and Project lead time other aspects $t^{\text{other}}_{\text{lead-time}}$. Information was only included from available data from Swedish projects that either completed or had project projections for permit and build lead times. The following projects was used for the analysis: Lillgrund, Kårehamn, Kriegers Flak (park), Kattegatt Syd and Finngrundet (Table 2).

Table 2: build and permit times; *project projections non completed projects

Project	permit lead-time project	build lead-time
Lillgrund	6 years	3 years
Kårehamn	10 years	2 years
Kriegers Flak park	14 years	4 years *
Kattegatt Syd	5 years*	6 years*
Finngrundet	2 years*	7 years*
	Average Permit lead-time	Average build lead-time
	7.4	4.4

Fraction of EIA process being offshore versus onshore

The offshore projects were analyzed regarding EIA of onshore aspects and offshore. Three values were estimated from the page count average, average excluding offshore wind projects, and average excluding cable projects (Table 3).

For the median value, it is the average of each fraction; the higher value only includes offshore wind, and the lower excludes offshore wind. The choice to include cable projects in the Swedish study is motivated by two aspects; first older applications do not include the connection to shore and miss environmental aspects of the cable. Secondly, large quantities of offshore will need better interactability of the regional and national grids, and in the Baltic Sea, it will result in more cable connections to the neighboring countries.

Fraction of offshore project costs being EIA process

The fractional cost of a project being in the application process was impossible to determine. In the case of completed Swedish projects, some had not their cost indexed in such a manner to determine which related to EIA costs. For this study, an international cost breakdown of EIA costs was used for the analysis.

The independent public organization 'Renewables Advisory Board' (RAB) commissioned a short study in 2010 on the breakdown of offshore wind's expected costs and concluded a

Table 3: Estimated fractions of EIA being offshore. Projects with a * are High Voltage cable projects

EIA report	Pages Offshore	Pages Onshore	Fraction
Beckomberga-bredäng*	31	40	31/71
Helsingborg-Helsingör*	33	22	33/55
Södra Midsjöbanken	51	1	51/52
Kriegers Flak park	99	6	99/105
Kriegers Flak kabel*	27	26	27/53
Marviken	27	10	27/37
Nordbalt*	17	55	17/72
Storgrundet	83	18	83/101
Fladen	50	1	50/51
Hansa Power Bridge*	32	44	32/76
Low Average High		$f_{\text{offshore}} = [0.44\ 0.666\ 0.89]$	

'Development & consent' to be 3% (Board (2010)).Alsubal et al. (2021) come to significantly larger estimates; A parametric whole life cost model for offshore wind farms is in figure eight in their work, presenting a pre-development and consenting (P&C) = 11%.

For projects of HV subsea cables, theace (2015)refer to Others (project management, regulatory, consents, studies…) to be 10% of the cost of a breakdown of 7 assets.

Another source is IEA Wind TCP Task 26:Offshore Wind Energy International Comparative Analysis (Noonan et al. (2018)), compare various countries' LCOE for offshore wind and countries with some 'pre government' , the cost of LCOE was reduced in the 'model'. For Denmark, this was about 1,5%, Germany about 3%, and the Netherlands about 4%, i.e., only implying a reduction in the expected "developing and consent", which is a cost covered by the respective government. Therefore this cost must be a smaller part of the total cost of "developing and consent" (in their model).

National Capacity Goals for Offshore wind in yearly MWh capacity

This study is based on governmental forecasts and plans for offshore wind installation and capacity expansion in line with marine spatial planning and political commitments regarding renewable energy. Three parameters in the model, 10 TWh being the lower estimate coming from the 2009 parliament, passed action plan for the year 2020, summarised in table 4.

Table 4: National Capacity Goals for Offshore wind in yearly MWh capacity

Report	Yearly capacity in TWh
2009-2020 action plan	10 TWh
Initial MSP proposal 2019 33% usage	23 TWh
Swedish Energy Agency report	89 TWh

The middle parameter is the estimated available capacity of 23 TWh with 33% space used from the proposal for the Swedish MSP (Marine Spatial Plan) in 2019. The upper estimate is the realizable 100 TWh at 80 EURO per MWh, minus the 11TWh of projects with permits as presented in the Swedish Energy Agency report (Swedish Energy Agency (2017)) equaling a parameter value at 89 TWh.

Permit failure rate per MWh

Wind power, in general, has expanded in size and quantity over the past decades in the world (Enevoldsen and Xydis (2019)). This trend is also seen for the land-based wind power in Sweden, but not to the same extent with respect to offshore installations, even though there is a potential as the Swedish national sea and economic zone in the Baltic Sea is large. Possible explanations for the Swedish situation of a relatively high failure rate could be; a situation that primarily took place in the early 2000s when 'prospectors' were betting that Sweden was going to set up a more favorable subsidizing regime for offshore wind, similarly to what happened in Norway (Inderberg et al. (2019)), this expectation may have led to excessive applications to be the first to acquire/secure stakes in the most favorable offshore wind options; Another circumstance may relate to a somewhat uncharted EIA process for large offshore installations this may potentially have yielded unpredictable outcomes resulting in the necessity to consider multiple projects; Lastly, the concerns of very long lead times in the EIA process, which at times taking up to 14 years, this results in a higher likelihood of the failing projects due to them no longer being economically feasible by unknown future

technology advancements, previously, this has been larger and taller systems manufactured every year, e.g. ,this type of development is demonstrated by the "new" application for Kriegers Flak for the same park but using taller but fewer windmills.
It is unclear if projects not being finalized/constructed, despite being approved, are a global problem or if it is localized to Sweden. However, it can be noted that both the Danish and German areas of Kriegers Flak have had operational offshore wind farms for some time.

Three types of failure rates were considered in the analysis; First, projects get dismissed/fail in the Swedish courts; Secondly, projects not being built with permits; Third, where no 'future' developments fail. In table 5 are the projects and status used to calculate the three failure rates used in the analysis $f_{\text{failure rate}} = 0, 0.8457, 0.9905$.

Table 5: Projects status and estimated capacity, mostly 2013-2015 status with found* project updates

Project	Status	Estimated Capacity TWh per year
Bockstigen	Built	0.006
Utgrunden I	Built	0.032
Yttre Stengrund	Built	0.015
Lillgrund	Built	0.348
Värnen	Built	0.105
Kårehamn	Built	0.182
Current capacity		0.688 TWh per year
Trolleboda	Have Environmental Permit	0.6
Utgrunden II	Have Environmental Permit	0.344
Kriegers Flak	Have Environmental Permit	2.56
Storgrundet	Have Environmental Permit	1.06
Stora Middelgrund	Have Environmental Permit	2.16
Taggen	Have Environmental Permit	1.2
Stenkalles grund	Have Environmental Permit	0.36
Potential capacity	with Environmental Permit, no dismissal.	8.284 TWh per year
Blekinge Offshore	dismissal	11.2
Södra Midsjöbankarna	dismissal	8.4
Finngrundet	dismissal	5.5
Kattegatt Offshore	dismissal	1.2
Vindplats Göteborg	dismissal	0.36
Potential capacity	with or without Environmental Permit	26.66 TWh per year

EIA Cost Distribution for Computational Components

Any DST or tool will not be completed instantly but will have a limited time being utilized until the energy goals have been met. Hence, it is essential to consider how fast the Decision Support Tool can be developed and if functionality is 'modularized' thereby allowing for continuously improved functionality and usage. In this study, the necessary functionality for the tool is unknown, and hence it cannot be used to differentiate updates to the tool. On the other hand, each pressure's specific impact on an ecosystem is considered and will represent the development step in the model. Further, the occurrence per impact pair was utilized to generate a distribution representing an associated cost of EIA and development. However, needed data or layers of developed functionality are hidden above in this representation, and in our case, only an estimate for a forecast of spent EIA (figure 2).

Assumption Application Content Relate Linear to Permit Application Costs

EIA aspects defined by impact pairs $PE\mu$ will have a different cost for their EIA. A secondary approach was utilized because there were no projects with bookkeeping for EIA costs available, which would offer a more direct cost assessment. An assumption was used to estimate the share of EIA costs of specific impact pairs $PE\mu$s, where a linear relationship with the amount of EIA permit content to the EIA costs. This study assumes that non-addressed EIs $PE\mu$s should not contribute to EIA costs. Hence, for roughly estimating the utilization of a DST, a linear relationship for the distribution will work well.

Analyzed Project Applications for Word Count Analysis

EIA reports (permit applications) were analyzed to generate a distribution of the various impacts (a combination of a Pressure and an Ecosystem ($PE\mu$s). The EIA was reviewed to identify analyses and assessments for analysis and assessments of impact pairs PE. The

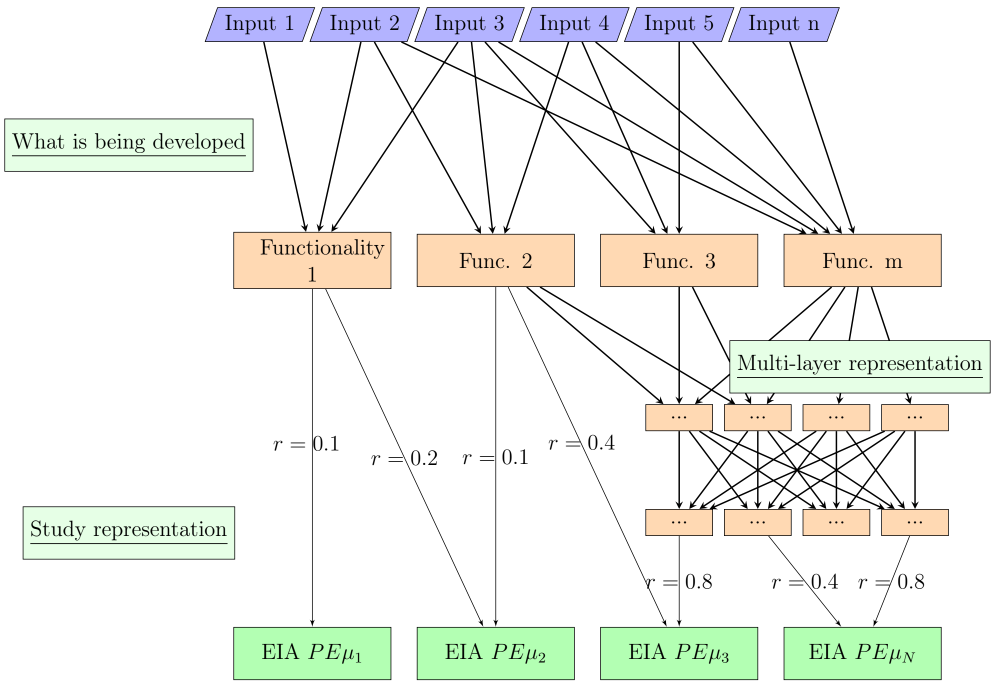

Figure 2: Cost representation and final EIA in green is, in addition, the representation of the functionality of the developed DST as they are developed in the model. In reality, it could be represented by the light orange functionalities, which would result in a more complex model. However, this analysis and the necessary functionality to be defined were beyond the scope and capacity of this study.

number of words for identified texts was collected from several applications EIA reports (Table 6). In the analysis, the defined Pressures and Ecosystems for the DST *Symphony* were

Table 6: Projects EIA reports assessed for impact pairs.

Project name
Kriegers Flak
Eon Helsingborg-Helsingör
Marviken
Storgrundet
Nordbalt
Midsjö
Fladen
Hansa Power Bridge

used as seen in Table,7 with the addition of three pressures in lower case where *Symphony* is part of SwAMs continuous efforts in developing a DST.
Each pressure/ecosystem contained in that category was counted when referencing higher-order pressures or ecosystems.

Results from word count are presented as a table diagram (Figure 3). The pairs of Ecosystems and Pressures are presented, where 14% were non-zero.

Non-zero data is presented as the $PE\mu$ distribution $d_{PE\mu}$ in figure 4.

Table 7: Pressures and Ecosystems beginning with starting capital letters are in the Symphony definition; those three starting with the lower case were added during the analysis of the applications.

Pressures	Ecosystems
Bird hunt	Mussel reef
Catch gillnet	Deep reef
Catch pelagic trawl	Haploops reef
Catch bottom trawl	Artificial reef
Turbidity bottom trawl	Plankton pelagic
Turbidity shipping	Hard bottom photic
Turbidity sand extraction	Hard bottom aphotic
Abrasion bottom trawl	Hard bottom deep
Habitat loss dumping	Transport bottom photic
Habitat loss fish farm	Transport bottom aphotic
Habitat loss mussel farm	Transport bottom deep
Habitat loss coastal exploitation	Soft bottom aphotic
Habitat loss infrastructure	Soft bottom deep
Habitat loss sand extraction	Shoreline Angiosperms
Noise 125Hz shipping	Sprat
Noise 125Hz wind power	Fish spawning
Noise 2000Hz shipping	Rivermouth fish
Noise boating	Eel migration
Explosions peak	Coastal birds
Explosions SEL	Seabird coastal wintering
Oilspill shipping	Seabird offshore wintering
Oilspill wreck	Rough bottom photic
Heavy metals background	Rough bottom aphotic
Heavy metals military area	Rough bottom deep
Heavy metals mine dump	algae
Toxic munition dump	benethic Organism
Synthetic toxins background	bats
Synthetic toxins harbor	Soft bottom photic
Synthetic toxins industry	Cod
Synthetic toxins treatment plant	Herring
Pollution boating	Porpoise baltic
Nitrogen background	Porpoise belt sea
Nutrients fish farm	Grey seal
Phosphorous background	Harbour seal
Anoxia background	Soft bottom photic
Electromagnetic field	
Climate change temperature	
Climate change acidification	
Disturbance wind power	
turbidity subsea works	
noise piling	
infrastructure temperature	

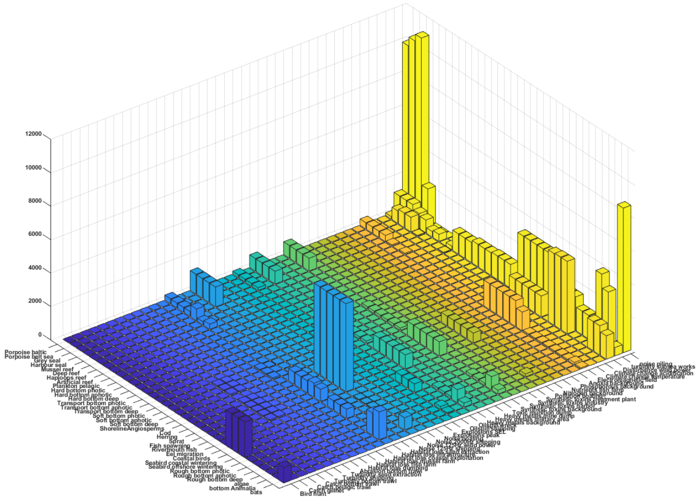

Figure 3: Combinations of Pressures P and Ecosystems E extracted from the analyzed project applications.

Model Assumptions

To make model forecasts, assumptions were necessary to limit the scope of the study, see sections below:

Linear Assumption Development Pace and Completion of the DSP

There are many factors governing how fast a toolkit can be developed. This study assumes a linear relationship between development pace and toolkit investment rate. I.e., this assumes the development project to be partitioned ideally between developers. However, in a real-world scenario, more extensive projects and additional developers would most likely add considerable communication overheads and tasks not being divisible to the ideal extent, adding additional cost and time to a development project (Brooks (1995)).

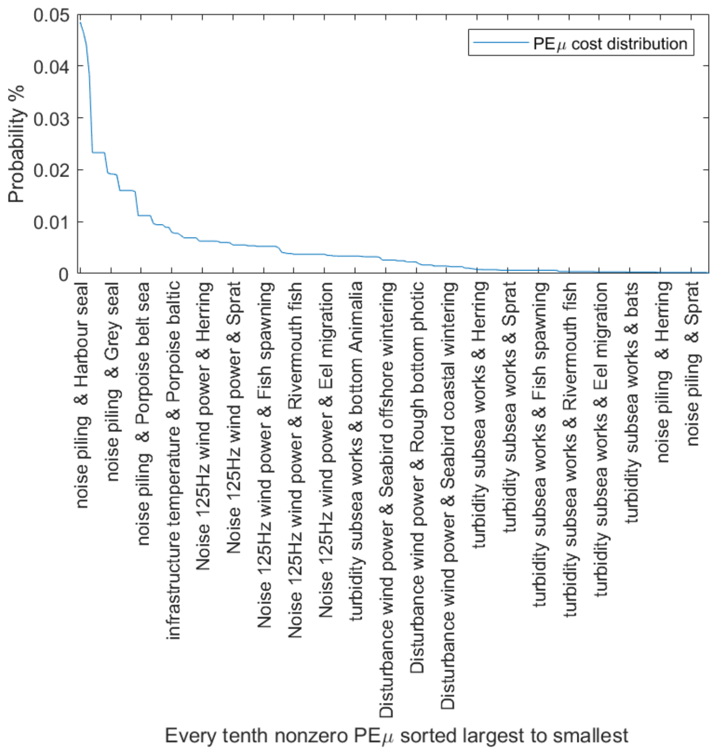

Figure 4: An estimated cost distribution of each non-zero impact pair $PE\mu$ on the x-axis where every 10th pair is displayed. Data include offshore renewable impact-related aspects present in the surveyed EIA applications for Offshore Wind and High Voltage Subsea Cables.

Linear EIA Costs Rate over Time

EIA cost analysis as it develops over time requires an estimation of the expenditure. In this study, a constant expenditure is assumed, being equivalent to a smooth continuous stream of EIA-related costs over the time window t_{total}. In a future implementation plan, there are, however, many factors that influence when the EIA costs are going to be "spent," e.g., political decisions about subsidies, electricity prices, or technology breakthroughs may affect when the bulk of the EIA cost is spent during the time window t_{total}. A substantial share would be employment costs, a relatively continuous expense that may increase or decrease over time.

Assumption Higher Quality Lead to Less Uncertainty

Increased knowledge and transparency are assumed to lead to fewer projects failing, i.e., a lower failure rate for projects. This increase of knowledge or transparency in this study takes the form of the toolkit's developed computational components, e.g., if analysis taking months would be a reduced to a check-in a national map tool, it would, in essence, be increased transparency, and in our assumption lead to fewer failed projects through significantly less spent EIA costs.

Assumption DST Efficiency r of Developed Features Reduce Future Costs

Any system built to reduce repetitive analysis or manual analysis at a large scale may effectively reduce future workload or fail to do so. In practice, the potential improved quality and speed of using an EIA DST in Swedish waters is unknown. In the worst case, the built DST would not significantly reduce analysis for any user of the DST. In better cases, it reduces some, or the majority, of the costs related to EIA. Either way, a proper analysis model should contain an estimation of this impact of the computational component built. However, this is hard to estimate as multiple factors play a role for a tool to be usable and for whom. Additionally, it is hard to measure the outcome, and it takes time, and things such as adaptation time, may be relevant to consider.

As possible outcomes of toolkit efficiencies are uncertain, it is sensible to consider multiple efficiencies of the toolkit's implemented computational components efficiency r. Parameters assumed and used in the model is DST efficiency 10%, 50% and 90% , defined as $r = [0.1, 0.5, 0.9]$.

Costs Components Assumed to Independently Decomposition Into Different EIA Aspects

The goal of an EIA DST is to take manual labor-intensive calculating and analysis tasks and apply them to a national data set and present outcomes and results of impacts on maps. Challenges for subsea analysis compared to land-based analysis include scarcity of data and lack of knowledge of the complex marine ecosystems. Therefore, an EIA DST is a considerable task, and there will be many interconnections or dependencies between different components of the tool (Figure 2). Further division of the tool components will require the development of functionality that does not directly lead to increased efficiency but components required for other functionality. There are many "small" parts of the components we describe that many computational components have in common for a realistic scenario. Other aspects may be higher-level analysis that requires multiple computational components' to be developed. This interdependence is present and should be fully taken advantage of or may dictate development order to solve some 'problems.' This study assumes that individual EIA cost aspects can be divisible in computational components that estimate the impact for that specific Pressure and Ecosystem $PE\mu$, as we have a cost associated with it.

Further, another aspect to consider in this divisibility is what accuracy is necessary for the computational components to reach 'enough' knowledge level or 'good enough' risk assessment to balance the cost of development and achieve tool efficiency.

Unoptimized Implementation of a DST in terms of EIA costs reduces to a randomly ordered implementation

We assume that optimal implementation can only be considered if EIA costs and DST computational components efficiencies and development costs are determined or with some accurate proxy. The model assumes the optimized scenarios for the most cost-effective component are developed first. The "unoptimized" scenarios are equivalent to not considering what components to develop first. Hence each option has an equal chance to be developed; therefore, the effectiveness is set to the average EIA cost $\frac{c_{\mathrm{EIA}}}{N_{PE\mu}}$, where $N_{PE\mu}$ is the number of components. Either each component can be considered in each development has the exact change to be developed, and hence the average in each step is considered, or a random implementation order can be considered, now generating results for many randomized orders and taking the average performance.

Cost of Development

Three reference values, 500 MSEK, 1000 MSEK, and 5000 MSEK, were used in the analysis, converted to Euro with 10 SEK = 1 Euro. These values are roughly equivalent to 50 or 100 developers during ten years versus 250 during ten years. As a point of reference, a recent Norwegian MAREANO program gathering and mapping subsea sediment/biotopes spent around 10 Millon euros a year for ten years in total 1277 MNOK (127M Euro).

$$c_{\text{development}} = [500 \cdot 10^6,\ 1'000 \cdot 10^6,\ 5'000 \cdot 10^6]$$

References

Noonan, M.; Stehly, T.; Mora Alvarez, D. F.; Kitzing, L.; Smart, G.; Berkhout, V.; Kikuch, Y. IEA Wind TCP Task 26: Offshore Wind Energy International Comparative Analysis. *National Renewable Energy Laboratory* **2018**,

Board, R. A. Value breakdown for the offshore wind sector. *Report RAB (2010)* **2010**, *365*.

Alsubal, S.; Alaloul, W. S.; Shawn, E. L.; Liew, M. S.; Palaniappan, P.; Musarat, M. A. Life Cycle Cost Assessment of Offshore Wind Farm: Kudat Malaysia Case. *Sustainability* **2021**, *13*.

UIC Report - Electricity infrastructure; Agency for the Cooperation of Energy Regulators: Brussels, Belgium, 2015; `http://www.acer.europa.eu/Official_documents/Publications/UIC_Electricity`.

Swedish Energy Agency, Havsbaserad vindkraft - En analys av samhällsekonomi och marknadspotential. 2017; `https://www.regeringen.se/contentassets/609980e5801242e8b62765c0ef32eaec/statens-energimyndighets-rapport---havsbaserad-vindkraft.pdf`.

Enevoldsen, P.; Xydis, G. Examining the trends of 35years growth of key wind turbine components. *Energy for Sustainable Development* **2019**, *50*, 18–26.

Inderberg, T. H. J.; Rognstad, H.; Saglie, I.-L.; Gulbrandsen, L. H. Who influences wind-power licensing decisions in Norway? Formal requirements and informal practices. *Energy Research Social Science* **2019**, *52*, 181–191.

Brooks, F. P. *The mythical man-month: essays on software engineering*, anniversary ed.; Addison-Wesley: Reading, Mass, 1995.

ABSTRACT

In the expansion of offshore sustainable energy systems, there is growing pressure on the environment and permit processes and the accumulation results in much higher total risk for accidents of future assets. Anticipating the problems at the design stage and improving verification is likely to increase energy development and reduce costs. This thesis explores offshore DST (Decision Support Tools) and risk verification of subsea cable assets.

For subsea cables, a statistical method is proposed utilizing measurement data together with shipping traffic data (AIS) to estimate the environmental risk and risk of accidents of installed cable assets. This should partially solve issues of improving design using more data and surveys and utilizing mechanical and sensor-specific characteristics to improve the confidence and burial estimation, contrary to today's methodology. The implication of the two studies of cable burial risk assessment techniques and verification shows how a developed methodology can solve issues for verifying the integrity of an installed asset. Putting our methodology into practice involves many challenges.

For the marine Decision Support Tool (DST) and sustainable energy development, to estimate potential savings if permit processes would be shorter and less burdensome without degrading the quality of the EIA (Environmental Impact Assessment). A method is proposed to model various scenarios of *effective* savings from the development of a DST to reduce costs spent on EIA permitting by the offshore energy developers. The study of the implication of the marine EIA DST shows a quantifiable estimate of the savings potential for permit processes for sustainable offshore development, and results indicate a need for optimization of DST development, which can be an essential factor in its implementation and success.

BLEKINGE TEKNISKA HÖGSKOLA · BTH ·

ISSN 1650-2140

2023:02

ISBN 978-91-7295-450-2