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Bachelor thesis

A naval design study on a small, unmanned surface vessel

by

Martin Sløveren Andressen & Roger Brokstad Mykland

Submitted as a part of the requirements for the degree:

BACHELOR IN MILITARY STUDIES WITH SPECIALIZATION IN LEADERSHIP
- NAVAL ENGINEERING

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Preface

This thesis is written by Martin Andressen and Roger Mykland between September to December 2022 as part of the study "Bachelor in military studies with specialization in leadership - naval engineering" at the Royal Norwegian Naval Academy. The thesis was written during the Erasmus exchange program at Helmut Schmidt Universität, Hamburg, Germany.

The thesis consists of a naval design study on a small, unmanned surface vessel and utilises PRINSIX as a method of procurement integrated in the bachelor template. However, due to the mechanical field of study, the thesis is centred around hull and propulsion.

We would like to take the opportunity to thank Commodore (R) Geir Kilhus for providing guidance and supervising throughout the entire work both day and night.

Furthermore, we would like to thank Principal Lecturer Gisle Strand, Univ.-Prof. Dr. -Ing. Christian Kreischer, M. Eng. Johannes Liebrich, and Principal Lecturer Arild Sæbø for providing technical supervision and support.

In addition, we would like to thank Mari Kleiven Lyngvær, coordinator unmanned and autonomous systems in the Royal Norwegian Naval Staff, for guidance with regards to conceptual solutions and requirements for the Royal Norwegian Navy.

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Bergen, Sjøkrigsskolen, 18-12-2022

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Abstract

The thesis is based on a naval study of a small, unmanned surface vessel. Furthermore, the study has been conducted in accordance with the Norwegian method of procurement PRINSIX. The study has been a preliminary project and involves the three first phases of the PRINSIX method: The idea phase (IP), the concept phase (CP), and the definition phase (DP).

The IP analysed three ideas of conceptual solution: Mine Counter Measurement (MCM), Intelligence Surveillance and Reconnaissance (ISR), and Force Sustainment USV's in light of operational needs in a top-down approach. Eventually, the output of the idea phase was a recommendation to further investigate the idea of ISR USV's.

The CP analysed analysed the capabilities and mission need for chosen alternatives, and further identified the capabilities for the conceptual solutions. The output of this analysis was four potential options: Continuation of current assets, small, passive ISR USV's in large numbers, small active and passive ISR USV's in limited numbers, and small active and passive ISR USV's in limited numbers with offensive capabilities. Furthermore, a trade-off analysis, risk assessment, and rought technical considerations regarding hull and propulsion was made. Consequently, the CP concludes with a recommendation to move forward with option 1, Small ISR USV's with a towable passive sonar in conjunction with deployable sonobuoys. Furthermore, the CP recommends moving forward with a conventional hydrostatic displacement hull and a hybrid propulsion configuration.

The DP started off with specifying the preliminary capabilities and requirements for the chosen conceptual solution. Furthermore, a preliminary vessel was chosen as a reference vessel. The chosen reference vessel was then subject of a trade-off analysis with respect to alternative solutions for hull, propulsor, drivetrain, energy producers, and energy storage. The preliminary design solution was then deducted through a parametric study based on the preliminary capabilities and requirements, and the parameters in the design spiral. Moreover, a set of optimized parameters and a final optimized solution was presented and further analysed with respect to a weight breakdown, cost assessment, and a risk assessment. Finally, a recommendation was made based on the findings in the points of decision and the associated risk analysis. In conclusion, the recommendation is to not move forward into a development- and completion phase, judging the current state of the vessel. Further optimization is essential to reduce the risk of procurement.

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Nomenclature and symbols

Nomenclature

ASAP	As Soon As Possible
AAW	Anti-Air Warfare
AO	Area of Operation
AC	Alternating Current
ASuW	Anti-Surface Warfare
ASW	Anti-Submarine Warfare
CODED	Combined Diesel-Electric and Diesel-Mechanical
CP	Concept Phase
CPP	Controllable pitch propeller
DP	Definition Phase
DC	Direct current
FPP	Fixed Pitch Propeller
FLASH	Folding Light Acoustic System for Helicopters
FW	Fresh Water
IEP	Integrated Electric Propulsion
IMO	International Maritime Organization
IP	Idea Phase
ISR	Intelligence surveillance reconnaissance
kn	knots
MCM	Mine Counter Measurements
MGO	Marine Gas Oil
MilSpec	Military Specifications
NAF	Norwegian Armed Forces
Nm	Nautical miles

NST	Naval Staff Targets
PMSM	Permanent Magnet Synchronous Machine
POSS	Passive Optical Sensor Systems
RNN	Royal Norwegian Navy
Rpm	Rounds per minute
SLOC	Sea Lines Of Communication
SW	Sea Water
USV	Unmanned Surface Vessel

Symbols

Symbol	Description	Unit
ρ	Density of saltwater	Kg/m^3
η_0	Propeller efficiency	
η_m	Mechanical Efficiency	
η_R	Relative Rotational efficiency	
η_{CODED}	Efficiency of Combined Diesel-electric and Diesel-Mechanical drive train configuration	
η_{IEP}	Efficiency of Integrated Electric Propulsion	
η_{GEN}	Efficiency of generator	
$\eta_{C.ENG}$	Efficiency of combustion engine in generator	
B.A.R	Blade Area Ratio	
B	Beam	m
B_{wl}	Beam waterline	m
C_b	Block coefficient	
D	Diameter	m
F_d	Drag Force	N

GM	Meta-centric radius	m
GZ	Righting arm	m
h_n	Lower heating value	J/kg
J	Advance coefficient	
kn	Speed	knots
K_T	Thrust coefficient	
L	Design length of vessel	m
L_{wl}	Length waterline	m
L/B	Length – Beam ratio	m
LCB	Longitudinal Centre of Buoyancy	m
LCG	Longitudinal Centre of Gravity	m
n_{screw}	Revolution per minute	rpm
P_e	Installed effect	W
P_E	Drag effect	W
P.C	Propulsion Coefficient	
P/D	Pitch – Diameter ratio	
Q	Torque	Nm
R_{TS}	Total resistance on ship	N
t	Thrust deduction coefficient	
T	Draft	m
T_{MAX}	Maximum load of propeller	N/m^2
V_A	The vessels advancement speed	m/s
V_S	The vessels speed	m/s & knots
VCG	Vertical Centre of Gravity	m
w	Wake fraction coefficient	

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1. Introduction

Utilizing unmanned vessels as a means of modernizing the navy is a well-known concept internationally. The demand for more efficient use of resources is a pressing challenge. The long-term defence plan for the Norwegian armed forces states that autonomous systems may provide addition presence and information input, which would increase situational awareness and reduce the risk of personnel involved in operations (Ministry of Defence, 2020-2021). Along with routine tasks and transport missions in areas challenging to human endurance, autonomous systems would provide social and economic gain by relief of human resources

> *"Increased battery, sensor, processor capacity, reduced weight and size and an increase in technological maturity has made unmanned systems a force multiplier" (Maritime The Norwegian Armed Forces, 2015).*

The use of unmanned surface vessels (USV) in naval context has evolved over the last decades. Previously, the implementation of today's technology in unmanned naval operations has been done with poor results. This research project seeks to help understand the vast majority of technological options available and give an example of how to implement them towards military operations. The findings of this study will benefit military departments looking for insight and knowledge within military USV concepts. The study shall seek to identify a suitable concept and further provide an optimized design solution.

1.1. Background

Today's society demands for a more effective use of resources. The use of technology to replace manned platforms have proven to be more effective in terms of cost, and a positive contribution to risk management. The use of existing technology may allow the nation to cover a greater area at a lower expense. With regards to the extent of the Northern Sea Territory, today's use of resources may be subject to improvement.

As a part of the education, the bachelor thesis is a mandatory, and highly prioritised aspect of the education. The use of USVs and state-of-the-art technology in military applications is a high priority to modernize today's military forces on an international basis.

1.2. Purpose

The purpose of this thesis is addressing a naval design study on a relatively small, unmanned surface vessel (USV), which is appropriate within a given operational area. Moreover, the design study shall propose a detailed, theoretical solution based on Naval Staff Targets and inputs from naval communities within the Royal Norwegian Navy.

The solution will be based on the Norwegian "PRINSIX" method of procurement. Furthermore, the tasks will be divided into two purposes: the integration of PRINSIX as a method of procurement, and the definition and optimization of parameters from the design spiral in order to present a suitable vessel for further development.

1.3. Task description

> *The design study shall propose a detailed solution based on staff requirements and inputs from naval communities.*
>
> *The solution shall define materials, energy consumers, energy source and its conversion. Details on the hull's flotation and stability properties and propulsion details are to be given in standard naval architectural drawings and tables.*

Initial clarifications regarding task description

Autonomy

For our thesis we will continue with International Maritime Organization's (IMO) definition on levels of autonomy for unmanned vessels as mentioned in Maritime21-Strategy (Maritime21, 2021). We will not include the fourth level of autonomy because it would make the USV manned.

1. Fully autonomic vessel that makes decisions and determine actions by itself.
2. Semi-autonomic vessel where actions are automatic, but decisions are made by humans.
3. Remotely controlled USV.

An USV does not have to be autonomic but could include either of these levels of autonomy.

Sea State

Level	**Height**	**Description**
0	0	Calm (glassy)
1	0 – 0,1 m	Calm (rippled)
2	0,1 – 0,5 m	Smooth (wavelets)
3	0,5 – 1,25 m	Slight
4	1, 25 – 2,5 m	Moderate
5	2,5 – 4 m	Rough
6	4 – 6 m	Very rough
7	6 – 9 m	High
8	9 – 14 m	Very high
9	Over 14 m	Phenomenal

Table 1: Definition of sea states (Sivle, 2018).

Norwegian coastal waters provide the sea state from 0-9. Depending on areas of operation (AO) this will affect a smaller vessels seakeeping ability and furthermore its design.

What is a small USV?

Small is a relative size when speaking about USV. The American Navy operates with a medium USV definition of 14 m to 58 m (45 to 190 feet) (O'Rourke, 2022). For this thesis it is suitable to think that a smaller USV would be less than 14 meters.

When referring to anti-surface warfare (ASuW) we imply operations with intent "to detect, identify and counter an adversary's capability". ASW consists of operations with intent "to deny an opponent the effective use of their submarines". AAW will strive to protect friendly forces from air-threats (Speller, 2014, p. 198). Seakeeping abilities is a ships behaviour in rough weather (Babicz, 2015, p. 542)

"The investment process is efficient when the Armed Forces acquire the equipment that provides the overall highest defence capability, at the lowest possible investment and implementation cost, at the right time." says Norwegian Defence Research Establishment (Presterud, Øhrn, & Berg, 2018, p. 10). In order to keep the investment and implementation costs low this thesis will need to deviate from technology that needs extensive research. Using already functional technology and development concepts with 5-10 years' time for implementation is ideal.

1.4. Limitations

Due to the field of study and magnitude of the bachelor thesis, the following aspects will not be considered:

- Autonomous control of the vessel and practical integration of autonomous technology.
- Operations outside the arctic environment.
- Construction of the vessel.
- Model testing in a towing tank.
- The development phase, the implementation phase, and the closing phase in accordance with PRINSIX.
- Comprehensive calculations of electrical components.
- Comprehensive considerations of communication and sensor technology.
- Comprehensive calculations and measurements of vessel signature.
- Procedures of operations with other assets.
- Transportation plans
- Mooring considerations

Further limitations with respect to technical considerations will be listed in relevant chapters throughout the study.

1.5. Method

The bachelor process will follow the Norwegian developed PRINSIX system. PRINSIX is a template from an idea to the acquisition of equipment for the Norwegian Defence. Our thesis will work through a simplified idea-, concept- and definition phase before a solution will be presented. The theory aspect of the thesis will be integrated within each phase, with emphasise on theory integration within the trade-off analysis in the concept phase and alternative solutions in the definition phase.

Figure 1: Visual representation of the translated PRINSIX method (PRINSIX, 2022)

Idea phase

The idea phase (IP) often starts with a request for a particular solution from a military department on an operational level. The request gives the groundwork for researching if there are several departments with the same need. Given interest from several departments one starts to describe the desirable need appropriately, mapping the dependencies and following consequences starting a project. Based on a well-defined problem formulation one starts to deduce superior functional needs and demands before one starts to derive measurable performance measures.

Concept phase

“The purpose of the concept phase is to create a documented and traceable connection from an identified need to a selected/chosen alternative» (Norwegian Defence Materiel Agency, 2022).

The selection of an alternative should be based on holistically assessment of the conceptual alternative which best fits the needs of society and the military departments. In our assignment we will start with a requirement analysis before investigating relevant factors and define identified capabilities. Afterwards we will conduct a trade-off analysis before ending with a recommendation for a conceptual solution with recommended hull and propulsion configuration.

Definition phase

The definition phase (DP) documents the basis of the project, adapts the project size, complexity, and uniqueness. The decision basis provides the foundation for a future acquisition of the project for the agency responsible for procurement of new equipment. The conceptual solution derived from the concept phase (CP) will be further analysed and more apt and substantiated. The thesis will conclude with an initial choice of technical specifications for relevant parameters within the design spiral. Furthermore, an optimized solution shall be recommended after a parametric study. The design spiral is a tool intended for the designer to address all relevant factors. As illustrated in figure 2, the designer will have to go several rounds in the design spiral in order to converge into an optimized design.

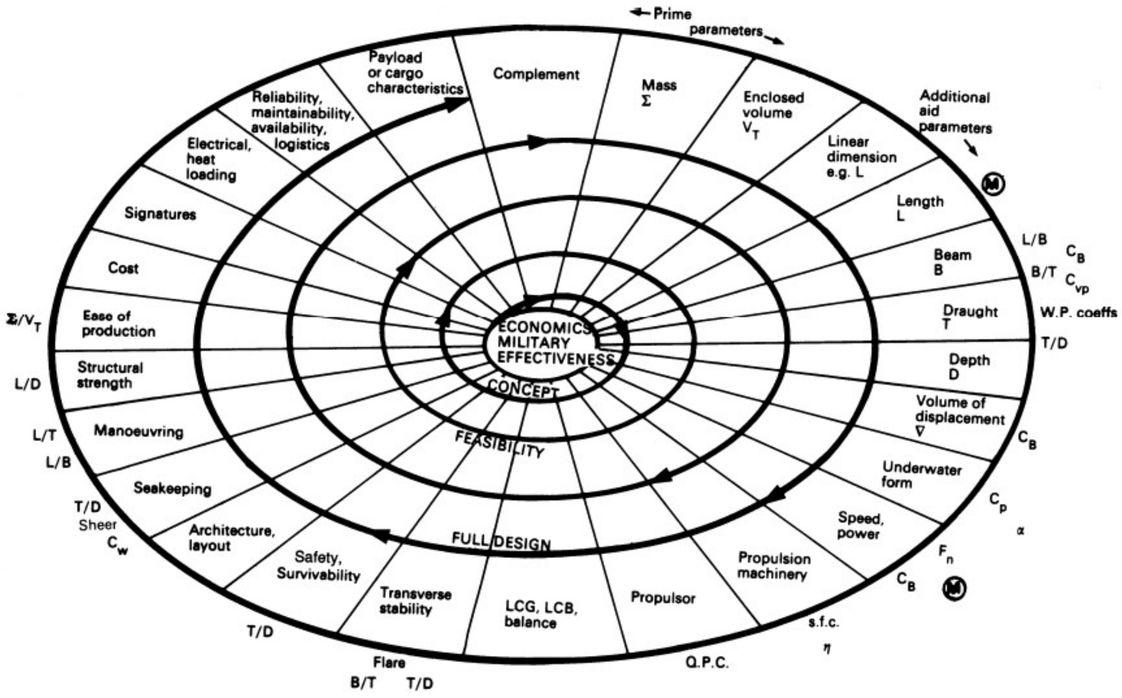
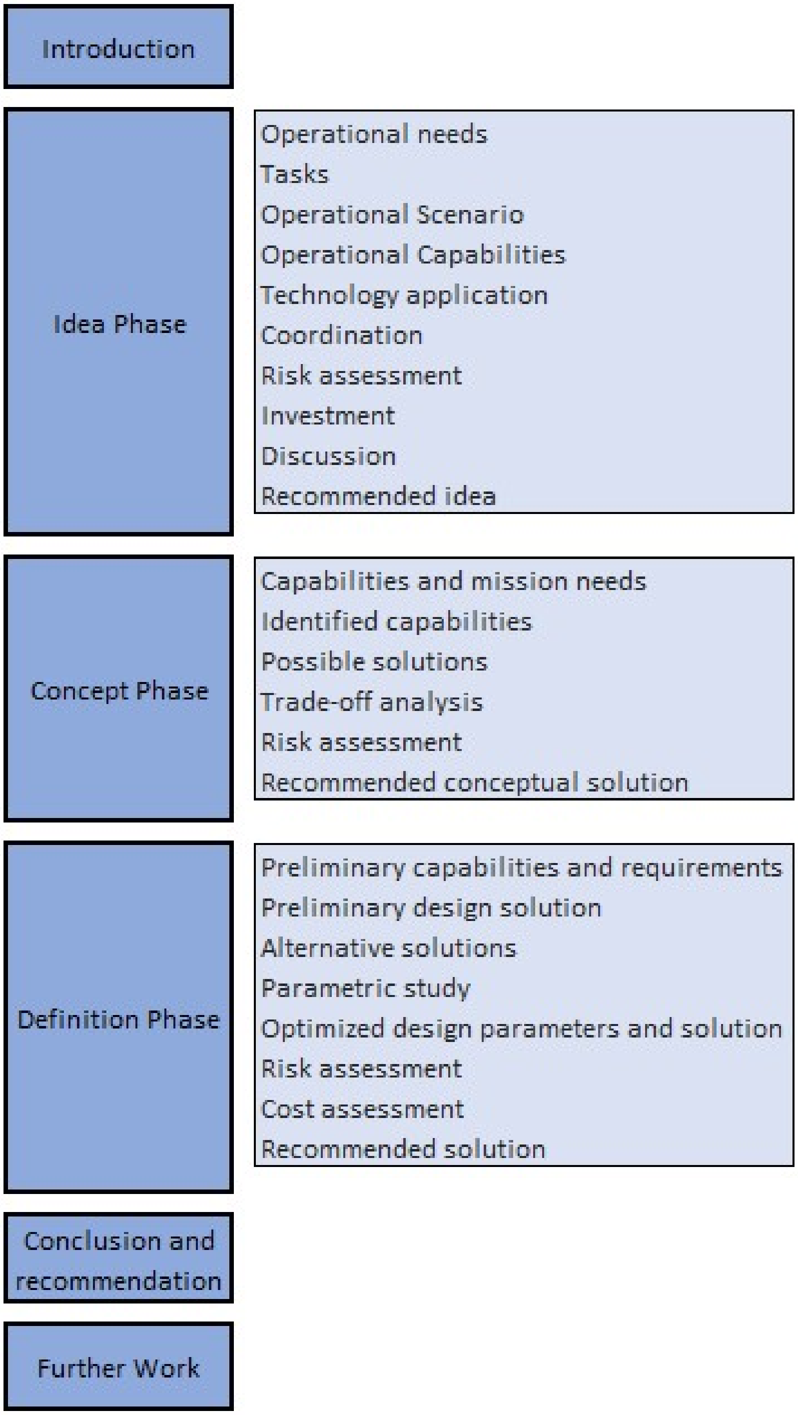


Figure 2: The design spiral (Rawson, 2001, p. 653)

1.6. Structure

The format of this thesis will diverge from standard format of writing a bachelor thesis due to the integration of PRINSIX. The theory aspect will be integrated as mentioned above in 1.5 Method.



Introduction	
Idea Phase	Operational needs Tasks Operational Scenario Operational Capabilities Technology application Coordination Risk assessment Investment Discussion Recommended idea
Concept Phase	Capabilities and mission needs Identified capabilities Possible solutions Trade-off analysis Risk assessment Recommended conceptual solution
Definition Phase	Preliminary capabilities and requirements Preliminary design solution Alternative solutions Parametric study Optimized design parameters and solution Risk assessment Cost assessment Recommended solution
Conclusion and recommendation	
Further Work	

Figure 3: Visual representation of PRINSIX integrated in the bachelor structure

2. Idea phase

The idea phase (IP) is the first phase in the PRINSIX method of procurement and will analyse the concepts in light of operational needs, in a top-down manner. The IP consists of analysing a set of relevant factors on an operational level and the output is a recommended concept to be investigated further into the concept phase.

2.1. Summary

In this phase we have analysed three given concepts: Mine Counter Measurement (MCM), Intelligence Surveillance and Reconnaissance (ISR), and Force Sustainment USV's in light of operational needs in a top-down approach. The work consists of the following factors: motivation and operational needs, tasks, operational scenario, threats, important operational capabilities, technology application, coordination between other units and actors, risk assessment and investment and costs. Furthermore, we have discussed the given factors with respect to the Norwegian Armed forces' tasks, long-term plans(Ministry of Defence, 2020-2021), and the advantages and disadvantages of manned versus unmanned platforms. Although all the concepts are viable options to investigate, the discussion has shown that the ISR USV's is the more suitable concept to investigate further into the concept phase.

2.2. Introduction

Today's society demands more effective use of resources. The use of technology to replace manned platforms has proven to be more effective in terms of cost, and a positive contribution to risk management. The idea of USV's as a military asset to solve tasks in the Norwegian Armed Forces is not an unknown topic. The list below consists of relevant tasks for the Norwegian Armed Forces with respect to the application of USV's in a maritime setting (Ministry of Defence, 2020-2021):

1. Prevent and handle episodes and security policy crises with national resources, including facilitating allied engagement.
2. Defend Norway and allies against serious threats, attacks, and attacks within the framework of NATO's collective defence.
3. Secure a national basis for decision-making through monitoring and intelligence.
4. Claim Norwegian sovereignty and sovereign rights.
5. Ensure the exercise of authority in limited areas.
6. Contribute to safeguarding the society and other key tasks in society.

This phase will address the idea of implementing smaller USV's in a military application, on an operational level. The central factors that will be addressed in the IP are operational needs, tasks, operative scenario, threats, capabilities, application of technology, coordination with other units and actors, risk assessment and cost. Furthermore, the idea of implementing or replacing manned platforms with USV's with respect to the long-term plan of the Norwegian Armed Forces will be discussed (Ministry of Defence, 2020-2021). Eventually, the output is a decision, with a recommended concept to be discussed further into the Concept Phase.

2.3. Motivation and possible operational needs

We have been in dialogue with several departments within the Royal Norwegian Navy and have made notice of three primary operational needs:

Option 1: Mine Counter Measurements (MCM) USV

> Replace and support current assets in terms of minesweeping with an unmanned platform. Eliminates need of high staffed vessels and reduces risks for involved personnel. Provides operational capability to clear Norwegian sea territory and prepare for allied reception.

Option 2: ISR USV for surveillance of surface and subsurface domains.

> The extent of the Norwegian coast is hard to monitor at a high level with today's manned platforms, to which requires an extensive amount of resources. The use of cost effective USV's may allow the nation to cover a greater area with the same amount of resources. The recent attack on subsea pipelines makes this kind of vessel a high demand capability. The alternative provides operational capability to detect, track and control Norwegian sea territory.

Option 3: Force Sustainment USV for resupplying troops near the coast.

> The need for an asset to resupply troops in a coastal environment with low signature, without the risk of human lives in transit to the area. The alternative eliminates the need for manned surface vessels in conflicted areas of operation and provides operational capability to control areas around littoral waters.

In addition to the primary needs, a selection of secondary needs that must be addressed is:

1. The need for a concept that is environment friendly.
2. The need for a concept that is efficient in terms of cost and effect.

3. The need for a concept that is capable of operating with low signature.
4. The need for a concept that is robust and in accordance with military specifications.

2.4. Tasks

A common task for the USV's is to support the Norwegian Armed Forces in claiming Norwegian sovereignty and sovereign rights in sovereign territory. The following tasks are derived from the relevant tasks of the Norwegian Armed Forces as stated in the introduction of the idea phase.

Option 1: MCM USV

- Secure sea lines of communication (SLOC) and facilitate for allied engagement in accordance with NATO's strategy for collective defence.
- Contribute to safeguarding the society and other key tasks in society.

Option 2: ISR USV

- Secure a national basis for decision-making through monitoring and intelligence.
- Contribute to safeguarding the society and other key tasks in society.

Option 3: Force Sustainment USV

- Support the exercise of authority in limited areas.
- Support troops in a coastal environment.

2.5. Operational scenario

All ideas will operate in a Nordic Sea territory with an arctic environment. The Nordic Sea territory holds a great variety of weather and sea states. With winds up to hurricane strength and sea states up to level 6 depending on AO.

Option 1: MCM USV

> The MCM USV is expected to operate alongside allied vessels clearing vital transit routes. More precisely in vicinity close to harbours and sea-lines of communication (SLOC). Variable weather conditions must be expected.

Option 2: ISR USV

> Operates in areas from outside littoral waters to the deep ocean. Often in packs of more than two platforms tracking enemy activity in surface and subsurface domains. Sea state up to level 6 and variable visibility should be expected.

Option 3: Force Sustainment USV

> Operates in littoral waters close to mainland and islands. The platform operates alone or in small teams and could provide support for smaller firearms teams or troops protecting SLOC nearby land areas. The AO is most likely a contested area between own and enemy forces. Close to land, the USV would have to expect sea state 6 and powerful currents produced by narrow sounds.

2.6. Threats

Common threats on an operational level are hostile interference and environmental conditions. Hostile interference could be cyberthreats, hybrid warfare or direct actions against the USV's. The following threats are considered of particular importance for the specific ideas.

Option 1: MCM USV

> Particularly vulnerable against enemy air threats in littoral waters.
> Low endurance regarding moving USV's to AO.
> The protection of the MCM USV's from a third party, must be considered on an operational level.

Option 2: ISR USV

> Particularly vulnerable against enemy air threats, hybrid warfare from civil marine traffic and collision with marine litter floating in AO.

Option 3: Force sustainment USV

> Particularly vulnerable against enemy countermeasures, and hard weather conditions in littoral waters.

2.7. Important operational capabilities

USVs can provide important operational capability if the platform solves tasks equivalent or better to current methods at a more reasonable price. Below we have listed the most important operational capabilities.

Option 1: MCM USV

> Provides semi-autonomous functions which in turn provide lower operational risk by excluding humans. The USV concept could potentially provide higher operational flexibility if operated by non-MCM ships. A MCM USVs concept, with more affordable platforms, could provide more MCM capability than a single fully manned MCM-vessel. Multiple platforms could potentially provide higher operational capability.

Option 2: ISR USV

> Provides presence and large volumes of data which raises situational awareness in AO. Autonomic functions with lower risk of human life at sea provides decreasing operational risk. Affordable platform with a greater number of vessels gives greater coverage and frees up operational resources for other tasks. In theory a USV has lower need for supplies and could provide operational enhanced endurance.

Option 3: Force sustainment USV

> The USV can reduce operational risk by eliminating humans in sustainment operations. The concept creates an unmanned alternative of force sustainment and may provide operational flexibility and endurance.

2.8. Technology application

Today, the necessary technology, education system, and infrastructure to design, construct and operate an USV already exist. The available technology often exists in small professional environments and makes greater demands for cross-sector international cooperation. The Norwegian Armed Forces have stated in its long-term plans, that the use and integration of commercially available state-of-the-art technology from the civil sector is a high priority (Ministry of Defence, 2020-2021, pp. 67-68). In order to use commercially available state-of-the-art technology in certain military applications, it is necessary with some level of further development to fit military specifications. One of the primary rationales for the application of technology is to raise the efficiency of the National defence.

Additionally, a study done by the Norwegian Defence Research Establishment finds that the vessels and airborne vessels account for over 85% of the total emission in the Norwegian Armed forces (Voie, 2019, p. 21). This supports the NAF's long-term plan to use technology to reduce emission (Voie, 2019).

2.9. Coordination between other units and actors

The USV platforms are dependent on having existing departments ready to receive and employ the systems. Dependencies are sufficient funding and maintenance structure, education, and necessary staffing structure. Joint and civil-military operations regarding national and international efforts, will require cross-sector coordination in establishing procedures for the use of the given USV's.

Option 1: MCM USV

> The system is operated by the Royal Norwegian Navy with possible detachment to the Norwegian Coast Guard and allied units.

Option 2: ISR USV

> Managed and operated by the Norwegian Navy and will provide a basis for decision-making for The Norwegian Join Headquarters on an operational level. Possible intelligence is then distributed to the fleet and relevant allied partners.

Option 3: Force Sustainment USV

> Operated on a tactical level in the Royal Norwegian Navy. Coordination between sub-departments within The Norwegian Armed Forces is to be expected.

2.10. Risk assessment

Risk assessment plays a vital part in acquisition of new equipment. Performance, economy, and time are central factors, to which will be discussed further. Risk assessment is often considered a product of consequence and probability.

Unmanned platforms could constitute an operational risk because of the platform's reliance on digital communication. Manned platforms can react to new threats when digital communication fails. A USV will not (yet) understand when their operations do not align with the overall military goal and make managing military operations more difficult.

Integration of commercially available technology in certain military applications can constitute a risk. Military operations depend on the USV's to operate optimally. A higher use of commercially available equipment in military application increases the risk of failure.

A higher degree of advanced and unproven technology increases the risk of entering a development project. The investment cost can quickly increase if the project becomes a long-term development project, which in turn may become lost operational capability.

2.11. Investment and operational cost

The total lifetime cost is divided into investment and operational cost. To keep the investment cost low it is crucial to avoid entering a development phase. The use of existing commercially available equipment could lower the risk of entering a long and expensive development phase.

Operational cost includes the cost of maintenance, staffing and education. To keep the operational cost low it is necessary to keep a low staffing level.

Today, modern society demands an ever-increasing focus on environmentally friendly solutions. Nation's obligation to meet environmental demands makes environmental footprint directly linked to the overall cost assessment. Non-emission solutions could potentially lower future total costs.

The total cost must be within a realistic price range to satisfy the demand for a concept that is cost effective so that it may replace or supplement current capabilities.

2.12. Discussion

A smaller USV may be applied to certain military applications to supplement or replace manned platforms. In order for the Norwegian Armed Forces to solve the given tactical objectives while operating within the political framework, it is necessary to discuss the advantages and disadvantages of the application of USV's on an operational level. The discussion of the given ideas will be based on the relevant factors listed above with emphasise on the benefits of unmanned platforms versus manned platforms. The differences will furthermore be analysed with respect to how well it applies to the relevant tasks in the long-term-plan of the Norwegian Armed Forces.

Motivation and possible operational needs

When looking at possible operational needs in respect to The Norwegian Armed forces prioritised tasks one can observe that alternative 1. is important in regard to substantiating allied reception. On the other hand, option 2 would provide early warning and a wider operational decision basis early in the conflict spectrum. Meanwhile option 3 would be better suited in a possible defence against hostile forces. All alternatives suit the needs of the Norwegian Armed Forces, but option 2 is most needed early in the spectrum of conflict versus option 1 and 3.

Tasks

The Norwegian Armed Forces are depended on assets to solve its relevant tasks. All three options contribute with relevant assets to achieve the overall tasks. The MCM and ISR USV ideas contributes with facilitating for an allied reception and securing a national basis for decision-making. Although the tasks are high priority, they are solved to a certain extent by other assets in the current structure. The Force Sustainment idea would, on the other hand, strengthen NAF's ability to prevent and handle episodes, defend Norway, and ensure exercise of authority in limited areas. Although the Force Sustainment task is not solved by other assets, the MCM and ISR tasks are perceived to have a higher desired priority in regard to acquiring new assets.

Operational Scenario

Operating in an arctic environment in the Nordic Sea territory poses certain demands. USV's have more endurance, in contrast to manned vessels, because they don't need staff restitution. On the other hand, the operational scenarios demand high vessel and system robustness. If the USV's can't be reliable, it will have no use in military operations. Unlike manned platforms, USV's must be expected to be expendable and deployed to AO with a possible higher degree of conflict.

Looking at the probability of each alternative operational scenarios, it is most likely the scenario with the lowest conflict spectrum which will occur. The Force sustainment alternative is described to be operating in the most hostile environment followed by the MCM USV alternative. Even though the MCM alternative can operate in the lower conflict spectrum it is more likely that the ISR USV scenario is the one to occur.

Threats

Manned and unmanned surface vessels are all prone to hostile and environmental threats. The difference between the two ways of operating is that MSV tends to be more capable of reacting to new unforeseen situations. Threats as hybrid warfare and direct hostile actions could prove difficult to solve for USVs. Due to the relatively small size of the USVs, it becomes even more important to have good seakeeping properties in order to withstand environmental threats. The biggest difference between the alternatives is that MCM and Force sustainment USV provide somewhat decisive capability that is not so easily replaced when lost. However, the loss of an ISR USV could be replaced by other assets, thus does not necessary represent a lost capability in the bigger picture.

Important operational capabilities

Unmanned surface vessels could contribute with several desired operational capabilities. All alternatives could lower operational risk by excluding humans in AO. In addition, the MCM USV would provide operational flexibility and overall capability if it reaches its full potential. By comparison, the ISR USV would contribute with raised situational awareness, free up resources and enhance operational endurance. Whereas the Force Sustainment USV could deliver flexibility and endurance. It would appear that the ISR USV as a capability would provide a more specific contribution to the long-term operational tasks in the NAF.

Technology application

With the already available technology from the commercial market, the process of acquiring and application of technology is a matter of cross-sector and international cooperation. To take full advantage of state-of-the-art technology, the capability should be attainable within a range of 5-10 years in order to remain a viable option. Both the MCM and ISR USV’s will be based on technology already existing in manned platforms today. However, the Force Sustainment USV’s does not exist to the same extent and will require more development in terms of integrating commercially available technology to fit a military application. Compared to already existing MCM and ISR capabilities, the use of technology to enhance the capability in terms of using more environment friendly USV’s may pose a major advantage, considering the report done by the Norwegian Defence Research Establishment on emission in the Norwegian Armed Forces (NAF), and their plan to reduce it in the Navy (Voie, 2019, p. 21).

Coordination between other units and actors

The use of MCM USV will to some degree require more coordination with other units given the technical nature of an MCM platform. However, the necessary competence already exists to some degree within the current structure and may lessen the necessary coordination with respect to education and establishing procedures of operation.

On the other hand, the ISR USV is relatively easy to deploy, and in terms of operating, less dependent on other units. Nevertheless, in order to fully exploit the benefits of the ISR platform, one must expect coordination between similar units and actors on an operation level in the process of mapping a situation or an area. Additionally, the nature of the ISR USV may allow for a broad area of application, both military and civil sector.

The Force Sustainment USV’s nature is that of supporting sub-departments within The Norwegian Armed Forces and allied forces, hence coordination between departments on an operational level is to be expected. In addition, the use of a Force Sustainment USV’s may prove to be relevant in supporting the civil sector in cases of national crisis. The ability to use USV’s to transport supplies to inaccessible communities instead of using other relevant manned platforms could potentially be a positive contribution. Nevertheless, the MCM and Force sustainment USV’s appears to require slightly more coordination between other units and actors in comparison to the ISR USV’s.

Risk assessment

In terms of risk, the probability and consequence of failed acquisition may have different outcomes for the given USV concepts.

The risk of procuring the MCM USV’s is related to the implementation of existing MCM technology and commercially available technology. Given the technologically demanding nature of the MCM USV’s, the probability of entering a development project is high even though the asset already exists on manned platforms.

The risk of procuring ISR USV’s is considered low due to the low impact should the system fail to operate as intended, and how well current assets can supplement the capability. However, the consequence of not satisfying the requirement of endurance and seakeeping abilities, given the operation scenario and AO, is to be considered high. Consequently, not meeting the performance goals will have a high impact on the capability.

The risk of procuring the Force Sustainment USV’s is focused on the performance. For the Force Sustainment USV’s to operate as intended, it is essential to meet the requirements for signature and performance. The probability of not satisfying the operational requirements is high and may risk entering a development phase.

The probability of entering a development project on all given USV concepts are considered high, but the consequence of entering a development project is considered lower for the ISR USV’s in comparison to the MCM and Force Sustainment USV’s.

Investment and operational cost

To keep the cost low, it is essential to avoid development concepts. Both MCM and ISR USVs would require integration and adaptation of different technologies while the Force Sustainment would rely on reliable low signature technologies. Depending on what technology is to be equipped, all the three alternatives could become a development concept. Nevertheless, if the unmanned platform is able to utilise electrical equipment and state-of-the-art technology, it might contribute to a lower environmental footprint and thus reducing total costs.

Both ISR and Force Sustainment USV provide low staffing level and would keep operational costs down. The MCM alternative still operates with a supporting vessel of some sort, which could mean higher operational costs. Perhaps the low operational cost could allow more investment in a sustainable solution that ensures more operational endurance or capability.

It would appear that all concepts are subjects of entering a development phase. However, the ISR and Force Sustainment USV's may require lower staffing level and less infrastructure compared to the MCM USV's.

2.13. Points of decision and conclusion

Points of decision and recommendation

The following points of decision are decisive: Performance, costs, time, and risk analysis with respect to performance, cost, and time. All alternatives suit the needs of the Norwegian Armed Forces, but the ISR USV's is most needed early in the spectrum of conflict compared to the MCM and Force Sustainment USV's. All though the Force Sustainment task is not solved by other assets, the MCM and ISR tasks are perceived to have a higher desired priority in regard to acquiring new assets. However, even though the MCM alternative can operate in the lower conflict spectrum it is more likely that the ISR USV scenario will occur. The biggest difference between the alternatives is that MCM and Force sustainment USV provide somewhat decisive capability that is not so easily replaced when lost. On the other hand, the loss of an ISR USV could be replaced by other assets, thus does not necessary represent a lost capability. It would appear that the ISR USV as a capability would provide a more specific contribution towards the long-term operational tasks in the NAF. Additionally, the Force Sustainment USV would require slightly less advanced technology application. However, the MCM and ISR USV depend on already existing technology, and would be a matter of integrating already existing technology. Nevertheless, the MCM and Force sustainment USV's would require slightly more coordination between other units and actors in comparison to the ISR USV's. The probability of entering a development project on all given USV concepts are considered high, but the consequence of entering a development project is considered lower for the ISR USV's in comparison to the MCM and Force Sustainment USV's. Eventually, the ISR and Force Sustainment USV's may require lower staffing level and less infrastructure compared to the MCM USV's, which may in turn reduce the overall cost. Based on the findings, we recommend investigating the idea of an ISR USV further into the concept phase.

Conclusion

In the idea phase (IP) we have stated and discussed factors regarding the use of the concepts on an operational level. The relevant factors are motivation and operational needs, tasks, operational scenario, threats, important operational capabilities, the application of technology, coordination between other units and actors, risk assessment, and investment and operational cost. We recommend investigating the idea of an ISR USV further into the concept phase.

3. Concept phase

The concept phase (CP) will process the idea and develop it further into one recommended concept. The CP will start with an in-depth analysis of needs and continues with stating necessary capabilities for different alternatives. Moreover, a trade-off analysis will be conducted with rough technical proposals for hull and propulsion. The output is a recommended conceptual solution to be further defined in the definition phase.

3.1. Conclusion from idea phase

The idea phase concluded with a recommendation to further investigate the implantation of ISR USV's as a concept and a possible capability for the Royal Norwegian Navy. The ISR USV as a concept is expected to be of high relevance with respect to the operational ambitions for the Royal Norwegian Navy.

3.2. Summary

The CP has stated and discussed relevant capabilities and mission needs for chosen alternatives. The relevant factors to be discussed are

1. Operational needs, missions, and tasks
2. Operational scenario
3. Threats
4. Autonomy
5. Technology application
6. Vulnerability, and survivability

Furthermore, the CP identified 5 relevant capabilities for the chosen alternatives in prioritised order:

1. Capability to conduct long-term operations in rough sea conditions
2. Capabilities to detect and track enemy activity in surface and subsurface domain
3. Capability to operate autonomously and operational cooperation with other units
4. Capability to operate with low signature
5. Capability for self-defence

The possible solutions were identified and discussed with respect to the identified capabilities, already existing capabilities, commercially available technology, hull, propulsion, and the risk assessment. The following alternatives were subject of discussion:

1. Option 0: Continuation of current assets
2. Option 1: Small, passive ISR USV's in large numbers
3. Option 2: Small active and passive ISR USV's in limited numbers
4. Option 3: Small active and passive ISR USV's in limited numbers with offensive capabilities

Based on the discussion, risk assessment, and points of decision the CP concludes with a recommendation to move forward with option 1, Small ISR USV's with a towable passive sonar in conjunction with deployable sonobuoys. Furthermore, the CP recommends moving forward with a conventional hydrostatic displacement hull and a hybrid propulsion configuration.

3.3. Capabilities and mission need for chosen alternative

The necessary capability for the concept is defined by given operational needs, missions, tasks, operation scenario, threats, vulnerability, and survivability. The goal of this analysis is to make sure that the proposed conceptual solution will fit the naval staff targets and operational demands.

Operational needs, missions, and tasks

The Royal Norwegian Navy's operational and tactical goals are given from political and strategic objectives. The long-term plan of the Norwegian Armed Forces states the following as a relevant operational and tactical ambition for the Royal Norwegian Navy:

> *"The Norwegian Navy shall contribute to the continuous monitoring of Norwegian and adjacent sea areas and shall establish and promote understanding of the maritime situation for national and allied command and control structures." (Ministry of Defence, 2020-2021, p. 101).*

Norwegian sea territories are estimated to be five times bigger than land areas (Norwegian Goverment, 2018), including 8800 km of gas pipelines and other important offshore infrastructure (Ministry of Petroleum, 2022). A key task for the Norwegian Navy is, to monitor and protect these national resources. Today, the Norwegian sea territories are monitored by satellite, coastguard, navy, and maritime patrol aircrafts in the surface domain while the subsurface domain is monitored by frigates and maritime patrol aircrafts (FFOD, 2019, p. 124). A common challenge for current assets is their limited endurance and range. Low numbers of each asset make it challenging to maintain presence in a large area of operation (AO), especially within the subsurface domain.

Future acquisition plan does not address investment in ISR capabilities, although project Sea power 2040 recommends “Autonomous sensors and communication relays should be introduced on a large scale" in the Norwegian structure (Strømmen, 2019, p. 21). Strømmen introduces drones as advanced sensors for existing platforms. He also addresses the need of “[…] phasing in a new corvette class with anti-submarine capacity to free up frigates for sea-going operations” (Strømmen, 2019, p. 21). Here, the ISR USV could operate as a warning and monitoring system for frigates and allied forces.

Operational scenario

The operational scenario consists of monitoring Norway's sea territories. The USVs would be working together to locate and track foreign assets primarily in the subsurface domain and secondary surface domain, while maintaining communication with other units and actors. The ISR USV’s are expected to operate in a level of conflict from peacetime to full-scale war. Operating in the sea from outside littoral waters to the deep ocean, the USV’s are expected to endure longer operations up to 14 days. This in addition to operate in sea-states of 3-4 and survive in hurricane strength winds and sea states up to level 6 in the AO (Hochet, Dodet, Ardhuin, Hemer, & Young, 2021, pp. 9-10).

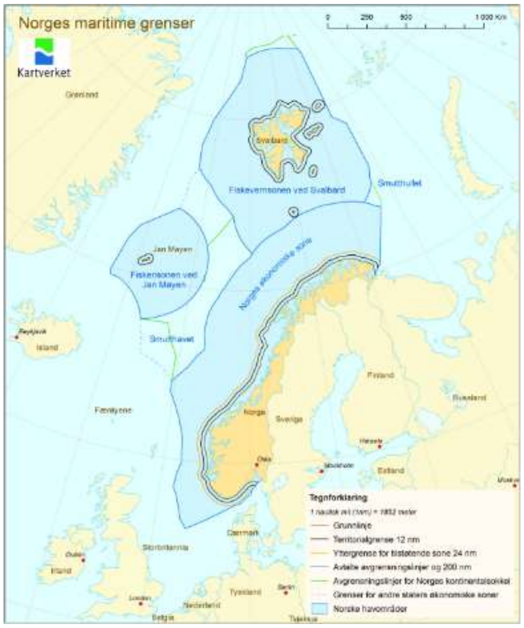


Figure 4: Norwegian Sea Territory (Kartverket, 2015)

Threats

The research program of The Royal Norwegian Navy towards 2040 states that Russian threats against Norwegian assets may include “… use of stealth, surveillance, overwhelming firepower and asymmetric approaches.” (Strømmen, 2019, p. 9). The USV’s should expect submarines in the subsurface domain and hybrid threats in the surface domain. Considering the ISR USV’s to be autonomous it will be vulnerable to any hostile action. Direct action from enemy vessels, submarines and cyberattacks may prove very efficient and difficult to prevent. Furthermore, the AO in the operational scenario is prone to higher winds and sea states.

Autonomy

Autonomous operations will allow for an increased flexibility in terms of operations. The level of autonomy shall reflect the operational need and be proportional with the task. Autonomy is not to be considered an isolated goal in itself (Maritime21, 2021, p. 50). The platform is intended to operate fully autonomous, with the possibility to override. Offensive capabilities, if present, is to be controlled by manned platforms in accordance with rules and regulations. The use of autonomous platforms will allow for a safer concept of operation by excluding humans in AO. From a safety perspective, the USV's must be able to cooperate and interact with maritime traffic.

Technology application

Technology application plays an important role in the process of procuring a new concept. This section will cover infrastructure, production, industrializing, and education of relevant personnel.

The production facilities to construct smaller ISR USV's already exist to a big extent in the civil sector, but divided into smaller, specialized environments. This will require personnel from different environments to work together, which will require allocation of resources from the Navy throughout the production process.

In terms of infrastructure, well established maintenance facilities are present throughout the Norwegian coastline. The smaller size will allow for more flexibility in terms of maintenance and dock of departure and arrival. However, the ISR technology is subject to smaller niche environments, and thus may require more consideration in terms of maintenance.

Most of the technology necessary to produce the ISR USV's already exist, and the concept is based on well known, and well tested commercial off-the-shelf technology. The necessary work is to integrate the given technology and developing procedures.

The use of unmanned platforms in the Norwegian Armed Forces is increasing. However, considering the ISR USV's is a new concept, resources must be allocated to integrate the concept into the current structure. Nevertheless, the Royal Norwegian Navy already has a well-established education system in terms of educating operators to which can process the acquired data and override if necessary.

Vulnerability and survivability

Smaller USV's are particularly vulnerable to enemy counter measures and environmental conditions. Smaller USV's are vulnerable against opposing firepower or intended collisions due to the limited ability to defend itself. In addition, the more the ISR USV platform relies on communication, the more vulnerable it will be to cyber-attacks (Savitz et al., 2013, p. 80). Furthermore, smaller USV's are vulnerable to higher winds and sea states, which will affect survivability and operational performance. Finally, the lack of sunlight and the harsh environmental conditions may cause lack of self-sustainability in the Norwegian and adjacent sea areas, and thus option 1-3 face the risk of needing support from other units to maintain presence in the AO.

Conclusion

This section has analysed the operational needs, possibilities, and limitations in order to identify the necessary operational capabilities. Considering operational ambition and today's assets it is necessary to acquire an asset which is capable of maintaining a continuous monitoring of the Norwegian- and adjacent sea areas, with emphasis on the subsurface domain. Furthermore, the concept should be capable of communicating with land or sea platforms. Moreover, the capability section must address the possibility for the ISR USV's to operate autonomously in order to counter opposing cyber-attacks. In addition, the USV's must be able to navigate autonomously in order to cooperate with seagoing traffic. Future acquisition plans do not address the need for an ISR USV capability. Nonetheless, one study by Strømmen suggests, that the capability has great potential (Strømmen, 2019). The concept will, if possible, be based on off-the-shelf technology in order to ease the integration process. However, some development will be necessary to combine the technologies. Furthermore, the infrastructure and production facilities to produce and operate are present in today's structure. The analysis has defined self-defence and signature as relevant factors. This suggests either equipping the USVs with self-defence capability or accepting the loss of a platform. The vulnerability against higher wind and sea states is considered vital with respect to maintaining operational performance and survivability in the AO. This suggests that in order to maintain survivability, it is crucial that the ISR USV's have a suitable hull, sufficient endurance, and propulsion power.

3.4. Identified capabilities for conceptual solutions

Based on the identified mission needs, the following capabilities were found as crucial in prioritised order.

Capability to conduct long-term operations in rough sea conditions

The optimized solution should be able to operate over a longer period of time without the need for supervision or resupply. Considering the AO, the vessel should optimally have self-correcting properties in order to regain stability in the event of capsizing. Furthermore, the vessel must be able to operate in sea states of 3-4 and survive in sea states of 6. In addition, the construction should be robust and have sufficient endurance to maintain continuous operations for an extended period of time without human interference. This implies that the vessel should have a capability to be self-sustainable from either wind, sun, or wave energy in addition to stored energy. Moreover, the vessel should be able to withstand shocks from waves and a construction with sufficient fatigue resistance. Bad weather can temporarily stop the platform from working, but performance and function should be resumed without human intervention.

Capability to detect and track enemy activity in surface and subsurface domain

The optimized solution should be able to detect hostile vessels on surface and subsurface domains. Tracking enemy activity implies the platform must be able to provide direction, but not necessarily pursue vessels. The included sensors should be able to identify the type of vessel on surface and/or subsurface. The solution is intended to utilise passive and/or active sonar capability to monitor subsurface domain.

Capability to operate autonomously and operational cooperation with other units

The optimized solution must resolve to a low staffing level. The concept must rely on being self-navigating (autonomic) and keeping clear of civilian traffic. All platforms should have the possibility of humans to remote control certain functions. Obtained intelligence should be processed automatically before it is shared with cooperating units and national command units.

Capability of operating with low signature

Low signature provides operation benefits in terms of staying undetected. Additionally, low signature provides better measuring conditions for potential sensors. The solution should be operating with minimal noise from propulsion and hull. The shape of the vessel should be constructed with low radar signature. Sensors should be passive, if possible, to make detection of the ISR USV more difficult.

Capability for self-defence

The optimized solution should possess the ability to initiate appropriate actions against hostile intentions. The capability should be able to act on opposing threats, either as a defensive or offensive capability.

3.5. Possible solutions

This chapter will define the already existing ISR capabilities in the Norwegian Armed Forces, commercially available ISR USV solutions, and possible solutions based on the identified capabilities.

Current ISR capabilities

In order to maintain classification level, the definition of current capabilities is kept on a general level, and thus will be difficult to compare in a non-classified thesis.

Current assets are able to conduct ISR operations in certain area for a limited time. Among some of the assets that is currently available in the Norwegian Armed Forces are:

- Surface and subsurface vessels in the Royal Norwegian Navy with towing capability
- Helicopters with folding light acoustic system for helicopters (FLASH) technology.
- P-8A Poseidon, maritime patrol, and reconnaissance aircraft.
- Smaller land and coastal based ISR units.
- Satellite capabilities in cooperation with allied nations.

These assets are of relevance when deciding which conceptual alternative that will best fit the operational need. In terms of missing assets and based on the recent termination of the NH90 contract (The Norwegian Ministry of Defence, 2022), the use of ISR USV’s to monitor and track subsurface traffic in an anti-submarine warfare (ASW) setting may be of high relevance to the Royal Norwegian Navy in the future. The ISR USV’s are not intended to replace any of the given assets, but rather a potential supplement.

Commercially available ISR USV solutions and technology application

Today's ISR USV solutions are still under development. A small number of USV concepts have been implemented in some country's defences, but it is reasonable to believe that most of the concepts need 5-10 years before complete implementation. Strømmen has addressed in his article the idea, that certain technologies may become irrelevant with the development of long-range, highly advanced systems.

> *"Technological developments, especially within hypersonic missiles, energy weapons, autonomous systems and electronic countermeasures, means that many traditional weapon and sensor systems are or will come more or less irrelevant within a few years"(Strømmen, 2019, p. 18).*

A platform with one purpose can become obsolete as technologies develops, modular solutions are therefore something that should be considered.

The following commercially available USV's are examples of platforms from the civil sector that may be able to supplement current assets or be further developed to fit a military application on a short notice. See attachment A for a comprehensive description of the concepts.

1. Mariner X
2. Wave Glider
3. Saildrone Explorer
4. SEA-KIT-H
5. PROTECTOR

Possible solutions based on identified capabilities

Based on the idea phase conclusion we will define four different alternative solutions with respect to the identified capabilities. Given that one of the derived goals of this thesis is to address cost-effective USV's to free up today's resources, the thesis will not include option 4: Actions that entail large new investments in accordance with the PRINSIX format. All the given alternatives are expected to handle the same sea conditions in the AO. Option 1-3 will address different conceptual solutions based on the idea of an ISR USV and will thus not involve the integration of non-USV concepts.

Option 0: Continuation of current assets. (status quo)

The alternative involves not acquiring ISR USV's but maintaining the current structure for monitoring Norwegian- and adjacent seas.

Option 1: Small, passive ISR USV's in large numbers.

This solution of the ISR USV's is to employ a swarm concept which envisages a more affordable alternative in large numbers of platforms with the ability to passively detect and locate activity in the subsurface and surface domain. Option 1 will utilise a passive towable sonar system, with deployable sonobuoys (Holler, 2013, p. 322). Once a hostile platform is identified, a manned platform is tasked with tracking and dealing with threats. The platform will utilise a passive low signature design rather than being equipped with offensive self-defence capabilities. Each ISR USV is autonomously navigating, cooperating, and providing intelligence with the opportunity to override control. Operations are monitored from control centres at sea or land.

Option 2: Small, active ISR USV's in limited numbers.

This solution relies on a smaller number of platforms with passive and active sensors to search for subsurface threats. With active sensors the platform should search, verify, and follow a threat until a manned platform could overtake operations. Option 2 will utilise a passive towable sonar system, with deployable active sonars similar to FLASH sonars which is actively used by Maritime Helicopter capabilities like NH90 (Rekstad, 2022). Furthermore, option 2 will employ a passive low signature design rather than being equipped with offensive self-defence capabilities. Operations are monitored from control centres at sea or land.

Option 3: Small, active, robust ISR USV's in limited numbers with offensive capabilities.

This solution envisages a robust ISR USV capable of dealing with enemy countermeasures. Each vessel operates autonomously with capabilities to primarily track subsurface activity and defend against surface threats on command. Option 3 will, similar to option 2, utilise passive towable sonar systems along with deployable active sonars similar to FLASH sonars. Furthermore, option 3 will utilise a passive low signature design in combination with offensive self-defence capabilities. The demand for a stable platform for mounted offensive capabilities will require a slight increase in size. Operations are monitored from control centres at sea or land.

Initial discussion of hull and propulsion

Based on the idea phase and identified conceptual capacities, the most relevant hull and propulsion options are subject of discussion in this section. To present a smaller working USV concept, the right choice of hull and propulsion is crucial.

Hull

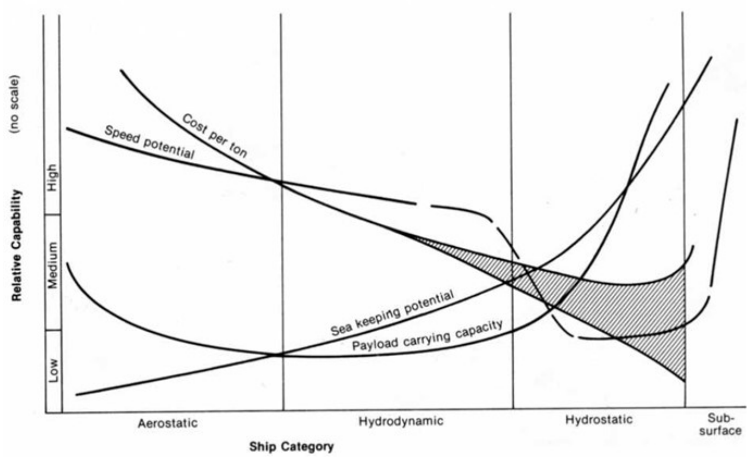


Figure 5: Relative performance and associated capabilities of the ship (Gillmer & Johnson, 1982, p. 10)

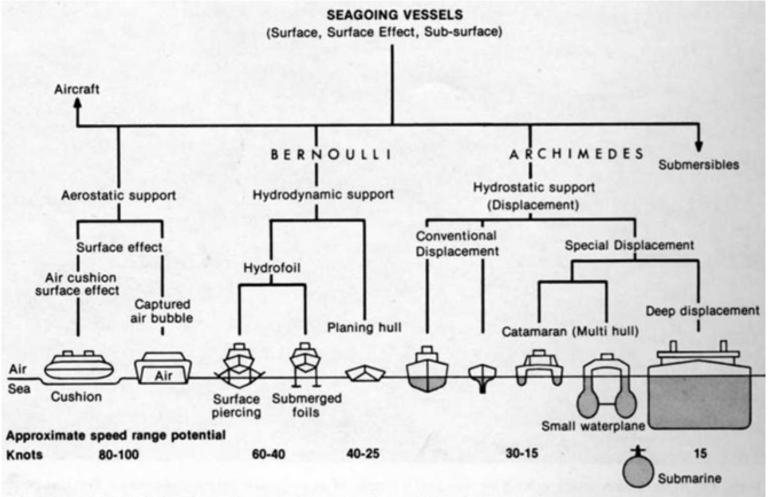


Figure 6: Categories of Seagoing Vessels According to mode of Support (Gillmer & Johnson, 1982, p. 8)

Hydrostatic conventional displacement hull

A conventional displacement hull is one of the most common hulls. The advantage of conventional displacement hulls is, that they often provide good seakeeping potential and decent payload capacity. The disadvantage of conventional displacement hulls is that they make it difficult to achieve higher speeds in comparison to catamaran and planning hulls. Conventional displacement is often associated with cheaper production costs and more robustness than catamaran hulls. One can also argue, that displacement hulls bear resemblance to a traditional fishing vessel, this which is positive in terms of signature in a military application.

Hydrodynamic catamaran hull

Smaller catamaran hulls are often used for passenger and work vessels. The advantage of catamaran hulls is, that it provides good stability in calmer seas, high speed, and better loading properties than conventional displacement hulls. The disadvantage of catamaran hulls is bad stability in higher sea states (Lundby, 2014, pp. 3-20). Catamaran hulls are often more expensive to manufacture and more difficult to repair in case of damage.

Hydrodynamic Half-planing and planing hulls

Planing hulls are used by vessels with a need for high speeds. The advantage of planing hulls is that they can provide low resistance and increased range if the propulsion method provides enough power to propel the vessel, so it planes (Lundby, 2014, pp. 3-21). The disadvantage of half-planing and planing hulls is that they require a lot of energy if they do not sail at planing-speeds. Half-planing and planing hulls may be cheaper than catamaran hulls but more costly than conventional displacement hulls.

There are few aerostatic supported hulls in existing USV platforms. Nonetheless, there are smaller USVs projects using multihulls, these types of hulls will not be included, as it often requires a lot of development.

Conclusion

Based on the above discussion, it is recommended to go with a Hydrostatic conventional displacement hull. The concept is intended to work in higher sea-states and the displacement hull could provide a more robust, affordable design. In addition, considering the platform is intended to operate in the lower spectre of speed, the displacement hull will be sufficient. Finally, the use of a displacement hull may cause for a signature that resembles a fishing vessel, which is considered a positive contribution in a military application with respect to signature.

Propulsion

This section will cover rough technical considerations with respect to propulsion and drive train. The drive train can be separated into a mechanical and electrical part. Furthermore, the propulsion can be separated into electric, hybrid and combustion solutions. The following list consists of the relevant configurations with respect to the design of a smaller ISR USV.

Electric

The choice of using an electric drive train involves the use of stored energy in form of batteries. This solution is intended to have a battery package, with an electric machine and is intended to be self-sustainable, with the possibility to recharge batteries during operations with solar, wind, or wave energy. In addition, the use of an electric system gives more freedom in terms of placing the components in the vessel. Furthermore, an electric configuration may provide a lower acoustic signature. Electrical solutions may also pose the most environment-friendly solution.

Hybrid

The hybrid solutions are considered a combination of combustion and electrical drive trains. A common configuration is the use of generators to recharge the batteries, and the use of an electrical machine to drive the propulsion. This setup will require more space, as it needs the capacity for fuel storage and battery packages. In addition, this solution may not be 100% self-sustainable. On the other hand, the use of a hybrid solutions may allow for more redundance, and thus prove more reliable in case of emergency. Furthermore, the use of a hybrid system will allow for reliability in terms of endurance if sustainable energy is absent.

Combustion

Mechanical solutions are considered direct or geared solutions, or a combination of direct and geared solutions for combustion engines. This configuration will primarily consider the use of diesel, hydrogen, or methanol in direct or geared solutions. The use of traditional combustions engines has the advantage of being robust, reliable and have a high efficiency. Furthermore, in a combustion setup, a shaft generator, or a separate generator to produce energy will be necessary to maintain sensor operation. The use of combustion engines may allow for more endurance compared to electric solutions in cases where self-sustainable energy in form of solar, wind, and wave energy is absent. However, if solar, wind, and wave energy sources are available, the electric or hybrid solution may allow for longer endurance. Finally, the use of traditional combustion engines may cause for a higher emission and acoustic signature.

Conclusion

Based on the above discussion, it is not recommended to go with a purely electric solution. One of the main concerns of the use of a smaller USV is that of endurance, where presence in the AO is considered a high priority. Considering the environmental conditions in the AO, gathering energy from solar, wind, and wave power is considered insufficient most of the year. Furthermore, “Electrical propulsion needs more power to achieve the same speed compared to mechanical systems” (Strand, 2020, p. 15). This points towards the use of a traditional combustion or hybrid solution.

3.6. Trade-off analysis

The trade-off analysis will discuss the different alternatives with respect to its ability to handle capabilities, technology application, degree of autonomy, possible modularity, and cooperation with others. All the given alternatives are expected to be fully operational in sea states 3-4, and survive in sea state 6, and thus the sea-keeping abilities is not to be discussed in this section.

Option 0: Continuation of current assets

Relative to the other alternatives this solution relies on already existing assets and do not develop today's capabilities regarding ISR operations. At some point in the near future, it might become necessary with more investment in new technology, midlife upgrades, new platforms or raised autonomic levels. However, the current capabilities do not need development of new infrastructure, production and education systems compared to option 1-3. Today's assets have relatively high capability within detecting and tracking enemy activity in surface and subsurface domains. Additionally, they provide high self defence capability. In terms of ISR capabilities, satellite, and maritime aircraft's ISR operations is somewhat limited in bad weather. Surface vessels with high staffing levels are very capable of ISR operations in bad weather but limited in numbers and endurance. Low numbers confine ISR operations to a smaller AO. Platforms with low autonomy and high staffing are resource intensive and considered costly. With great seakeeping capabilities, today's solutions are, to a greater extent, more flexible to carry out other types of tasks than ISR operations. In addition, the ability to cooperate with others are considered high.

Option 1: Small passive ISR USV in larger numbers

The first alternative addresses the possibility to employ a larger amount of small, passive ISR USV's to utilise a swarm intelligence concept. The passive nature of option 1 may allow for a higher level of autonomy compared to option 2 and 3, with pre-programmed operational profile. However, the platform is not utilizing AI and thus will require human override in certain situations. The first alternative is intended to operate with a towable passive sonar, deployable sonobuoys on demand, and a low signature construction, and thus will be able to operate with a lower signature compared to option 2 and option 3 with active sensors. On one hand, the passive sensors may prove a lower operational capability in terms of detecting activity in the subsurface domain compared to option 2 and 3. On the other hand, the increased number of platforms and deployable sonobuoys may allow option 1 to cover a greater area. Furthermore, option 1 will not have the same capability to act on offensive counter measures against the vessel compared to option 3. Finally, the concept of deploying sonobuoys already exist as a capacity in today's asset, and thus the procedures of operation and cooperation with other assets in the Royal Norwegian Navy already exist.

Option 2: Small active and passive ISR USV in limited numbers

The second alternative addresses the possibility to employ a limited amount of smaller active and passive ISR USV's with the capability to detect and trace targets of interest for a limited time. In terms of conducting long-term operations, the vessel will have a somewhat lower endurance due to the energy consumption of the active sensors. In comparison, option 2 can provide extended information about targets of interest by deployable active sensors and communicating live data to control centres at sea or land while following the target. Furthermore, the degree of autonomy for option 2 will be slightly lower due to the deployable active sensors. In addition, option 2 will have a higher signature than option 1 due to the active sensors. However, one of the disadvantages of option 2 is the increased cost, and no additional capabilities of self-defence against hostile actions compared to option 1 and 3. The use of FLASH technology from the recently discontinued NH90 capabilities may allow for an ease of integration, considering the procedures of operations and cooperation with other capabilities in the Royal Norwegian Navy already exist. Consequently, the implementation of technology intended for helicopter into USV's may cause for an increased development phase.

Option 3: Small active and passive ISR USV in limited numbers with offensive capabilities.

The third alternative addresses the possibility to employ a limited amount of slightly larger ISR USV's than option 1 and 2 with passive towable and active deployable sensors in conjunction with offensive capabilities. In terms of conducting long-term operations, the vessel will have lower endurance, compared to the other alternatives due to the energy consumption and weight of the active sensors and offensive capabilities. Similar to option 2, option 3 will be able to provide an extended amount of information about potential targets compared to option 1, with an increased ability to verify targets due to the active deployable sensor. What set option 3 apart from the other alternatives is its offensive capabilities, and ability to defend against hostile actions. By extent, option 1 and 2 will require a slightly lower level of autonomy in order to safely conduct offensive operations. Thus, the platform will require more manned stations in order to supervise operations due to the offensive nature of the platform. In addition, the ability to both carry out ISR operations, and act on hostile intents will make the platform more complex in construction and operation. The complex construction may require more resources in the construction phase, by combining small niche environment, compared to option 1 and 2. However, the offensive platform is flexible and may allow for a broad selection of armed capabilities, thus making the platforms slightly more modular.

3.7. Risk assessment

This section will cover an in-depth analysis of the risk involved by going forward with the alternatives. The chosen approach will address the risk of procuring the alternative concepts with respect to performance, costs, and time investment.

Option 0: Continuation of current assets

In terms of performance, the risk involved by moving forward with option 0 is the risk of halting the development of ISR capabilities within the Royal Norwegian Navy. Today's asset is capable of conducting ISR operations in a limited area, for a limited time. However, the risk of not meeting future demands is high. Furthermore, manned platforms in today's asset are subject to reduced endurance due to human limitations (Hareide et al., 2018, p. 3). Option 0 may be subject to increased cost by maintaining today's asset in ISR operations. The investment cost may be disregarded due to the capability already existing. However, it will be necessary with life-cycle costs and upgrades of current platforms in order to maintain the capability to conduct ISR operations in the future. Furthermore, option 0 relies on the use of manned platforms, to which may pose a risk of human lives. However, allocating today's assets towards ISR operations represent an increasing risk of wasting potential manned assets

Option 1: Small passive ISR USV in larger numbers

Making sure the USVs work seamlessly with the current structure may pose the biggest risk in regard to performance, cost, and time. Furthermore, the risk is high with option 1's small hull, reducing seakeeping abilities in bad weather. The use of exclusively passive sensors may also affect the USVs ability to detect enemy activity in subsurface domain. Implementing passive sensors gives the ability to detect activity, but not directly locate positions. However, the effect of using unmanned platforms still gives an advantage in covering larger areas with less use of human resources. The alternative also increases redundance with implementing a larger number of platforms. Implementing acoustic sensors on the ISR USV may be expensive. Sonobuoys is already commercially available and thus reduce risks for additional costs. A larger number of simple platforms may simplify production and maintenance, and thus reduce the risk of increased procurement costs. Furthermore, the smaller vessels could be berthed at normal marinas reducing the need for investment in expensive infrastructure. Option 1 relies on commercially available state-of-the-art technology, and therefore reduces the risk connected to implementation and development time.

Option 2: Small active and passive ISR USV in limited numbers

Integrating several moving parts in towable sensor types on an ocean-going USV increases the risk of poorer performance. Higher consumption with active sensors creates a risk of not meeting requirements in relation to range. Using the well-known Flash sensor reduces the risk of poor interoperability in collaboration with today's ISR assets due to already established procedures for operation. Procurement of several advanced sensors increases the risk of higher costs in regard to operation and maintenance, which may make the whole concept more expensive. An active sensor may cause for a higher level of education, and increase dependency of well-trained sonar operators, to which may prove a risk in terms of cost and time. Option 2 will, similar to option 1 and 3, seek to utilise commercially available state-of-the-art technology in order to reduce the risk connected to implementation and development time. However, the use of active sonars may call for a higher level of infrastructure in terms of facilities for sonar operators and other units and actors and thus increase the risk of spending more time on the procurement project.

Option 3: Small active and passive ISR USV in limited numbers with offensive capabilities.

In terms of performance, the offensive capabilities may prove a higher operational capability in wartime scenarios and by extent reduce the operational risk. Furthermore, the ability to protect itself against hostile actions may also reduce risk of losing the platform and by extent reduce economic risk. Procuring a comprehensive system with passive sensors, active sensors, and offensive capabilities will produce a more complex system. The more complex system may in turn cause for a higher economic and operational risk should one of the systems fail to operate as intended. In addition, the use of both passive, active and offensive capabilities will result in a higher consumption and thus face a risk of not meeting the requirements with respect to endurance in AO. The implementation of passive sonars, active sensors, and offensive capabilities may require a higher level of education and increased dependency of well-trained sonar operators. The increased requirements may prove a risk both in terms of cost and time by entering an extensive development phase. Option 3 will, similar to option 1 and 2, seek to utilise commercially available state-of-the-art technology in order to reduce the risk connected to implementation and development time. However, the use of active sonars and offensive capabilities may call for a higher level of infrastructure in terms of facilities for sonar operators, operators of offensive capabilities, and other units and actors. Consequently, the requirement of infrastructure may increase the risk of spending more time.

3.8. Points of decision

This section will gather all the sub-conclusions from the trade-off and the risk assessment, in order to form a basis for decision. The following points is to be decisive: Performance, cost, time, and risk analysis. Risk analysis will be further divided into performance, cost, and time.

The trade-off analysis has made a comparison of the given solutions with respect to the identified capabilities, technology application, degree of autonomy, possible modularity, and cooperation with other units. In terms of handling long term operations in rough sea conditions, each alternative is expected to handle the same sea-states. However, alt 1 will be able to conduct longer operations, compared to option 2 and 3, due to the increased energy consumption by the use of active sensors on option 2 and 3, and offensive capabilities on option 3. From a perspective of conducting ISR operations, option 2 and 3 may be able to gather an extended amount of information compared to option 1. However, due to the reduced number of platforms intended for option 2 and 3, the ISR performance is a matter of quality vs quantity. On one hand, the increased quantity may allow for a better coverage of the AO. On the other hand, the increased quality of option 2 and 3 may perform better. In terms of operating autonomously and cooperate with other units, option 3 will diverge slightly from option 1 and 2 in sense that it will need to coordinate and be controlled by an operator in order to carry out offensive actions. Furthermore, both option 2 and 3 will be operating with active sonars, and thus will produce higher signature than option 1 which will operate with only passive sonars. The only platform with dedicated self-defence systems is option 3, to which is the only alternative which can defend against hostile actions. Relevant infrastructure and education systems to operate, manufacture, and the ability carry out maintenance are present in the current infrastructure. In addition, option 1-3 will require a greater amount of planning in terms of integrating off-the-shelf technology during construction and establishing procedures of operation.

Due to the scope of task and size of the vessel, modular solutions can be a compromise between the ability to solve the given task in an optimal way versus the ability to handle modular solutions in a less optimal way. The thesis will therefore assess the appropriateness of modular solutions with regard to the use of different relevant technologies within the category of sensor packages and offensive capabilities. Nevertheless, a modular solution is very appropriate in terms of development in the future where efficient use of resources is desirable.

The risk assessment has made an analysis of the risk involved by moving forward with the alternatives and is intended to make the base for a recommendation in the points of decision section. In conclusion, the risk with respect to performance is considered higher on option 1 given that the platforms have less operational capability compared to option 2 and 3. However, the apparent higher level of complexity in option 2 and 3 may cause for a higher risk of not meeting the operational ISR requirement. Furthermore, the risk of cost appears to be higher in option 2 compared to option 1 and 3, given the lower cost of option 1, and option 3's ability to defend against hostile actions. In addition, option 2 is slightly more exposed to hostile actions than that of option 1 with passive sensors, making it harder to detect. Furthermore, the risk with respect to time is considered higher in option 3, given by the risk of entering an extensive development phase due to the complex nature of the platform with both passive and active sensors in conjunction with offensive capabilities. Finally, the use of commercially available state-of-the-art technology on option 1-3 will reduce the risk with respect to time by easing the process of implementation and thus reduce development time.

3.9. Recommended conceptual solution

This concludes with a recommendation of moving forward with option 1, a smaller ISR USV platform with a passive towable sonar in conjunction with deployable sonobuoys.

Furthermore, the CP recommend utilizing a conventional hydrostatic displacement hull in order to maintain seakeeping abilities and utilise a heavier payload with towing capabilities.

Finally, the CP recommend implementing a hybrid solution, with electric drive train, supplied with one generator in order to maintain redundance and operational capability throughout the AO all year round. It is not recommended to develop a solution that relies on renewable energy in form of solar power. The nature of the AO implies that solar energy is unavailable, and at times insufficient, the majority of the year.

The CP do not recommend developing a modular solution. Modular solutions have a higher risk of not meeting the operational requirements and may reduce performance. Consequently, it is recommended to develop a specialized solution, with the possibility to upgrade and replace ISR capabilities within the category of towable sensors and deployable sonobuoys.

Option 1 with passive sensors may have a slightly higher risk in terms of performance. However, the cheaper price and the reduced signature may allow for a lower risk with respect to cost. Moreover, the risk of entering an extensive development phase is considered lower, due to the commercially availability of state-of-the-art technology and the ease of operation, production, and maintenance with today's infrastructure.

3.10. Conclusion

The CP has analysed capabilities and mission needs for the ISR USV alternative, and further derived it into 4 options based on the identified capabilities for the conceptual solutions. Based on the discussion, risk assessment and points of decision it is recommended to move forward with option 1, Small ISR USV's with a towable passive sonar in conjunction with deployable sonobuoys. Furthermore, it is recommended to move forward with a conventional hydrostatic displacement hull and a hybrid propulsion configuration.

4. Definition phase

The definition phase (DP) will specify the technical considerations for the chosen conceptual solution based on identified capabilities, functional- and non-functional demands and requirements. Furthermore, the DP will continue with a preliminary design solution as a reference point for further optimization through a trade-off analysis of different solutions, and a parametric study before presenting a final optimized design solution. In conclusion, the output of the DP is an optimized design based on the parametric study and a recommendation for further work. Due to the magnitude of the thesis, the definition phase will be limited to two rounds in the design spiral.

Due to relevance in field of study, magnitude of the thesis, and time available, the following aspects will not be addressed by the DP:

1. The safety aspect with respect to the PRINSIX method.
2. Comprehensive calculations on electrical components
3. Comprehensive calculation on sensors.
4. Technical aspects of autonomous navigation and operation.
5. Technical aspects of manoeuvrability, including rudder and navigation.
6. Technical considerations about bearings, more specifically thrust bearings.
7. Physical model testing.
8. Technical considerations with respect to mooring.
9. Identified capability to self-defence.
10. Operation of ISR and communication capabilities.

4.1. Summary

The DP started off with specifying the preliminary capabilities and requirements for the chosen conceptual solution. Furthermore, a preliminary vessel was chosen as a reference vessel. The chosen reference vessel was then subject of a trade-off analysis with respect to alternative solutions for hull, propulsor, drivetrain, energy producers, and energy storage. The preliminary design solution was then deducted through a parametric study based on the preliminary capabilities and requirements, and the parameters in the design spiral. Moreover, a set of optimized parameters and a final optimized solution was presented and further analysed with respect to a weight breakdown, cost assessment, and a risk assessment. Finally, a recommendation was made based on the findings in the points of decision and the associated risk analysis. In conclusion, the recommendation is to not move forward into a development- and completion phase, judging the current state of the vessel. Further optimization is essential to reduce the risk of procurement.

4.2. Conclusion and recommendation from concept phase

The CP concluded with a recommendation to move forward the option 1, a small ISR USV with a towable passive sonar in conjunction with deployable sonobuoys. Furthermore, the DP recommends moving forward with a conventional hydrostatic displacement hull, and a hybrid propulsion configuration. The choice was based on the relevant capabilities and missions needs for the chosen alternatives.

4.3. Preliminary capabilities and requirements

Based on the identified capabilities in the CP, the preliminary capabilities and requirements will be derived into functional and non-functional requirements. The rules and regulations with respect to development and operating USV's is still in a development phase, and thus is regarded as guidelines.

Conduct long-term operations in rough sea conditions	
The USV must be operational during long-term operations and rough sea. Must be fully operational in sea state 3, reduced functionality in sea state 4 and survive sea state 6.	Vessel must endure 20 days of operation or 1400 nautical miles fully operational, in sea state 3. Vessel must endure 10 days of operation in sea state 4 with reduced functionality. Vessel must be able to survive sea state 6 for 3 days, and resume operations in sea state 4. The vessel performance will be tested in accordance with requirements at a later stage in the development phase.
The USV must be able to conduct long-term operations	The vessel must be able to transit in 7 kn in sea state 3.

Vessel needs enough stored energy to meet demand of prolonged operations	The vessel must be able to tow the sonar in 5kn in sea state 3. The vessel must have enough fuel to endure 1000 nm in a 5 kn towing condition in sea state 3.
<u>The USV must self-right in bad weather</u> The smaller vessel will need to self-right in harsh weather conditions.	GM must be >0 in all loading conditions. GZ must be >0 for all angles of heel from 0-180° Hull must be sealed and tested after production.
<u>The hull needs enough strength, endurance, and fatigue to withstands rough seas</u>	The hull material must endure shock and maintain strength in sea state 3-4 and survive sea state 6. Selected material will be tested according to appropriate standards in the development phase.
<u>The USV must be able to operation in sub-zero climate</u>	The vessel must be equipped with defrost-capability on deck. Functionality maintained down to -20°C in arctic conditions. Superstructure surface area must be limited to prevent destabilisation from icing.
<u>The USV must handle internal threats</u> Operating unmanned the vessel needs systems to compensate for internal threats. Specifically firefighting and disrupted power generation.	The internal firefighting system must be tested to extinguish internal fires. A second source of power must supply the vessel 12 full hours in case of disrupted power generation.
<u>The ISR USV must be able to navigate autonomously.</u> Requires suiting navigational systems and computer processing.	The vessel must be equipped with suitable navigation system and data processing units. Essential in terms of other requirements but will not be addressed in this thesis.
<u>Survivability and vulnerability</u> The vessel must have sufficient redundance	The vessel must have two drive trains or means of propulsion.
Detect and track enemy activity	

The USV must be able to handle ISR operations	The vessel must be equipped with passive towable sonar. The vessel must be equipped with deployable sonobuoys. The vessel must be equipped with camera for surface detection and navigation. Sensor and processing equipment must be tested and verified in terms of being able to detect submarines. See appendix B for information on sensors.
The USV must be able to tow sonar at 5 knots velocity	Towing operations including manoeuvrability must be tested and verified in 5 knots velocity in sea state 3 as reference condition.
Autonomy operations and cooperation with other units	
The USV must communicate with national and allied command structure.	Must be able to cooperate with existing ISR assets. Sensor performance must be verified by testing. Will not be addressed.
The USV must cooperate with manned platforms	The USV control unit must be able to communicate with other units and actors in AO. See appendix B for sensor specifications.
Signature	
The USV must have low acoustic signature	The vessel's acoustic signature from hull and propulsion for 5 kn towing condition in sea state 3 must be mapped.
The USV must have low sensor signature Data communication must transmit data in ways to stay hidden or show presence in AO.	Will not be addressed. The vessel must be measured for signature control with hull, propulsion, and all passive sensors active.

The USVs superstructure must have low radar signature	Vessel's superstructure must be designed and mapped to ensure low radar signature In order to keep low profile in AO it is important to keep radar signature low.
Low electric and magnetic signature	Electric and magnetic signature must be mapped and if necessary enclose relevant components.

Table 2: Preliminary capabilities and requirements

4.4. Preliminary design solution

In order to arrive at an optimized design solution, we must choose a reasonable starting point that can be optimized as the process progresses.

ISR capability

In order for the ISR USV to do ISR operations it will need a suitable sensor. This thesis will not address the choice of sensors. See appendix B for a description and justification of the selected sensor.

Estimated drag force on object, 5 knots with tow.	Force
F_d on 280 m cable, diameter 18,5 mm	403,94 N
F_d on 250 m sensor, diameter 40 mm	535,29 N
Summary	943,23 N / 0,9 kN

Table 3: Estimate drag force (Appendix B)

Calculations estimate a drag force of 0,9 kN during 5 knots towing in calm waters. We will add 20 % increased resistance to account for additional resistance from waves and weather. The chosen passive sensor requires an estimated 1,8 meters width to fit the vessel.

Hull

Firstly, in naval engineering Length / Beam ratio is used to describe a vessels dimensions and characteristic. Higher L/B ratios provides a longer and leaner hull with less wave-making resistance. Wave resistance does not introduce an absolute speed limit for the hull, but a speed limit where the wave resistance increases non-linearly and thus increase power consumption. When the hull-length is short, the hull experiences increased wave resistance at lower velocities. Less resistance is important for our vessel to keep fuel consumption low. L/B ratio 4 to 6 is optimal to get a slim hull with low total resistance.

Secondly, if the beam of the vessel is too small, the waterline area will be small and further affect the vessels initial stability negatively. The preliminary design tests a beam of 2,8 meter and L/B ratio 4.

$$\frac{L}{B} = 4 \rightarrow L = 2{,}8\,m * 4 = 11{,}2$$

Using the formula below, the potential velocity for a hull with waterline length 11,2 m (in feet) is calculated.

$$V_{Hull} = 1{,}34 * \sqrt{L_{Waterline}} \rightarrow V_{Hull} = 1{,}34 * \sqrt{11{,}2 * 3{,}28} = 8{,}1\ knots$$

Calculating V_{hull} gives us a potential maximum speed of 8 knots. As concluded in the concept phase we have recommended to go with a conventional displacement hull. Due to limited time, we have opted to go for a hull known for being the workhorse of oceans. A trawler towing marine tools from the stern. A stern trawler provides a larger displacement hull with relatively good sea going capabilities. Using Deltftship Pro online model database we found several stern trawler designs made by M. van Engeland. Furthermore, we have used DELFTship Pro to scale his stern trawler design according to the below mentioned parameters.

Parameter		Size
Design length	L	10,8 m
Length waterline	L_{wl}	11,553
Beam	B	2,8 m
Potential hull velocity	V_{hull}	8 knots
Draft	T	0,96 m

Table 4: Preliminary hull parameters

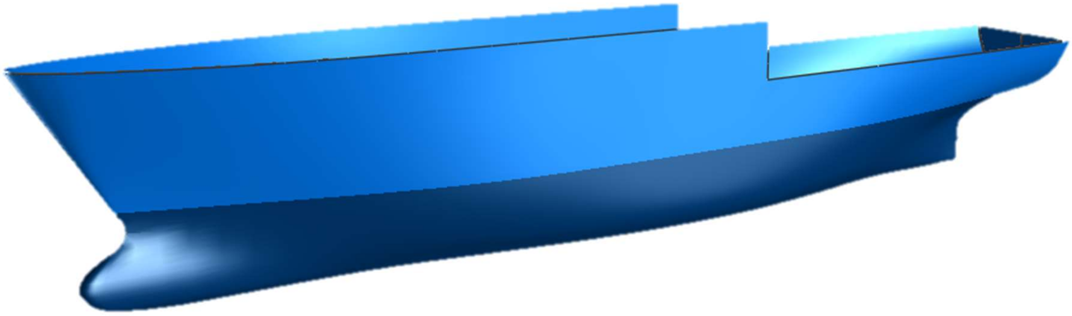


Figure 7: Screenshot from DELTHship

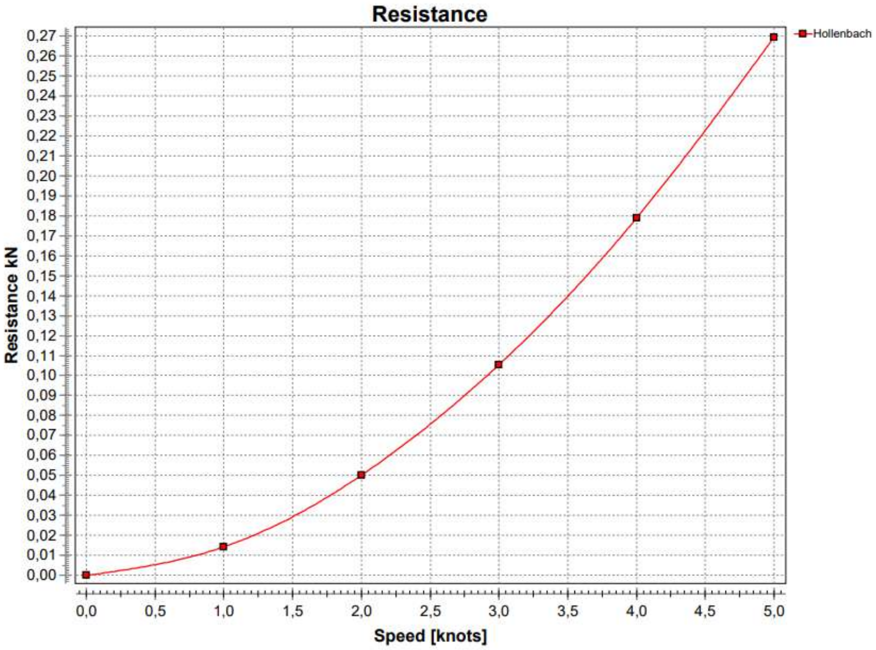
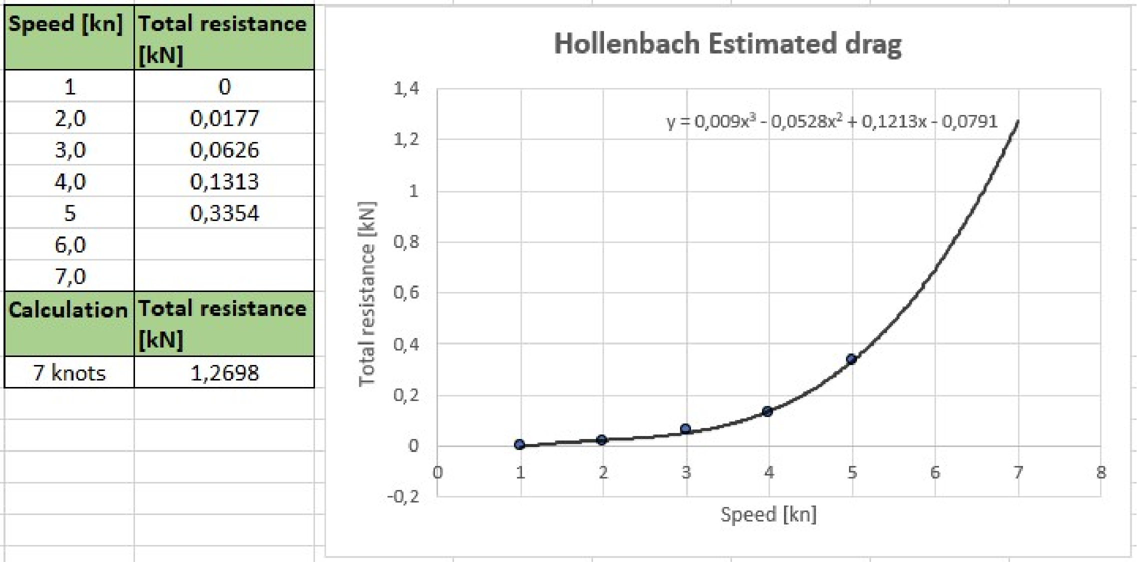


Figure 8: Hull drag resistance (Appendix C)

Figure 8 shows the drag resistance for the chosen hull using the Hollenbach method for estimating resistance (Hollenbach, 1998). The Hollenbach method would in this case not go higher than 5 knots. In order to meet the preliminary requirement to transit in 7 knots an approximation has been made. Furthermore, figure 9 shows the estimated drag based on the numbers from figure 8.



Speed [kn]	Total resistance [kN]
1	0
2,0	0,0177
3,0	0,0626
4,0	0,1313
5	0,3354
6,0	
7,0	
Calculation	**Total resistance [kN]**
7 knots	1,2698

Figure 9: Estimation of drag 7 knots (Appendix C)

4.5. Alternative solutions

This section will address the various parameters in the design spiral and discuss different alternative solutions. Each parameter will be defined in the given order, considering the relation between the parameters, and how all the factors affect each other. The economic factor will not be governing in this section, where technical functionality is prioritised and central in the technical considerations. However, a rough estimation of cost shall be presented after presenting the optimized solution. Based on experience, the following systems and sub-systems are to be investigated. The weight estimate of each component will result in a weight calculation that gives feedback for the parametric study.

- Hull
    - Material
    - Superstructure and self-righting ability
- Propulsion system
    - Choice of propulsor
    - Drivetrain
    - Electrical engine
    - Generator
- Energy Storage
    - Consumers
    - Fuel and operational profile
    - Lubrication oil
    - Battery
- Alternative solutions not technically considered
    - Rudder
    - Navigation
    - Autonomy, control, and communication.

Hull

Hull material

The preliminary requirements describe the need of a hull material with high endurance and low acoustic signature. Furthermore, the stability requirement dictates that the hull must be self-righting. Regardless of material choice, the hull's centre of gravity will be in the same location, but the weight of the hull decides how easy it is to shift the vessel's centre of gravity downwards. The lowest possible centre of gravity is desirable for a self-righting hull.

Material	Density [kg/dm^3]	E modulus [GPa]	Cost estimates [€/kg]
Steel	7,8	210	0,6
Marine Aluminium	2,7	72	2
Sandwich-composite (woven glass fibre reinforced glass)	1,7	20	3.3

Table 5: Properties of example materials ***(Pflug, Vangrimde, & Verpoest, 2003, p. 3)***

A hull made of steel would provide a strong, fatigue- and puncture-resistant hull. On the other hand, steels density would add so much weight that the vessel's loading capacity would be greatly reduced. Furthermore, steel gives a higher acoustic signature and maintenance cost than most materials. On the other hand, acquisition and production cost of a steel hull would be cheaper relative to other materials.

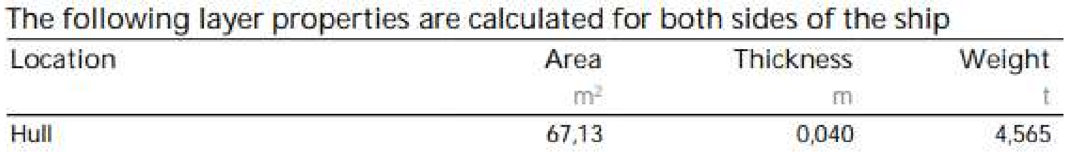
A hull made of marine aluminium would provide less strength and fatigue compared to a steel hull. Furthermore, marine aluminium would give a higher acquisition and production cost. On the other hand, maintenance cost and fatigue strength is considered lower compared to steel hulls (Samatham, Naik, Reddy, & Kumar, 2018, p. 6). The properties of aluminium means that it does not corrode like a steel hull, but it is nevertheless susceptible to galvanic corrosion. In regard to acoustic signature, steel and aluminium hulls are considered the same, but the load capacity with aluminium would be better.

Composite materials with its low density have a relatively high strength and stiffness in relation to weight. Composite alone is weak towards fatigue stress, UV-light and colder temperatures. By contrast, composite can be used in a sandwich construction allowing for optimalization based on need. According to SINTEF (Pedersen, Stokke, Amble, Friberg, & Lønseth, 2005, p. 31) ”…composite in sandwich can be characterized by high strength and stiffness, very low weight, good thermal and acoustic insulation and high damage resistance”. Sandwich-composite properties is on the other hand highly dependent on chosen material, fibre orientation and production. Compared to steel and aluminium, the hull is considered to have lower maintenance costs, but high production and acquisition cost.

In the Royal Norwegian Navy (RNN) steel hulls are used on the Nansen-class frigates, aluminium hull on the Seabear 25 MK-3 and a composite-sandwich on the Skjold-class corvettes (Andersen & Stokke, 2004, p. 33).

There are several factors to consider when choosing a hull material. Initially, we have considered three different materials with regard to density, strength, acoustic properties, cost of maintenance, production, and acquisition. In order to keep the loading capacity high and acoustic properties low the choice landed on a sandwich composite with rigid PVC foam in the core and fiberglass-reinforced thermosetting plastic in the skin laminates. This material is used by the RNN in their Skjold class corvette.

In order to calculate an initial hull weight, the hulls girders are smeared into the overall hull, making the mean hull thickness greater. Girders needs to be addressed further before construction. As an estimate, the density of woven glass fibre reinforced glass is used to calculate the hull's weight in DELFTship. With mean hull thickness at 4 cm, DELFTship calculates a total weight of 4,565 tonne. A weight of 4,565 is considered high for a sandwich-composite hull but allows for the inclusion of many longitudinal and transverse girders on a later stage.



The following layer properties are calculated for both sides of the ship

Location	Area	Thickness	Weight
	m^2	m	t
Hull	67,13	0,040	4,565

Figure 10: Screenshot DELFTship weight estimate

In lack of specific pricing, the price is based on standard price for woven glass fibre reinforced plastics. A cost price of 3,3 €/kg (table 4) gives a material cost estimate of 15 000 euros or 158 000 NOK. Additional costs in manufacturing is to be expected.

Hull superstructure and self-righting ability

The preliminary requirements require the hull to be self-righting. According to Hakan (Aktildiz & Simsek, 2016, pp. 46-47), a self-righting hull must fill three fundamental requirements:

- Positive GZ curve throughout the full 360 degrees’ rotation.
- Become unstable when inverted to initiate the righting process until the vessel turns upright again.
- Remain buoyant and watertight.

In order to keep the vessel self-righting, the vessel needs to be properly shape, ballasted, and sealed. The design must create a superstructure that provides instability when the vessel is upside-down. Secondly, the vessel needs heavy ballast near the keel to keep centre of gravity low in all loading conditions. Thirdly, the vessel needs to be buoyant and watertight. A watertight hull can be fixed with implementing effective one-way mechanical ventilation systems for all openings.

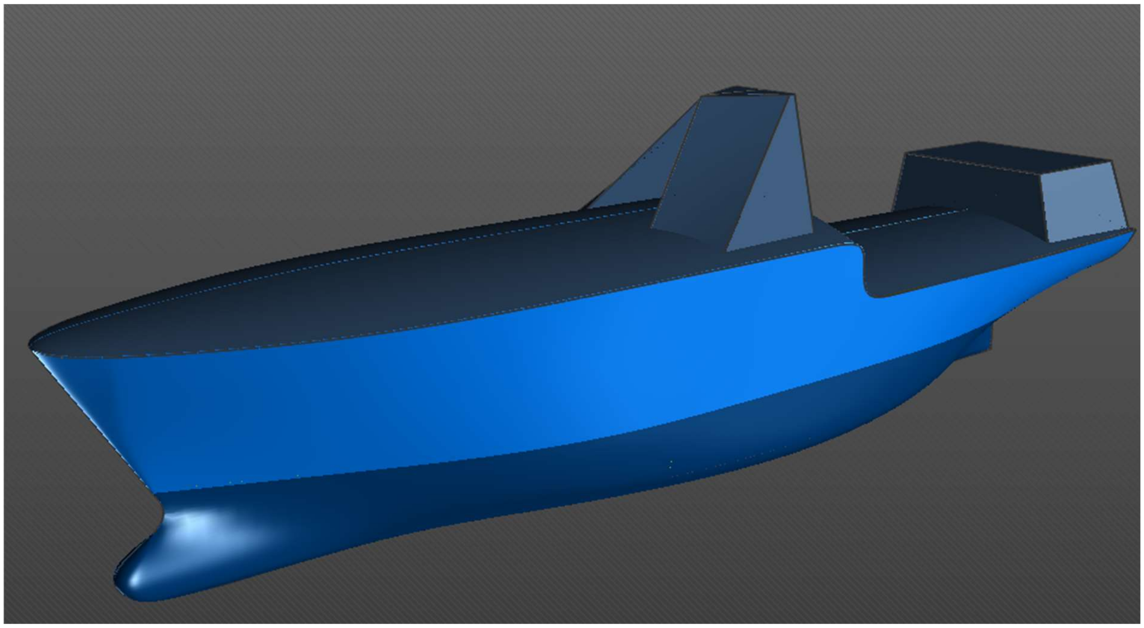


Figure 11: USV with deck and stability design

Figure 11 shows a draft of the initial hull design with superstructure, tower and sonar included. The tower structure provides a platform for communication systems and additionally destabilizing buoyancy when the vessel is inverted.

Propulsion system

Choice of propulsor

The initial selection and dimensioning of propellers will be based on the chosen hull design. Furthermore, the initial reference point will be based on experience in designing propellers. One of the main concerns is that of propulsion efficiency with low speed and a high resistance. Furthermore, acoustic noise plays a vital role in selection of number of blades, Blade Area Ratio B.A.R and Fixed Pitch Propellers (FPP) vs Controllable Pitch Propellers (CPP) and whether to utilise a nozzle or not. The output of this section is to determine the necessary propeller diameter D, the optimal revolution n, the Propulsion Coefficient P.C, the necessary installed effect P_e and applied torque Q.

The selection and dimensioning of the propeller will be based on the towing condition, considering the demanding nature of the operation with the highest load. In addition, a service addition of 20% will be added initially to consider environmental conditions in the AO, degrading, and fouling, which may be subject of discussion in the parametric study.

The use of a nozzle in a propeller configuration is commonly referred to as “ducted propellers”. Ducted propellers are suitable for heavy loaded propellers and could potentially work as a protection from physical damage (Rawson, 2001, p. 400). Based on the operational conditions, it is recommended to base the initial design on a ducted propeller due to the heavy load. An estimation of 25% increase in construction diameter due to the nozzle is expected. However, a % addition on a smaller vessel might not be accurate, a static number should be a adressed at a later stage.

The choice of a single- or twin-screw ship is in this case a matter of hull size and the need for redundance. One of the preliminary requirements states the need for redundance. Similar, the design of the hull dictates that the propeller may be restricted in diameter. The following estimation will determine the appropriate diameter. It is recommended to start the initial design with a twin-screw in order to maintain redundance in the propulsion system. The propellers will be outward turning in order to reduce cavitation, which means the starboard propeller is right-handed, and the port propeller will be left-handed (Rawson, 2001, p. 395).

Regular screw propellers are often divided into Fixed Pitch Propellers (FPP) vs controllable pitch propellers (CPP). The use of controllable pitch propellers will allow an adjustment of torque while maintaining constant revolution per minute. This will allow for higher efficiency when operating in different modes, for instance towing and transit. On the other hand, the use of CPP will entail a larger propeller hub due to mechanical properties, and thus reduce the maximum efficiency (Rawson, 2001, p. 399). On the other hand, a FPP will allow for a simpler, more robust solution, with high efficiency for a given loading condition. Due to increased complexity of construction, and potentially loss of efficiency, it is recommended to base the initial design on an FPP.

With the initial recommendation of a FPP in a nozzle configuration, propellers from the well-known and thoroughly tested propellers from the Wageningen K_a screw-series will be utilized.

The B.A.R indicates the ratio between the diameter and the size of the propeller. A higher B.A.R may reduce the probability of cavitation and a lower B.A.R may provide a higher efficiency. In addition, the B.A.R will directly impact the estimated diameter of the propeller, which will be addressed later.

The choice of blade numbers is essentially a matter of cavitation and signature. The number of blades and tip clearance is dictated by the excitation frequency and depend on bracket, nozzle, and rudder configuration. The initial design will be based on a 3-bladed ducted propeller and may be subject of discussion in the parametric study.

In order to start the initial dimensioning of the propeller, wake fraction coefficient w and thrust deduction coefficient t for a twin-screw configuration will be estimated based on the Block Coefficient C_b = 0,5288 from the hydrostatic data of the hull (Appendix C) (Society of Naval Architecture And Marine Engineers, 1970, pp. 394-395).

$$w = 2 * C_b^5 * (1 - C_b) + 0{,}04 = 2 * 0{,}5288^5 * (1 - 0{,}5288) + 0{,}04 = \mathbf{0{,}079}$$

$$t = 0{,}7 * w + 0{,}06 = 0{,}7 * 0{,}079 + 0{,}06 = \mathbf{0{,}115}$$

During the design process, it is necessary to state the maximum thrust force on the propeller. It is recommended to use $80 \mathrm{kN/m^2}$ if nothing is specified. However, the lower the max load is, the higher the efficiency. In addition, the lower the max load is, the higher the diameter D will be. In order to correct for the higher load in low speeds, it is reasonable to use $10\ \mathrm{kN/m^2}$ as a reference point for the initial design. This parameter can be adjusted during the design process and may be subject of improvement in the parametric study.

In order to estimate the diameter of the propeller, the following initial parameters in table 4 is utilised in a ducted twin-screw propeller configuration with 3 blades.

Parameter	Value
B.A.R	0,65
V_S	2,57 m/s
R_{TS}	1,34
w	0,079
t	0,1153
T_{MAX}	10 kN/m^2
C_b	0,5288

Table 6: Initial dimensioning design parameters

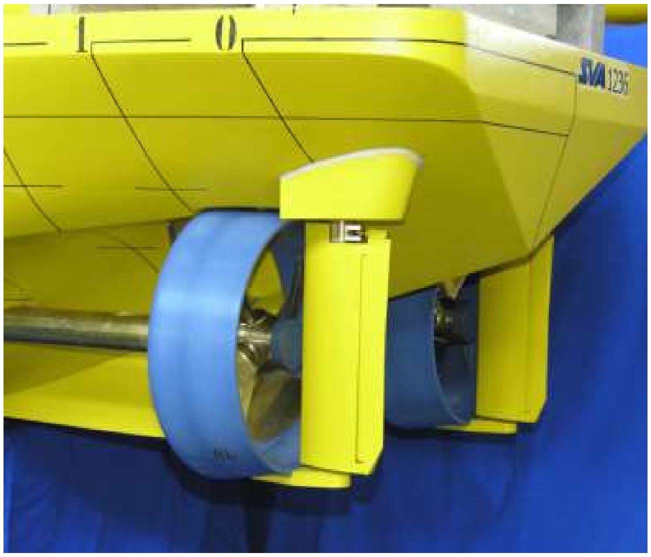


Figure 12: Illustration of a ducted 3-bladed twin-screw configuration with rudder (SVA-Potsdam)

The following procedure will define the initial diameter D of the propeller. See appendix H for more details on the calculations.

$$V_A = V_S * (1 - w) = 2{,}57 * (1 - 0{,}079) = \mathbf{2{,}37\frac{m}{s}}$$

$$T_{screw} = \frac{R_{ts}}{(1 - t) * number\ of\ shafts} = \frac{1{,}34}{(1 - 0{,}1153) * 2} = \mathbf{0{,}757\frac{kN}{screw}}$$

$$A_E = \frac{T_{screw}}{T_{MAX}} = \frac{0{,}7177}{10} = \mathbf{0{,}076\frac{m^2}{screw}}$$

$$D = \sqrt{\frac{4 * A_E}{\pi * B.A.R}} = \sqrt{\frac{4 * 0{,}0718}{\pi * 0{,}65}} = \mathbf{0{,}385m}$$

The calculations estimate an optimal diameter D of 0,385. The next step will be to establish an expression for the thrust coefficient K_T with relation to advance coefficient J and plot the given values of K_T and J (Table 7) in the propeller series graph in figure 13.

$$\frac{K_T}{J^2} = \frac{T_{Screw}}{\rho * D^2 * V_A^2} = \frac{0,7177}{1025 * 10^{-3} * 0,375^2 * 2,37^2} = 0,8874 \rightarrow K_T = \mathbf{0,887J^2}$$

J	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1,0	1,1	1,2
K_T	0,035	0,080	0,142	0,222	0,319	0,435	0,568	0,719	0,887	1,074	1,278

Table 7: Given values of K_T with respect to J

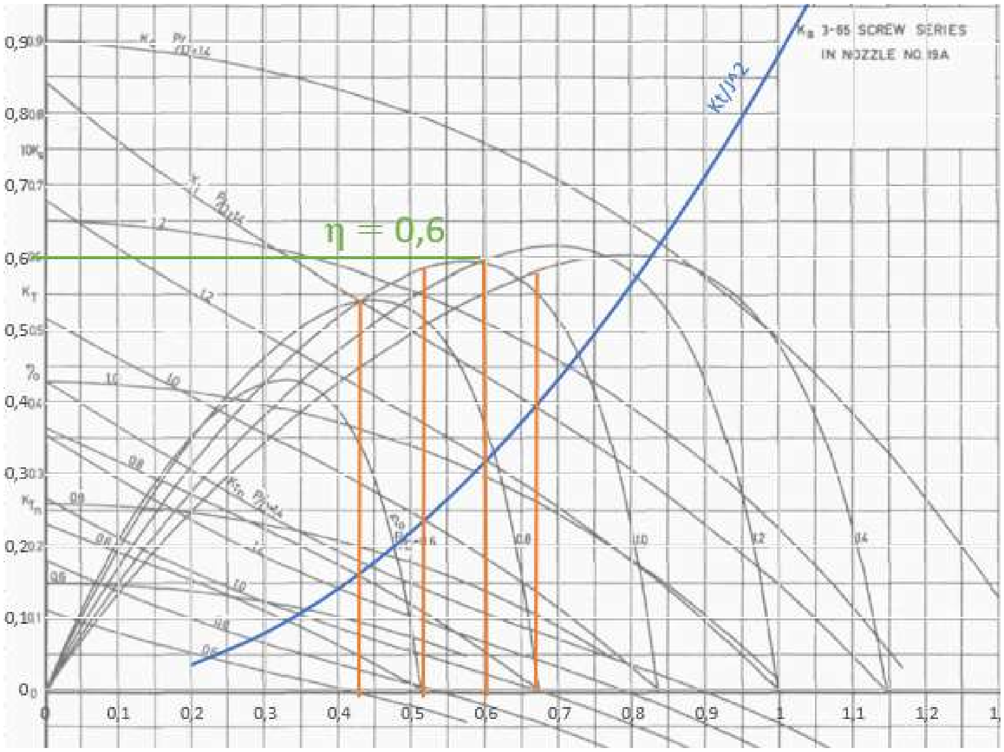


Figure 13: Wageningen KA 3-65 screw series in nozzle NO.19A

The parameters in table 8 is extracted from the graph and will be used to estimate the optimal revolution n, the propulsion coefficient P.C, and the necessary installed effect P_e and applied torque Q with 20% service addition.

P/D	1,2
J	0,6
η_0	0,6

Table 8: Extracted parameters from propeller series

$$n_{\mathrm{Screw}} = \frac{V_A}{J * D} = \frac{2{,}369}{0{,}6 * 0{,}385} = \mathbf{615\ rpm}$$

$$P.C = \eta_0 * \frac{1-t}{1-w} * \eta_R * \eta_m = 0{,}59 * \frac{(1-0{,}1153)}{(1-0{,}079)} * 1 * 0{,}91 = \mathbf{0{,}522}$$

$$P_E = R_{TS} * V_S = 1{,}34 * 2{,}57 = \mathbf{3{,}447\ kW}$$

$$P_e = \frac{P_E}{P.C} = \frac{3{,}447 * 1{,}2}{0{,}522 * 2} = \mathbf{3{,}96\ kW/screw}$$

$$Q = \frac{P_e * 1000 * 60}{2 * \pi * n} = \frac{3{,}96 * 1000 * 60}{2 * \pi * 615} = \mathbf{61{,}52\ Nm/screw}$$

The initial estimation has given the following optimal values for each screw with 20% service addition and will be dimensioning in the drivetrain and power requirement section.

n_{shaft}	615 rpm
P_e	3,96 kW/screw
Q	61,52 Nm/screw

Table 9: Initial estimation of optimal value for screw

Thrust bearings will be addressed in another section.

Drivetrain and energy production

The necessary power to propel the vessel in a towing condition with hotel load in 5 knots is estimated to be 19,92 kW (appendix G). However, the most demanding operational mode is during winching in/out of the sonar in 3 kn, which is estimated to be 21,01 kW based on data from the sonar manufacturer, which includes a 20% service addition to consider environmental conditions.

Drivetrain

There is an extensive number of combinations of possible drivetrain solutions. The CP recommended a hybrid solution where one uses fuel-based and/or electric propulsion in combination. When choosing a drivetrain solution, it is important to ensure high endurance, efficiency and redundance, while costs and signature should be kept low. Furthermore, choice of propulsor stated the need of two driveshafts to keep propeller diameter sufficiently low.

Two drivelines in combination with battery storage increases the USVs cost, but also flexibility and redundance. A larger battery bank could have an environmental benefit with electric operations relying on battery. Moreover, the battery can be the sole power source in emergency situations for a limited time when generators fail to operate or in cases with high demands to operation with reduced acoustic signature.

With these factors in mind, the two relevant options are as following:

Option 1: Combined Diesel-Electric and Diesel-mechanic (CODED) drivetrain:

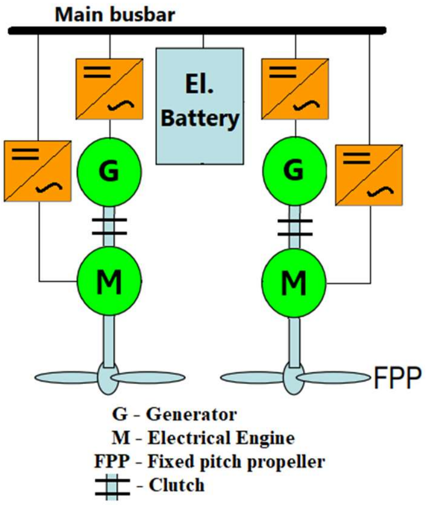


Figure 14: Simplified illustration of Combined Diesel-Electric and Diesel-mechanical (CODED)

The presented CODED drivetrain provides the vessel with two separate drivetrains and shared battery capacity. Each generator has its own drivetrain line. The propulsion setup allows the propeller to be driven directly with the generator-engine. Thus, requiring a mechanical/hydraulic clutch to connect the generator engine to the driveshaft. Although implementing a clutch increases loss, this setup could provide greater flexibility by being able to drive the driveshaft directly at speeds optimal for the generator engine’s highest efficiency.

Furthermore, one generator could possibly supply propulsion at low speeds and power demand imposed by hotel consumers. Putting all load on one generator could let it run at optimal load and thus reducing overall fuel consumption. In addition, directly driving the propeller removes losses inflicted by the generator, rectifiers and the electrical engine and raises the overall efficiency at lower speeds.

However, the propeller is optimized for the highest possible efficiency, it makes sense to let the engine run according to the optimized shaft revolution. In this case, this equals to 615 RPM. As a consequence, it might be necessary with a reduction gear in connection with the clutch to let the generator run at optimal load, thus lowering efficiency.

The efficiency of the drivetrain will be compared with respect to the total efficiency from the propeller directly operated from the combustion engine in the generator. The calculation will factor in the Propulsion Coefficient (P.C), which involves the electrical engine, and thus this efficiency must be excluded from the equation, hence dividing by $\eta_{Electric\ engine}$.

$$\eta_{CODED} = \eta_{Combustion\ Engine} * \ \eta_{Reductiongear} * \eta_{Clutc} \ * P.C * \frac{1}{\eta_{Electric\ engine}}$$

$$\eta_{CODED} = 0{,}55 * 0{,}95 * 0{,}90 * 0{,}522 * \frac{1}{0{,}91} = \ 0{,}328$$

At last, the two electric motors are supplied with power via rectifiers. The engines are equipped with a frequency converter, which makes it possible to regulate the speed of the shaft according to speed requirements.

<u>Option 2: Integrated Electric Propulsion (IEP):</u>

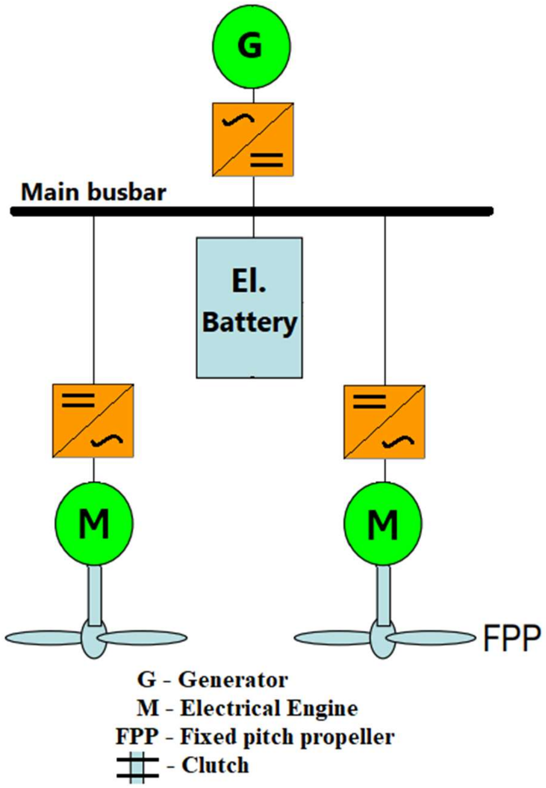


Figure 15: Simplified illustration of Integrated Electric Propulsion (IEP)

An IEP solution eliminates the need for reduction gears and clutches. Frequency converters with-in the electrical engine controls the speed of the electric motor. In terms of efficient operation, an electric motor will provide an inferior efficiency compared to a mechanical solution which connects the shaft directly to the generator.

The efficiency in option 2 is calculated with respect to the total loss from the generator to the thrust generated by the propeller. The calculation uses P.C, where the efficiency of the electrical engine is integrated, and equals to an estimation of 0,91 for initial comparison.

$$\eta_{IEP} = \eta_{Generator} * \eta_{Rectifier} * \eta_{Rectifier} * P.C$$

$$\eta_{IEP} = 0{,}4 * 0{,}98 * 0{,}98 * 0{,}522 = 0{,}2$$

Several small generators will operate at a lower efficiency in comparison to one larger. However, using one generator will impact redundancy, and by extent the survivability of the vessel. Based on the efficiency demands of the vessel, it is recommended to base the initial design on a single generator.

In addition, option 2 will allow for a cheaper construction. The more simplified construction and lack of redundancy will allow for an overall cheaper vessel, providing less economic risk of procurement.

In conclusion, the main difference between the two options are the increased efficiency and redundancy at the cost of increased complexity and cost. Where option 1 will provide a higher efficiency, more redundancy and a higher complexity and cost. Option 2 will provide a simplified construction, less efficiency, less redundancy, and a reduced cost. Considering the vessel is unmanned with an intended battery package in conjunction with two drive lines, it is recommended to base the initial design on option 2. However, the possibility of different driveline configurations should be addressed in a separate development phase.

Electrical engine

The choice of electrical engine will be based on commercially available state-of-the-art technology for marine applications. This section will cover the selection of an electrical engine based on the preliminary capabilities and requirement, the necessary revolution range, power, and torque with respect to the drivetrain configuration. The goal is to implement a commercially available engine with sufficient efficiency, effect, and torque with the given parameters.

The initial choice of electrical will be based on Bellmarine – Drivemaster 15w (Appendix D).

Figure 16: Visual representation of Bellmarine – Drivemaster 15W (Appendix D)

The technical specifications do not include torque Q. Based on given effect P, the maximum Q can be calculated at nominal speed.

$$Q_1 = \frac{P}{\omega} = \frac{10\ 000\ W}{\frac{1500\ RPM}{60\ S} * 2\pi} = 63{,}66\ Nm \quad \rightarrow \quad Q_2 = \frac{P}{\omega} = \frac{10\ 000\ W}{\frac{615\ RPM}{60\ S} * 2\pi} = 155{,}27\ Nm$$

One Drivemaster 15W will be sufficient to deliver a maximum of Q = 61,52 Nm in a 5kn towing condition with 20% service addition. In addition, the engine comes with a pre-installed thrust-bearing which is sufficient below 20kW. The efficiency is an estimation based on input and output at nominal speed from a similar engine from Waterworld (Water World Electronics, 2020). However, the propeller is to be run optimally at 615 rpm, and the electrical engine is running at a nominal speed of 1500 rpm. Running the engine at lower revolutions and higher torque, may result in a higher need for cooling. This is not an optimal operating condition, but sufficient cooling will allow this engine to be suitable.

Another solution is to use a reduction gear in order to apply the appropriate revolution to the propeller, while maintaining the optimal condition of the electrical engine. However, this will add more complexity to the system, a loss in efficiency in the gear, increased cost, and addition space requirements. This engine will be sufficient in the initial design. The dimensions, weight, efficiency, and price are based on a similar engine from WaterWorld 10,0kW and standard data for similar sized engines.

Parameter	Stats
Voltage	48 V – DC (AC input)
Effect P	10 kW
Torque Q	63,66 Nm – 155,27 Nm
Nominal revolution n	1500 rpm
Dimensions (L x W x H)	681 x 290 x 271 mm
Weight	76 kg
Efficiency η	0,91
Price (Estimated, commercial)	6695 Eur ~ 68.760 NOK

Table 10: Estimation of dimensioning parameters Drivemaster 15W (Appendix D)

The following ideal torque characteristics curve will be used in the parametric study to further optimize the relation between the choice of propeller and electrical engine. Due to the lack of data from the manufacturer, we opt to use a general characteristic diagram of permanent magnet synchronous machines (PMSM) in figure 17. The optimal design speed of the propeller is lower than the nominal speed of the electrical engine. Consequently, this will be sufficient for the initial design given appropriate cooling and considering the charactersttics of PMSM machines with constant torque up to nominal speed.

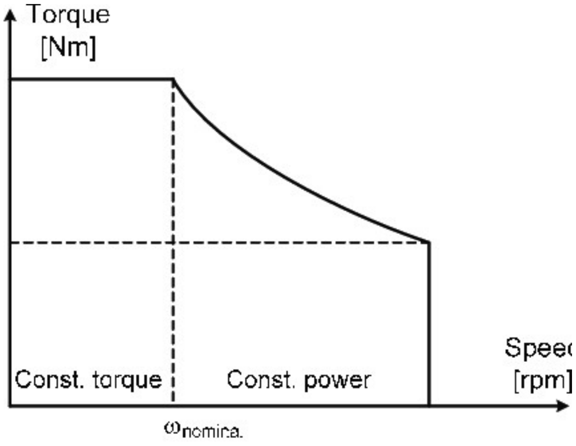


Figure 17: The ideal torque characteristic curves for the Permanent Magnet Synchronous Machine (Rudnicki, Czerwinski, Polok, & Sikora, 2015, p. 563)

Generator

The initial choice of generator will be based on a commercially available generator set with marine specifications. In addition, the produced noise was a relevant factor, considering the raised acoustic signature of the vessel and its degrading effects on the acoustic sensor capabilities.

The choice landed on M-SQ Pro 25, maritime generator by Whisper power (WhisperPower). The manufacturer data indicates a continuous power output of 22,5 kW which is sufficient for the most demanding operational profile of 21,01 kW. This results in a load of 89% in towing scenario and 93% in a winching scenario, both with service addition. The estimated load is relevant for further calculcations of fuel consumption. In addition, the noise level is classified to 58 dB. See table 12 for relevant parameters.

One of the challenges if this chosen generator is the maximum operating angle. The engine is limited to a max operating angle of 25° in all directions. Based on probable sea states in the AO, this may have a severe impact on the operational capability.

If the vessel is inverted, the generator will turn off and all openings as air- and exhaust ventilation will be shut. This function must be provided by a sensor that overrides the power generator and triggers the batteries to power the vessel.

Figure 18: Whisper Power – M-SQ Pro 25 (Appendix D)

Data	Value
Continuous power	22,5 kW
Revolution	1800 rpm, 60 Hz
Voltage	230 V - AC
Fuel Consumption (No load – Full load)	1 – 6 Litres/Hour
Dimensions (L x W x H) - Cabinet	1555 x 749 x 805 mm
Weight (Dry)	640 kg
Noise level	58 dB
η_{Gen}	0,4
$\eta_{C.Eng}$	0,55
Price (Estimated, Commercial)	40.000 EUR ~ 411.000 NOK

Table 11: Relevant Parameters for Whisper Power – M-SQ Pro 25 (Appendix D)

Based on the data given by the manufacturer the fuel consumption is extracted for the following scenarios. The fuel consumption is an estimate and will vary depending on operating conditions and fuel quality. The following values are with hotel load, and 20% service addition in order to maintain power equilibrium in the battery. The calculations can be found in appendix G.

Condition	Generator Load	Fuel Consumption [Litres/Hour]
3 kn Transit	29%	2,44
7 kn Transit	53%	3,67
5 kn Towing	89%	5,43
3 kn Winching	93%	5,67

Table 12: Estimation of fuel consumption based on loading condition (Appendix G)

Electrical components

Rectifiers must be utilised in order to generate 48V into the main busbar as shown in the drivetrain configuration. Similar, one must use a rectifier to supply the electrical engine and auxiliary power with AC at an appropriate voltage. In order to utilise commercially available technology, a 48VDC to 48VAC rectifier is used. Likewise, a 48VDC to 230VAC is utilised for auxiliary power initially. The efficiency of a rectifier is estimated to be roughly 0,98-0,99. An estimation of 0,98 will be utilised in this scenario to account for variables.

Energy storage

Due to the environmental conditions and commercially available state-of-the-art technology intended for arctic environment, the use of renewable energy in form of solar, wind, and wave energy will not be further investigated. The risk of not meeting the operational requirements with renewable is considered too high.

In order to define the energy storage, it is essential to estimate the necessary fuel and battery capacity. Based on the preliminary capabilities and requirements, the USV is expected to operate with the following framework:

- 1000 Nm range in sea state 3 at 5 kn towing condition
- 20 days of endurance in sea state 3
- 10 days of endurance in sea state 4.
- 12 hours of operation in a 5 kn towing condition with batteries in case of disrupted energy supply.

Consumers

Furthermore, the auxiliary consumers are factored into the hotel category of the vessel and include the following with an initial estimation of 10kW with all systems activated.

- De-icing
- Navigation systems
- Communication system
- SW and FW pumps
- Ventilation system
- Manoeuvring systems, including rudder.

Fuel and operational profile

The choice of fuel type is based on the recommendations of the generator set. The choice will be based on diesel fuel in accordance with the ASTM No.2-D standard. However, due to limited available open source data, the estimation will be based on average diesel fuel data, see appendix D (Lundby, 1979, p. 73). This estimation may not be entirely correct, and the actual numbers will vary. In addition, the choice of fuel must have low viscosity in order to maintain functionality in an AO with low environmental temperatures.

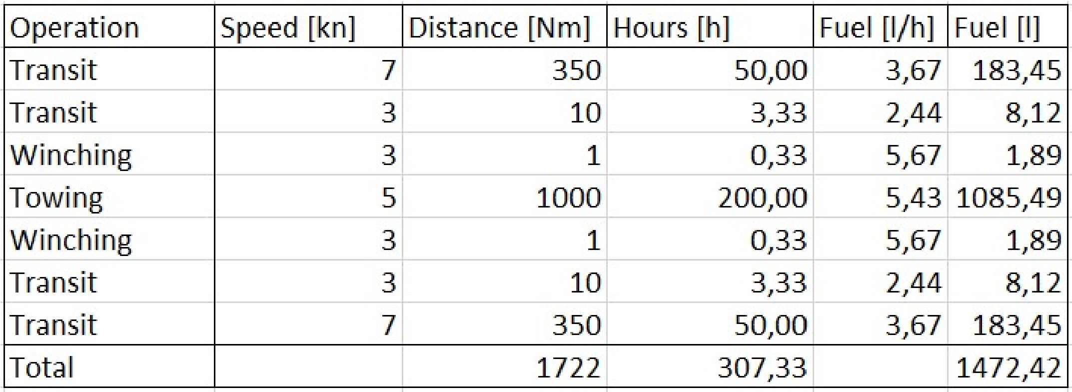
The reason behind not using biofuel, methanol, hydrogen, and other relevant environmental-friendly solutions is the problematic of lower efficiency and limited available infrastructure in the AO to maintain continuous supply.

The following data will used initially to estimate the fuel capacity based on numbers from Bunker Oil, which is the fuel distributer of the RNN. Fuel prices are volatile and lowers the accuracy of an estimate.

Parameter	Data
Type	Marine Gas Oil (MGO)
Density [ρ]	855 kg/m^3
Lower heating value [h_n]	42,7 MJ/kg

Table 13: Initial parameters to estimate fuel capacity (Appendix D)

Based on the initial framework, the following scenario is a rough estimate of a probable operational profile for the vessels with associated fuel consumption, see appendix G for detailed calculations. The vessel is optimized for 5 kn towing, which is the most frequent operating condition.



Operation	Speed [kn]	Distance [Nm]	Hours [h]	Fuel [l/h]	Fuel [l]
Transit	7	350	50,00	3,67	183,45
Transit	3	10	3,33	2,44	8,12
Winching	3	1	0,33	5,67	1,89
Towing	5	1000	200,00	5,43	1085,49
Winching	3	1	0,33	5,67	1,89
Transit	3	10	3,33	2,44	8,12
Transit	7	350	50,00	3,67	183,45
Total		1722	307,33		1472,42

Table 14: Rough estimation of operational profile with associated fuel consumption

Based on the operational profile, the necessary fuel capacity is estimated to be 1473 litres. The normal application in maritime construction is to assume a 95% filling of the fuel tanks. This will result in an estimated fuel tank capacity of 1550 litres of fuel storage, which equals to 1,55 m^3.

In military applications, its common to assume an operational profile that will allow the vessel to operate above 35% of fuel capacity. However, due to the fact that he USV is considered an extended tool, it may not prove necessary to carry increased capacity compared to manned platforms. Due to this reason, the preliminary design is to operate above 35% fuel capacity. This will estimate the necessary fuel capacity to 2300 litres. With 95% filling grade, this estimates to a total of 2450 litres fuel storage capacity, which equals to 2,45 m^3.

The total installed capacity will be 4400 litres in 4,615 m^3 of storage compartment. The increase in capacity is to address the need of 20 days of 5 kn towing operation in sea state 3.

Lubrication oil

The arctic environment in the AO will demand a lubrication oil with high viscosity index in order to ensure low viscosity in low temperatures. The section will not consider technical calculations, but rather a rough estimate of a suitable lubrication oil and the necessary installed capacity.

Following is an example of a suitable heavy duty synthetic lubrication oil from 49 North with high viscosity index, intended for arctic environment, see appendix D for further details.

Parameter	Value
Viscosity grad	0W-30
Density	843,82 kg/m^3
Viscosity Index	178
Kinematic Viscosity @ 40°C	59,34
Kinematic Viscosity @ 100°C	10,92
Pour point	-51 °C
Flash Point	226 °C
TBN (ASTM D2896)	10
Price	Unavailable

Table 15: Specifications 49 North Arctic Synthetic heavy duty engine oil, 0W-30 (Appendix D)

The necessary amount of lubrication oil for the system is determined by the expected consumption. The expected consumption is estimated to be 0,5% of fuel consumption based on a general estimate of smaller high speed diesel engines in the given effect range.

The estimation is based on a 5 kn towing condition with 20% service addition. Given a 95% filling grade, and at least 35% remaining capacity at all times, this estimates to 19 litres lubrication oil and 60 litres of storage, which equals to 35 kg and 0,06 m^3. The number is rounded up in order to consider cases of increased consumption. The amount is subject of discussion in a further optimization.

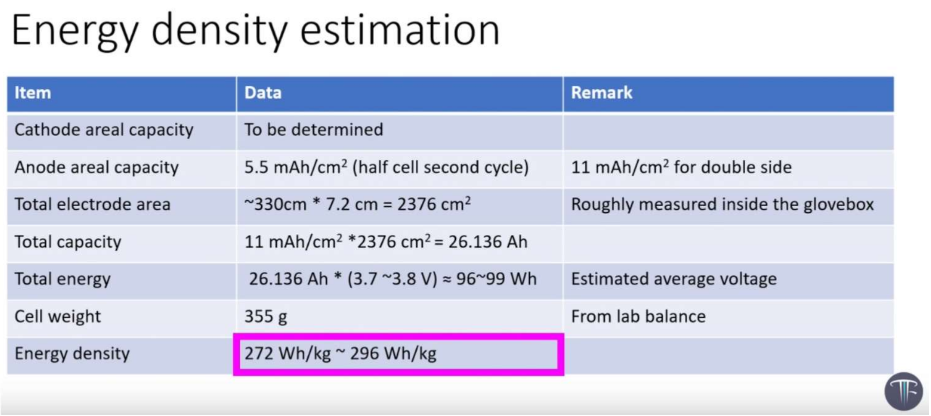
Battery

The main concerns regarding choice of battery are commercially available state-of-the-art technology, ability to handle cold environment, and sufficient energy density. In addition, the balance between the energy discharge and the ability to store energy must be addressed.

There are several relevant battery types available. The most relevant battery types for this application are saltwater-batteries and lithium-ion batteries. The saltwater-batteries will provide a more environment-friendly solution. However, the energy density of the saltwater-batteries is not comparable to litium-ion batteries.

Furthermore, the choice of battery will be based on the preliminary stability requirement, which indicates a necessity for compact, modular battery packages that can be placed low in the vessel to maintain stability requirements. Placing the battery lower in the vessel will provide a positive contribution to the stability, given the static and heavy weight of the battery package. Thus, the initial choice will be based on a lithium-ion battery and are subject of change in the parametric study.

Based on the preliminary requirements, the choice is to base the initial design on a lithium-ion battery cell developed by Tesla, the 4680, which is applied to the 2022 Model-Y vehicle (Kane, 2022). The 4680 battery cell data from table 15, is used as an initial reference point and is subject of discussion in the parametric study in order to address the possibility to apply more commercially available battery packages. The use of Tesla's 4680 battery cell will require a development phase in terms of integration. Following are the initial parameters in terms of battery design. The initial choise will be dimensioning in the estimate of the necessary battery capacity to satisfy the demand for 12 hours of operations in cases of disruption in a 5 kn towing condition.



Energy density estimation

Item	Data	Remark
Cathode areal capacity	To be determined	
Anode areal capacity	5.5 mAh/cm^2 (half cell second cycle)	11 mAh/cm^2 for double side
Total electrode area	~330cm * 7.2 cm = 2376 cm^2	Roughly measured inside the glovebox
Total capacity	11 mAh/cm^2 *2376 cm^2 = 26.136 Ah	
Total energy	26.136 Ah * (3.7 ~3.8 V) ≈ 96~99 Wh	Estimated average voltage
Cell weight	355 g	From lab balance
Energy density	272 Wh/kg ~ 296 Wh/kg	

Table 16: Tesla 4680-type cylindrical lithium-ion battery cell (Appendix D)

As a rough estimate, the initial necessary capacity of the batteries is set to 250 kWh and a 40% reduction in capacity to consider the cold operating environment's negative effects on the battery.

The average density value with 40% reduction in capacity:

$$Energy\ Density = \left(\frac{min + max}{2}\right) * 0{,}6 = \left(\frac{272 + 296}{2}\right) * 0{,}6 = 170\frac{Wh}{kg}$$

The estimated total weight of the battery:

$$Weight = \frac{Necessary\ Capacity}{Energy\ Density} = \frac{250 * 10^3}{170} = 1470kg.$$

The cell dimensions are estimated to diameter Ø = 46 mm and height h = 80 mm. In order to estimate the necessary installation volume each cell is regarded as a rectangle. The needed volume is estimated to:

$$Volume_{Cell} = D^2 * h = 46 * 46 * 80 = 169280\ mm^3 = 0{,}000169\ m^3$$

$$No.of\ cells\ neccesary = \frac{Necessary\ weight}{Weight\ of\ cell} = \frac{1470}{0{,}355} = 4141\ cells$$

$$Volume_{Battery} = Cell\ volume * No.of\ cells = 0{,}000169 * 4141 = 0{,}7\ m^3$$

The calculation is a rough estimate of the necessary space required to install the battery. Due to the necessity of a development phase in order to implement the battery, this value is subject of improvement, and only used as a rough estimation of the initial necessary volume, weight, and density. In addition to the estimated volume, additional space for enclosure, monitoring equipment and cables are necessary to address. Based on this, a volume of 1.0 m^3 is reasonable in the initial design. The price of the battery cells is currently unavailable, and thus shall be based on available Tesla modules for cars.

Alternative solutions not technically considered

The following factors will not be further evaluated from a technical perspective due to time and scope.

Manoeuvrability

Manoeuvrability is an essential part of the design process. On a surface vessel this will be defined as the ability to control the direction in the horizontal plane by going straight, staying stationary, turn or avoiding obstacles or ships (Rawson, 2001, p. 539).

Rudder

This section will list the relevant parameters regarding the choice of rudder configuration.

The vessel is intended to use two active half-balanced rudders behind the ducted propellers as shown in figure 12 in the choice of propulsor section.

Conditions that must be investigated during choice and dimensioning of rudder are:

1. Torque calculations
2. Centre of pressure
3. Cavitation
4. Structure and arrangements
5. Stress and fatigue analysis.

Due to the time available, this section will be limited to addressing the relevant parameter. There will be no technical considerations regarding construction of rudder in the initial design.

Navigation

This section will list the relevant factors regarding the implementation of the Passive Optical Sensor Systems (POSS) necessary for autonomous navigation, listed in prioritised order (Williams & Scharre).

1. By-wire steering and propulsion
2. Determination of vehicle position and time derivatives
3. Determination of vehicle attitude
4. Object detection and collision avoidance
5. Mapping of the environment
6. Mission guidance, operator view

Due to the relevance of our field of study and limited available time, there will be no further technical considerations regarding this topic.

Autonomy, control, and communication

Autonomy, control, and communication are three aspects closely linked together, and will be defined by the intended operational concept. The contents of this topic are not relevant to the field of study this thesis is based on. Consequently, it will not be a part of the alternative analysis due to the limited time available, but must be addressed at a later stage.

4.6. Preliminary weight breakdown

A complete weight breakdown off vessel with components are shown in appendix E. The weight breakdown is done to ensure adequate stability at different loading conditions.

Lightweight condition is vessel with all components with internal fluids, but without fuel. A design margin of 10 % is added to include additional weight gained from the production of detailed drawings and a 5 % building margin is added to implement weight gained from production. The margins constitute the corrected lightweight condition.

Standard weight consists of corrected lightweight with 50 % fuel load. Furthermore, full weight is corrected lightweight condition with 100 % fuel loaded (95 % tank filling) and 5 % extra margin for future growth. The following data is the result of the weight breakdown.

Condition	Weight [tonne]	GM>0	0-trim	0-yaw
Lightweight	11,71	0,26	0,18	0
Standard weight	13,61	0,30	0,05	0
Full weight	16,28	0,34	-0,09	0

Figure 18: Preliminary weight breakdown (Appendix E)

Figure 18 shows the vessel has more than sufficient GM for stability and alright longitudinal trim during the three conditions. Walls will be installed in fuel tanks in order to counter free-surface effect and a secure sufficient GM.

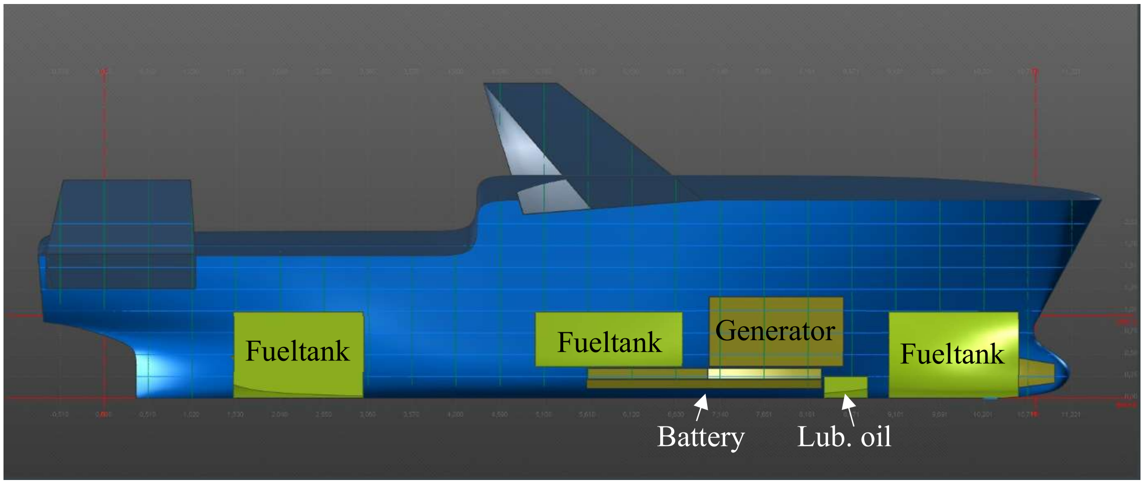


Figure 19: Screenshot of preliminary design layout

Figure 20 gives an overview of where the different components are located within the hull. The electrical engine and driveshaft are not visible in this screenshot. All parts and their centre of gravity is found in appendix C.

The cross curves provided from DELFTship have been used to predict the righting-arm (GZ) for the vessel in all three loading-conditions. Results from predicting the righting-arm is completed in appendix E and shown in figure 20.

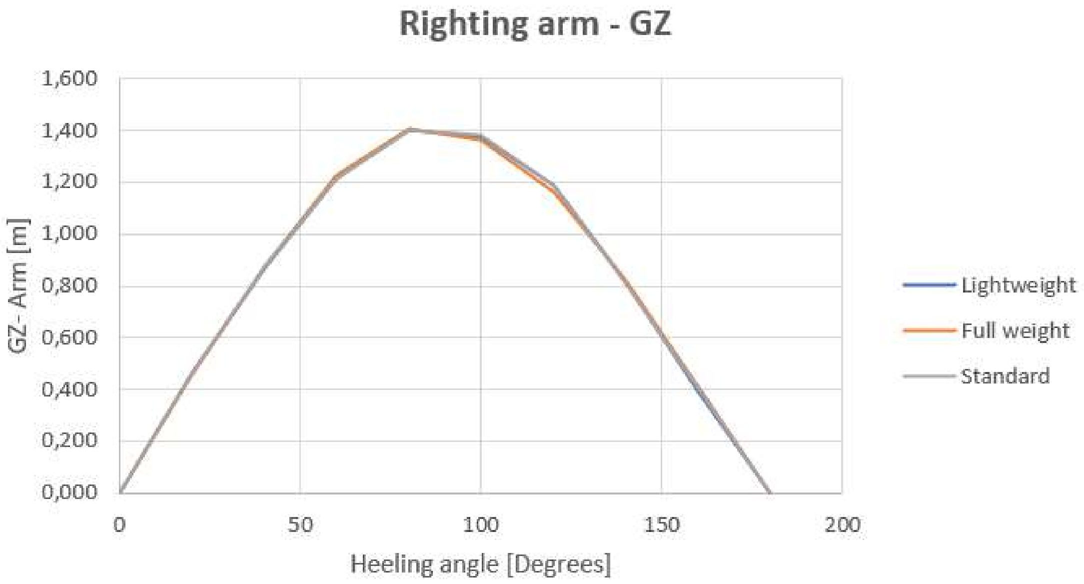


Figure 20: Vessel's righting arm (Appendix E)

4.7. Preliminary conclusive evaluation

The purpose of this section is to address the initial choices from the alternative solutions, and how balanced they are with respect to the preliminary design.

The following table represents the sub-systems and concluded outputs from the alternative solution section.

Sub-system	Choices
Hull Material	Sandwich composite with rigid PVC foam in the core and fiberglass-reinforced thermosetting plastic in the skin laminates. The overall smeared hull thickness is 0,04 meter thick.
Hull superstructure and self-righting ability	The vessel must be constructed with a superstructure that provides instability when the vessel is inverted. The vessel needs heavy ballast near the keel to keep centre of gravity low in all loading conditions. Tank walls will be implemented to counter free surface effect. The vessel needs to be buoyant and watertight. A watertight hull can be fixed with implementing effective one-way mechanical ventilation systems for all openings.
Choice of propulsor	Wageningen K_a 3-65 ducted propeller series 3 blades, 0,65 B.A.R, FPP, twin-screw propellers with nozzle. – D = 0,385m – P_e = 3,96 kW/screw – Q = 61,52 Nm/screw
Drivetrain	Hybrid IEP configuration with 2 electrical engines, 1 generator, 48VDC main busbar and 48V battery.
Electrical engine	Bellmarine – Drivemaster 15W with 20 kW thrust bearing
Generator	Whisper Power – M-SQ Pro 25
Consumers	Total hotel consumption of 10 kWh – De-icing – Navigation systems

<table>
<tr><td></td><td colspan="4">- Communication system
- SW and FW pumps
- Ventilation system
- Manoeuvring systems, including rudder.</td></tr>
<tr><td>Fuel and operational profile</td><td colspan="4">MGO, 95% filling grade, 35% remaining fuel capacity
Necessary installed fuel capacity of 2300 litres in a 2,45 m^3 storage.
Total installation of 4450 litres in a 4,6 m^3 storage will be installed.</td></tr>
<tr><td>Lubrication oil</td><td colspan="4">49 North Arctic Synthetic heavy duty engine oil, 0W-30, 50 litres in a storage of 0,06 m^2. Weight estimate of 35 kg.</td></tr>
<tr><td>Battery</td><td colspan="4">Tesla 4680-type cylindrical lithium-ion battery cell, total capacity of 250 kWh, 1470 kg, estimated volume of 1,0 m^3. Will require a substantial development phase.</td></tr>
<tr><td>Rudder</td><td colspan="4">Not addressed.</td></tr>
<tr><td>Navigation</td><td colspan="4">Not addressed.</td></tr>
<tr><td>Autonomy, control, and communication</td><td colspan="4">Not addressed.</td></tr>
<tr><td rowspan="4">Weight breakdown</td><td>Condition</td><td>Weight [tonne]</td><td>GM>0</td><td>0-Trim</td></tr>
<tr><td>Light weight</td><td>11,71</td><td>0,26</td><td>0,18</td></tr>
<tr><td>Standard weight</td><td>13,61</td><td>0,30</td><td>0,05</td></tr>
<tr><td>Full weight</td><td>16,28</td><td>0,34</td><td>-0,09</td></tr>
</table>

Table 17: Concluded output from alternative solutions

The overall conclusion from the alternative solutions is that the system is balanced, but subject of improvement. The constructions allow for an increase in overall propeller diameter. Furthermore, utilizing an off-the-shelf battery package may be beneficial in terms of avoiding an extensive development phase. The total fuel capacity may be reduced in order to reduce the total weight. The price aspect has not been a driving factor in this section but is a highly relevant factor to discuss further into the parametric study. The alternative solutions, with weight breakdown concludes that the added margins have caused for a slight addition in weight and gives a higher weight estimate.

4.8. Parametric study

The parametric study is intended to identify possible parametric changes in order to optimize the vessel. The study will be based on relevant factors within the design spiral (figure 21). The relevant factors will be listed with a description and the adjusted values. Furthermore, the factors that will not be addressed is described as “not applicable” in the description. This section will highlight the capabilities and requirements not satisfied and the adjusted parameters.

A certain amount of limitations is made in order to address relevant factors with respect to the field of study this thesis is intended for. Furthermore, certain set of limitations is made due to limited time available.

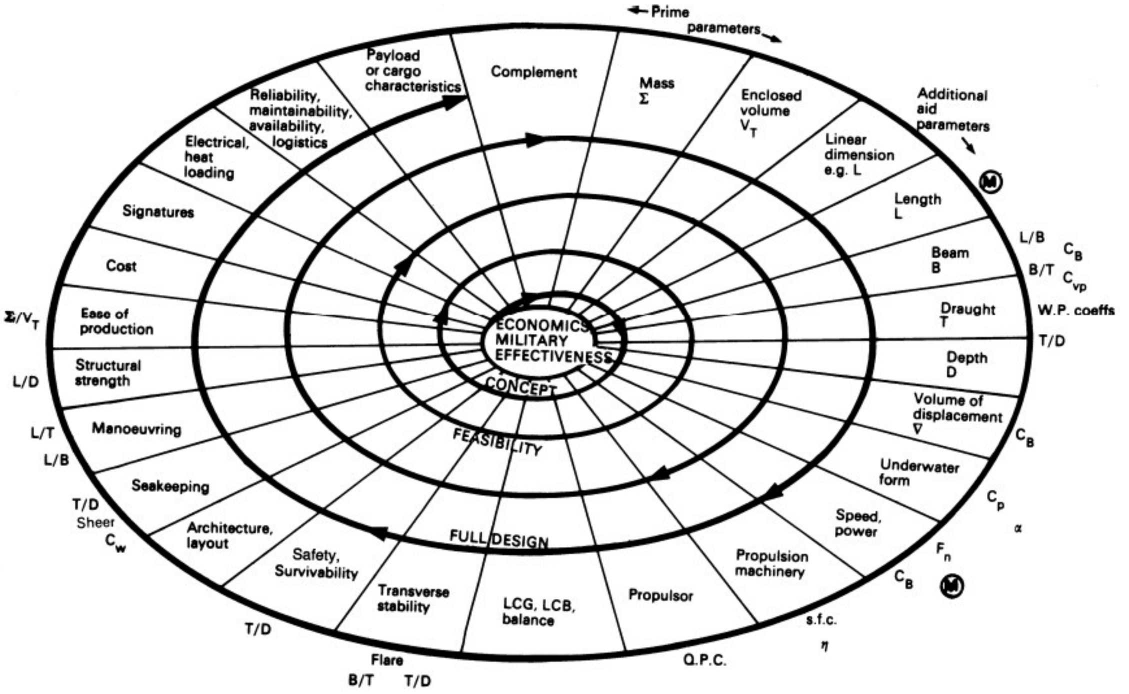


Figure 21: The design spiral (Rawson, 2001, p. 653)

Parameter	Previous value	Adjusted value
Design length	10,8	12
Beam	2,8	2,65
$L_{waterline}$	11,553	12,837
$B_{waterline}$	2,818	2,667
$L_{waterline} / B_{waterline}$	4,099	4,813
Smeared hull thickness	0,04 m	0,035 m
Propeller max load	10 kN/m^2	6 kN/m^2
Propeller max diameter	N.A	0,5
Fuel Storage	4400 litres	4100 litres
Battery package	Tesla 4680 battery cell	6 x Transfluid 48V 41,0 kWh battery packages.
Architecture Layout	N.A	Changed the overall layout of the superstructure to account for better waterflow over deck and stability.

Table 18: List of adjusted parameters from the parametric study (Appendix F)

4.9. Optimized design parameters and final design solution

The following section will present an optimized solution based on the adjusted parameters from the parametric study. The presented solution aims to converge towards a more efficient vessel and will be subject of further optimization.

Hull

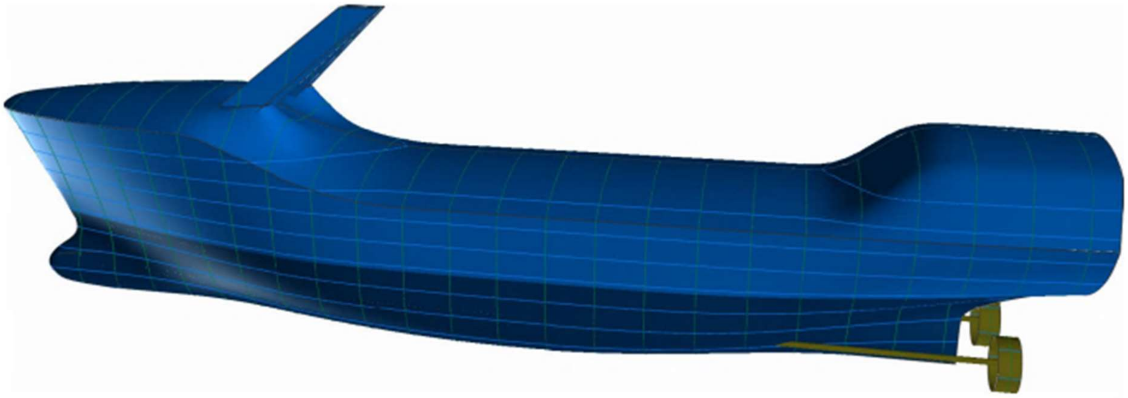


Figure 22: Screenshot of optimized design

Hull material

The hull material is not adjusted and will be based on a sandwich composite with rigid PVC foam in the core and fiberglass-reinforced thermosetting plastic in the skin laminates. However, the estimated smeared thickness has been reduced from 0,04 m to 0,035 m. The initial thickness was considered an over-estimation and has been adjusted to a more appropriate value based on experience.

Hull superstructure and self-righting ability

The vessels superstructure and hull are designed to better limit surface area for ice to stick, and to make water slide off, see figure 22. The righting arm GZ is positive and the area under the GZ-curve is greater than the preliminary design in all loading conditions from 0-180 degrees heel. See figure 26 or appendix E for more details.

Propulsion system

Choice of propulsor

The addressed limitations on the propeller diameter will be used as a dimensioning parameter for the propeller, while addressing the need for a lower load limit. The lower load limit presents an increased overall P.C. The following dimensions is an outline from the calculations with 20% service addition.

Parameter	Value
Propeller type	Wageningen K_a 3-65 ducted propeller series
Blades	3
B.A.R	0,65
Screws	2, outward turning
Pitch adjustment	FPP
Load limit	6 kN/m^2
D	0,497
P/D	1,2
n_{screw}	408
P.C	0,54
P_e	3,84 kW/Screw
Q	89,74 Nm/Screw

Table 19: Optimized propulsor parameters (Appendix H)

Kumera Marine AS department Hjelset provided a price estimate of the a CPP propeller configuration with similar dimensions. Table 18 shows the prices

Parts	Price
2 x propeller, sleeve, coupling	11.500 Eur
2 x fixed nozzle for Ø500 propeller	6.700 Eur
Total	18.100 Eur

Table 20: Price estimation from Kumera Marine (Kumera Marine AS Department Hjelset, 2022)

Drivetrain and energy production

Drivetrain

The drivetrain is not adjusted and will remain the same as presented earlier.

Option 2: Integrated Electric Propulsion (IEP):

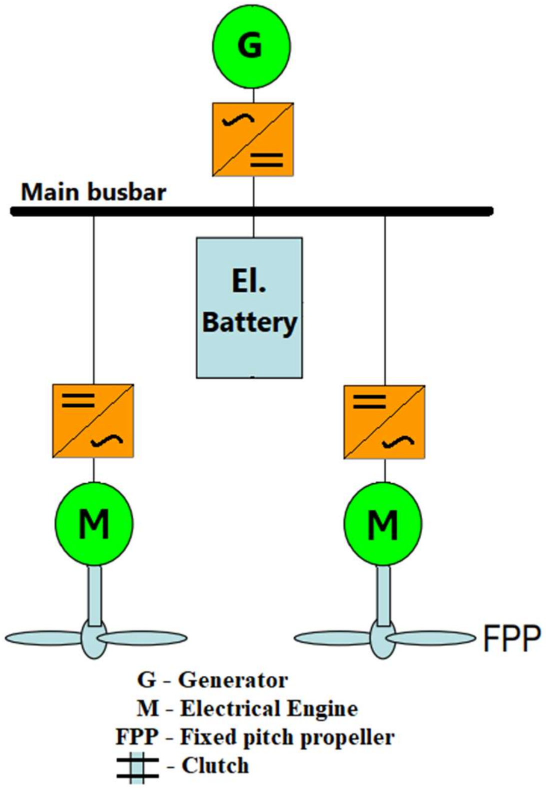


Figure 23: Simplified illustration of Integrated Electric Propulsion (IEP)

Electrical engine

The electrical engine is not adjusted, as it will be able to deliver the necessary power and torque.

Figure 24: Visual representation of Bellmarine – Drivemaster 15W (Appendix D)

Generator

The generator is not adjusted, as it will provide sufficient effect to maintain power equilibrium during winching operations in 3kn. Which based on the optimized design is reduced to 20,89 kW. See table 12 for further details on the dimensioning parameters regarding the generator.

Figure 25: Whisper Power – M-SQ Pro 25 (Appendix D)

Electrical components

No adjustments have been made on electrical components. It is still necessary with a rectifier in order to adjust the current and voltage.

Energy storage

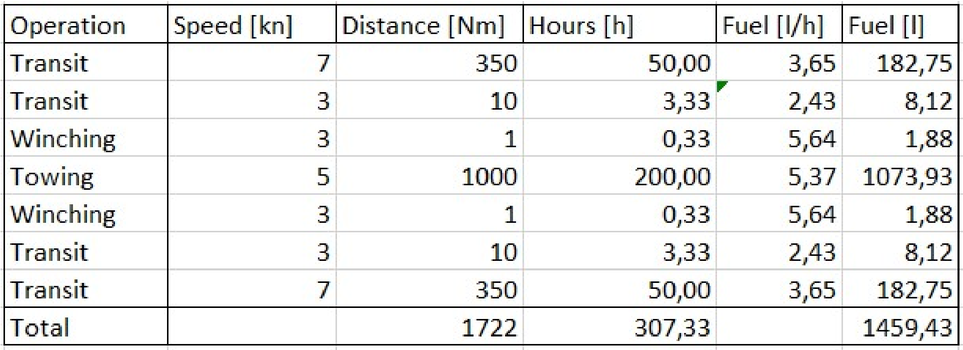
Consumers

No additional adjustment has been made and the estimated hotel power requirement is still 10 kWh, which is a reasonable number for further optimization.

Fuel and operational profile

The necessary fuel storage has been adjusted from 4400 litres to 4100 litres in order to not carry excess fuel based on the initial operational profile, with respect to the dimensioning requirement of 20 days operation in 5 kn towing condition in sea state 3.

The following is the estimated operational profile based on the optimized parameters.



Operation	Speed [kn]	Distance [Nm]	Hours [h]	Fuel [l/h]	Fuel [l]
Transit	7	350	50,00	3,65	182,75
Transit	3	10	3,33	2,43	8,12
Winching	3	1	0,33	5,64	1,88
Towing	5	1000	200,00	5,37	1073,93
Winching	3	1	0,33	5,64	1,88
Transit	3	10	3,33	2,43	8,12
Transit	7	350	50,00	3,65	182,75
Total		1722	307,33		1459,43

Table 21: Operational profile based on optimized parameters (Appendix G)

Lubrication oil

No adjustment has been made to lubrication oil. 49 North Arctic Synthetic heavy duty engine oil, 0W-30, is still applicable.

Battery

The parametric study identified the possibility to utilise a off-the-shelf battery package from Transfluid, 6 units of the 48V, 41,0 kWh battery packages (Transfluid, 2020). However, this resulted in an added weight of 1650 kg. This added weight had a severe negative impact on the stability of the vessel, which is why the choice is still to utilise the Tesla 4680 battery cells. The study still recommends looking at alternative battery solutions.

4.10. Weight breakdown

A complete breakdown of all loading conditions is gathered in appendix E. The loading conditions are included with 10 % design margin, 5 % building margin, and 5 % future growth margin as in 4.6 Weight breakdown.

Condition	Weight [tonne]	GM>0	0-trim	0-yaw
Lightweight	12,57	0,11	0,09	0
Standard weight	14,37	0,18	-0,02	0
Full weight	16,98	0,24	-0,12	0

Table 22: Optimized weight breakdown (Appendix E)

Initially the GM in lightweight and standard loading condition was perceived to short as some often recommend GM to be at least 0,15 m. However, due to the small size of the vessel, the GM value may be suitable as an initial value due to the relatively large angle of maximum righting moment, range of stability and the area under the righting arm curve shown in figure 26.

> *“The primary yardstick for the safety of a ship is neither the GM nor the range of stability, but the maximum righting arm and the angle at which this maximum arm occurs” (Gillmer & Johnson, 1982, p. 146)*

Looking at figure 26 the maximum righting arm is 1,45 meter and occurs at 100 degrees heeling angle for all loading conditions. This suggest the stability of the ship may be sufficient as long as the righting arm is greater than forces from waves and wind. The area under the GZ curve is also larger compared to the preliminary righting arm curve. If the optimized vessels GM should be improved, the vessels waterline area should be made larger.

Figure 26: Righting arm optimized design (Appendix E)

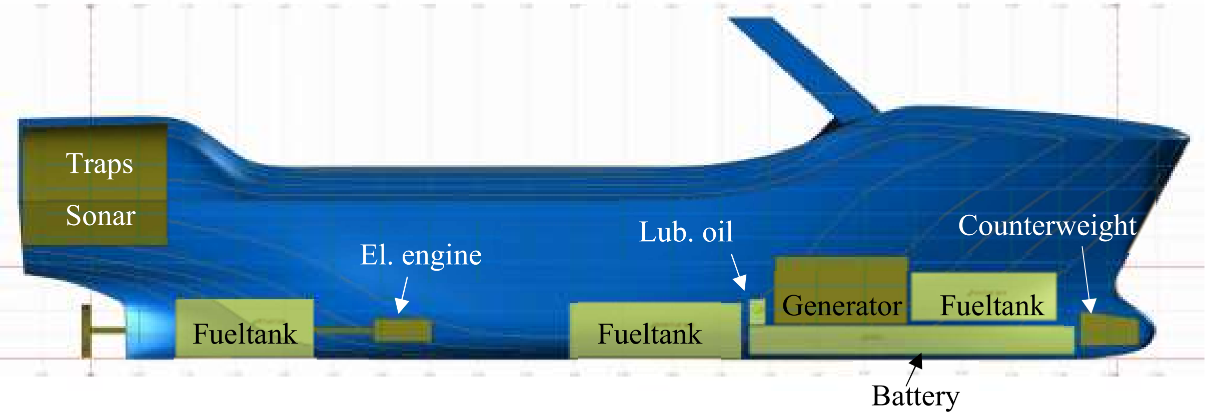


Figure 27: Screenshot of optimized design layout

All components are placed with centre of gravity as low as possible in order to secure sufficient GM.

4.11. Cost assessment

The following table is a very rough estimate for comparison. All numbers in the table below are rounded up in order to consider changes. The consumables will be estimated on average prices of December 2022 and presented as a total price of one cycle in the operational profile. The price of a streamlined production will reduce the unit price. The estimation will be based on a vessel prototype.

System	Price
Hull material	3,3 euro/kg = 19.140 euro
Propeller, propeller nozzle and shaft	18.100 euro
Electrical engine	2 x 6695 euro
Generator	40.000 euro
Electrical components	Not applicable
Fuel	1,82 euro/litre x 1460 litres = 2657 euro/cycle. (OilMonster, 2022)
Lubrication oil	25 euro/litre x 60 = 1500 euro/cycle. Estimated value.
Battery	75.000 euro Estimated value.
Sensors	70.000 euro Estimated value
Estimated total without maintenance.	235.630 euro + 4157 euro/cycle
Estimated total with maintenance (40% of procurement cost)	330.000 euro + 4157 euro/cycle
Rough estimate of total cost	~ 400.000 euro + 4500 euro/cycle.

Table 23: Cost estimate

In conclusion, a price range of 400.000 – 1.000.000 euro is to be expected for an initial prototype, factoring in work hours, development, and production facilities.

By comparison, the estimated price tag of the Norwegian frigates was 404.000.000 euro per unit in 2003. Which estimates to 561.560.000 euro per unit in 2022 if accounting for inflation (Markussen, 2007). The values are meant as a means of rough comparison for further evaluation in the points of decision.

4.12. Risk assessment

The risk assessment in the DP shall seek to address changes in risk involved with moving forward with the optimized solution with respect to performance, costs, and time.

Due to the cold and harsh environment of the AO, the probability of icing on the vessel is one of the main concerns regarding performance. The current design relies on a functioning de-icing system in order to maintain stability and de-ice the sonar winch. Icing on the vessel will directly reduce the already small margin in terms of stability and may prove a risk in terms of performance.

The probability of failure with today's commercially available state-of-the-art technology indicates a low risk in terms of performance. However, the risk of entering an extensive development phase with respect to the integration of Tesla 4680 battery cells is considered high. Given the high risk, it is strongly recommended to utilise off-the-shelf batteries with high energy density within the vessels current weight limit.

The use of a simple, yet robust, drivetrain configuration with one generator may prove a liability should the one generator fail to operate as intended. Furthermore, the current generator has a limited operating angle of 25°, which pose a challenge. In order to minimize the risk of operational failure, further optimization should address the possibility to utilise a different generator or higher number of generators.

The study has had to make several limitations due to scope and time. These limitations must be addressed before moving forward with the design process. Moving forward with the current configuration for further optimization is reasonable but may provide an increased risk.

The risk of not meeting the intended performance goal might lead to an increased risk with respect to procuring the initial protypes.

4.13. Points of decision

The following section shall gather all the sub-conclusions from the alternative solutions, parametric study, the optimized solutions, and the risk assessment in order to establish a foundation for further recommendation. The findings shall be addressed with respect to the preliminary capabilities and requirements, and relevant parameters in the design spiral.

Performance

In terms of performance, the vessel does satisfy the preliminary capabilities and requirements with respect to endurance and stability. The following values are deducted from the optimized design.

- 20,68 days of operation in a 5 kn towing condition with 20% service addition and 35% remaining fuel.
- 2481 nm in a 5 kn towing condition with 20% service addition and 35% remaining fuel.
- The vessel is able to conduct the operational profile with 20% service addition and above 50% remaining fuel.
- GM above 0 in all loading conditions
- GZ above 0 for all angles of heel from 0-180° in all loading conditions
- Conduct 12,7 hours of operation in a 5 kn towing condition on battery.
- Equipped with de-icing system.

Cost

The total cost estimates to 400.000 euro + 4500 euro/cycle. This is a rough estimate, and the risk of increased cost for the prototype is high due to the needed manpower for the actual construction, potential development of new technology, and lack of streamlined production. However, compared to the cost estimate of bigger seagoing vessels, the price is low. The actual production cost may be lower if a bigger number of units is procured.

Time

The estimated time for construction and implementation is not directly addressed in this study. Before the construction of prototypes, the conceptual solution will require more optimization. In addition, the development of prototypes will require more time compared to streamlined productions. By utilising off-the-shelf technology, the optimisation and construction time may be mitigated.

Risk analysis

The following risk analysis will address the risk involved by moving forward with the current optimized solution with respect to performance, cost, and time. Moving forward with the current configuration for further optimizing could provide an increased risk if the limitations stated in the DP is not addressed properly. The limitations of particular importance are the sensor systems, manoeuvrability, navigation, and electrical components.

Performance

Icing on the vessel will directly reduce the already small margin in terms of stability and may prove a risk in terms of performance if the installed de-icing system fail to operate properly. Additionally, in order to minimize the risk of operational failure, further optimization should address the possibility to utilise a different generator set or number of generators due to the operating limit of 25% heel in all directions. The vessel is not yet tested in the operating area, which may pose an operational uncertainty. Consequently, the risk of not meeting the intended performance goal stated in the requirements and capabilities might lead to an increased risk with respect to procuring the initial prototypes. The operational risk of losing a platform due exposure by signature is considered low considering its an unmanned platform.

Cost

Given the risk of increased cost, it is recommended to utilise off-the-shelf batteries with high energy density within the current weight limit. Furthermore, it is recommended to further analyse the use of off-the-shelf technology in general in order to minimize the production and development cost. It is too early to conclude the possible economic risk of procurement given the necessity for further optimization. However, the low price tag compared to other projects in the RNN may allow for the construction of an early prototype for further testing. In terms of signature, the economic cost is not directly adressed, but should be considered in the further optimization. The economic risk of losing the platform versus the economic risk of installing signature dampening equipment is relevant to address at at later stage.

Time

Similar to the cost analysis, the use of technology that requires a development phase may prove an increased risk of spending more time in the production and implementation process. It is recommended to further analyse the use of off-the-shelf technology in order to minimize the production and development time. Moreover, further optimization and construction of prototypes does add a degree of uncertainty to the project. This uncertainty may provide an increased risk with respect to development time and production time of prototypes.

4.14. Recommendation

Judging the current state of the vessel, we do not recommend moving forward into a development- and completion phase. Further optimization is essential to reduce the risk of procurement. Moving forward with the current configuration for further optimization is reasonable but could provide an increased risk if the stated limitations is not addressed. Limtations of particular interest are autonomous navigation, sensor systems, manoeuvrability, and electrical components. Finally, it is recommended to further analyse the use of off-the-shelf technology in general in order to minimize the production cost and time, and to ease the process of streamlining the production.

4.15. Conclusion

The DP has defined optimized design parameters and an optimized solution based on the parametric study. Moreover, the parametric study analysed the preliminary design with respect to the preliminary capabilities and requirements. The design process was limited to two rounds in the design spiral due to the magnitude of the thesis. Nonetheless, the design process has been a time consuming and educational process. Furthermore, a weight breakdown, cost, and risk assessment were made before moving into the decisive phase. In conclusion, the recommendation is to not move forward into a development- and completion phase, judging the current state of the vessel. Further optimization is essential to reduce the risk of procurement.

4. Conclusion and recommendation

This study has processed the task of designing a smaller unmanned surface vessel from three ideas to a defined conceptual solution with a recommendation for further work. The use of USV's to free up resources, raise situational awareness, and reduce the risk of personnel has a great potential.

The IP states the possibility to investigate three ideas: MCM, ISR, and Force sustainment USV's. Consequently, the IP concluded with a recommendation to further investigate the idea of an ISR USV.

Furthermore, the CP analysed four conceptual solutions with respect to the identified capabilities. Passive ISR USV's is an appropriate subject to further investigate based on the long-term plans of the Norwegian armed forces, and studies related to potential use of autonomous systems. The CP concluded with a recommendation to investigate option 1: Small ISR USV's with a towable passive sonar in conjunction with deployable sonobuoys. In addition, the CP recommend moving forward with a conventional hydrostatic displacement hull and a hybrid propulsion configuration.

Finally, the DP analysed and specified technical aspects with respect to the identified capabilities and requirements. The Design spiral were a central tool in the design process. Furthermore, the DP presented an optimized solution based on the parametric study. Optimizing the solution was done with respect to the chosen components and performance. Moreover, economic cost was not the dimensioning factor for the optimized design. The consequence of not meeting the performance thresholds may have severe ripple effect for cost and time. Eventually, the design process ends with a recommendation to further optimize the vessel. Nonetheless, the DP have proven very educational in terms of the sensitivity of parameters in the design spiral and the relation between them. Primarily, the linear dimensions: length, beam, and draft, and how they affect stability, seakeeping abilities, and loading characteristics. One of the main concerns of the study is stability, and risk involved with pushing the limits of the linear dimensions, in particular the L/B ratio.

It is not recommended to move forward into a development- and completion phase judging the current state of the vessel. Further optimization is essential to reduce the risk of procurement.

The majority of the thesis is focused on the mechanical aspect of hull, stability, and propulsion, with minor technical considerations regarding electrical components. The aspects of autonomy, manoeuvrability, and sensors are central area of study not included, and should be addressed.

5. Recommendation for further work

With respect to the findings in the study, we recommend further work on the following aspects of the design process:

- Investigating the possibility for the USV to act as a communication node for submarines.
- Investigate the possibility to use the USV in coastal waters
- Investigate the possibility to utilise digital optimization tools to adjust relevant parameters.
- Physical testing of reference model
- Run more rounds in the design spiral.
- Optimizing the sensor packages.
- Address autonomous navigation and control.
- Optimizing hull strength and construction aspect.
- Considerations regarding dimensioning of bearings.
- Dimensioning and optimizing rudder configuration.
- Optimizing shaft size and material.
- Address the total efficiency of different drive-train configurations
- Testing engine and propeller performance, and consider the synergy of the systems, subject of change due to the fact that the given values are general characteristics of PMSM engines.

References

Aktildiz, H., & Simsek, C. (2016). Self-righting boat design. Retrieved from https://dergipark.org.tr/en/download/article-file/1044834

Andersen, A., & Stokke, R. (2004). *Kompositt-/sandwichmaterialer for bruk i fiskeflåten*. Retrieved from https://komposittforbundet.no/media/1069/kompositt-_sandwichmaterialer-for-bruk-i-fiskeflaaten.pdf

Babicz, J. (2015). *WÄRTSILÄ Encyclopedia of ship technology* (Second ed.): WÄRTSILÄ CORPORATION.

Gillmer, T. C., & Johnson, B. (1982). *Introduction to naval architecture* E. & F. N. Spon Ltd.

Hareide, O. S., Relling, T., Pettersen, A., Sauter, A., Mjelde, F., & Ostnes, R. (2018). Fremtidens autonome ubemannede kapasiteter i Sjøforsvaret. *3*, 123-148. doi:10.21339/2464-353x.3.2.123

Hochet, A., Dodet, G., Ardhuin, F., Hemer, M., & Young, I. (2021). Sea State Decadal Variability in the North Atlantic: A Review. *Climate, 9*(12), 173. Retrieved from https://www.mdpi.com/2225-1154/9/12/173

Hollenbach, K., U. (1998). *Estimating Resistance and Propulsion for Single-Screw and Twin-Screw Ships*.

Holler, R. A. (2013). The evolution of the sonobuoy from world war II to the cold war. *U.S. Navy Journal of Underwater Acoustics*, 27. Retrieved from https://www.navairdevcen.org/PDF/THE%20EVOLUTION%20OF%20THE%20SONOBUOY.pdf

Kane, M. (2022). Tesla's 4680-Type Battery Cell Teardown: Specs Revealed. Retrieved from https://insideevs.com/news/598656/tesla-4680-battery-cell-specs/

Kartverket. (2015). Norwegian Maritime Borders. In *PDF* (pp. Visual description of Norwegian Maritime boarders.). Kartverket.no.

Kumera Marine AS Department Hjelset (2022). [Price estimate of propeller configuration with shaft, coupling, sleeve, propeller and nozzle.].

Lundby, L. (1979). *Forbrenningsmotorer I.* (3 ed. Vol. 1): Universitetsforlaget.

Lundby, L. (2014). *Havromsteknologi - Et hav av muligheter*: Fagbokforlaget Vigmostad & Bjørke AS.

Maritime21. (2021). *Maritime21-Strategy*. Maritime21.no: Maritime21 Retrieved from https://www.maritim21.no/siteassets/maritim21_final-2.pdf

Markussen, H. M. (2007). KNM «FRIDTJOF NANSEN». *Skipsrevyen*. Retrieved from https://batomtaler.skipsrevyen.no/knm-fridtjof-nansen/knm-fridtjof-nansen/1101758

Ministry of Defence. (2020-2021). Prop. 14 S (2020-2021) Evne til forsvar - Vilje til beredskap, langtidsplan for forsvarssektoren. Retrieved from https://www.regjeringen.no/no/dokumenter/prop.-14-s-20202021/id2770783/?ch=1

Ministry of Petroleum. (2022). The oil and gas pipeline system. Retrieved from https://www.norskpetroleum.no/en/production-and-exports/the-oil-and-gas-pipeline-system/

Norwegian Defence Materiel Agency. (2022). PRINSIX. Retrieved from https://www.fma.no/prinsix/prosjektfaser/konseptfase

Norwegian Goverment. (2018). Havnasjonen Norge. Retrieved from https://www.regjeringen.no/en/topics/havet/innsiktsartikler/the-ocean-nation-of-norway/id2605291/

Norwegian Minestry of Defence. (2022). Future Acquisitions For the Norwegian Defence Sector 2022–2029. 39.

O'Rourke, R. (2022). *Navy Large Unmanned Surface and Undersea Vehicles: Background and Issues for Congress*. Retrieved from https://sgp.fas.org/crs/weapons/R45757.pdf

OilMonster. (2022). BERGEN BUNKER FUEL PRICES. Retrieved from https://www.oilmonster.com/bunker-fuel-prices/west-northern-europe/bergen/127

Pedersen, R., Stokke, R., Amble, A., Friberg, R., & Lønseth, M. (2005). *Kartlegging av behov for nye materialløsninger i fiskeflåten*. Retrieved from https://komposittforbundet.no/media/1068/kartlegging-av-behov-for-nye-materialloesninger-i-fiskeflaaten.pdf

Pflug, J., Vangrimde, B., & Verpoest, I. (2003). Material efficiency and cost effectiveness of sandwich materials. *48*, 1925-1937. Retrieved from https://www.researchgate.net/publication/293222844_Material_efficiency_and_cost_effectiveness_of_sandwich_materials

Presterud, A. O., Øhrn, M. W., Kristin , & Berg, H. (2018). *Effektive materiellanskaffelser i Forsvaret - kartlegging av tidsbruk, forsinkelser og gjennomføringskostnader*. Retrieved from https://www.ffi.no/publikasjoner/arkiv/effektive-materiellanskaffelser-i-forsvaret-kartlegging-av-tidsbruk-forsinkelser-og-gjennomforingskostnader

Rawson, K. J. T., E.C. . (2001). *Basic Ship Theory Vol. 2* (5. Edition ed. Vol. 2): Longman Group Limited 1968.

Rekstad, J. E. (2022). Maritime helicopter operations [Assessmentof Maritime Helicopter operations in the Norwegian Armed Forces.]. Retrieved from https://www.stratagem.no/maritime-helikopteroperasjoner/

Rudnicki, T., Czerwinski, R., Polok, D., & Sikora, A. (2015). *Performance analysis of a PMSM drive with torque and speed control*. Researchgate.

Samatham, M., Naik, R., Reddy, B., & Kumar, G. (2018). A Study on Improvement of Fatigue Life of materials by Surface Coatings. *International Journal of Current Engineering and Technology, 8*. doi:10.14741/ijcet.v8i01.10878

Savitz, S. B., Irv, Buryk, P., Button, R. W., DeLuca, P., Dryden, J., Mastbaum, J., . . . Potter, A. (2013). *U.S. Navy Employment Options for Unmanned Surface Vehicles (USVs)*. Retrieved from https://apps.dtic.mil/sti/citations/ADA588081

Sivle, A. D. (2018, February 27th 2018). Sjøgang. Retrieved from https://snl.no/sj%C3%B8gang

Society of Naval Architecture And Marine Engineers. (1970). *Principle of Naval Architecture* (E. V. Lewis Ed.): SNAME, Society of Naval Architecture And Marine Engineers.

Speller, I. (2014). *Understanding Naval Warfare*: Routledge.

Strand, G. (2020). [Powerpoint presentation: Valg av fremdrifsmaskineri_diesel].

Strømmen, T. I. (2019). Sjøforsvaret mot 2040. Eit forslag til framtidig styrkestruktur for Sjøforsvaret. Retrieved from https://fhs.brage.unit.no/fhs-xmlui/handle/11250/2600546

SVA-Potsdam. Ducted propellers. In (pp. Illustration of 3-bladed ducted propellers). https://www.sva-potsdam.de/en/propulsion/#ducted-propellers: SVA-Potsdam.

The Norwegian Armed Forces. (2015). *Doctrine for maritime operations,* . Bergen: The norwegian defense staff.

The Norwegian Armed Forces. (2019). *The Norwegian Armed forces' joint operational doctrine* (M. as Ed.): The Norwegian Defence Staff, Norwegian Defence University College.

The Norwegian Ministry of Defence. (2022). Norway terminates its contract for the NH90 [Press release]. Retrieved from https://www.regjeringen.no/no/aktuelt/norge-leverer-tilbake-nh90-helikopteret/id2918079/

Transfluid. (2020). Battery Pack- innovative energy system for marine application. Retrieved from https://www.transfluid.eu/wp-content/uploads/2021/01/batterie-tf_gb_20.10_lq_rev2.pdf

Voie, Ø. (2019). *Det grønne forsvaret?* Retrieved from https://publications.ffi.no/nb/item/asset/dspace:6448/19-02096.pdf

Water World Electronics, B. (2020). WW 10.0 Manual. Retrieved from https://destilleboot.nl/wp-content/uploads/2020/08/Manual-WaterWorld-3.0-july-2020-English.pdf?__hstc=201047473.7bf9b801fb1a4d97cc16e4691efbf773.1669368789036.1669368789036.1669368789036.1&__hssc=201047473.1.1669368789037&__hsfp=3062105323

WhisperPower. Specifications M-SQ Pro 25. *M-SQ*. Retrieved from https://www.whisperpower.com/diesel-generators/m-sq-generators/m-sq-pro-25

Williams, A. P., & Scharre, P. D. *Autonomous Systems* (A. P. S. Williams, Paul D Ed. Vol. 2). act.nato.int: NATO.

Appendixes

Appendix I and J will come as separate files due to format.

- Appendix A: ISR concepts
- Appendix B: Sonar choice
- Appendix C: Preliminary design hydrostatic report
- Appendix D: Energy production and storage
- Appendix E: Weight breakdown
- Appendix F: Parametric study
- Appendix G: Energy consumption and operational profile
- Appendix H: Optimization of propulsor
- Appendix I: Linesplane A3 Preliminary
- Appendix J: Linesplane A3 Optimized