DEPARTMENT OF DESIGN, MANUFACTURE & ENGINEERING MANAGEMENT

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Feasibility study into a novel vessel design for accessing offshore wind turbines

By

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Signed:

Robert Macdonald

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Finally I would like to thank my family for support throughout the research and write up process.

Abbreviations

MPhil – Master of Philosophy

JONSWAP – Joint North Sea Wave Project

SWATH – Small Waterplane Area Twin Hull vessel

OWA – Offshore Wind Accelerator

DRM – Design Research Methodology

RC – Research Clarification (Stage 1 of DRM)

DS I – Descriptive Study I (Stage 2 of DRM)

PS – Prescriptive Study (Stage 3 of DRM)

DS II – Descriptive Study II (Stage 4 of DRM)

IRM – Initial Reference Model

FRM – Full Reference Model

TDM – Total Design Methodology

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Abstract

This thesis reports an investigation into the feasibility of a novel vessel concept, designed to allow safe access for personnel to and from offshore wind turbines in sea states in which the facility would be currently inaccessible. The problem of accessing offshore wind turbines is an issue that has been identified as a major cause of turbine downtime. Access is required to carry out maintenance and repairs but is often delayed by days or even weeks due to the weather conditions and the limitations of the current access procedures.

Blessing's Design Research Methodology was adopted to give the research structure. A literature review was conducted to identify the cause of the problem and establish the working window for which the vessel must be designed (the specification) and a review was completed to identify existing technology that could be utilised in the development phase. The concept design was then developed using Pugh's Total Design Methodology and a number of alternatives were developed and reviewed before a single concept was selected. The selected concept is a catamaran vessel with the capability to take on significant ballast water whilst jacking the deck away from the hulls, creating two distinct vessel configurations: the transit mode where it operates as a standard, fast catamaran for getting to and from sites and the transfer mode where it has a higher displacement and a reduced waterplane area, reducing deck movement in rough seas.

The developed design was analysed to identify the stability and sea-keeping characteristics of the design both computationally and physically in a hydrodynamic laboratory. The analysis identified significant reductions in vessel movement in heave, pitch and roll in the transfer mode when compared to the transit mode. This will allow safer personnel transfer in higher seas than the current crew transfer catamarans. The research concluded that the concept is feasible and outlines the further work required to commercialise the design.

1. Introduction

During the author's Undergraduate Product Design Engineering project work, issues were identified with access to and from offshore wind turbines. The current procedure was found to be dangerous and limited, causing costly time delays in accessing offshore turbines when maintenance or repair was required. A vessel concept was designed, shown in Figure 1, which increased the operational weather window and increases safety by minimising deck movement caused by waves. This MPhil thesis outlines further detailed research conducted to investigate the feasibility of this vessel concept in order to increase the safety and operational range of personnel transfers to offshore wind turbines.

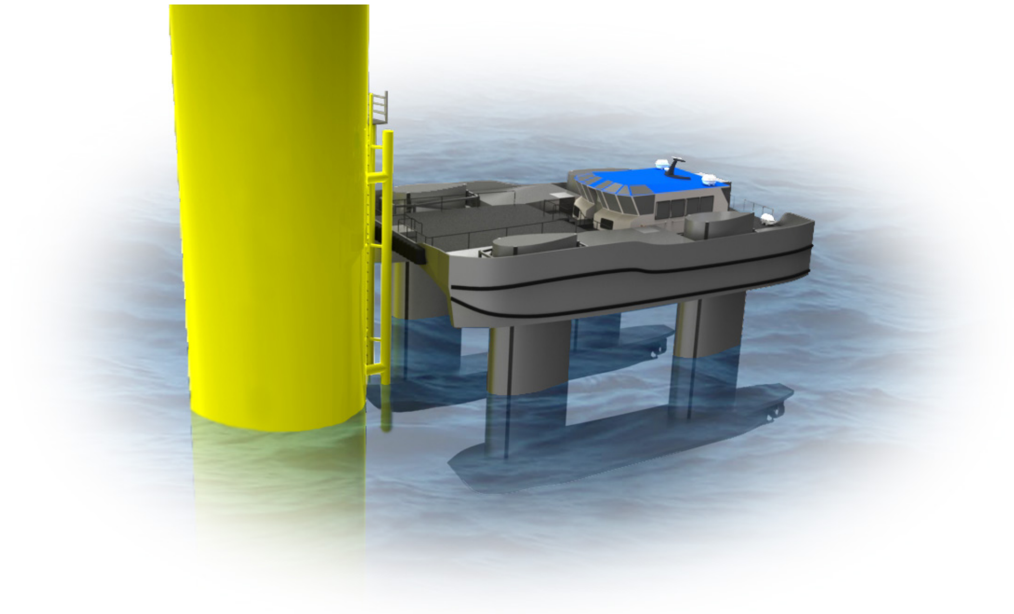

Figure 1 - Proposed vessel concept

Chapter 1 gives an overview of the thesis including background to the work, how the research area was identified and the context of the study. The chapter also highlights the aims and objectives of the work, the scope of the work and outlines the contribution to knowledge.

1.1. **Background to Project**

There is currently a government-led drive to reduce the cost to the consumer of electricity from offshore wind by addressing the technical challenges associated with producing energy offshore (Department of Energy and Climate Change, 2013). This has led to the identification of the reduction of production loss as a key area to reduce the cost per unit of electricity production (Crown Estate, 2012). Research (Macdonald, 2011) has shown that if the current procedures for operation and maintenance are not radically modernised, some £1.1 billion worth of production will be lost, annually, due to turbine downtime by 2020, in the UK alone.

One key contributor to this production loss is the difficulty in maximising the time that personnel can access the turbines for repairs and maintenance, even in adverse weather conditions due to the remote and hostile locations of the turbines (Smith, 2014). There is little in the literature addressing this issue. The access problem has formed the basis of this MPhil research, and the intention is to fill the research gap in this area.

The Carbon Trust (2010) conducted research that suggests personnel access to offshore turbines can only be gained around 50% of the year due to the limitations of the current procedures utilised. This means that turbines are often “down” (i.e. not producing power) for extended periods of time with respect to a comparable onshore turbine. This is compounded by the fast development of offshore technology, increasing the depth of water in which turbines can be located and the weather conditions they can withstand. Alongside this, the size of turbines is increasing (the most recent turbines are rated at up to 10MW) hence production loss is growing during periods of turbine downtime. Indeed it has been suggested that by 2020, over £385 million could be saved annually in the UK alone by increasing the access availability from the current 50% to 85% (Macdonald, 2011). This potential saving has been recognised by the industry and, to remedy it, significant time and funding is being put into research and development of innovative solutions. The Carbon Trust, supported by Det Norske Veritas (DNV) and the Crown Estate launched the “Offshore Wind Accelerator

Access Competition" (OWA) in 2010, which identified 20 technologies that they wished to see commercialised (Carbon Trust, 2014). A consortium of eight of the largest energy suppliers[1] has been gathered to contribute towards the development process, with the intention of commercialising technologies now. This will reduce installation and operational costs in the future, hence increasing the commercial viability of wind power.

The present thesis builds on the author's Undergraduate Product Design Engineering Degree project work, which produced a two-fold concept to increase the safety and operational range of access to offshore wind turbines. This concept comprised of two distinct aspects;

i. a transfer gangway, allowing safe passage from the deck of a moving ship to a fixed point on a wind turbine, and

ii. a novel ship concept on which the gangway would be mounted, with the ability to transform its configuration to best suit the task in hand.

The transfer gangway was the focus of the author's Undergraduate Degree, which set out to design a low cost solution to the access problem by developing a system that could be retrofitted to existing vessels to maximise safe access in high sea states. This design was shown to reduce the effect of the movement difference between a vessel deck and a fixed structure, however it was known that access would be maximised through the development of a vessel with reduced deck movement.

The novel ship concept was selected as a shortlisted entry, along with twelve other designs, in the Carbon Trust OWA Access competition. It was identified by industrial experts as having the capability to improve dramatically the time turbines are available to produce power and the safety of people during the transfer to turbines (Carbon Trust, 2010b). This MPhil research will focus on te second aspect of the two-fold concept.

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[1] Companies involved in the Carbon Trust OWA: *Scottish power, Scottish and Southern Energy, E.On, Dong Energy, Statoil, Stakraft, RWE, Mainstream Renewable Power*

1.2. Research Aim, Hypothesis and Objectives

The research aim was defined early in the work based on the knowledge developed in the literature review. The objectives were then set to define the steps required to achieve the goal. These are noted below:

Aim: To identify the feasibility of a novel vessel concept designed to increase the safety of access to offshore wind turbines in higher sea states than the currently available vessels.

Objectives: To achieve the aim, the following objectives were developed to undertake the research:

1. Review the current turbine access methods to identify any problems with them and the potential for improvement

2. Develop a suitable vessel concept in line with the hypothesis developed during the research

3. Evaluate the vessel concept for;
   I. the limiting operating environment;
   II. the operational procedures;
   III. the correct safety standards, and;
   IV. the operational practicalities of the design.

Hypothesis: Following the literature review a hypothesis was derived based on the developed knowledge of the problem, the environment and influences on vessel design.

> The proposed vessel concept will be shown to have significantly less deck movement in high sea states than the current service vessels. Hence it will allow safe transfer to offshore structures in more adverse weather conditions, whilst still maintaining the advantages of speed and maneuverability.

Throughout this thesis the objectives will be tackled individually and the overall suitability of the concept for the proposed purpose will be scrutinised in the discussion.

1.3. **Scope of Thesis**

The research conducted for this thesis focused on filling the gap identified in the literature review; i.e. research into vessel concepts suited to providing personnel access to offshore structures, in particular, wind turbines. The identification of this knowledge gap was a development of the author's Undergraduate project and was confirmed as an area of research by the Carbon Trust's provision of funding for the development of concepts in the discussed field. The research utilised a design approach to define the overall particulars of the concept, allowing analysis to be carried out on a detailed design concept. The feasibility was then analysed based on the vessel's response when subjected to simulated seas, generated to be representative of those found at offshore windfarm sites. The research scope extended to cover computational analysis and scale tank tests with a review of the outputted results. The outcome is an analysed design with a set of recommendations and further work, ready for the next cycle of development.

1.4. **Contribution to Knowledge**

The purpose of conducting research is to contribute new knowledge to the field in which the study is conducted. This research set out to identify if the innovative vessel concept proposed was feasible for the task it was designed for, providing an outline envelope for the design and development of a commercially viable vessel with the end goal of reducing the cost and increasing the safety of offshore wind turbine access. The following chapters outline the approach taken to identify how the knowledge gap was filled with a positive outcome that can now be used to develop further work.

2. Research Approach, Methodology and Methods

A recognised research approach has been used to guide the study and increase the potential for a successful outcome. This chapter gives an overview of the approach adopted for the study, the methodology selected for the research and the methods used at each stage. It also provides a visual map of the thesis with an overview of the work conducted during each section of the methodology.

2.1. **Significance of the study**

This study aims to determine the practical feasibility of a novel offshore vessel design, the purpose of which is to reduce vessel movement to allow vessel-to-structure transfers in higher sea states, with the intention of developing the vessel for the offshore wind industry if proven feasible. The access problem for offshore structures exists in a number of industries and has been the focus of considerable research (Leske, 2009; van Bussel et. al., 2001; Musial and Butterfield, 2006) for a number of years for two reasons; increasing the safety of personnel and reducing costs of offshore operations.

The identification of a vessel design that increases the safe operational range of offshore operations is therefore significant in an industrial application and can then be used to attract investment for development. The significance of this phase of the study is to determine if the concept is feasible and therefore provide information to make an informed decision as to whether to develop the vessel design further.

2.2. **Approach**

To ensure academic rigour is adopted when approaching research, many academics suggest research methods must be aligned by selecting an approach prior to commencing the research (Saunders et al., 2003; Easterby-Smith et al, 2008). This includes an epistemological stance, a research approach and a methodology. By defining this at the start of the research, the correct strategy and methods can be used for the study.

Easterby Smith et al. (2008) describe three types of epistemological stances: Positivist, Relativist and Interpretivist (also known as social constructivist). The main differences of these stances are shown in Table 1 below.

Elements of Methodology	Positivism	Relativism	Social Constructionism
Aims	Discovery	Exposure	Invention
Starting Points	Hypothesis	Propositions	Meanings
Designs	Experiment	Triangulation	Re-flexibility
Techniques	Measurement	Survey	Conservations
Analysis/ Interpretation	Verification/ validation	Probability	Sense-making
Outcomes	Causality	Correlation	Understanding

Table 1 - Methodological Implications of Different Epistemological Stances (Easterby-Smith et al., 2008)

This research was based on the discovery of an existing problem within an established industry, which led to the development of hypothetical solutions to the problem. Identification of the root cause of the problem led to the commencement of a design process to identify a solution to the issues highlighted. Computational models were used in experiments to gather quantitative results with respect to measurable criteria and used to analyse the designs. The results were then validated using physical models and the causality of the outcomes was discussed. Based on Easterby-Smith et al.'s definitions a positivist approach was therefore selected for the basis of this research – one of discovery, hypothesis, experiments and validation. Table 2 below identifies the stages of this research with respect to a positivist stance.

Elements of Methodology	Positivism	This Research
Aims	Discovery	Identification of the access problem through literature review
Starting Points	Hypothesis	Development of a suggested design and how it would work
Designs	Experiment	Computational analysis of design
Techniques	Measurement	Outputs of computational analysis
Analysis/ Interpretation	Verification/ validation	Tank testing of physical model
Outcomes	Causality	Discussion of impact of results

Table 2 – Stages of research with respect to positivist stance

To support the positivist research stance, a deductive approach was also chosen. Trochim (2006) states there are two types of reasoning approach: deductive and inductive.

A deductive study is sometimes informally known as a “top down” approach, whereby a theory is converted to a testable hypothesis, through which confirmation is sought through observation.

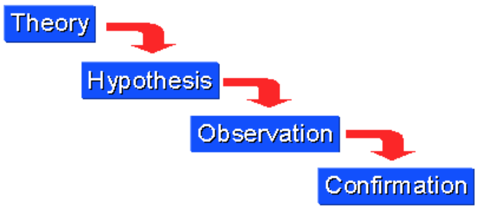


Figure 2 - Deductive Approach

In this research a deductive approach was chosen to provide quantitative confirmation that the specific design developed was suitable for the purpose.

2.3. **Methodology**

This research was developed from undergraduate Product Design Engineering Masters work, which focused on the identification of a range of solutions to the problem of accessing offshore wind turbines. The concept developed during this research was theorised during the undergraduate work.

A review of various methodologies, both research and design based, led to the selection of two: Blessing’s Design Research Methodology (DRM) (Blessing, Chakrabati and Wallace, 2009) was used as the overall methodology for this thesis, and stages of Pugh’s Total Design Methodology (TDM) (Pugh, 1991) were employed during the design phase of the study.

Blessing’s DRM was selected as it provides a rigorous and structured approach that is intended to address all facets of the phenomenon of design in a circular process. This allows research to be carried out in a methodical way, with clearly defined processes and iteration loops built into the methodology (Blessing, Chakrabati and Wallace, 2009). Figure 3 gives a high level overview of the DRM process, with identification of the use of Pugh's design research methodology during the Prescriptive Study.

Total Design is said to be the *systematic activity necessary to take a product from the identification of the need through to the selling of a successful product to meet that need* (Pugh, 1991), and DRM is said to *help design research become more effective and efficient,* specifically by *providing a framework for design research* (Blessing, Chakrabati and Wallace, 2009), amongst other objectives. It was therefore considered that the combination of the two methodologies provided the research with a structure throughout the project.

Since this research undertook the development of a concept, a specific product design research methodology was adopted. Pugh's Total Design Methodology was selected as a systematic approach to identifying the market need, defining the specifications, developing and selecting concepts, detailing the design and preparing the design for the market. Specifically, stages 2, 3 and 4 were utilised: Specification, Conceptual Design and Detailed Design and Analysis. The selection of a product design methodology rather than a ship design methodology was intentional, as discussions with a number of naval architects highlighted the potential advantages of tackling such a unique design problem with a 'blue sky' approach. Figure 3 below gives an overview of Blessing's TDM and highlights where Pugh's TDM was utilised.

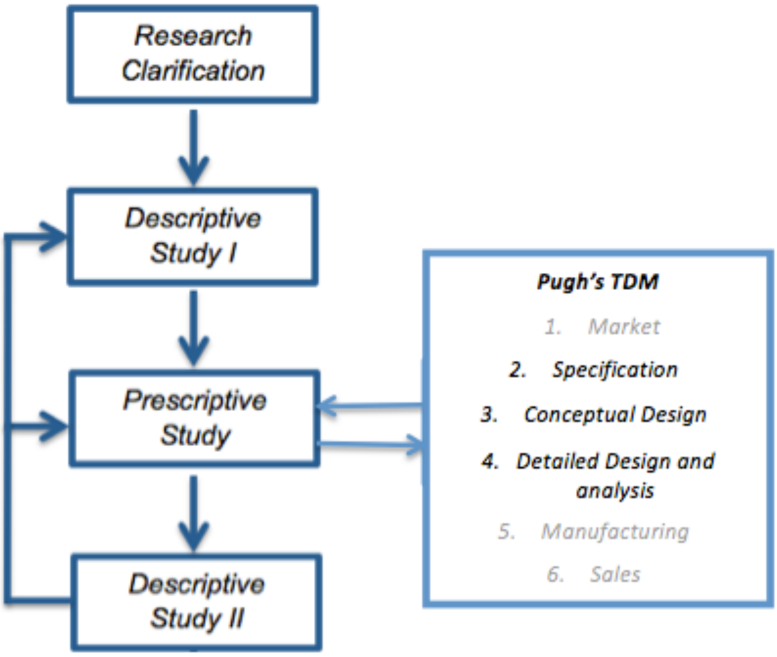


Figure 3 - Blessing's Design Research Methodology

2.4. Research Methods

The use of the two methodologies allowed flexibility in the methods used throughout the research process. This section gives an overview of the methods used in each stage of the process, which is tabulated with the outputs of each stage in Table 3.

Research Stage	Methods Used	Outputs
Stage 1: Research Clarification	Semi-structured interviews Observations Case Study Literature Review	Aims, Objectives & Hypothesis Initial Reference Model
Stage 2: Descriptive Study I	Literature review Technology review Data Analysis	Full Reference Model
Stage 3: Prescriptive Study	Brainstorming Focus Groups Fast Visualisation Evaluation Matrix	Concept CAD Model Variable design parameters
Stage 4: Descriptive Study II	Scale Modelling Data Collection Quantitative and qualitative data analysis	Analysis results Verification

Table 3 – Methods used at each stage of research

Stage 1: Research Clarification – A review-based approach was adopted for the first stage of the DRM, as an extensive literature review, a technology review and a functional review had been conducted in the UG Masters project (Macdonald, 2011). A literature review was conducted to gather secondary research, industry experts were consulted through semi-structured interviews and site visits allowed observations to be made. Case studies of current state of the art vessels were also conducted, to determine the method currently adopted to overcome the access problem. Through this research an Initial Reference Model (IRM) was developed, based on the current standard for accessing offshore turbines.

Stage 2: Descriptive Study I - As with Stage 1, the initial descriptive study was conducted using a review-based approach. A thorough literature review of work conducted in ship design for accessing offshore structures was conducted, alongside a detailed technology review of equipment and designs currently utilised in offshore industries.

Data analysis was conducted on wave data representative of sites where the vessel is expected to operate. During this stage a Full Reference Model (FRM) was developed from the initial model outlined in Stage 1. A reference vessel was developed to allow direct comparison of the analysis results.

Stage 3: Prescriptive Study – Stage 3 focused on developing a conceptual design to address the issues identified in the literature review with accessing offshore wind turbines that could be used for analysis purposes. Concept generation methods were used, with the primary aim of developing alternatives to the proposed design. These included brainstorming, idea generation focus groups and morphological charts.

Concept selection methods were then employed with the intention of tailoring the concept to the industry. An evaluation matrix was drawn up and criteria were chosen to evaluate the concepts against, including cost, safety and reliability amongst others, in comparison to the Reference Model drawn up previously. CAD models were developed as a fast visualisation method to allow industrial input to be gathered through focus groups. These groups helped identify any aspects of designs that would inhibit commercial uptake, the likes of which may have been overlooked.

The selected design was developed using a combination of CAD modeling and hand calculations, allowing initial analysis to guide the development of the design. Weight distribution, waterplane area and other factors influencing the seakeeping of the vessel were explored.

Stage 4: Descriptive Study II – The final stage of the research focused on gathering the results from the performance of the vessel, allowing an analysis to be made on the functional and commercial aspects of the design. Hand calculations from the previous stage were refined to increase the accuracy of the design, before it was analysed computationally by a professional company: Safety at Sea. The analysis collected data using NAPA software to identify static and dynamic characteristics of the design and a resistance evaluation was carried out to determine the likely speed the vessel could travel through the water. On competition of the computational analysis the design was validated through modeling and testing in a hydrodynamic laboratory.

Once the quantitative results had been analysed, a qualitative analysis was made on the impact of the design on the industry. Industrial partners were consulted to determine if the specific aspects of the design were considered suitable for the application, and the literature was further referred to for comparison to the current state of the art vessels.

2.5. **Thesis Structure and Map**

This section gives an overview of the chapters and provides a thesis map (Figure 4) showing the links between the methodology and the chapters and the methods used at each stage.

Chapter 1 introduces the purpose of the study, gives a background of previous work carried out by the author and the significance of the study, highlights the research hypothesis and objectives and the scope of the thesis.

Chapter 2 details the research approach adopted, the methodology employed and the methods used at each stage of the study. A thesis map is also provided which gives a visual overview of how the stages of the methodology tie in with the thesis chapters.

Chapter 3 assess the current literature available on the subject. This section is split into four sections:

1. Wind farm research
2. Environmental research
3. Vessel design methods
4. Technology review

Firstly, a review of the current offshore wind industry is carried out, including the expected growth, the effects of this on the access market, the current access procedures and the environmental factors. Following this, the environmental conditions expected at site are reviewed and the operational boundaries are defined. Vessel design methods are researched subsequently and the current methodologies and procedures used when developing new vessel concepts are reviewed. Finally, the technology review identifies the standard vessels used for personnel access on operational wind farms, the technology being developed to improve access and technology that could be utilised in the design of a new concept.

Chapter 4 focuses on the vessel design. It gives an overview of the original concept, the considerations that were taken into account when developing the concept, the functional requirements, a brief overview of some of the alternatives considered and the selection criteria. A Full Reference Model is detailed in this section to allow direct comparisons during evaluation.

Chapter 5 gives details on the development of the design, with an overview of the outputs from the design process along with the safety requirements and general layout. Supporting information is available in the appendices, specifying the way that the structure, hull form, and specific drive mechanisms were selected. This chapter also gives an overview of the analysis methods used on the vessel concept, including; initial calculations, speed and resistance analysis, stability analysis, sea-keeping analysis and tank testing. The results of the analysis are also given in this section.

Chapter 6 discusses the results of the analysis and the meaning of these in an operational context. The stability results are reviewed with respect to the correct design standards and a comparison of the sea-keeping results between the two modes of operation is made. The tank testing results are also discussed identifying the differences between the computational and physical results as well as the meaning of these on a full scale vessel.

Chapter 7 draws the thesis to a conclusion, with reference to the original research objectives. Future work is also discussed, including the next steps in the development of the design, the further evaluation required, further modelling and the potential for carrying out an economic study to take the concept to market.

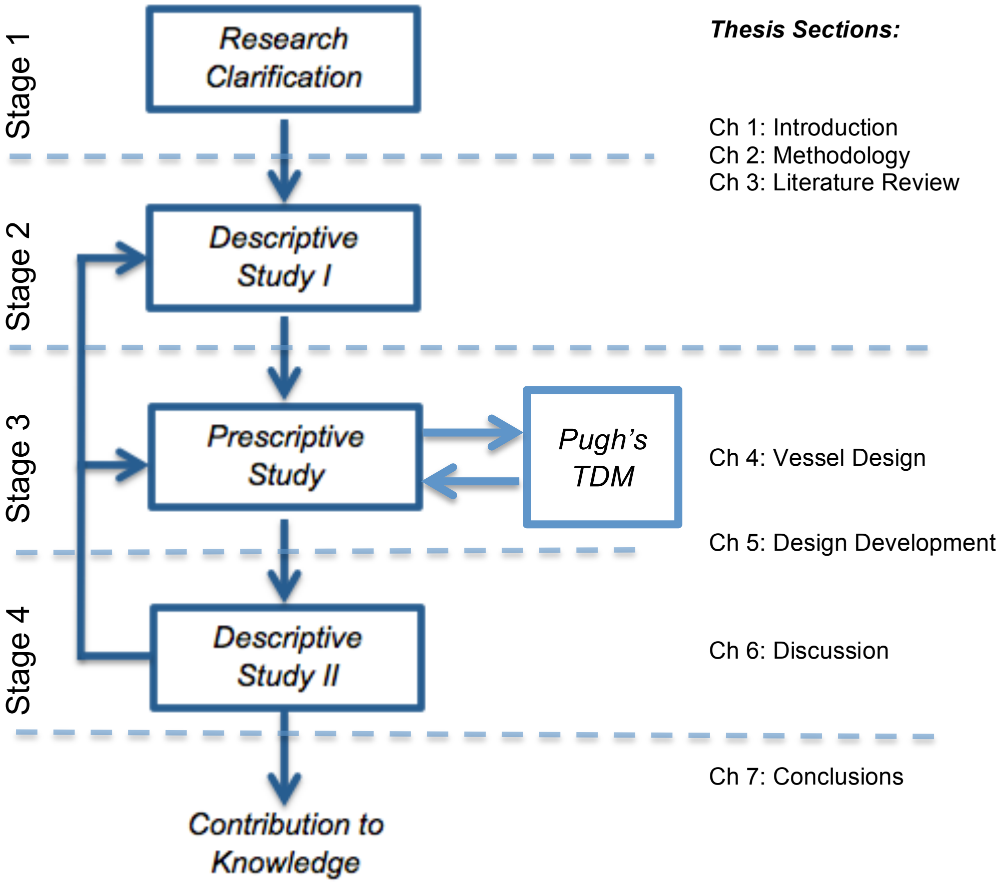


Figure 4 - Thesis Map

3. Literature Review

A literature review was conducted in line with the selected methodology for two of the DRM stages: Research Clarification (RC) and Descriptive Study I (DS I). This section gives an overview of the research conducted, with specific focus on the offshore wind industry and in particular the access market. An environmental review is detailed with specific focus on the expected operating area and ship design methodologies and design analysis approaches have been researched. A technology review was also conducted and the section concludes with the description of the Initial Reference Model developed from the work conducted in RC and DS I.

3.1. **Offshore Wind Research**

Low cost renewable energy is crucial to the development of a diverse, sustainable and low-carbon energy mix (DECC, 2013) and offshore wind is poised to play a very significant role in this. Development zones for offshore wind farms were allocated by the Crown Estate in 2010 with the potential of producing a quarter of the United Kingdoms total electricity needs by 2020 (Crown Estate, 2010) and it is believed the coast of Scotland could provide up to 25% of the entire European resource if harnessed effectively (Scottish Renewables, 2013). Assuming just one third of the UK wind potential was developed, the country could become a net exporter of electricity (i.e. produce more energy than is used) by 2050 (Huhne, 2010) however research has shown that if the current procedures for operation and maintenance are not radically modernised, some £1.1 billion worth of production will be lost, annually, due to turbine downtime by 2020 in the UK alone (Macdonald, 2011).

The UK Government are committed to developing the Offshore Wind industry due to the ambitious carbon reduction targets they have set. This commitment is already evident as *the UK has been the world leader in offshore wind since October 2008, with as much capacity already installed as the rest of the world combined* (Renewable UK, 2014). This resource provides opportunity for both significantly reduced carbon emissions and substantial revenue (Crown Estate, 2012).

3.1.1. ***Market Research - Offshore Wind***

The offshore wind market is seen in the UK, and globally, as a huge opportunity to produce low-carbon energy reliably and, in the long run, in a cost effective manor. It is believed the sector could deliver in the order of £7 bn Gross Value Added (GVA) to the UK economy (excluding exports) and support over 30,000 full-time equivalent UK jobs (Ogilvie, 2013). Offshore wind is still small compared with global onshore capacity but it is growing rapidly across Europe and worldwide (Neddermann, 2014), largely driven by the huge energy potential available.

Targets have been set to accelerate the development of the industry, with the UK government estimating 13 GW of installed capacity by 2020 (DECC, 2011). Investments are being made across the country to develop the supply chain to meet this goal, with significant expansion of the industry, said to have grown by a record 79% in a 12 month period in 2012-13 (Renewable UK, 2013). In 2013, the United Kingdom added 1.9 GW to the grid, 39% of which was offshore (DECC, 2014). Table 4 below identifies there is almost half as much offshore turbine capacity in construction as there is already operational, and almost three times as much in the pipeline, highlighting the growth rate over the coming years.

UK Offshore Status – 30 June 2013		
Status	**Number of Schemes**	**MW**
Operational	20	3,321
Under Construction	4	1,297
Approved (not built)	8	2,048
In Planning	11	7,662

Table 4 – Offshore Windfarm statistics June 2013. Source: Renewable UK, 2013

Looking forward, this growth is expected to continue. *In the UK alone, the expectation is for 25 GW of offshore wind power by 2020, with a maximum planned potential of 32.2 GW* (Cockburn, Stevens and Dudson, 2010). Table 4 indicates the way in which the industry is growing: namely larger capacity per project, shown by the operational schemes averaging 166 MW per scheme, schemes under construction averaging 324 MW and those in planning boasting over 500 MW per scheme. This increased project size will be provided by larger capacity turbines, built in larger numbers per farm with higher overall efficiency. In 2013, the average size of wind turbines delivered to market was 1.9 MW, up from 1.8 MW in 2012 (REN21, 2014), however the average offshore turbine installed in Europe in the same period was 4MW (Bell, 2013).

The Crown Estate is in charge of leasing the seabed to potential developers, which they are coordinating in using leasing rounds (Renewable UK, 2014b).

- **Round 1** launched in 2001 and saw the promotion of 18 sites in England and Wales, with a potential capacity of 1.5 GW. Development of this round is now almost complete.

- **Round 2** then followed, in 2003, and was much larger following the success of Round 1. Sites were located further offshore and in deeper waters formed in three strategic areas; Greater Wash, Greater Thames and Irish Sea. Round 2 will add another 7 GW of capacity when fully operational.

- **Round 3**, released in 2010, makes up the largest leasing round to and is comprised of nine UK based zones, further offshore with the potential for more capacity.

These rounds, supported by the statistics outlined in Table 4, clearly show the trend of increasing farm capacity, turbine size and distance from shore. The increase in power of turbines and size of farms has been made possible due to the development of turbine technology, making them more efficient and therefore more powerful, coupled with the additional research on how turbines are secured in position, allowing them to be developed in more locations which provide higher, more consistent wind speeds and therefore energy yield (Siemens, 2010). To date, seabed mounted foundations adapted from the oil and gas industry have been the focus for deep-water offshore installations, but new designs are under development for floating offshore structures, allowing more energetic sites to be developed on (see Figure 5 below).

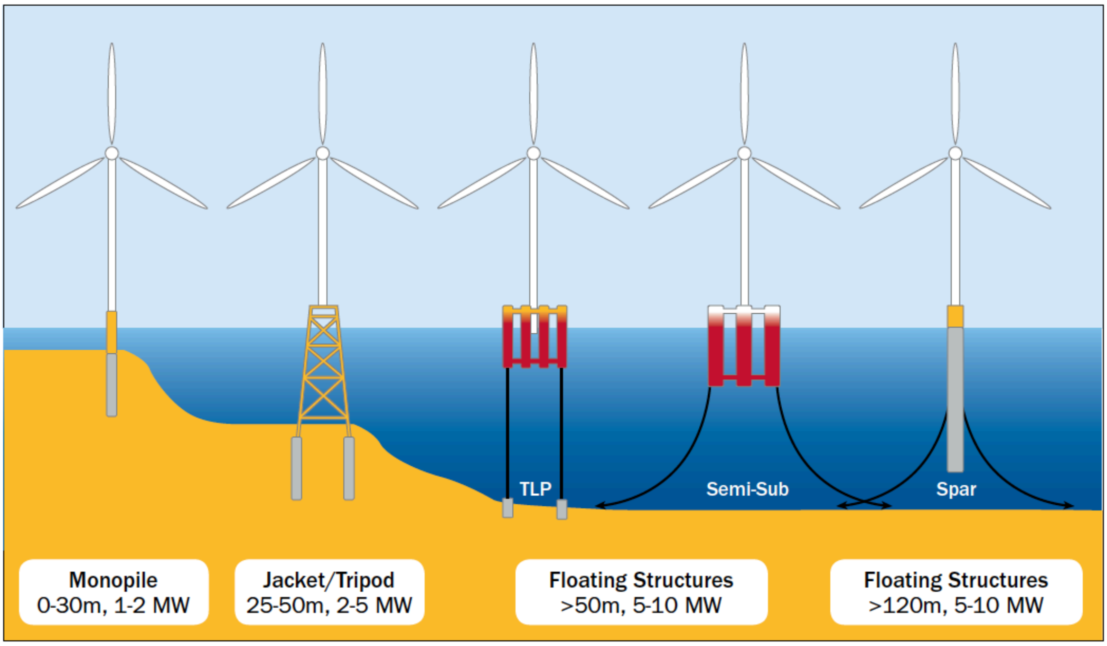


Figure 5 – Foundation structures for offshore wind turbines. Source: EWEA, 2013

This rapid development means there is a requirement for the supporting supply chain to develop quickly to support the industry, and building a strong supply chain remains a priority for deep offshore deployment (EWEA, 2013). Moving further offshore poses challenges for accessing the sites on a daily basis and the increasingly energetic sites will mean greater sea-states, increasing the complexity of operations and maintenance.

3.1.2. ***The Value of Energy Production***

The offshore wind industry, as with other energy industries, creates revenue by generating and selling electricity. Although many factors influence the rate at which an energy production technology is adopted, for example impact on environment, land space usage, proximity to market, emission of greenhouse gasses (Ocean Energy Council, 2014), the main driver is the cost of energy production. The wholesale cost of electricity fluctuates significantly due to the variations in demand and generator capacity (van de Ven et. al., 2011) and the cost to the end user is determined on the costs over an extended period, hence to compare energy production technologies it is useful to understand the lifetime costs.

A commonly adopted measure of cost-effectiveness is the Levelised Cost of Energy (LCOE). The LCOE is the lifetime cost of the project per unit of energy generated (Crown Estate,

2012) which may not directly reflect the cost of energy at a specific time but is a very useful tool for ranking technologies based on cost-effectiveness over an extended period. Branker, Pathak and Pearce (2011) say it is *abstraction from reality… made to remove biases between technologies* and Allan et. al. (2011) advocate LCOE as a way of *benchmarking the economic viability of different electricity generation technologies.*

The estimated LCOE of offshore wind in 2012 was said to have levelled at around £140-160 per MWh (Carbon Trust, 2012) which, as Figure 6 shows, is relatively high compared to other large-scale energy production technologies in the UK (Harris et. al., 2013).

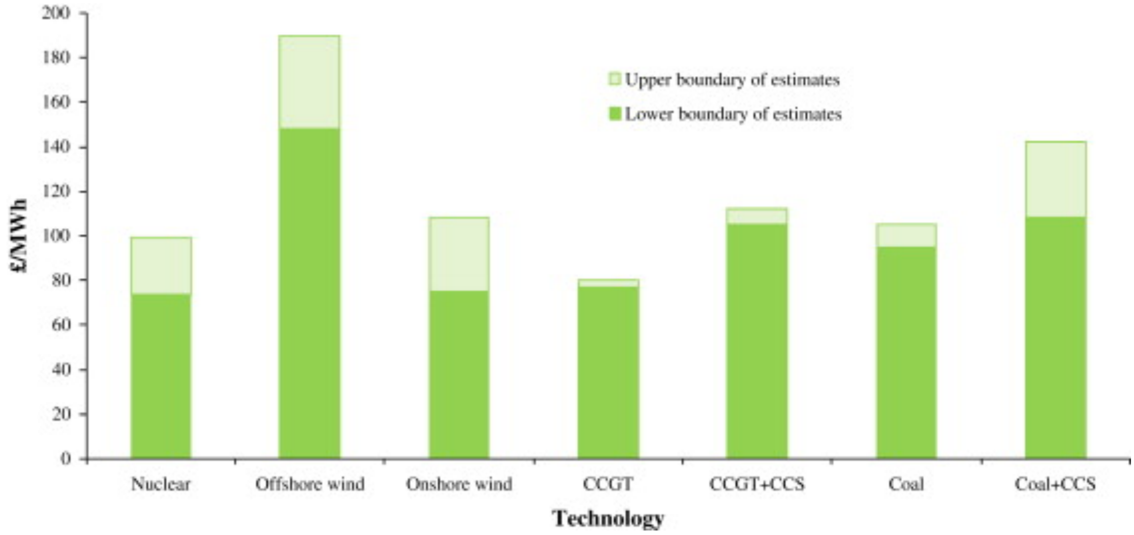


Figure 6 - Comparative LCOE of large-scale energy production technologies in the UK. Source: Harris et. al. (2013)

The Frankfurt School–UNEP (2014) estimated that between 2009-2014, the LCOE of onshore wind fell by around 15%, however the LCOE of offshore wind in the same period rose by roughly 41%. This increased cost is associated with increased water depths of windfarms, increased distance from shore, more energetic sites and increased demands on construction and operation vessels (Carbon Trust, 2012). It is estimated the total capital expenditure for offshore wind projects for developing 30 GW of offshore wind in the UK is between £72 bn and £84 bn (Scottish Enterprise, 2009).

Although the costs are high in comparison with other technologies, the UK government has made clear its commitment to offshore wind (Fulton, 2011) as it is seen as the best opportunity to reach the 2020 targets set to produce at least 15% of the country's energy demand from renewable sources (DECC, 2011). To achieve this the industry must grow and the costs must come down.

To maintain growth of the industry and encourage the adoption and development of renewable energy production, the government are currently supporting the offshore wind industry heavily, in two ways. Firstly, the cost of energy produced is subsidised so that it can be sold to consumers at a competitive price. Feed in Tariffs (FITs) make the production of energy worthwhile for developers, without the cost being directly passed to the consumer. Secondly, there is heavy investment in reducing the LCOE. The Offshore Wind Cost Reduction Task Force aims to reduce the levelised costs of offshore wind to £100 per MWh by 2020 (DECC, 2014b) to make it more cost competitive with alternative energy production methods and less reliant on government support.

As the LCOE is calculated on the lifetime cost, including installation, operations and electricity export, three target areas for reduction of the LCOE have been identified.

1. Reduced capital costs
2. Reduced transmission costs
3. Reduced operations & maintenance (O&M) costs

Significant investment is driving research into increased efficiency wind turbines, reduced cost installation methods and improved cable deployment techniques (Maples et. al., 2013) to reduce capital costs in setting up offshore windfarms. Transmission costs are being targeted by investing heavily in the grid infrastructure throughout the UK, allowing easier and therefore more cost effective hook up of farms onto the national grid, whilst targeting co-ordination of offshore projects in the aim of reducing overall costs (Green and Vasilakos, 2011). Finally, operations and maintenance strategies are being reviewed to identify cost reductions over the operational life of the windfarms.

3.1.3. Operations and Maintenance Research

Due to the rapid expansion of the offshore wind industry, the primary focus to date has been on the development and construction of the equipment offshore, however as more offshore turbines come online the challenge of keeping them operating is starting to require considerable attention (GL Garrad Hassam, 2013). Operations and maintenance activities are conducted throughout the life cycle of any power plant to ensure the equipment is maintained in good order and account for up to 25% of the LCOE of an offshore wind farm (Smith, 2014) hence reducing cost of O&M activities can have a significant impact on the LCOE. However, another key focus of O&M on wind turbines is maintaining a high turbine availability to reduce any lost revenue.

Onshore wind turbine availability (the percentage of time it is capable of operating at full capacity) is often upwards of 98%, however this is maintained by an average of four turbine visits per annum for bi-annual routine maintenance and repair actions, estimated twice a year (van Bussel and Zaaijer, 2001). Offshore wind turbine availability is significantly lower.

Harman, Walker and Wilkinson (2008) researched the reasons for reduced availability of offshore wind turbines by reviewing the availability trends at operational wind farms. The research identified access to turbines as a key factor in the reduced availability, due to the inability to access turbines when they require repair. Further research (Maples, 2011; DECC, 2011; GL Garrad Hassan, 2013) supports this, identifying the two key limitations of access to be;

1. **Transit** to and from site from a base location, which is often limited or severely extended by poor weather, and
2. **Transfer** of personnel between the access vessel and the turbine to carry out the work required once on site.

These issues will be compounded as technology advances, allowing turbines to be located further from shore in more energetic sites. This will mean longer transit times and increased sea states on site. Furthermore, operations and maintenance costs will increase in significance in the LCOE as the development of new technology (for example floating platforms) allows reduced installation costs. With seabed mounted foundations, offshore wind turbine installation is a capital-intensive technology, however this is not believed to be the case in some designs of floating platforms, where devices can be assembled onshore then towed out to sea.

The National Renewable Energy Laboratory (NREL) conducted a study into the impact on turbine availability and reduction in revenue losses of six changes in operations and maintenance strategies (Mapels et al., 2013) including;

- Mother Vessel accommodation
- Helicopter Access
- Vessel contracts
- Improved Crew Transfer System
- Spare part storage
- Advanced Condition Based Monitoring

The results of NREL's investigation highlighted the top two changes in strategy to have the largest quantitative advantages as mother vessel accommodation and improved crew transfer systems. Both of these strategy changes focus on increasing availability of turbines by increasing the accessibility of the turbines. Mother vessel accommodation allows increased access due to a reduction in weather window required to carry out work; shorter good weather periods are required due to the reduced transit time. Improved crew transfer systems focuses on increasing the accessibility by increasing the safe operational range, effectively increasing the operable weather windows. From this research it was deduced accessibility to turbines is key for the reduction in the LCOE of offshore wind.

3.1.4. ***Offshore Wind Turbine Access Research***

Access has been identified as key for reducing the costs of O&M strategies on offshore wind farms, however it is also crucial during the installation phase. The Offshore Wind Cost

Reductions Pathways Study (2011) has identified an increase in operational access working windows could reduce installation programs by up to 8% by reducing the time limitations on activities such as cable hook-up procedures.

The limitations of being unable to access offshore turbines was estimated to cost the industry over £1.1 bn per annum by 2020 in the UK alone (Macdonald, 2011) and the Carbon Trust have estimated that over the lifetime of the Round 3 windfarms, upwards of £3 bn additional revenue could be created by *keeping turbines generating electricity in the harshest sea conditions…and would also save an extra 1.3 Mt CO2 per year* (de Villiers, 2012).

The current personnel transfer procedure, referred to as 'bump-and-jump', has to date been conducted by butting a vessel against the fender bars on the transition piece, whilst the technician steps from the vessel onto the ladder on the side of the structure (see Figure 7). The issue with this procedure however is that the vessel will undoubtedly be moving and the turbine will be static, creating a situation which has been likened *to requiring a cowboy to dismount from a bronco while it is still bucking wildly* (Marsh, 2013).

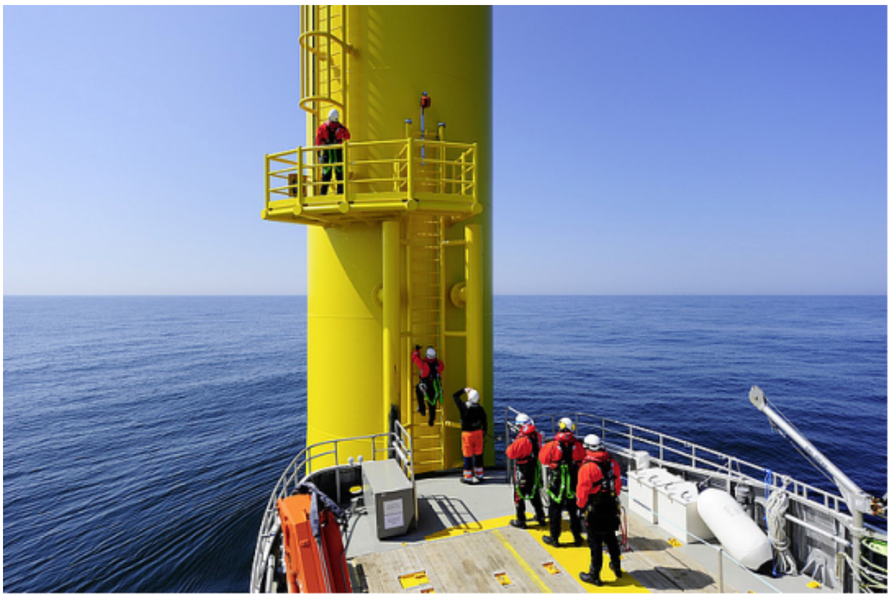


Figure 7 - Current Access Procedure. Source: Simon (2014) Marine Renewables News

The current vessels, reviewed in more detail in Section 3.4.1, provide access in wave heights of up to 1.5 metre significant wave height (SWH) (Carbon Trust, 2011; Macdonald, 2011; Marsh, 2013). Research conducted by the Carbon Trust (2010) identified this allows access in around 200 days per year on average, giving an accessibility of around 55% at the current sites. As wind turbine technology develops, this accessibility at a 1.5 m SWH will reduce as the average wave height is expected to increase.

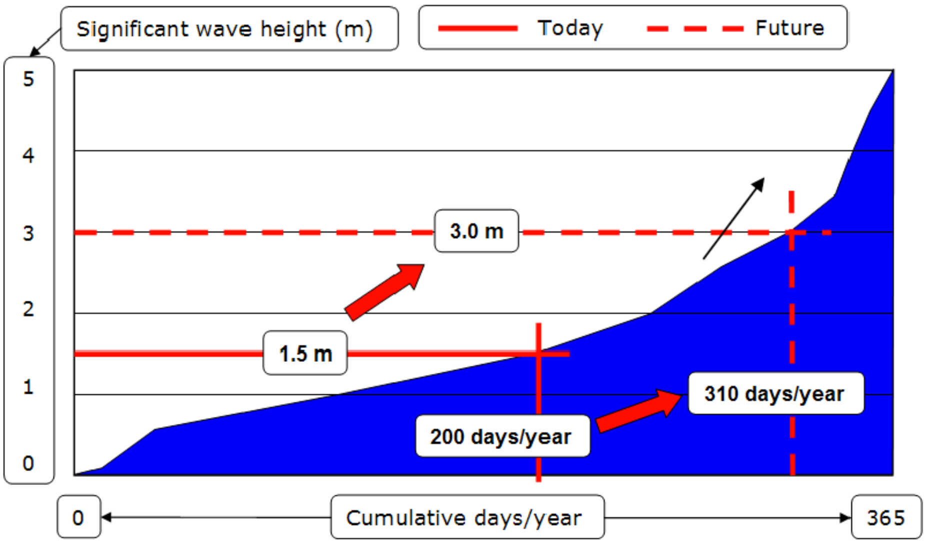


Figure 8 - Cumulative frequency of significant wave height in an average year. Source: Carbon Trust, 2010

Two main issues have been identified with the present access system; wave height and safety (Macdonald, 2011). Access is limited by the sea conditions and, as mentioned previously, is currently restricted to wave heights of 1.5 m SWH. From informal interviews with vessel crew from North Hoyle Windfarm even the 1.5 m threshold is often unachievable, dependant on the other variables including bumper orientation, wave period, wind and tide. These factors induce movement difference between the bow of the vessel and the turbine that can make it difficult to step from one to the other and can also hamper the ability to maintain vessel position in high sea states. Both of these factors make it unsafe to perform transfers in sea-states over 1.5 m SWH.

The safety risks are compounded by the unpredictable nature of the sea. Figures released by the governments Marine Accident Investigation branch in early 2014 highlighted an increased number of collisions between windfarm service vessels and offshore turbines, quaysides and other vessels (Crisp, 2014). This follows concerns raised by Dai et. al. (2013) that increased traffic and size of wind turbine maintenance vessels may cause future problems. Dai et. al. state the main underlying cause of collisions of this type in the oil industry are complex structures, inadequate training and violation of operating procedures.

Procedures are set out prior to work commencing, however once on site the conditions cannot be easily and accurately measured and therefore the transfer is based on judgement of the vessel skipper and of the transferee. The decision to make the transfer is made by a mutual agreement after assessing the conditions at three stages; firstly an assessment of the weather conditions and forecast from onshore is made, then an assessment on site before docking with the turbine before a final assessment when the vessel is at the base of the turbine. Crisp (2014) however has identified workers are often pressured into working in adverse conditions to get jobs completed, especially if conditions change on site.

A number of practices are in place to try to reduce the risks however these can also cause additional issues. The current practice of powering the vessel towards the turbine creates a serious risk of crushing the technician should he/she fall. Fall arrest systems are used but these can cause problems as there have been instances where the transfer vessel's bow has dropped in a wave trough and the fall arrest wire has pulled the technician from the deck.

This standard transfer procedure should be conducted in a safe and regulated manor. There are a number of procedures that have been adopted by the industry to reduce risk, such as imposing a minimum gap between the bow of the transfer vessel and the ladders to minimise risk of crushing, however the procedure is still regarded as relatively dangerous and more rigorous safety standards are required (Marsh, 2013).

3.2. **Environmental Review**

The drive for the development of renewable power is focused on deriving energy from the environment; hence any study focusing on developing a design to operate in the renewable energy sector must consider the environmental factors. This section identifies the key aspects of the environment that will influence the design approach and reviews the research carried out in each of the focus areas.

3.2.1. Wind Resource Research

A reliable and predictable local wind resource is one of the most important factors influencing the economic feasibility of a windfarm (Haaren and Fthenakis, 2011). Offshore sites boast a high resource when compared to onshore sites, as the wind is unobstructed by land masses (Gonzáleza et. al., 2010). The high resource leads to an increased capacity factor; the measure of how much energy a generator produces over a period of time as a percentage of the maximum it could produce in optimal wind conditions (Danko, 2014). The overall production is never 100% as the wind does not always blow, however offshore windfarms have an average capacity factor roughly 10% higher than onshore windfarms, averaging 36% compared to an average of 27% for onshore wind farms (Boyle, 2006). This generates increased revenue per turbine; an attractive lure for developers even with the high installation costs (Danko, 2014).

Forecasting a wind resource is crucial for a number of reasons; combined with historical weather data it is used to select a site for development of the wind farm, it is required to forecast operational windows during installation, operation and maintenance and it is used to predict the energy yield from a wind farm, important to provide a balanced energy mix (Higgins et. al., 2014). Wang, Guo and Huang (2011) classify forecasting techniques into three time categories:

1. Immediate-short-term (8 hours-ahead) forecasting,
2. Short-term (day-ahead) forecasting, and

3. Long-term (multiple-days-ahead) forecasting.

These can be predicted with a physical approach, using data such as atmospheric pressure and temperature, or a statistical approach, using historical data.

Capacity factor is heavily affected by turbine downtime: if a turbine is offline for a period of days, it has a large impact on the capacity factor. Onshore turbines can be accessed as soon as the technician can get to site, however offshore the weather plays a large part in how quickly the turbine can be accessed: often delays in accessibility can be measured in weeks rather than hours. Kusiak, Verma and Wei (2012) identify the main causes of turbine inefficiency (and therefore reduced capacity) as power curtailment, caused by turbines being shut down when too much energy is being produced, and faults. Additional causes of downtime are scheduled maintenance, where the revenue lost is relative to the wind speed during the period of work. Increased accuracy in forecasting could be used to predict energy yields, hence reduce curtailment requirements by scheduling grid input levels. Furthermore, forecasting to schedule maintenance for periods of low wind could maintain efficiency and reduce lost revenue due to downtime.

3.2.2. ***Wave Research***

For vessel design, the dominant input to the design process is dependant on the specific task to which that ship is to be used for. For example a ship designed for transport of goods from point to point will be driven largely by the hydrodynamic efficiency (and therefore fuel efficiency) of the hull. As the purpose of this study is to identify a design to improve access in higher sea-states by reducing vessel movement, waves are the dominant factor.

Waves can be generated by a number of factors, including objects moving in the water and large land mass movement, however the most common cause of waves is wind (Presnell, 2013). Wind waves are the transfer of energy through the water, generated by the interaction of the air, in the form of wind, with the water surface. Wind generates ripples on the water surface that grow through levels of roughness, the size driven by three factors

(Oceana, 2014); wind speed, wind duration and fetch (the area over which the wind is blowing).

> *The generation of waves on a body of water depends on the strength of the wind, the length of time for which it has been blowing (duration) and the distance over the water for which it has been acting (fetch) (Owen, 1987).*

Waves generate under any wind system, the size and limit of the growth of the waves driven by the factors detailed above, ranging from ripples on the water surface to fully developed seas. They are said to reach a mature sea state when they are limited by the wind speed (Kinsman, 1984).

Waves can be classified by wavelength, ranging from very short wave length capillary waves with a period of less than 1 second (surface ripples) to trans-tidal waves with periods of over 24 hours. Research in the cause and effects of waves over a number of years has defined the most common form of waves found at sea as gravity waves (Munk, 1951; Kinsmann, 1984; Owen, 1987). Gravity waves are defined as wind waves in the generation phase, when they are building through the action of the wind on the water, and swell when they propagate away from the area of generation (Semedo, Sušelj and Rutgersson, 2009). Wind waves are strongly coupled to the local conditions and hence can change quickly with changing local wind conditions. Swell on the other hand is generated over a sustained period of time and is more uniform and less likely to change quickly. Semedo, Sušelj and Rutgersson (2009) state that for this reason, waves do not necessarily always reflect the local wind field characteristics, however local wave fields are a combination of local and remote wind forcing.

The proposed locations of the next round of offshore wind farms is further offshore in less sheltered waters and, due to the target for a high power resource, in areas of expected consistent and strong winds. It is therefore expected that the wave climate at Round 3 sites will be higher than that of current wind farms, and with the development of technology allowing turbines to be located further offshore, this trend is expected to continue.

3.2.3. ***Wave Modelling Research***

Wave modelling is carried out to give a representation of a wave climate in a particular area at a particular time. *The state of the sea changes constantly, and it is therefore neither very practical nor very useful to describe the sea for an instantaneous point in time* (Vanem, 2010). Sea states are therefore often described using a number of averages and extreme conditions, frequently referred to as *Integrated Sea State Parameters.* These include:

- **Significant wave height (H_s)** – defined as the average wave height, from trough to crest, of the one-third largest waves that is observed during the period.
- **Mean wave period** – defined as the amount of time (in seconds) it takes from the moment one wave crest passes a fixed point until a second wave crest passes that same point.
- **Mean wave direction** – defined as the average heading from North from which a wave approaches (Sponsler, 2013)

As there are so many external influences on a wave system, the parameters cannot be estimated for a site mathematically, so stochastic models are used (Lindgren, Bolin and Lindgren, 2010; Vanem, 2010). This allows generation of 'random' wave sets, which are considered to best represent a 'real' sea-state, made up of a series of different wave heights, directions and periods that are statistically likely to occur. The generated sea-states are therefore averages over a given period of time, often hours rather than days/months/years due to the computational power required to generate them. When designing a ship with a design life of 20 years plus, a longer period must be considered. To do this a model is usually generated for average sea states, to determine the usual operational aspects of the design, and also for extreme sea states, to ensure the design can continue to operate safely in the most severe conditions. Significant wave height is therefore often quoted in vessel design with an “m-year return period”, defined as the value of Hs that is exceed once every ‘m’ years (Vanem, 2010).

To generate statistical models historic data is required, which can be collected from a number of sources. A comparison of some of these data collection methods is given in Table 5 below, drawn from literature by Vanem (2011), Benetazzo et al (2012) and Fedele et al.

Method	Description	Advantages	Disadvantages
Wave Buoy	Height of waves measured by static buoys	Very accurate Reliable	Limited spatial coverage Equipment prone to damage Expensive
Satellite imaging	Satellite images used to estimate wave heights	Covers a very large area Accepted to be in agreement with buoy measurements	Can be biased towards high/low Hs Requires extensive data analysis
Ship borne wave recorders	Measurements made by altimeters on ships	Covers a wide area Data populated in areas of interest (i.e. shipping routes)	Does accurately represent extreme weather (as ships tend to avoid this)
Visual observations	Voluntary input of visual observations from boats/land	Low cost Covers a wide area Data populated in areas of interest (i.e. shipping routes)	Unreliable Does not accurately represent extreme weather (as ships tend to avoid this)
Stereo Video Techniques	Video analysis of a specific site	Creates a 3-D model Captures movement and height of waves	Limited spatial coverage Requires high processing power Mounting location above sea-surface required

Table 5 – Wave Data Collection Methods

This historical data can then be used to model wave climates to predict average wave heights, directions and periods at a certain point or area, allowing designs to be tailored to an expecting operating environment.

Wave modelling approaches have been the focus of much research, especially in the 1960’s and early 70’s. Hasselman et. al. (1973) realised that although there were advancements in mathematical techniques and computer facilities for numerical wave forecasting, the was a lack of detailed field studies to validate the data. This led to a detailed data collection project, known as the Joint North Sea Wave Project (JONSWAP) that saw the deployment of 13 wave measurement stations over a 160-kilometre profile in the North Sea in 1969. The correlation of this data with the theories identified previously, led to the development of the JONSWAP Spectra - an empirical relationship that defines the distribution of energy with frequency within the ocean (Codecogs, 2012). This research built on previous work by Pierson and Moskowitz (1964) who developed the Pierson Moskowitz spectra for a fully developed ocean sea. The JONSWAP theory highlighted that the wave spectrum is never fully developed and therefore changes over time.

3.2.4. ***Tidal Research***

For the purposes of this research, it was considered the predominant environmental factors were wind and wave climate, as discussed in Sections 3.2.1 and 3.2.2, however tidal influence at the base of turbines was also a factor which would affect the design.

Tidal changes at the base of an offshore wind turbine will have two influences:

1. The height of water and therefore exposure of foundation above the sea surface
2. The current flowing past the base of the structure

Research conducted by the Carbon Trust during the OWA identified a maximum tidal flow around the base of the turbines of 2 m/s and a maximum tidal rise and fall of 5 metres.

3.2.5. ***Expected Operating Conditions***

As the vessel was to be designed to accommodate both current and future wind farms, research was conducted into the expected operational areas and data ranges were extracted from this to guide the development of the vessel.

The Offshore Wind Cost Reduction Pathways Study (2011) identified a trend in wind speeds for locations of offshore sites. Increasingly high wind speeds are being targeted, with an estimated typical annual average wind speed at wind farms developed in 2007/8 of between 7 and 8 m/s, and the average wind speed of wind farms becoming operational at the time of the report (2011) reaching 9.5 m/s.

A review of available environmental data available for sites across the UK, both operational and proposed, was carried out utilising data from the Carbon Trust OWA (2010) and Renewable UK's Wind Energy Database (2012). Early research highlighted the need for the vessel to operate in up to 3.0 m significant wave height and be able to cope with varying wind speeds and tidal flows. Metocean data provided by the DNV was used during the detailed analysis of the vessel concept, however initially the figures detailed in Table 6 were used to direct the development process.

Offshore Wind Farm Environmental Data		
	Current Wind Farms	***Next Generation***
Typical number of turbines	30-200	200- 2500
Distance from shore	<20 km	Up to 300 km
Water depth	5-30 m	15-70 m
Turbine Capacity	3-5MW	>5MW
Vessel types	Catamarans 10-30 m length 20-30 knots speed	Developing technologies
Maximum wave height for access	1.5 m SWH	3.0 m SWH (targeted)
Wave Period	4-10 seconds	
Tidal range	1-5 metres	
Current speed	0 – 2 m/s	
Typical wind speed	7.5 m/s	9.5m/s
Foundation Types	Monopiles	Monopiles, jackets, gravity bases and piled tripods
Access method	Transfer from port	In field transfers or transfer from port

Table 6 – Offshore wind farm environmental data

3.3. **Vessel Design research**

Ship design is driven by a desire to develop a vessel which meets particular needs, predominantly selected based on the end use of the vessel (Brown, 1998). The criteria for design focus can then be prioritised and the design parameters selected. This section identifies the approaches adopted for ship design, the evaluation methods used and researches the design standards available for the specific area of interest.

3.3.1. ***Approaches/Methodologies***

Initial research into 'traditional' vessel design approaches identified a lack of focus on the concept design phase, with much of the development work focusing on analyses later in the product development cycle. Mistree et. al. identified a focus on the scientific aspects of the analysis rather than early design work.

> *Much attention has been paid to development of a scientific base for the analyses that are a part of the design process. Little attention has been paid to design itself, or to the planning and execution of design decision processes.*

McGee (1999) puts this conservative design approach down to the historical complexity of making design changes and highlights that innovation was constrained in early ship design due to the unpredictability of any changes made on the behaviour of a ship at sea. Evans (1959) identified the complexity in the design process was caused by the interdependency between ship components. For example, structural loads are caused by overall vessel weight, but component size (and therefore weight) cannot be identified until the loads are known. It is therefore essential to use an iterative process, where early weight estimates are inputted into the design process to allow an outline design to be developed, which is subsequently refined as the accuracy of the calculations increases. This process has been dubbed the 'naval architecture design spiral' (Evans, 1959) the speed of which has been increased significantly with the use of computer simulations (Ocada and Neki, 1992; Watson, 1998; Narciki, 2012) however the requirement of a spiral starting point leads to the utilisation of existing designs as the basis. Whitcomb and Szatkowski (2000) state the use of a spiral has been consistent over the years however there have been several variations in the 'spokes' of the process. Figure 9 gives an example version of the naval architecture design spiral.

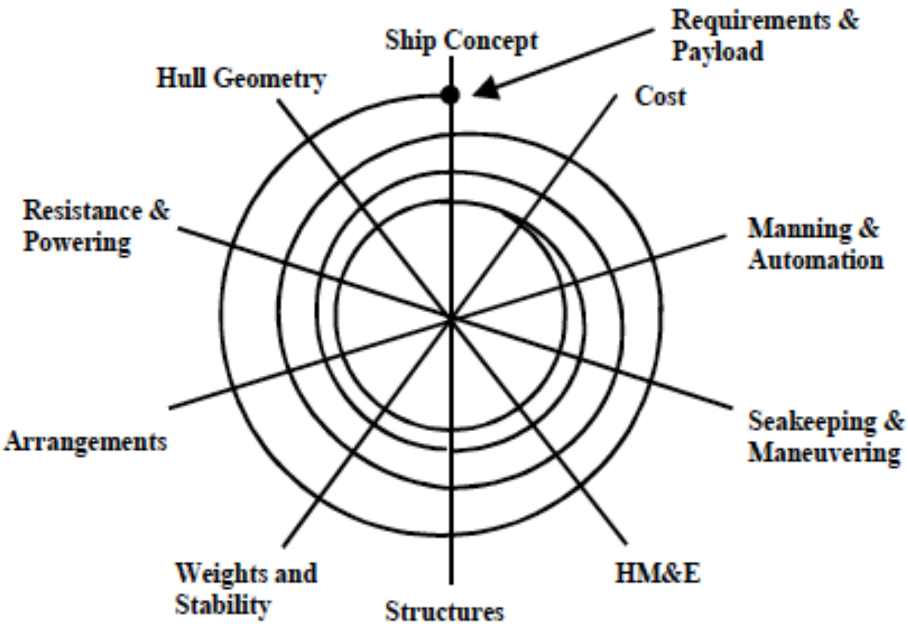


Figure 9 - Naval Architecture Design Spiral, Source: Whitcomb and Szatkowski, 2000

Laverghetta and Brown (1999) highlighted the need for a system approach to vessel design not only to improve performance, as earlier approaches had focused on, but also to reduce cost and timescale while meeting the customer requirements more thoroughly. Commercial success was noted from the implementation of 'product design' based approaches; Integrated Product and Process Development (IPPD), concurrent engineering, open systems architecture, Total Quality Management (TQM) and Integrated Design Environments (IDE) were reviewed by Leverghatta and Brown. The problem however was the utilisation of these processes in later projects due to the lack of a standardised framework (Keane, Fireman and Billingsley, 2007).

Review of the literature suggested the ship design process was heavily focused on the latter stages of an equivalent product design process, with more work on the analysis and optimisation of specific aspects of a ships performance than the overall conceptual design phase. This led to a further review into evaluation methods for ships and ship designs.

3.3.2. Vessel Design Evaluation

As shown in Figure 9, the naval architecture design spiral incorporates a number of evaluation processes throughout the iterative stages of a ships development. There are a number of ways in which these evaluation processes can be carried with varying degrees of precision, and therefore varying timescales, dependant on the iteration stage of the process. For this research, specific stages of the cyclic process were targeted to reduce the timeframe for development. Research was therefore focused on Resistance and Powering, Weights and Stability and Seakeeping evaluation.

Whitcomb and Szatkowski (2000) identify a technique known as 'the math model' used in the early stages of concept design for monohull surface combatants. This model, formally known as the Ship Synthesis Model, is a parametric model linking high level design aspects (i.e. weight, propulsion power, waterplane area etc) to ship characteristics. This type of model is said to be an effective and quick way to evaluate basic conceptual changes at minimal cost for flat water conditions (Čudina, 2008), however the reliability is higher for designs similar to existing ships (Whitcomb and Szatkowski, 2000).

When considering a vessel underway or in ocean conditions, more complex evaluation methods must be adopted. St Denis and Peirson (1953) are regarded as the first to hypothesise that the motion of a ship in irregular seas can be predicted. The theory states that an irregular sea state is made up of regular seas, therefore the vessel motion can be considered as the summation of responses to regular seas of all frequencies. Salvesen and Flatinsen (1970) built on this work to develop a system to predict the motions of a vessel in six degrees of freedom and develop an early computer program to predict these movements. Modern computer programs still use the linear diffraction theory developed during this period of research to allow calculations to be made for static stability of a vessel and seakeeping in regular and irregular sea states. Computational analysis software plays a crucial role in modern ship development to quickly and cost effectively analyse designs at an early stage of the design process.

Speed and resistance analysis methods were also of interest during this research, as this would drive both the weight of the propulsion system, which would have significant effects on the stability and seakeeping of the vessel, and the speed at which the vessel could travel, which would influence the application of the vessel offshore. Studies into the powering of ships have been undertaken since the early 1870's, when Froude (1872) linked the powering requirements to the friction and geometry of a vessel. Froude identified the main cause of friction on a vessel was the skin-friction between the surface of the ship and the water and the residuary friction of the vessel pushing through the water, mainly wave making. Mollond, Turnock and Hudson (2011) give an overview of the modern practice of estimating ship power requirements which utilise Froude's theories on hull geometry and blockage area for initial analysis with the use of computational fluid dynamics (CFD) as a more refined and accurate analysis tool.

Further analysis of vessel stability, seakeeping and resistance can be conducted using a hydrodynamic laboratory, or test tank. Tank testing is *a fundamental process utilised by naval architects for conducting physical model experiments within a controlled environment (Australian Maritime College, 2012).* Rojas, Cabezas and Iglesias (2003) state that since the widespread adoption of CFD for analysis purposes, hydrodynamic tanks are now being utilised for correlation tests to validate numeric calculations and Pinsker (1998) describes the use of testing tanks as expanding. Uses of hydrodynamic tanks include fundamental tests of basic phenomena, validation tests for numeric simulation, systematic tests used to establish the effects of varying single parameters, feasibility tests, used to confirm estimates of designs at an early stage in development, and design tests, used to produce data about a specific design.

Overall the research has identified that evaluation of a vessel design can be carried out in a number of ways and best practice is to utilise a combination of these evaluation processes to gain a broad and validated understanding of vessel characteristics.

3.3.3. ***Design Standards***

Further to specific design approaches and evaluations, a vessel designer must also consider the area in which the ship is to operate to ensure the correct design standards are met during the development process. For vessels to operate commercially, they must legally comply with the relevant coding rules set out for the specific class of vessel, areas they are operating and number of people on board.

Hoppe (2005) identified that a new goal-based approach has been adopted within the certification authorities to encourage innovation by allowing alternative ways of reaching compliance rather than setting specific regulations that must be met.

Research at the early stages of the project identified the International Convention for the Safety of Life at Sea (SOLAS) as the most commonly adopted design standards in merchant shipping. The SOLAS convention specifies *minimum standards for the construction, equipment and operation of ships, compatible with their safety* (IMO, 2014). No specific legislation was identified for offshore wind turbine access, however during the development process the DNV released the first class rules for wind farm service vessels. These rules filled a gap in the market, allowing classification to be met without unnecessary demands imposed on vessels operating in other markets (DNV, 2012).

Most offshore transfer vessels are "Small commercially operated vessels" which covers vessels up to 24 metres load line length and carrying no more than 12 passengers (GOV.uk, 2014). The vessel will therefore have to adhere to the relevant rules set out for small workboats. Table 7 overleaf gives an overview of the design standards that must be considered during the design process.

Design Standard	Overview
Marine Guidance Note 280	Guidelines for UK vessels of up to 24 metres load line length which are engaged at sea in activities on a commercial basis, which carry cargo and/or not more than 12 passengers, or provide a service in which neither cargo nor passengers are carried, or are UK pilot boats of whatever size
Marine Guidance Note 371	Highlights issues that need to be taken into consideration when assessing the impact on navigational safety and emergency response (search and rescue and counter pollution) caused by offshore renewable energy installation developments, proposed for UK internal waters, territorial sea or in a Renewable Energy Zone beyond the territorial sea
Marine Guidance Note 372	Identifies issues to be taken into account when planning and undertaking voyages in the vicinity of offshore renewable energy installations (OREIs) off the UK coast
Guidelines for the Selection and Operation of Jack-ups in the Marine Renewable Energy Industry	These guidelines, published by the BWEA, are aimed at jack-up operators, contractors and developers and are primarily for construction jack-ups however the concept design incorporates a jack-up deck and therefore these guidelines may be appropriate although the vessel legs will not be on the sea bed.
DNV Wind Farm Service Rules **Windfarm Service 1** **Windfarm Service 2**	The DNV have developed two class notifications specifically for vessels designed for the offshore wind industry; The class notation for domestic operations is voluntary and represents a complete technical standard. The notation includes requirements as to not only the construction, machinery, systems and watertight integrity of the craft, but also the craft's stability and lifesaving, fire safety and navigation properties. Windfarm Service 2 applies to craft intended to carry up to 60 persons and are typically longer than 24 metres in length. For these vessels the class and statutory sections in the rules may be applied separately to satisfy the requirements of the selected Flag State.

Table 7 – Design Standards

3.4. **Technology Review**

A technology review was conducted to identify where there is existing technology that could be utilised in the design. A review of existing and evolving designs for the offshore wind industry was conducted, identifying the current state of the art in offshore wind turbine access. Both jack-up rigs and semi-submersibles were also reviewed, as the design has similarities with both. Finally, existing vessel stabilisation methods were reviewed, with a specific focus on reduction in movements caused by waves.

*3.4.1. **Wind Turbine Service Vessels***

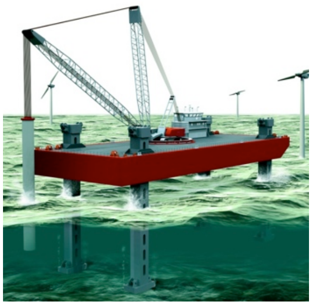
Research has identified that to date the industry has tended towards a similar design of vessel for servicing offshore wind turbines; catamaran work boats with flat bows and shaped bumpers to locate with the ladder uprights on the side of the turbines. These vessels are usually between 15m and 24m long and operate with anything up to twelve passengers (i.e. technicians) and two or three crew. The current vessels usually operate on near-shore wind farms and have a limited range (under 300 nautical miles) and usually cruise between 20-25 knots. These vessels have a working limit for transfer of 1.5 metre SWH. Figure 10 below shows a commonly used vessel currently utilised for accessing offshore wind farms.

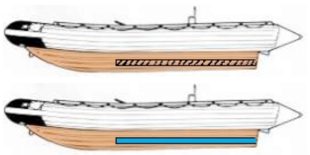
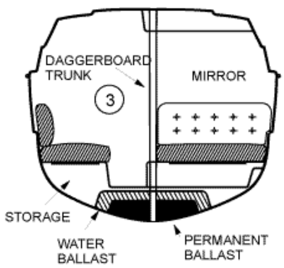
Figure 10 - Commonly used vessel for offshore wind turbine access. Source: Dong Energy

A number of vessel concepts in development specifically for accessing offshore wind turbines have been identified, sharing the same primary focus; increasing passenger comfort and safety whilst maximising the range and operating conditions in which transfers can be made. The developing technology is aiming to allow safe access in wave heights of 3 metre SWH and higher. Many of the vessels utilise motion-dampening systems and stabilisers to reduce movement and the vessels are now being modified specifically for the wind industry, however vessels specifically designed for the purpose of providing personnel access were not in production at the start of the design process. Details of the full review conducted of these vessels can be found in Appendix A.

*3.4.2. **Applicable Technology***

The review of applicable technology was conducted by utilising expertise on existing technology from marine engineers and naval architects (Hitchin, 2012; Dodsworth, 2011) combined with research into developing concepts accessed online or through the Carbon Trust OWA (2011). The outputs of the technology review are summarised in Table 8 below.

Technology	Overview	Current/ Developing Applications
Jack-Up Barges  *Figure 11 – Offshore Wind Jack-up Source: Maritime Journal (2002)*	Provides a floating platform that can 'stand' on the seabed Creates solid platform that can be lifted away from the waves Stable deck capable of handling variable loads Independent leg or matt type Cylindrical leg or truss structure available	Offshore oil exploration Offshore construction Construction phases offshore wind turbines Water depths <100 m
Semi-submersibles  *Figure 12 - Semi-submersible Source: Rigzone (2011)*	Floating structure with majority of buoyancy submerged when operational, away from wave effect with small supports through water plane During transport, lower buoyancy de-ballasted and floated on surface to reduce drag On site, pontoons ballasted and submerged to reduce motions in waves in comparison to standard vessels	Deep water oil and gas exploration Developing technology includes: • Floating offshore wind turbines • Survey vessels

Ballasting Vessels	Research identified a number of vessels that utilise changeable ballast arrangements by changing water storage	Slow speed or stationary stability, reduced weight at higher speeds
Avon Searider  *Figure 13 - Avon Searider* *Source: Avon (2011)*	Passive ballasting RIB 4 inch diameter cavity in hull which fills at slow speeds but drains quickly when the boat is accelerating Increased stability and lower in the water when stationary Weight reduced quickly allowing lightweight planning vessel	Sports Fishing Small rescue craft
MacGregor 26  *Figure 14 - MacGregor 26* *Source: Macgregor (2002)*	Trailable sail or powerboat Allows vessel to be a self-righting, ballasted sailboat when required and a lightweight, un-ballasted vessel for powering or trailing Underwater compartment can be flooded with over 500 kg of water in under 5 minutes	Towable pleasure vessel
Stabilisation Methods	Stabilisation methods are often employed to reduce vessel movement	Minimise movement
Keels  *Figure 15 - Longitudinal keel* *Source: Kasten Marine (2002)*	Fins on underside of vessel running longitudinally Additional keels on larger vessels utilised to reduce lateral roll	Used on boats to reduce lateral movement when underway and on larger vessels to reduce lateral roll

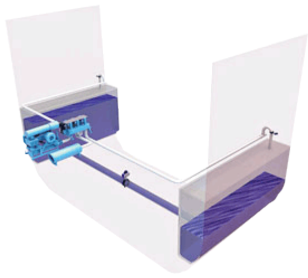
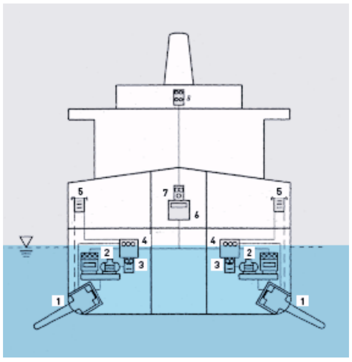
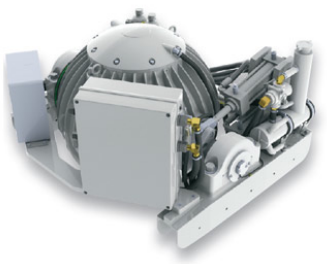
Tank Stabilisation  *Figure 16 – Tank Stabilisation* *Source: Rolls Royce (2011)*	Tank stabilisation allows water to be pumped transversely across a vessel to combat roll	Reduction of vessel roll, both when underway and when stationary
Fin Stabilisation  *Figure 17 - Fin Stabilisation* *Source: Fincantieri (2014)*	Fins reduce roll usually in vessels underway by creating a restoring force if a vessel starts to heel through hydrodynamic flow over the fin. The angle of attack can be varied to change force. New technology allows stabilisation at rest by driving the fins as paddles through the water	Reduction of vessel roll while underway New technology allowing stabilisation at rest
Gyroscopic Stabilisation  *Figure 18 - Gyroscopic Stabilisation* *Source: Seakeeper (2014)*	Gyroscopic stabilisation utilises the angular momentum generated by spinning a flywheel to counteract external torque	Reduction of vessel roll, both when underway and stationary

Table 8 – Technology review summary

The knowledge gained during the literature review gave the author a broad understanding of the types of technology available and already utilised in combating vessel movement and proved invaluable during the design phase of the research.

3.5. Initial Reference Model

The IRM was developed by the author using knowledge gathered during the literature review to set a benchmark to which the vessel could be compared to and analysed against. It was also used to set goals for the development. The model highlights the crucial specifications of a transfer vessel capable of operating in the predicted environment and is presented in the form of a vessel specification. The IRM, combined with the environmental data outlined in Table 6, was utilised in the early stages of the design development.

Ship Parameter	Initial Reference Model Target Range	Goal
Ship size Length Overall Draft Beam	 Maximum 24 metres <1.5 metres 7-9 metres	 Minimise dimensions to reduce overall manufacture and operational costs
Cruising speed	>28 knots	Maximise
Max sprint speed	40 knots	Maximise
Passenger capacity Passengers Crew Max POB	 12 4 16	 Meet MCA Small Workboat regulations
Construction Materials	Fiberglass	Reduce Weight
Deck Space **Fore** **Aft**	 30 m^2 20 m^2	Maximise deck space for working
Range	700 km	Allow transit from shore to a Round 3 site and return in a working day
Sea-keeping Max deck movement Safe operating range Safe wave height for transfers	 1.5 m (in 3.0 m SWH) Up to 5 m SWH 3.0 m	 Minimise deck movement Make vessel operable in maximum sea conditions
Load Capacity	10 tonnes	Maximise to allow equipment transfer
Transfer Method	Step transfer	Reduce complexity and eliminate requirement for additional access system
Additional Capabilities	Rescue zone Storm survival mode Passenger facilities	Allow safe working for a full day offshore

Table 9 - Initial Reference Model

3.6. **Literature Review Summary**

The literature review was conducted to identify gaps in the research area and determine the current state of the art in the industry. This was accomplished by reviewing the wind industry, the environmental issues and vessel design approaches.

Research identified that the wind industry is in a growth period and is heavily backed by the UK government. It is seen as a key technology to reduce carbon emissions and is therefore receiving significant funding to develop larger, higher capacity windfarms. The value of energy production was identified and key areas of lost production researched – this identified a major focus on reducing the costs of operations and maintenance, by increasing the available working range. The access to offshore wind turbines was then reviewed and the research identified the current system is only allowing access roughly 50% of the year which is limiting turbine availability levels and costing the industry in lost revenue.

An environmental review was conducted and a high wind resource was identified as key for the success of offshore turbines, but alongside this it was identified as the cause of many of the access issues. Research into how waves are formed and the link to wind resource was conducted, highlighting that the exposed locations of the next round of wind farms will mean higher localised wind waves and higher ocean swell, reducing the accessibility of the farms significantly. The expected operating conditions for current and developing windfarms were reviewed and key figures were detailed to use in the design process.

A technology review identified the current type of vessel used for accessing offshore wind turbines and emerging designs specifically targeted at servicing offshore windfarms. Applicable technology was also studied to identify key ways in which to tackle the access challenge.

Finally, an initial reference model was developed to guide the initial stages of the design work.

4. Vessel Design

This chapter gives an overview of the development of the vessel concept. It focuses on stages 2 and 3 of Pugh's Total Design Methodology (Pugh, 1991); Specification and Concept Design, and in doing so gives an overview of the development path taken during the design of the vessel. Pugh's Total Design Methodology was used as it gave structure to the design process. The initial stage of TDM, Market Research, was covered in the literature review detailed in Chapter 3. The work completed during the Specification and Conceptual Design phases builds on the Initial Reference Model described in Section 3.5. This was used to develop quantifiable specifications that the design was to meet and a Product Design Specification (PDS) was drafted, leading to the development of the Full Reference Model. Concepts were then developed to fulfil the desired requirements and these were evaluated based on criteria drawn from the reference model. Chapter 4 concludes with an overview of the selected design.

1. Market
2. Specification
3. Conceptual Design
4. Detailed Design and analysis
5. Manufacturing
6. Sales

Figure 19 - Pugh's TDM: Stages in Chapter 4

4.1. **The Proposed Concept**

The original concept, shown in Figure 20, outlined an access vessel capable of undergoing a transformation at sea. The purpose of this transformation was to reduce deck movement through a combination of creating an air gap between the deck and the water, by jacking it up away from the swell, and moving the hulls away from the worst of the wave energy, by submersion under the water. The idea was conceptualised during the author's undergraduate Product Design Engineering Masters degree, however the development of the vessel concept was not embarked upon until the start of the MPhil research and the potential of the design was recognised by the industry through the Carbon Trust Offshore Wind Accelerator competition. Funding was gained to analyse the feasibility of the design, however the details of the design were not defined, allowing scope for concept generation based on the original principle.

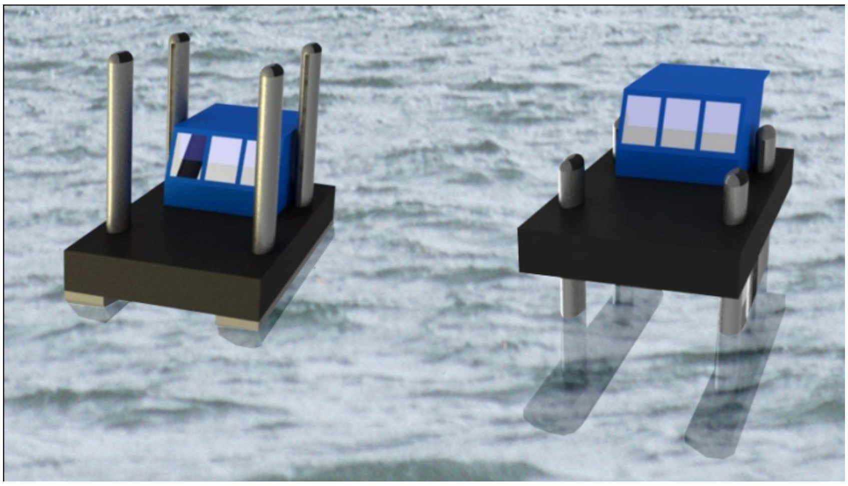


Figure 20 - Proposed Concept

4.2. **Specification Development**

In line with Pugh's TDM, required specifications were developed before the conceptual design phase started, providing a design target. The project adopted a forward thinking design process where the final use of the vessel was considered early on, allowing it to influence the design. The following sections outline the considerations that were taken into account throughout the development of these specifications and how they were used to develop the outline specifications and the Full Reference Model, detailed in Sections 4.2.3 and 4.2.4.

4.2.1. Functional Requirements

As discussed in Section 3.3.3 of the literature review, much of the regulation surrounding ship construction is goal-based. This regulatory practice was developed to encourage innovation, as it was believed the conventional prescriptive regulations did not allow alternative ways of achieving compliance (Hoppe, 2005). This research has therefore endeavoured to adopt this goal-based strategy, by developing requirements with objectives, rather than defining set requirements.

Research into the procedures and practices currently carried out on transfer vessels, combined with foresight into future expectations through meetings with industry partners, allowed the identification of three key scenarios where personnel transfers may be required. These scenarios are analysed below with brief discussions as to how they have affected the design of the transfer vessel.

1. **Accessing Current Wind Farms** – The vessel must be capable of providing transfers to and from current turbines to increase the access availability, reduce downtime and therefore increase production. In this case, the concept vessel may be supported by standard transfer vessels during good weather and become the only support vessel for rough conditions. This means the vessel should operate in the water depths of current turbines (minimum 5 metre) and should not require any modifications to the existing structures. In good conditions, the vessel may not have to change configuration to provide a platform for transfer.

2. **Transit and Transfer to Next Generation of Wind Farms** – The vessel should provide a system for fast and comfortable transit to far offshore wind farms (up to 300 km from shore) and then provide a safe and stable transfer base in the conditions it experiences. This will require a fast transit speed with minimal fuel consumption and a method of creating a stabilised platform when at site. It will also require a safe access method in larger sea-states than the current method provides, targeting up to 3.0 metre significant wave height.

3. **In-field Transfers** – Due to the increasing distance offshore in which windfarms are now being developed, the possibility of on site accommodation, on a mothership or fixed accommodation platform, is being extensively researched (Mapels et. al., 2013). If this is realised, the vessel may also be used primarily for in-field transfers from the accommodation to turbines. This scenario will require the vessel to perform a high number of shorter transfers and be on-site for extended periods of time. In this situation the vessel should still be able to act as a fast transit vessel to and from the port for the replenishment of supplies and the change of personnel. The concept vessel should be able to operate with launch and recovery systems and should include a 'safe mode', in which the vessel can survive storms.

These scenarios, combined with the project aim, were used to determine the overall requirements of the vessel and, through the use of a function tree, these requirements were broken down into specific constituent functions. The eleven constituent functions are listed below and the full function tree is shown in full in Appendix B.

1. Provide floating and reserve buoyancy
2. Have sufficient structural strength to survive operating conditions
3. Meet the appropriate legislative and regulatory guidelines
4. Travel quickly, in varying sea conditions
5. Travel efficiently
6. Provide Shelter
7. Have sufficient storage space for equipment
8. Provide basic amenities for a days work offshore
9. Provide a personnel transfer system from the ship deck to a turbine
10. Reduce movement of deck in high sea-states
11. Hold station at base of turbine

These functions were then used throughout the development cycle to maintain a link to the original project aim and ensure all requirements are met.

4.2.2. Safety Considerations

Alongside the functions detailed above, safety was of paramount concern during the design of the vessel, as one of the key aims was to offer *safe* access to offshore structures. It was therefore crucial not only to meet the expected standards but also to exceed these and integrate general safety principles into the design. A 'Design for Safety' philosophy was adopted throughout the design process, developing strategies from established naval architecture techniques as well as considering the safety implications of each design decision. Some of the key considerations are given below.

Manoeuvrability - The vessel is designed primarily for use in areas populated by wind turbines and must be able to hold position at the base of the turbine. The vessel therefore must have sufficient manoeuvrability to avoid collision with the turbines so as not cause damage to the vessel or the turbine structures.

Visibility – It is crucial that the skipper can see the vessel's contact point with the turbine and the transfer of personnel. For a docking procedure to be carried out safely, the skipper's view of the vessel bow should not be impeded either temporally or permanently.

Because of the nature of the design, the legs will impede the all-round view from the deckhouse. To overcome this problem, video cameras have been considered and remote operating stations have also been discussed.

Vessel Movement – During the personnel transfer in high seas, no vessel configuration will remove all movement. The vessel design should therefore minimise movement to an acceptable level for transfers in 3.0 m SWH. An 'acceptable level' is deemed to be similar to that of the current access vessels, in wave heights below 1.0 m SWH, when transfers are carried out on a regular basis.

Air Gap - The air gap between the raised vessel deck and the water surface must be sufficient to eliminate any chance of slamming and swamping, which would be a safety hazard for crew and technicians working on deck. As the vessel is designed to operate in wave heights of 3.0 m SWH, this air gap must accommodate the highest amplitude wave in these conditions.

Excessive Flooding of Ballast Tanks – If ballast water is used to sink the hulls below the water surface, the vessel must have a failsafe system to prevent potential sinking of the craft through over-flooding the water ballast chambers. The vessel must therefore have sufficient fixed and permanent buoyancy. Compartments used to ballast down the vessel will segregate the ballast into small sections and the sequence of ballasting will be straightforward. There may be a need for hull fairings that are not pressure vessels to be vented to the sea during ballasting to ensure that differential pressure is eliminated. This will considered once the initial concept is proven.

Damage Stability – The vessel should meet the correct damage stability requirements, with crucial focus on the areas operating close to the fixed structures. Segregated ballast compartments in the hulls should prevent flooding of adjacent compartments if damage should occur.

From the legislation identified in the literature review, a number of safety requirements were identified which must be adhered to in a vessel design of this size. These safety requirements, amongst other requirements and objectives, are set out in the PDS.

4.2.3. ***Outline Specification***

Outline specifications for the vessel concept were developed to focus the design process, based on the research documented in this section. These specifications were documented in a Product Design Specification (PDS), of which the current version can be found in Appendix C. The PDS quantifies and details the specifications in an open document, allowing dynamic updates as the concept is developed, as many of the parameters could not be detailed until the concept design was finalised.

Quantification of the specifications was, where possible, drawn from a combination of literature and a comparison with the currently available transfer vessels, outlined in Section 3.4.1. This facilitated the development of the Initial Reference Model, discussed in the literature review, to the Full Reference Model, detailed in the following section.

*4.2.4. **Full Reference Model***

The work carried out during vessel design allowed the author to identify a full set of criteria for the FRM, building on the IRM developed earlier in the research process. The model highlights the crucial specifications of a transfer vessel capable of operating in the predicted environment, and is presented in the form of an ideal (but achievable) ship design, to allow targets to be set for conceptual development. The details of the FRM are given in Table 10 below, alongside the IRM targets.

Ship Parameter	Full Reference Model Target	Notes
Ship size		
Length Overall	20-24 metres	24 m maximum to maintain 'Small Commercial Vessel' classification
Draft	1-3 metres	Deep drafted vessels are restricted in the ports they can enter
Beam	10 metres	
Cruising speed	24 knots	Fully loaded in reasonable sea conditions
Max sprint speed	30 knots	A high top speed will be beneficial for emergency response capabilities
Passenger capacity		
Passengers	12	Maximum passenger numbers are defined by the Small Commercial Vessel code MGN280
Crew	4	
Max POB	16	
Construction Materials	Steel/Aluminium Alloy/Fiberglass	Or a combination
Deck Space		
Forward	30 m^2	Main deck space required at the front of the vessel to allow equipment transfer or use of a transfer system
Aft	20 m^2	
Range	700 km	Next generation wind farms are expected to be anywhere up to 300 km offshore
Sea-keeping		
Max deck movement	1.5 m (in 3.0 m SWH)	Target defined by current available transfer threshold of 1.5 m SWH
Safe operating range	Up to 5 m SWH	Not including transfers
Safe wave height for transfers	3.0 m	

Load Capacity	6 tonnes	Maximum 3 tonne units, based on current maximum weights for single wind turbine components
Transfer Method	Step transfer	Initially the vessel should be designed to allow for ship-structure transfers without the need for additional equipment
Additional Capabilities	Rescue zone Storm survival mode Passenger facilities	Required for MOB situations Would allow vessel to stay on site during storm conditions Shelter and basic amenities required for full days of offshore work

Table 10 – Full Reference Model

4.3. **Conceptual Development**

This section details the work completed to build on the initial concept, developed during the author's masters project. The development of alternative concepts is outlined, based on the key criteria set out in Section 4.2.1; the selection of three alternatives and a review of these concepts is given; and the final selection of the optimum concept is discussed. In Section 4.3.5, an overview of the selected concept is given. This is then taken forward to Chapter 5: Design Development and Analysis.

4.3.1. ***Concept Generation***

The aim of this research was to identify and evaluate a particular vessel concept; detailed in Section 4.1. Although this concept defined the general design principle, there was still considerable scope for consideration of alternative designs, based around the initial concept. Pugh (1991) highlights the advantages of generating a large number of alternatives in the concept design phase, to broaden the search area for technologies or solutions that may fulfil the requirements best. A number of methods were employed for concept generation, which saw the development of a wide range of concepts.

Idea generation focus groups were utilised to create a high number of ideas in a short period of time and participants from a range of fields, including Product Design, Renewable Energy, Naval Architecture, Mechanical Design and Marine Engineering, were involved. These informal idea generation sessions were conducted in groups of three to five people and carried out in various manners to suit the parties involved, but were structured similarly. The problem was described to the group and emphasis was placed on encouraging radical solutions. Individuals put ideas forward and the group was encouraged to expand on these, whilst criticism was reserved for the initial idea generation period. Due to the value placed on the groups' time, evaluation sessions were conducted after the initial idea generation, which often encouraged supplementary ideas to be developed.

The focus groups were mainly utilised to develop 'big picture' solutions, however additionally the specific functions of the vessel were also considered discreetly. The functions, developed using the function tree described in Section 4.2.1, were split into components of the ship:

- The **hull** and **structure** of the ship were considered to identify solutions for functions 1-3; to provide sufficient buoyancy, strength and to meet the guidelines established in the specific regulatory guidelines (outlined in Section 3.3.3).
- The **powering** mechanism, along with the **hull form**, was used to develop a design that was efficient and travelled quickly, targeting functions 4 and 5.
- The **deckhouse and deck layout** were optimised to provide shelter for personnel and ensure there was sufficient storage for equipment and tools, meeting functions 6, 7 and 8.
- The **transfer method** was considered to target function 9.
- Finally the **Jacking system, ballasting system** and **legs** were considered alongside the powering to ensure functions 10 and 11 were fulfilled.

Vessel Component	Functions addressed
Hull	Provide floating and reserve buoyancy Meet the appropriate legislative and regulatory guidelines Travel quickly, in varying sea conditions
Structure	Have sufficient structural strength to survive operating conditions Meet the appropriate legislative and regulatory guidelines
Powering	Travel quickly, in varying sea conditions Travel efficiently Hold station at base of turbine
Deckhouse and Deck Layout	Provide Shelter Have sufficient storage space for equipment Provide basic amenities for a days work offshore
Transfer Method	Provide a personnel transfer system from the ship deck to a turbine
Legs	Additional subsystems required to facilitate concept operation
Jacking System	
Ballast System	

Table 11 – Vessel components developed from constituent functions

The definition of these ship components then allowed development of a function-solution matrix, targeted at developing solutions for individual functions rather than looking at the problem as a whole. The matrix, which can be found in full in Appendix D, was completed in a number of ways; identifying the individual aspects of the ‘big picture concepts’ that could be separated from the rest of the design, reviewing technology to identify solutions from other design fields that could be utilised, and employing ‘blue-sky thinking’ to identify radical solutions to the specific problems.

Concepts were then sketched out for the specific functional problems, and evaluation was commenced stating the advantages and disadvantages, based on three main criteria; cost, practicality and safety. The concepts and the evaluations can be found in Appendix E. Once a wide number of concepts had been developed, these were put into a morphological chart. Full concepts were then developed by combining ideas from each function level from the matrix and developing a series of solutions that fulfilled all the desired functions.

A review of the developed concepts was then conducted, utilising industry specialists *Safety at Sea.* Insight was gained on the perceived feasibility of each of the designs, and high level evaluation of the ideas identified three concepts as the most practical and likely to succeed. An overview of these concepts is given in the subsequent section.

4.3.2. *Concepts*

From the concept generation phase three conceptual ideas were produced utilising different aspects from the matrix. The three concepts are outlined in Table 12, with more detail, including the advantages and disadvantages of each, given in Appendix F.

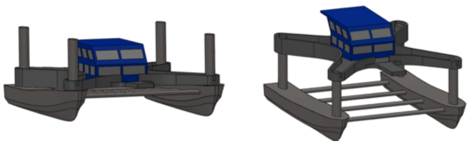
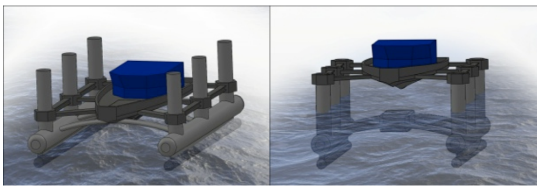
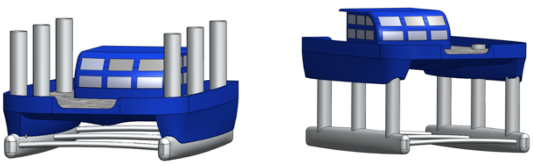
Concept	Overview
Concept 1 - Catamaran Hull Design  *Figure 21 - Concept 1*	Planing hulls allow vessel to operate like current catamaran workboats when in transit mode Hulls can be ballasted and submerged and deck can be raised at site In transit mode hulls would provide buoyancy In transfer mode, hulls would only provide sufficient buoyancy when combined with the buoyancy provided in the legs
Concept 2 – Tubular Hull Design  *Figure 22 - Concept 2*	Concept developed to increase performance in both transit and transfer states. In transit, vessel operates as a small waterplane area twin hull vessel (SWATH) and buoyancy provided by lower hulls Reserve buoyancy provided by the upper hulls to allow the vessel to drive through waves In transfer mode, lower hulls flooded completely - required buoyancy supplied by upper hulls and legs
Concept 3 – Non-ballasting design  *Figure 23 - Concept 3*	In transit mode deck combined with hulls provides floating buoyancy In transfer mode, buoyancy reduced by jacking deck up clear of water Buoyancy provided by the lower hull plus additional buoyancy in the legs No ballast water required to sink lower hulls

Table 12 - Concept Overview

4.3.3. ***Concept Evaluation***

Evaluation of the concepts was carried out in two stages. Firstly, CAD models were developed as fast visualisations of the designs to allow focus groups, formed from experienced professionals in the offshore wind industry, to be carried out. These groups helped identify any aspects of designs that would inhibit commercial uptake, the likes of which may have been overlooked without this input. During this evaluation the information gathered was put into an evaluation matrix. Key criteria were selected based on the Full Reference Model, and each of the concepts was rated in order against the criteria. Three additional criteria were included; cost, safety and reliability. Factors identified in the initial evaluation are discussed in Appendix G for each of the three concepts, along with the full evaluation matrix.

4.3.4. ***Concept Selection***

The matrix discussed above identified that Concept 1 provided the most practical solution, with the potential for it to be made into a planing design scoring high in the speed category, so the catamaran hullform was therefore selected for development.

A number of design aspects were adopted from Concept 3 to increase the practicality of the design. The use of the upper hulls as reserve buoyancy was utilised to reduce the overall weight of the vessel, as it was considered reducing the size of the lower hulls would minimise material usage and therefore weight. Adopting a complete deck was also considered sensible, both for structural strength and practicality reasons. The design was also modified to reduce the hull spacing and increase the waterplane area of the columns, whilst still allowing access to the mechanical components in the lower hulls.

This allowed the development of a selected concept, of which an overview is given in Section 4.3.5.

4.3.5. ***Overview of selected concept***

The selected concept, shown in Figure 24, was developed from the three concepts taken forward from the concept generation phase. The principle of the design is that it will operate as a standard catamaran when in transit mode, with the lower hulls providing sufficient ballast to float but no reserve buoyancy – this will be provided by the upper deck. The vessel will therefore have a waterline relatively close to the split between the lower hulls and the deck. The catamaran hulls will allow it to achieve high speeds with the potential to plane.

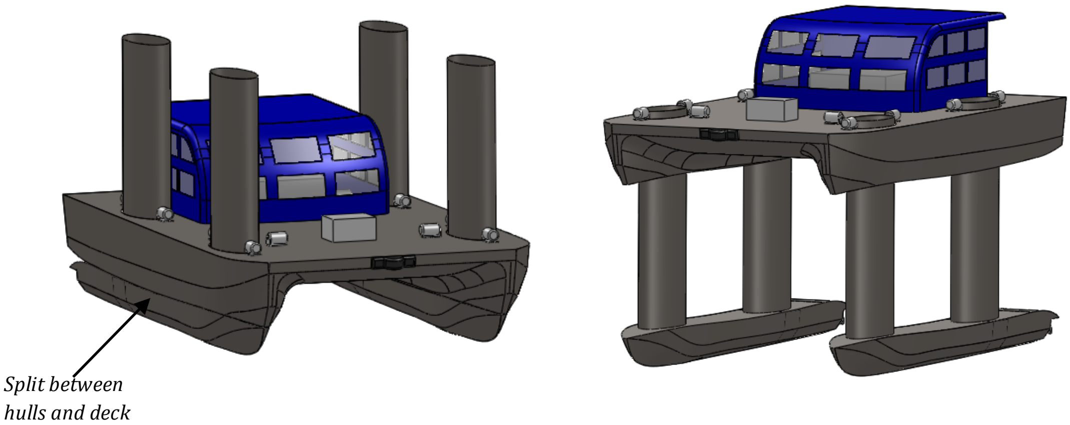


Figure 24 - selected vessel concept

Once on site, the vessel will take on ballast water before jacking the deck up. In the jacked up mode the buoyancy will be provided by the lower hulls and the submerged volume of the legs. The lower hulls will be submerged to 3.5 m and the air gap will be sufficient to allow a sea of 3 m SWH to pass without interaction with the deck.

Once the transfer is complete the vessel will offer two options – to move from turbine to turbine in the transfer mode (at a reduced speed but without the need for the jacking procedure) or to jack down and de-ballast to allow swift transit if the distances are significant. The design will aim to minimise the time for the procedure to offer a more versatile solution.

4.4. **Vessel Design Summary**

This section has focused on the development of the initial concept so that the outline specifications and operation could be documented. The proposed concept has been reviewed, the specifications for the design have been developed using a function tree to identify constituent functions, and the safety considerations have been reviewed. The results of this development work were used to develop a Full Reference Model and a Product Design Specification. Concepts were then generated in line with the defined specifications and early analysis identified three concepts to be taken forward. These three concepts were then put through a thorough evaluation process and a single concept was developed utilising some of the aspects from each concept. The selected concept was detailed and this chapter concludes with a concept ready for further development.

5. Design Development and Analysis

Chapter 5 covers Section 4 of Pugh's TDM: Detailed Design and Analysis. The design was split into sub-sections during the concept generation phase and the design detailing process builds on these sub-sections. An overview of this process is given, supported by a detailed account of the development activities and reasoning in the appendices. This chapter also details the analysis carried out on the vessel, conducted in two distinct stages: computational analysis and tank testing. The sections of this chapter detail the initial evaluation leading to a refined vessel design, which was subsequently inputted into naval architecture computer software to carry out static and dynamic evaluations on the vessel in various configurations. Tank testing was then conducted to validate the computational analysis and review the effect of loading the vessel in a controlled environment. The chapter concludes with an overview of the analyses and how they interrelated, before moving onto a discussion of the results in Chapter 6.

Figure 25 - Pugh's TDM: Stages in Chapter 5

5.1. **Design Detailing**

As discussed in Section 3.3.1 of the literature review, a cyclic design process is required to develop a vessel concept due to the interdependency of the vessel components. Naval architecture design approaches focus on the latter stages of the design development and often optimise an existing design rather than start from scratch, however this research required an alternative approach as the concept being investigated could not be developed from an existing design. A product design based approach was therefore initially utilised for each of the sub-systems of the design, by reviewing the requirements, identifying alternative options and developing a completed design.

Three-dimensional computer aided design (CAD) modelling was utilised to *visualise and documenting a design solution* (Maher et. al. 2006), a process often utilised in product development. The model allowed rapid visualisation of individual components and how they interrelated but also allowed a single point of dynamic documentation. Aspects of the research were inputted directly into the design without loss in an ever-increasing mass of text. It also facilitated modelling of parts which would otherwise have been costly and time consuming.

A parametric model was developed allowing the key dimensions of the design to be varied easily, with the resultant dimensions updating automatically. This process accelerated the modelling considerably at the iterative stages of the design cycle, as the width, volume and depth of the hulls and legs were varied numerous times to optimise the design based on performance estimations carried out using initial calculations (see Section 5.4.1), hence the workload was substantially reduced.

The design concept was then split into sub-sections and solutions for each of the smaller problems were identified individually, making the design task a simpler process.

5.2. **Sub-System Development**

As discussed in Section 4.3.1, the vessel requirements developed from the function tree were used to classify a number of sub-systems that required further development. The sub-systems identified are shown in Figure 26.

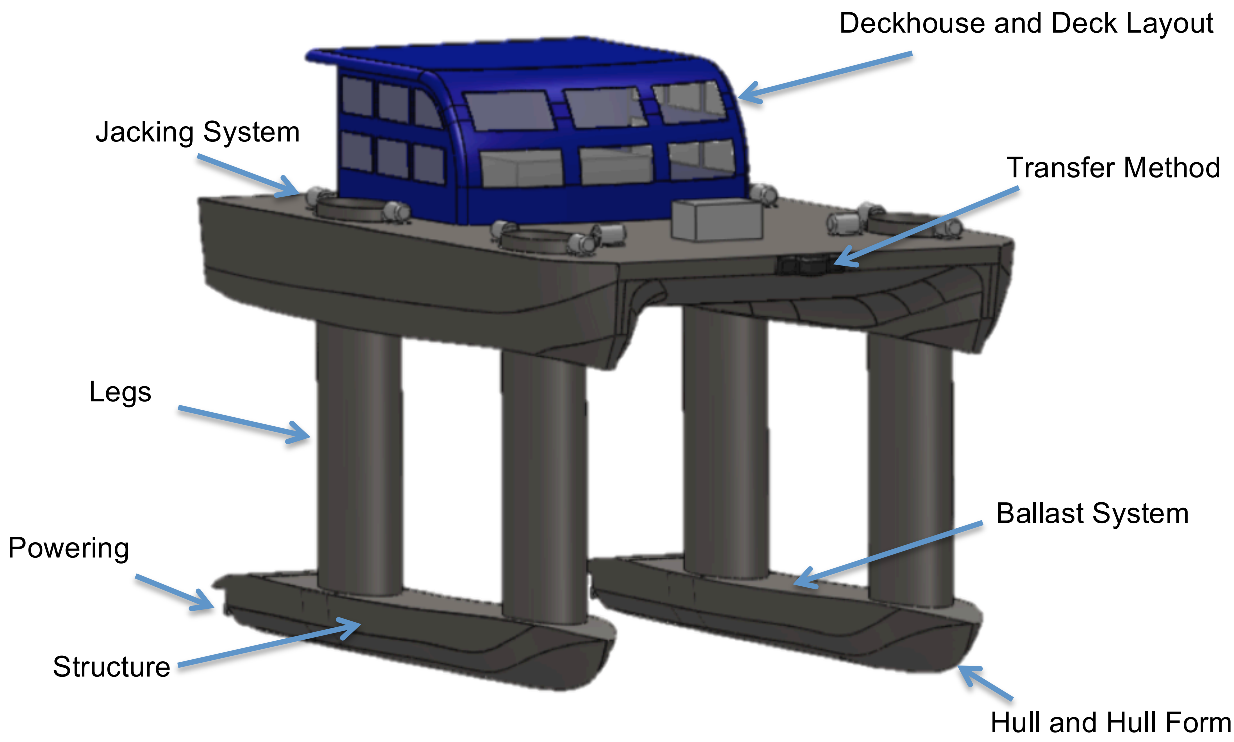


Figure 26 – Visual representation of ship sub-systems

Due to the integration of each of the sub-systems the design development process was cyclic, as many of the factors changed during the detailing phase influenced other sub-systems. The design process was therefore iterative and a concurrent engineering approach was adopted to develop the systems in parallel. An overview of the sub-systems is given in Table 13 below and more detail, including the links between the sub-systems are discussed in Appendix H.

Vessel Sub-system	Overview	Outcome of Design Detailing
Structure	Structure of the vessel in the hulls, legs and deck must ensure strength is sufficient to withstand operating loads Estimation of the weight crucial to ensure feasible design is used for evaluation	Construction methods reviewed and overall construction detailed Overview structure developed and weights estimated to define centre of gravity
Hull	Hull form of vessel would inform the submerged displacement and blockage area, key to determine the stability, seakeeping and resistance of the vessel	Hull form developed from similar catamaran designs Volumes and arrangements parametrically modelled to allow variation of displacement and centre of buoyancy
Powering	Powering is required to provide energy to propel the vessel through the water Powering considers the source of energy and the propulsion mechanism	Review of vessel layout identified direct drive diesel engines not an option due to inability to access for maintenance Diesel electric system developed allowing diesel generators to be placed on deck with electric power plants in the lower hulls Propulsion mechanisms reviewed and ducted, steerable propellers selected
Legs	Legs in vessel concept serve two purposes: - Support structure for deck in semi-submersible configuration - Provide waterplane area when in semi-submersible configuration	Truss structure reviewed but eliminated due to low waterplane area Tubular section selected initially and stability analyses run to determine waterplane area required Profile of leg revised to foil section to reduce drag underway
Jacking Mechanism	Jacking mechanism required to lift deck up legs	Review of jacking mechanisms identified rack and pinion system as simple and reliable Calculations conducted based on estimated weight to establish power requirements Electric motors selected for

		drive mechanism and locking system designed to ensure system stays jacked until required
Ballasting System	Ballasting system required to reduce buoyancy of lower hulls so draft of vessel increases	Sea water ballast system utilised Pumps selected and volumes + ballast tie used to set power requirements Ballasting mechanism reviewed and operation of system proposed
Deckhouse and Deck Layout	Deck layout and deckhouse details required to establish if there was sufficient room and to determine weight requirements	Deck optimised for transit of goods and personnel to offshore sites Large leg spacing required for stability in semi-submersible mode gives plentiful room for requirements Deckhouse concept detailed and weights estimated
Transfer Method	Transfer method required to allow personnel to cross from vessel to offshore wind turbine	Review of transfer systems identified requirement for large deck area Research identified vessel should allow step transfer without transfer system Flat bow incorporated into design and 'push in' method utilised for locating at base of turbine

Table 13 – Overview of Vessel Sub-systems

The safety requirements of the vessel, as defined in Section 4.2.2, were also considered paramount during the design detailing. Considerations for the provision of a safe vessel have been made at every stage of the development process. The vessel has been designed to comply with the relevant safety standards, shown throughout the analysis process, and the conceptual development of the sub-systems and procedures has also been heavily influenced by safety considerations.

The deckhouse has been designed to have plenty room for storage of the required safety provisions and a rescue zone has been incorporated into the deck design. Life rafts are mounted on the deck and coach house roof where they can be easily launched, there will be provision for both an instrument console and a navigation table in the cabin and the correct emergency equipment such as distress radios will be mounted there. A detailed evacuation plan and instructions for on-board maintenance will be provided when the ship is in operation.

Other safety concerns raised in Section 4.4.2 included the manoeuvrability of the vessel and the movement of the deck in the waves. The vessel has not been designed to take a dynamic positioning system however during the powering analysis detailed in Section 5.4.2, steerable nozzles were selected to ensure the vessel can be manoeuvred safely around a windfarm. This will make the vessel very agile and therefore able to avoid collisions with turbines and other equipment on site. The vessel is designed to be positioned at the base of turbines in a similar way to the current access vessels, however if a transfer system is adopted this may be reviewed. The addition of bow and stern thrusters to increase the station-keeping may be considered in the next phase of design development however the focus at this point is to minimise deck movement.

On development of the CAD model it was clear that due to the nature of the design, the visibility in catamaran mode would be severely hampered by the legs protruding well above the deck. This is a fundamental design problem and to maximise foredeck space the deckhouse has been located at the aft, which compounds the problem. A number of solutions were considered, including an auxiliary cabin for the crew at the bow of the vessel, however it was felt that cameras and digital displays would suffice to reduce the visibility problem.

Safety issues were also considered with the way in which the vessel is ballasted and jacked. A simple procedure has therefore been specified for the transformation mechanism that means the hulls have to be fully ballasted before the deck is jacked. This has increased the buoyancy requirements of the upper deck however reduces the likelihood of human error. The ability to remain floating when fully flooded also eliminates potential problems with over flooding.

An air gap of 3.5 m was selected to minimise the chance of wave slamming, which could also pose as a safety hazard. To minimise this further the deck has been raised in the centre and the underside has been curved upwards in a tunnel form to reduce the exposed flat surface. Segregation of the hulls and deck using bulkheads has also been a factor of the design to account for possible damage to the structure. A full damage assessment should be completed later in the design process.

5.3. **Vessel Layout**

The layout of the design was a crucial aspect of the process, as the vessel must be fit for purpose and capable of transferring technicians and equipment. A review of current vessels was conducted during the literature review. The functional requirements during offshore O&M were considered during the literature review and this drove the layout and arrangement of the deck space, however the overall vessel geometry was governed by the requirements in the semi-submersible mode. The separation of the columns had a dramatic effect on the stability of the semi-submersible, and as the columns were mounted on the hulls, this governed the hull spacing. In comparison to standard catamarans the hulls are therefore very far apart, so the overall deck width is greatly increased compared to a standard work catamaran of the same length. The other driving factor was the weight distribution, as static equilibrium was sought in both modes, which largely determined the positioning of the main components.

The deck shape was governed by requirements for a high tunnel between the hulls to reduce the likelihood of slamming into waves (both in catamaran mode and semi-sub mode) and low weight, whilst maximising the capability to transfer technicians and equipment to offshore turbines. The large foredeck space allows equipment to be carried and also allows the transfer of technicians with the conventional ‘step-transfer’ method. The large deck space also provides an area to mount a transfer system if this route is selected.

These considerations, combined with the outcome of the sub-system development, allowed the overall layout of the vessel to be specified. As discussed in Section 5.1, these details were inputted to the CAD model, resulting in a design ready for analysis. An overview of the design layout is given in Table 14 and Figure 27, Figure 28 and Figure 29.

Vessel Property	Value
Length overall	24.0 m
Length of hull	23.5 m
Beam over all	14.0 m
Draft Transit Transfer	 1.8 m 5.3 m
Lightship	+/- 120 tonnes
Hull material	Steel
Fwd deck space	+/- 105 m^2
Aft deck space	+/- 46 m^2
Speed (Departure)	+/- 18 kts (90% MCR)
Speed (Arrival)	+/- 22 kts (90% MCR)
Passengers	12
Crew	2-3
Cargo	3 tonnes FWD, 3 tonnes AFT

Table 14- Design Layout Overview

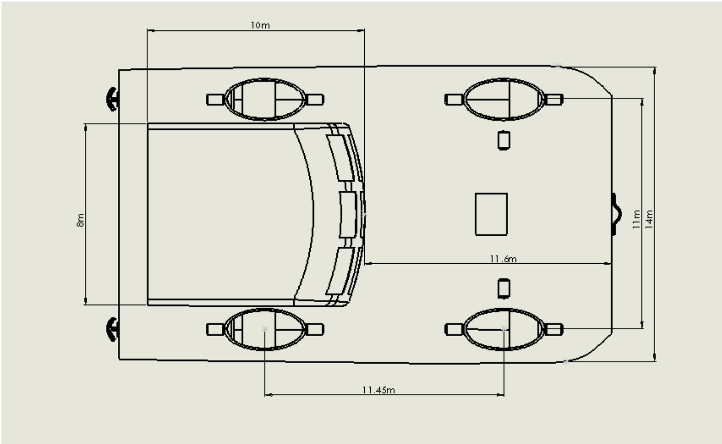


Figure 27 - Design Layout Plan View

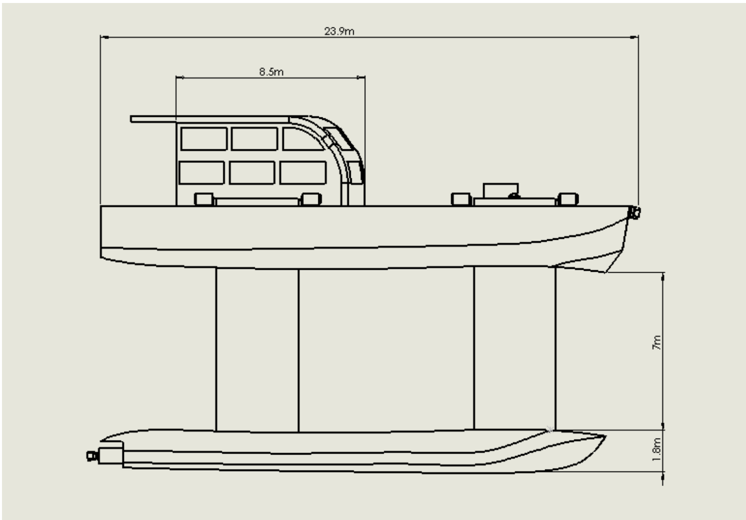


Figure 28 - Design Layout Elevation View

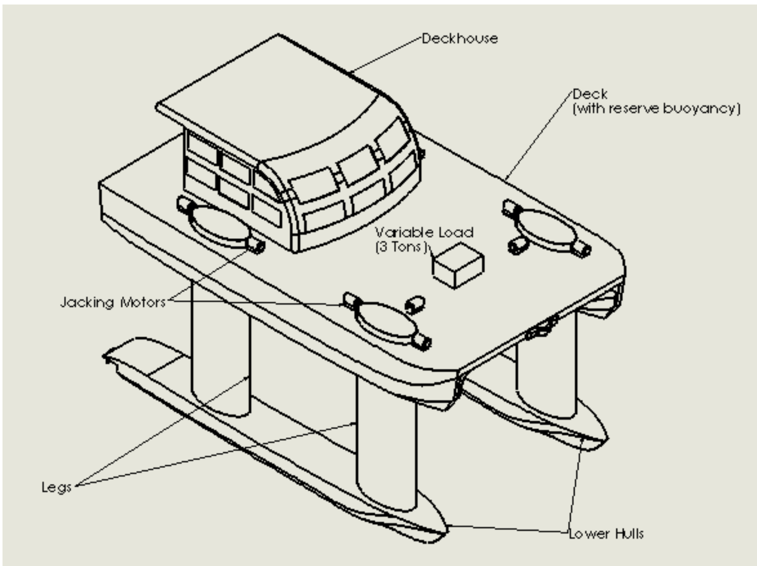


Figure 29 - Design Layout Isometric View

5.4. **Computational Analysis**

As highlighted in Section 3.3.2, computational analysis allows evaluations to be made on a vessel design early in the design process to reduce time and cost during a vessel development process. Initial calculations were conducted utilising equations based on the Math Model detailed in the literature review, however computational software was required for further analysis.

5.4.1. ***Initial Calculations***

Initial calculations were carried out to analyse the effect of varying the main parameters in the design. These included the pontoon dimensions, the hull separation, the leg arrangement and the weight distribution amongst other variable factors. Using a component based spread-sheet coupled with the parametric CAD model, the centre of gravity of each component alongside the submerged volume (for those which would displace water) was determined. This allowed the centre of gravity of the complete system and the centre of buoyancy to be plotted.

The vessel metacentre was estimated based on various parameters, such as the water-plane area, distribution of buoyancy and the submerged volume, and from this the metacentric height (GM) value was calculated. Equations to estimate the free surface effect of the ballast water and to determine approximate values for the roll and heave periods were developed based on the Math Model and the inputs specified above gave resultant values for vessel characteristics.

These calculations allowed variations to be made to the main parameters of the design with a quick feedback loop to analyse the effect of the changes. Using this method the design was optimised, balancing weight distribution, ballast intake and dimensions amongst other variables. This reduced the need to fully evaluate a large number of varying concept configurations which were not be possible or practical during this phase of the research.

A review of the wave data supplied for two offshore windfarms identified wave periods of between 4 and 7 seconds, hence a minimum target of 10 seconds was set for natural periods for roll and pitch. From review of legislation, specifically Marine Guidance Note 280: MCA small craft rules, a minimum metacentric height of 0.35 m was required, after correction for free surface effects. A metacentric height of 0.4 m was therefore targeted, as it was believed this would give sufficient de-coupling from the waves whilst still providing adequate stability and staying above the minimum required GM.

Iteration of the initial analysis process optimised the design to a point where the natural periods of roll and pitch of the vessel were adequately different for those of the operating environment, whilst still maintaining a sufficient metacentric height to provide a reasonable righting moment. At this stage further sensitivity calculations were not producing dramatic effects and therefore the concept was taken forward to the next stage of evaluation.

The design taken forward had the following characteristics:

Characteristic	Measurement
Longitudinal Leg Spacing	12 m
Transverse Leg Spacing	11.45 m
Leg area	6 m^2 (per column)
Metacentric height (GM)	0.416 m
Natural period of roll	25.44 s
Natural period of heave	9.88 s

Table 15 – Design Characteristics

5.4.2. *Speed and Resistance Analysis*

A resistance evaluation of the proposed design was carried out to determine the approximate speed of the vessel. The weights estimated in the design development process were used to calculate displacement, allowing the submerged volume to be defined. The selected hull form allowed calculation of the wetted area and waterline length and the design for the deckhouse and leg arrangement was used to work out the windage area. These details were inputted to a computation based on Froudes early work, detailed in the literature review. A method developed by Voitkunski (1985) was utilised due to the experience Safety at Sea had working with the method.

A review of available power systems coupled with the complexity of carrying out maintenance in the lower hulls led to the selection of a diesel-electric power. By estimating the power required based on similar vessels, two CAT diesel generators of 1100 kVA (880 ekW) were selected to power two ABB electric drive motors, with a direct connection to four-blade propellers with steerable nozzles. Using this information and the ship data given below, an estimation was made for the speed in both transit and transfer. The main data shown in Table 16 was used for the evaluation and the results are given in Table 17 below.

Feature	Catamaran mode (Transit)	Semi-sub Mode (transfer)
Length of waterline (L_{WL})	22.61 m	24.10 m
Demihull Beam/ leg beam	2.68 m	1.76 m
Draught (T)	1.7 m	6.15 m
Demihull/ leg separation (c-c)	11.45 m	11.45 m
Total wetted surface (S)	206 m^2	526.00 m^2
Total transversal windage area (A_{VT})	87.22 m^2	66.50 m^2
Total displacement volume (V)	143.9 m^3	334.70 m^3

Table 16 - Ship Main Data for resistance evaluation

Speed [knots]	Catamaran mode	Semi-submersible mode
Calm weather speed	21.7	13.4
Service speed	20.7	13.1

Table 17 - Ship Speed Preliminary Predictions

The implications of these results are discussed in Section 6.2.1 of the discussion.

5.4.3. ***Stability Analysis***

On completion of initial stability calculations, as discussed in Section 5.4.1, the relative centre of gravity and mass of each of the individual components was detailed. This information was then utilised, using computational analysis software, to model the vessel structure and conduct more accurate stability calculations.

Ideally an evaluation would be conducted for all possible geometries of the vessel as it changed, in three separate loading conditions; fully loaded, partially loaded and minimally loaded. On review of this however it was unrealistic given the timescale and budget. The worst case scenarios were therefore identified that, when analysed, would also prove the stability of the more stable geometries.

To identify the worst case scenarios the jacking method was analysed. It was proposed that to reduce complexity of the procedure and to maximise stability the vessel would be fully ballasted before jacking. Three discreet loading conditions were therefore chosen to simulate firstly the vessel in transit mode, acting as a standard catamaran, secondly the vessel in semi-submersible mode, with the deck fully jacked up and full ballast water on board, and finally the vessel with all ballast water on-board but without the deck jacked up.

The three scenarios were as follows:

> **Loading Condition 1** (LC01) – Vessel in catamaran mode with no ballast water and deck down, fully laden with crew, passengers, equipment and fuel etc.
>
> **Loading Condition 2** (LC02) – Vessel in semi-submersible mode, fully laden with passengers, crew and fuel etc. and deck jacked up with all ballast water on board.
>
> **Loading Condition 3** (LC03) – Vessel in catamaran mode but with all ballast water on-board and fully laden.

The results from the stability analysis produced the following summary:

Case	Displacement (t)	Draft (m)	Trim (m)	GM_{fluid} (m)	Water Ballast (t)
LC01	144.0	1.675	-0.169	23.994	0.0
LC02	333.5	6.311	-0.114	0.413	189.5
LC03	333.5	3.123	-0.617	13.320	189.5

Table 18 – Stability Analysis Results

The results show a dramatic change in GM between the catamaran mode and the semi-submersible mode, however to de-couple the semi-submersible movement from the waves a low GM is necessary. To determine if the analysed stability was sufficient the results were compared to the criteria set out in Marine Guidance Note 280. The comparison, discussed in Section 6.2.2, highlighted that the vessel meets and exceeds all but one of the criteria, and for the case it did not meet the criteria it meets secondary criteria set out in MGN 280.

5.4.4. ***Sea-keeping analysis***

Following the stability analysis, a sea-keeping analysis was conducted to make a comparison between the two extremes of the variable geometry craft; the vessel in catamaran mode for transit with the deck down and minimal ballast water on board, and the semi-submersible mode when the vessel is fully ballasted and the deck is fully raised, ready for transfers. The aim of the analysis was to determine the difference between the two modes of operation to establish if ballasting the hulls and jacking the deck had a considerable effect on vessel movement, and hence prove the purpose of the concept.

Wave data supplied by Det Norske Veritas was used to determine the expected environmental conditions and the analysis was carried out in the frequency-domain and the time-domain to fully understand the vessel behaviour. The studies were performed for monochromatic waves and random seas characterised by the JONSWOP wave variance spectrum, with a range of periods between 3 and 20 seconds. A 1 m wave amplitude (and 1 m SWH for the JONSWOP spectrum) was used for the analysis as the comparison between the vessel modes was the crucial factor therefore for larger wave heights the comparative difference could be scaled.

The results, shown in the graphs below, show that between wave periods of 4 to 10 seconds, the vessel movement is reduced to between 30-50% of the relative movement of the catamaran mode in the same conditions. The sea-keeping of standard crew transfer vessels has not been analysed however it is considered that they will behave similarly to the concept vessel in catamaran mode.

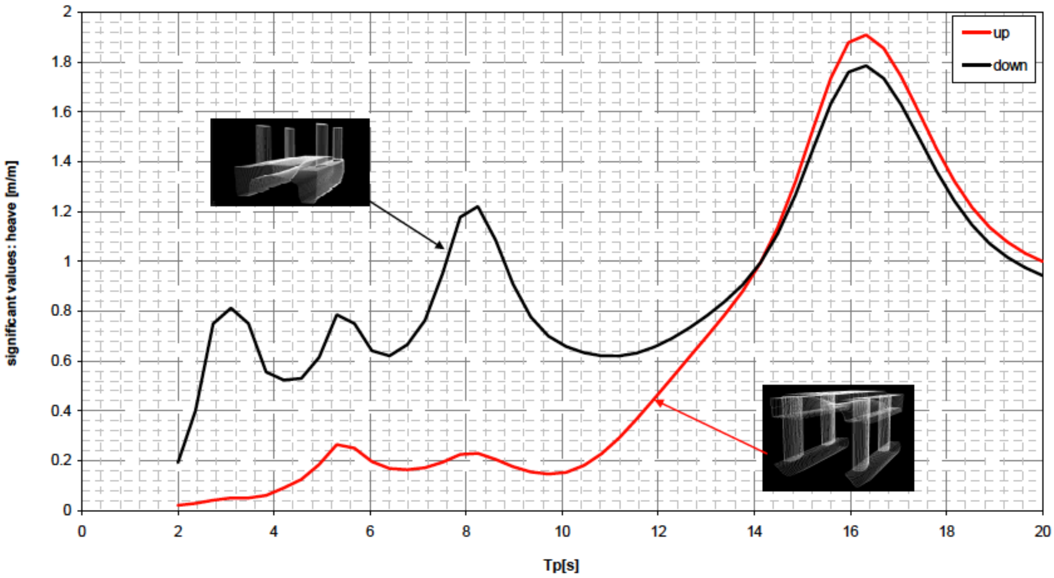


Figure 30 -Comparison of heave motion between two modes

Figure 30 shows the relative heave motion of the two concepts. The black line represents the motion in metres of the vessel in catamaran mode with respect to wave period in seconds. The red line represents the heave motion of the vessel in semi-submersible mode with respect to wave period. The graph shows that for wave periods below wave periods of 10 seconds the vessel will have significantly less heave when in semi-submersible mode. Further to this, Figure 31 shows the comparison of roll angle between the two vessels and Figure 32 the comparison of pitch angles, both with respect to wave period. The roll angle is considerably reduced throughout the range of study and the pitch angle considerably reduced below wave periods of 10 seconds. The pitch angle is higher for the semi-submersible mode above 12 seconds, as this frequency of waves is relatively close to the natural pitch frequency of the vessel in this mode, however on review of the environmental data provided at this stage it was identified there would be very few waves with this period hence it would not pose problem. Further information provided for later tests identified additional wave sets with longer wavelengths; this is discussed in Section 6.2.3 of the discussion.

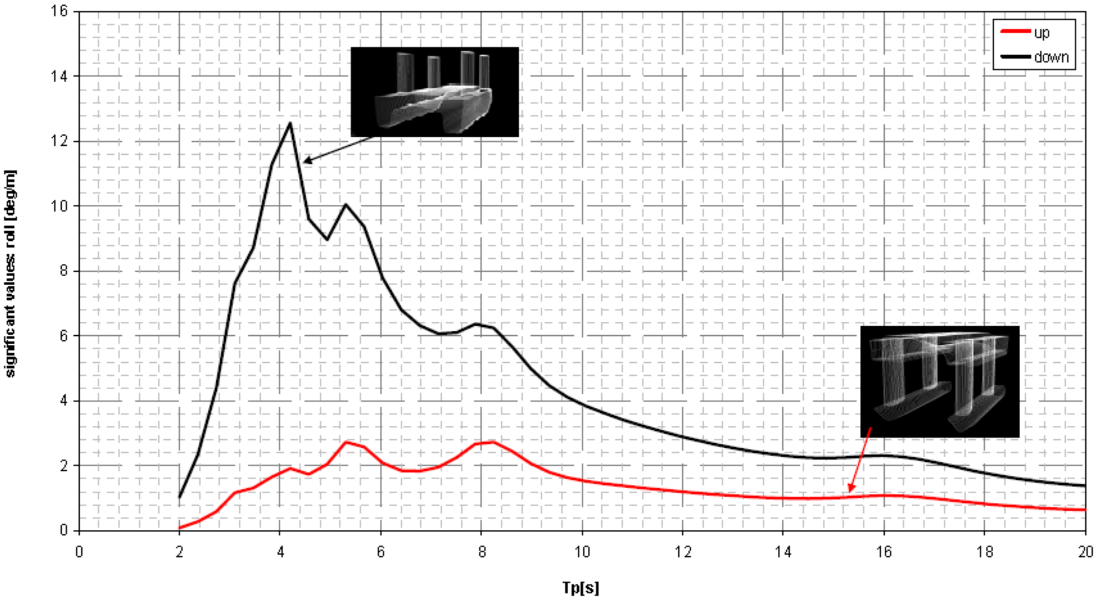


Figure 31 - Comparison of roll angle in two modes of operation

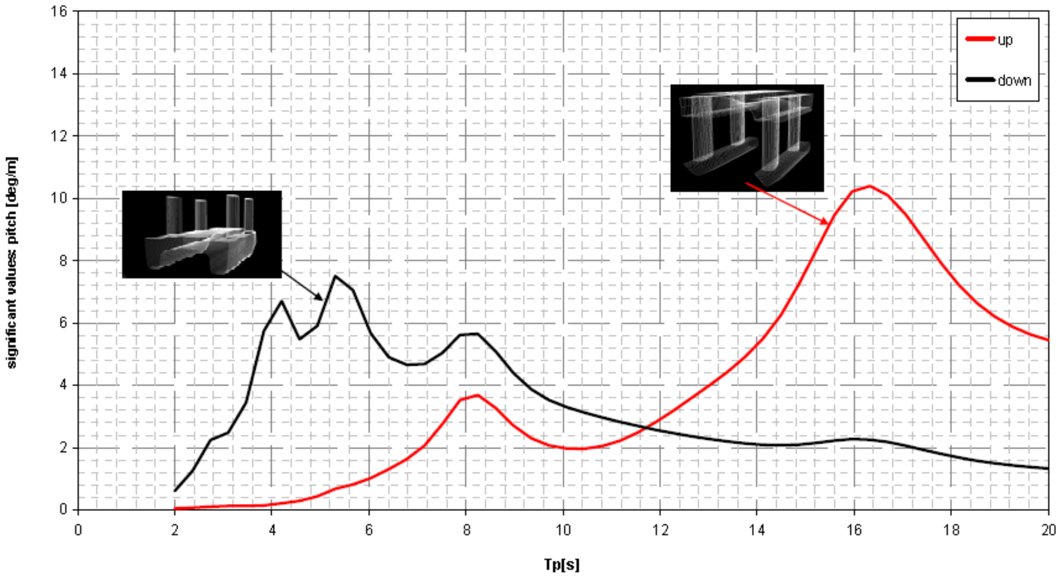


Figure 32 - Comparison of pitch angle in two modes of operation

Figure 33, Figure 34 and Figure 35 show the comparison of heave, roll and pitch, respectively, of the two modes for a given wave period. These graphs clearly demonstrate the reductions in vessel motions achieved by the change in configuration.

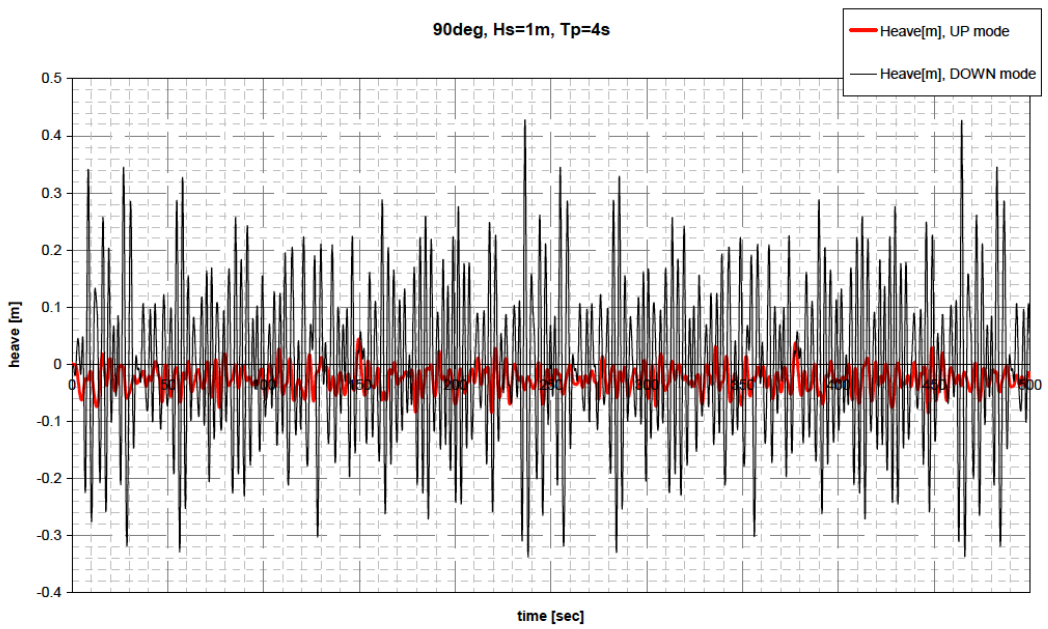


Figure 33 - Heave comparison time series

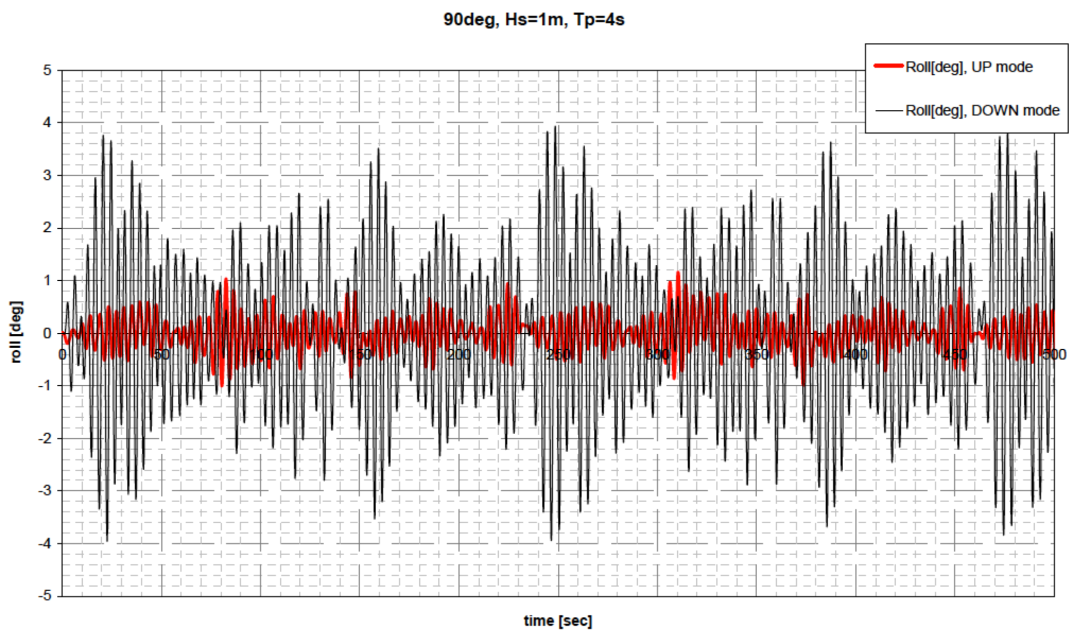


Figure 34 - Roll Comparison time series

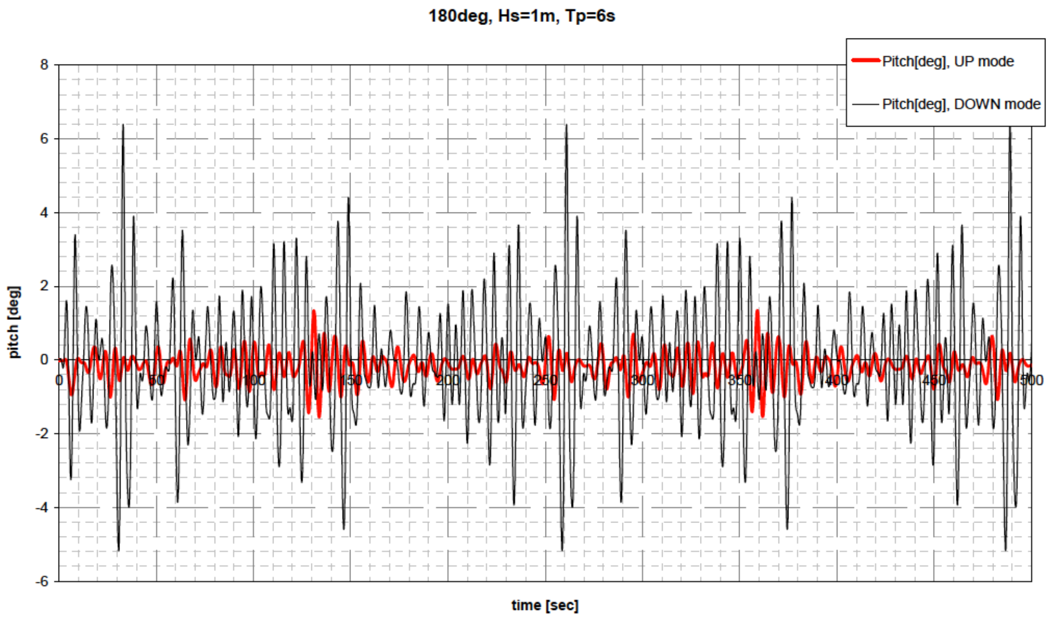


Figure 35 - Pitch comparison time series

The implications of these results are discussed in Section 6.2.3.

5.5. **Tank Testing**

The next phase of analysis to be conducted was tank testing. Research identified that tank testing is used in many vessel development cycles to validate the results of the computational analysis. In the case of this design, it was also employed to try to gain a deeper understanding into the motion of the vessel in irregular waves and a further test, simulating loading on the bow of the vessel, was carried out. The latter was brought into the test schedule after discussions with industry partners highlighted concerns over load transfers from the vessel to and from turbines; a crucial part of the maintenance process.

The main body of the tests, conducted in June 2012 at the Kelvin Hydrodynamics Laboratory in Glasgow, were carried out in irregular waves. The model was tested in six sea states at five headings between bow and stern waves, at standstill (i.e. zero forward or aft motion). Further testing under forward motion was considered however the key area of concern was for the transfer period, when the vessel would be stationary at the base of the turbine. Simulating the effect of the turbine structure in the waves was also considered, however at the time of testing this was still under investigation and it was considered the addition of the turbine structure could dilute the results.

A second set of tests in the same sea states were undertaken with the equivalent of a three tonne mass situated on the foredeck of the vessel, to simulate the loading conditions discussed earlier. Finally, in order to gain greater understanding of the irregular sea state results, an additional set of tests was undertaken in single-frequency waves to establish the Response Amplitude Operators (RAOs) for the vessel in head seas.

5.5.1. ***Model Development***

The model was developed based directly on the CAD model, which had been used previously for the computational analysis, at a scale of 1:12. The 3-D modelling technique employed earlier in the design process proved very efficient at this stage, as the model was simply scaled and manufactured using computer-aided-manufacturing techniques. Due to the difference in construction materials between the scale model and the proposed final design, weight distribution was controlled by manufacturing the model significantly underweight and adding ballast in appropriate positions to gain the correct overall displacement and centre of gravity.

The model was constructed using a combination of different materials including fibreglass, foam and a wooden structure. In this form the model was overweight, and significant challenges were encountered to achieve the appropriate displacement and centre of gravity. The manufacturing technique was found to be inadequate and the pontoons started to leak and eventually split. The manufacturing process was consequently revised, leading to lengthy postponement of the test program. The model was modified and redelivered with solid pontoons machined from Divinycell foam with aluminium stiffeners. In this form it proved extremely difficult to achieve the required centre of gravity; in the end lead ballast was installed in pockets machined into the pontoon. In addition, bracing was added fore and aft between the pontoons in order to stiffen the structure sufficiently to resist the expected loads in beam and quartering seas, as the model materials did not have the strength expected in the final vessel design.

The proposal for tank testing was to evaluate the vessel in both the catamaran and the semi-submersible configurations (un-jacked and jacked respectively), however because the ballast had to be inserted into the hulls, and the time constraints due to the initial model issues, it was only possible to evaluate one configuration. The jacked configuration was deemed the most important therefore the model, shown in Figure 36 below, was fixed permanently in this configuration. The figure shows the reflective markers used for the motion tracking system, the struts fore and aft used to provide stiffening and their attachments that were used for the four-point mooring system. Some of the pockets cut into model to give correct centre of gravity can also be seen.

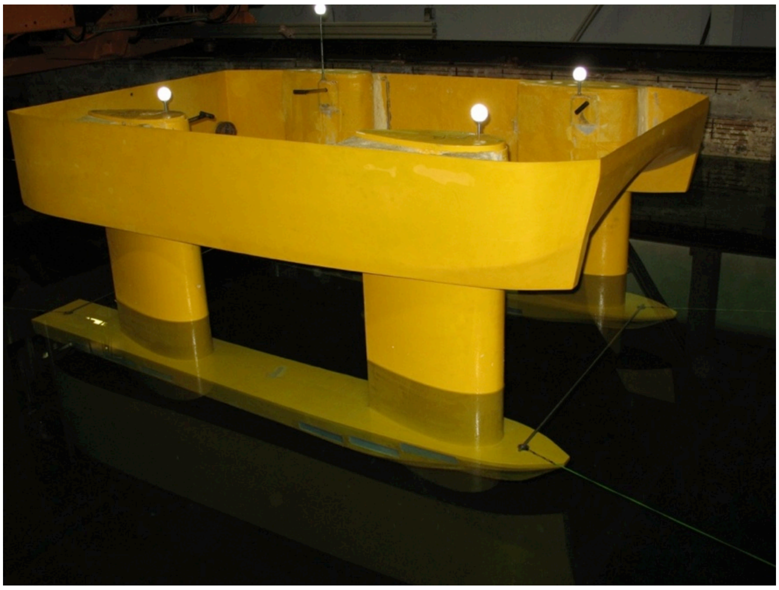


Figure 36 Model of Solid Sea Transfer installed for head seas tests

In order to yield correct motion properties in waves, the centre of gravity and radius of gyration were set by adjusting the position of the ballast weights. The model was inclined to measure the metacentric height and the ballast adjusted accordingly to vary the centre of gravity and hence give the correct GM value. Key model data with respect to the full-scale design is summarised in Table 19.

Dimensions	Full Scale	Model Scale	Units
Length overall (LOA)	24.0	2.0	m
Beam (B)	14.0	1.167	m
Draft (T) (design)	6.234	0.5195	m
Displacement (T)	334	193.28	T / Kg
Centre of Mass (KM)	4.66	0.388	m
Centre of Gravity (KG)	4.169	0.374	m

Table 19 - Key Dimensions and Hydrostatic Data

5.5.2. Test Procedure

The vessel was installed in the tank and restrained on a soft four-point mooring. The natural period of the mooring system was designed to be greatly different from the wave periods of interest in order that the restoring forces of the mooring system were not excited by the waves. The full-scale natural period of the mooring system in surge was found to be 134 seconds in head seas. The mooring system can be seen in Figure 37 for head seas and Figure 38 for quartering seas.

Figure 37 Model of Solid Sea Transfer installed for head seas tests: stern view

Figure 38 Model of Solid Sea Transfer installed for bow quartering seas test

Wave elevations were measured upstream in the tank away from the test area and locally to the vessel, using a combination of ultrasonic and resistive wave probes.

Six irregular JONSWAP sea states were generated, each representing half an hour duration at full scale. Prior to the vessel testing, the sea-states were run without the vessel in the tank and tuned to provide significant wave height statistics within 5% of the target values. Additionally a second version of some of the sea states was generated using a different random seed in order to check repeatability of the results.

The conditions tested are tabulated below:

Generated Sea	Target significant wave height	Period	Error Hs
	(m)	(s)	(%)
1	0.75	4.5	-2.2
2	1.25	5.5	-0.3
3	2.25	6.5	-0.9
4	2.75	7.5	-1.1
5	1.75	8.5	-1.6
6	1.75	9.5	-3.1

Table 20 - Wave conditions

5.5.3. ***Data Collection***

The six degree-of-freedom motions of the vessel relative to the centre of gravity were measured using a Qualisys optical motion tracking system, allowing the vessels response to be accurately determined in real time. The reflective markers used by the Qualisys system can be seen in Figure 36. Alternative systems for measurement of the model motion were considered, however the availability of the Qualisys system at the Kelvin Hyrdodynamics lab coupled with the knowledge that the system was utilised at a number of tank test locations instructed the selection of the Qualysis system.

The vertical motion of the vessel at the bow was then reconstructed in real time from the heave and pitch motion data to allow a comparison to that of the simulated sea-state.

5.5.4. ***Data Analysis***

Analysis of the tank test results was carried out based on the results from the tests in both regular and irregular waves. The irregular wave spectra were run for a duration corresponding to half an hour full scale. Two measures of the motions were investigated. Firstly the significant values of the various motions were calculated in order to indicate typical motions. The root-mean-square (RMS) values of motions are calculated from the time histories as:

$$\text{RMS}(\zeta) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\zeta_i^2}$$

where ζ_i represents the ith measurement of the motion ζ. The significant values of each degree of freedom of motion and of the vertical motion at the bow were then calculated from the corresponding RMS values using the standard formula:

$$H_{S,\zeta} = 4 \times \text{RMS}(\zeta)$$

Additionally the ranges of the motions, defined as the difference between the maximum positive and negative motion, were calculated in order to indicate the extremes.

The tests carried out in regular waves were analysed by calculating response amplitude operators for the vessel motions of interest and for the water elevation inside the dock relative to the vessel. The RAOs are defined as:

$$Heave\ RAO = \frac{Heave\ amplitude}{Wave\ amplitude}$$

$$Pitch\ RAO = \frac{Pitch\ amplitude}{Max\ Wave\ slope}$$

$$Bow\ Motion\ RAO = \frac{Bow\ Motion\ amplitude}{Wave\ amplitude}$$

All of these values are non-dimensional, and can be assumed to represent full-scale ratios. Periods of the RAO points should be scaled according to Froude similarity: i.e. time scales as $\sqrt{\lambda}$ where λ is the scale ratio (here 12).

Both wave and vessel motion amplitudes were calculated by fitting sine functions to the measured data. This approach is appropriate for a linear system with sinusoidally varying excitation. In this case, the waves far away from the ship behave sinusoidally, and the response of the vessel is sinusoidal at the same frequency as the waves.

5.5.5. ***Tank Testing Results***

The vessel was tested in the standard configuration for each of the seas tabulated in Table 20 for five heading angles: 0/45/90/135/180 degrees, where 0 degrees corresponds to head seas. The vessel can be seen under test in beam seas in Figure 39 and in quartering seas in Figure 40.

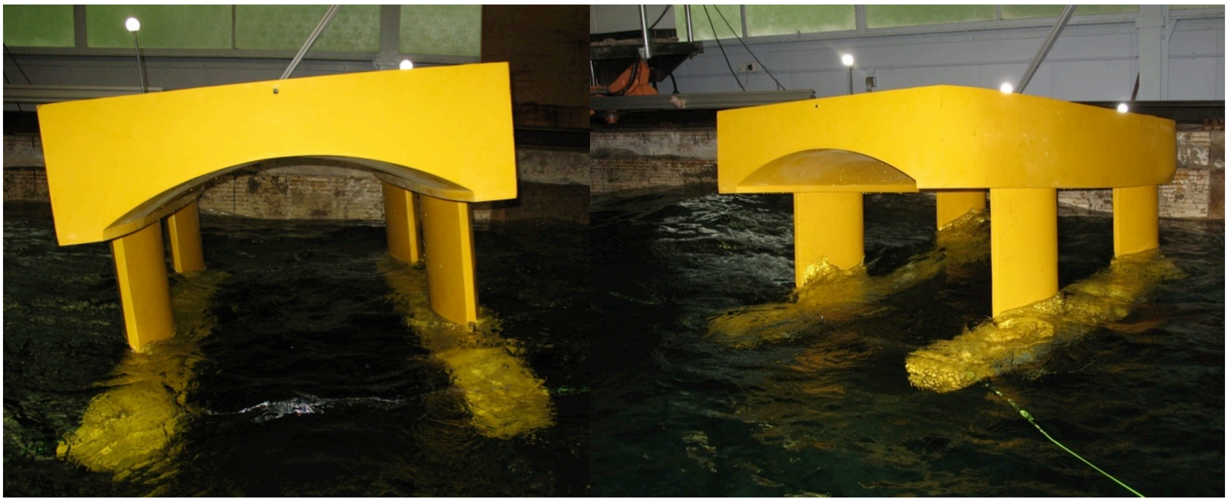


Figure 39 - Vessel under test in irregular waves in beam seas

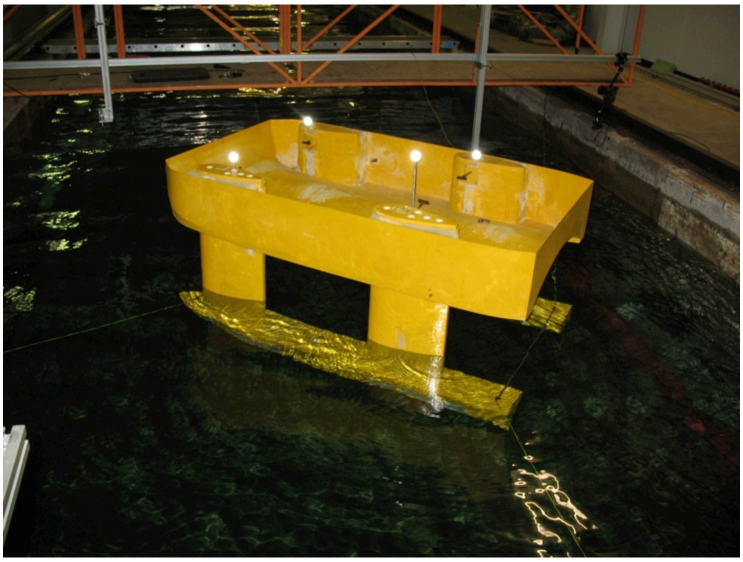


Figure 40 Vessel under test in irregular waves in quartering seas

The significant bow motion response of the vessel in its standard configuration for the sea states shown in Table 20 is shown in Figure 41. At the lower peak periods (7 seconds and below) the significant vertical motion at the bow is around half of the significant wave height; however for the highest peak period values, the significant bow motion increases substantially in comparison with the wave height, reaching a value of 1.6 times larger than the significant wave height for all heading angles for the sea state with Tp = 9.5 seconds. The range of motion is shown in Figure 42. These values vary from around 1.4 - 2.2 times larger than the corresponding significant wave heights, though the results are rather more scattered than the significant wave heights due to the relatively short time histories.

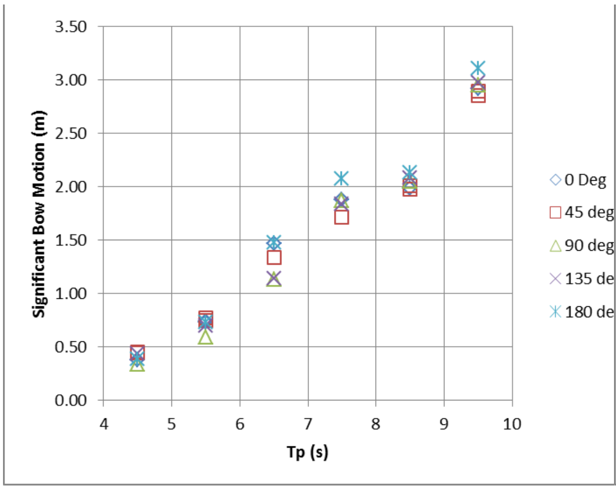


Figure 41 Significant Bow Motion: irregular sea states

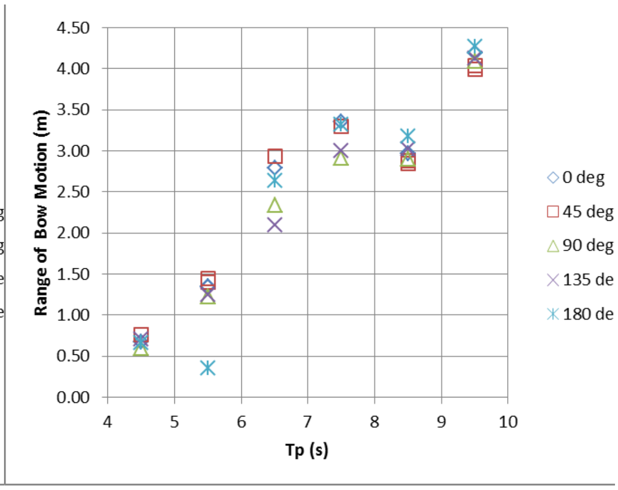


Figure 42 Range of Bow Motion: irregular sea states

The heave and pitch motions can be seen from Figure 43 to Figure 46. It can be seen that the majority of the bow motion results from the vessel heave: for example at Tp = 9.5 seconds, the significant bow motion is around 3.0 m, whilst significant heave motion is around 2.0 m.

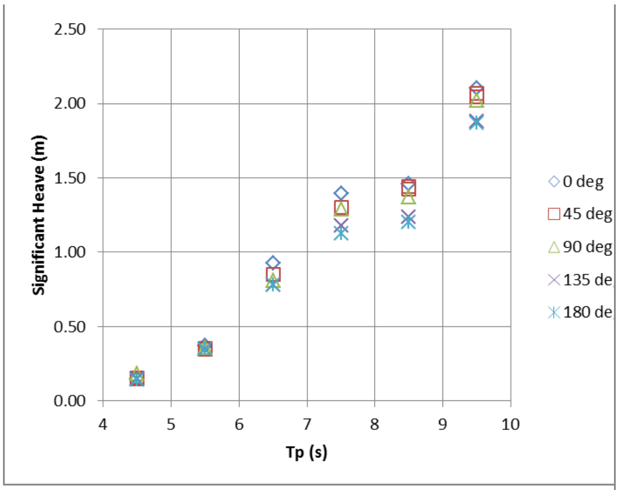


Figure 43 Significant Heave Motion: irregular sea states

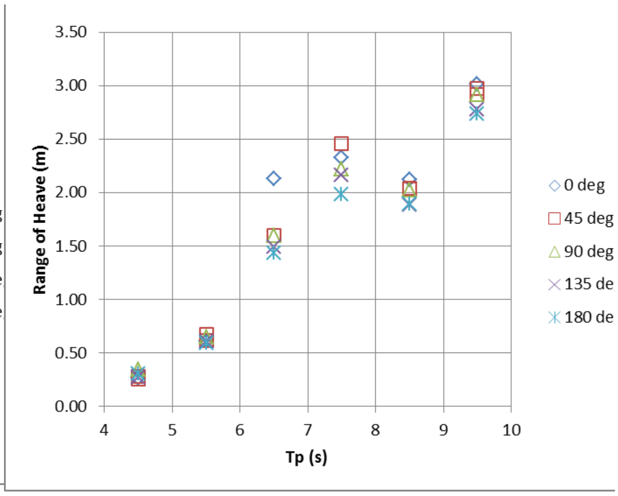


Figure 44 Range of Heave Motion: irregular sea states

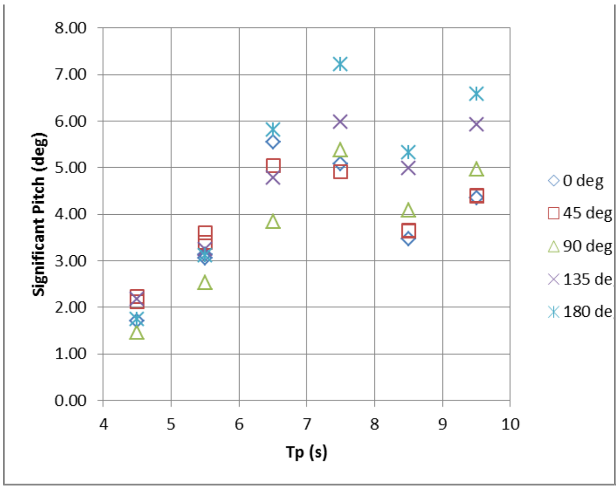


Figure 45 Significant Pitch Motion: irregular sea states

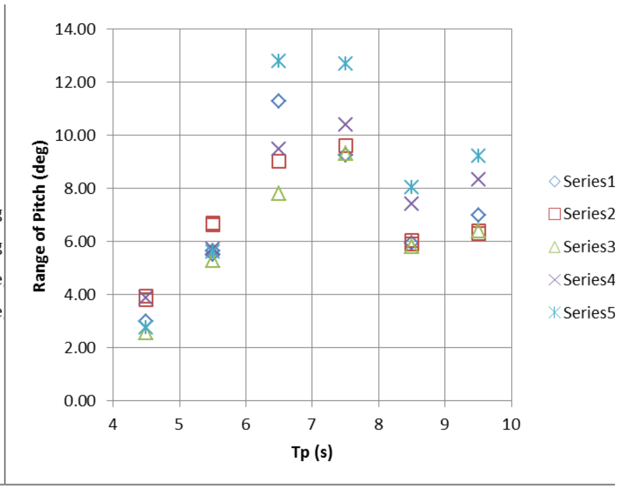


Figure 46 Range of Pitch Motion: irregular sea states

Finally the corresponding roll motions are shown in Figure 47 and Figure 48. Note that these are not considered to contribute to the vertical motion at the bow. It can be seen that there are some extreme roll angles in anything other than head and stern seas especially for sea states with peak period between 6-8 seconds.

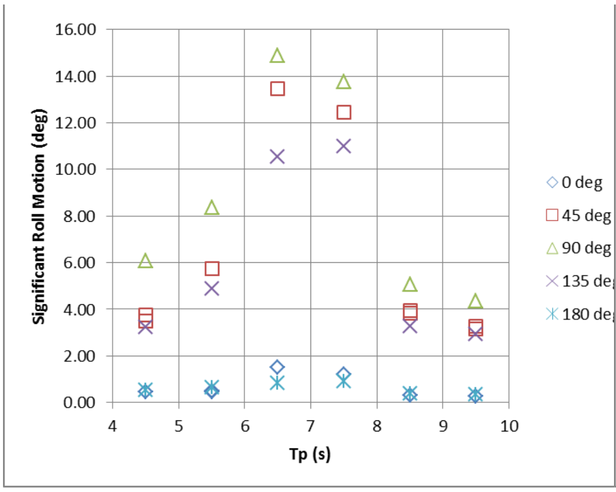


Figure 47 Significant Roll Motion for irregular sea states

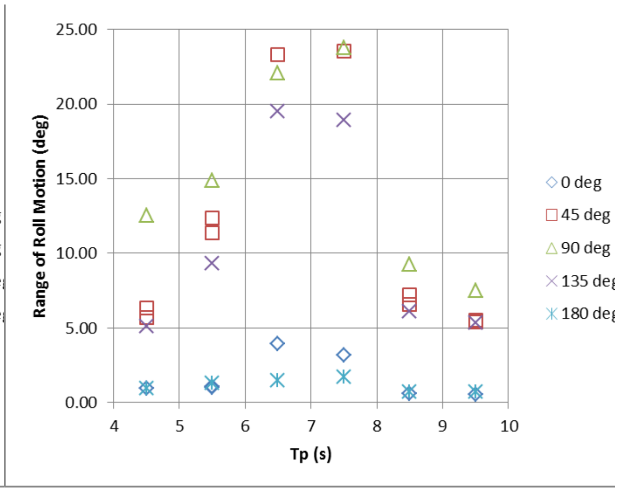


Figure 48 Range of Roll Motion for irregular sea states

In order to throw further light onto the results and gain greater understanding of the response of the vessel a series of regular wave tests was also carried out in order to determine the response amplitude operators (RAOs) as described in Section 5.5.4. Tests were carried out in waves of constant height, equating to 0.36 m at full scale. The bow motion RAO is shown in Figure 49; it can be seen that at the peak of the curve, the bow motion is over four times the wave height.

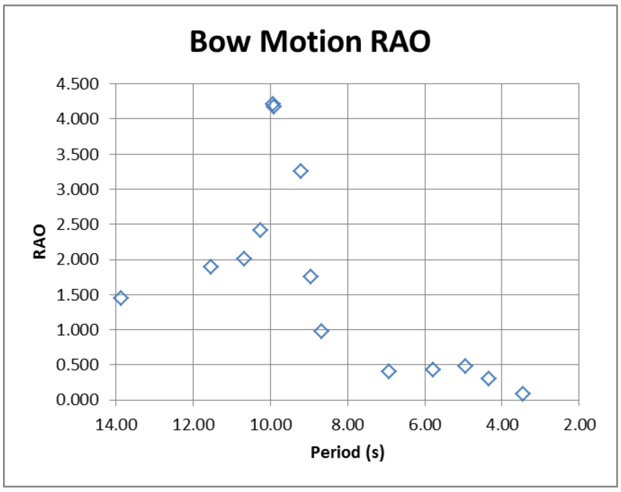


Figure 49 Bow Motion RAO: Head Seas

The heave and pitch RAOs can be seen in Figure 50 and Figure 51. It can be seen that the peak response in heave and pitch coinside at a wave period of around 10 seconds. At this period, the heave response is nearly three times the wave height and the pitch response is two and a half times the wave slope.

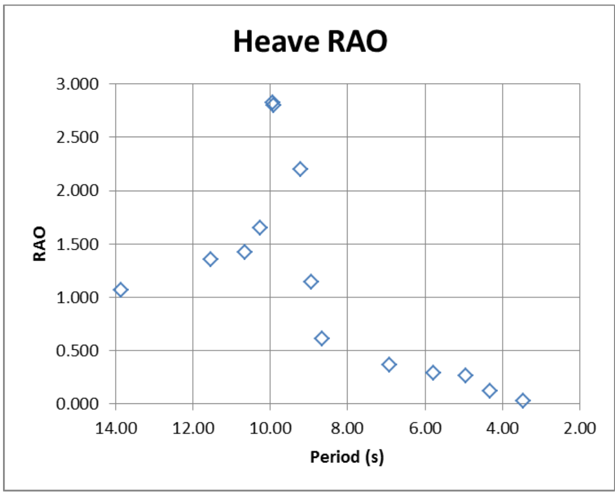


Figure 50 Heave RAO: Head seas

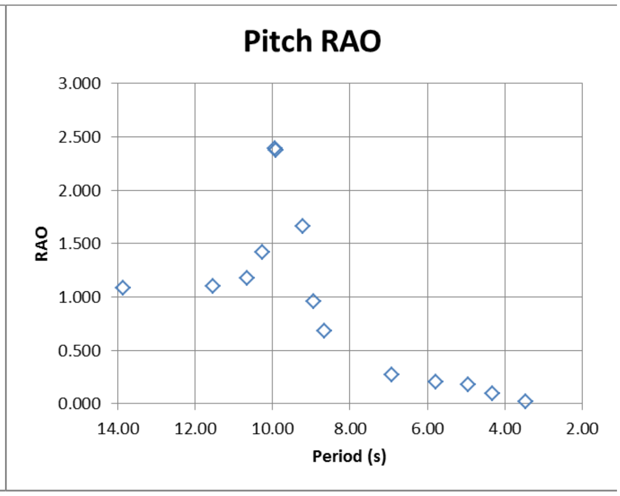


Figure 51 Pitch RAO: Head Seas

A discussion of the impact of these results can be found in Chapter 6.

A second set of tests was carried out for the vessel with the equivalent of a 3 tonne mass located on the bow. Three heading angles of 0/45/90 degrees were considered for these tests. In this condition the vessel trimmed by 7.1 degrees by the bow in calm water.

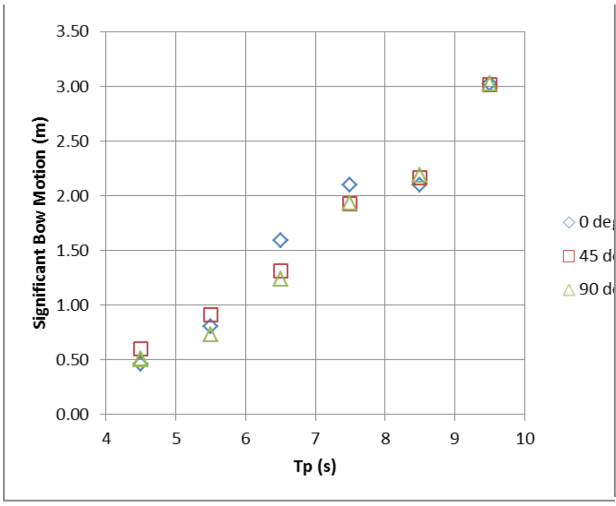


Figure 52 Significant Bow Motion: irregular sea states trim by bow

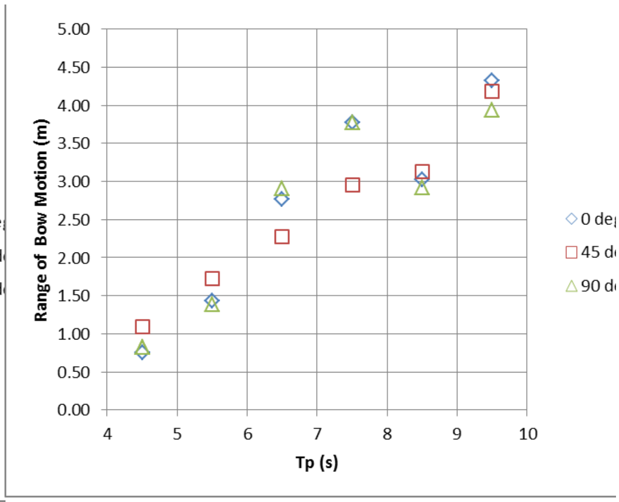


Figure 53 Range of Bow Motion: irregular sea states trim by bow

Results for significant bow motion are shown in Figure 52 and Figure 53. It can be seen by comparison with Figure 41 and Figure 42 that the dynamics of the vessel bow motion are not substantively affected by this large trim angle, though motions generally increase very slightly. A similar observation can be made for the heave pitch and roll motions shown in Figure 54 through to Figure 59. It can be seen from Figure 56 that the slight increase in bow motions compared to the standard condition results from a slight increase in pitch motions.

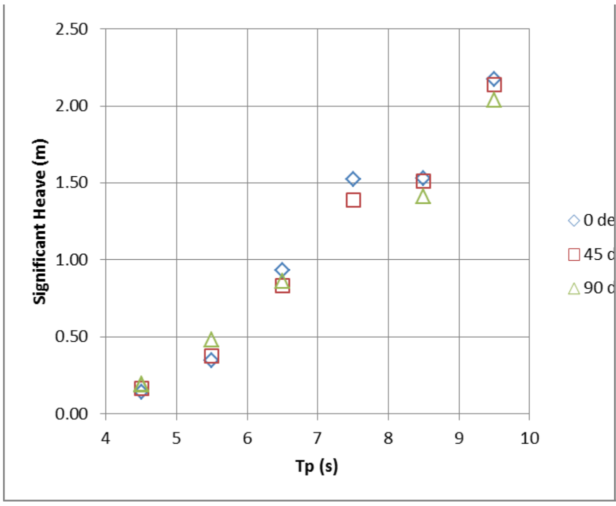


Figure 54 Significant Heave Motion: irregular sea states: trim by bow

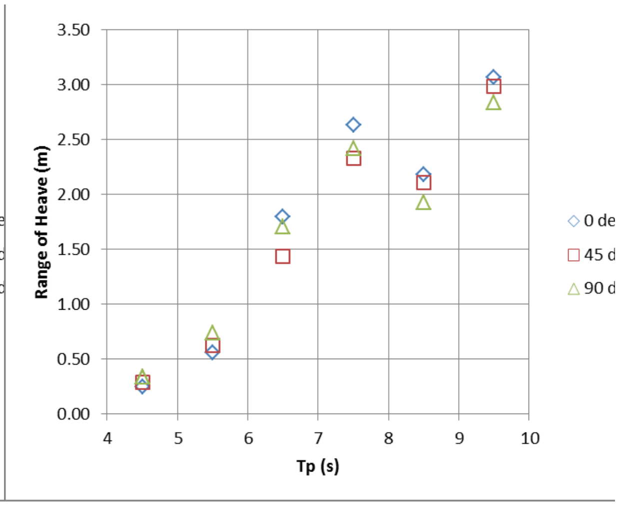


Figure 55 Range of Heave Motion: irregular sea states: trim by bow

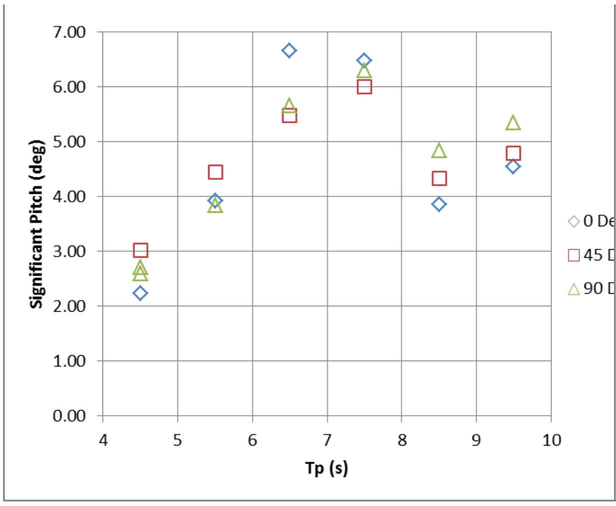


Figure 56 Significant Pitch Motion: irregular sea states: trim by bow

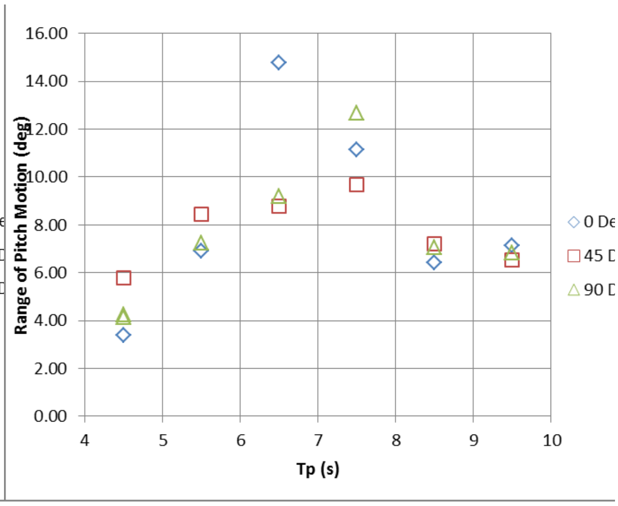


Figure 57 Range of Pitch Motion: irregular sea states: trim by bow

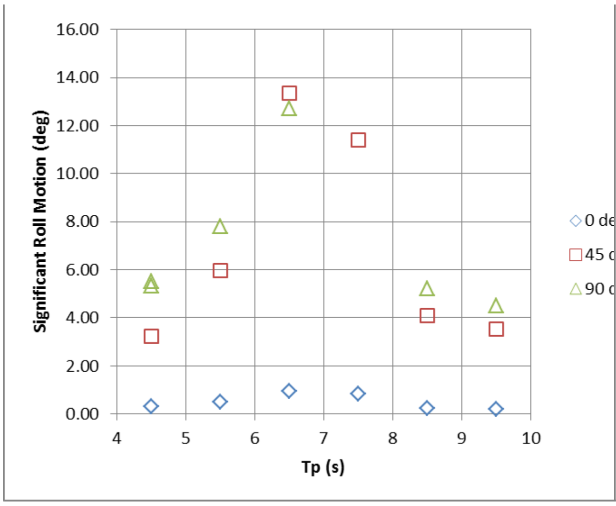


Figure 58 Significant Roll Motion: irregular sea states: trim by bow

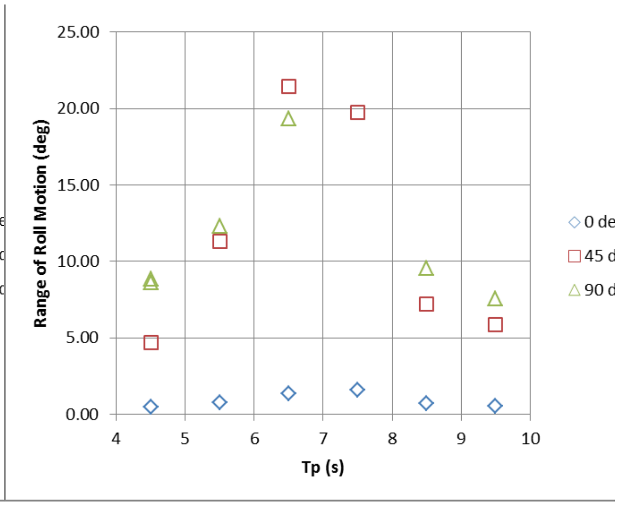


Figure 59 Range of Roll Motion: irregular sea states: trim by bow

A further study was conducted into the behaviour of the boat as the mass was placed onto the deck and as it was lifted off. Two tests, once making the transition quickly (Test 1) and once lowering the weight on slowly over a period of 8 seconds (Test 2) indicated that the speed of loading/unloading had a negligible affect on the vessel motions (see Table 21).

	Test 1		Test 2	
	Scale 1:12	Full scale	Scale 1:12	Full scale
Trim angle induced	6.8°	6.8°	6.5°	6.5°
Bow deflection	112 mm	1.34 m	108 mm	1.29 m
Oscillation amplitude	38 mm	0.45 m	36 mm	0.43 m
Time to settle	68 s	235 s	64 s	221 s
Oscillating frequency	0.1 Hz	0.029 Hz	0.1 Hz	0.029 Hz

Table 21 - Transition Loading Results

The results show a similar deflection on the bow to that caused by constant loading however the vessel took a long time to settle after the change, with a very slow period of oscillation.

5.6. Analysis Summary

Development of the vessel concept focused on sub-component design supported by initial analysis to guide the development towards a practical and seaworthy solution. The CAD model, developed for fast visualisation in the concept selection stage, was developed to incorporate the selected aspects of each of the concepts, allowing an estimation of vessel layout and operation to be made. From the modelling, key sub-systems were identified and the research was re-visited to identify optimal solutions for each sub-system. The CAD model was used to test the integration of technology into the subsystems and facilitated the initial analysis by allowing an accurate weight distribution model.

The analysis of the vessel was conducted in two stages: computational analysis and tank testing analysis. The computational analysis was conducted for three loading conditions. The stability analysis identified metacentric heights of over the target values for all three loading conditions and the seakeeping analysis suggested an average of around 50% less motion in heave, roll and pitch in the semi-submersible mode compared to the catamaran mode within the operational envelope.

The vessel was then tested in a variety of operational sea conditions in a test tank to indicate the performance in terms of vertical bow motions and rigid body motions in heave, pitch, and roll. Results indicate good performance in waves with periods less than around seven seconds; however large dynamic magnification of the motions is exhibited in waves between around seven to twelve seconds.

6. Discussion

The purpose of carrying out the design and evaluation work was to develop a vessel concept that could allow safe access to offshore wind turbines in greater wave heights than currently possible, hence reducing the time delay in carrying out maintenance and therefore increasing the productivity of the turbines. The thesis so far has detailed the practical approach taken to carry out this work. This chapter reviews the work conducted with respect to the Hypothesis:

> ***Hypothesis:*** *The proposed vessel concept will be shown to have significantly less deck movement in high sea states than the current service vessels and hence will allow safe transfer to offshore structures in more adverse weather conditions, whilst still maintaining the advantages of speed and manoeuvrability.*

The discussion will focus on how the results detailed in the previous chapters support the Hypothesis and provides the author's objective view of the outcomes of the research. The chapter is structured to reflect the progress of the design development; the initial concept is critically reviewed before the outcomes of the testing, both computationally and physically are reviewed and the correlation between the two is examined. The development method and analysis approaches are discussed, with specific reference to the approach adopted. Finally, the limitations of the study have been identified and considerations have been made for future work.

6.1. **Concept development**

One of the reasons that the concept gained industrial interest in the early stages of the project was the significant difference to a standard vessel design, amalgamating aspects from completely different fields of design; the jacking aspect from seabed mounted jack up rigs, the small waterplane area from semi-submersibles and SWATHs and the size and manoeuvrability of small work boats. A number of experienced naval architects were consulted once the initial evaluations had been made and the feedback gained was negative; that the combination of these factors in such a small vessel was too radical to succeed. As the researcher did not have experience in vessel design it was not immediately apparent that the concept may be flawed, allowing a body of evidence to be gathered on the contrary before this was highlighted. This early dismissal of concepts has been highlighted by this research to be a potential contributing factor in the similarity of many modern vessel designs, and it is believed a design approach based on a product design methodology could be advantageous to the industry. This is discussed further in Section 6.5.

The initial conceptual model was selected prior to the research, and the general principle, a small-scale bi-configuration vessel, was the basis of the research, hence drastically alternative designs were not considered. This limited the early stages of the design process, as the project was started with a concept in mind rather than the more widely accepted approach of starting with the problem and finding a solution. The design brief was however very open, and within the scope of the initial concept design many alternatives were considered. At this stage an extensive technology review had been conducted to identify existing solutions to problems encountered, however a broader experience of vessel design/construction would have benefitted the design process considerably. This opposes the previously stated advantage that the design approach benefitted from lack of dismissing evidence, and this experience/expertise could easily be called in at various stages of the design process.

6.2. **Computational Analyses**

The computational analyses were conducted to identify if the ship design was fit for purpose, with the key focus on the difference in deck movement between a conventional vessel and the proposed concept.

Initial analysis was conducted before the design was completed to allow a feedback loop to be integrated into the design process. This permitted a degree of optimisation of the design towards target values set out in the early design phase, but as discussed in Section 5.4.1, the evaluation accuracy was limited therefore the optimal ship geometry may not have been reached during the cyclic process. It did nevertheless inform the researcher that there was a viable solution obtainable; hence the next stage of the development process was justified.

The next three phases of the computational analyses; resistance analysis, stability analysis and sea-keeping analysis; were conducted in a single pass due to the time and funding constraints of the research. The outcomes of these analyses and the implications of the results on the design are discussed in Sections 6.2.1 - 6.3.3. In a commissioned ship design project funded by the successful launch of a ship, where it is estimated 90% of the total building cost of a ship is decided during the design phase (Kumakura and Sasajima, 2001), significantly more time would be spent iterating the computational analyses. This would allow a further stage of more detailed optimisation to be included in the design process. Further analyses on the structure, hullform and material selection are considered a requirement amongst others. A detailed review of this is given in Section 6.5.2.

6.2.1. Speed and Resistance Analysis

The speed and resistance analysis focused on the speed in transit mode (de-ballasted, deck down) for a number of reasons; the ship is less than half the displacement in transit configuration than transfer configuration, the deck is lowered in transit mode therefore there is expected to be considerably less windage on the superstructure, and the draft is considerably less meaning the hulls can be semi-planing with less water resistance. This is therefore the configuration the vessel will be in for any long passages such as transiting to and from site, as it will be lighter, more efficient and better suited to high speed. The speed in transfer mode was also analysed despite the prior knowledge that this would be considerably lower – this information would be crucial in analysing the in-field operation of the vessel (i.e. whether or not to de-ballast and jack down to transit between turbines). This is revisited in Section 6.5.3.

If the mother/daughter-ship concept is adopted then there would be less requirement to transit to and from site, but it is thought that it is still important to be able to return to shore quickly for various reasons, for example if a major storm is forecast.

The results identified a cruising speed of around 20 knots and a sprint speed of just under 22 knots for the transit mode, and a speed of around 13 knots in transfer mode, for in-field positioning. Although these are preliminary evaluations it predicts that the vessel is capable of similar speeds to the current transfer vessels when in catamaran mode. An initial estimation has predicted a range of around 700 nautical miles on 10,000 litres of fuel based on power requirements, speed and fuel usage per hour.

Originally it was proposed that the ship should reach 30 knots in transit mode, however this figure was targeted prior to commencement of any design work. It was soon clear that 30 knots was unrealistic for this type of vessel. On review of the current access vessels a more realistic speed of 24 knots was chosen as the target speed however this would still prove difficult to achieve.

The preliminary design proposed jet propulsion, however the analysis on speed of the semi-submersible ship configuration was considered too complex for this project. The propulsion method was therefore changed to propeller propulsion with a steerable nozzle. The submersion of the jets was also highlighted as an issue; the effect of fully submerging the jet-nozzles up to 3.5 metres being unknown.

It is believed further optimisation of the hull-form and propulsion methods could increase the speed and efficiency of the vessel, however this was outwith the scope of this research. Further discussion can be found on this in Section 6.5.2.

*6.2.2. **Stability Analysis***

The purpose of the stability analysis was to determine if the conceptual ship design was safe and stable in the sea-states that it was to be operated in. As identified in Section 3.3.3 of the literature review, vessels operating at sea, for commercial purposes, are required under merchant shipping legislation to have the appropriate certification. For this vessel a certificate issued in accordance with Marine Guidance Note 280 is sufficient to provide a legal alternative to a Maritime and Coastguard Agency (MCA) Load Line Certificate, as it is a small seagoing vessel in commercial use.

To determine if the vessel concept met the required standards, the analysed stability for all three loading conditions was compared to the criteria set out in MGN 280. The guidance note sets out five criteria that the vessel must meet to be deemed stable. These are discussed in turn below.

Criteria 1 - The area under the righting lever curve (GZ curve) should be not less than 0.055 metre-radians up to 30 degrees angle of heel and not less than 0.09 metre - radians up to 40 degrees angle of heel or the angle of downflooding if this angle is less;

Analysed Stability	Area under GZ curve up to 30 degrees	Area under GZ curve up to 40 degrees
Criteria	>0.055 m rad	>0.09 m/rad
LC01	1.929 m rad	2.502 m/rad
LC02	0.095 m rad	0.456 m/rad
LC03	1.664 m rad	2.470 m/rad

Table 22 – Analysis of design against MGN 280 criteria 1

All three conditions meet the requirements set out in MGN 280.

Criteria 2 - The area under the GZ curve between the angles of heel of 30 and 40 degrees or between 30 degrees and the angle of downflooding if this less than 40 degrees, should be not less than 0.03 metre - radians;

Analysed Stability	Area under the GZ curve between 30 and 40 degrees
Criteria	>0.03 m rad
LC01	0.573 m rad
LC02	0.361 m rad
LC03	0.806 m rad

Table 23 – Analysis of design against MGN 280 criteria 2

All three loading conditions satisfy the requirement set out in MGN 280

Criteria 3 - The righting lever (GZ) should be at least 0.20 metres at an angle of heel equal to or greater than 30 degrees;

Analysed Stability	Minimum righting lever at 30 degrees
Criteria	>0.20 m
LC01	3.726 m
LC02	0.715 m
LC03	4.877 m

Table 24 – Analysis of design against MGN 280 criteria 3

All three loading conditions show sufficient righting lever at 30 degrees (and above) to comply with the MGN 280 requirements.

Criteria 4 - The maximum GZ should occur at an angle of heel of not less than 25 degrees;

Analysed Stability	Maximum GZ	Angle of occurrence
Criteria	n/a	>25 degrees
LC01	4.85 m	15.0 degrees
LC02	5.25 m	47.5 degrees
LC03	4.95 m	26.5 degrees

Table 25 – Analysis of design against MGN 280 criteria 4

Loading conditions 02 and 03 meet the requirement, however the maximum GZ for LC01 occurs at 15.0 degrees. Referring back to MGN 280:

the area under the righting lever curve (GZ Curve) should not be less than 0.085 metre-radians up to Θ_{GZmax} when Θ_{GZmax}=15º and 0.055 metre-radians up to Θ_{GZmax} when Θ_{GZmax}=30º. When the maximum righting lever, GZmax, occurs between Θ=15º and Θ=30º the required area under the GZ Curve up to Θ_{GZmax} should not be less than:

$$A = 0.055 + 0.002(30^\circ - \Theta_{GZmax}) \text{ metre-radians}$$

where: Θ_{GZmax} is the angle of heel in degrees at which the righting lever curve reaches its maximum.

For Loading Condition 01, Θ_{GZmax}= 15 degrees, therefore the required area under the GZ curve up to 15 degrees must be;

$$A = 0.055 + 0.002\,(30^\circ - 15)$$

$$= 0.055 + 0.002*15$$

$$= 0.085 \text{ metre-radians}$$

The area under the graph up to 15 degrees = 0.75 metre-radians, hence significantly exceeds the requirements.

Criteria 5 - After correction for free surface effects, the initial metacentric height (GM) should not be less than 0.35 metres

Analysed Stability	Corrected GM
Criteria	> 0.35 m
LC01	23.994 m
LC02	0.413 m
LC03	13.320 m

Table 26 – Analysis of design against MGN 280 criteria 5

Again, all three loading conditions meet the requirements set out in MGN 280.

The results in the section above show that the concept vessel meets and exceeds the regulations set out in MGN 280, in all three loading conditions analysed, therefore sufficient stability is provided to gain certification.

On review of the stability curves, it is apparent that the ship in catamaran mode (LC01) is very stiff, compared to the ship in semi-submersible mode (LC02) which is, in contrast, very tender. This was the design theory as it was known that tender vessels are less likely to respond to wave motion than stiff vessels, hence the more tender the ship the less movement caused by waves. This theory was tested by carrying out a seakeeping analysis.

6.2.3. ***Seakeeping analysis***

The seakeeping analysis was carried out on the two main extreme loading conditions; LC01 – transit mode, and LC02 – transfer mode. The results demonstrate significant reductions in heave, roll and pitch motions in a range of wave periods.

The Hypothesis of the research, set out in the early stages of the project, stated: *the proposed vessel concept will be shown to have significantly less deck movement in high sea states than the current service vessels and hence allow safe transfer to offshore structures in more adverse weather conditions, whilst still maintaining the advantages of speed and manoeuvrability.*

The seakeeping analysis supports this hypothesis for the majority of analysed wave motions, hence it can be said that the design was proven successful. The aim of the project was: to *identify and evaluate a vessel concept to offer safe access to offshore turbines in wave heights of up to 3.0 m, hence increasing turbine efficiency by reducing downtime.* Reduced vessel movements will have a direct correlation with the ease and safety of offshore transfers; the relative motion between the vessel and the structure being accessed has been identified as the reason current transfer methods are limited in wave height, therefore reducing the wave motions by up to 50% should allow safe access in wave heights twice the size. The current maximum wave height for safe transfers has been identified as 1.5 m, hence this proposed design should allow safe access up to 3.0 m, meeting the research aim.

The most significant motion reductions were identified between wave periods of 4-10 seconds. When analysed in wave periods above 12 seconds, the heave and roll motions of the transfer mode were similar to the transit mode, but the pitch motion was exaggerated. This was expected as the natural period of heave was known to be around 10 seconds. The initial wave data supplied by the Carbon Trust in October 2011 was utilised as the basis of the design criteria, and Table 27 and Figure 60 below show that this data highlighted a very small likelihood of waves with periods over 7 seconds, hence a 10 second natural period was deemed adequate, as this was considered significantly different from the wave periods of the operating site to allow safe operation.

Metocean Data set 1998-2007	Percentage of waves with a period of 7s and below	Percentage of waves with a period of 7.5s and below
Area 4-East	99.79%	99.97%
Area 4 -West	99.61%	99.83%
Area 5	99.61%	99.83%
Average	99.67%	99.88%

Table 27 - Met ocean data period figures

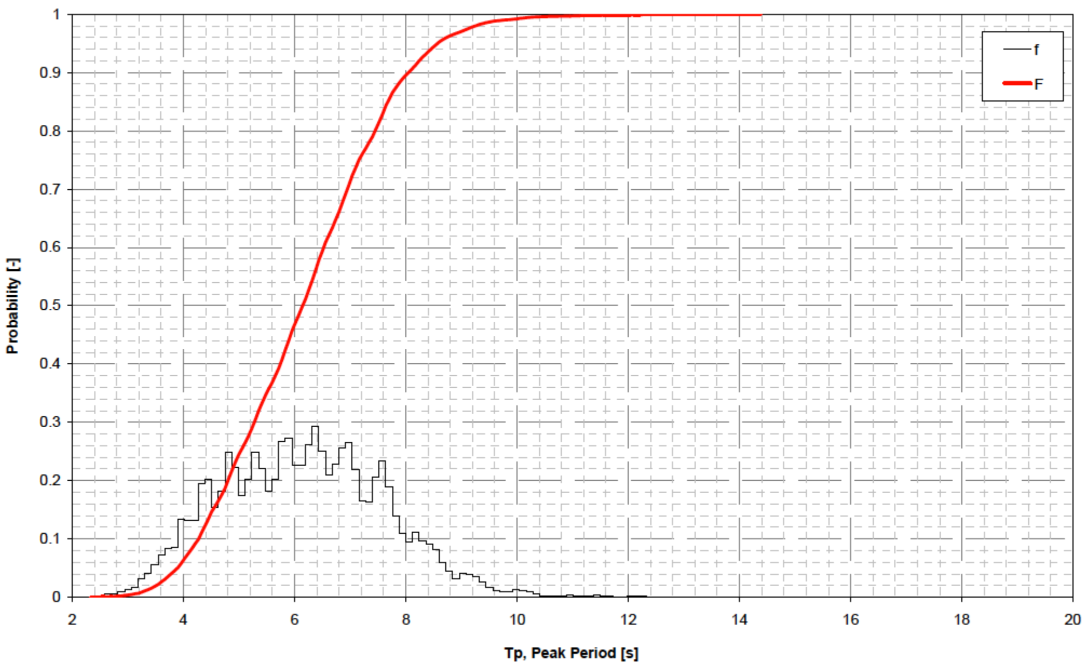


Figure 60 - Distribution of probability for peak period at the operational site.

The poor vessel performance in higher wave periods was identified as undesirable, however the dynamic analysis of the vessel in lower wave periods confirmed that the ship operated as expected, and combined with the knowledge that SWATHs are prone to high excitation around the natural periods, the design was taken to the next stage of testing; tank testing.

During the tank testing, undesirable movements were identified at lower wave periods, and longer wave periods were introduced into the design scope. The implications of this are discussed in Section 6.2.4.

6.2.4. Tank Testing

The objective of the tank testing was to determine the vessel performance in a simulated environment. This was conducted by analysing if the mathematical evaluation of the vessel designed in the computational analysis stage was accurate, through hydrodynamic laboratory testing. The vessel motions were measured as random wave sets, and regular wave sets were generated in the wave tank. The results highlighted reduced motions in waves with periods less than 7.5 seconds, which corresponds with the results of the initial evaluation, however for wave periods between 7.5 and 10 seconds the results do not support the findings in the computational analysis, showing the vessel movements *increased*, rather than reduced.

When the RAOs of the ship were measured it was clear that a wave period of around 10 seconds caused significant excitation of the ship, as expected due to the natural period of heave identified. RAOs such as this, with a peak at certain wave periods, are characteristic of SWATH vessels; heave and pitch oscillations are strongly linked and peak responses occur at closely related frequencies. Wave radiation damping is very small for these vessels due to their small waterplane area, and so the vessels exhibit highly tuned peak responses with large dynamic magnification.

The data used for tank testing was received after the model had been manufactured and was significantly different from the original data (see Table 28 in comparison to Table 27). This data was collated from two east coast sites, Moray Firth and the Firth of Forth, whilst the previous data had been collated from a West coast site, hence the change in periods.

Generated Sea	Significant Wave Height (m)	Period (s)
1	0.75	4.5
2	1.25	5.5
3	2.25	6.5
4	2.75	7.5
5	1.75	8.5
6	1.75	9.5

Table 28 - Sea States used for Tank Testing

Although the vessel was not designed for wave periods of this length, the first phase analysis indicated that the vessel would perform well in wave periods up to 10 seconds and therefore a decision was made to carry out the tests using these results to determine the performance of the vessel in longer wave periods and therefore at these other sites.

Vessel motions were as expected in waves with periods below 7.5 seconds, however vessel motions were magnified in longer period waves and hence the vessel would not offer a stable platform for accessing offshore turbines in thee wave lengths.

The current design would operate well in seas where the mean wave period was below 7 seconds, such as those identified in Table 27, however it is felt that the ship should be capable of operation in all seas with potential for offshore wind farm development, hence further iteration of the design is deemed necessary. A further discussion of this can be found in Section 6.3.1.

The second set of tests, carried out to determine the vessels capability for carrying loads, highlighted that a 3 tonne load on the bow caused the vessel to trim by 7.1 degrees. The study also showed that when the mass was placed onto, or lifted off from the bow, the vessel oscillated very slowly for an extended period of time (over 3 minutes at full scale). This is a common issue with small water-plane vessels but is considered undesirable in this context as periods of inactivity required to wait for this motion to settle would be considered costly time delays.

6.3. A review of the current design

Although the design is not at a stage where it can be manufactured and used offshore, the application of the ship in its current form has been pitched to the technical working group (TWG) for feedback into the design loop. The vessel particulars were presented in a similar fashion to current crew transfer vessels (see Appendix I) and simulations of the comparative vessel motions were displayed. This section reviews the proposed operation of the ship on site (i.e. how it will be used), some of the limitations identified with the design and potential alternative uses for the concept.

A review of the concept with regard to the initial- and full- reference models has been conducted, shown in Table 29, highlighting overall compliancy with the goals set throughout the project. The IRM target speeds were higher than achievable and the seakeeping was difficult to quantify exactly, however the design results have been positive.

Ship Parameter	Initial Reference Model Target Range	Full Reference Model Target	Developed Design
Ship size Length Overall Draft Beam	 Maximum 24 metres <1.5 metres 7-9 metres	 20-24 metres 1-3 metres 10 metres	 24.2 metres 1.7 metres (transit) 14.5 metres
Cruising speed	>28 knots	24 knots	18 knots
Max sprint speed	40 knots	30 knots	22 knots
Passenger capacity Passengers Crew Max POB	 12 4 16	 12 4 16	 12 3-4 16
Construction Materials	Fibreglass	Steel/Aluminium Alloy/Fibreglass	Steel & Aluminium Alloy
Deck Space	30 m^2 20 m^2	30 m^2 20 m^2	66.6 m^2 33.2 m^2
Range	700 km	700 km	700 nautical miles = 1300 km
Sea-keeping Max deck movement Safe operating range Safe wave height for transfers	1.5 m (in 3.0 m SWH) Up to 5 m SWH 3.0 m	1.5 m (in 3.0 m SWH) Up to 5 m SWH 3.0 m	Vessel movements reduced by 50% in correct conditions
Load Capacity	10 tonnes	6 tonnes	6 tonnes
Transfer Method	Step transfer	Step transfer	Step Transfer
Additional Capabilities	Rescue zone Storm survival mode Passenger facilities	Rescue zone Storm survival mode Passenger facilities	Rescue zone Passenger facilities

Table 29 - Review of Design Against IRM and FRM

6.3.1. Proposed In-Field Operation

How the vessel is utilised on site will have significant impact on the efficiency of the operations. Various methods of operation have been considered, with the intention of trying to maximise efficiency by reducing cost.

Discussions with the TWG identified the requirement for fast and simple transfers in mild sea states. During these times the vessel should operate as a ‘standard’ work vessel (i.e. the vessel would not be ballasted and deck would not be jacked), hence the speed (and therefore cost) of the transfers will not be affected. In larger sea-states the transfer time will go up, as the transformation process between catamaran and semi-submersible modes will take time, however the cost impact of this must be assessed. Increasing the power of the jacking mechanism and ballasting pumps will increase the speed of transformation, but will also increase the cost, so an economic balance must be found.

It is proposed that the vessel is used for every day operations and it will be the skipper’s responsibility to determine if the weather conditions require the vessel to be transformed for transfers or if this can be carried out in the transit mode. When the sea-states are high the vessel will be put into transfer mode for the duration of an operation, moving between turbines on-site in the jacked mode. Once the operations are over the vessel will then return to transit mode for the passage back to shore.

At this stage the use of a transfer gangway is not recommended, due partially to the increased weight of the systems in development to date (this weight will negatively affect the GM as it would be positioned above deck) and partially to the accelerations caused by a dynamic system. These accelerations would have a similar impact on the vessel motions to the study conducted with the cargo transfer, carried out during the tank testing, which would have a negative impact on the vessel operation. Instead the conventional transfer method is recommended; driving the vessel towards the turbine and using the friction between the bow fenders and the structure to hold station.

6.3.2. *Limitations of current design*

A review with the TWG, who represent the end users of the ship, was considered highly beneficial before a further design iteration was conducted. A number of limitations were identified during this process, and are discussed below.

As recognised in Section 5, the current arrangement of the ship provides excellent performance in certain wave periods, but performance is severely reduced in longer periods. There are a number of options to improve the performance of the vessel. These include reducing the water plane area of the vessel, increasing the vessel size or utilising motion-damping systems such as fins. It is thought that further reducing the water plane area could potentially compromise stability however the use of motion damping systems is still to be investigated, although this would only reduce the affect of the waves and not change the natural frequency of the vessel, so is considered a secondary preference. Increasing the size of the vessel is a consideration, as the feedback from the TWG highlighted that the vessel may be a good option for equipment transfer. For example if the vessel size were doubled (i.e. if the displacement increased by 8) the peak response period of the vessel would be expected to increase significantly (to an estimated 11 seconds), and the vessel response would be much less than wave height, up to around 10 seconds period. Naturally this would have substantial cost implications however may also have alternative advantages in the form of equipment transfer which could justify this.

Another limitation to the current design, identified in Section 5.5.5, is the undesirable trim caused by carrying loads in transfer mode and the unfavourable motion caused by lifting weight to/from the deck in this mode. Although the increased trim of the vessel did not have a significant affect on the vessel motions caused by the sea state, it is expected that this would make the vessel difficult to walk around on deck and would be off-putting for the crew, and the extended periods of motion after cargo has been removed from or lowered onto the deck has been identified as a negative for equipment transfer offshore. Increasing the scale of the vessel would reduce the deflection caused by the same mass and the extended period of oscillation however an alternative consideration would be to transfer cargo in the catamaran mode where the effect of loading would be reduced. There may also be scope to study the load transferring capabilities of the vessel in a transition mode, partially jacked/ballasted. Further to this, the cargo transfer procedure must be considered. For example, if the 'thrust-in' transfer technique is adopted, the affect of friction between the bow and the structure will likely dampen the oscillations caused by loading/unloading.

A number of options have been considered to increase the vessels ability to carry heavy loads, including increasing the water-plane area, dynamic ballasting/weight positioning and increasing vessel size. As alluded to previously in this section, increasing the water-plane area would have a negative affect on the vessel motions without changing other factors, and dynamic systems were previously considered but dismissed due to the complexity and potential risks of such systems. Again, a larger vessel size seems like a suitable alternative, which may be considered for the next stage of development.

The time taken to perform the offshore transformation (from transit mode to transfer mode) has also been highlighted as a potential limitation. An estimated time of 15 minutes was proposed, however feedback from the TWG was that this would eat into the working day considerably; especially if this transformation was to happen at every turbine, both before and after crew transfer. As discussed in Section 6.3.1, it is proposed that short passages between turbines within a farm would not require the full transformation to take place, however it is believed reducing this transformation time would increase the competitive edge gained over conventional crew transfer vessels. Identification of faster ballasting pumps and a higher powered jacking system would speed up this process, and further analysis into the stability of the vessel during the ballasting may allow jacking and ballasting to be carried out simultaneously, which would significantly shorten the process.

Finally, the design is currently specifically targeted at use for transfers to offshore wind turbines. This limited design scope significantly reduces the market for the ship, hence alternative uses have been considered in the next section.

6.3.3. ***Alternative uses and practical applications***

The current ship arrangement was specifically developed for use in transferring crew and equipment to offshore structures, specifically wind turbines. This has driven many of the design choices throughout the process, however alternative uses for the vessel have been considered. Ship to ship transfers are currently conducted regularly to transfer pilots onto large ships as they come into ports. This is often hampered by the difference in response to the sea conditions between the pilot vessel and the ship, hence a fast ship that could get out to transfer position and have the ability to transform to reduce the movement difference between the two boats could make the process safer and easier to conduct in higher sea states. Offshore survey work often requires a stable platform to increase the accuracy of measurements conducted; hence a ship design such as that proposed could allow survey work to continue through adverse weather conditions. Fast emergency response with a stable platform once on site to transfer or assist casualties is another potential market for this design. Further to this, attention has been given to analysing the effectiveness of the ship as a helicopter support vessel; the theory being the vessel could quickly and cost effectively transport fuel and supplies to far offshore sites, where helicopters could use it as a base for offshore operations.

These alternative uses, and others, should be considered carefully before the design is finalised, as the more applications the vessel has, the stronger the economic argument for development is.

6.4. **A Review of the Research Approach**

Throughout this research the design approach adopted has been somewhat different from a traditional naval architecture approach, as a product design style was adopted rather than a traditional naval architecture design approach. At points this has been beneficial, allowing a high degree of flexibility, while at others it has been unfavourable, in such areas where detailed knowledge of naval architecture would have increased the efficiency of the process. This has highlighted the potential for the development of a revised research methodology in the ship design process. An overview of the process utilised for this project and further discussion on how this could be improved is given below.

As discussed in Section 2, the methodology adopted was a combination of Blessing's DRM and Pugh's TDM. This led to the clarification of research intent through the review of the market and identification of customer needs. The current access procedures and state of the art in the industry were identified at this stage and a reference model was developed to set design goals, reviewed throughout the process. A descriptive study was then conducted by carrying out a thorough literature review, including a technology review. A prescriptive study was then carried out utilising Pugh's TDM (traditionally a product development tool) to identify and review a number of alternative designs based on effectiveness against set criteria. The selected concept was then detailed and analysed in varying sea conditions.

A researcher with limited background knowledge of naval architecture design approaches drove this design. Experience was called upon in the form of external advisors as and when required throughout the development of the vessel. Advantages of this methodology include the investigation of a wide range of technologies and approaches, rather than the conventional selections that would likely have been made by experienced naval architects, alternative idea generation, not limited by the conventional thought process, whilst still maintaining firm checkpoints of the viability of the design as a whole. Disadvantages were also noted, specifically in the time taken to develop and analyse the design, however it is thought this approach could be developed to reduce the disadvantages and spur innovation through an alternative design approach.

6.5. **Proposed Future Work**

The work conducted during this research has identified a concept vessel that, theoretically, could be implemented on offshore wind farms to reduce the overall cost of operations and maintenance and therefore increase the production yield of the turbines, however, to take the vessel to the market it is felt there is considerable future work to be conducted. The viability of the vessel, both technically and economically, must be proven to ensure a successful entrance to this market.

6.5.1. ***Technical Development of Design***

During the research, the design was developed to an adequate level to prove the feasibility of the concept as a whole. To do this within the timeframe, and because the concept had not yet been proven viable, certain aspects of the design were not developed in as much detail as they otherwise would have been. It was considered that if the concept was proven to be unfeasible then there was little need to expend a large amount of time and effort on certain details. The next development phase of the design is therefore to refine these aspects.

The hull, as discussed in the design development section, was developed parametrically to allow the volume, beam and height to be varied, however the detailed refinement of the hull form was not carried out. If the design is to be taken to the next stage a refined hull will be required to maximise efficiency. The demi-hull separation should be taken into account during this refinement to ensure that the wave interaction between the hulls does not disrupt the efficiency of the vessel.

The detail of the design of the jacking mechanism should also be developed further. To date, evaluations have been made on the weight of the structure to be jacked and the speed at which it is to move, which has allowed power and weight allocations to be made for the equipment. As jacking mechanisms of this type are implemented in proven designs (see Section 3.4.2) it is proposed this aspect would be sub-contracted to an experienced third party to provide a system. The author has already engaged with a reputable manufacturer of jack-up barges (Howard Marine Ltd.) and this aspect of the design is being progressed.

The powering mechanism of the vessel should also be considered carefully in subsequent work. As discussed, a direct electric drive to a four-blade propeller with a steerable nozzle has been chosen for the concept. This was selected based on experience from the advisors within Safety at Sea and it is thought a detailed analysis of the most appropriate drive mechanism should be considered before the mechanism is developed in detail. The use of jet-drives should be re-visited, as the implementation of a jet system could considerably reduce fuel consumption on the transit legs of the vessels duty. Considerations should also be made into the requirements for bow and stern thrusters to aid station keeping at the turbines and the transfer method will determine if there is a requirement for a dynamic positioning system on the vessel.

The material choice throughout the design should also be examined closely. As discussed in the report, the vessel was originally designed from steel however the deck weight had to be reduced and therefore the material choice was changed. A detailed analysis of the weight and strength with the two materials should be carried out and a choice should be made on one or the other so the materials do not negatively interact.

6.5.2. ***Further Evaluation***

An analysis has been carried out which has shown that the concept vessel in semi-submersible mode provides a more stable transfer platform than the catamaran mode within the operational envelope however there are a number of areas which would benefit from further analysis. Firstly, it has been assumed that current crew transfer vessels will have similar seakeeping to the concept vessel in catamaran mode. This should be fully evaluated to show that the concept vessel offers a considerable advantage over the existing technology.

The strength of the vessel deck, hulls and legs has not yet been evaluated. The initial design was based on current vessels, which have sufficient strength to support similar loads, and experience from various advisors. A much more detailed analysis should be carried out to prove that the structure has sufficient strength for the application. At this stage the forces on the hulls should also be evaluated. In the current design iteration the port and starboard hulls are independent of one another. A review of the transverse forces acting on the pontoons and the bending moments this causes in the hull structure should be carried out to evaluate if there is a need for cross-members between the hulls.

On completion of the design, the stability and sea-keeping analysis should be returned to as the distribution of weights is likely to change. This will have an effect on the centre of gravity of the vessel and should therefore be taken into account in a more detailed analysis. Further loading conditions must also be considered, as MGN 280 states:

> *Curves of statical stability (GZ curves) should be produced for:-*
>
> 1. *Loaded departure, 100% consumables;*
> 2. *Loaded arrival, 10% consumables;*
> 3. *Anticipated service conditions; and*
> 4. *Conditions involving lifting appliances (when appropriate).*

The offshore transfer method from vessel to structure should also be considered, and the use of a transfer gangway analysed, as if this was used the stability analysis should take the maximum forces produced from this into consideration as one of the loading conditions. If a gangway is to be installed on deck the forces imposed on the vessel should be evaluated, especially if a dynamic system is used. Alongside this a damage assessment should be carried out to determine the effect of hull piercing and damage to the legs/deck. The criteria to gain appropriate classification must be revisited to ensure the vessel is safe to operate on site. Detailed design will specify the requirements for safety equipment, structural strength and integrity, water-freeing arrangements and machinery amongst others. The criteria that must be met are all detailed in Marine Guidance Note 280.

6.5.3. ***Economic Study***

The vessel concept has been developed to increase the productivity, and therefore the revenue production, of offshore turbines. For this reason it is crucial an economic study is conducted to determine if the benefits of using the vessel will significantly outweigh the initial outlay cost of the equipment. To determine this a detailed cost analysis should be carried out. It is estimated the vessel will cost approximately 150% of the cost of a conventional crew transfer vessel. As the design develops this will need reviewed and it is thought this process should be iterative, due to the changing nature of the design and available technology as the concept develops. A full economic study was outwith the scope of this MPhil research due to the development required in the engineering design to fully analyse the cost of the vessel alongside the lack of information available on exact turbine downtime due to weather. Further work on this would benefit from a close working relationship with an offshore wind farm operator.

How the vessel is utilised should also be considered. The relative speeds of the ship in the two modes will have a significant impact on the in-field procedure; the best practice for moving from turbine to turbine will be based on a cost analysis. It has been identified that increasing the number of personnel on a small workboat beyond ten or twelve people is not advantageous for offshore wind turbine maintenance, as the technicians work in pairs and are dropped off at a turbine sequentially, hence it should be possible to drop all teams of two off at the start of the working day and collect them towards the end. This will maximise the productivity of the workforce. A review of the in-field application of the vessel has been given in Section 6.3.1 however a further review of this should be conducted with external factors such as working hours, operational costs and sea-state change over time, to predict fully the most cost beneficial operation.

The interaction with the turbines and with the port or mothership should also be considered at this stage. The vessel should work with a launch and recovery system however due to the vessel weight this may not be possible. It is thought that an on-board launch and recovery system could be developed utilising the jack-up technology already on the vessel.

Overall, commercialising the vessel will mean a higher capital expenditure for the vessel owners if they are to select this vessel over the alternatives, and this must be justified from a business aspect. A review of the increased turbine availability due to access in higher sea-states is required and the increased cost of the vessel must be taken into account to prove if the design is commercially viable. This evaluation should also consider the seemingly intangible benefits of increased passenger comfort on site and the increased safety provided by a standardised transfer procedure.

7. Conclusions

This final chapter of the thesis summarises the work undertaken in this research and the outputs of the study. Section 7.1 gives an overview of the thesis and how the work met the aim and objectives set out in Chapter 2. The contribution to knowledge is then detailed in Section 7.2 before the limitations of the study are considered in Section 7.3. Finally, the authors reflects on the research in Section 7.4.

7.1. Summary of work

This research explored the feasibility of a vessel concept that could increase the efficiency of offshore wind turbines by increasing the safe wave height for crew transfers. The target was to allow access in wave heights of up to 3 metres, which would allow access 85% of the year compared to the current systems that only allow access around 50% of the year.

> ***Aim:*** *To identify and evaluate a vessel concept to offer safe access to offshore turbines in wave heights of up to 3 m, hence increasing turbine efficiency by reducing downtime.*

A conceptual ship design had been proposed in the author's undergraduate project, and the purpose of this present study was therefore to develop and analyse the concept's effectiveness.

The author hypothesised that:

> *The proposed vessel concept will be shown to have significantly less deck movement in high sea states than the current service vessels and hence allow safe transfer to offshore structures in more adverse weather conditions, whilst still maintaining the advantages of speed and manoeuvrability.*

The research set out to prove or disprove this hypothesis by first conducting a thorough background study into the problem cause, current literature, and appropriate technology that could be utilised in the design. Chapter 3; Literature Review, gives a review of the work carried out to meet **Objective 1:**

> *Carry out research into current turbine access methods; identify problems with the methods and the potential for improvement*

Throughout this process a thorough understanding of the issues surrounding offshore access was built up and a concept was developed that targeted two of the key operational issues identified; fast and efficient transit to site and provision of a stable platform on site. This was achieved through the design of a catamaran vessel with the ability to undergo a transformation on site, where it can take on significant ballast and submerge the hulls of the vessel under the wave troughs whilst the deck is raised on relatively slender columns away from the wave crests. The effect of this is a vessel configuration with significantly different displacements and waterplane areas, two aspects of a ship design that would otherwise have to be balanced to achieve both efficiency under way and stability at standstill.

Chapters 4 and 5 outline the review of a number of concepts and the development of the selected idea into a vessel concept design including weight estimates, preliminary layout drawings and overall characteristics that would allow an evaluation of the expected speeds, stability and sea-keeping characteristics to be conducted. A preliminary evaluation was conducted (see Section 5.4.1) that allowed the variations in concepts to be compared and outputted initial indications of stability and seakeeping. This section of the work satisfied **Objective 2:**

> *Develop a suitable vessel design in line with the hypothesis and research problem*

The developed design was then taken forward to computational analysis, consisting of a speed and resistance analysis, a stability analysis and a sea-keeping analysis. The results of these analyses proved that the concept vessel provides a more stable platform for transfers when in the semi-submersible mode than when in the catamaran mode. The vessel motions predicted by the modelling in the catamaran mode were considered similar to that of current crew transfer vessels and therefore the computational analysis prove that the proposed ship concept has better sea-keeping characteristics than current transfer vessels.

The concept was also tested in a hydrodynamic test tank, to corroborate the predictions made by the computational analysis. This was conducted in a variety of operational sea conditions.

By evaluating the ship design, both computationally and through use of a test tank, and by reviewing the ship application against the intended task, the study fulfilled **Objective 3:**

> *Evaluate the vessel with regards to;*
>
> i. *the limiting operating environment;*
>
> ii. *the procedure of work;*
>
> iii. *the correct safety standards, and;*
>
> iv. *the operational practicalities of the design.*

The stability of the vessel was shown to meet the recommended guidelines and the powering analysis showed that the vessel could maintain speeds of around 20 knots, similar to that of the current access vessels, hence still provide an efficient transit route to and from site. The semi-submersible mode was shown, through computational and tank test analyses, to have up to 50% less motion in heave, roll and pitch in comparison with the catamaran mode within the operational envelope, which would suggest that access could be gained in sea-states twice as big as the current threshold. From this it can be deduced that the ship, in the transfer mode, will allow safe access to wind turbines in up to 3.0 metre significant wave heights, hence meeting the **aim** set out at the start of the project.

The evaluation process identified that the vessel is technically feasible, with improved sea-keeping abilities in the ballasted mode with respect to the catamaran configuration. The analyses have shown a considerable reduction in vessel heave, roll and pitch for wave periods of 4-7 seconds with stability characteristics that meet and exceed the appropriate guidelines. A speed analysis has shown the current design is capable of around 20 knots fully loaded with 12 passengers and 6 tons of equipment in transit mode, and 13 knots in transfer mode.

7.2. **Contribution to Knowledge**

This research contributed to knowledge by proving the feasibility of a unique vessel concept, the likes of which has never been designed and built before. A review of literature identified a lack of specific research into the problem of providing personnel access to offshore wind turbines, with much of the existing technology having been adapted from other applications. This identification of a knowledge gap led to the investigation into the problem, detailing of the causes and development of a vessel concept to increase the safe operational wave height for personnel transfer.

The study determined that the vessel will operate efficiently and safely within the given operational window by conducting analyses, both computationally and physically, with generated waves matching the expected operating environment. The results of the analyses validated that the concept is feasible for the specific application of transferring personnel to offshore wind turbines, by showing that the deck movement of the vessel concept is roughly half that of a standard access vessel. This reduced deck movement coupled with proven stability shows that the same transfer procedure can be carried out in rougher sea conditions from the vessel concept than can with the existing vessels.

The results, described in this thesis, amount to the contribution to knowledge in the form of a design basis that can be utilised to allow further development of this type of vessel. Research has been conducted into the operational constraints, the intended procedure of work and the further work required to develop a vessel with the end goal of commercialising technology that will reduce energy costs from offshore wind farms.

7.3. **Limitations to work**

As discussed throughout this thesis, a number of limiting factors hindered the full development of this research. Firstly, the research was funded by the Carbon Trust Offshore Wind Accelerator, which dictated the exploration into the originally proposed concept. As discussed in Section 6.1, this limited the design scope where instead of starting with the overall problem, the research started with a potential solution to a problem. Although this could be seen as a limitation, the work conducted prior to this thesis evaluated the problem as a whole, and the concept was developed from that, hence it can be said that the origins of the development work were based on the problem.

The funding body also set strict time constraints on the research, hence the development of the concept in the early stages was driven forward quickly to meet the industry led timescales set out by the OWA. This limited the scope of the investigation and iteration phase of the design, and it is felt with further time and funding the design would significantly benefit from an iteration of the development cycle.

Hand in hand with the limitations discussed above came the drive to commercialise the design. The design gained considerable interest in industrial circles and at times there seemed great opportunities to take the design to market. Although this would have proven the success of the research beyond doubt, the accelerated drive to make the vessel commercially attractive limited the research conducted at the earlier stages of development.

Furthermore, as discussed in Section 6.5.3, an economic study was started but availability of comparative data, energy production data and costing for manufacturing did not allow a full financial analysis to be conducted.

Finally, although the design background of the researcher was felt beneficial at the early stages of the design process, it is believed this limited the full development of the ship concept at later stages. Knowledge of a traditional ship design process would have allowed the design to be developed to a fuller extent within the given time period, however this could also have hindered the innovative thinking at times.

7.4. **Reflections**

Conducting this research has been both challenging and rewarding, providing an opportunity for the author to work in a new design area – that of ship design. Working in this area has not only been interesting but has also exhilarating at times, with a close relationship to key industrial partners posing exciting opportunities and driving the development of a concept with a real end use. Having the opportunity to develop the design with support from industry experts and developing a scale prototype to use at the hydrodynamics lab has proven an invaluable experience. Writing up the thesis has taken considerably longer than anticipated due predominantly to career opportunities in this area presenting themselves during the write-up period. The author has held a full time post as Project Engineer with Nautricity for a considerable part of the research, developing a marine current turbine to harness energy from tidal streams.

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9. Appendices

Appendices to the report can be found in this section and are organised as shown in the list below.

9.1. Appendix A – Offshore Access Vessels

9.1.1. ‘Standard’ access vessel from Turbine Transfers

The wind turbine transfer vessels currently utilised in the UK are all relatively similar; a catamaran hull with a flat bow, on which a shaped fender is attached to locate with turbine ladder uprights. This allows a fast transit speed (20-25 knots) and a relatively stable transfer platform in good weather conditions. A few of the key manufacturers/designers are detailed below with a brief review of the vessels they offer plus the capabilities of each.

South Boats

South boats are one of the leading manufacturers of turbine transfer vessels. A lot of companies who offer vessels utilise vessels designed and built by South Boats. They produce a range of GRP and aluminium catamaran workboats and claim *exceptional sea-keeping capabilities, unrivalled cargo carrying capacity and crew comfort even in the harshest conditions.*

Range:

Vessel Model	Vessels in service	L.O.A.	Length hull	Beam overall	Draft	Lightship	Hull material	Fwd deck space	Aft deck space	Speed (Departure)	Speed (Arrival)
12m Workboat	3	12.4m	12.0m	5.4m	1.3m	10 tonnes	GRP	6m2	28m2	26kts (85% MCR)	21 kts (80% MCR)
15m WFSV MR	1	15.8m	14.0m	6.4m	1.0m	24 tonnes	MGA	9m2	42m2	21 kts (85% MCR)	23 kts (85% MCR)
15m WFSV	13	15.8m	14.0m	6.4m	1.0m	24 tonnes	MGA	26m2	16m2	21 kts (85% MCR)	23 kts (85% MCR)
15m WFSV FB	5	15.8m	14.0m	6.4m	1.0m	24 tonnes	MGA	21m2	22m2	21 kts (85% MCR)	23 kts (85% MCR)
18m WFSV	2	19.1m	17.0m	7.3m	1.2m	40 tonnes	MGA	34m2	21m2	21 kts (85% MCR)	23 kts (85% MCR)
18m WFSV MR	1	19.1m	17.0m	7.3m	1.2m	40 tonnes	MGA	18m2	44m2	21 kts (85% MCR)	23 kts (85% MCR)
18m WFSV AS	6	19.1m	17.0m	7.3m	1.2m	40 tonnes	MGA	37m2	20m2	21 kts (85% MCR)	23 kts (85% MCR)
20m WFSV MR	1	20.9m	18.4m	8.0m	1.2m	50 tonnes	MGA	25m2	50m2	21 kts (90% MCR)	23 kts (90% MCR)
20m WFSV	2	20.9m	18.4m	8.0m	1.2m	50 tonnes	MGA	41m2	21m2	21 kts (90% MCR)	23 kts (90% MCR)
Total number vessels	**34**										

South Boats are now designing vessels tailored to specific sites, offering the operators, developers and owners input in the design stage. New designs are lighter than the current models with more versatility on deck space, both front and aft, and offering faster cruising speeds (28-30kts compared to the current 21-23kts).

- Standard; 2-3 crew, 12 passengers
- All new designs to comply with DNV Wind Farm Service 1
- 19 m, 24 m and 30 m designs ready for Houlder TAS secondary access system

- Modular superstructure and cargo for maximum versatility

Ben Coleman, technical director of South Boats, said "*South Boats continues to develop new designs and has recently tested a new fine entry, high raft model and a semi-SWATH model alongside our conventional hull to compare sea-keeping and motions. With very different results depending upon wave pattern it is hoped that in the future the different concepts will suit the different requirements of each offshore wind farm project to offer minimum downtime and maximum time at sea*"

There are a range of companies using South Boats vessels including Turbine Transfers (Part of Holyhead Towing) who already operate a range of South Boats and have ordered seven more; 2 of which are ready for the Houlder TAS and one which will have the first commercial TAS available included.

Wind Cat

Wind Cat is a specialist company which provides personnel transfer for the wind turbine industry. They provide the vessels, crew and site management to allow operators and owners to focus on the running of the turbines.

Range

Vessel Model	Vessels in service	L.O.A.	Length hull	Beam overall	Draft	Lightship	Hull material	Fwd deck space	Aft deck space	Speed (Departure)	Speed (Arrival)
Windcat MkI	4	15m	13.0m	6.1m	0.9m		MGA			25 kts	22 kts
Windcat MkII	4	18m	16.0m	6.1m	1.8m		MGA			28 kts	25 kts
Windcat MkIII	20	18m	16.0m	6.1m	1.8m		MGA			28 kts	25 kts
Windcat MkIV	1	27m	14.0m	9.0m	1.7m		MGA			31 kts	26 kts
Windspeed	4			3.7m			FRP			24 kts	24 kts
Total number vessels	**33**										

Wind Cat vessels are offered with a number of facilities, including bunks, showers and toilet as well as lounge facilities for the crew during transit. The company's larger vessels are also offered with space to mount containers for transport of equipment and spares, and large passenger lounges with widescreen T.V.s and Playstations etc. The Windcat MkIV is a much larger vessel, capable of carrying up to 45 passengers with a range of over 800 miles.

Marineco and Damen

Marineco, an Edinburgh based company, have recently bought a Damen High Speed Support Vessel 2610, one of the pioneering vessels in the industry. Damen are an established Dutch company offering vessels for a range of marine operations, including cargo vessels, ferries, yachts and 'specials'; bespoke vessels to suit the circumstances required.

Specifically developed for the offshore wind industry, the company offers a Twin Axe Catamaran, the Damen High Speed Support Vessel (HSSV) 2610 (see image below). The company claims that this vessel offers much better sea-keeping offshore and at the same time has much lower fuel consumption than similar crafts.

SPECIFICATIONS:

- Dimensions 26 m x 10 m
- Speed 26 knots, with a range of 1000 nm
- Fuel transfer system
- Three-point mooring system
- Extensive cargo capacity, 15 Tons deck load
- Fuel capacity of 20,000 litres
- 20 tm deck crane
- Accommodation for four crew
- Licence to carry 12 passengers
- Seating up to 24 persons
- Diving/ MOB recovery platform

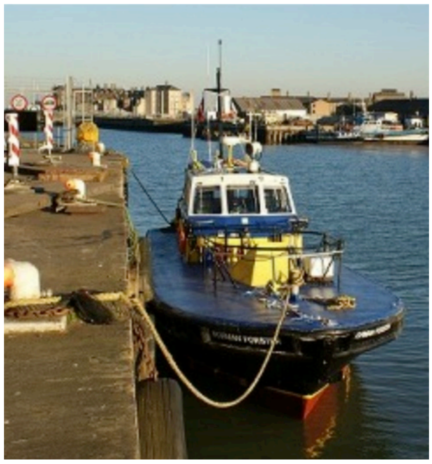
Offshore Wind Power Marine Services Ltd

OWPMS have just formed a joint venture with Brooke Henderson to build 60 wind farm transfer vessels. Currently they only have 2 vessels however this order makes them a serious player in the market. Their designs are based on South Boats vessels (as the commercial director is formerly South Boats) but little else is known about the particulars of the vessels to date.

Wind Wave Workboats

Wind Wave Workboats have two operational vessels in the offshore wind industry; the Pamela P and the Samson B. Both vessels, shown in the adjacent images, are of similar construction to the vessels already mentioned. The vessels are 12 x 5 m and 17.5 x 6.4 m respectively and both take 12 passengers and 2 crew.

Eastern marine Services



Eastern Marine services currently utilise RIBs and converted tugs to service wind turbines on a one-off basis. They have a 'wind farm nose' which they use on various vessels to locate with the ladder uprights, effectively converting standard work vessels into transfer vessels. This system is slightly rudimentary and the vessels on which it is based, including the Norman Foster (adjacent), are relatively slow (12- 15 kts) and not specifically designed for turbine transfers. They are therefore in the process of developing a vessel specifically for wind turbine transfer but have given little information on it other than that it is 'an innovative design'.

9.1.2. *Conceptual Wind Turbine Access Vessels*

The issue of offshore turbine access has become prominent in the last few years, driven by government initiatives such as the Carbon Trust OWA. To this end, many companies are in the process of developing offshore transfer vessels with increased sea-keeping abilities to provide increased access range and increased safety during transfers. This section details some of these vessels and the advantages they offer over the current vessels.

<u>Houlder</u>

Houlder ltd are designing and developing a range of wind turbine transfer vessels, both to operate as standalone designs and as a base for their wind turbine access system. They are offering 3 configurations, as detailed below;

17m Wind Farm Support Vessel	E4079
Shipyard:	N/A
Status:	Design
Number in Service:	0
LOA:	17.40 m
Beam:	6.50 m
Passenger Capacity:	12
Design Service Speed:	24 knots
Additional Information	

20m Wind Farm Support Vessel	E4079
Shipyard:	N/A
Status:	Design
Number in Service:	0
LOA:	20.40 m
Beam:	7.40 m
Passenger Capacity:	15
Design Service Speed:	24 knots
Additional Information	

24m Wind Farm Support Vessel	E4079
Shipyard:	N/A
Status:	Design
Number in Service:	0
LOA:	24.00 m
Beam:	7.70 m
Passenger Capacity:	24
Design Service Speed:	26 knots
Additional Information	

Although these vessels themselves do not seem very different from the vessels other companies are offering, the combination of the vessels with the TAS (see below) will provide a competitive advantage on safety and access range (increasing the maximum save wave height for transfer to 2.0 m SWH).

These vessels will offer a competitive advantage over the existing vessels in the access range and safety, although rely on the TAS rather than the vessel design to do so.

CTruk

CTruk have recently launched a range of 'multi-purpose catamarans' for the offshore wind industry. Their USP is the 'flexible pod system', which allows all deck components (including the wheelhouse and 'passenger pod') to be moved in a matter of hours. This allows the vessel to be set up for the specific job, giving it more foredeck/more aft deck/balanced deck as required.

CTruk are also developing a SWATH access vessel which they claim will eliminate the need for an access system. The vessel offers superior comfort during transit to and from the site, faster crossings in rough seas with comparison to the standard catamarans and a more stable platform for transfer.

Design objectives of CWhisper:

- Dramatic improvement in comfort for technicians transiting out to the wind farm. Motions will be approximately ¼ those of conventional catamarans

- Increase in speed in rough seas. The SWATH hull form will allow much higher speeds than conventional catamarans in seas of over 1.0m significant

- Increase in transfer limit wave heights to 2.0m significant. Tests have shown that the force needed to hold CWhisper against the TP are ¼ those needed for a catamaran.

Main Particulars

- Length over all: 19.5m
- Beam over all: 7.8m
- Draft: 1.48m
- Displacement: 30 tonnes
- Hull material: Infused composites
- Forward deck space: Up to $44m^2$
- Aft deck space: Up to $44m^2$
- Speed: 26 knots
- Cruising speed: 23 knots

Classifications

- Design Class: DNV 1A1 HSLC R2 Wind Farm Service, MCA Category 2
- Flag: UK, Germany, Denmark, Netherlands,Sweden or Norway
- Passengers: 12
- Crew: 2

Propulsion

- Power: 2 x Scania 625 HP, Fixed propellers, Bowthruster assisted
- Generator: Beta 11kW
- Fuel: 6,000L
- Fresh Water: 300L
- Invertor: 5kW 240v/110v

Austal Wind Express Series

Austal, Australian shipbuilders, have developed a range of vessels specifically designed for the burgeoning offshore wind farm industry. The vessels, of which there are a selection of hull forms from catamarans to SWATH trimarans, all incorporate the Austal patented Ride Control System (RCS) which is a bow-mounted fin to reduce movement of the vessel both when underway and when stationary.

Principal Particulars of Austal vessels:

	Wind Express 19	Wind Express 28	Wind Express Triswath 28
Length overall	19.3	28.5	28.5
Beam	6.0	9.0	10.0
Hull Draft	1.5	1.9	1.5
Max Deadweight	10	20	20
Personnel	12	52	52
Crew	4	4	4
Speed	26	26	26
Range	300	300	300

9.2. **Appendix B – Function Tree**

<table>
<tr><td colspan="10">Transfer technicians and equipment to offshore wind turbines safely, in wave heights up to 3.0 m</td></tr>
<tr><td colspan="2">Fulfil basic ship requirements</td><td colspan="2">Transit to and from offshore sites</td><td colspan="3">Carry people and equipment</td><td colspan="3">Provide transfers on site up to 3.0 m</td></tr>
<tr><td>Provide floating and reserve buoyancy</td><td>Have sufficient structural strength to survive operating conditions</td><td>Travel quickly, in varying sea conditions</td><td>Travel efficiently</td><td>Provide Shelter</td><td>Have sufficient storage space for equipment</td><td>Provide basic amenities for a days work offshore</td><td>Provide a way to transfer personnel from the deck to a turbine</td><td>Reduce movement of deck in high sea-states</td><td>Hold station at base of turbine</td></tr>
</table>

9.3. Appendix C – Product Design Specification

1. Performance

1.1. The primary function of the vessel is to create a stable, floating platform for transfers to offshore wind turbines

1.2. The vessel should minimise the effect of waves on the movement

1.3. The bow of the vessel should move in a safe and predictable manner in sea-states up to and including 3.0 m SWH (in any direction) when at the turbine

1.4. The vessel should operate as intended in waves up to 3.5 m SWH

1.5. The vessel should be able to operate in higher sea states, possibly in a 'safe' working mode

1.6. The craft should have a system for aligning to the turbine (shaped fenders, attachment mechanism, DP or a combination of these)

1.7. The vessel should be able to be easily kept at the base of the turbine for up to 5 minutes while transfers take place without having to re-position

1.8. The vessel must maintain performance in a range of weather conditions, including effects of wave, wind and tide

1.9. There should be enough room for (minimum) 12 passengers plus vessel crew

1.10. There should be sufficient facilities on board

1.10.1. Comfortable seating area

1.10.2. Toilets

1.10.3. Cooking area

1.11. The vessel should aim to cruise at 22 kts and have a top speed of 24 kts

1.12. The design must be able to transport, and deliver, a load of up to 3 tons

1.13. The craft must have sufficient deck pace for a 10 ft by 4 ft container

1.14. The vessel must comply with DNV Wind Farm Service 1

1.15. Vessel must reduce the following effects of waves;

1.15.1. Heave

1.15.2. Yaw

1.15.3. Surge

1.15.4. Sway

1.15.5. Roll

1.15.6. Pitch

2. Environment

2.1. The vessel will be operating in offshore environments – specifically Round 3 sites for offshore windfarms

2.1.1. Moray Firth

2.1.2. Firth of Forth

2.1.3. Dogger Bank

2.1.4. Hornsea

2.1.5. Norfolk

2.1.6. Hastings

2.1.7. West of Isle of Wight

2.1.8. Bristol Channel

2.1.9. Irish Sea

2.2. The vessel should be able to operate in a minimum depth of 5m (if it is to operate in Norfolk zone, where 5 m is minimum water depth)

2.3. Must be able to operate and perform safe transfers in all wave heights between 0 m and 3 m

2.4. Must function in all periods of 5 to 10 seconds

2.5. Product must function for, minimum, 10 years in the corrosive, salt water environment

2.6. The vessel must operate correctly in conditions of varying temperatures

    2.6.1. Air temp; -20 C to +40 C
    2.6.2. Water Temp; -5 C to 20 C

2.7. Vessel must be prepared for heavy seas

    2.7.1. Plentiful grab handles
    2.7.2. Secure lines for attaching harnesses
    2.7.3. Railing support at access point
    2.7.4. MOB recovery point and equipment

2.8. The vessel must perform adequately in the following ranges of conditions

    2.8.1. Tidal Range – up to 10 m
    2.8.2. Tidal flow – up to 5 knots
    2.8.3. Wind direction – variable
    2.8.4. Wind speed – force 6
    2.8.5. Wave period – 5 to 10 seconds

3. Safety

3.1. The vessel will be designed in accordance with MGN 280 and, where possible DNV Wind Farm Service 1. The following safety requirements have been identified:

3.1.1. Minimum of 2 lifebuoys

3.1.2. At least 1 lifebuoy with light

3.1.3. At least one lifebuoy with buoyant line

3.1.4. Minimum of 1 lifejacket for each passenger and crew member

3.1.5. At least 12 parachute flares

3.1.6. At least 6 red hand flares

3.1.7. At least 2 buoyant smoke signals

3.1.8. Thermal protective aids for each passenger and crew member

3.1.9. Portable VHF

3.1.10. An EPIRB distress radio

3.1.11. A general alarm (as there is >750 kW installed power)

3.1.12. Life-saving signals table

3.1.13. Training manual

3.1.14. Instructions for on-board maintenance

3.2. The vessel will be designed with safety considerations taken into account throughout the design process

3.3. Primarily direct safety will be employed where possible (removing the potential risk completely)

3.4. Fail-safe mechanisms will be included into the design which will be utilised in the event of a first stage safety failure

3.5. Procedures of use and safety guidelines will be developed and incorporated into the vessel design

3.6. The vessel will have multiple bulkheads in underwater compartments to stop flooding

3.7. The vessel must adhere to the appropriate legislative requirements, including;

3.7.1. Marine Guidance Note 280

3.7.2. Marine Guidance Note 371

3.7.3. Marine Guidance Note 372

3.7.4. Guidelines for the Selection and Operation of Jack-ups in the Marine Renewable Energy Industry

3.8. The vessel should be built in accordance to the DNV Wind Farm Service Rules

4. Product Life Span

4.1. Product will be designed to last 5 years without any serious overhaul

4.2. Product should last 15 years + with the correct maintenance

4.3. Spare parts will be available for a further 5 years after ceased production

4.4. The vessel should be serviced regularly to increase its life span

5. Life in Service

5.1. The vessel should be designed to operate for 10 years minimum

5.2. The vessel will be expected to run for 12-18 hours a day

5.2.1. Extended periods of cruising will subject the vessel to speeds of 25-30 kts for 5-10 hour periods

5.2.2. The boat will be expected to idle for periods of work and no transfers

6. **Quantity**

6.1. The quantity of vessels produced will be relatively low, however the business model will allow leasing of the boats and therefore create a steady income

6.2. Quantity will be demand drive

6.3. Vessels will be produced to order

7. Costs

7.1. Rental costs should be between £1000-£2000 per day

8. Marketing

8.1. The product is designed to be safe and reliable and these will be the basis of the marketing strategy

8.2. The vessel is initially intended for use in Round 3 offshore wind farms around the UK

8.3. The marketing will be based on specific safety standards and documents which prove the integrity of the design

8.4. The target market is primarily the offshore wind industry, which includes;

8.4.1. Service operators (i.e. SSE, Scottish Power ect)

8.4.2. Vessel manufacturers and shipyards

8.4.3. Transfer companies

8.4.4. Manufacturers

8.5. Expansion will be considered into the following markets when the product has been developed sufficiently for the wind industry;

8.5.1. Offshore oil

8.5.2. Wave and tidal market

8.5.3. Ship to ship transfer

8.5.4. Ship to land transfer

8.5.5. Lighthouse access

9. Size and Weight Restrictions

9.1. The vessel should be a maximum of 24 m LOA

9.2. The operational length should be suited to the conditions in which it is expected to be used

9.3. The weight will be governed by the size and weight of the cargo

9.4. The vessel must take minimum 12 passengers and 2 crew members

9.5. The vessel must carry 3 tons of cargo plus passengers

9.6. The deck area should have space for a 10 f x 4 ft container

9.7. The foredeck should provide a mounting point for a suitable access system (gangway)

10. Shipping

10.1. The vessel will be made to order and therefore shipped accordingly

10.2. Where possible the vessel will be built close to where it will be operated

11. Manufacturing Processes

11.1. The vessel must be produced commercially so all design must consider manufacturability

11.2. Manufacturing will be carried out dependent on the materials however will use the widely adopted processes for ship building

11.3. Where possible standard parts will be used to reduce manufacturing costs

12. Materials

12.1. The materials will be chosen for strength and weight properties (Most likely Marine Grade Aluminium or steel)

12.2. The materials must be corrosion resistant, or treated to make them so

12.3. The hull must withstand high impact from waves at speeds of 30 kts

12.4. The materials must be able to withstand constant and cyclic loading

12.5. The materials cannot be toxic and must not harm the environment they operate in (i.e. the sea)

13. **Aesthetics**

13.1. The vessel will primarily be designed with function in mind however aesthetics should be considered as they will influence the marketing of the vessel

13.2. The boat should be in line with the 'green' message, as it is primarily intended to work in wind farms and therefore should look environmentally friendly where possible

13.3. The interior aesthetics should promote a relaxed and friendly environment

14. **Ergonomics**

14.1. The vessel should consider anthropometrics in every aspect of the design which will come into contact with users

14.2. The bridge and wheelhouse must be as comfortable and useable as possible, as crew members may spend full days working from this area

14.3. The passenger compartment should provide a comfortable place for technicians to be transported safely

14.4. Hand rails should be positioned appropriately with respect to anthropometric data

14.5. Any seats or supports will also adhere to anthropometric guidelines

14.6. Any controls must be mounted in an accessible position relative to the operator i.e. waist height - around 1 m, to accommodate 95% of the working population

14.7. All controls should be hand operated, requiring one-hand operation with a maximum force of 1.5 N/m2

15. **User Requirements**

15.1. The vessel should provide a stable platform for transferring technicians to offshore wind turbines

15.2. The vessel will provide an option of standard ‘bump and jump’ transfer or transfer with use of one of the following access systems;

15.2.1. SolidSeaTransfer

15.2.2. Houlder’s TAS

15.2.3. Divex Crew Access Bridge

15.2.4. Momac MOTS

15.2.5. AdHocs compensated gangway

15.2.6. Odfjell's Undertun Safety gangway

15.3. The vessel should provide a safe and comfortable area for passengers to rest to and from sites (for transit times up to 10 hours)

15.4. Facilities for crew and passengers will be provided, including;

15.4.1. Toilets

15.4.2. Shower

15.4.3. Kettle

15.4.4. Cooking area

15.4.5. Individual seating

15.4.6. Power adapters and laptop workstations

15.4.7. Navigation and chart tables

15.4.8. Communication devices

15.5. The vessel should reduce the requirement for personal judgment from transfer procedure

15.6. Procedure should be standardised so product is used correctly

15.7. Standardised procedure should be documented

16. Training

16.1. System should be designed to require minimal training

16.2. Nature of industry dictates all personnel using the equipment must have had formal training

16.3. Training should be carried out onshore before boarding the vessel and the correct qualifications should be obtained by all crew

17. **Competition**

17.1. The product must be a viable solution to the current access method

17.2. Other offshore access vessels for wind turbines are available and more are in development. The vessel should aim to offer one or more of the following competitive advantages;

17.2.1. Provides safer access

17.2.2. Provides access in larger sea-states

17.2.3. More efficient transit

17.2.4. Cheaper alternative

17.3. Some companies are developing competitor products. These should be monitored and responded to accordingly.

18. **Maintenance**

18.1. The vessel must provide adequate access to all machinery for maintenance

18.2. A dedicated maintenance procedure should be developed

18.3. Parts requiring lubrication should be easily accessible without the use of special tools or equipment

18.4. All fasteners used should comply with BS6105 (Specification for Corrosion-resistant Stainless Steel Fasteners)

18.5. No special tools should be required for maintenance

19. **Testing**

19.1. The vessel will be subject to initial model tests, evaluations and sea trials before commercialisation

19.2. Testing is to be carried out on all initial prototypes

19.3. Testing will initially be carried out on scale prototypes (1:5 or similar) before being prototyped full scale for user testing if the design is deemed viable

19.4. Testing is to be carried out on all commercially produced units

9.4. **Appendix D – Function-Solution Matrix**

	Hull Form	Powering				Leg Configuration	Jack-up Mechanism	Deckhouse and Deck Arrangement	Ballast Mechanism			Control System - Height and ballast	Transfer Method
		Positioning System	Prime Mover	Final Drive	Transmission				Ballast Pumps	Ballast Water Containment	Ballast Control		
1	Sectional hulls (i.e. Many vertical pillars)	Dynamic positioning	2 Engines on deck	Exposed propeller	Direct Drive via prop shaft	Lattice structure (as 'standard' jack-ups)	Rack and Pinion	Modular	Electric pumps into and out of tanks	Segregated tanks	Manifolded system valve control intake and outlet	Dynamic control - Moves up and down with waves to counteract wavelengths longer than vessel	Step Transfer
2	Double skin hull - flood in between skins to decrease buoyancy or empty it to increase buoyancy	Friction location with ladder uprights at bow of deck	4 engines on deck	Electric motor in tube & external prop	Direct drive thro right-angled gearboxes	Tubular pillars	Hydraulic rams to drive legs up/down	Pod like	Hydraulic pumps into and out of tanks	Passive - empties when vessel slows below a certain speed (i.e. as in Avon Seariders)	Compressed air to push water out	Sensory control - senses water level below deck and adjusts deck height accordingly	Gangway

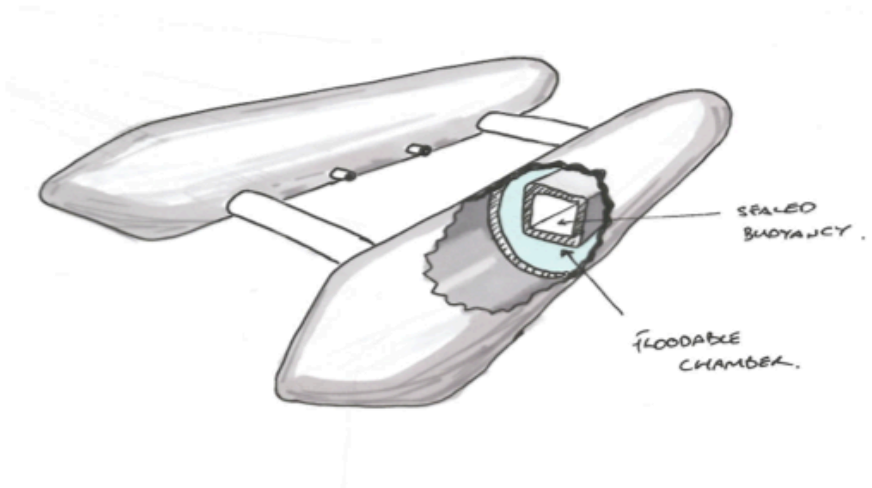
3	Tubular - To act like SWATH when de-ballasted	Vertical fender from deck to hulls to create double contact point	Single Diesel engine in each hull	Electric motor in tube & internal prop to make jet drive	Hydraulic pump & motor	Oval Pillars - Allow reduced drag in forward/aft motion whilst still offering suitable buoyancy	Replace legs with inverted hydraulic rams	Similar to standard work boats	Direct Drive pumps into and out of tanks	Opening sections, 'instant' flooding		Calculative deck height - ballast tanks are x% full therefore deck height should be x% up/down	Dynamically controlled system
4	Catamaran hulls - i.e. Shaped to operate like a normal vessel when de-ballasted but sealed at the top so they could be ballasted and submerged (original concept)	Transfer system with location system	Dual engines in each hull	Electric motor & prop as azmuthing pod	Electrical generator & motor	Aerofoil cross section pillars	Cable and pulley	Large fore deck to accommodate transfer system	Submerged pumps into and out of tanks		Water metering system		Passively controlled system
5	Tubular - To act as cylindrical catamaran hulls or ballasted pontoons	Fender at deck level only	2 Turbines on deck	Side Thrusters		Telescopic legs - allow reduced deck height when in transit and maximum depth when in transfer mode	Chain Winch	Minimal deck space (Walkways only)	Leadscrew		Flexible membrane water/air segregation		Third party design
6	Flexible form allowing individual segments to move independently, hence reducing loading of waves					Pivoting arms - legs do not come through deck but rather pivot from one position to another,	No jack-up (solid legs)		Air controlled Plungers		Use extra ballast in main hull to increase buoyancy therefore reduce draft		

						increasing air gap as they move							
7	Single hull with jacking deck - hull becomes pontoon					Hydraulic Rams (complete leg is ram)							
8	Two level tubular cat hulls with profile joining tubulars					Folding Trimaran design - see picture							
9	Box Section					Pivoting arms - legs pivot forward and aft and pivot deck to change air gap							
10						Box Section							

9.5. Appendix E – Initial Concepts and Evaluations

Double Skin Hull

The idea of the double skin hull is that the ballast can surround the sealed buoyancy, and therefore the centre of buoyancy can be lowered. Individual sections would allow control of the ballast.



Advantages

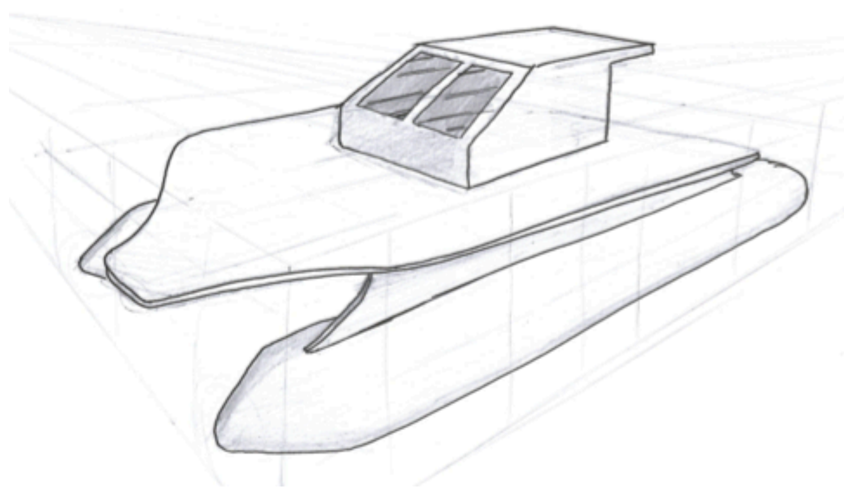
> Sealed buoyancy - cannot over flood
> Maximises use of space
> Simple design

Disadvantages

> Difficult to fix if something goes wrong
> Difficult to detect leaks
> Would require additional pumping system

Tubular hulls

The tubular hulls offer a way of creating buoyancy but allowing the nature of a SWATH to be maintained. This concept could be combined with the double skin concept



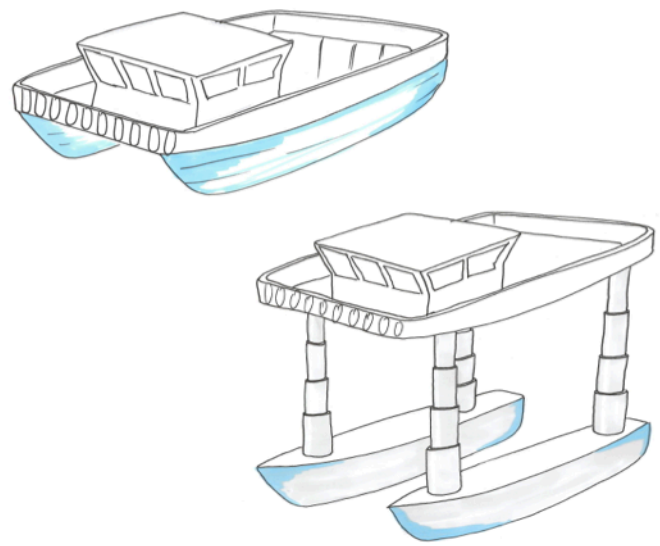
Advantages

> Simple design
> Acts like SWATH in transit => smooth and fast
> Would work with various ballasting systems

Disadvantages

> Efficiency of cylindrical shape through water not good
> Complexity of conical shape at bow

<u>Catamaran hulls</u>
This was the original concept proposed. The idea is that the submergible hulls are the same shape as a standard catamaran but can be detached from the vessel and submerged, by extending legs of some sort and bringing on ballast.



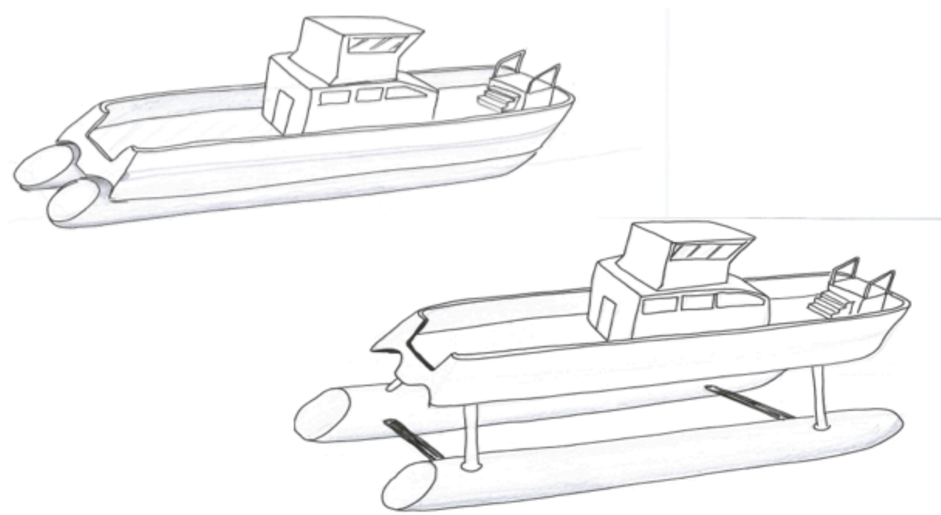
Advantages

- Would perform as an ordinary catamaran during transit
- Would not require to ballast hulls in benign conditions
- Hull form tried and tested in un-ballasted mode

Disadvantages

- Hull may be expensive and difficult to produce
- May not provide the correct properties underwater

<u>Cylindrical hulls</u>
This design is similar to the tubular hulls however the cylinders are intended to be de-ballasted completely and float on the surface of the water (similar to standard cat hulls) rather than act as SWATH hulls.



Advantages

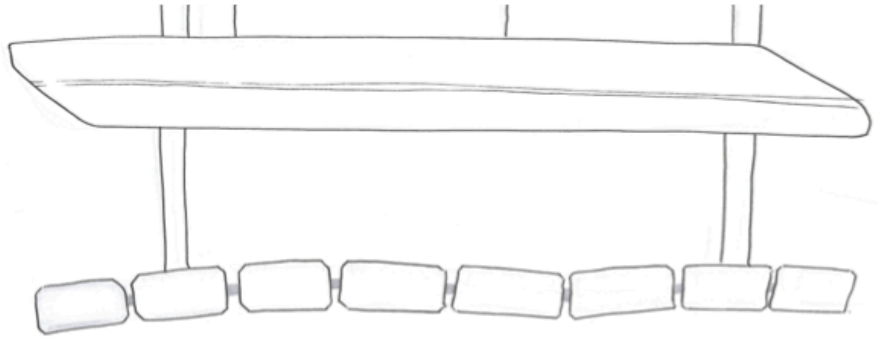
- Neat design when not ballasted
- Provides a vessel much like the standard one

Disadvantages

- Difficult to provide the sufficient height
- Hulls close together therefore they may require to be extended diagonally to give the vessel enough balance
- Hull form may not perform well floating on water

Flexible Hulls

This concept is a row of segregated tanks which combine to make a hull. The tanks are connected by a stiff but flexible rod, which allows the tanks to move with the wave to an extent, therefore reducing the effect of the wave



Advantages

> Moves with waves therefore effect should be reduced

> Segregated tanks mean higher safety - less likelihood of complete failure

Disadvantages

> Individual tanks would be expensive to produce

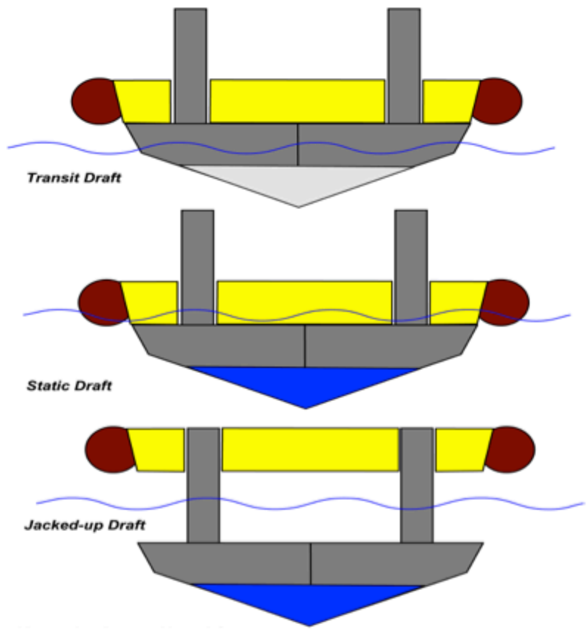
> Ballasting system would have to work for all tanks/ would need one for each tank

> Complex system

> Slight movement may not reduce wave effect

Single Pontoon

This concept eliminates the need for catamaran pontoons by simply using a single hull which is ballasted and deck raised as shown in the picture



Advantages

> No need for strengthening pieces between separate hulls

> Free flooding - ballast water vented at speed

> Stable when static

Disadvantages

> Single hull may reduce transit comfort

<u>Two Level Tubular</u>

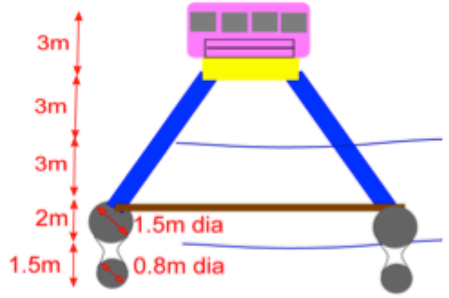
Two tubular hulls on each side of the catamaran vessel - one of which provides permanent buoyancy and the other provides an opportunity to bring on ballast. Profiled flooding skin joins two sections

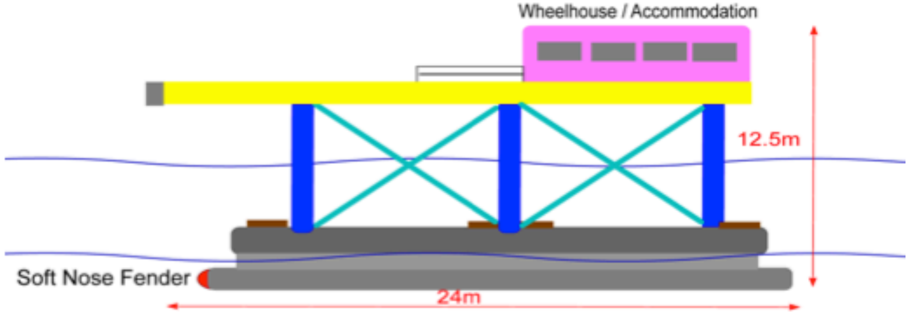
Advantages

> Runs as SWATH when de-ballasted, with one tubular on the surface and one below surface
> Provides buoyancy which cannot be flooded accidentally - therefore safe

Disadvantages

> Requires four hulls - expensive
> Complex system
> Heavy due to extra hull





9.6. **Appendix F – Concepts Taken Forward**

Concept 1 – Catamaran Hull Design

The initial design was based on the original concept; that the vessel would operate like the current catamaran workboats when in transit mode, but could ballast the hulls and submerge them when at site, raising the deck to allow an air gap between the surface of the water and the underside of the vessel. In transit mode the hulls would provide plentiful buoyancy to enable the vessel to sit with a waterline only part way up the hull and still have plenty freeboard, allowing it to power through waves with sufficient buoyancy to stop it nose diving. In transfer mode, the hulls would be partially filled with water so that the hulls would only provide sufficient buoyancy when combined with the buoyancy provided in the legs. The depth which the hulls would submerge to would therefore be governed by the extra buoyancy provided by the submerged depth and the cross sectional area of the legs.

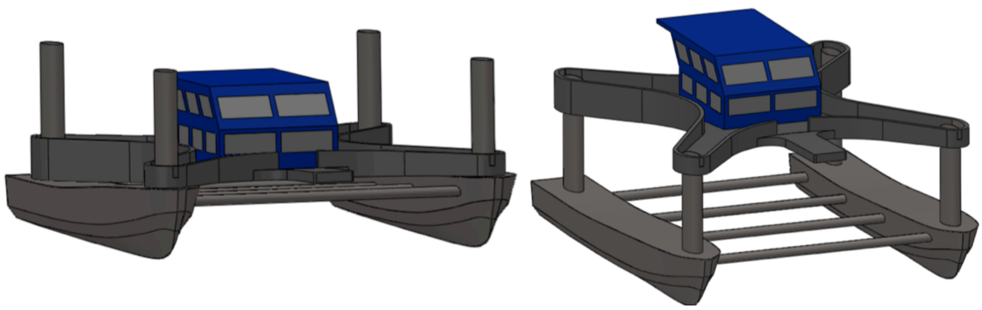


Figure 61 - Concept 1

For this concept, catamaran hulls were developed based on current crew transfer vessels. A novel deck was also developed to try to minimise deck weight and therefore lower the centre of gravity to increase the stability, whilst still maintaining access to the bow for transfers. From initial modelling it was found that although the hulls had proven performance in current designs, modification to hull spacing may invalidate this assumption.

Concept 2 – Tubular Hull Design

This concept was developed to create a vessel that increases the performance in both transit and transfer states. Research into small waterplane twin hull vessels (SWATHs) identified a huge reduction in vertical accelerations at speed in waves. This concept was therefore developed based on the principle of the SWATH design. Buoyancy would be provided by the lower hulls when in transit with reserve buoyancy provided by the upper hulls to allow the vessel to drive through waves, without the fear of nose-diving due to minimal buoyancy.

When the vessel submerges, the lower hulls would be flooded with water completely together with a proportion of the upper hulls. The required buoyancy is then supplied by the remaining buoyancy of the upper hulls and that of the legs as they sink below the surface.

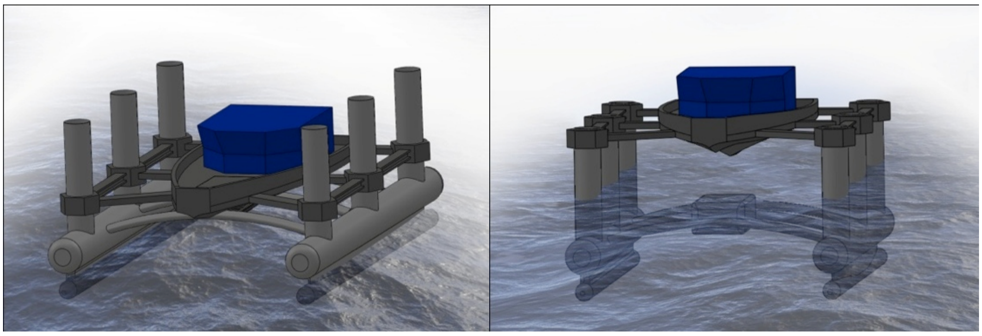


Figure 62 - Concept 2

The key advantage of this design is the ability for the vessel to operate as a SWATH, which should allow it to perform better in transit than the catamaran shaped hulls. The added advantage of the upper hulls is that when the vessel hits a wave there will be sufficient buoyancy to allow it to ride over the waves, rather than nose-diving through them. This design also investigated the use of extra legs to try to maintain the strength whilst reducing the overall water-plane area in transfer mode, and the deck incorporated a chined hull shape to eliminate the chances of slamming.

Concept 3 – Non-ballasting design

Research highlighted a need to reduce the buoyancy in the hulls to allow them to sink below the surface of the water in semi-sub mode, whilst still having sufficient buoyancy to float in catamaran mode. The concept of a “minimum-ballast” design was generated in the focus groups when the function of changing buoyancy was investigated. This concept operates by using the upper hulls as an integral part of the floatation in catamaran mode, which is removed from the water by jacking more buoyancy downwards through the deck, hence no ballast water is required to “sink” the lower hulls.

In the transit state, buoyancy is provided partially by the submerged cylindrical hulls and partially from the upper hulls. When the vessel is required to operate in the static stable mode, the deck is simply jacked up, which forces the submerged hulls down. The deck will start rising out of the water when sufficient buoyancy is provided by the lower hull plus the additional buoyancy in the legs.

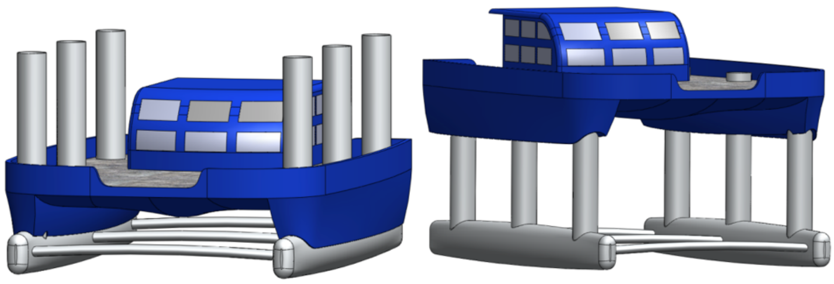


Figure 63 - Concept 3

The advantages of this system are that the simplicity of the jacking system reduces weight and eliminates any complexity of a pumping system. In transit mode the vessel always has enough buoyancy, as this varies passively to suit the loading of the vessel.

9.7. **Appendix G - Concept Evaluation**

Concept 1 – Catamaran Hull Design

Concept 1 met critical reviews from the focus groups for a number of reasons. Although this design offered the potential for a planing hull form, the increased distance between the hulls was highlighted as a concern for reasons of the power required to reach the desired planing speed. Reducing deck area should, in theory, reduce the structural weight, but it was thought this may be minimal due to the structural strength which must be added to the diagonals to compensate for the lack of cross members. The reduction in deck area was also highlighted as a concern as deck space is thought of as a premium in the offshore transit market where the potential to transport equipment as well as personnel is high.

Concept 2 – Tubular Hull Design

Evaluation of Concept 2 identified tubular hulls as simpler to build as pressure vessels than chine hulls but the use of double tubulars was thought to increase weight, as the surface area of the hulls will increase. The hydrodynamic capabilities of a basic tubular shape were highlighted as a point of concern by the professionals in the focus group, as this could have a big impact on speed and fuel economy.

Initial hand calculations on the stability of a semi-sub identified that increased separation of the waterplane area in this mode increased stability, therefore four larger legs were found to be more desirable than six with the same overall water-plane area.

Although the SWATH option was possibly desirable it was considered by the experts in the project team that it would complicate the development process that would have a major impact on the timescale of the project.

Concept 3 – Non-ballasting design

On modelling concept 3 it was found to be a much simpler design due to the lack of ballasting equipment needed and the simple shape of the deck. It was found however that because the deck was required to be much larger, with the addition of hulls which lifted clear of the water, the centre of gravity was much higher. This was compounded by the lack of ballast water in the lower hulls, meaning the centre of gravity could not be kept low.

This was highlighted as a major issue for stability later in the design process.

Criteria	Weighting	Concept 1	Concept 2	Concept 3
Estimated relative speed	1	3	1	2
Deck Space	1	1	2	3
Load Capacity	2	3	2	1
Inherent Design Strength	1	1	2	3
Cost	2	3	2	1
Safety	3	3	1	2
Reliability	1	2	1	3
Total (sum of scores)		28	17	21

Table 30 - Concept Evaluation Matrix

9.8. **Appendix H – Sub-System Development**

9.8.1. Structure

The vessel structure, particularly that of the deck, was crucial to the feasibility of the design, as this would determine the weight and weight distribution and therefore the centre of gravity, hence if the structure weight was calculated incorrectly it could nullify the results of the analysis.

To estimate the hull, leg and deck weight the construction of each was considered. A decision was made to develop the structure based on a plate and stiffener, whereby an overall outer shape is defined and split into plating sections, and the structure below this is built up of longitudinal stiffeners and transverse frames.

The outline shape of the hulls was first developed which influenced the deck shape heavily as the deck also served as the upper hulls, providing the reserve buoyancy for the ship, therefore was required to be shaped appropriately. Transverse frames and bulkheads were then designed accordingly and the longitudinal stiffeners were accounted for by increasing the thickness of the deck plating by 10%, as advised was common practice by Kuipers Woudsend BV. Communications with Danish shipbuilder Kuipers Woudsend BV [2], combined with knowledge from various academics at the University of Strathclyde and professionals at Safety at Sea, identified that the vessel plating should be around 5 mm thick for steel and 8 mm for aluminium vessels, with transverse frames at around 1 m spacing and bulkheads where required for watertight integrity. The longitudinal stiffeners were placed based on the design shape.

Dimensions for the vessel were estimated based on a number of considerations. The maximum overall length was limited by the legislation; MGN280 defines a Small Commercial Vessel as a ship under 24 metre LOA and carrying no more than 12 passengers, and a total of 16 people on board. Review of current transfer vessels

[2] Kuipers Woudsend BV (2013) Phone correspondence with R Macdonald discussing ship construction methods

highlighted the need for size both for the practicalities of transferring crew and equipment and also for sea-worthiness. A decision was therefore made to design the vessel as large as possible whilst keeping under the 24-metre threshold. The width was driven by the initial evaluation, as the separation of the legs in semi-submersible mode was a crucial factor on the stability calculations. Iteration o the design identified an optimal leg spacing of 11 metres, leading to an overall vessel width of 14 metres. At this width the underside of the deck required re-modelling to reduce the chances of slamming, which had been brought up as a concern earlier in the design process.

The construction of the hulls, legs and deck, which can be seen in the image below, was then used to estimate the weight of the components.

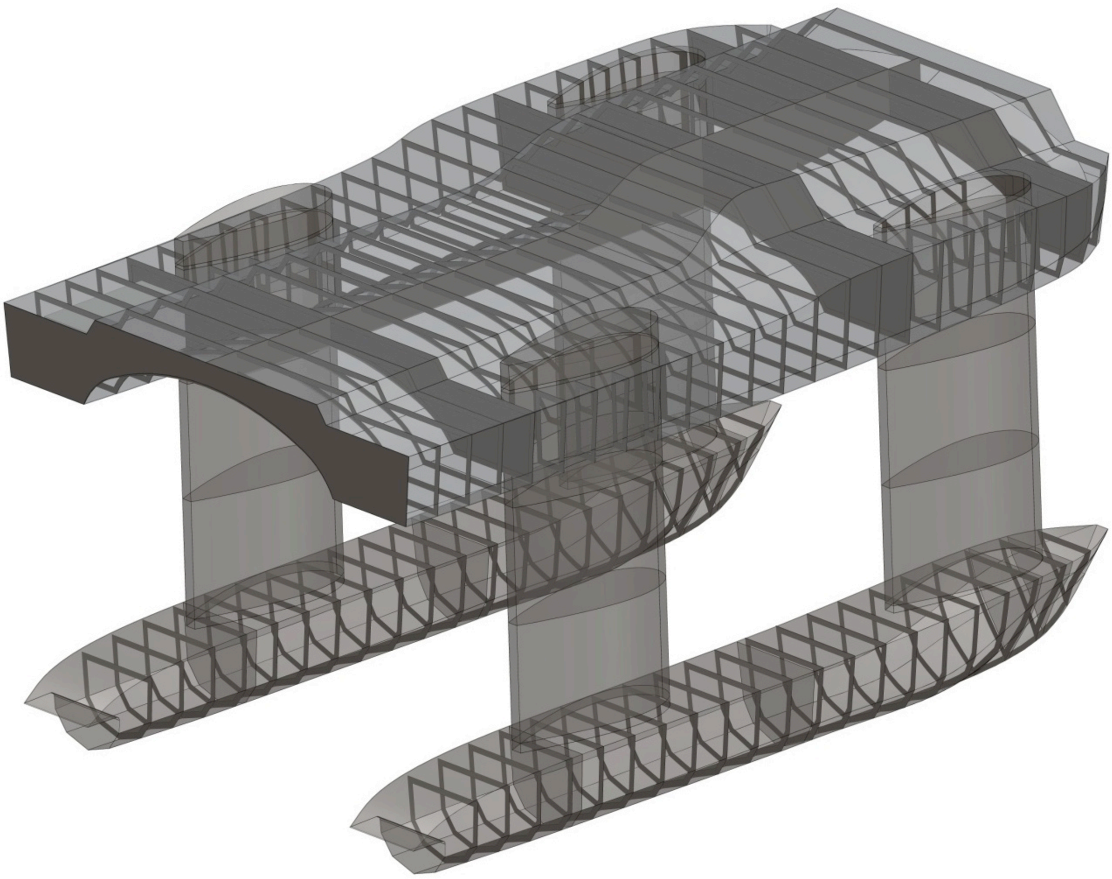


Figure 64 – Structure of ship design

9.8.2. *Hull Form*

The design of the form used for the hulls of the catamaran was a complicated process. It is crucial for the final design but was not within the area of expertise of anyone in the project team. A basic hull was therefore modelled, developed from current catamaran work vessels, with the ability to vary the crucial parameters as desired. At this point in the design process the volume, length, draft and beam were the crucial parameters and it was considered that the detailed shape could be optimised at a later date. The evaluation of the design was therefore based on these parameters.

The spacing between the hulls was also a variable in this novel catamaran design. For the transit mode (i.e. catamaran mode) it was found that a suitable distance between hulls was around 1.25 x demi-hull beam (Rawson and Tupper, 1976), however when operating as a semi-submersible the stability was highly dependent on the transverse leg spacing; stability increasing with the square of the spacing. Varying the width of the vessel as well as the height was considered (i.e. having a relatively slim catamaran widening as it becomes a semi-submersible) however this was found to complicate the design so an optimal hull spacing for the semi-sub was found and the hull shape was optimised as best as possible to accommodate the catamaran mode.

9.8.3. *Powering*

Powering the vessel was another key stage of the design development. Initially it was thought that diesel engines could be located in the lower hulls, with a direct drive to jet drives or azimuth thrusters. On review of this it was clear that although there was sufficient room and diesel direct drive would technically be possible, it would mean there was no access to the engines at sea for maintenance, so this was not considered a viable solution. To remedy this issue a diesel-electric system was selected; diesel generators located in the upper deck, with easy access for maintenance and repairs, and more reliable electric motors located in the lower hulls to provide the drive. Although this would not eliminate the need for access to the lower hulls completely, it drastically reduces the frequency of maintenance and an access hatch is provided for repairs and servicing in a dry dock or slipway.

From a review of vessels of similar size and speed jet drives were originally selected for the propulsion method. On analysis of the hydrodynamic resistance of the design, it was concluded that the speeds predicted (which were lower than originally targeted) meant that jets would be inefficient. Also, the efficiency of jets was found to drop dramatically if the drive is deeply submerged, and for this reason four blade propellers were selected, with steerable nozzles to increase the manoeuvrability of the craft. A powering analysis is detailed in Section 5.4.2 estimating the speed of the vessel.

9.8.4. ***Legs***

The legs of the concept vessel serve two purposes; to support the deck as it is jacked and to provide a water-plane area for the vessel in semi-submersible mode. Strength to transfer the weight of the deck to the pontoons was required, however truss legs could not be utilised as they would not provide sufficient water-plane area. Hollow tubes were therefore selected. Initial design iterations utilised cylindrical tubes so that the water-plane area and submerged volume could be easily calculated as the design was varied. Once a leg area which gave sufficient stability was found, the cross sectional shape of the legs was reviewed. An aerofoil shape was selected to maximise speed in the forward direction, and a standard shape (NACA 0035 symmetrical foil) was chosen to aid evaluation.

As discussed previously the transverse leg spacing was driven by the semi-submersible stability and the desire to minimise the catamaran hull spacing. Longitudinally however the leg spacing had different governing factors. Originally it was proposed that the legs should be as far apart as possible to maximise longitudinal stability, by locating the forward legs as close to the bow as possible and the aft legs as far aft as possible. This spacing significantly reduced the ability to access the hull machinery however so the aft legs were moved forward, allowing access to the hulls whilst still maintaining sufficient stability.

Another issue with the leg design was that the electric power from the generators, and fuel from the tanks located in the legs, has to be transferred between the hulls and the deck whilst still allowing the deck to move vertically. On review of a number of telescopic products such as cherry pickers, it was clear that this aspect of the design would be achievable. Due to the limited timescale of the project however the detailed design of this was not carried out and was considered an area for further work.

9.8.5. ***Jacking Mechanism***

The jacking mechanism sub-system was defined as any equipment required to lift the deck from the hulls to the top of the legs. Reviewing existing technology, it was clear a jacking system for the concept would be achievable as jack-up rigs are commonplace in the offshore oil industry. First it was necessary to calculate and evaluate the forces and weights to be jacked. The size and power requirements of the motors were dependent on the weight of the vessel deck and the configuration would be selected accordingly. The height to raise the deck was also to be considered together with the time required to carry out the operation.

The development of the jacking system was carried out with input from a number of expert advisors; John Howard from Howard Marine Ltd (a key member of the International Jack-up Barge Owners Association), Bruce Davis from Weir Power & Industrial and Kieran Dodworth of Safety at Sea were consulted to estimate the weight and size of the jacking mechanism. Rack and pinion (using either electric or hydraulic motors), stepper hydraulic and chain drive mechanisms were all considered however it was concluded that the rack and pinion type mechanism would suit this application best. As discussed in Section 9.8.3 the power for the vessel drive would be based on a diesel-electric system, therefore to utilise this available power an electric jacking mechanism was selected. The power to the drive motors would be minimal during jacking, as this would be carried out at slow speeds or even stationary, and power calculations indicated an excess of electric power available.

A detailed design of the jacking system was out with the capabilities of the project team within the timeframe of the project however numerous similar designs were identified and a concept for an electric rack and pinion jacking system is detailed. Supporting calculations showing the required power to lift the deck and layout drawings of the mechanism can be found below. On top of the equipment required to jack the structure rollers and guides were also required, as well as a locking mechanism to stop the deck moving either up or down in the case of sudden impacts or changing loads.

Three motors on each leg were chosen and positioned around the legs and racks were added to the legs as shown in the figures below.

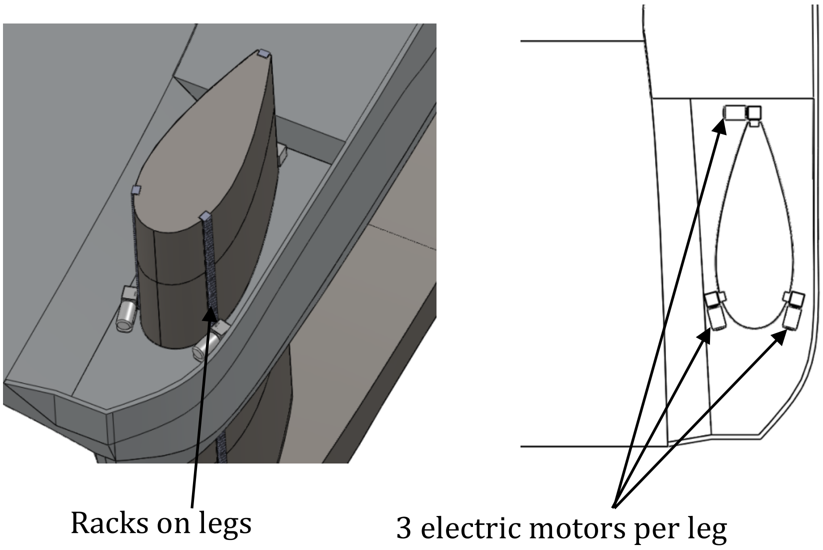


Figure 65 – Jacking Mechanism: Rack and Motor Position

A power calculation was carried out to enable motors to be selected. On review of potential motors, a 5.5 kW motor was selected as this safely covered the required power.

A frame was designed to house the motors, and racks on the legs ran the full length of movement. The motors drive pinion gears, which react against the racks providing a force to lift or lower the deck relative to the legs. A simple locking mechanism was devised consisting of a 750 mm section of rack that could be forced against the racks on the legs when locked, transferring the load directly to the deck. The arrangement is shown below.

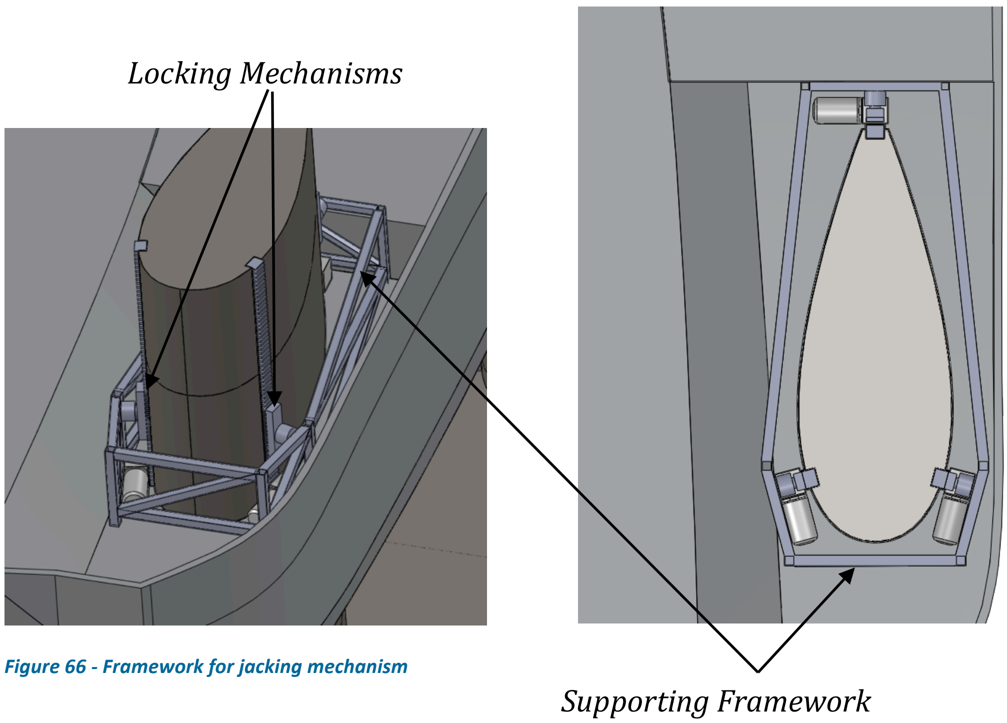


Figure 66 - Framework for jacking mechanism

It was also felt rollers were required to allow the legs to move through the deck smoothly. A sleeve was therefore incorporated and is shown below.

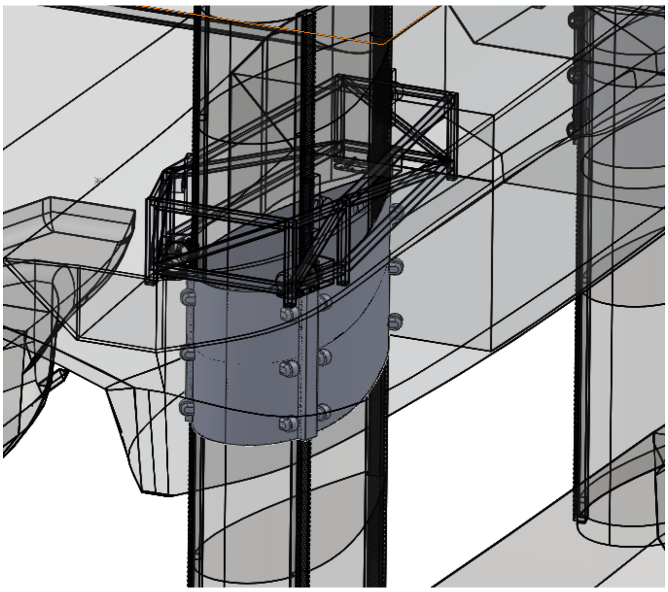


Figure 67 - Rollers for jacking mechanism

Finally the component weights were estimated and a system weight was calculated, shown in the table below.

Component	Unit weight	Number of	Net weight
5.5 kW electric motor	35	12	420
Gearbox	50	12	600
Locking Mechanism	100	4	400
Racks	100	12	1200
Frame	100	4	400
Sleeve and rollers	50	4	200
		Total	**3220**

Table 31 – Weight Estimates for Jacking Mechanism

A weight of 3.22 tons for the jacking system was estimated by breaking the system into components and estimating the weight of each. A dynamic deck was considered, that could be moved to oppose the movement of the waves to reduce movement further, however the complexity of this coupled with the added power required from the jacking motors ruled it out of this stage of the development process. This may be considered if the initial design is proven.

9.8.6. *Ballasting System*

In the early stage of the development, the ballast system had not yet been detailed however similar technologies had been identified from a range of applications (semisubmersibles, submersibles, ships, etc). A number of aspects were considered during the development including how the ballasting process is controlled, the pumping of seawater, the hydrostatic balance during this procedure and the effect of the free surface in the tanks.

The volume of ballast water was determined by the added displacement required to submerge the hulls to the desired depth. A full review of the optimal submergence depth was not carried out, however a decision was made to submerge the pontoons so that the upper surface would be at a depth of 3.5 m and therefore the average waterline would be half way up the legs. Once the required volume of ballast water was determined, and the components within the hull had been selected, the design focus was to establish where the ballast tanks should be located. This was governed by the requirement for static equilibrium (i.e. the requirement for the longitudinal centre of buoyancy, LC_B, to be vertically in line with the longitudinal centre of gravity, LC_G) alongside the need to maintain reasonable stability. After many iterative steps a solution was found which allowed all conditions to be satisfied; sufficient room for the ballast water and components, equilibrium of LC_G and LC_B and a reasonable metacentric height.

As the ballast pumps were to be located in the lower hulls and were relatively inaccessible at sea, two pumps were chosen for each hull, allowing a redundancy factor in case of a malfunction. Ballast pumps were then reviewed and four electric centrifugal pumps were selected, each with a capacity of 450 m^3/hour (weight ~ 250 kg). This allowed a ballasting time of 7 minutes to be achieved.

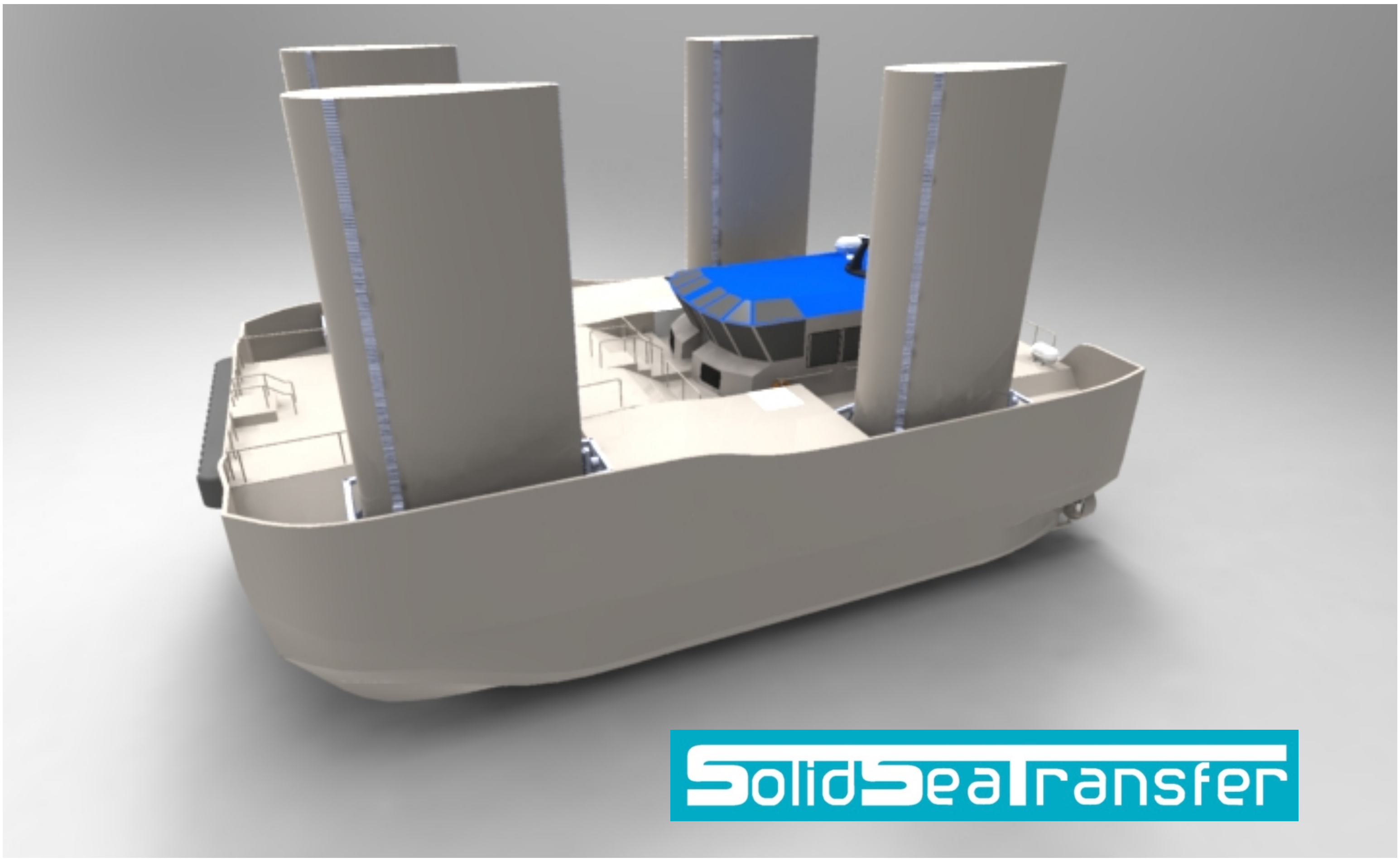
9.8.7. ***Deckhouse and Deck Layout***

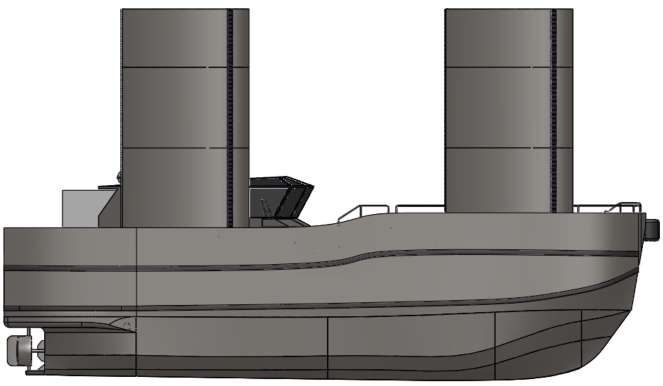
The deckhouse for the vessel was designed for on-site operations, as the vessel will be transporting personnel from a fixed base (either a port or mothership) on a daily basis. Reviewing current transfer vessels, it was clear a safe, comfortable environment must be created to provide the personnel with an area to prepare for work and also to relax if required. The class limits that the vessel is designed to operate in limit the passengers to 12 people, therefore the deckhouse is designed to seat 12 technicians comfortably, equipped with connection points for laptops to allow work to be carried out during transit, weather permitting. The concept has a small galley and a toilet on board. The crew have an operational area away from the passengers where there is a navigation table and a communication table. Further to this, the cabin has a forward facing door to allow technicians to pass straight to the bow of the vessel, as this is where they will transfer to the turbines. Storage for spares and equipment has been accommodated for in a container situated on the aft deck of the vessel. The detailed layout of the deckhouse has not been finalised however it is clear there is sufficient space for the purposes discussed.

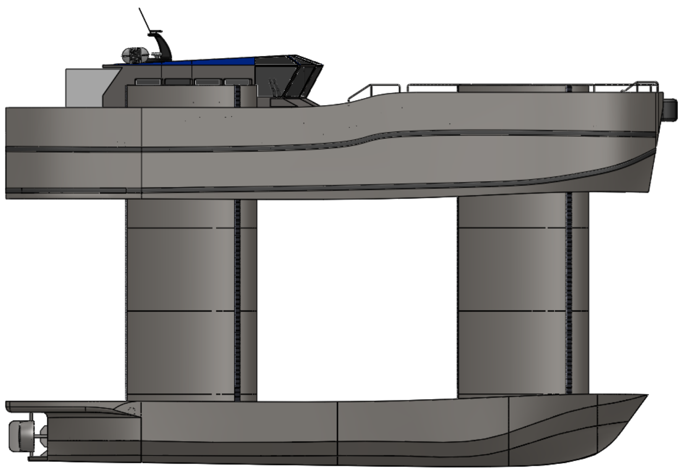
9.9. **Appendix I – Vessel Particulars**

24m Offshore Access Vessel

Bi-configuration vessel designed specifically for the offshore wind industry

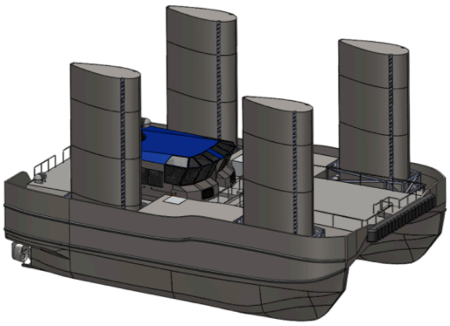




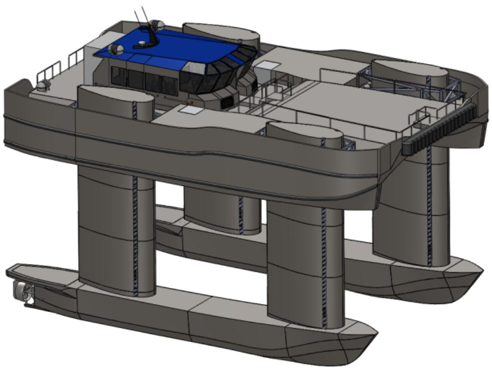


24m Access Vessel

The purpose designed access vessel has capabilities for both fast transit and stable transfer, utilising two configurations and a unique transfer ability to be able to change from a fast, efficient catamaran into a stable semi-submersible on site.



Transit mode



Transfer mode

Length over all	24.2m
Length hull	23.3m
Beam over all	14.5m
Draft	
Transit	1.7m
Transfer	6.3m
Lightship	approx. 126 tonnes
Hull material	Steel
Deck material	Aluminium
Fwd deck space	approx. 66.6m^2
Aft deck space	approx. 33.2m^2
Speed	
Departure	approx. 18 kts (90% MCR)
Arrival	approx. 20 kts (90% MCR)
Transfer mode	approx. 13 kts
Passengers	12
Crew	2-3
Cargo	3 tonnes FWD
	3 tonnes AFT
Propulsion	2 x ABB 1100kW electric drive motors (in hulls)
Main Generators	2 x 1100kVA CAT generators
Propulsion Method	2 x directional ducted propellers
Fuel	10,000 ltr
Fresh Water	700 ltr
Black Water	400 ltr
Jacking time	12 mins
Ballasting time	7 mins

Other Equipment
Individual suspension seating for 12 passengers
Power supplies and laptop work stations
Galley, toilet and storage lockers
Simple transfer platform on bow
Ample foredeck for transfer system
Container for turbine spares
Chart and navigation tables