OFFSHORE WIND COST OPTIMISATION:

DEVELOPING MARKET STRATEGIES FOR THE NEXT GENERATION OF OFFSHORE WIND FARMS.

Submitted by

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The University of Exeter, the University of Edinburgh, and the University of Strathclyde as a Thesis for the degree of Engineering Doctorate in Offshore Renewable Energy

2020

IDCORE

This thesis is submitted in partial fulfilment of the requirements for the award of an Engineering Doctorate, jointly awarded by the University of Edinburgh, the University of Exeter, and the University of Strathclyde. The work presented has been conducted under the industrial supervision of The Energy Technologies Institute as a project within the Industrial Doctoral Centre for Offshore Renewable Energy.

ABSTRACT

The renewable energy sector, especially offshore wind, has a major part to play in future energy systems. As a rapidly maturing technology, offshore wind can help meet the decarbonisation target, create economic prosperity and increase energy security. In the UK, meeting the recent Net Zero target by 2050 will require unprecedented innovation across the economy. Innovation not just in new technologies, but in new ways of deploying existing technologies, new sites, supply chain, policy, and market design. A strategic approach to innovation is sought to unlock further innovation in the offshore wind, thus optimising offshore wind farms' future deployment. This thesis provides valuable design methodologies and tools that can help inform the offshore wind stakeholders to address the technical barriers to further innovation and commercialisation.

The developed approach has been developed in such a way that each methodology can be deployed individually or combined to optimise the proposed design outputs. The approach is presented through several case studies, showing the effectiveness and proposed solutions of integrated design methodologies. This is achieved in three stages: First, a review of the current state of the sector is undertaken to understand the key drivers to innovation and market growth; secondly, design theories and methodologies are reviewed for the most effective applications of the design methods, and the appropriate methodologies are developed and validated using offshore wind case studies.

The review of the conceptual design methodologies identified the Quality Function Deployment, the Theory of Inventive Problem Solving and the Failure Mode and Effect Analysis methods as the most appropriate integrated tools that can assist the designer to consider all the interactions between technical solutions to a problem and the necessary compromises that are required to meet the design requirements. The structured innovation approach is presented and validated in two case studies: a 6MW direct-drive generator and a floating subsystem.

“*C’est dans les moments les plus sombres qu’on voit le mieux les étoiles.”*
Charles A. Beard

DECLARATION

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

Parts of the work outlined in this thesis have been published:

- Section 2 is based on Inès Tunga, Adam Thirkill, Susanna Elks. Energy Technology Benchmarks for Net Zero WP3- Floating offshore wind, *InnovateUK*,2020, London
- Section 2.4 & 2.5 based on Laura Morris, George Day, Inès Tunga, Stuart Bradley. Analysing the impacts of preparedness: Offshore Wind. *ETI, 2016.* Loughborough
- Section 3.3 is based on Inès Tunga, Stuart Bradley. Technical Requirements for the implementation of Structured Innovation in Ocean Energy Systems, *Horizon2020-DTOceanPlus*,2019, Bilbao
- Section 3.3 is based on Donald Noble, Anup Nambiar, Inès Tunga, et al., Functional requirements and metrics of 2nd generation design tools, *Horizon 2020- DTOceanPlus*, 2018, Edinburgh.
- Section 3.3.6 is based on Inès Tunga, Donald Noble, Jonathan Hodges, et al. Structured Innovation design tool- Alpha version, *Horizon 2020- DTOceanPlus,* 2020, Derby.

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ACKNOWLEDGEMENTS

Undertaking this Engineering Doctorate programme has been a truly life-changing experience. It would not have been possible to do without the support and guidance that I received from many people. Acknowledgement, with gratitude, is due to the following:

Firstly, I would like to express my sincere gratitude to my supervisors Prof Lars Johanning and Dr Stuart Bradley, for the continuous advice, support, insight and encouragement throughout this programme. Your patience, motivation, encouragement, and immense knowledge would not have been achievable without your guidance and continuous feedback.

My sincere thanks also go to the Energy Technologies Institute who hosted the three-year industrial element of this Engineering Doctorate and, in particular, the Offshore wind Programme team who supervised this work. Without their precious support, it would not have been possible to conduct this research.

Special thanks also go to my dear friends Jan, Carla, Pitchou and Deborah, for offering advice and encouragement throughout this process.

To my family: Christophe and Skylar, it has been tough juggling life! Thank you for being my rock! To Maman, Bera, Gaju, Basinga and Papa Idi, thank you for all your encouragement and love.

Finally, funding from the Energy Technologies Institute (ETI) and the RCUK Energy Programme for the Industrial Doctoral Centre for Offshore Renewable Energy (Grant number EP/J500847/1) is gratefully acknowledged.

“Le voyage est la récompense”

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Abbreviations and Acronyms

AC	Alternating Current electricity
AHP	Analytic Hierarchy Process
ANP	Analytical Network Process
ASP	Administrative Strike Price
BEIS	Department of Business, Energy & Industrial Strategy
CAPEX	Capital Expenditure
CCC	Climate Change Committee
CCS	Carbon Capture and Storage
CfD	Contract for Difference
CFD	Computational Fluid Dynamics
CM	Condition Monitoring
DC	Direct Current electricity
DCOV	Design- Characterise-Optimise-Verify
DD	Direct Drive generators
DECC	Department of Energy & Climate Change
DFMA	Design for Manufacturing and Assembly
DfSS	Design for Six Sigma
DMAIC	Define-Measure-Analyse-Improve-Control
DMEDI	Define-Measure-Explore-Develop-Implement
DR	Design requirements
DRP	Device Rated Power
DTOcean	Design Tools for Ocean Energy systems
DTU	Technical University of Denmark
DUKES	Digest of UK Energy Statistics

EINA	Energy Innovation Needs Assessment
EMR	Electricity Market Reform
ESC	Energy Systems Catapult
ESME	Energy Systems Modelling Environment
ETI	Energy Technologies Institute
FEED	Front-End Engineering Design
FIDeR	Final Investment Decision for Enabling Renewables
FIT	Feed-in Tariff
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode and Effects Criticality Analysis
FOAK	First of a Kind
GB	Great Britain
GHG	Greenhouse Gas
GPS	Global Positioning System
GVA	Gross Value Add
GW	Gigawatts
HAZAN	Hazard Analysis
HAZOP	Hazard and Operability study
HoQ	House of Quality
HTC	High-Temperature Superconducting
HVDC	High Voltage Direct Current
IDC	Interests during construction
IEC	International Electrotechnical Commission
INCOSE	International Council on Systems Engineering
IRENA	International Renewable Energy Agency
ISO	International organisation for standardisation

IT	Information Technology
KPI	Key Performance Indicator
LCCC	Low Carbon Contracts Company
LCOE	Levelised Cost of Energy
MW	Megawatt Capacity
NOAK	Nth of a Kind
NPV	Net Present Value
O&M	Operation and Maintenance
OEM	Original Equipment Manufacturers
OFTO	Offshore Transmission Owner
OPEX	Operational Expenditure
OREC	Offshore Renewable Energy Catapult
OWIC	Offshore Wind Industry Council
PM	Permanent Magnet
QC	Quality Characteristics
RAMS	Reliability, Availability, Maintainability, Serviceability
RD&D	Research, Development And Demonstration
R&D	Research & Development
ROC	Renewable Obligation Certificates
THM	Top Head Mass
TLP	Tensioned Leg platform
TPL	Technology Performance Level
TRL	Technology Readiness Level
TRIZ	Russian acronym for Theory of Inventive Problem Solving
TSO	Transmission Systems Operators
UK	United Kingdom

VOC	Voice of the Customer
VSC	Voltage Source Converter
WACC	Weighted average cost of capital

Definitions of key terms

Art-of-the-possible	The phrase refers to achieving what can be ideally done rather than what is possibly achievable, i.e. ideal solutions beyond constraints. It refers to exploring boundaries of what a system can do (i.e. the laws of physics).
Contract for Difference (CFD)	The Contract for Difference is an agreement between two parties, the buyer (e.g., Investor) and the seller (e.g., offshore wind generator), to exchange the difference in the value of a financial product the contract opens and closes. Introduced in the UK by the Energy Act 2013, the CFD is set to support new generations of low carbon electricity generators (LCCC), replacing the Renewables Obligations scheme. The Administrative Strike Price set out the maximum support, the amount paid for each MWh of electricity produced over a 15-year Contract for Difference (CfD) term. The Government offers each technology developer a given delivery year, known as the reserve price [1]. The CFD entitles the generator to payment for the difference between the Strike price and reference price (average market price for electricity in the GB market) [2].

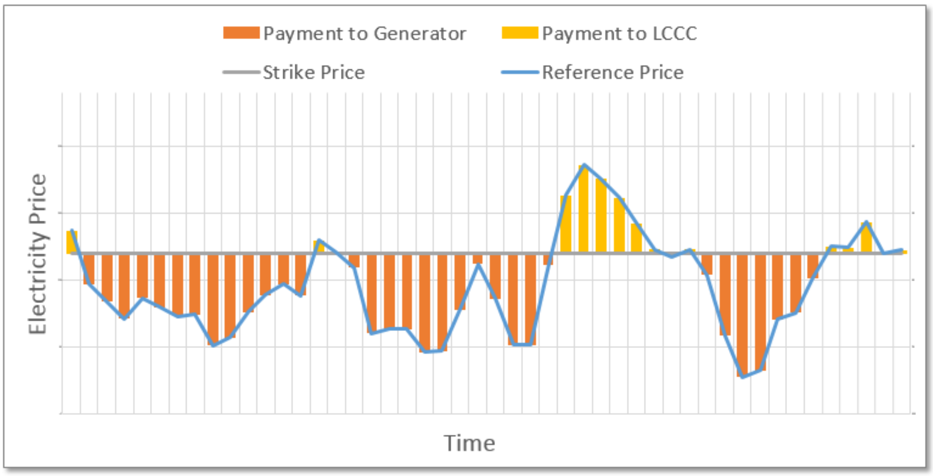

Figure 0.1- Electricity price, Strike Price, and reference price [2]

After the 15 year term, the developers are reliant on the market electricity price only. These prices are expected to be higher than the levelised cost of energy (LCOE) to allow developers' profits over the lifetime of the wind farm projects [1] [3].

Customer requirements	The customer needs, also known as the Voice of the Customer, are defined to satisfy their requirements. These requirements are captured in various ways, such as customer specifications, surveys, interview.
Design methods	Methods are regarded as any procedures, techniques, aids, or tools for designing different design methods that have different purposes and may be relevant and applicable to specific aspects or stages of the design process.
Design requirements	The design requirements are the necessary design features or functional requirements describing the customer requirements in technical terms. These requirements are measurable and meaningful, stated in such a way that particular solutions are implied.
Design theory	The prescriptive theory describing how a design process can be carried at a conceptual or abstract level
Failure Modes and Effects Analysis	A methodology used as a risk and mitigation tool to improve development ventures. The concept or design FMEA mitigates risks associated with the various concept selections at the concept and design phases.
Failure causes	The underlying cause of the failure, or things that initiate processes that lead to failure (such as a defect in design, system, process, quality or part application)
Failure effects	the immediate consequences of a failure on the operation, function or functionality
Failure mode	How a failure is observed
Failure Severity	the consequences of a failure mode, framed in the worst-case outcome, degree of injury, property damage or harm
Feed-in Tariff	A Feed-in Tariff (FIT) are tariff rates set by the authorities (in the UK by The Department for Business, Energy, and Industrial Strategy (BEIS)) to support the development of renewable energy sources by providing a guaranteed, above-market price for producers. Feed-in Tariffs (FITs) usually involve long-term contracts, from 15 to 20 years. These rates are annually adjusted, reflecting the FIT year rate of all tariffs [4] [5].

Organisation impact	In the House of Quality, the technical difficulty in implementing the design requirements to meet the customer needs were assessed. The difficulty for each design requirement to be implemented was rated based on the difficulties to engineer and deliver (supply, procure, and deploy).
Quality Function Deployment (QFD)	A methodology used to identify, prioritise customers’ requirements and translate them into technical requirements for each stage of product development and production. It is achieved using the House of Quality (HoQ), a matrix used to describe the most important product or service attributes or qualities.
Risk	In concept and design FMEA, risks are described as the potential failure of new or improved designs' functions. Failure to mitigate the risks associated with potential risks will result in system failure.
Theory of Inventive Problem (TRIZ)	A systematic problem-solving approach employed to resolve contradictions, using a library of universal principles of creativity, patents, and research. The methodology looks to identify the generic concept problems and solutions and eliminate technical and physical contradictions.
Functional fixedness	A cognitive bias that adults employ to understand quickly the operation of an object (for example, we might think of the ‘natural’ way of using a Smartphone, but might not consider using it as a hammer as a toddler might – even if this is not its intended use, there might be instances when its destruction is irrelevant compared to the gain).
Target values	The design parameters' target values provide the quantitative technical specifications for these parameters to satisfy the customer requirements.
Ideality	Ideality is best defined as the aspirational State-of-the-art parametric values that can drive innovation and identify opportunity and newness relative to current capability. In other words, an ideal state of a system is a system where all its functions are achieved with no harm caused.

Contradictions / Conflicts	Contradictions occur between two or more features, with one feature to be improved and the other worsened. An example of this could be- to generate more electricity for a turbine, a bigger turbine might be required (improved features), but this will result in a heavier machine, increasing its costs (worsened features).
Occurrence	In FMEA, the occurrence is defined as a ranking number associated with the likelihood that the failure mode and related causes will be present in the function being considered
Severity	In FMEA, severity is the ranking associated with the extremely severe effect of failure modes.
Detection	The current controls of the systems determine the probability of detecting a failure before the effect is realised. Detection raking is associated with how likely a failure can be detected.
Risk Priority Number (RPN)	The RPN, the product of occurrence, severity, and detection rankings, assess risks to identify critical failure modes. Caution is required when assessing risks using RPN values.

1. Introduction

This chapter begins with an overview of the current energy market demand. It is developed further by describing where the offshore wind is positioned in relation to current renewable energy generation. The offshore wind industry's current state is described in section 1.1, along with its global energy challenges. An overview of the UK’s response to these challenges is presented in section 1.2, and as a response, the setup of the Energy Technologies Institute, described in section 1.3. The research motivation, problem statement and research goals are presented in section 1.5, describing the project's objectives and the thesis structure.

1.1. Background & Motivation

The world’s economic growth has increased significantly since the last century, particularly in countries where demand is driven by significant growth in the markets, such as India and China. This growth has resulted in a substantial increase in the global energy demand, relying mainly on conventional fossil fuels, which still account for more than three-quarters of the world energy consumption [6]. However, the generation of energy from these sources come with very high levels of greenhouse gases emissions. The global commitment for all parties to reduce their environmental footprint resulted in adopting the Kyoto Protocol in 1997, setting an internationally binding emission reduction target. This protocol has been revised and adapted to each country with specific targets and architecture for agreement on climate change [7].

The European Union (EU) directive 2009/28/EC states that renewable energy should comprise a 20% share of the total energy production in the EU in 2020. The 28 EU member states were given mandatory national targets [8]. In 2008, as one of the EU members, the UK agreed to a legally binding target to reduce greenhouse gas emissions by at least 80% (from the 1990 baseline) by 2050, bringing about the growth and development of low-carbon technologies [9]. The need for low carbon generation and policy mechanisms led to the growth in renewables.

Currently, of all the renewable energy sources, wind energy is one of the most advanced and well-established technology with a capacity of over 12.1 GW onshore and 6.3 GW offshore; accounting for a CO_2 reduction of 13 million tons of carbon dioxide according to the Department for Business, Energy, and Industrial Strategy (BEIS) [10] [11]. According to the latest Digest of UK Energy Statistics (DUKES) figures, renewable energy accounted for 29.3% of the UK’s electricity generation mix in 2017, with wind accounting for half of the renewable mix (8.6% from onshore wind and 6.2% from Offshore wind) [11]. The onshore wind played an essential role in the energy mix and was deployed successfully. Nevertheless, a decision in 2015 to end the government’ subsidies for onshore wind projects was taken to enable the investment of less mature technologies. However, this decision may be overturned by allowing onshore wind projects to compete for subsidies in future CfD auction in May 2019[1] [11].

In recent years, offshore wind's contribution significantly impacted the UK's whole energy systems. At the end of 2017, about 6.3 GW offshore wind was deployed and fully installed in UK waters, meeting over 5% of the UK energy demand [10].

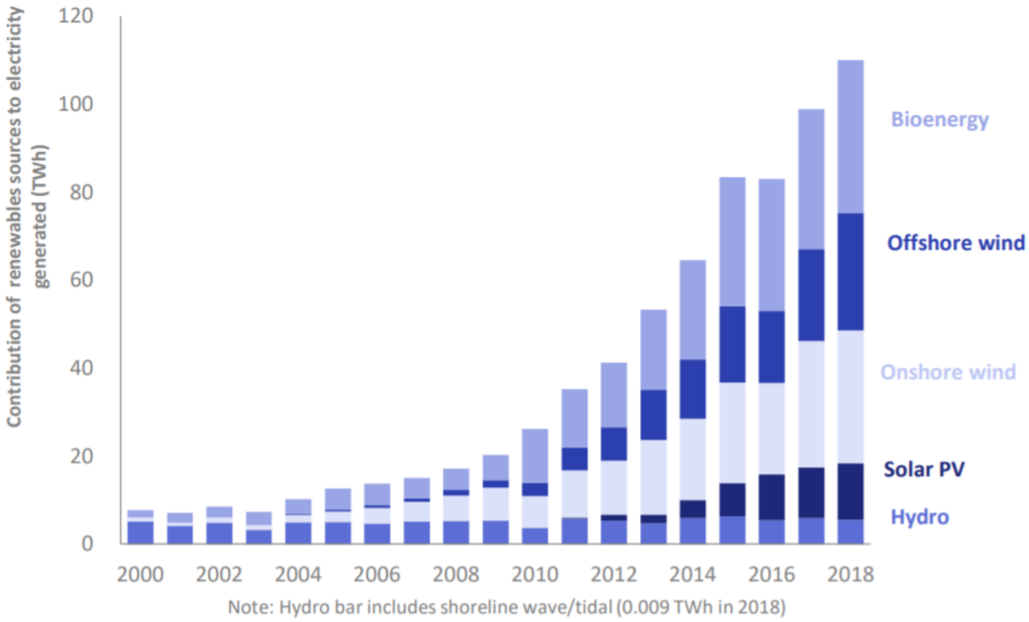

Figure 1.1: UK electricity generation by renewable sources, 2018 [12]

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[1] On the 2nd March 2020, the UK Government overturned the block on new onshore wind subsidies [362]

The UK has a substantial wind resource in deep seas further offshore, offering an inexhaustible energy source with greater wind intensity and minimal visual impacts than onshore wind. The UK industry is home to the world's largest portfolio, and the sector has been developed through 18 years of government support. The UK Government has been explicit that future support for Offshore Wind will be tied to cost reductions [13] [14]. The Clean Growth Strategy, published in October 2017, provided a clear policy signal on the Government's commitment to the offshore wind: "We will work with industry as they develop an ambitious sector deal for offshore wind. Provided costs continue to fall, and this could result in 10GW of new capacity built in the 2020s" [14].

The cost of electricity from offshore wind has come down significantly in the last five years, with the 2020 government's target of £100/MWh reached four years ahead of schedule [15]. In fact, since the start of this research project in 2014, the trend of offshore wind Strike prices has significant fall from the first round of Contract for Difference (CfD) awarded at £144/MWh in 2014 to as low as £57.50/MWh for Hornsea 2 (1386MW) and the Moray Offshore (950MW) wind projects awarded at £57.50MWh for the delivery years 2022/23 by the end of 2017 [2] [16] [17].

"The UK government will invest in offshore wind power generation, with a view to powering every home in the country in the next decade," said the prime minister [18]. Offshore wind is seen as a major player in meeting the UK's renewable energy and carbon emission targets. It is likely to remain an important energy source for at least the next decades because it has proven to be a deliverable and scalable, low carbon technology with a clear pathway to cost reduction and sustainability [19]. It also currently appears to be subject to less political and social complications that onshore wind, nuclear, Carbon Capture and Sequestration (CCS) and bioenergy [14] [20]. Nuclear and CCS are expected to play significant roles in decarbonising UK power; however, recent large-scale deployment in the UK have yet to be delivered [20].

At the end of 2018, the UK had more Offshore Wind capacity installed than any other country in Europe with 44% of all installed capacity, clear plans for further deployment, and with the largest operational wind farm- Walney 3 extension (657MW) [21] [22]. Figure 1.2 presents the top five countries' cumulative installed capacity in Europe.

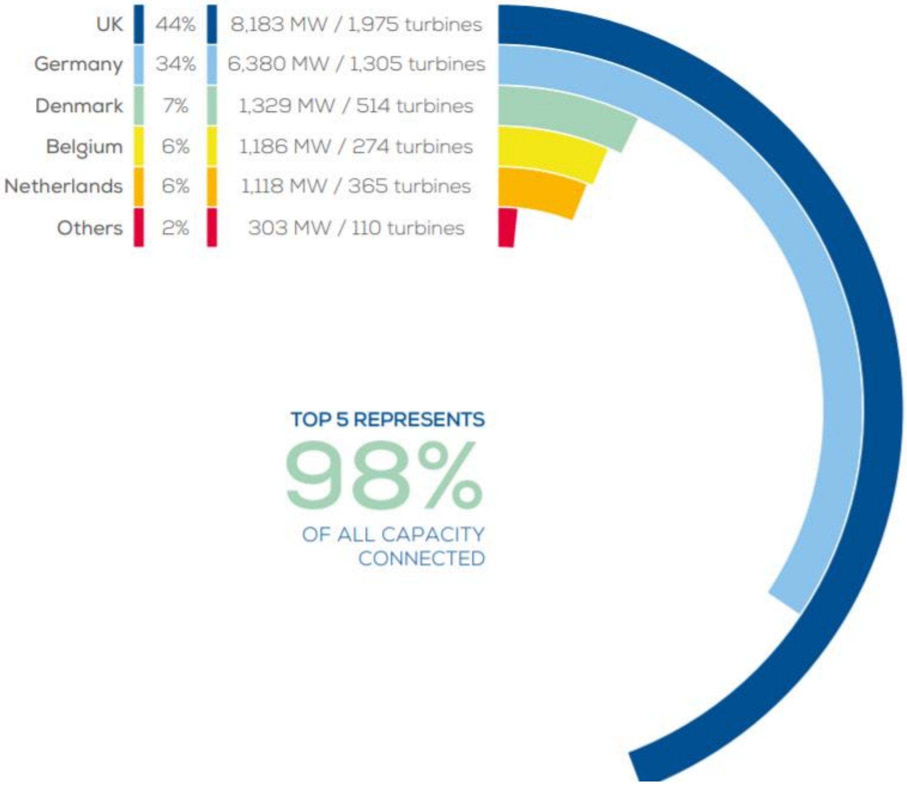

Figure 1.2: Offshore Wind Capacity, 2018 [21]

As more offshore wind farms were deployed in the UK, the government focus “shifted to energy supply and reduction cost of low carbon solutions. The Levy Control framework was guaranteed in size only until 2020/21” [20]. This meant that the offshore wind industry had to reduce costs and remain competitive to maintain the Government’s support.

The drivers for the recent growth of offshore wind farms and cost reductions are mainly: competition, technical innovation, and economies of scale: bigger turbines, decrease in financing costs, technology (know-how) learning [16] [17]. The turbine capacities have increased significantly from 1.5 MW in the 2000s to 8MW turbines in 2018 and recently announced 14MW[2] machines. The wind farms installed capacities soared from about 60MW in 2003 (e.g. North Hoyle) to developments exceeding 1GW (e.g. Hornsea Project One 1218MW) in 2018. Competitive auctions have reduced subsidies to a record low of £57.50 per MWh for the Hornsea Project two announced for projects commissioning in 2022/23 [17].

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[2] Siemens Gamesa- SG14-222 DD: [363]

The costs of financing wind projects are very high early on due to capital costs, which means higher risks for investors to finance these projects before operations start, and high-interest rates [23]. As the offshore wind sector matured, these financial costs decrease with lower perceived risks for investors and higher investment. According to [21], the UK attracted 48% of new investments in Europe, worth €40bn, making it the biggest offshore wind market over the last nine years.

Beyond the UK Government's 2017 industrial strategy, the 2019 Offshore wind sector deal announced several objectives for 2030 and beyond. These aims include the deployment of at least 30 GW offshore wind, an increase in investment for the supply chain (£250million), and increase in export (fivefold), at least 60% of UK contents for the supply chain, £557millions of CfD auctions, innovation in tackling the technological and economic challenges to commercialisation of floating offshore wind [24] [25]. Driving competitiveness through innovation is one of the deal's objectives to create opportunities for its growth and economic benefits. The Sector deal states that "Innovation activity to include a focus on increasing the UK competitiveness of goods and services, including digital and robotic technologies for surveying and operations and maintenance, and next generation technologies contributing to cost reduction" [25].

In June 2019, the UK Government passed the Net Zero emissions law, to bring all its greenhouse gas emissions to Net Zero by 2050" [26] [27]. The addition of renewable energy, the shift from coal and other fossil fuel-based electricity to renewable energy sources, the use of international carbon credits to offset own emission, and the drive to tackle the transport and heating sector are seen as some of the major areas to achieve this target [28] [29] [30].

Extensive electrification of the energy sector with the added shift from the transport and heating sector will mean that a more significant increase of renewable and other low-carbon power generation is vital. The Committee on Carbon Change [29] forecasts the electricity demand will double with all power produced from low-carbon sources (compared to 50% today). This could mean 75 GW of offshore wind by 2050, compared to 8 GW today and 30 GW targeted by 2030 [24].

Therefore, it is crucial to identify the opportunities for offshore wind's role in delivering innovative solutions to a whole energy system mix.

1.2. Research Context

This research was conducted at the Energy Technologies Institute, and it has been tailored towards the company's offshore wind programme objectives. A lot of the insights provided in this thesis have been derived from work carried out with the subject matter experts from the different programmes within the organisation. This Engineering Doctorate (EngD) thesis mainly encompasses the technology and project developers' view, research and development questions, and government and engineering companies' challenges. Although focused mainly on the offshore wind sector, the methodologies and results presented apply to other emerging sectors such as ocean energy.

1.3. The Energy Technologies Institute Wind Programme

The Energy Technologies Institute (ETI) is a £400 million industry and UK government partnership into low carbon energy system planning and technology development. As a public-private partnership between global energy, engineering companies and the UK Government, the ETI acted as a conduit between academia, industry, and the Government to accelerate low carbon technologies deployment [31] [32].

The ETI commissioned engineering projects delivered by partners from the UK and abroad, developing affordable, secure, and sustainable technologies to help the UK address its long-term emissions reduction targets and deliver nearer term benefits. The ETI made targeted investments across a portfolio of technology programmes across heat, power, transport, and the infrastructure that links them. The key challenges were to build industry and energy sector confidence in the transition pathway and support the development of effective policy frameworks.

With a strategy to better understand the UK energy challenges, the ETI created a national energy system design and planning capability to inform the UK Committee on Climate Change and the Department for Business, Energy, and Industrial Strategy. Evidence and data helped support policy recommendations and informed industry groups to target future investments [32]. The Energy Systems Modelling Environment (ESME), developed by the ETI, is one of the UK energy system optimisation models that provide a whole system, least-cost optimised strategic view of the UK energy system.

As a linear optimisation model, ESME provides the lowest-cost energy system designs that satisfy various system constraints (e.g. constraints due to CO_2 budgets). As a policy-neutral model, the model provides long-term pathway scenarios of the system's various aspects. The model focuses on the physical components of such a system (e.g. infrastructure, costs) without considering the commercial aspects or communications between actors [31]; is illustrated in Figure 1.3.

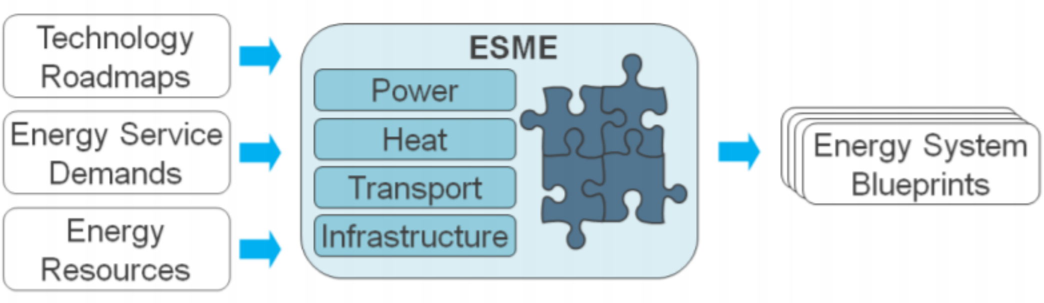


Figure 1.3: A Schematic diagram of the ESME model [31]

The ETI’s Offshore wind programme was identified as a critical area of focus given the UK vast offshore wind resource and a significant contributor to the UK’s energy demands. The objective of the programme was to accelerate the development, deployment, and grid integration of offshore wind technologies by [20] [33]:

1. Undertaking targeted investments to accelerate the reduction in the levelised cost of electricity production from offshore wind technologies.
2. Supporting the demonstration of technologies and systems to inform decision making and increase industry confidence.
3. Investing in onshore testing capability to de-risk new offshore wind technology

1.4. Research Motivation

The Energy Technologies Institute (ETI) sponsored this research to investigate the latest developments in the offshore wind sector, identifying anticipated technology developments and their likely impact on capital and operational costs; and to develop suitable design methods intended to innovate to reach alternative designs and practices or even more advanced designs using new technologies.

Unleashing innovation in the offshore wind sector at the pace and scale desired (40GW by 2030 and more than 75GW by 2050 [34] requires an optimal strategic approach to innovation and offshore wind deployment. Significant innovation and deployment required a systematic approach to identify ideal deployment pathways.

1.5. Aim and Objectives.

There is currently a good understanding of the economic benefits supporting offshore wind as a sustainable and cost-competitive part of the UK’s long-term whole energy systems. The industry has evolved to be one of the largest low-carbon technologies to become a commercial, large-scale technology that will help meet the UK’s 2050 Net Zero emission targets. This is mainly due to technological innovation and the policy mix's implementation to enable a higher innovation and energy market boost.

The research aims to develop design methods to support the offshore wind sector's innovative needs to achieve its Net Zero targets and accelerate the levelised cost of electricity (LCOE) reduction.

The specific project objectives are as follows:

1. Review the current state-of-the-art on design theory and methodologies for successful applications of design methods.
2. Identify the design methods implemented in mature sectors, and identify which conceptual design method(s) to deploy for innovation in the offshore wind sector.
3. Develop a structured innovation approach based on the identified design methods.
4. Validate the innovation methods by comparing and demonstrating the design methods' outputs using two case studies to inform offshore wind stakeholders to better manage their innovation processes.

1.5.1. Thesis Outline

The thesis is divided into five main stages to address the research aims and objectives, as outlined in Figure 1.4.

Chapter 1 introduces the thesis background and motivation. An overview of the offshore wind industry's status is discussed, and the research motivation and objectives are outlined.

Chapter 2 & 3 are the literature review sections, in which Chapter 2 provides an in-depth review of market drivers of the offshore wind industry and the mechanisms impacting its growth. In Chapter 3, the current state-of-the-art of innovative design theories and methodologies are explored. Based on the offshore wind industry and design methods review, structured innovation approaches are selected to address the problem statement.

Chapter4 presents the research methodology, describing the structured innovation design methods for innovative assessments. A detailed description of how the selected design methodologies were applied for concept design is provided. Innovation analysis and international design standards are described with initial conceptualisation for representing system requirements.

Chapter 5 contains a detailed description of how the selected design methodologies were applied for the two case studies to assess the offshore wind system's innovation intervention measures.

Chapter 6 presents the design outputs of the two case studies. The approach shows the conditions under which the design approach operates.

Chapter 7 & 8 presents the discussion and concluding remarks, including a summary of the research findings and their contribution to knowledge

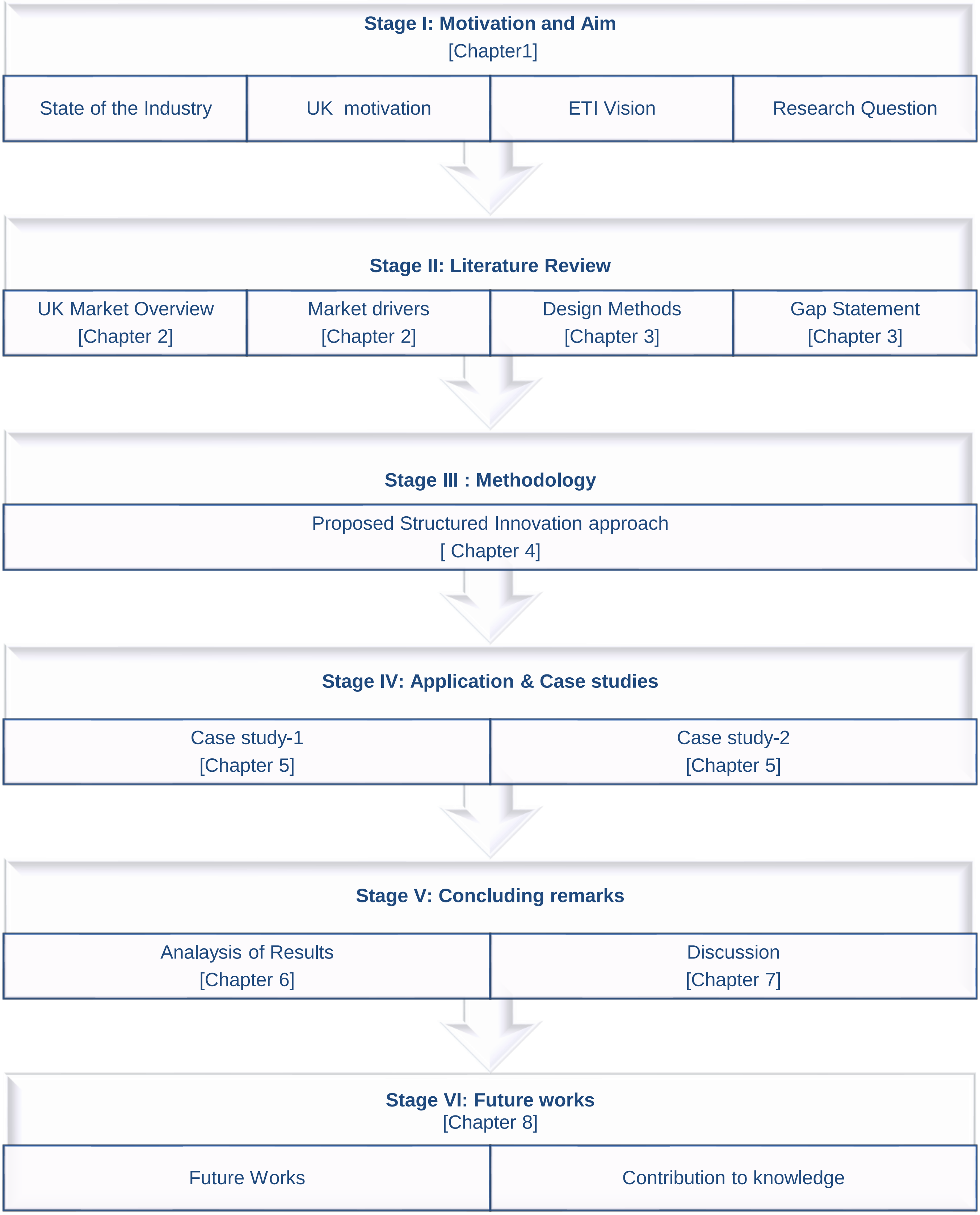


Figure 1.4: Thesis Structure

2. UK Offshore Wind Market

This chapter is the first step towards establishing the research goal of this thesis. A review of the UK offshore wind market strategies is presented, including the current state-of-the-art technologies and key market drivers related to renewable energy systems, particularly to the offshore wind sector. Section 2.1 provides an overview of the Electricity market and an introduction to the market scope and stakeholders' key features. The Great Britain (GB) whole electricity market is reviewed in Section 2.2, highlighting strategies taken by the UK government to boost investment and the market. This is followed by reviewing the costs drivers and mechanisms that impact the market in Section 2.3, the financial drivers in Section 2.4 and technology drivers in Section 2.5. Finally, the market strategies in terms of innovation in the offshore wind market are discussed in Section 2.6. The flow diagram in Figure 2.1 summarised the review of the market strategies in this chapter.

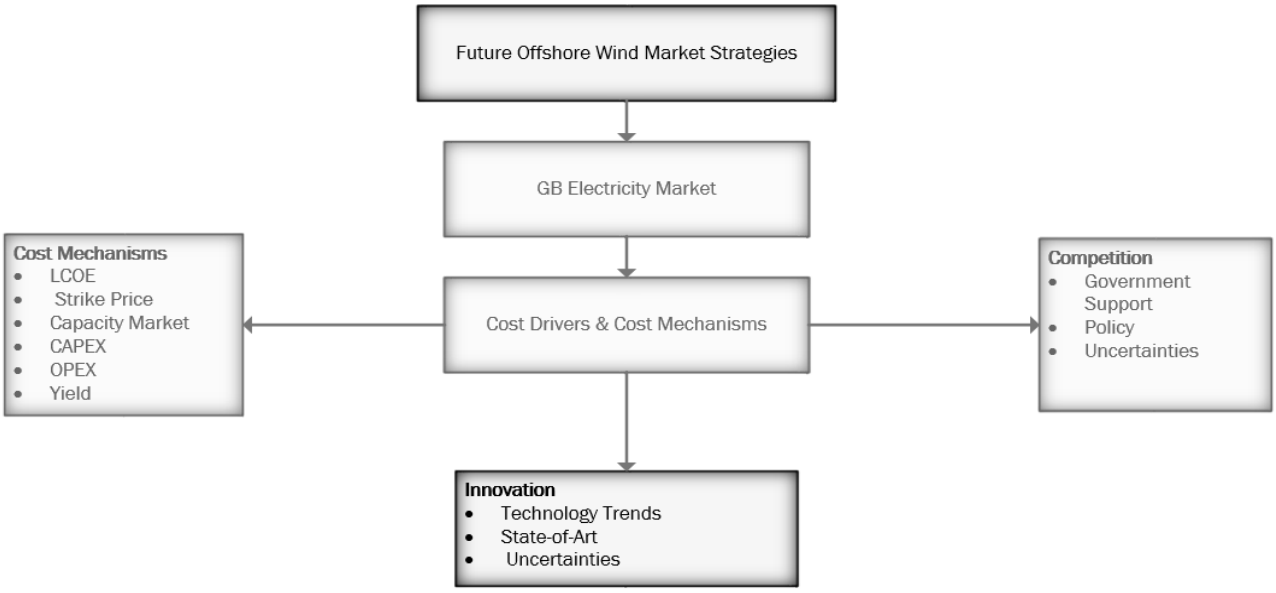


Figure 2.1: Defining Offshore wind Market strategies.

2.1. Electricity Market Strategy Overview

According to the Energy Information Administration (EIA) [35], global energy consumption was about 176TWh by the end of 2017 and is projected to be around 216TWh by 2040. Traditionally, fossil fuel in the form of oil, coal and natural gas were the primary sources of energy in addition to nuclear and hydropower plants; however, in recent years, there has been a dramatic drop in the use of coal due to governments' commitment to cleaner, more sustainable energy [35]. With renewables being the fastest-growing energy source and particularly wind energy, an understanding of the electricity market strategy is required to comprehend how the sector's growth will impact the future electricity market and its measures.

As a commodity that can be purchased and traded, electricity varies continuously and cannot be stored easily in large quantity (i.e., no advanced storage facilities to date). The electricity market requires a strong cohesion between all the major players involved with these three segments: the generation, transmission, and distribution, to enable the grid's stability and balance between supply and demand. An illustration of these segments is shown in Figure 2.2.

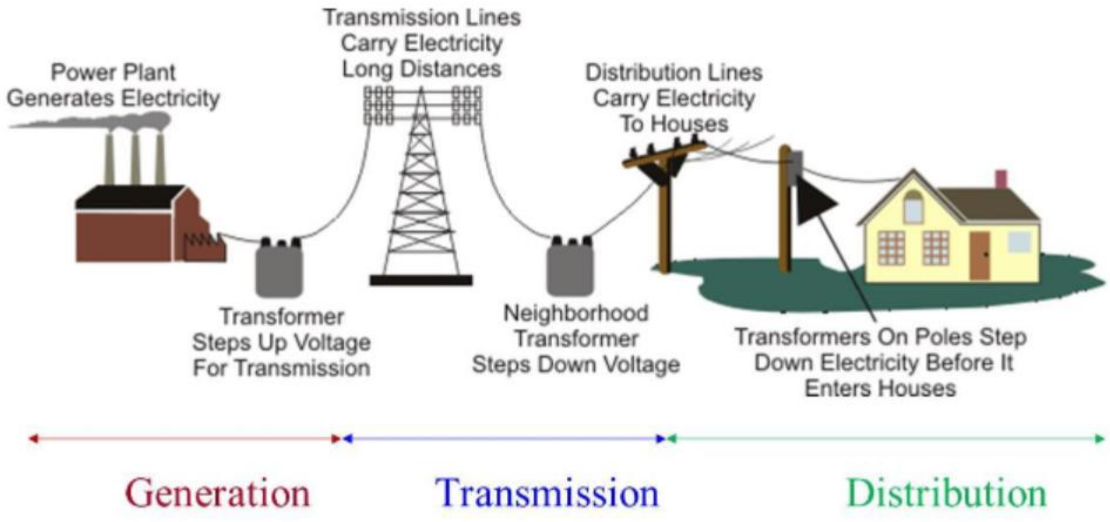


Figure 2.2:Electricity supply chain segments [36]

Several players support these functions, including the electricity generators, the utility companies, the investors, regulators, traders, contractors, etc., creating a very complex supply chain. In the UK, this can be the government bodies such as The Crown Estate leasing and managing the UK land and seabed, market regulators-Ofgem (The Office of Gas and Electricity Market), system operators National Grid, etc. The electricity market is a long-interconnected power system set up so that the generators produce the electricity required for large-scale power stations to meet their customers' demand.

The customers here, usually large entities, distribute the required electricity to the consumers via distribution lines. Through contracts with their consumers, these suppliers determine the estimated capacity needed for a given period and agree with the generators to meet their demands. In some scenarios, intermediate traders are involved in facilitating demand/supply requirements. System operators have a role in ensuring balancing the capacity generated, transmitted and distributed on the network [37] [38].

Moving towards greater reliant market strategies, the electricity market defines the organisation and structure of electricity’s supply and demand portfolio, including energy policies and regulations required to encourage the development of a competitive energy industry [37]. Although measured at the point of electricity delivery, the electricity market's design starts way before investors/generators contract to a specific generation capacity, to the end-users and a balanced system. The energy market strategies aim to capture and implement the various factors impacting a sustainable and competitive market [39].

2.2. GB Wholesale & Retail Electricity Market

The GB electricity markets are regulated by the Office of Gas and Electricity Market (OFGEM) with a role “to protect the interests of existing and future electricity and gas consumers by promoting value for money, the security of supply and sustainability, a competition where appropriate and regulation and the delivery of government schemes” [40]. A wholesale retail market with bilateral or exchange trading and contracts are agreed upon over a long time. The UK market participants ensure that demand and supply are met. The National Grid Electricity Transmission (NGET) acts as a balancing mechanism to ensure the supply matches the demand on a second-by-second basis and incentive and cash-out prices offered to the various trades through facilitators to match offers and bids [41] [42]. Essentially system operators (generators, transmission, distributors) ensure contracts are withheld as agreed and demands are met. As the Department for Business, Energy and Industrial Strategy (BEIS) said, "….we want our renewable energy sector to continue to thrive; however, an investment in new technology must represent value for money for the UK taxpayer as well as the consumer" [43].

Over the past 20 years, the UK government has supported renewable energy, and in particular, the offshore wind sector primarily provides economic growth by introducing subsidy frameworks for electricity generators to incentivise investments in these low-carbon projects. According to Richard Harrington, minister for energy and industry [44], "the sector provides the necessary certainty for investment, which drives the cost of decarbonisation, benefits customers and creates highly skilled jobs and growth in local economies". In the last couple of years, the UK and Europe offshore wind industry and supply chain have passed a significant milestone from an expensive and high- risk investment to one of the lowest renewable energy generation sources. The year 2017 was a turning point for the industry with rapidly falling prices, more significant competitions and investments, technology advancements and first hints towards a subsidy-free industry [44] [45] [46].

By the end of 2017, the UK as the world leader in offshore wind with over 6.8GW of installed capacity, 36 wind farms fully connected to the grid and an increased load factor of 55%; was valued at £17.5bn following the Government's latest auction for support contracts in September 2017 [47]. Hence, the Government's current market strategy approaching an overall turnover of low-carbon emission technologies of £44bn, and job creation of more than 234,000 people (directly and indirectly) in the sector, and an increase of over 50% UK content [48]. With a market strategy to establish a stable government and industry partnership to support significant and sustainable investment in the Offshore Wind sector, the UK government, through the industry-led Offshore Wind Task Force (2012), aimed to support the industry in developing UK local contents (greater than 70%), to advance innovation and technology readiness levels of new technologies and to guarantee price support [49] [50].

Through the various financial support schemes, the Renewables Obligation (RO) support scheme was first introduced in 2002 to accredit renewable operators with Renewable Obligation Certificates (ROC) and in return to the operators meeting their agreed energy generation and consumption [51]. Through the Electricity Market Reform (EMR) Delivery plan published in 2013 [37], the UK government introduced strike prices for renewable technologies alongside limits on annual spending as agreed in the Levy Control framework [13]. The main goal of the EMR is to ensure the energy trilemma was met by enabling secure, accessible, affordable energy supply from renewable and low-carbon sources. The ROC was replaced with the contract for Difference (CfD) scheme guaranteeing long-term government/investors commitment through the 15-year fixed strike price and achieving the overarching target of 80% emission reduction by 2050 following the Climate Change Act 2008 [3] [49]. A summary of the type of UK support schemes is presented in Table 2.1.

Table 2.1: UK Government Support scheme for the Offshore Wind sector [46] [49]

Support Scheme	Examples of application
UK Government-Industry Collaboration	Offshore Wind Cost Reduction Task Force
	Offshore Renewable Energy Catapult
	Offshore Wind Accelerator (Carbon Trust)
	Innovate the UK
	EU level (Horizon 2020, TINAs)
Financial Support Scheme	Renewables Obligation (RO)
	Contracts for Difference (CfD)
	Demonstration schemes (ETI Very long blades, Component technologies development-InnWind 10MW Demo)
Other Incentives	Climate Change Levy control framework exemption
	Carbon Price Floor & EU Emission trading scheme

Keeping the offshore wind cost as low as possible is vital in ensuring a secure and stable energy mix. Through its Contract for Difference (CfD) support scheme, the UK government is reassuring its long commitment to supporting the sector, and this has a pivotal role in the overall cost of offshore wind [1]. The various players in the sector ensure that the cost of generating electricity is at its lowest, while through the strike price of the CfD feed-in-tariff, the generators sell their electricity at the market price with the price difference either topped up by the CfD or paid back throughout the contract (currently 15-year fixed contract) as shown in Figure 2.3 [1] [53]. The offshore wind in the UK is now a proven, scalable deployed technology with currently approximately 6.8GW of offshore wind installed capacity in the UK waters funded through a mixture of (ROCs), Final Investment Decision for Enabling Renewables (FIDeR), and (CfD).

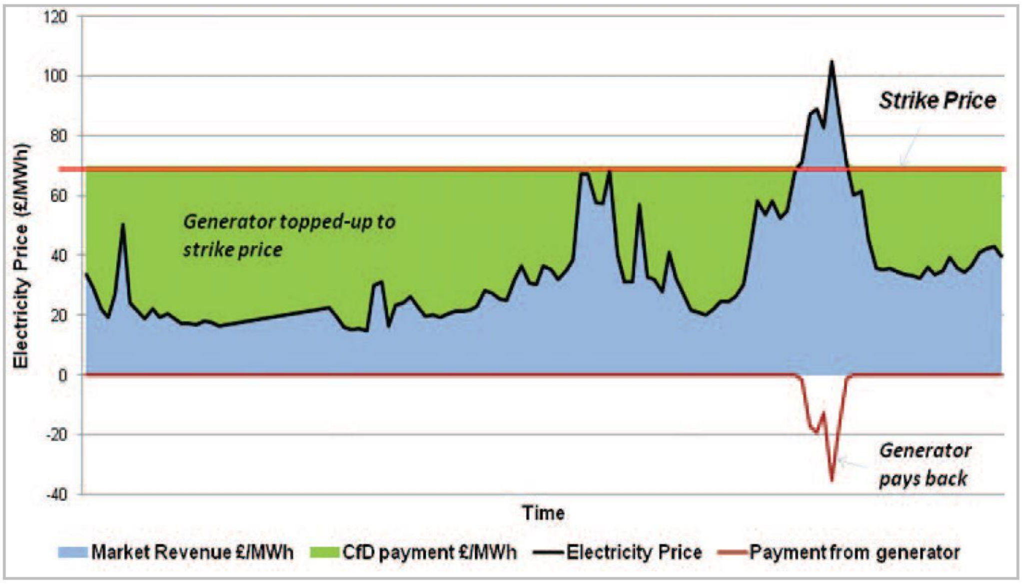


Figure 2.3: Strike Price Vs Market Price- Illustration of CfD [3]

In addition to the government financial support scheme, the offshore wind market scale and visibility is critical to driving the cost of generating electricity down through increased competition and system innovation. There needs to be ongoing cost reduction across all parts of the system. The costs of offshore operations at the installation and maintenance stages, in particular, should not be underestimated as well as reliability, availability and the scaling up of the turbines. This section considers the key cost drivers and mechanisms for the UK offshore wind.

2.3. Cost Mechanisms

To determine future market strategies, assessing current and potential UK offshore wind resources, policies, and technologies are critical in informing what drives the cost of generating electricity and the mechanisms to reduce the Levelised Cost of Energy (LCOE). These drivers are illustrated in Figure 2.4. The LCOE as a metric is used to capture offshore wind farm lifecycle costs better, thus allowing various projects to be compared efficiently.

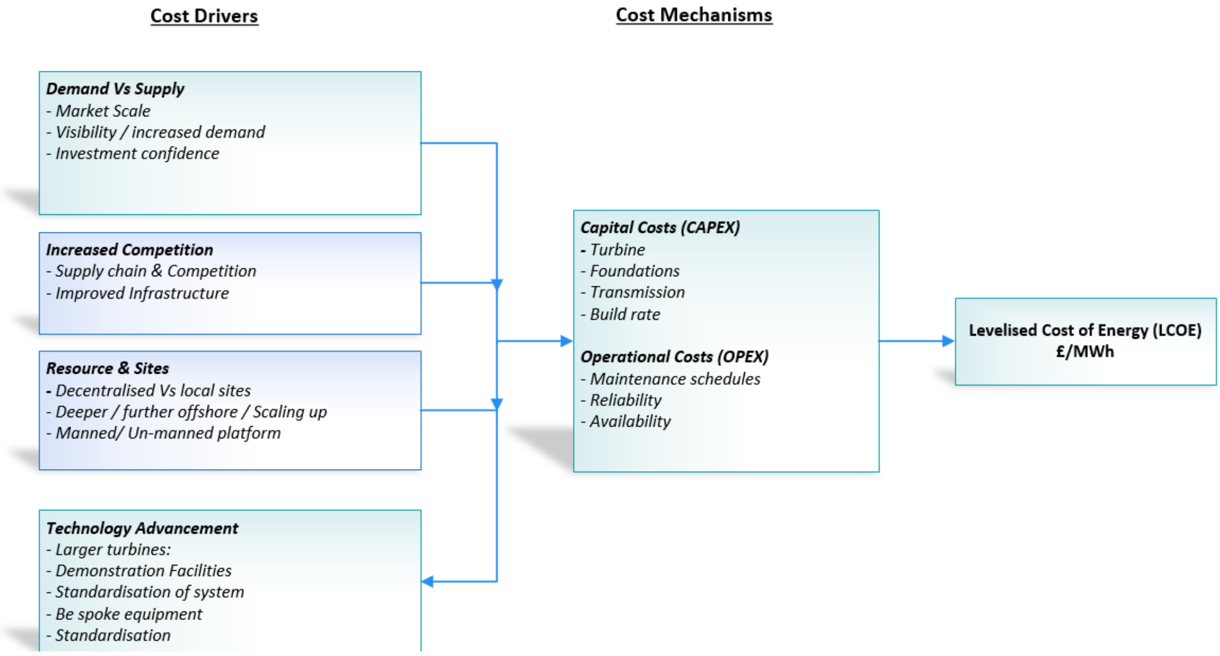


Figure 2.4: Offshore Wind Financial drivers and cost mechanisms (adapted from [18])

The UK offshore wind market holds a leading position in the offshore wind industry, with a competitive supply chain, strong government policies and regulations, and significant technological advancement. However, achieving a least-cost offshore wind industry is essential for sustainable and competitive energy generation in the UK and globally. To date, the UK offshore wind is the most significant secondary market, followed by Sweden and Germany with a combined traded capacity of 70% at development, construction and operational phases of all the EU projects [54]. With the

Hornsea 2 offshore wind farm as the largest offshore wind farm to be constructed with a capacity of 1.4GW and Hywind, the first floating offshore wind farm in Scotland with 30MW, the UK market needs to remain competitive to be cost-effective. As of the end of 2017, UK-based companies supplied nearly 50% of UK offshore wind farms' total content and exported cutting-edge technology to countries such as China, India, Taiwan, the USA, and other countries [54]. Figure 2.4 highlights the key cost drivers that have impacted offshore wind deployment in the UK to-date.

The Ministry for Business, Energy, and Industrial Strategy (BEIS) uses the Levy Control Framework (LCF) to monitor and control energy initiatives' costs. The LCF commitments are set out to provide a sustainable capacity market, ensuring predictable demands to be met by the generators and, in return, secured revenue streams. An efficient electricity market is summed up by system operators meeting consumers' demands by providing instantaneous supply. As for fossil fuel as primary energy generation baseload (oil and gas, coal), the offshore wind generators require to meet primary demand needs and provide instantaneous response to energy demand such as backup technologies (baseload or quick response such as gas turbines, battery/storage). The cost drivers and mechanisms are discussed below, emphasising how they have impacted the UK market to-date and their future potential strategies [1] [13].

Strike Prices were introduced as part of the Electricity Market Reform programme, reflecting the cost of investing in particular low carbon technology. It is intended to bring economic growth and certainty, and stability of generators' revenues and a reduced market risk level [1] [3].

There are many ways of comparing different sources of energy generation. One of the methods discussed is the levelised cost of energy (LCOE), a metric widely used to compare offshore wind farm generation with other energy-generating projects. Unlike the strike price, which is calculated for the 15 years fixed contract, LCOE is calculated over the wind farm's lifetime. The LCOE is a product of input variables associated with the capital and operating expenditure, energy generation, decommissioning, and other financial variables. It is defined as the sum of the annual capital cost (a factor of the total capital spent each year, finance cost and lifetime assets) and annual operation cost divided by the annual energy produced [55] [56].

The calculations are made in today's value and are as follows:

$$LCoE = \frac{ICC*FCR+O\&M}{E} \qquad (1)$$

Where?

- **LCOE**- levelised cost of electricity (£/MWh)
- **ICC**= Installed Capital cost (£) is the total capital expenditure (CapEx) associated with planning, development, manufacturing, deployment, and project management
- **FCR**= Fixed Charge Rate (%) is the annual return needed to meet investors' revenue requirements.
- **O&M** = total annual operating expenditure costs (£/ year), which includes fixed & variable operating costs, fuel, and carbon costs
- **E**= The average Annual Energy Production (MWh/annum) delivered to the point of AC grid connection

2.3.1. Capital expenditure (CAPEX):

CAPEX is the total cost of developing and constructing a wind farm including, the farm, of the turbine the, support structure, the installation, and infrastructure. As part of the total CAPEX, the consenting and development costs, construction, and all financial costs (such as the interests during construction (IDC) and the Net present value (NPV) factors) are considered.

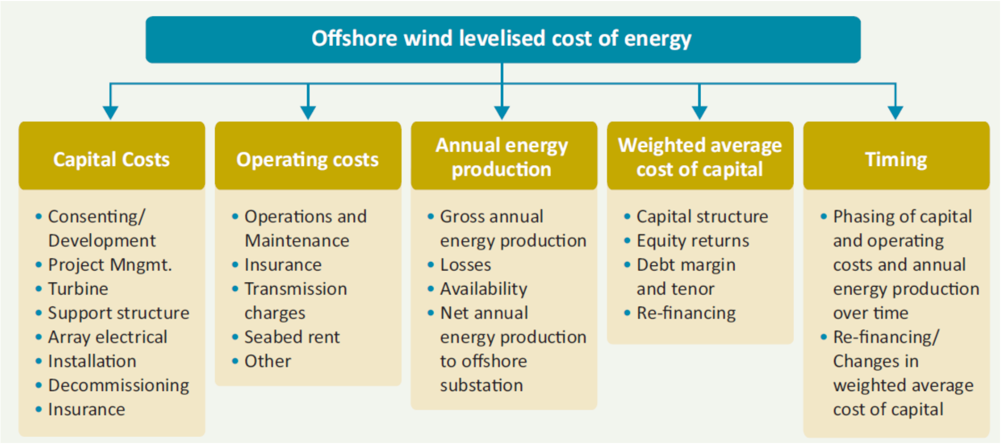


Figure 2.5: the levelised cost of Energy model for OSW site [57]

Financing offshore wind projects from the consenting to operating stages, substantial capital is required to finance all the business activities. The vast majority of commercial wind farms have been funded through project finance. These financing bodies inspect the projects proposals based on their return on investments (ROI) to ensure the developer's credibility and ability to pay back within the agreed period. A review of the cash flow, equity and debt are the main sources of capital. The equity capital refers to investment from the developers or owners taking full responsibility to bring a project from the conceptual to operation stage, whereas the loan capital is a contractually arranged loan repayable within the agreed period. Both types come with risks-high or low (i.e., interest rates on finances) based on the project outcome's maturity and certainty. These financial costs are represented by a weighted average cost of finance (WACC), where the weighting is based on the share funds provided by the various sources. This value is a combination of equity shares, the percentage of expected realisation for the equity providers, debt, the interest rate on debt, the lending period, and the inflation rate. Below are some of the factors influencing the decision and prior investment assessment [54] [55].

- **Discount rates** reflect the interest rates used to determine the present value of future cash flows in the absence of technology risk or a specific market (Risk-free rate+ premium for risk perceived).
- **Net Present Value (NPV):** The amount invested today is compared to the future cash receipts from the investments (discounted by a specific rate of return)
- **Internal Rate of Return (IRR):** Interest rate at which NPV of all cash flows from the project and investment equal zero.
- **Economic life:** period beyond which replacing or scrapping the turbine/ system is profitable.
- **Payback period:** period required to return funds spent.

2.3.2. Operating expenditure (OPEX)

The OPEX includes the total operating costs from the first year of a project's operation, given annual costs per unit of installed capacity (£/MWh). It accounts for all the annual operation and maintenance costs, including the balance of plant maintenance and operation management, fixed and variable operating costs. Representing a significant proportion of the overall cost of generating offshore wind (a quarter to a third of the overall LCOE), the operation and maintenance strategies are vital to minimising costs associated with maintenance and the overall OPEX [55] [58].

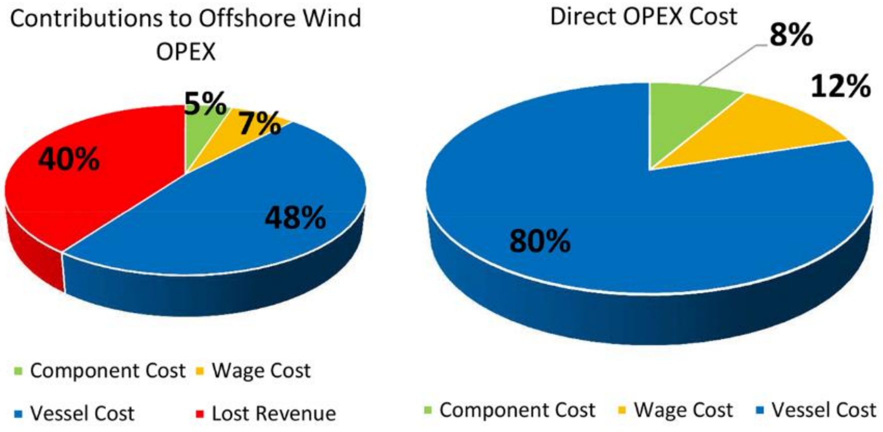


Figure 2.6: Cost breakdown of OPEX [58]

The combination of scheduled maintenance, the failure rate and repair of components, accessibility of turbines and duration of repairs all have a significant impact on the overall operating costs in addition to non-equipment costs, as shown in Figure 2.5 and Figure 2.6.

2.3.3. The Annual Energy Production (AEP):

The Annual Energy Produced considers the total rated capacity expected to be produced in MWh or kWh and the factors impacting the wind turbines' availability, such as the capacity factor, the losses, the variable wind speed, and the operational capacity of the wind farm. The capacity factor, also known as load factor: is the ratio of the electricity generated in a given year to the electricity that could have been generated at continuous full-power operation or 8,760 full hours. Depending on the size, the location (wind conditions) and the first service date of the turbines, the load factors may vary between 29 to more than 45% [59] [60] [61].

LCOE Uncertainties

The LCOE has been widely used to compare different technologies. However, as a cost metric, it does not portray actual system costs in terms of the flexibility of generation and dispatchability; and the correlation between supply and demand with respect to settlement period (time of the day and weather conditions) as well as technological parameters such as the volatility of materials, costs associated with fabrication, installation methods and system availability (for example redundancy measures) [62].

For this research, the LCOE is used mainly to understand market strategies' impact on the sector's costs and performance. Although beyond this research scope, further analysis is recommended to understand the impact of potential back-up systems on the Extended Cost of Energy (ECOE), on long-term subsidy arrangements and government premium-priced contracts; and other external factors (technology and resources) impacting the overall cost of energy and in turn the market strategies.

2.4. Financial drivers

For offshore wind, the cost mechanisms and financial drivers are intertwined so that, for example, an improvement in the offshore wind infrastructure or deployment methods could increase the AEP and reduce the system costs (see Figure 2.4). The cost mechanisms were discussed in the section above, followed by the key indicators driving the cost of energy from offshore wind.

Here, the various financial drivers that impact the cost of offshore wind in the UK are discussed, illustrating financial inputs such as debt terms, inflations, tax rates, interest rates, insurances, rate of return on investments as well as the impact of technology advancements of the system and policies and regulations in place.

DONG Energy’s winning bid of €72.7/MWh for Borssele I and II offshore wind sites was a great achievement for the offshore wind industry in 2017 in terms of the significant cost reduction in the auction big [63] [64].

This announcement was followed by the Vattenfall bid for two wind farms (Vesterhav Nord and Vesterhav Syd) for a combined capacity of 350MW just off the west coast of Jutland with a CfD price of €64/MWh (Figure 2.7).

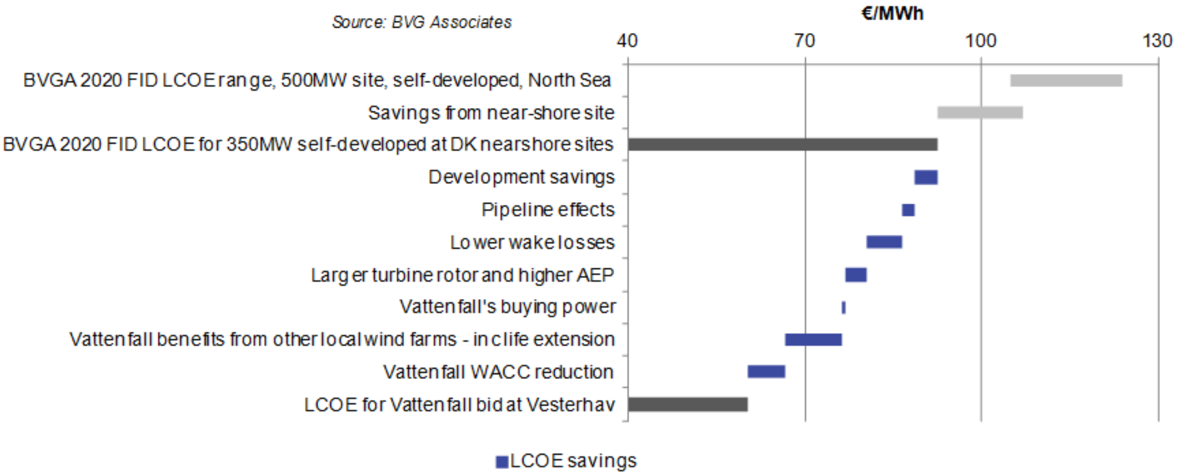


Figure 2.7: Example of Financial drivers impacting an offshore wind project - Borselle and Vattenfall LCOE [63]

In both bids, the cost reduction was made possible due to [59]:

- Wind resources: in locations near shore with the advantage of shared infrastructures, ports, technologies, supply chain, and good wind speed sites.
- Technology innovation allows capturing more energy (AEP) with larger turbines that are more reliable and reduced losses.
- The cost of finance: The industry's maturity has demonstrated lower risks to investors and hence, lower interest rates, WACC, supply chain, and to top it up, the government policies and regulations in place to support the sustainability and growth in the sector.

These factors were also supported by the reports presented in Table 2.2, emphasising the significant growth of the sector: the UK has an abundant wind resource of nearly a third of the total European offshore wind resources and nearly half of the UK total content. Technology innovation has advanced significantly to very long blades, gearless machines, extra-large fixed monopiles, floating platforms, and with a strong

UK government policy and regulation supports in place. There has been a massive shift in offshore deployment wind in the UK with significant cost reductions. Innovation in the sector is at its peak with GE announcing the 12MW Haliade X wind turbine to be deployed in 2019 [65], transmission cables using 66kV instead of the traditional 33kV for increased transmission, various testing facilities for new generation 15MW machines [66].

Table 2.2: UK offshore Wind drivers

Key drivers	Details	Benefits	Reports
The exploitation of OSW Resource	1/3 of EU resources. More deployment further off-shore (deeper and further out) & lower leasing costs	More efficient deployment, more planned infrastructure	Wind Europe [21] [61]
Financial support schemes (Policies & regulations)	Improved market conditions Steady and clear deployment strategies Certainty in the market - Medium to long-term UK government commitment	Reduced CAPEX- 55% cost reduction Increased yield Greater competition & improvement in supply chain Steady deployment	CCC report [67] Business Green [68] RenewablesUK [69] [70]
Technology Innovation	Mainly at commercial scale but innovation & demonstration in some areas of the value chain Advanced R&D, Demonstrator projects Standardisation of OSW components/services	Up to 45% by 2050 Reduction in CAPEX- larger turbines, foundation & installation Yield Increase Reduction in OPEX- O&M	Carbon Trust [71] TINA [72] CRMF [73] [74]

2.4.1. Offshore wind resources in the UK

Nearly half (45.9%) of the global offshore wind installed capacity is attributed to the UK, with the majority of wind farm projects operational in water depths of up to 40m and 40 km from shore in the crown estate leasing rounds 1 and 2 and extended to a water depth of up to 50m and below 60 km. The majority of offshore wind projects in round 3 in the construction or planning stage will be constructed in deeper and harsher conditions further from shore (50- 70m deep and up to 250 km from shore).

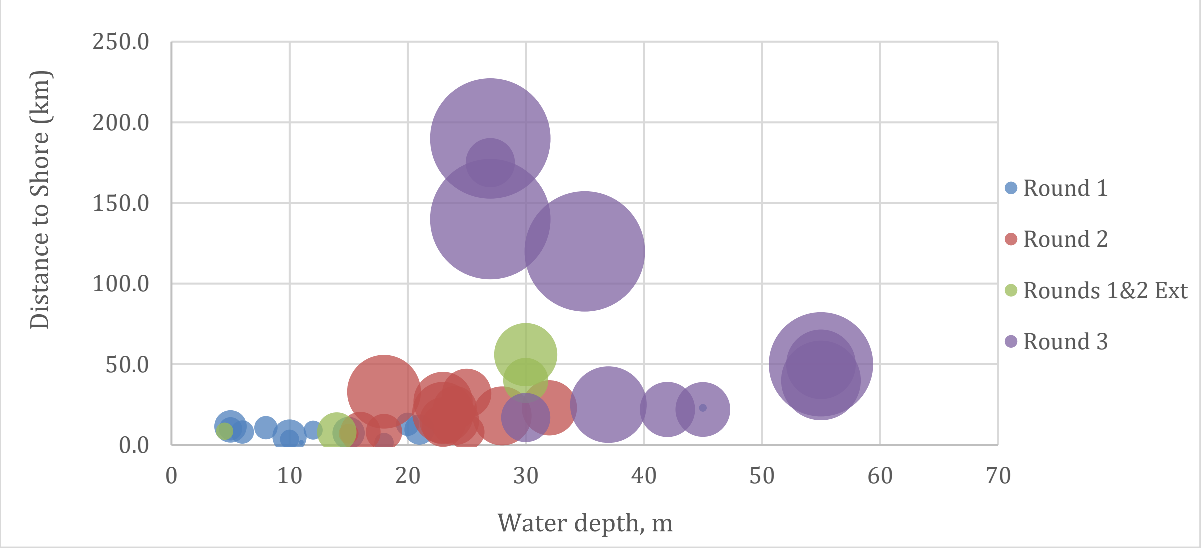


Figure 2.8: UK offshore wind leasing sites- water depth Vs distance to shore.

Looking at the potential energy available in the UK waters, the unexploited regions in deeper waters (higher than 60m deep) and far from shore are the most favourable for high capacity extraction with higher wind speed and energy yield. The UK is the largest offshore wind market with over 36% of installed capacity and with the majority of the exploited sites concentrated mostly in the east of the UK waters and relatively in shallow waters (around 30 m water depth) and nearshore (below 25 km from shore).

The Crown Estate manages property owned by the Monarchy. In this context, the Crown Estate has held three rounds of bidding and leasing the site development rights in UK waters. With Round 1 sites leased since the early 2000s in shallow waters and nearshore, the round consists of twelve installed wind farms with a cumulative capacity of 1.19GW. The Beatrice wind farm was developed as a demonstration project with a maximum water depth of 45m and 25 km from shore to study the impact of deeper water projects. Licences for Round 2 were awarded to 15 projects from late 2003 with a total generating capacity of 7200 MW [15]. The Triton Knoll project of 1.2GW capacity was the largest awarded project of the round. Additional projects extending existing wind farm projects in round 1&2 were approved by the crown estate for maximum addition of 1.5GW. Round 3 projects sites were awarded further from shore (water depth 50- 70m and up to 250 km from shore) to nine zones. The combined capacity is expected to yield a total capacity of 32GW) [75]. A significant resource is located in deeper waters (>50m) in rounds 3 with higher quality winds, and further seabed leasing rights have been considered by the crown estate and stakeholders with a potential of Round 4 leasing sites being considered (as of July 2018) with the goal to accessing sites with higher quality winds and in turn, higher energy yield [76].

Table 2.3: The Crown Estate leasing rounds [77] [78] [79]

	Capacity (GW)	Number Turbines	Max water depth (m)	Max Distance to shore (km)
Round 1	1.19	391	25[3]	25
Round 2	7.2	1231	32	35
Round 3	32	<1700	75	215

2.4.2. Financial support schemes

Over the last decade, the offshore wind industry has proven its worth by demonstrating its economic benefits nationally and internationally. Offshore wind has been proven to be a deliverable and scalable, low carbon technology with less political and social conflicts than the onshore wind in the UK. The ETI's ESME cost ranges suggested: "… between 10-15GW may be appropriate (cost-effective) offshore wind capacity in the power sector where large scale and timely Carbon Capture and Storage (CCS) and Nuclear are delivered; However, in a scenario where CCS and Nuclear are delayed or

---

[3] Maximum water depth for 25 for the London Array 1 wind farm. However, the Beatrice demonstration farm has a water depth of 45m

constrained, optimal deployment is likely to increase – potentially to around 20GW by 2020 and 56GW by 2050" [20]. In their stakeholder engagement programme [80], BVG Associates also evidenced the relative impacts of the key drivers of energy cost.

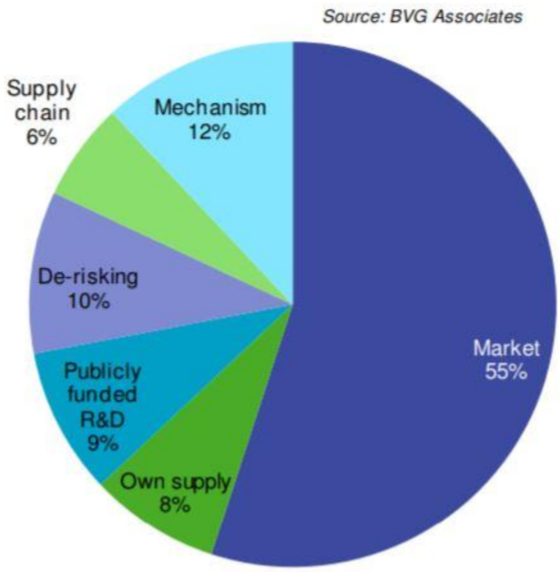


Figure 2.9: Impact of various policy drivers on CoE reduction [80]

To date, the UK government has sent strong signals ensuring its commitment to the sector by announcing further auctions for CfD and the announcement of rolling CfD rounds every two years from May 2019, which will provide further certainty in the deployment rate and confidence in the sector [81] [82].

Hence, to maintain a sustainable and competitive offshore wind market, there is a need for a strategic and sustainable deployment rate to provide confidence and clarity for the supply chain players and the investors. As covered in section 2.2, the government support scheme ensures certainty in the market, which attracts a large amount of investment which in turn enables direct or indirect growth in the supply chain, medium-to-long-term investment decisions, advanced innovation as well as the development of skills and research and development capabilities [80].

2.5. Technology drivers

According to Alex Chisholm, BEIS permanent secretary: “The UK government is now looking beyond the initial focus on the energy trilemma to respond to changes to a dynamic market competitive at the global level with the rise of smart, low-cost digital energy and increased distributed energy sources. The main focus is to create a market that drives innovation and competition, supporting growth and keeping costs down for consumers” [83]. “The UK market and enabling governance are altered to enable stronger innovation and technology-neutral competition to revolutionise the electricity system; efficient electricity market strategies will require unlocking innovation and advanced systems…. [62]”. With the UK government's support through policies and regulations, the offshore wind industry has received substantial investment and achieved significant cost reduction. Realising cost efficiencies across the offshore wind turbine system was essential to encourage competitiveness and continued investment in offshore wind, and technology innovation remains a crucial driver to achieve this. Over the last decade, the industry has objectively done with a combination of larger turbines with higher capacity, better wind resource, improved supply chain and operation and maintenance strategies.

Understanding parameters affecting dominantly the cost of generating electricity and their impacts on geographical distribution is critical in determining the trends and technology influences on the LCoE. This section presents the offshore wind technology trends and how innovation has impacted the electricity market to date. A review of the current state of the industry globally and locally (the crown estate leasing rounds) is carried out, and classification of dominant structures (turbines rotor, nacelle, foundation types, transmission characteristics) is given; followed by an initial summary of state-of-art technologies with their strengths and weaknesses.

2.5.1. Turbine

There are currently over 100 offshore wind models installed or under development, each with specific characteristics depending on the sites, the infrastructure and the maintenance strategies. Unlike the wind turbines installed onshore restricted by noise levels and visibility, offshore wind design drivers offer more leeway concerning their rotor tip speeds, visibility (out of sight, out of mind) and harnessing more electricity. Different concepts have been considered for offshore wind applications. Some more commercially accepted than others. The various concepts are wind turbines with a vertical-to-horizontal axis, two-to-three bladed, upwind-to-downwind, smaller-to-large scale turbines (<1 to 8-12MW), single-to- multi-rotor concepts, fixed-to-floating structure, airborne to a standard fixture. The following section explores commercially available three-bladed upwind horizontal axis turbines with fixed or floating foundation, trends, and functionalities.

The drivers that have significantly influenced technology innovations are:

- The upscaling of turbine rotors to bigger turbines with higher capacity ratings.
- The improved reliability of machines offshore
- More effective operation and maintenance strategies

Examining operational wind farms installed in the Crown Estate rounds 1& 2, Siemens and MHI Vestas led the way in terms of installed capacities with respectively the SWT-3.6-107 and V90-3MW respectively; characterised by 3-bladed turbines, upwind rotors with pitch-to-feather variable speed control, 3-stage gearboxes, and asynchronous generators with a partially rated converter.

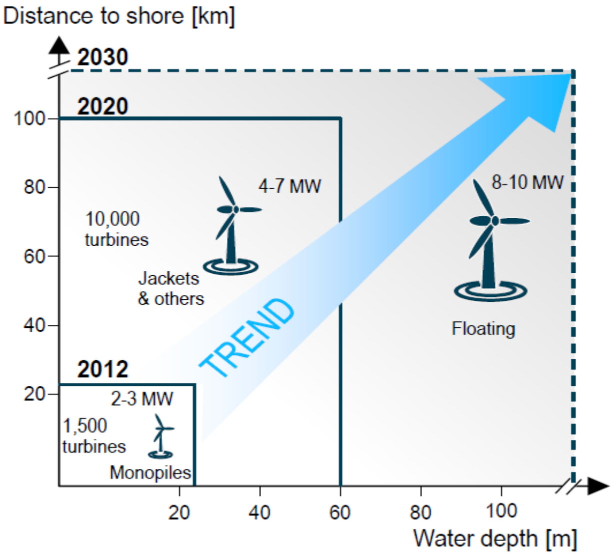


Figure 2.10: Installed turbines capacities & Evolution of generation 2000- to date [364]

Introduction of direct drive generators by Siemens with the SWT-6.0-154 turbines fully converter power electronics is observed later in the extension rounds; machines with low speed 2G permanent magnet synchronous generators used by MHI Vestas in their V164-8.0MW machines. The rotor diameters have steadily increased from the 66 metres Vestas V66-2MW turbines installed at the Blyth demonstration offshore wind farm to 164 metres of the Vestas V164-8MW machines in the extension rounds and rounds three projects.

State of the art:

Further advancement in innovation will see progressive development of the larger and higher rated power machines, such as developing the GE Haliade-X 12MW underway with the 220-metre rotor and a total height of 260m, with a capacity factor of 63 %. Innovation continues to move at a significant pace towards possible 15-20MW capacity turbines [84], And also innovation from disruptive technology such as the design and demonstration of a 50 MW wind turbine with a Segmented Ultralight Morphing Rotor (SUMR), which are folding blades facing downhill that takes advantage of modularity and less structural mass [85].

Other state-of-art points are the introduction of

- Advanced blade design to accommodate for their increase in size, weight, and material.
- Advanced pitch control mechanisms for floating machines [86]
- Demonstration and testing facilities from prototype to full scale.
- Improved reliability through Failure prediction measures
- Improved design, manufacturing & integrated design

2.5.2. Foundation and support structure

The support structure's challenge is to withstand and adapt to the various seabed conditions, extended exposure to harsh wave loading, and provide support and dynamic stability to the whole system at minimal costs and with minimal environmental impacts.

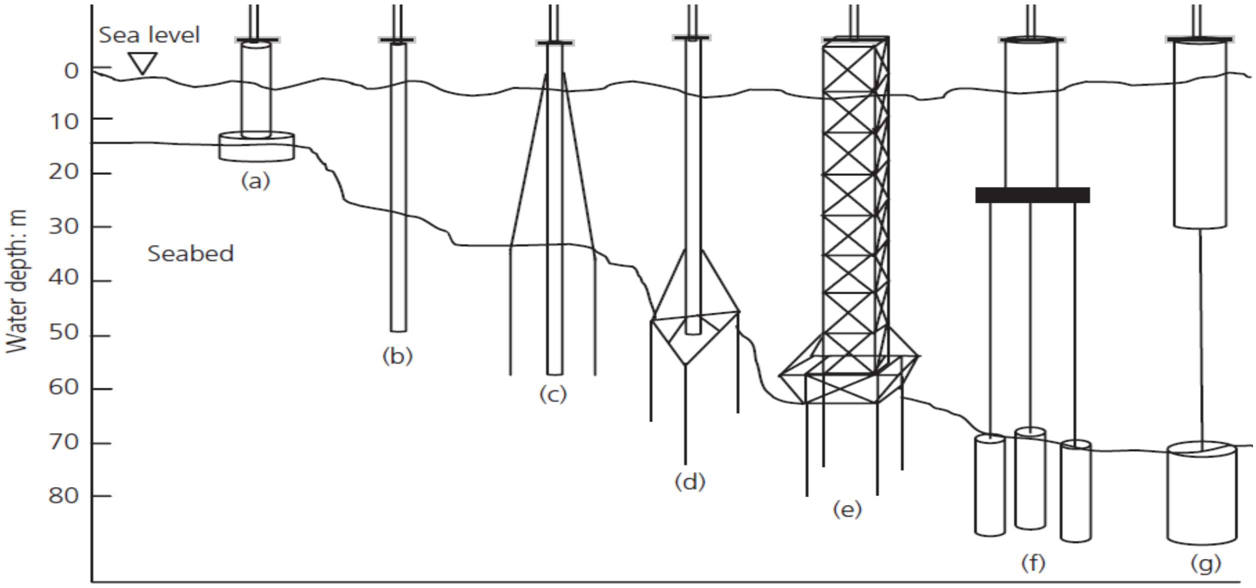
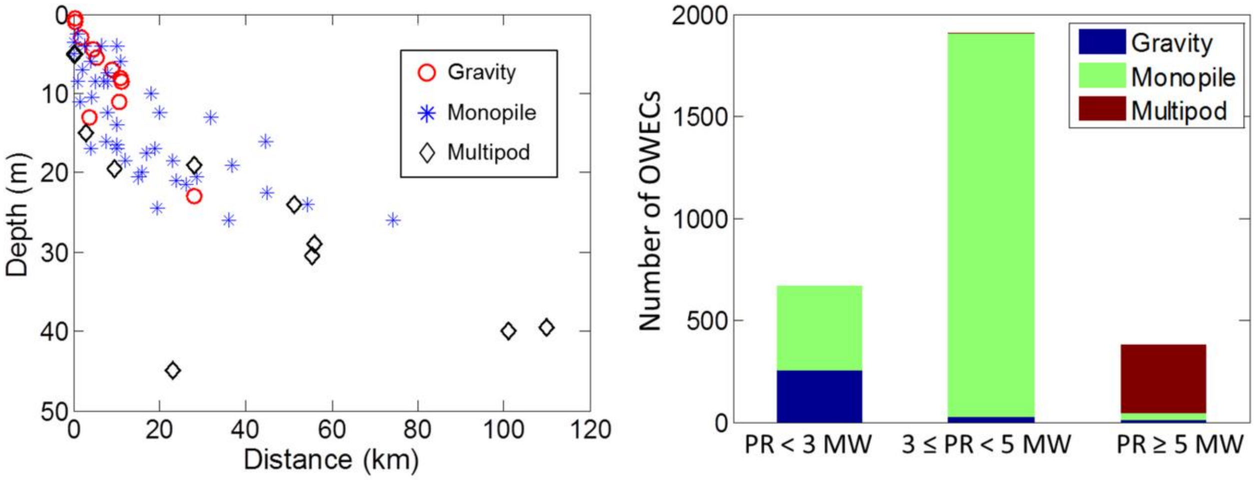


Figure 2.11: Offshore Wind turbines support structures: from (a) gravity-based, (b) & (c) Monopile and Monopile with guy wire, (d) Tripod, (e) braced frame, (f) Tension leg with suction buckets, (g) Buoy platform [87]

The majority of operational offshore wind farms in the UK are at water depths of less than 30m. As the sector continues to expand further from the shore and at deeper water sites, there is a constant need for a suitable and more economically feasible support structure. The primary foundation types are the bottom-mounted foundations such as the monopile, gravity, tripod and jacket foundations, and the floating foundation's concepts such as the barge floating substructure, the semi-submersible platform, tensioned leg platform and spar buoy floating structure.

By the end of 2017, the monopile foundations accounted for over 80% of the UK's commissioned offshore wind turbine foundations. These monopile foundations are made of steel tubular sections and use the thickness and diameter to transfer the applied loading to the seabed. Although well-established, these monopiles are limited by water depth (up to 30 m) due to stiffness issues and their structural mass. Over the years, these monopile foundations' design was modified to preserve larger turbines' stiffness in deeper waters by introducing larger. Monopile foundations (XL and XXL diameter and thickness).

The gravity-based and braced support structures such as the jacket or the tripod foundations can be used for deeper waters (<40m) and support larger turbines. Beyond shallow waters, floating foundation designs are favoured over fixed mounted foundation to withstand the impacts associated with Deepwater areas, reduced costs of deployment and maintenance being tested, and the first UK floating wind farm was deployed in Scotland deployed (Hywind 30MW wind farm). Moreover, it is more likely that floating turbines will continue to exploit deeper sites (>60m) that are not suitable for fixed foundations.



(a) (b)

Figure 2.12: Installed Offshore Wind substructures with (a) Foundation type for sites (b) the total number of offshore wind structures [87]

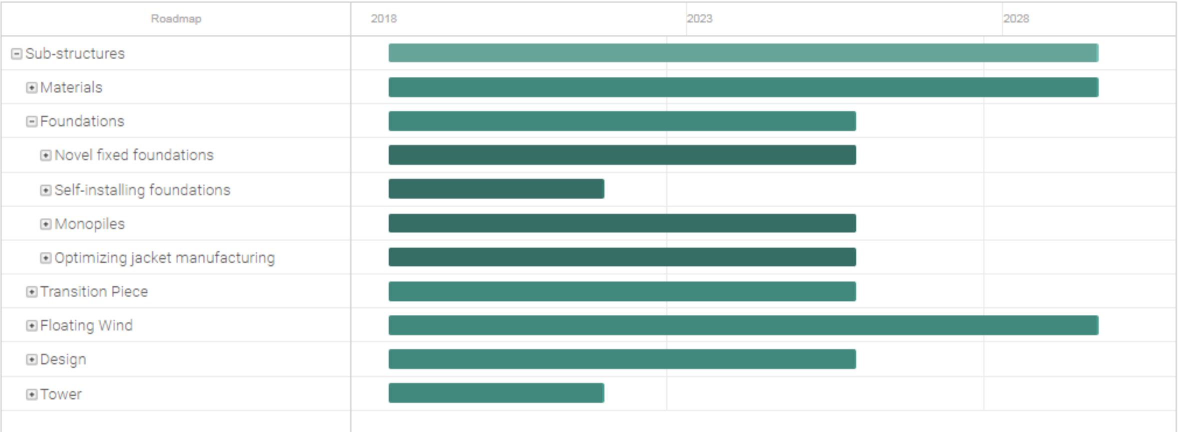


Figure 2.13: State-of-art trend for foundation and sub-structures. [86]

2.5.3. Drivetrain

A standard 3-bladed upwind rotor configuration has been adopted in the majority of large wind turbines. However, for the drivetrain, various arrangements have been used. The nacelle contains all electromechanical components enabling electricity to be generated from offshore wind (Torque * Speed = Power). The main components are the gearboxes (in any), bearings, the generator, and the converter.

From constant speed multistage gearboxes with squirrel-cage induction generators in the early 1990s to standard variable-speed machines with doubly-fed induction generators (DFIG) in the late 1990s, the industry has evolved into manufacturing more low ratio gearboxes to gearless generator systems mainly to reduce failures and maintenance issues which accounts for over 26% of turbine downtime [88].

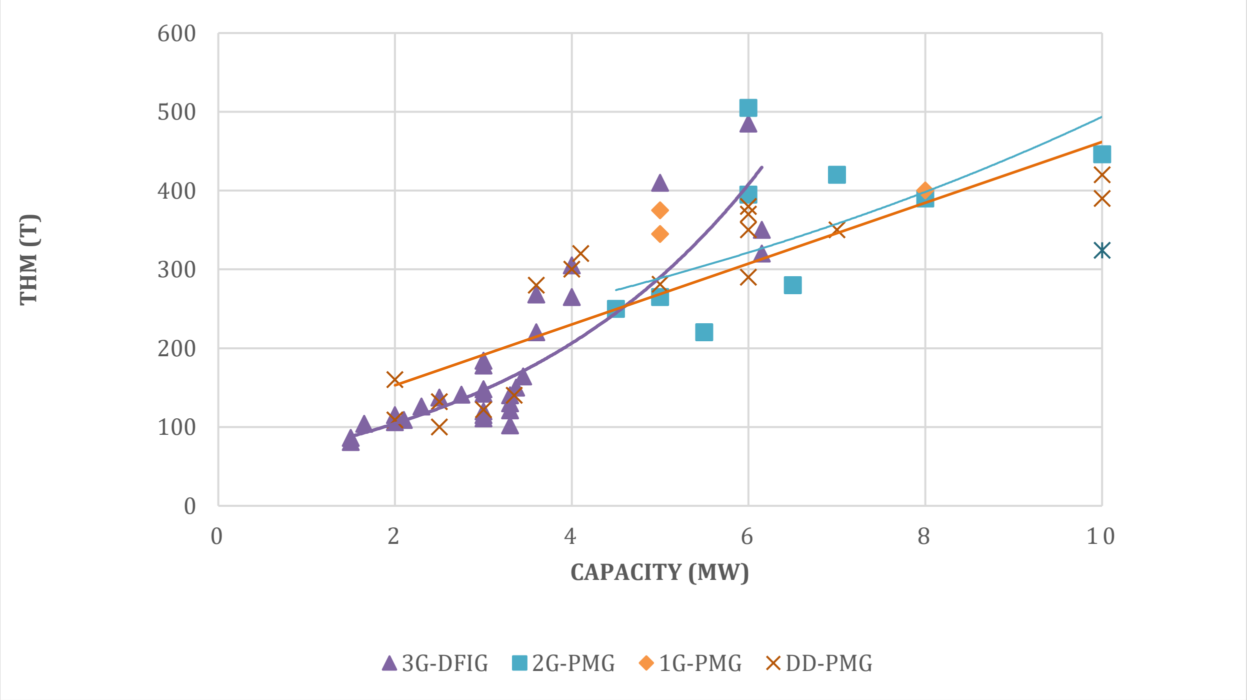


Figure 2.14: Trend of Geared and direct-drive generators (up to 2017)

Figure 2.14 shows a transition from high-speed three-stage geared drivetrain to direct-drive generators over the years. From this trend, the top head mass (THM) of these turbines increases with their power rating, resulting in larger and heavier nacelles. Adopting bigger turbines with advanced gearless direct drive systems has contributed significantly to the overall wind turbine system's reliability and efficiency. However, with the layout where the gearbox is eliminated, the electrical machine copes with very large torque and forces. Hence it needs to be bigger, heavier, and more robust than a conventional high-speed generator.

The drivetrain commonly found in the UK waters are the DFIG geared drivetrain, the permanent magnet rotor generator with a full converter to generate power through a speed range, and to achieve high torque, direct-drive generators using either electrically excited or permanent magnets as excitation field to allow high inductor field with low iron losses.

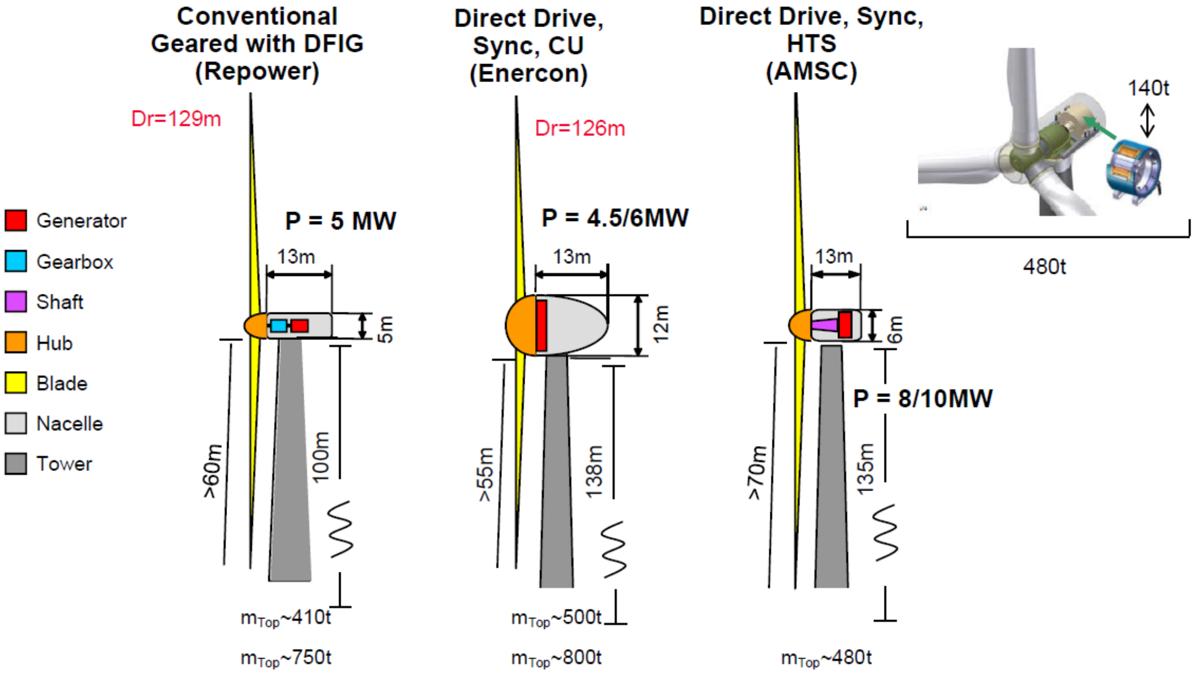


Figure 2.15: Comparison of Scale-up 5MW DFIG machine and 5MW Enercon direct-drive Copper generator against an 8MW HTS generator [89]

Innovation has had a significant impact on the development of drivetrains to mitigate their complexity, performance, cost, weight, and reliability. This continued push for innovation of the drivetrain focuses on reducing several moving components, lower dependency on volatile materials, ease of manufacture, installing and maintaining, and overall costs.

The concept of superconducting machines has been investigated to mitigate alternative design without permanent magnet materials, the mass and volume issues, and the ability to produce high shear stresses with minimal excitation losses at critically high temperatures. Because of their critical temperatures and magnetic fields, these machines are seen as the alternative to permanent magnet direct drive generators producing better power quality (due to high power density) and smaller and lighter machines. The claim is that the introduction of High-temperature superconducting machines (HTS) as efficient and reliable machines will enable cost savings due to having fewer, lighter, and larger turbines with a lower number of components (no gear and robust cooling system).

Ongoing research projects have looked at advanced materials to reduce the size of the direct-drive generators and reduce or eliminate the rare earth materials used, for example, pseudo-direct-drive generators and the use of ferrite-magnet in the generators [85].

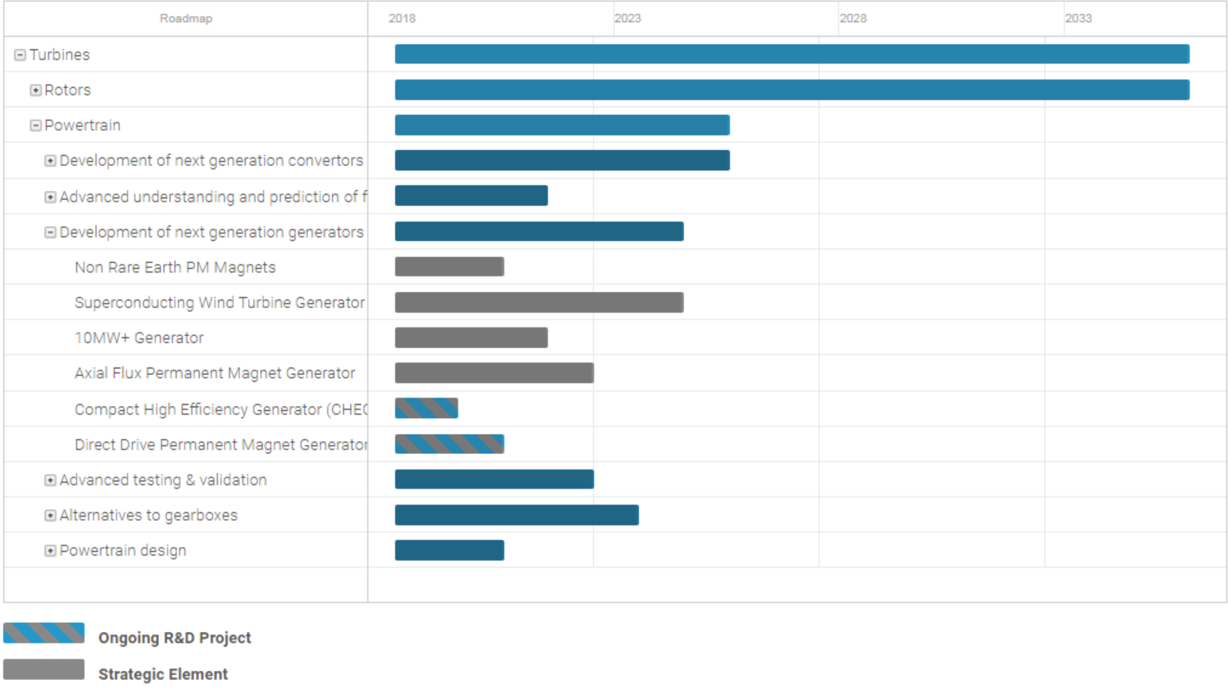


Figure 2.16: OWIC State-of-Art drivetrains [86]

2.5.4. Transmission system

In the UK, the transmission costs account for approximately 10-15% of the LCOE depending on the environmental factors, site locations, wind farms' capacity, the available technologies, and the financial constraints. As offshore wind turbines continue to increase in size and capacity, so are their distances to shore and the grid, impacting the cost of transmission and the overall system. These costs can be covered by the government or by the developers. The UK developers can either provide the grid connection themselves or via Transmission Systems Operators (TSO). In the case of TSOs in the UK, OFTO (the Offshore transmission Owners) is accountable for building, operating and maintaining the transmission assets within licensed areas, and revenue is agreed by Ofgem and recovered from the National grid [89].

The transmission system transfers the generated electricity from these wind turbines using inter-array cables to an offshore substation through step-up transformers, then to shore via export subsea cables and the onshore substation via buried onshore cables. Traditionally, transmission systems were made of medium voltage alternative current (HVAC) connection to shore. However, since the early 2000s, more wind farms have been built further to shore, requiring longer connections with higher capacity, and hence the introduction of High Voltage Alternating Current (HVAC) and offshore substations reduce inter-array cables and overall grid connection costs. Some wind farms have used two substations for economic reasons, and the use of booster stations was analysed and assessed to enhance the overall transmission efficiency (Hornsea one Project). However, depending on the distance of transmission, the amount of power to be transmitted. With costs of cables and substation increasing significantly as distance and capacity increases, High Voltage Direct Current (HVDC) cables have been explored for longer distances to shore and reduce the high-power losses due to the extra current in long AC cables [89].

Research have looked into the cost benefits of HVDC over HVAC and have proposed that for wind farms with a capacity of over 1GW and cable lengths exceeding 80km, it is more economical to use HVDC subsea cables due to better quality power transmission. Although the cable costs might be cheaper, it is worth noting that a DC transmission system will have additional costs for the offshore AC/DC and onshore DC/AC converter stations [90].

State of the art

Commercially, HVDC transmissions have only been used for long-distance terminals, also known as point-to-point transmission. Further research into the multi-terminal HVDC grid is considered to reduce the number of converters needed [90] [91].

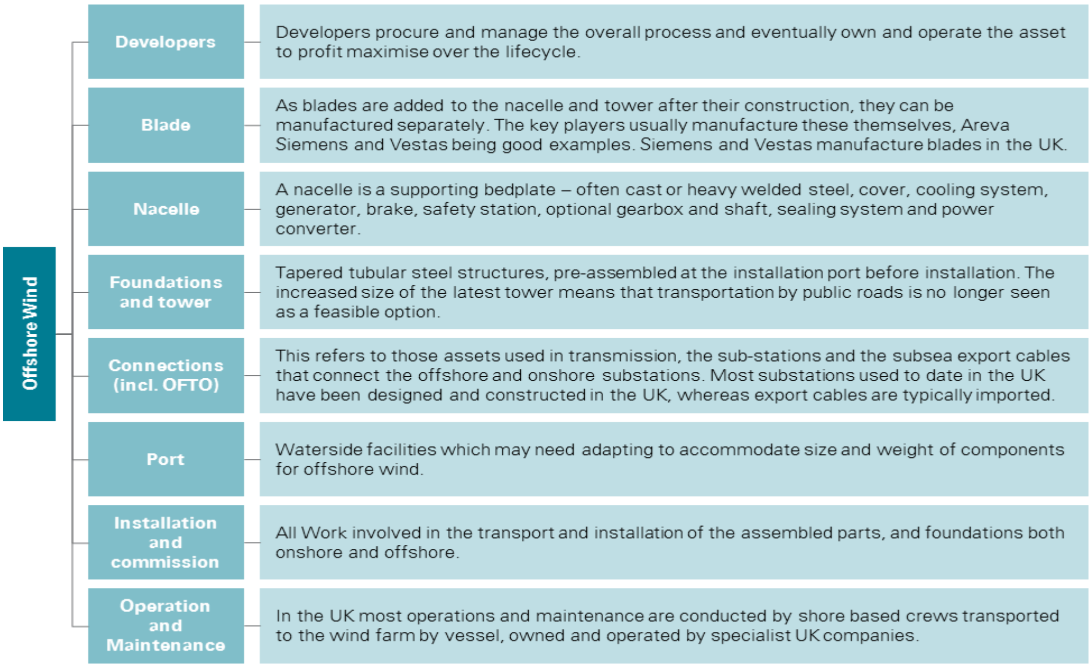
- The use of higher voltage transmission: compact HVDC platform and Multi-terminal DC cluster connections
- The deployment of ‘Super grid connections’ linking the UK with other European countries.
- The standardisation of Lightweight AC platforms for optimum cost and high reliability
- The standardisation of 66kV array cables over conventional 33kV for higher capacity and lower electrical losses.

2.5.5. Supply chain (Installation and Operation and Maintenance)

The offshore wind market holds strong shares mostly in the North of Europe in countries such as the UK, Germany, Denmark, and France; and emerging in the US, Japan, and China. Through its offshore wind industrial strategies (Clean growth plans), the UK governments can support an innovative and competitive UK supply chain to enhance economic growth and make offshore wind a cost-effective part of the UK’s energy mix [86]. With 7.4 GW offshore wind operating capacity and over 1764 turbines installed (as of the end of 2017) accounting for one installed turbine a day in 2017, the supply chain has to adapt to the sector's significant growth [92].

The challenge for the supply chain as the sector grows is to keep up with the demands of the markets and to adapt to continuous advanced technologies and practices through innovation and scaling-up. The rate at which turbines are built and commissioned are partly dependent on the supply chain: the limitation of the order books, the manufacturing process, and their factory capabilities.

This section outlines the manufacturing, installation and operation and maintenance (O&M) strategies used to-date to support the UK offshore wind market and the areas proposed for future innovation.



Offshore Wind

Developers	Developers procure and manage the overall process and eventually own and operate the asset to profit maximise over the lifecycle.
Blade	As blades are added to the nacelle and tower after their construction, they can be manufactured separately. The key players usually manufacture these themselves, Areva Siemens and Vestas being good examples. Siemens and Vestas manufacture blades in the UK.
Nacelle	A nacelle is a supporting bedplate – often cast or heavy welded steel, cover, cooling system, generator, brake, safety station, optional gearbox and shaft, sealing system and power converter.
Foundations and tower	Tapered tubular steel structures, pre-assembled at the installation port before installation. The increased size of the latest tower means that transportation by public roads is no longer seen as a feasible option.
Connections (incl. OFTO)	This refers to those assets used in transmission, the sub-stations and the subsea export cables that connect the offshore and onshore substations. Most substations used to date in the UK have been designed and constructed in the UK, whereas export cables are typically imported.
Port	Waterside facilities which may need adapting to accommodate size and weight of components for offshore wind.
Installation and commission	All Work involved in the transport and installation of the assembled parts, and foundations both onshore and offshore.
Operation and Maintenance	In the UK most operations and maintenance are conducted by shore based crews transported to the wind farm by vessel, owned and operated by specialist UK companies.

Figure 2.17: Offshore Wind supply chain [93]

The UK has an established supply chain with additional transferable expertise from the oil and gas sector. The market scale and visibility mostly drive the supply chain's sustainability. With added certainty provided by the UK government through the CfD auction schemes, pipelines of projects enable investments and growth in the supply chain. Most of the supply chain is EU-wide, so UK demand changes must be seen in this broader context.

Table 2.4: Summary of Offshore Wind Supply Chain [data collected from [21] [94] [20]

	Geographical Market	***Future requirements***	***Manufacturers***
Blades	In the UK Siemens factory in Hull (6MW), MHI-Vestas in Isle of Wright (8MW), In France- Factor in Cherbourg In Denmark- Aalborg In Germany- Portside factories in Stafe and Bremerhaven	Further R&D funding to support demonstration sites Additional suitable sites near ports for manufacturing and lower transport costs Increased deployment rate (increased order book for more investment) Local factories to enable competition and solutions on lower transportation costs Flexibility with production lines to accommodate non-standard designs	Siemens Gamesa Renewable Energy MHI Vestas Senvion Adwen WinWind Ltd Vestas Wind Systems A
Drivetrain	As with blades, nacelles are constructed close to the site due to their large size, assembly requirements and transportation limitations. Siemens factory- Cuxhaven, Germany	More local or near port sites in the UK. Advancement of SMEs for parts Demonstration of integrated nacelle units Skills and Expertise	Siemens (Germany and Denmark) GE Alstom (Port in St Nazaire) MHI Vestas (Denmark) Smaller part companies- Jupiter, EM-Fiberglass, Bach Composites and Eikboom
Transmission System	Nordic companies- Oil & gas and subsea experience UK- Substations manufacturing facilities (***)	More skillsets - Siemens research and development centres: Keele, Sheffield, Manchester More demonstration facilities for HVDC transmission systems, Optimised OFTO process	Inter-array Cables: JDR Cable systems, Prysmian Powerlink, Nexan, NSW technology Ltd Export cables: Prysmian, NSW, NKT cables Substations: ABB, Alstom Grid, Siemens Energy

Substructures	European market mainly. Transferable skills to make most of the equipment (Tower, foundations) from civil engineers, oil & gas, welders	Automation and standardisation of components More bespoke shipping transportation vessels/ trucks Companies' diversification to supply market	EEW, Statoil, Bladt (Danish), Global Energy, Fahime, SIF, GoSea, MT Hojgaard, Burntisland Fabrication, Offshore Structures, Seaway Heavy Lifting, TAG energy solutions.
Owners / Developer	Most developers are large international companies such as Dong, RWE, EON and Vattenfall. A developer constructing assets in the UK will typically base a project team in the country, and several also have offices elsewhere in Europe	More pension funds and financial investors ownership More financial O&M providers (ExceCo, Greencoat for North Hoyle) Currently still relies on strike prices with potential subsidy-free auctions	Ownership of UK offshore wind project is dominated by Utility owners mainly- 62%. Mostly International companies with a range of sectors: Osted (Dong), EON, SSE, Innogy, Statoil, Vattenfall, XceXo Ltd, Edf, London Array Ltd, E.on.

There is a good supply of existing companies in the UK and Europe capable of handling a large offshore wind deployment volume. However, a combination of certainty in deployment rate and more competition in the supply chain is critical to a more cost-effective sector — it also standardises components and services and more research, development, and demonstration, including full-scale facilities.

2.6. Innovation

Having reviewed the role of offshore wind in the energy system, the state-of-the-art technologies and key market drivers of the offshore wind sector, this section tries to understand the market strategies in relation to innovation in the offshore wind sector.

A significant innovation in offshore wind technologies has accelerated the cost reduction trajectory, improved the technologies' reliability, and increased investors’ confidence, with the economies of scale playing an important role in the market (refer section 2.5).

To meet the previous 80% target and now Net-Zero emission target in 2050, innovation, beyond learning-by-doing, is required to reflect areas of priority with the most valuable impact on costs and meeting the targets. To provide the key innovations, one has to understand the opportunities available (e.g. export, Gross value add) and the barriers to innovations (e.g. market barriers). Can design methods help identify areas of innovations for offshore wind? An overview of how industries have approached innovation is discussed below.

IRENA defines innovation as “…the engine that powers the global energy systems' ongoing transformation” [95]. These transformations in the energy systems come in different forms, from disruptive, first-of-a-kind innovations to less radical incremental innovations within existing technologies, from innovation at the system-level to component-level innovation, and many more.

John Kao, the author of Innovation Nation [95], defines innovation as “the capability of continuously achieving a desired future” [96]. In his book, Kao emphasises that innovation, whilst it creates new and valuable products, processes, or services, it is “a narrow defined technical area of competence”, requiring multi-disciplinary inputs, “different bodies of knowledge, perspectives, and disciplines brought together” [95] [96] [97].

Innovation is also broadly defined as “the ability to continuously transform knowledge and ideas into new products, processes and systems, to the benefit of both the organisation and the shareholders" [98], and addressing areas of unmet user needs, problem-solving, creativity, organisational business model, and applied invention [97] [98].

Over the years, innovation has gained great importance for many organisations worldwide due to intense competition and rapid technology development. Developing new ideas and innovating is a competitive advantage, representing why customers may opt for one company to another disadvantage.

Nowadays, most companies developing new products or services use a well-defined innovation process to identify, create, and develop innovative solutions, measure 'success' against their competitors and manage the uncertainties and risks associated with the implementation processes. This is seen across various sectors in companies such as ExxonMobil, Ford Automotive, Rolls-Royce, companies in the medical and pharmaceutical industry, and many more. The challenges for industries have evolved from their willingness to innovate to take a step towards implementing responsive strategies, a coordinated approach to innovation, along with the culture and people. Figure 2.18 presents a funnel model, representing an innovation approach from idea generations to concepts and commercialisation.

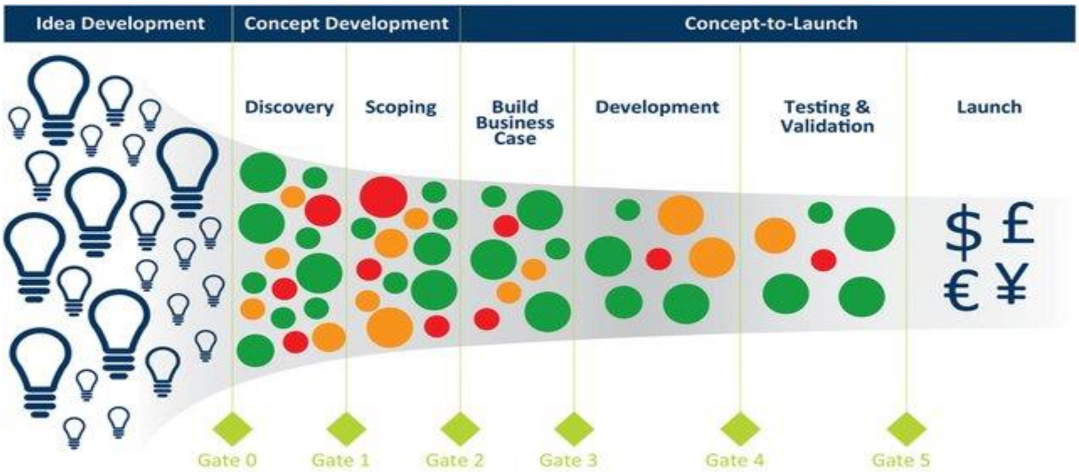


Figure 2.18: Innovation Funnel [99]

These processes by which products or services are developed commonly derive from the combinations of simple conventional design approaches to problem definition within a system, problem-solving, and creative thinking, which form the basis for systematically innovating and generating new ideas.

An overview of the various design theories and methodologies is reviewed in Chapter 3 to establish innovative design approaches adopted by the industries.

3. Innovative design theories and methodologies

The first step of the literature review was to identify the UK offshore wind market strategies, including the current state-of-the-art technologies and key market drivers of the offshore wind sector. This chapter is the second step in establishing the research methods of this thesis. An overview of the innovation theories and conceptual design methodologies are presented, from which three were then identified and selected. A review of current literature for each of these methods was performed to identify limitations that would make them unsuitable for the application. Section 3.1 presents the methodological approach used to review the literature, followed by details of each of the four phases developing the knowledge required in design theory and methodology in Sections 3.2 to 3.5. This chapter concludes with a critical analysis of the design methodologies and the three to form the design methods.

3.1. Methodology approach

This thesis's methodological approach was based on a multi-phased literature review, as shown in Figure 3.1. The objective was to establish what had been previously reviewed and develop areas of knowledge required in innovative product and conceptual design theory and methodology. Four phases were implemented to set out the research gap and, in turn, the thesis research statement. These phases are:

Phase-1: reviews the literature of existing design theories. This analysis aimed to establish the areas of interest and to categorise the design theory approaches.

Phase-2: narrows the boundaries of areas of interest to identify the current state-of-the-art for innovative designs at the conceptual stage; the innovative methods and creative thinking theories; and product development methods. This phase aimed to identify and select the capabilities of the specific methods and tools taken forward and the basis of exclusion of other methods.

Phase-3: screens further the current state-of-the-art innovative design theories to establish the capability, focus, and drive of the selected methodologies. This step was to assess the selected innovative methodologies in terms of viability for innovative design and development in the energy sector. Having selected these methodologies, other methods that can achieve the same aim were assessed and an explanation provided for their exclusion.

Phase-4: details the justifications for the chosen methodologies. The aim is to select structured innovative methods to establish how these methodologies compare and complement each other and their (lack of) applications in the renewable energy sector.

A summarised approach of the literature review is shown in Figure 3.1.

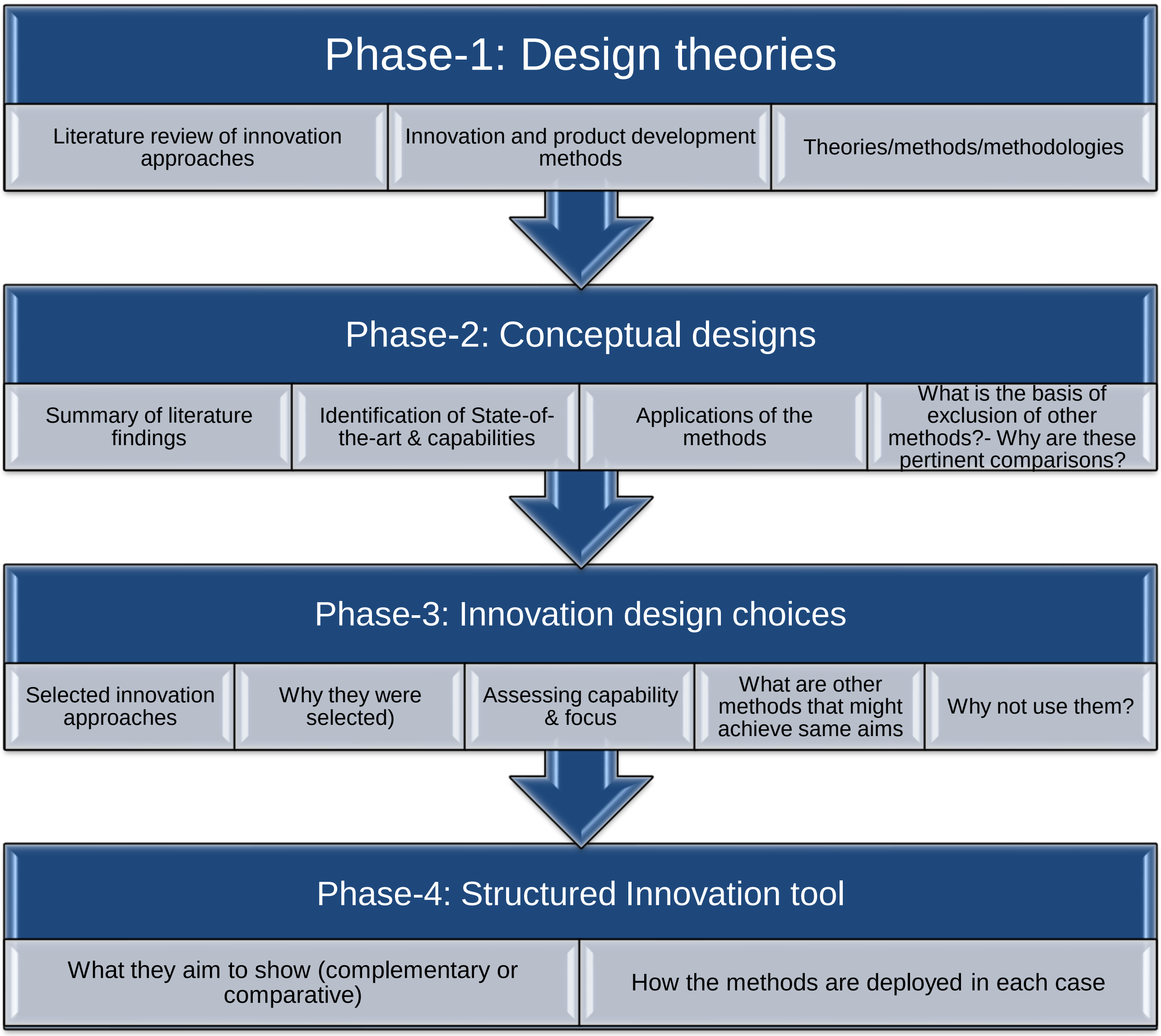


Figure 3.1: Diagram showing a summarised approach of the literature review.

The methodology was to collate data from the high level of conceptual design knowledge (Phase-1) towards the research's specific design focus (Phase-3&4) to identify the innovative processes to conceptual design approaches, creativity, and problem-solving techniques. Google Scholar, Research Gate, and Elsevier (Scopus) were used as the main search engines. For each phase, a variation and combination of keywords were used, as simplified in Figure 3.2.

The various conceptual design methods were presented in tabulated forms to compare each method's approach concerning their systematic approach, creativity, and improvement process.

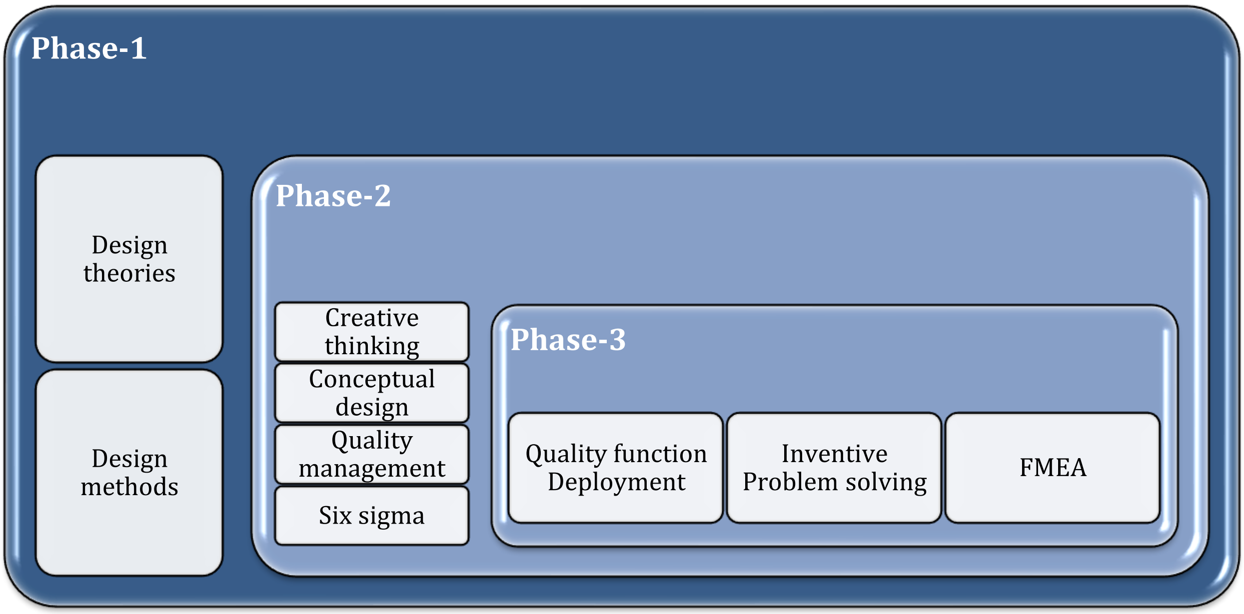


Figure 3.2: Literature review Methodology

Phase-1 focussed on the existing knowledge of design theories and methods. Keywords searches “design methods”, “design theories”, “systematic design” were used with various variations and combinations, and including their abbreviations. The findings were reviewed and compared based on the research criteria and references provided.

Phase-2 explicitly reviewed the current state-of-the-art conceptual designs in product development, narrowing the search to the research criteria. Keywords such as “conceptual design”, “product design approach”, “innovative design”, “inventive thinking”, “creative thinking”, “product quality management”, “six sigma”, “total design”, were performed to narrow the boundaries of the areas of interest considered. This phase led to the selection of three design methodologies.

Phase-3 focussed on specific reviews of the capability and limitations of the three selected methodologies: the Quality Function Deployment (QFD), Theory of Inventive Problem-Solving (TRIZ) and Failure Mode and Event Analysis (FMEA). A variation of keywords such as “QFD”, “Quality Function Deployment”, “TRIZ”, “FMEA”, “Failure Mode and Event Analysis” was used to understand the applications of these methods and the reason for the exclusion of others.

Phase-4 details the complementary and comparative elements of the selected methodologies and their deployment. The search combined a variation of “QFD application”, “FMEA Wind”, “TRIZ offshore Wind”, “Innovation in Energy” to capture areas where these methods were applied as standalone techniques or as part of an organisational process.

3.2. Phase-1 Review of design theory approaches.

Design methods are a combination of tools, techniques, and procedures for design processes and improvements of a broad range of design problems. The design methods are established from designer and scientist's explorations and findings that form the design processes. Several design procedures are field-specific. The design methods aim to provide a more generic practice that can be applied more widely to various systems.

Design methods can be traced back to the Romans times with Vitruvius in the ten books on architecture [100], Durand with his refinement on the theory of modern architecture in 1802 [6], and in the early 1960s in response to industrialisation, which resulted in the foundation of the Design Research Society to influence systematic design methods in engineering, communications, industrial design and architecture [102] [103]. Systematic design refers here as "a process of design that looks not only at the problem that needs to be overcome, but also at the surrounding environment, and other systems that are linked to the problem" [104].

Several research and publications on design methods were published in the late 1960s, attempting to describe and categorise the theories and design methods into prescriptive and descriptive processes [105] [106] [107] [108]. In his publication "The science of the Artificial" [109], Simon illustrates the integration and adaptation of design methods to artificial artefacts. Jones, in his publication "Design methods: Seeds of human futures" [109], argued that design processes are needed to support intuition and rationality of the designers' process; and introduces descriptive approaches to the design methods (including procedures such as data-gathering, innovation, taxonomy, evaluation) [110].

Many scholars such as Bruce Archer [107], Tomas Maldonado [111], Horst Rittel [112] led the integration of design methods in the education system to develop a systematic form of design processes in science and engineering fields such as cybernetics, systems theories.

From the early adoption of design theories in the early 1960s, the term Design science defined as "the systematic form of designing, where the research on design methodology falls in the field of science" [113], was later introduced by Fuller and adopted more widely. Its application spread across various sectors such as Artificial intelligence, information systems, complex engineering, and much more [113].

The design philosophy continually evolved, with many scholars developing systematic forms of design processes for various applications. There have been significant efforts to improve design theories' objectivity and operationality in the various practices, sciences, and disciplines (e.g. management, information systems). Phase-1 in this study builds on the numerous (but scattered) theoretical proposals, as shown in Table 3.1, noting that the reviewed reports and articles are not exhaustive but attempt to review the multiple proposals that addressed design theories.

Table 3.1: Summary of design theories and methodologies reviewed.

Author/Designer	Proposed design approach
Vitruvius (20 BC) [100], Howe (1999) [115]	De Architectura: An abstract definition of architecture to help architects deal with a variety of knowledge beyond the specificity of each building's properties and characteristics.
Gordon (1961) [116] [117]	Synectics- is a technique created to enable competitiveness in creative designs. A technique only considered for processes that can be concretely described and are usable in teaching methodology to increase creative output for individuals and groups
Jones (1963) [102] Christopherson (1963) [118]	Design research led to a systematic design process for fields like medicine, engineering, computer science. A creative set of techniques focussing on analysis, synthesis, and evaluation of designs
Simon (1969) [109], Gero et al. (1987) [119] [120]	Information processing models detailing the various design aspects on Artificial Intelligence (AI) concepts.
Yoshikawa (1981) [121] [122]	General Design theory- a mathematical theory for building computer-aided design (CAD) systems The approach aims to explain the design and guide the development of CAD tools focussing on the structure of design knowledge, assumptions (axioms) and predictions (theorems).
Vladimir Hubka & Ernest Eder (1988) [123]	Theory of technical systems as a framework that connects the whole lifecycle from designing to disposing of a system; Serve as the integrating factor between individual disciplines
Gero (1990) [124]	Design prototypes (representation schema) provide a framework as structured to a design and its functions.

	The representation schema enables production, analysis, and evaluation of a design
Suh (1990) [125] [126]	Axiomatic approach to design- industrial design principles with scientific-knowledge instructions. The design theory emphasises on conceptualising design approaches and exposition of fundamental axioms and applications.
Taguchi (1993) [127] [128]	Based on universal decision criterion, Statistical and investigative method for quality improvement of designs. The method is used to verify the influence that each design parameter has on the functional requirements; First-order solution with a mathematical formulation for improving existing processes
Hatchuel & Weil (2002) [129] [130]	Concept-Knowledge (C-K) design theory- a unified design theory that expands on the space of concepts (C) and knowledge (K) to explain invention, creation, and discovery
Shai & Reich (2004) [131]	Infused design- is an approach for establishing collaboration between designers and engineering fields. The design problem is translated to a mathematical meta-level (discrete mathematical models) as a common language to all disciplines to achieve infused knowledge, methods, and solutions applicable to several fields.
Zwicky (1965) [132] [133] [134]	Morphological analysis- is a design method that attempts to derive all the possible solutions from a defined multi-dimensional list of problems. A problem-solving technique that uses morphological charts to analyse if designs are met.
Osborn (1948) [135] [136] [137]	Brainstorming techniques- a design methodology, collaborative and creative that gathers a group of people to generate as many new ideas as spontaneously as possible to solve a problem
Van Aken 2004, 2005b [138]	Cognitive process from design and creation to evaluating the artefact in use. Prescriptive rather than descriptive theories, Action-oriented process to design problem-to-solutions

As illustrated in Table 3.1, there have been many attempts to define and categorise design theories and methods. A common understanding from the rich literature is that design theories should explain the generalised solution components with related generalised requirements in a simple, clear, and structured way. However, there is not a complete agreement about the components and specific characteristics of the design theories. On the one hand, design theory has been described as descriptive, aiming at understanding the nature of theory (knowledge-producing activity), and on the other hand, as prescriptive aiming at improving performance (knowledge-using activity) [139].

Richard Baskerville [140] argues that where "the notion of science of design entails the notion of a theory of design, … the specific characteristics of design theory seem rather elaborate and overly complicated". He proposed that design theory consists of two components: a design practice theory and explanatory design theory.

Salvatore March and Smith describe design theories as "an attempt to create things that serve a human purpose, a technology-oriented. Rather than producing general theoretical knowledge, design scientists produce and apply knowledge of tasks or situations to create effective artefacts." [139].

Joseph Walls [141] defines information system design theory as a prescriptive theory that specifies how a design process can be carried out effectively and feasibly; and is made up of a design product and a design process.

Goldkuhl [129] and Van Aken [138] emphasises that design theories should be practical and prescription-driven Design theories consist of knowledge of a practical character, i.e., for practical purposes. [142]"

Most observations have acknowledged at least that design theories explain the theories behind designs- "…not only for descriptive and prescriptive purposes but also serve functionally descriptive purposes" [140].

3.2.1. Phase-1: Key findings

A holistic understanding of the design process is needed to consider all characteristics and components of design theories.

Tomiyama et al. [143] [144] categorised design methods into two groups:

- *Abstract*:
  a. *Abstract-general*: includes the general approach to design theory, processes, and knowledge, that applies to a wide range of artefacts (e.g., General design theory)
  b. *Abstract-individual*: considers specific design methods for an aspect of the original design, including design methods such as the Taguchi method.
- *Concrete*:
  a. *Concrete-general*: consists of design methods that focus on process or product design development. Although the methods apply to individual design cases, they can be applied to wider artefacts. These methods have concrete processes adopting prescriptive methods for quality management and product development such as the Quality Function Deployment tool (QFD), the theory of inventive principles (TRIZ), Pahl and Beitz's work [145] [146]
  b. *Concrete-individual*: consists of design methods applicable to specific cases, specific problems solved using procedures specific to that system (e.g. aircraft).

In his categorisation, Bakerville [140] also highlights that design theory consists of two parts: the explanatory and practice design part. The theory part prescribes principles related to "the definition of functional and scientific requirements" to an incomplete description of an object (the design problem). The practical part of the design theory specifies in a practical way how to design an object.

The current definitions of design theory suggest that it comprises the intellectual processes that occur when approaching a design (Abstract/ explanatory) and the design processes and products (Concrete/Practical).

The section presented scholars' various approaches to separate design theories into design practice theory and design methods. The general design theories explored, provided the basis of the thinking behind design approaches. Having reviewed these theories, general design methods (abstract-individual) were next reviewed to identify concrete design methods.

3.3. Phase-2: Conceptual design methods

The literature review in phase-1 identified the *Abstract-general* approaches to defining design theory and methodology, establishing the system of interest in general design theories and the categories of design methods. Phase-2 expanded on the design methods to focus on the *Abstract-individual* approaches applicable to an original design's specific aspects. The objective was to refine the system of interest in terms of the existing conceptual design methods, to select the methods taken forward to Phase-3 and the basis of exclusion of any other methods.

The offshore wind sector's primary focus is to create a market that drives innovation and competition, as discussed in the literature section. Conceptual design methods that focus on mathematical algorithms or optimisation aspect of designs were reviewed and presented in this section, including any exclusions.

Conceptual design is the earliest phase of the design process in which an artefact's functional requirements are defined. The process involves understanding the needs of the end-users and how to develop new or improved products, processes or services that benefit them, and at the same time, are sustainable in the market. The conceptual design approach aims to recognise viable solutions by considering possible interactions, experiences, processes, and alternatives to design a design.

There are many existing design approaches developed for conceptual designs and creative thinking. These can further be grouped into three categories: (1)- design for the generation of ideas for concept design, (2)- design for concept design evaluation, and (3)- design for a specific design purpose [147].

This section elaborates on some of these design methodologies and techniques used for the concept design of product developments.

3.3.1. Systematic Approach- Pahl & Beitz

According to Pahl and Beitz [148], engineering designs require careful planning and systematic execution. This systematic approach emphasises the need for engineering design methods to integrate different design aspects, including the customers' needs and priorities. Pahl and Beitz' Systematic Approach describes the engineering design process as a sequence of phases and distinct steps: (1) clarification of the task, (2) Conceptual Design phase, (3) Embodiment Design, and (4) Detail Design [148] [149] [150]. The model is presented in Figure 3.3.

Pahl & Beitz stress that “design methods should assist broader, system-building efforts, such as electronic data processing, and modern management science thinking, and a balance must be found between an intuitive approach and a systematic one” [150]. However, the approach acknowledges the complexity of design and implementation; and the need for a comprehensive and clear approach to system design to follow” [150] [151] [152].

This system approach provides logical steps to a design process, which arguably, according to Jensen [138] does not “recognise that solutions may come from different sources than a systematic approach”.

Table 3.2: Summary of Pahl & Beitz approach strength and weaknesses

Strengths [137] [140]	**Limitations** [132] [139]
Concrete design application	Adopts creative process external to the model.
Problem-oriented approach	Flexible approach
Strategic method prioritising classification of tasks and validating process.	Solution-neutral approach- wider solution scope (consideration of everything possible) [132]
A systematic process, including defining user requirements.	Less holistic and more serialistic
Function- structured model	Predicting Designer behaviour

The systematic approach is one of the many design methodologies that divide the design process into several phases and steps, focussing on specific products. A review of literature has highlighted Pahl & Beitz design model’s limitations as being a very prescriptive approach to design and viewed as a checklist against models to verify [51] [57] [58] [60]. The systematic approach sets out a strategy for developing solutions aiming to increase product design's technical and economic success. Some limitations in the approach were observed around limiting the creative process.

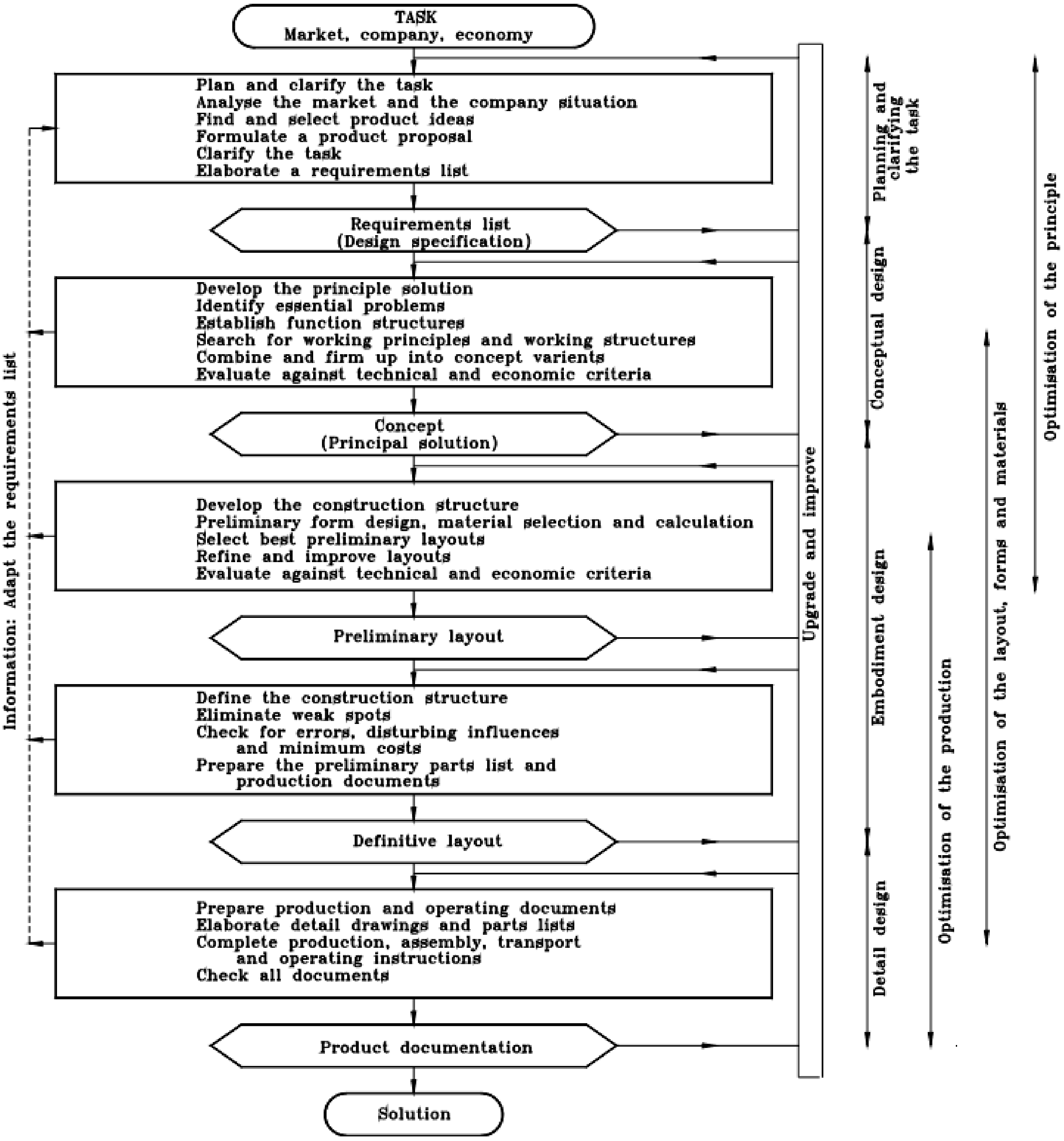


Figure 3.3: Pahl & Beitz proposed design process (figure adapted from [153])

3.3.2. Total Design method- Pugh

Pugh’s Total Design method consists of several core activities complementing and influencing each other, allowing the designers to meet customer needs. These core activities are the basis of a holistic approach to the development of the product design specification from the identification of a market needs to the commercialisation of the product to satisfy the market need (i.e. the development of conceptual design and detailed design, the product manufacture and sale of the finished product) [155] [156].

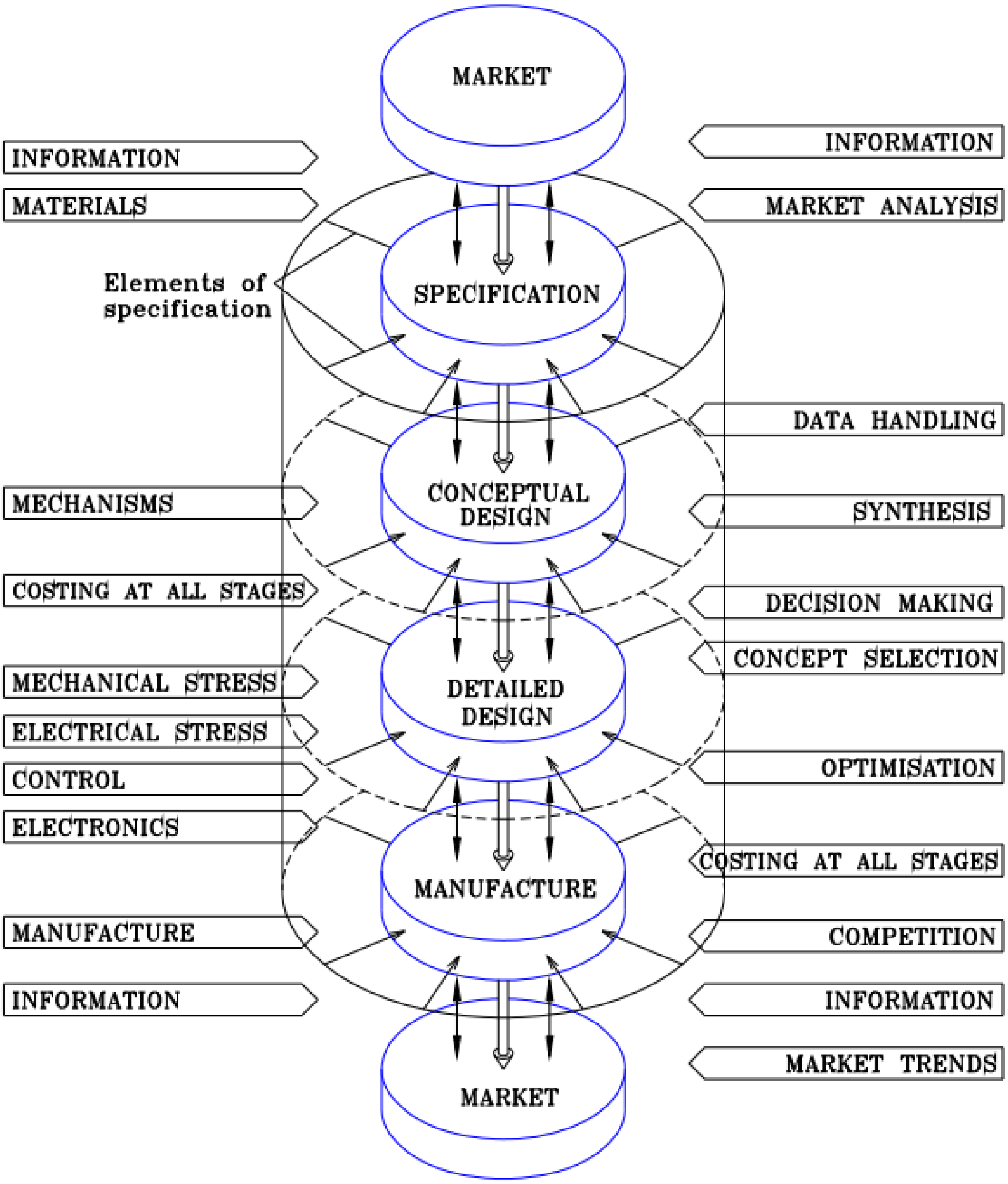


Figure 3.4: Total design models proposed by Pugh [156]

The total design is defined as a systematic and flexible framework that encourages interdisciplinary inputs and combination with various techniques and computer-aided tools [152] [155].

Table 3.3: Summary of Pugh Methods- Strengths and weaknesses

Strengths	**Limitations** [152]
Ability to simplify the required design inputs. Problem-oriented approach Strategic method prioritising classification of tasks and validating process. Iterative feedback working methodology	Requires extensive know-how. Exhaustive and lengthy approach Flexible approach Restricting creative thinking Also seen as too prescriptive and serialistic as opposed to holistic. Control over application of the tool

The total design method has been criticised as being over-formalised, thereby posing a hindrance to creativity. Childs [152] describes the Pugh model as " …a product creation model that requires an understanding of the mental process as a driver in the development of design methodologies that allow us increasingly to exploit the creative process and therefore even better models will in due course emerge".

The comprehensive design tool aims to structure and follow a strategic method to the design due to the complexity and nature of product design processes. The design structured approach is an essential design methodology that requires adaptation of creativity's mental processes.

3.3.3. Innovative and Creative thinking methods

Innovation is broadly defined as "the ability to continuously transform knowledge and ideas into new products, processes and systems, to the benefit of both the organisation and the shareholders" [157]. According to [158] [159], the different definitions of innovation focus on newness, improvement and spread. Innovation has been defined in various ways due to unmet user needs, problem-solving, creativity, organisational restructure, and applied invention [157]. There has been a consistent change over the years to move towards more inventive ways of thinking to keep advancing growth, processes, and services within organisations. These theories and definitions of innovation focus on a specific situation or state of the system of interest. The innovation sought might differ from one system to another; the innovation approach can be commonly defined.

Creative and innovative thinking is one of the opportunities for driving significant progress and achieving success. Cognitive processes have looked at vast approaches to creativity that have resulted in methods, tools and models involving creative guides, application, methodologies. Consequently, this section aims to review existing creative thinking approaches, innovation theories, methodologies, and techniques and discuss their objectives, applications, strengths and weaknesses, and the complexities of systematic design methods.

In the early 1970s, creativity was measured by the rate of ideas a person would come up with over a specific time. The assumption was that a “quantitative increase of ideas would necessarily bring about a qualitative improvement” [136] [160].

There have been numerous work dedicated to the understanding of creativity, describing the different approaches used in studies of creativity and the factors affecting creativity such as social impacts, nature influences, and other issues [161] [162] [163] [164] [165]. Robert J. Sternberg, in the handbook of creativity [164], describes creativity as “…the ability to produce work that is both novel and appropriate”. Mark Runco defined “creativity as a useful and effective response to evolutionary changes, besides, to be part of a problem-solving process; that allows individuals to remain flexible” [162] [165].

From the various definitions, creative thinking can be described as the ability to imagine and invent something new from initially generating several (fresh, unorthodox, outside the box) possible solution paths in time, and evaluating the effectiveness of these solutions, to choosing and implement the best solution. It contributes to change and evolution as a reaction to problems or challenges.

Several methods and techniques have been identified for applying creative thinking and producing creative results. Some of the most common techniques are brainstorming, lateral thinking, Synectics, random simulation. These techniques mostly use five fundamental methods: incremental improvement (evolution), synthesis of existing ideas, revolutionary approach, reapplication beyond the stated application, and creative insight (a complete shift or changing of direction).

Although there is a vast amount of innovative and creative problems solving methods, only a few are reviewed here based on the adequate amount of literature available, their popularity (again based on available literature), and the cognitive approach. These creative methods are explored further below:

Brainstorming

One of the earliest publications on principles and procedures of Creative Problem Solving was the *Applied Imagination* book by Alex Faickney Osborn [137] , founder of an American advertising agency, in which he introduced the techniques of Brainstorming.

"brain to storm a problem" [166], is a technique that gathers a group of people to generate as many new ideas as spontaneously as possible to obtain solutions around specific challenges. This technique emerged back in the 1940s, introduced by Alex Faickney. Osbon developed creative thinking concepts and later published them in [136] [135]. The technique encourages capturing all ideas as they are brought forth with no evaluation or criticism allowed; wild, outside-the-box, impractical ideas are encouraged. All the ideas are then improved or built upon by adapting, adding, combining, or evaluating the promising ideas to generate a list of promising practical solutions.

Table 3.4: Brainstorming -Summary of strengths and weaknesses

Strengths	Limitations
Accessible to any industry Encourages free speech through spontaneous thinking, creativity, discovering new perspectives. Enables equal participation, organisation buy-in	Time-consuming before a solution is reached. Functional fixedness or bias from the group Requires preparation and commitment to an adopted creative process. Based on intuition and team knowledge Might result in unrepeatable or unpredictable outcomes

Synectics

Synectics is a creative problem-solving method developed by William Gordon and George Prince in the late 1950s. Derived from the Greek words "syn" meaning "bring together" and "ectikos", meaning "diversity", the approach aims to "demonstrate the power and value behind non-traditional creative thinking practices versus traditional, analytic thinking processes" [116] [167]. Gordon & Prince explained: "…People rely heavily on their analytical ability and find it very difficult to entertain ideas that they are foreign to the rules that have learned; because the conscious mind tends to be inhibited by the logical basis, the learning, and known hypothesis" [75] [168]. The approach suggests that where all humans are born creative, this is hindered by their failed experience, destructive thinking, and behaviour habits. In the publications *Synectics* [116], and *The Practice of Creativity* [168], Gordon and Prince investigated the impacts of creative thinking and the interaction between psychological mechanisms during a creative process. Gonzalez defines the method as a "Logical analysis of the assumptions, beliefs and values underlying the conduct, thought, knowledge and nature of a phenomenon" [167].

Synectics method is based on analogical thinking encouraging speculation and creative behaviours, tapping into the emotional and irrational components, i.e. The notion of making the strange familiar and the familiar strange, to achieve creative solutions.

Table 3.5: Synectics summary of strengths and weaknesses

Strengths [116] [167] [168]	**Limitations** [167]
Recognises functional fixedness due to norms, rules, and belief systems. Encourages ideal thinking via the use of metaphors and analogies, emotional and irrational components. Encourages group cohesion and Creative-thinking techniques.	Extensive time in learning & implementing techniques. Difficult to make the problem-solving process explicit. More complex for Multi-level analysis filtering from the level of abstractions

Lateral thinking

As opposed to vertical or logical thinking, lateral thinking can think creatively to solve a problem, a disruptive thinking sequence that solves a problem from another angle. Edward de Bono, a leading author on conceptual thinking, defines lateral thinking as a "deliberate process of using the mind as logical thinking- but in a very different way" [169]. This process brings about the description of achieving results creatively. On the one hand, Lamb [170] defined lateral thinking as "an integrative cognitive system responsible for integrating disparate outputs, and production of new, original, and divergent products". On the other hand, Gonzalez [167] argues that lateral thinking is not a creative problem-solving method or framework but a "behavioural approach concerned with changing concepts, patterns and perceptions".

From the various literature [167] [169] [170] [171] [172], the core of lateral thinking is to break the established "linear or vertical" thinking process to see the world (conflicts, problems, challenges) from different perspectives, and in turn, generate novel solutions. This approach led to the development of several thinking concepts and techniques such as the Six Thinking hats (Parallel thinking)- designed to maximise thinking in specific directions at a specific point in time, Direct Attention Thinking Tools (DATT)- designed as a ten-strategy tool to allow the user to weigh risks, reach solutions, and remove obstacles quickly; and Cognitive Research Trust (CoRT) thinking- designed as lesson packages for constructive thinking in schools.

As a whole, the lateral thinking approach was reviewed, including De Bono's various toolkits and techniques to compare the strengths and weaknesses in relations to their approach to the systematic design process, creativity, and risk mitigation.

Table 3.6: Strengths and limitations of Lateral thinking

Strengths [145] [172]	**Limitations** [167] [170]
A radical approach to creativity (Seeking alternatives, challenging assumptions, looking beyond "the obvious." Based on provocation (think outside the box) & movement (deferred judgements)	Not a holistic process but a combination of individual techniques (evaluation, refinement, implementation) May lead to a wide range of results; Incomplete on its own- requires vertical thinking

As highlighted in Table 3.6, lateral thinking is one of the many toolkits developed by Edward de Bono that systematically encourages various thinking tools to address issues or problems. Ensuring the right tools is critical to solving the problems.

3.3.4. Theory of Inventive Problem Solving

TRIZ, a Russian acronym ''Teoriya Resheniya Izobretatelskikh Zadatch'' translates to the Theory of Inventive Problem Solving, is a problem-solving tool based on resolving conflicts between design properties or requirements. The tool was invented and developed by the Soviet inventor Genrich S. Altshuller and colleagues from 1946 in the USSR [173] [174]. The problem-solving tool goes beyond intuition, used logic, data, and research derived from studies of invention patterns in the global patent literature - patterns of inventive solutions to specific fundamental problems [173] [175].

TRIZ provides a toolkit of instruments and tools to support creative thinking in solving conflicts in design and finding an ideal solution without compromise. These design conflicts arise when increasing the value of the design of one feature of the design is a detriment to another feature.

TRIZ has been described in various ways in the literature as a methodology, a science [176], a philosophy [177], a toolkit. Semyon Savransky [178] defines TRIZ as “a human-oriented knowledge-based systematic methodology of inventive problem solving; Approach that combines the knowledge of philosophical concepts, the results of cognitive sciences for suppression of psychological inertia, the use of nature science effects and phenomena for improving technical systems and technological processes, and analysis of breakthroughs to recognise design principles to extract trends in technology evolutions”. Fey and Rivin [179] describe TRIZ as a systematic innovation methodology for developing new systems, including principles that describe how technologies and systems evolve. Gadd [81], and Livotov [180] describe TRIZ as a comprehensive toolkit for inventive and creative thinking methodology and comprises all problem-solving attributes.

The value of TRIZ is “ the suggestion of innovative principles that may stimulate the TRIZ practitioners’ creative thinking in overcoming a design conflict” [146]. TRIZ tools are primarily based on two concepts: (1)- generalising problems and solutions and (2)- eliminating contradictions.

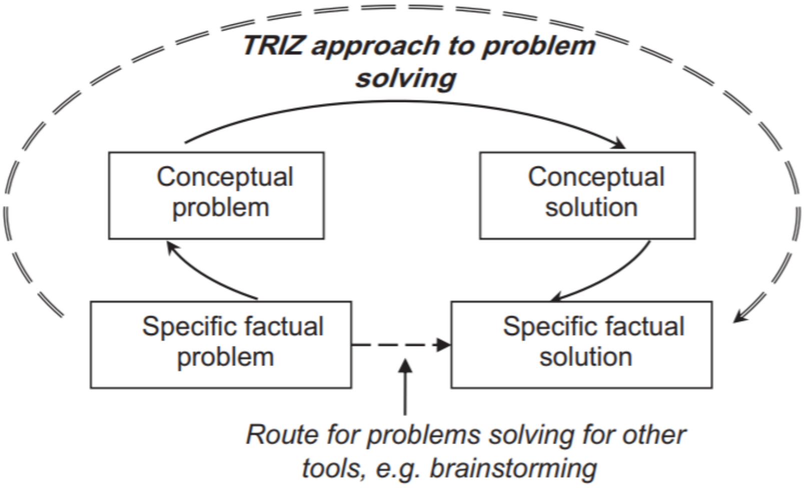
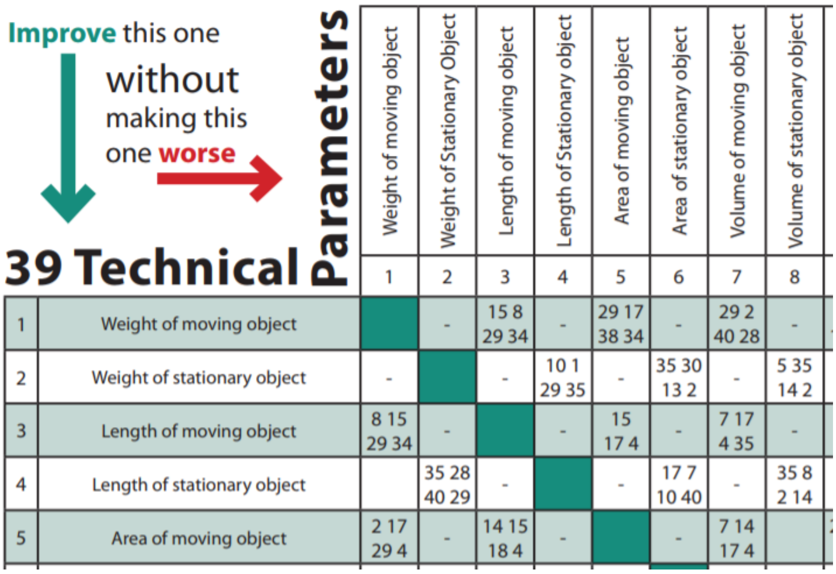


Figure 3.5: TRIZ systematic approach to problem-solving [173] [181]

TRIZ comes with a range of tools and techniques beyond the basic principles outlined above. These presented in the next subsections.

TRIZ Contradiction Matrix

The contradiction matrix, also known as the 39 Engineering parameters, consists of specific parameters identified by Altshuller that can improve or worsen the design of a system. The 39X39 contradiction matrix presents these parameters based on their ability to either improve or worsen the design or operational conditions [173] [176]. Figure 3.6 represents the improving features on the first column and worsening features on the top row. In each of the matching square is a list of inventive principles that can resolve the contradiction. Various software has implemented this matrix into algorithms following a step-by-step process to solve the contradictions (e.g. TechOptimizer, Goldfire Innovator, CreaTRIZ, TriSolver, TRIZ Explorer, TRIZContrasolve, Guided Brainstorming) [170] [171]. The full 39X39 contradiction matrix is shown in Appendix Table 9.24.



Improve this one without making this one **worse**

39 Technical Parameters

		Weight of moving object	Weight of Stationary Object	Length of moving object	Length of Stationary object	Area of moving object	Area of stationary object	Volume of moving object	Volume of stationary object
		1	2	3	4	5	6	7	8
1	Weight of moving object	🟩	-	15 8 29 34	-	29 17 38 34	-	29 2 40 28	-
2	Weight of stationary object	-	🟩	-	10 1 29 35	-	35 30 13 2	-	5 35 14 2
3	Length of moving object	8 15 29 34	-	🟩	-	15 17 4	-	7 17 4 35	-
4	Length of stationary object		35 28 40 29	-	🟩	-	17 7 10 40	-	35 8 2 14
5	Area of moving object	2 17 29 4	-	14 15 18 4	-	🟩	-	7 14 17 4	

Figure 3.6: Partial representation of the TRIZ 39X39 Contradiction Matrix

Typical contradictions, as presented in Figure 3.6, can be grouped into physical contradictions and technical contradictions.

- Physical contradictions refer to object or system subjects to harmful impacts due to different requirements. An example will be a car should be user-friendly and simple enough to drive but at the same time complex with the most advanced features such as contactless, driverless, and fuel-efficient.

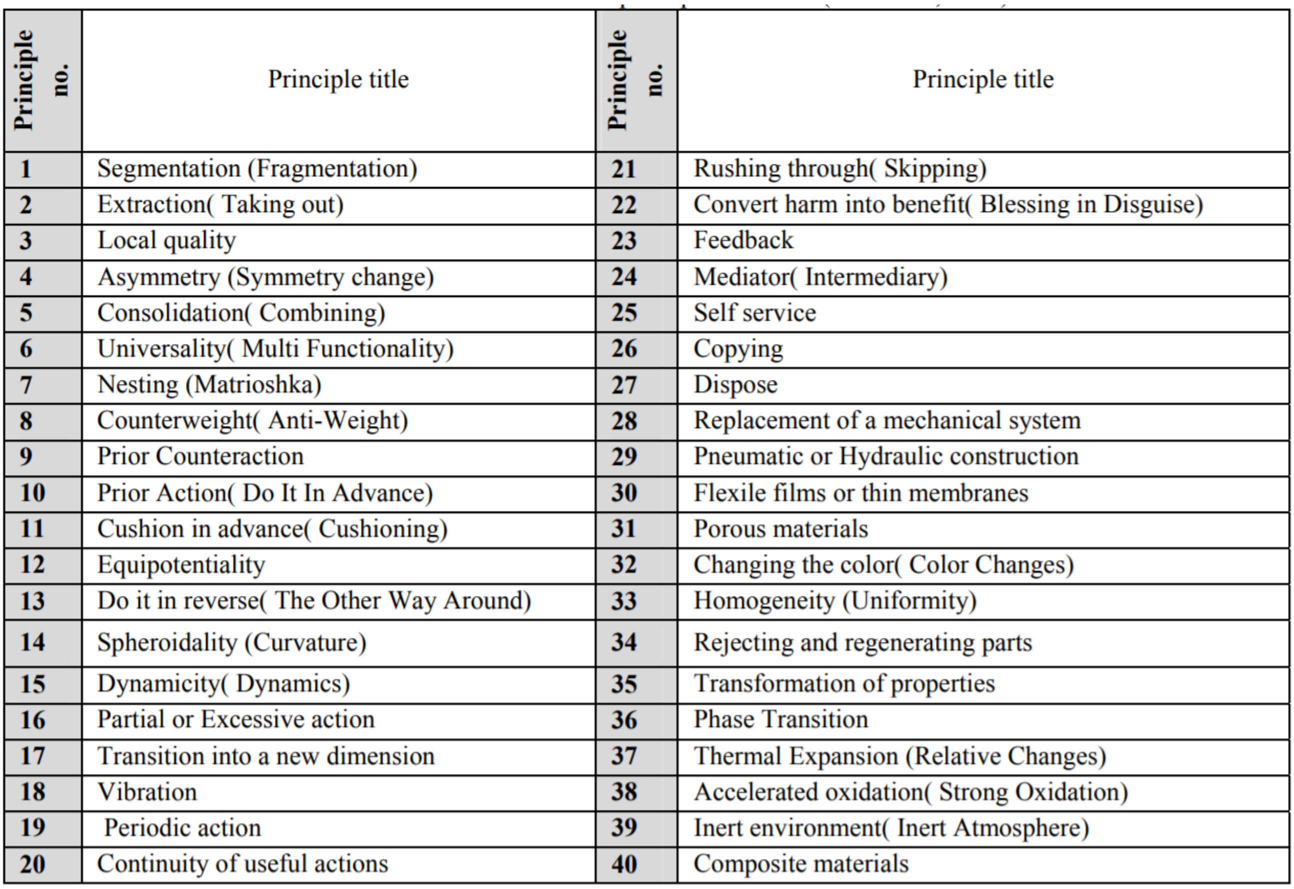
- Technical contradictions, on the other hand, are typical trade-offs in the system. E.g. direct-drive generator machines are more reliable than geared machines.

TRIZ Inventive Principles

What is usually done when contradictions arise during the design of products or processes, a trade-off of one design parameter at the expense of another occurs. The standard or traditional approach resolves around the brainstorming and trial-and-error process, resulting in the inability to resolve contradictions beyond existing knowledge and experience. Altshuller reviewed hundreds of thousands of patents and inventions and came up with the distinguished 40 Inventive Principles based on breakthrough inventions. These inventive principles are solutions to overcome the contradictions patterns described in the 39X39 contradiction matrix [174] [184]. The contradictions and inventive principles are generic enough to apply to various sectors.

Each matrix cell points to inventive principles that have previously been used to resolve the contradictions. These principles will have to be evaluated to determine the most relevant one for the system.

Table 3.7: TRIZ 40 Inventive Principles [185]



Principle no.	Principle title	**Principle no.**	Principle title
1	Segmentation (Fragmentation)	**21**	Rushing through(Skipping)
2	Extraction(Taking out)	**22**	Convert harm into benefit(Blessing in Disguise)
3	Local quality	**23**	Feedback
4	Asymmetry (Symmetry change)	**24**	Mediator(Intermediary)
5	Consolidation(Combining)	**25**	Self service
6	Universality(Multi Functionality)	**26**	Copying
7	Nesting (Matrioshka)	**27**	Dispose
8	Counterweight(Anti-Weight)	**28**	Replacement of a mechanical system
9	Prior Counteraction	**29**	Pneumatic or Hydraulic construction
10	Prior Action(Do It In Advance)	**30**	Flexile films or thin membranes
11	Cushion in advance(Cushioning)	**31**	Porous materials
12	Equipotentiality	**32**	Changing the color(Color Changes)
13	Do it in reverse(The Other Way Around)	**33**	Homogeneity (Uniformity)
14	Spheroidality (Curvature)	**34**	Rejecting and regenerating parts
15	Dynamicity(Dynamics)	**35**	Transformation of properties
16	Partial or Excessive action	**36**	Phase Transition
17	Transition into a new dimension	**37**	Thermal Expansion (Relative Changes)
18	Vibration	**38**	Accelerated oxidation(Strong Oxidation)
19	Periodic action	**39**	Inert environment(Inert Atmosphere)
20	Continuity of useful actions	**40**	Composite materials

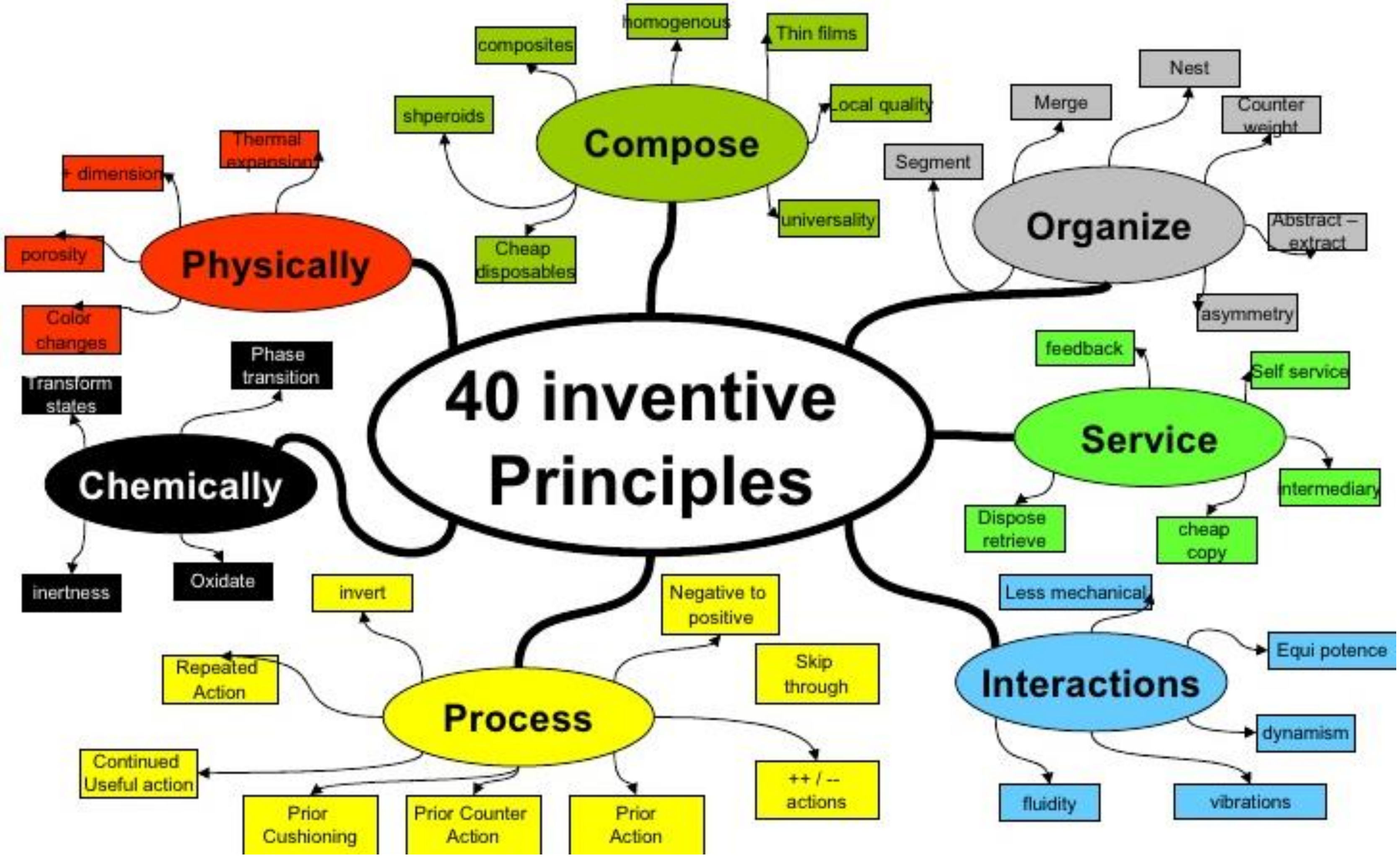


Figure 3.7: Mind Map- TRIZ 40 inventive principles (slide 22/33 of [186])

TRIZ Separation Principles

What about contradictions within a parameter? If a cup of coffee is needed hot but cool to touch, TRIZ separation principles consider problems in time, in space, between parts and whole, and upon conditions. The physical contradictions are resolved by separating the contradictory requirements.

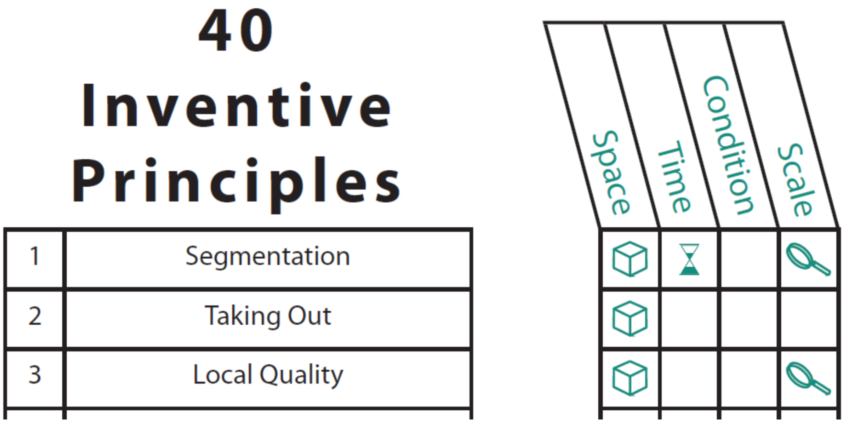


Figure 3.8: A screenshot illustrating the 40 inventive principles in time, space, condition and scale.

In time, the schedule of operations may be arranged so that requirements are met at each time or phase of operation (one example of that would be the traffic lights). In space, the contradictory requirements are defined in phases, where a particular phase or sub-system does not require a specific implementation of parameters (e.g., a seesaw or bi-focal reading glasses). The separation between part and a whole considers using the characteristics of a system to be represented as parts of the system, meaning - "at the same critical moment in time and the same space, a grouping of objects can have a collective property, and its parts can have the opposing property" [187]. This enables minimal critical interaction with some parts of the system. An example of that would be a sub-structure with mooring lines for redundancy measures. If a mooring line fails, the station keeping of the sub-structure will not be affected as a whole. Moreover lastly, separation under different conditions means the design will consider achieving one requirement in one condition and another in another condition (e.g. transition glasses) [176] [187].

TRIZ trends of Evolutions

The eight trends of evolution refer to the profile of observed technologies or systems as they mature. These trends map out the patterns to construct technology or system roadmaps.

Table 3.8: The 8 TRIZ patterns of innovation (adapted from [188]

Evolution trends	***Descriptions***
Evolution Toward Increased Ideality	Maximise the ratio of useful to harmful effects and approach ideality.
Stages of Technology Evolution	S-curve that forms the basis of the maturity: from concept to commercialisation, value-added and return-on-investment, to decommissioning.
Non-Uniform Development of System	Non-linear S curve systems with different components, schedules, and their inherent limits
Toward Increased Dynamism and Controllability	More flexibility of system over time means easier to control
Increased Complexity, Then Simplification	More features and functions but simpler over time with multi-functional capability, automation
Evolution with Matching and Mismatching Elements	Ability to use matched or mismatched elements of the system to improve performance or compensate for undesired effects
Evolution Toward the Micro-level and Increased Use of Fields	The transition from macro- to micro-systems, with different energy fields, used to achieve better performance and control during this transition
Evolution Toward Decreased Human Involvement	A trend toward automation & integration (e.g. Alexa, driverless cars)

TRIZ Standard Solutions

Different systems have different problems with specific solutions in various sectors. Altshuller identified and documented TRIZ 76 standard solutions- "…a set of standards directly derives from the laws of technical systems evolution, guiding the synthesis and transformation of these systems by implicitly eliminating technical contradictions" [189]. These solutions represent standard solutions to typical types of problems not related to specific areas of technologies. Used as part of the Substance-field analysis (Su-field model) - an abstract solving and interpretation method, the standard solutions tool help identify constraints and effectively achieve innovative solutions.

The strategies of innovation in the Standard Solutions tools are classified into five groups:

- Improvement by creating, transforming, and eliminating the element of the systems;
- Improvement by development or substantially change the systems;
- System transition (from system to system of systems, or microsystems)
- Standard detection and measurements of the system.
- Guidelines on the application of simplifications and improvements of solutions

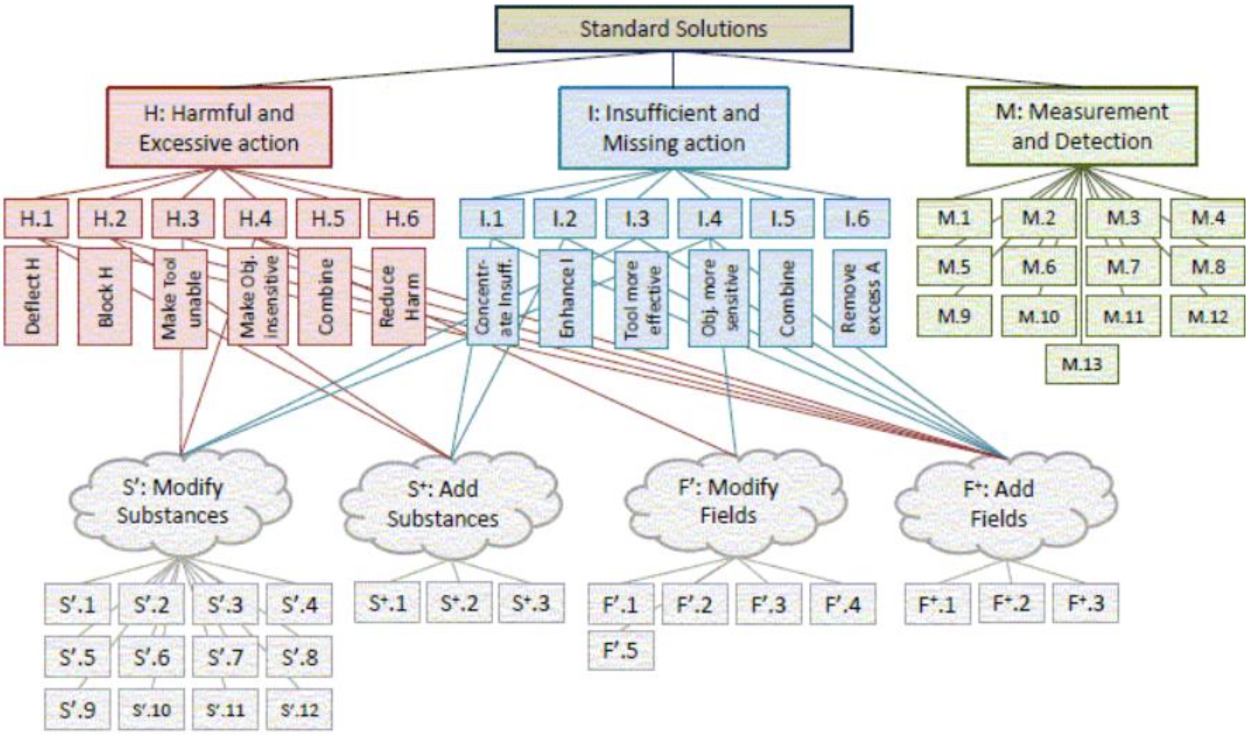


Figure 3.9: Example of a standard solutions Map [*[190]*

Having reviewed the literature around what TRIZ is, its offers, users of the TRIZ toolkit will implement the most appropriate or combined method(s) to eliminate the harmful effects and retain the system's useful functions. Many authors have researched the methodologies of TRIZ tools and applications. Some examples can be found in [176] [186] [188] [189] [191].

Table 3.9 highlights the benefits associated with TRIZ knowledge and the challenges associated with its application.

Table 3.9: Strengths and weaknesses of TRIZ

Strengths [178] [181]	**Limitations** [180] [181]
A focussed and structured approach to thinking Knowledge-based systematic methodology covering all aspects of problem understanding and solving. Comprehensive for inventive and creative thinking Predictable and governed by certain laws	Difficult to adapt to various situations. Investment in time and resource for training & application of the tool Adoption and integration issues in existing organisational cultures

TRIZ has been one of the most widely used tools for discussing group creativity, obtaining many potential innovative design options using inversion and analogies [169] [180]**.** TRIZ application has been extended to various derivatives for specific applications. A few TRIZ derivative examples are SIT (Systematic inventive thinking), USIT(Unified Structured Inventive Thinking), TRIZICS (Methodology for systematic application of TRIZ).

One of the TRIZ derivatives is presented below:

Unified structured inventive thinking

The Unified Structured Inventive Thinking (USIT) is a tool developed in the mid-1990s and adapted into the automotive world by Ed Sickafus at Ford Motor, intending to simplify and reorganise TRIZ into a ‘six-box scheme of creative problem solving’ in non-technological domains by multidisciplinary teams [193] [194]. According to [193], the goal of the USIT is “to enable analysts or designers to invent multiple solution concepts in a short time as possible for real-world problems”. The methodology focusses on three stages:

- Problem situation and definition- focussing on identifying and filtering out the unwanted effects of a situation and defining the problem within its boundaries,
- Problem analysis uses the various processes within the USIT to ways to view the problems.

- Problem solutions apply techniques based on the objects, attributes and functions defined.

The common philosophy to these innovative methods, illustrated in Figure 3.10, is the push for continuous improvement to the products, to the organisation and the specific sectors.

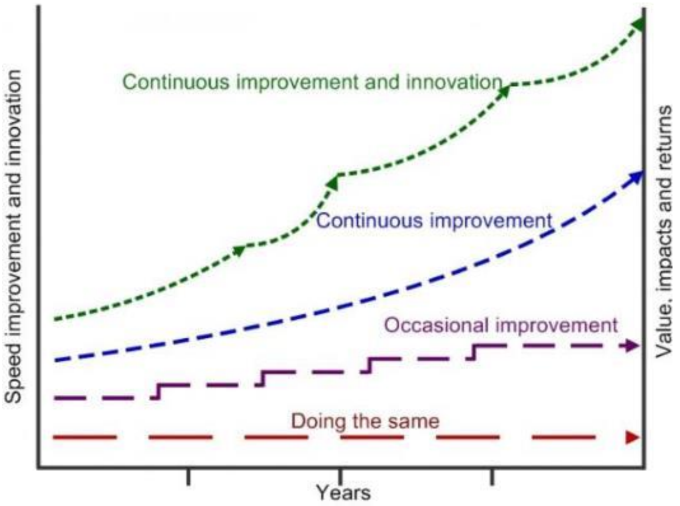


Figure 3.10: Illustration of relative value from continuous improvement and innovation [195]

3.3.5. Axiomatic Design

Axiomatic Design (AD), developed by Nam Pyo Suh in 1970, is a methodology used to identify fundamental laws for solution finding and decision making in engineering design. The name derives from the word “axiom”, meaning fundamental truth and attempts to approach a design from an alternative perspective [125] [126]. The objective of the tool, as described by Suh, is to “establish a scientific basis for design” [125].

In his research [125] [126] [196], Nam P. Suh acknowledges the limitations of the available information in the initial phases of a design process. Where Taguchi’s method [127] uses a “combination of statistical techniques to improve quality in product design and manufacturing processes” [126] [127] [196], Suh proposes the Axiomatic Design techniques as a way to evaluate decisions made during creative processes using axioms as basic principles using formal logic [196]. The design techniques aim to establish design objectives that satisfy customers, generate ideas for plausible solutions, analyse alternative solutions and implement the selected design. Thus, it applies to the design’s concept stage to satisfy the conceptual design technique [196].

The AD methodology is based on four domains: the customer domain, the functional domain, the process domain, and 4- the physical domain, as shown in Figure 3.11.

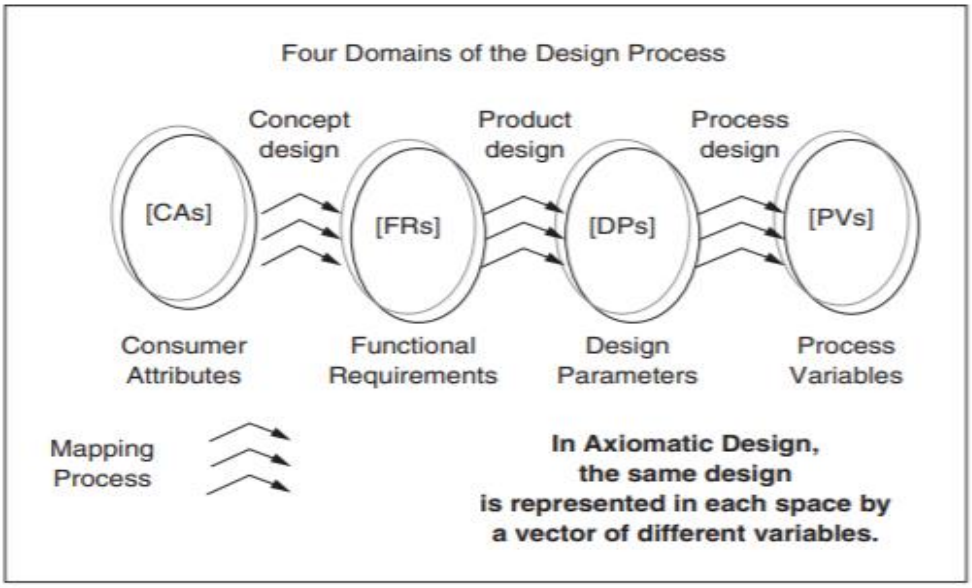


Figure 3.11: Design process from an Axiomatic Design perspective [145]

Customer's needs, referred to as Customer Attributes (CA), are determined in the customer domain. The Functional Requirements (FRs) and Constraints (Cs) are defined in the functional domain, and the Design Parameters (DPs) are derived to satisfy the FRs. The Process Variables (PVs), describing the processes needed to fulfil the FRs, are developed in the process domain.

Identifying and satisfying the motivation of the customers is key to the AD methodology and is based on two axioms: Axiom 1- Maximum independence, the independence axiom, can be stated in several ways but maintain the independence of the functional requirements and design parameters; Axiom 2- Minimum information; and well-defined theorems specific to each [196]. These axioms can be used as basic principles or logical arguments to evaluate the decision made at the earliest concept stages, with more qualitative rather than quantitative information.

According to Dieter and Schmidt [197], AD's strength lies in its mathematical base, where its model of axioms, theories, and corollaries are made with a mathematical approach. However, Benavides argues in [196] that the "weaknesses of AD lie in the fact that the axioms must be true to accept the methodology". Table 3.10 summarised the high-level method's strengths and weaknesses.

Table 3.10: Axiomatic Design- Strengths and Weaknesses

Strengths [196] [197]	**Limitations** [145] [146] [198]
Separation of functional requirements and constraints in formulating the design problem. A solution-neutral approach- design problems approached independently of any solutions. Based on the mathematical model of axioms, theories, and corollaries-hence applicable to many fields.	The axioms must be true to accept the methodology, and there is no proof that the independence axiom is false. Seen as complex for design systems at a project level but more useful at a component level. Require extensive training with examples of solutions & organisation cultural change. Does not offer innovative solutions to uncouple identified couplings

3.3.6. Quality Function Deployment

Quality Function Deployment (QFD) is a quality customer-driven design methodology that supports the design process for product development. The QFD was developed in Japan by Yoji Akao and Shigeru Mizuno in the late 1960s to ensure the Voice of Customers (VoC) features in the design engineering characteristics of products being developed [199]. As a structured approach, QFD is used to identify, prioritise the VoC and translate them into applicable technical requirements for each stage of product development and production. It is achieved using the House of Quality (HoQ), which is a matrix used to describe the most crucial product or service attributes or qualities [200] [201]. The step-by-step process is achieved by constructing a single or series of HoQ matrices to translate the customer needs into design characteristics, manufacturing target and final products ready for deployment. This approach allows collaboration between the various teams and capturing and visualising information in one place.

QFD has been defined in literature as an approach, a method, a system, customer-driven engineering, a product planning tool, decision matrices. The QFD Institute, for instance, defines QFD as “ a comprehensive quality system that systematically links the needs of the customer with various business functions and organisational processes, such as marketing, design, quality, production, manufacturing, sales, aligning the entire company toward achieving a common goal” [202]. Common across all the authors and practitioners definitions is the mutual understanding of the QFD's ability to ensure the customer needs and desires are integrated into a product's final design.

In the conventional QFD, the step-by-step process is linear and can be performed in four phases: product planning to design deployment, manufacturing, and product deployment. Each phase will have a common approach to building the HoQ:

1- Define & prioritise the Voice of the Customer or Customer requirements (WHATs)
2- Define the Technical descriptors to each requirement (HOWs)
3- Describe the strength of relationships between the WHATs and HOWs.
4- Understand the relationships between the HOWs (strong, weak, and positive or negative, meaning conflicts)
5- Assess competitive advantages(HOW MUCHs)
6- Prioritise the Technical descriptors (HOWs)

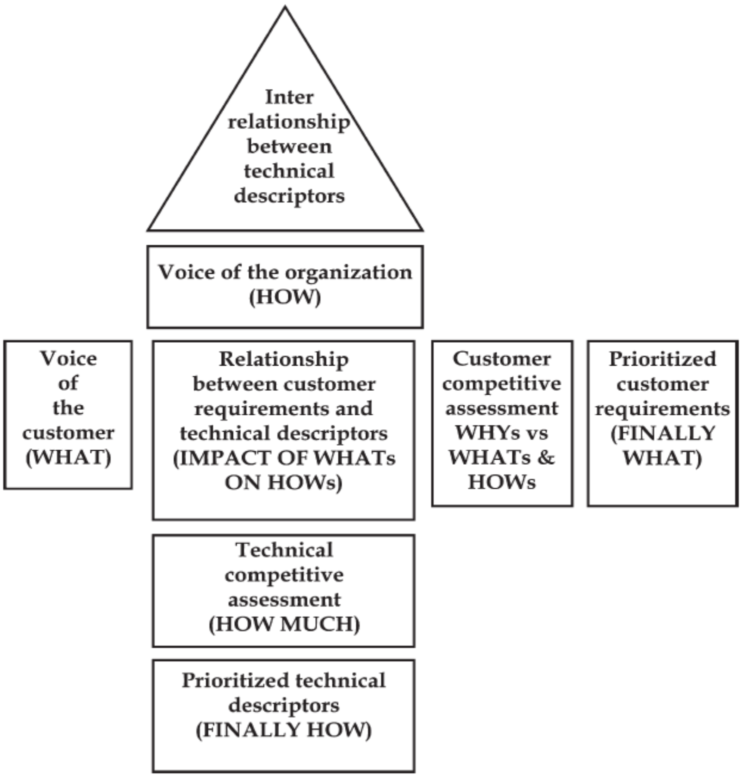


Figure 3.12: Building the House of Quality (HoQ) [201]

The traditional QFD approach continues to evolve in response to the various needs of the industries- market and business practices, technology, customer lifestyle. Modern QFD, derived from the Blitz approach, was developed in response to "today's business models that are agile, global and technology-infused" [179]. The adapted QFD approach, part of the

ISO 16355, aims to tailor the QFD processed on the Voice of business, enabling a focused approach on speed and efficiency, capturing the unspoken customer needs, including psychological and lifestyle needs [202].

Research shows that the QFD method provided to practitioners and organisations several benefits. Table 3.11 presents the different benefits and limitations of using QFD.

Table 3.11: Strengths and weaknesses of TRIZ

Strengths [146] [199] [201]	**Limitations** [146] [203] [204]
Integrate customer needs into the design resulting in improved customer satisfaction. Reduces implementation time – future development redundancies, assumptions. Promote teamwork- structured documentation visually tracked and adaptable to changes. Translate qualitative user needs to quantitative parameters	The qualitative nature of QFD Complex multi-level analysis & Data-intensive Not offering direct innovation tools but coordinate the thoughts of the customer and designer. Risk of functional fixedness considering 'easy solutions.

Table 3.12: QFD comparison Original vs Modern QFD [205]

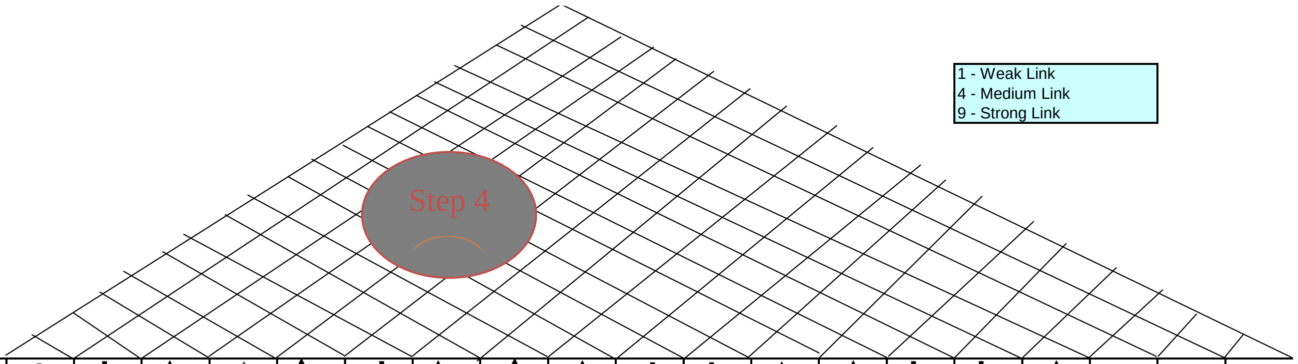
	Original QFD	**Modern QFD (ISO)**
Emerged	1980	2009
Aim	Automobile component industry	Standardise global best practices for QFD and robust design beyond the automobile
Added value		Time, people, constraints
Application	Classical 4-phase model	Design for Six Sigma Lean Sigma Design for Lean Sigma Mazur 2012 Hoshin Kanri (policy deployment)

ISO 16355- a descriptive standard that recommends the use of the QFD and its methods as a framework for product development, and not prescriptive- requiring a specific sequence or set of tools) [206]

Table 3.13: QFD Original and Modern comparison in terms of process

Classical QFD	**Modern QFD**
Start- Voice of the Customer	Start- Voice of the Business (satisfy internal drivers and strategies). Include Policy deployment (Hoshin Kanri)
Capturing the customer needs	Gemba- crime scene: Evidence of needs/ requirements (spoken and unspoken needs)- how to capture & analyse
Use HoQ matrices and charts to address all the aspects of product quality	Prioritise efforts where they matter most to the customer. The Maximum value table uses all matrices' key elements into one chart by focusing only on the top 3-5 customer needs.
From Customer requirements to functional/product requirements	From market/customer requirements to product requirements and specifications. - what the product does - Technology agnostic of how it is performed. - Translation using cause-to-effect and effect-to-cause diagrams
Calculation/ assessment based on ratings using 1-5 ordinal scale	Changing the ratio scale values in all QFD calculations- project selection, customer importance and satisfaction, competitive benchmarking, HoQ matrices, technology selection, FMEA. ** Use of Analytic Hierarchy Process (AHP) to develop these scale values

QFD Study
for the
Electrical Driveline



1 - Weak Link
4 - Medium Link
9 - Strong Link

Direction of improvement		↓	↓	↑	↑	↑	↓	↑	↑	↑	↓	↓	↑	↑	↓	↓	↑			
		Solutions																		
Hows	**Maker Importance**	Lowest Component count	Low mass LRU	Device gearing or amplification	Full power conversion	…ant and bypass systems	…n Based Mon… …ance	Direct Drive electric…	High drive to line efficiency	No Divers required, ROV use minimised	Material selection using low amounts of rare / costly parts	Subsea foundation number reduction	Customised installation Vessel	Integration and modularity for driveline	Effective Array Design Tools	Cost Effective, reliable Offshore umbilical connectors	Optimisated structural devices (Stiffness / Mass Ratio)			
System Requirement — Low Capital cost to Power rati	8	9	4	9	4	[illegible]	[illegible]	9	9	4	4	4	4	9	1	9	9			
Machine Efficiency	6	4		9	9	[illegible]	[illegible]	9	9	4		1	1	9	9		4			
Driveline System Low Mass	4	1	1		4	[illegible]	[illegible]			4	9	1		4			1			
Maximised Availability	10	9	9	4	4	9	9	4	4	1	1	4	4	9	1	9	4			
Quick and simple to install and commission	7	4	9	4	9	1	4	4		9		9	9		4	9	9			
Short lead time to make and deploy	1	9	1	9	4	1		9		9	9	9	9	9		4	9			
Resistance to Grid faults, distrubances, LVRT	2	4	1		4	9	9		4	9			[illegible]	[illegible]		1	1			
Graceful degradation	3		1	4	1	9	4	4	4		1	4	[illegible]	[illegible]		1	1			
Grid Code Compliance	6	1			9				4		1		[illegible]	[illegible]		4				
Proven Design, reduced risk, [illegible] and relaibility	9		1	4	9	1	1	4	9	1		4	[illegible]	[illegible]	9	1				
Manufacturing / Supply Chain impact																				
How Much / Description		5 main components	25kG mass	Greater than 5:1	100% Power	N+1 redundancy, no single point of failure	Monitoring 95% of monitorable parameters, lower cost by 0.8p/kWh	No gears or aux drives	Greater than 95%	8 hours per inmstallation	Materials Audit strategy	Less than 5	HD vessels able to meet demands	Driveline made from modules designed for adaptability, maintenanc and production						
Engineering Assessment (1= low, 5= highly difficult)																				
Organisational Impact (High = most difficult)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Customer's Absolute Importance		**235**	**195**	**215**	**220**	**221**	**220**	**215**	**186**	**172**	**90**	**166**	**158**	**270**	**100**	**234**	**217**	**0**	**0**	**0**
Importance Ranking		2	10	8	5	4	5	8	11	12	16	[illegible]	14	1	15	3	7	17	17	17

Step 1

Step 2

Step 3

Step 5

Step 6

Step 7

3.3.7. Manufacturing methodologies

The automotive industry has evolved significantly over the years, along with the manufacturing methodologies to maintain its competitive advantages. Automotive companies, such as Ford and Toyota, have been the enablers behind the need for methodologies providing guidelines and techniques to improve their end-products' quality.

Some of these methodologies are Total Quality Management (TQM), Six Sigma, and Lean Production. The methodologies are discussed briefly in this section:

Total Quality Management (TQM)

TQM is a quality management approach focusing on continuous quality and performance improvement to meet or exceed customer needs. The TQM approach's quality discipline embeds strategy, data, and effective communication into its culture and activities [207]. “Do the right things, right the first time, every time” [208]. Developed in response to the Japanese Deming application prize’s competition and W. Edwards Deming's work, TQM became popular in the early 1990s.

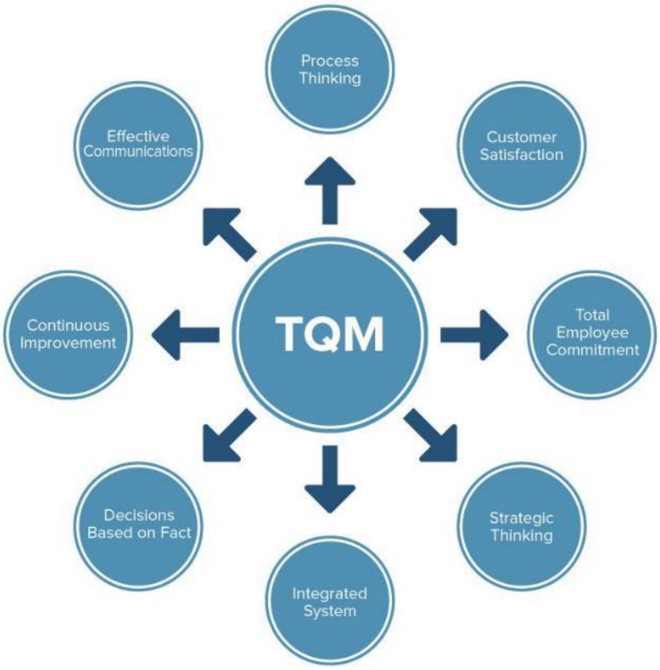


Figure 3.13: The eight principles of TQM [209]

The eight main principles of TQM are:

1. **Customer satisfaction**: The quality of a product is determined by the customer.
2. **Total Employee commitment**: The whole organisation shares the vision, and "all employees participate in working towards common goals". The organisation is encouraged to invest in empowering employees by providing: all employees' training, recognition and celebration schemes, self-managed work teams, high-performance work systems. [207] [208]
3. **Strategic thinking** is the strategic and systematic approach to achieving its mission, goals, and vision. This stage includes all the strategic planning and management commitment and processes to integrate quality as a core component. This stage has been often defined as Plan-Do-Check-Act (PDCA) approach, where Plan (drive, direct), Do (deploy, support, participate), Check (review), Act (recognise, communicate, revise) [207] [208].
4. **Integrated system**: This step emphasises the horizontal processes interconnecting the different departments and specialities of the organisation to continuously improve and exceed the customer, the employers, and the stakeholders' expectations.
5. **Fact-based decision making:** This step continually measures the organisation's performance to enable accuracy in decision making, predictions, and consensus. Some of the tools used are statistical process control tools, Failure modes, and event analysis (FMEA) TOPS- Ford 8D's team-oriented problem-solving. [207] [208]
6. **Continuous improvement:** These steps ensure the organisation continuously attain, maintain, and improve its processes and standards. It enables the organisation "to be both analytical and creative in finding ways to become more competitive and more effective at meeting stakeholder expectations" [207].
7. **Effective communication:** ensures maintained motivation, transparency, and morale of the teams to maintain synergies as part of day-to-day operations.
8. **Process thinking:** This step combines all the above steps taking inputs from all the parties to deliver products and services that meet customer needs. The processes and performances are continuously reviewed to deliver 'quality'.

Table 3.14: TQM Strengths and weaknesses

Strengths	**Limitations** [209] [210]
People-oriented process (Employees as a source of ideas and solutions): Management commitment Employee empowerment Loyal customer focus Process improvement (fewer defects) Fact-based decision making, Continuous improvement,	Loss of productivity due to continuous outward approach (customer focus at all times), Employee empowerment scheme There is no recognised body of knowledge with a standardised approach as a method adapted and deployed differently to fit organisational needs. The continuous need for customer approval Offer results over time

Quality Management systems (QMS):

QMS are formalised systems that define and document business processes, procedures, and responsibilities for delivering high-quality products and services that meet customer and regulatory requirements [211]. The QMS adoption across the entire organisation brings all the operations in line, with the same requirements and standards, to deliver quality at all levels. According to [207], QMS is a successor to TQM with the following key principles [211]:

1. **Customer focus:** The organisation's focus on understanding customer needs is crucial to delivering the expected services with exceeded satisfaction. This focus results in continuous improvement and innovation of products, processes, or services to the customer's satisfaction.
2. **Leadership:** As with the TQM, a clear vision and goal are crucial to businesses by ensuring they are actively involved and engaged in achieving them.
3. **Engagement of people:** a culture of recognition, empowerment, engagement of all the employees are required to enhance the capability of an organisation and deliver value.
4. **Process Approach:** The organisation can effectively and efficiently manage the interrelated processes to form a coherent and optimised system.
5. **Improvement:** The ability for organisations to adapt to ever-changing markets is only possible if continuous improvement is the ongoing business objective.

6. **Evidence-based decision making:** The ability to inform decision-making based on facts, data, evidence, and analysis is key to lead to greater objectivity and confidence in decision making.
7. **Relationship management:** The relationship with the interested stakeholders (suppliers, partners, employees.) is important to optimise performance and sustain success.

These principles are the foundation that the International Standards Organisation ISO 9001 certification is built on. ISO 9001 is the international standards that define the specific requirements for a QMS. First published in 1985 and developed by ISO/TC 176, the focus was to set quality standard processes for organisations looking to improve their quality and performances and certifications [211] [212].

The ISO 9001:2015 is the current version of the ISO 9001 released in September 2015 [211] [212]. Other related quality standards deriving from some of the QMS principles are:

- **ISO 9000 series** (ISO 9000, ISO 9004)
- **ISO9001:2015** specifies the requirements of a QMS that organisations can use to develop their programs.
- **ISO 14001** (Environmental Management Systems)
- **ISO 13485** Quality management systems for medical devices
- **IS 19011** Auditing management systems.
- **ISO/TS 16949** Quality management systems for automotive-related products
- **ISO27001** Information security managements

Table 3.15: QMS Strengths and weaknesses

Strengths [213]	**Limitations** [212] [214]
Commit to continual improvement, Customer focus & satisfaction, Provide strong leadership & focus on supplier relations, The standardised process to implement, monitor and audit. ISO9001 certifications and Link to other ISO standards related to quality management	The certification process requires significant resources- time, effort, and great accountability. An expensive process, especially for smaller companies

Six Sigma

Six Sigma is a technique that focusses on improving manufacturing processes using design processes. In the late 1980s, Bill Smith, a Motorola Engineer, was looking to address its chronic problems of meeting customer needs in a cost-effective way. Six Sigma was developed to improve the quality of final products by systematically analysing the problems (e.g. defects) and continuously monitor these throughout the manufacturing process. The Six Sigma technique is based on four phases: Measure, Analyse, Improve, Control; aiming to increase the quality of the end product, revenues, and customer satisfaction by reducing process cycle time, costs, waste, and rework [208] [215].

Six Sigma has since been adopted in several organisations, such as General Electric (GE), in 1987 after Motorola - integrating training and applications of Six Sigma into the whole organisational culture [145] [216]. There are numerous adaptations of Six Sigma used for design, to mention a few: MAIC (Measure-Analyse-Improve-Control), DMAIC(Define-Measure-Analyse-Improve-Control), DMADV (Define-Measure-Analyse-Design-Validate), DMADOV (Define-Measure-Analyse-Design-Optimise-Validate) [217].

Table 3.16: Six Sigma Strengths and weaknesses

Strengths [209] [215] [217]	Limitations [215] [218]
Eliminate waste and streamline the process. Data-driven problem-solving process Enabling improvement and confidence in the process due to repeatability and performance tests	May limit flexibility for specific problems and restrict innovation. Ability to integrate with other tools or methods

3.3.8. Phase-2: Key findings

Phase-2 expanded on the approaches applicable to specific aspects of design methods, i.e., the *abstract individual* methods such as the Taguchi, AD method; and on the concrete design methods applicable to various systems, i.e., *Concrete and general* methods such as QFD, TRIZ, Pahl and Beitz's work [145] [146]. The objective was to refine the system of interest in terms of the existing conceptual design methods, to make an informed decision on the design methods to expand further in Phase-3 and the basis of exclusion of any other methods.

The design methods such as Pahl & Beitz and Pugh's were excluded based on their less holistic approach to a systematic design process and limitation of the creative process within their tools.

The innovative problem-solving approaches, such as Synectics, Lateral thinking, Six Thinking hat, and Brainstorming, were also excluded based on their High-level abstraction, the extensive revisions of their framework leading to confusion with the extensive scientific languages, the need to use different external thinking tools, and the fact that their core principles are the foundation of other design methods.

Of the manufacturing methodologies, the design management tools such as the TQM, QMS, and Six Sigma were excluded because of their closeness to process management tools and because their principles are based on concrete design methods such as the QFD- providing a strategic thinking element to the product design.

TRIZ was selected based on the suggestion of innovative principles in overcoming design conflicts and stimulate creative thinking. TRIZ is seen as a tool that can complement the QFD in that it does not innovate but coordinate the thought of the customer and the designers.

AD's strength is in the systematic nature of separating the functional requirements and constraints in formulating the design problem; the tool does not directly offer innovative solutions to various couplings. Since this research aims to seek design methods to develop a tool for an innovative approach for the offshore wind sector in which the primary focus is to create a market that drives innovation and competition, AD was also excluded from further analysis.

Upon the above reviews, it was decided to focus on these two design methods, QFD and TRIZ, for Phase-3 review. The well-defined nature of these methods with research publications and combined with the abundance of educational resources, justified their selection.

3.4. Phase-3: Selected methods current state-of-the-art in the literature

Having selected the QFD and TRIZ methods, Phase-3 aims to assess these selected innovative methodologies for their feasibility for innovative design and development in the offshore wind sector. The literature review for each method was reviewed to establish the selected methodologies' capability and applications and justify their inclusion or exclusion. The findings are presented in Table 3.17.

Table 3.17: Summary QFD applications and findings

Review of application & Benefits	References
Ford integrated QFD to the Ford Automate Operation framework to: • Balance quality and resource benefits • Provide methods for new product or service developments. • Capture stakeholder requirements from all the involved groups (external and internal) Integration of QFD/TRIZ approach to Ford tools (e.g. EQIP- Engineering Quality Improvement Programme Integration of QFD into Market Research operation team for Customer Satisfaction triangle	[219]
Rolls Royce integrated QFD into their 'Design for Process Excellence' tools to: • Ensure the customer needs are addressed and translated into the engine's functional requirements. • Assess the various options against the user requirements before settling on a design solution (QFD/Pugh Matrices) • Ensure the trade-offs between attributes are resolved without increasing the design complexity. E.g. Integration of QFD/dFMEA as part of the Define Phase Roadmap in the DCOV to understand and structure new engine programme	[220] [221]
GE (former Converteam) integrated the QFD/TRIZ/ FMEA into the development of novel electric drive systems to • Identify innovative areas with commercial benefits. • Represent the Voice of the Customer through the technology decision process. E.g. Integration of QFD with paired question analysis to derive relative importance of the customer needs.	[203] [204]

Software developer AT&T integrated QFD to their Total Control Management to: • Better translate the user needs into the software requirements. • Enable better communication between stakeholders. • Assist in understanding aspects of competition from a design aspect. Also, IBM, Philips, Motorola, and Intel adopted the QFD approach. Hewlett Packard (HP) integrated the QFD in their Interactive Visual Interface and used it as a product planning tool.	[222] [223] [224]
Military aircraft (F-1 Falcon) for maintenance application redesigned using QFD and TRIZ to: • Reflect on the customer needs during the new product development process. • Capture improvement areas and Enhance internal and external input to the new design. • Enable systematic product development. Australia's defence (First Principles Review) explored the implementation of QFD for conceptual systems analysis in the new Defence Capability Life Cycle design process. QFD analysis used for the design of autonomous underwater robots owned by the Thai Navy Office of Naval Research and Development	[225] [226] [227]
The aerospace industry, e.g. Boeing 787 Dreamliner, adapted QFD/TRIZ methods as a strategy to: • Meet the requirements of the multiple stakeholders (interior design) • Ensure no omission of the key technical considerations. • Introduce a radical innovation approach across multiple supply chain players. • Investigate possible conflicts and risks associated with the multiple players.	[228] [229] [230] [231]
Tidal energy Converter demonstrator project applied QFD/FMEA to: • Identify and prioritise key technology and deployment issues. • Use the Standardised tool (ISO 16355, ISO9000) for the credibility of the results. • Develop a design with a competitive edge (prices, learning curve) • Identify dependencies and their strength. QFD/TRIZ combination found to enhance teamwork, assist in trade-off decisions, visualise objectives and performance measures	[232] [233]
General research & case studies conclusions : • Method for a new product or service development • A tool that identifies dependencies and unacceptable attributes • Assist in understanding details of competition from a design aspect.	[234] [143] [196] [202]

- A tool that captures the rapidly changing customer expectations - A fundamental tool for specifying problem definitions. - The ability to assign a weighted value to each customer requirement. - A tool that facilitates multi-team involvement	[220] [227] [235]
QFD Integrated applications - Online database company using Fuzzy QFD/TRIZ to increase service quality. - Hybrid QFD/TRIZ to identify critical features for Product Service System models - QFD/TRIZ integration in research and development of the 4-phase QFD for a notebook product (LCD monitor for a notebook - Modern QFD/ AHP– Agile approach (ISO 16355-5:2017, 10.4.2.3)	[236] [237] [238] [239] [234] [202] [240] [206]

The reviews indicated that various sectors have adopted the QFD, more advanced and matured in some sectors (e.g. automotive) than others (wind or tidal), to identify and prioritise optimal designs for their products. The approach was found to help define a design problem, reduce the possibility of omitting dependencies between requirements, support the identification of trade-offs, and effectively manage the relationships between the objectives and performance measures. However, some limitations highlighted were how complicated the management of the process could be for larger matrices, the extensive effort required to collect the Voice of the customer (known and unknown needs), the tool's inability to find alternative solutions to the identified contradictions.

Table 3.18: Summary TRIZ applications and findings

Review of application & Benefits	**References**
Ford Motor: - TRIZ application to implement a cost-effective rear suspension to medium-size cars. - Ford Automate Operation integrating QFD/TRIZ/FMEA Telematics (In-vehicle information &multimedia system)- integration of TRIZ principles for cost-effective product realisation TRIZ integrated into Design-to-cost innovation framework.	[180] [217] [218]
Toyota- TRIZ integration to Toyota Kata, their core continuous improvement tool to: - Generate better and more innovative solutions. - Have a systematic way to address trade-offs.	[219]
Medical Device (Equivital Life Monitor)- TRIZ integrated into the device model (SERVQUAL) to improve the quality of the patient's services and improve strategies needed to service provided.	[162] [220]
	[221]

Siemens Automation and Drive group adopted TRIZ training and integration to the organisation culture for the concept finding phase.	
Rolls Royce integration of QFD/TRIZ to capture their customer’s needs and resolve trade-offs between attributes.	[196]
General research & case studies conclusions (Intel, Samsung, Proctor & Gamble): • Most widely used for discussing creativity • Brought radical change and integration of new technology. • Focus on solution space, considering problem characteristics and dependencies. • A logical approach to inventive-problem solving. • Resolves physical and technical contradictions. • Beyond identifying problems/root causes, TRIZ finds solutions.	[132] [133] [169] [180] [181] [221] [222]
TRIZ Integrated applications: • Ford Automate Operation integrating QFD/TRIZ/FMEA • TRIZ/ QFD • TRIZ/ AD / FMEA • TRIZ/ Kano model/ FMEA • TRIZ/FMEA	[181] [163] [223] [133] [168] [224] [222]

TRIZ is seen as a unique method for producing innovative and creative products. Its application, although widely used, seem to be limited to specific early adopter industries. TRIZ tends to be implemented with other tools to enable a systematic approach to problem definition and creative solutions. The hybrid application of TRIZ with other tools accentuates the necessity for TRIZ to advance the design process, particularly at the conceptual stage.

Some limitations highlighted were the lack of risk mitigation attributes for the solutions proposed, the tool's complexity, the need for training and change in organisational culture.

3.4.1. Phase-3 Key findings

The purpose of the hybrid methods is that shortcoming in one methodology is overcome by another's strengths. QFD is used as a quality management tool to support product development, to ensure the Voice of customers are well defined, and to prevent the omission of key technical considerations. TRIZ, a knowledge-based systematic tool to inventive problem-solving, creates impactful, innovative solutions where there are trade-offs or a lack of impact in the existing designs.

In designing complex systems, trade-offs and safety are the main constraints. Integrating TRIZ into QFD will support the process of resolving the trade-off and obtaining innovative solutions. The Phase-3 literature review highlighted no argument to the unsuitability of the QFD or TRIZ as designs for applying the concept and design. The Failure Mode and Effects Analysis (FMEA) method was widely integrated into these methods to mitigate potential failures at the early stage of concept design.

To this end, the FMEA is detailed below, expanding on its strengths, weaknesses, and applications. Its merits to be included in the methodology sought in this research will also be analysed.

Failure Mode and Effects Analysis (FMEA)

Failure mode and effects analysis (FMEA) is a systematic method used to identify and evaluate potential system failures and mitigate or eliminate the change of failure. The US Armed forces and NASA were the earliest adopters of the FMEA in the early 1960s. Its use has since widely spread in various industries such as the automotive industry in the 1970s, wastewater treatments in 1973, and now in semiconductors, food service, software, healthcare [248] [190]. As a design tool, the FMEA can provide a means to compare various machine configurations by identifying possible root causes of failure(s), failure modes and estimation on relative risks, to drive towards higher reliability, quality, and enhanced safety [190].

In FMEA, each failure mode is ranked in order of the Risk Priority Number (RPN), which is calculated by multiplying the severity (S), probability of occurrence (O) and the probability of detection before the effects of the failure are realised (D).

The values of these three risk factors of a failure are represented by numbers, generally between 1 (no risk) and 10 (worst case) [248]. Based on the threshold, the potential failure is prioritised, and recommended actions are required to minimise the RPN. The steps of the methodology are shown in Figure 3.14.

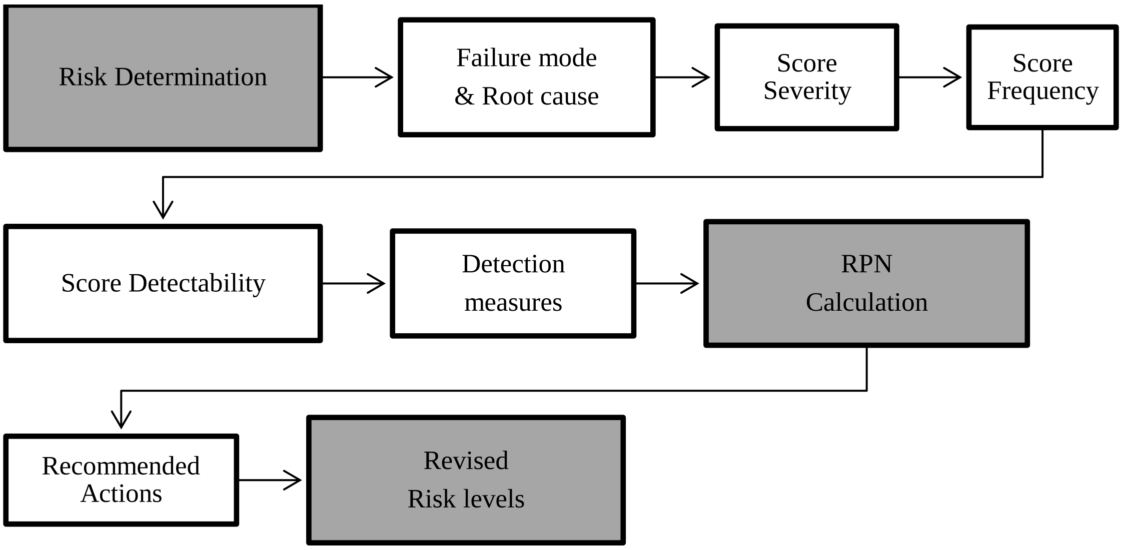


Figure 3.14: Standard FMEA process

There are several applications of FMEA, historically split into design and process FMEA, with design FMEA supporting the early stage of design and process FMEA, the later stages of product development. FMECA, Failure Mode Effects Criticality Analysis, is another extension of the FMEA that includes a criticality analysis for each identified failure mode.

FMEA is mainly used for operation and performance's risk assessment and less for design or conceptual assessment. As a bottom-up approach, the system is broken down into component, process, or function elements [249]. The component failures are analysed and linked to the bottom-up; consequences and severity are understood by spanning all the hierarchy levels from bottom to top.

The following steps to complete an FMEA remain the same across all FMEA types:

1. The determination of the function or component of interest by breaking down the system to an element as granular as needed,
2. For each function or component, all the potential failure modes are determined.
3. For each failure mode, identifying possible root causes and effects of failures is analysed and ranked using specified scoring criteria.
4. The occurrence (O), the likelihood of detection (D) and severity (S) of these failures are then established and ranked.
5. The risk level is quantified using the Risk Priority Number (RPN), which is calculated by multiplying the Severity, Occurrence, and Detection ratings associated with each failure: RPN= O*S*D

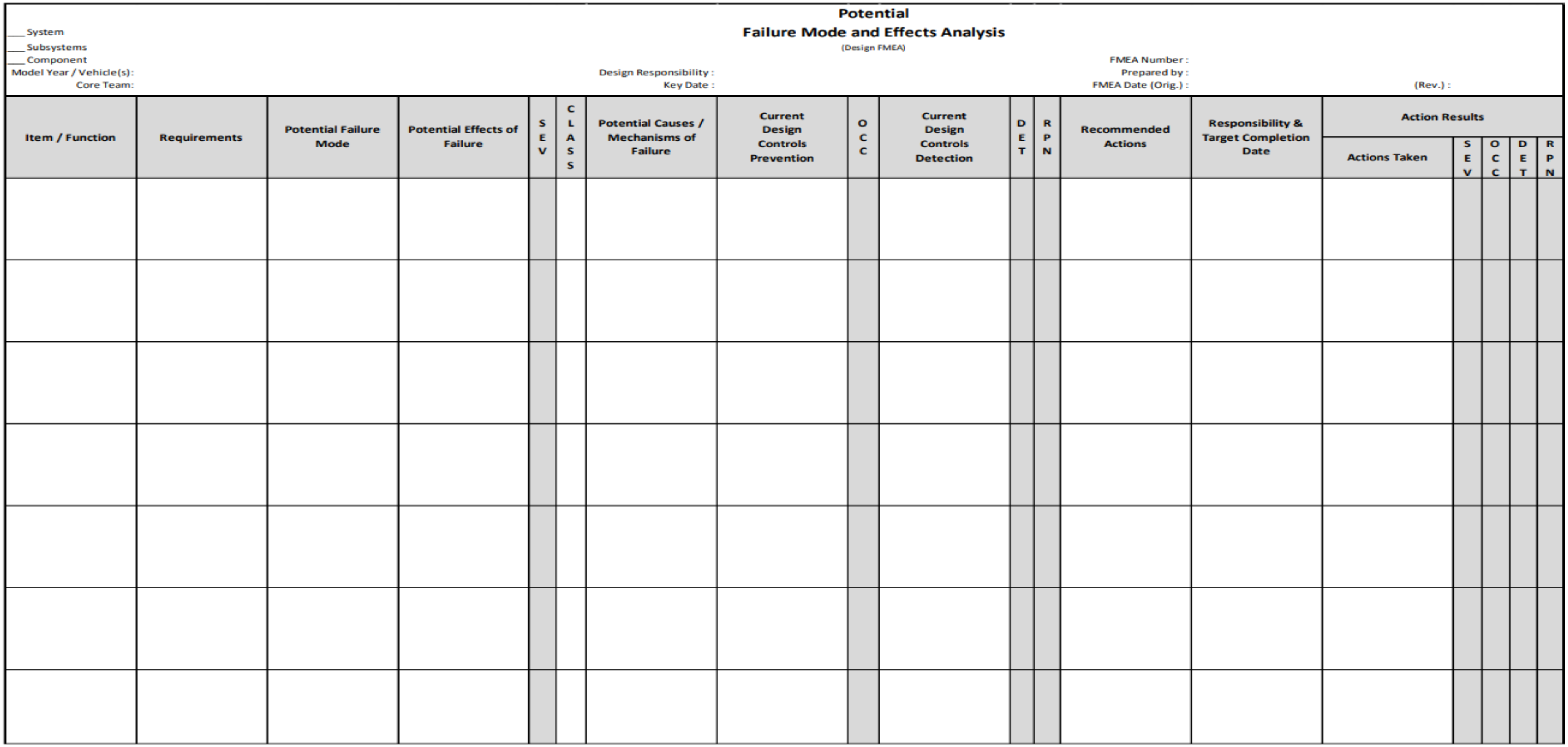
6. The potential risks levels, ranked by RPN, highlight the most critical elements that require mitigation. Determining how to minimise, detect, eliminate, or mitigate those risks is key to this step; This consists of defining recommended actions for implementation.
7. Based on the completed actions, the risk levels are revised to ensure that the risk goals are met.

The FMEA scoring scale is determined by the team collaboratively based on their knowledge of the product, function, or process lifecycle. Several standard ratings can be adapted for specific applications, such as the British Standard- BS EN 60812:2006, the Mil Stan 1629A- Procedures for Performing a Failure Mode Effects and Criticality Analysis. [248]. An example of Severity categories and corresponding severity ratings are given below in Table 3.15, and A template of an FMEA worksheet is shown in Figure 3.15.

Table 3.19: Example of severity rating [140]

Severity Rating	Severity Definition	Severity Level	Ranking Value
Minor	It would be unreasonable to expect that this failure's minor nature would cause any real effect on system capability. The failure might not be noticed.	Minor	1
Low	The nature of the failure causes only a slight deterioration of system capability that may require minor rework action.	Minor	2, 3
Moderate	Failure causes some deterioration in System capability which may generate the need for unscheduled rework /repairs or may cause a minor health hazard or minor injury to the user.	Marginal	4, 5, 6
High	Failure causes loss of system capability or may cause a serious health hazard or serious injury to the user.	Critical	7, 8
Very High	A potential failure could cause complete system loss and the death of the user(s).	Major	9, 10

In the early stages of product development, Concept and design, FMEA are used. These were adopted later than the process FMEAs; however, they can assess potential risks as early as possible in the product development process.



Potential
Failure Mode and Effects Analysis
(Design FMEA)

___ System
___ Subsystems
___ Component
Model Year / Vehicle(s):
Core Team:

Design Responsibility :
Key Date :

FMEA Number :
Prepared by :
FMEA Date (Orig.) :
(Rev.) :

Item / Function	Requirements	Potential Failure Mode	Potential Effects of Failure	SEV	CLASS	Potential Causes / Mechanisms of Failure	Current Design Controls Prevention	OCC	Current Design Controls Detection	DET	RPN	Recommended Actions	Responsibility & Target Completion Date	Action Results				
														Actions Taken	SEV	OCC	DET	RPN

Figure 3.15: Example Design FMEA worksheet

Some have described FMEAs as a critical tool among businesses that are ‘increasingly intent upon bringing more precision to solving their risk management challenges” [250]. However, it has also ben argued that although the techniques used are inherently simple, their application has frequently been misinterpreted and consequently failed to gain sufficient benefits. The following section intends to present the different benefits and limitations of using FMEA and its applications in various industries.

Table 3.20: Strengths and weaknesses of FMEA

Strengths [219] [248] [250]	**Limitations** [250] [251] [252]
Understanding of factors influencing the reliability of the system An effective way to evaluate processes. Highlights areas needing improvement. Reduced development time & cost Identify how to improve areas where performance is lagging. Ability to break the process into manageable elements to investigate	It can only be used to analyse single-point failures. Limited to knowledgeable and input of teams Actions beyond FMEA might be required to reduce or eliminate failure modes. Requires to be integral to the production process for continuous improvement and to consider the interaction between elements. An accurate way of prioritising the risks

The literature reviews indicated that FMEA is a well-known, widely adopted analytical method carried out as part of an organisation's reliability design process to define the designed products' potential failures and eliminate these defects at the designing stage. The international standards, such as IEC 60812:1985[4], provide guidelines for the preparation of FMEA reliability tool standardised by international standards [231]. Although described as one of the most well-known reliability tools adopted, the FMEA has been adapted or integrated with other tools for specific applications. Table 3.21 below highlights a summary of FMEA applications in various industries, in addition to the FMEA hybrid applications.

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[4] International Electrotechnical Commission IEC 60812:1985, *Analysis techniques for system reliability — Procedure for failure mode and effects analysis (FMEA).*

Table 3.21: Summary FMEA applications and findings

Review of application & Benefits	**References**
Financial Services- Integrated into banking processes to reduce the risk of fraud	[250]
Manufacturing- FMEA integrated to process to: • Higher product quality and reliability • Improve electric motor control system for heating/ventilation vehicles. • Advance the application of design and process at Garrett Automotive Ltd	[250] [254] [255]
Healthcare HFMEA and FMECA incorporated into the Prospective Hazard Analysis tools to: • Analyse prospective hazard. • Assess possible Human errors. • Determine parts of the system requiring in-depth analysis. FMEA to support the safety of chemotherapy and Intravenous drug administration	[250] [254]
General research & case studies conclusions : • A systematic and simple bottom-up step-by-step approach • Lower cost solutions due to early discovery • Team collaboration – whole lifecycle • Integrated continuous improvement of design. • Error Proofing method	[204] [219] [248] [249] [254]
FMEA Integrated applications • Hybrid QFD/FMEA for quality process planning & prevent design errors. • Hybrid QFD/FMEA to identify wastes and address risks to lean implementation. • Performance Quality interface (QFD/FMEA), FMEA/FMECA implementation • FMEA into Structured What-if technique (SWIFT) • Hazard analysis techniques (HAZOP) • Fuzzy QFD/FMEA approach	[252] [256] [219] [257] [255] [258] [259]
Development of Standards • Military standard of United States (MIL-P-1629) – FMECA • Society of Automotive Engineers (SAE International)- ARP5580 • Quality engineering- Black belt certification • International Standard- ISO/TS 16949	[248] [260] [261] [262] [263] [264]

As a bottom-up approach, the FMEA identifies all possible failures in design, manufacturing, assembly, or service, starting at the lowest level of the process or product and working its way up to the subsystem's effects, then the system. Industries such as healthcare have alternated between the implementation of Hazard Analysis techniques (e.g. HAZAN) and FMEA to have a top-down analysis and the system's low-level component view.

The FMEA is an essential part of the design process, and its outputs should feed into an integrated reliability tool to continuously improve the designs. Hence, the considerable hybrid models of the FMEA integrated into the QFD, and other tools, as an optimum way to “bring the voice of the customer and voice of the engineer closer together along the “performance quality line.” [219]. This serves as a validation of FMEA improving design reliability and robustness efforts, and QFD to achieve customer satisfaction.

Key findings

The review of the current state-of-the-art of the QFD, TRIZ and FMEA emphasised no reasons to exclude these design methods for creative and problem-solving design applications. The literature review highlighted the complementary benefits to integrate the FMEA method alongside the QFD and TRIZ methods for conceptual designs.

The next step was to review these methods further and detail the complementary and comparative elements of the selected methodologies and their deployment in each case.

3.5. Phase-4: Structured Innovation Approach

The objective of Phase-4 was to detail the justifications for the chosen methodologies, to establish how these methodologies compare and complement each other and their (lack of) applications in the renewable energy sector. In this section, each method's methodology is reviewed with respect to its definition of the data inputs, processes, and expected outputs.

3.5.1. Quality Function Deployment (QFD)

QFD is a structured methodology used to identify the Voice of the Customer and translate them into applicable technical requirements for each stage of product development and production [265]. The House of Quality (HoQ) matrix enables this analysis by capturing the customer, the design characteristics, the relationship and correlations between the customer requirements and the design parameters, all the information in one place. The data required to run the QFD is detailed in this section.

The QFD process starts with capturing the voice of the customer, representing what the customer wants- the spoken or unspoken requirements. The literature review in Phase-3 emphasised that this step was crucial in understanding what truly the customer wants. These requirements were obtained from various market analysis, surveys, interviews, quality control, and complaints in the reviewed literature. Larger organisations have dedicated departments to capturing and updating these requirements continuously. The implementation of Modern QFD has been seen as an advanced and more accurate way to identify the customer or organisation's voice and a better understanding of current and future needs [240] [206]. In some applications [219] [234] [266], pairwise techniques, like AHP- Analytic Hierarchy Process, were used to help identify and prioritise these requirements.

The design characteristics, also referred to as the voice of the engineer, are the interpretations of the technical requirements to achieve the customer needs. The several applications in the literature make use of teams' expertise to define and specify these requirements. This approach allows collaboration between the various teams, enabling the creation of multiple solutions to each customer requirement, defining the strength of the relationship between the requirements and solutions, and highlighting the trade-offs [265] [267]

The QFD outputs a set of solutions specific to the analysis performed, including the functional requirements' metrics, the conflicts and interrelationships, and the impact and organisational efforts. In the literature reviewed in Phase-3, several applications outputted at a list of improvement areas for innovation and proposed functional requirements within acceptable FMEA targets. The Authors in literature [203] [204] noted the extensive time and resource needed to complete the multi-level anal, highlighting the need to follow all the important steps to obtain innovation solutions.

All the reviews noted that the QFD tool is a structured method that enables multiple teams to find innovative technical solutions to the customer needs more objectively. The QFD has been described as a tool that helps the designers in thoroughness in conceptual designs. The tool's limitations were based on the extensive training needed and the inability to resolve the contradictions.

3.5.2. Theory of Inventive Problem-Solving (TRIZ)

TRIZ is made up of a set of problem-solving tools that provides inventive inspiration to the designers – encouraging to look for existing solutions to similar problems at different scale and times. “Someone somewhere has already solved it”. This allows the team to adopt similar principles that might offer idealised solutions from other industries, countries, and times in history.

Identifying contradictions is the first input to the TRIZ process. The designer (or organisation) is required to define the general cause(s) of the problem(s) that needs resolving; this can be obtained from feedback, complaints, design analysis or known improvement areas. Once defined, the trade-offs should be explicitly stated- the parameter improved, and the parameter negatively impacted.

Once the specific TRIZ method is used to resolve the contradictions, general solutions are generated, proposing various improvements. TRIZ uses focused solution space, only considering the problem characteristics within the problem boundary. The most relevant solutions must be converted to a specific solution for the problem at hand.

The literature emphasised that TRIZ is a unique method for producing inventive and creative solutions and has helped many companies develop new technologies. However, the limitations highlighted are around the complexity in converting the general solutions to solutions relevant to the problems. An important emphasis is on the involvement of multi-disciplinary teams capable of producing quality solution concepts.

3.5.3. Failure Mode and Effects Analysis (FMEA)

The reliability of a system is critical to its performance. FMEA is a widely used design process implemented in the product design to evaluate the high priority failure modes to estimate their performance and reliability.

From its origin traced back to the military standards of United States (MIP-P-1629), various organisations have expanded the implementation of the FMEA based on their specific needs as a standalone tool (e.g. PFMEA, FMECA…) or integrated into their design processes (e.g., QFD/FMEA, FMEA/Hazard …). The literature review in Phase-3 highlighted that one of the key benefits of implementing FMEA in product design early in the design phase is that the design can be improved and substantially reduce the cost of modifications at later development stages.

The FMEA ensures that the design of each function or element within the system of interest enhances customer satisfaction. This means that the first FMEA step clarifies the system of interest's function and investigates the root cause factors to problem and failure modes of the system's function and interacting systems.

As outputs, the FMEA assesses and prioritises the systems' functions requiring actions to ensure the recommended targets are achieved. Similarly to the QFD, the literature also emphases that the implementation of the FMEA requires a multi-disciplined team effort.

The Phase-3 review indicated no constraints to implement the FMEA from concept definition to product design. However, from the literature review, its most common application was at the later stage of development, Process FMEA, as the clear benefits are more easily visible.

Applications at concept stages were also observed, integrated with other qualitative tools such as the QFD and Taguchi methods. Clausing [257] described the FMEA as a value-added “piece part expectation” detail to the QFD process. Ginn [219] emphasised that the FMEA can be used as a reliability tool, and its successful application is improved when integrated into a complete product development process. This suggests the use of FMEA in hybrid methods, emphasising that other methods seek to include FMEA for the benefits of the overall design process.

Despite the limitations of multi-disciplinary team involvement, the biggest endorsement for FMEA is the growing number of publications associated with the organisation's ability to problem-solve issues more objectively to improve design reliability robustness effort.

3.5.4. Links between the design methodologies

As demonstrated in the literature review, QFD, TRIZ, and FMEA are technical tools applied to a wide range of industries, enabling company-wide multi-disciplinary teamwork to achieve quality products for customer satisfaction. Individually, the application of each tool resulted in positive feedback. Nonetheless, these tools are generally implemented with other tools within the organisation overall design processes.

Integrating the QFD and FMEA ensures the voice of the customer is translated into a product design through the voice of the engineer. The customer's satisfaction is achieved by delivering high and performance quality (QFD) and robust products at the same time (FMEA). If implemented in the early stages of development, the QFD will help validate the customer requirements' continuous integration into the component specifications. Merging both methods forms a decision tool that identifies the most suitable design solutions and mitigation measures for the associated risks. Combining the tools also provide a way to prioritise the order of mitigation actions beyond the RPN values.

Both QFD and FMEA require experts from multidisciplinary teams to extend the customer requirements and engineering characteristics throughout the product or process, enabling an interaction between the customer's various failure modes and degree of satisfaction concerning the product performance and services.

Phase-3 reviews highlighted that the integration of QFD and TRIZ is one of the most popular product planning combinations. The fundamental concept of the QFD is the ability to capture and convert the customer requirements into design characteristics, to define organisational impacts, interrelationships, and target values of the design, to satisfy the customer demand. The contradictions that may arise from the interrelationships between the design requirements can be resolved using TRIZ by proposing innovative solutions that meet the customer demands. These tools can be used in isolation. However, the lacking input information is replaced with assumptions instead of complemented by the other tools.

Both QFD and TRIZ require the designers to identify the customer's spoken and unspoken needs; these needs can relate to completely new design or improvement of existing designs. The slight difference is that the QFD seeks to develop and deliver a design that meets the customer needs. In contrast, TRIZ looks to innovate due to a problem (or contradiction) within an existing design. The integration of TRIZ into QFD can be initiated for solution exploration- when defining functional requirements, during the conflict assessment- where a solution is seen as a block, and during impact analysis. When TRIZ is used, the integrated process will allow the designer to quickly create innovative solutions using the TRIZ tools and inventive solutions within the QFD process. For example, suppose there is a lack of impact on the user's solutions. In that case, TRIZ might allow the user to think of impactful alternative solutions by reference to the TRIZ toolkit – thinking of past, present and future inventions that meet a similar problem, or perhaps with a difference of scale – micro or macro.

3.6. Summary:

The literature review highlighted applying the three methods in various industries and their integrations to its overall design processes. However, the literature did not detail successful and unsuccessful implementations due to these tools, particularly; possibly due to confidentiality and maintaining competitive advantages.

QFD, TRIZ and FMEA are only three of many quality tools available within the system engineering framework. These were reviewed to validate their suitability for innovative product and conceptual design methodology. No reasons were found to exclude these tools for use design methods for offshore wind design concepts. The lack of examples of these design methods in the offshore renewable energy field, in general, shows a potential gap in the application of these design methods.

Therefore, based upon the analysis of the state-of-the-art in design methods, the QFD, TRIZ and FMEA methods have been selected to be applied to design offshore wind concepts.

4. Structured Innovation Approach

This chapter presents the methodology of the thesis. The three design methodologies and recommendations developed to support the design of innovative concepts in offshore wind are introduced. The integration of the three design methods, namely Quality Function Deployment (QFD), Theory of Inventive Problem Solving (TRIZ), and Failure Mode and Events Analysis (FMEA), aimed to help the user in thoroughness and in speeding up the innovation process.

Individually, each methodology's application resulted in useful outputs that can advance innovative design concepts for offshore wind. However, each methodology's limitations were compensated with another's; hence, the rationale behind integrating the three methodologies to lead to ideal design solutions. Each method's outputs were considered, analysed, and then selectively entered as the subsequent method's input.

The chapter is outlined in three sections: Section 4.1 introduces the Structured Innovation approach in the offshore wind sector context. Section 4.2 summarises the reasoning behind each methodology within the proposed Structured Innovation approach. The following sections 4.3-to-4.5 detail each design methodology proposed to build the system innovation approach: Quality Function Deployment (QFD) tool — to capture, structure and review the user requirements, TRIZ— to solve the compromises and trade-offs between the user requirements and FMEA— to validate the concept design via technical risk mitigation approach. Finally, section 4.6 provides an example describing the implementation of the approach.

4.1. Introduction

In anticipation of the offshore wind industry's rapid growth, there is a need for a Structured Innovation approach to support the design of systems to maximise production, reduce the costs of the generation and carbon emissions, and improve the security and sustainability of supply.

Innovation has already had a significant impact on the sector's growth, especially in mitigating complexity, performance, cost, competitiveness, and systems reliability. This continued push is key to keep the offshore wind sector and its systems sustainable and competitive. Integrating technology innovation at each level of the offshore wind system has and will bring added values to investors' confidence in the sector in addition to a low-cost energy source to the UK energy mix. However, innovation starts with concepts that need converting into requirements to enhance the original product or concept designs and increase its market acceptability [268] [269].

The Structured Innovation approach brings together a systems engineering approach to generate ways to innovate the system(s). INCOSE, the International Council on Systems Engineering, defines System Engineering as "an interdisciplinary approach that enables the realisation of successful systems by integrating customer and stakeholders' needs and system functionalities early in the design stages. By bringing all disciplines that form a structured development process from conceptual to operation, a system engineering approach provides a quality product that meets the user needs" [270] [271].

Integrating a Structured Innovation approach early on in the design process will significantly impact cost competitiveness, technology readiness level (TRL), and technology performance level (TPL), as shown in Figure 4.1. This approach is useful in identifying the potential risks of the system's failures and showcasing the system's potential areas of innovation.

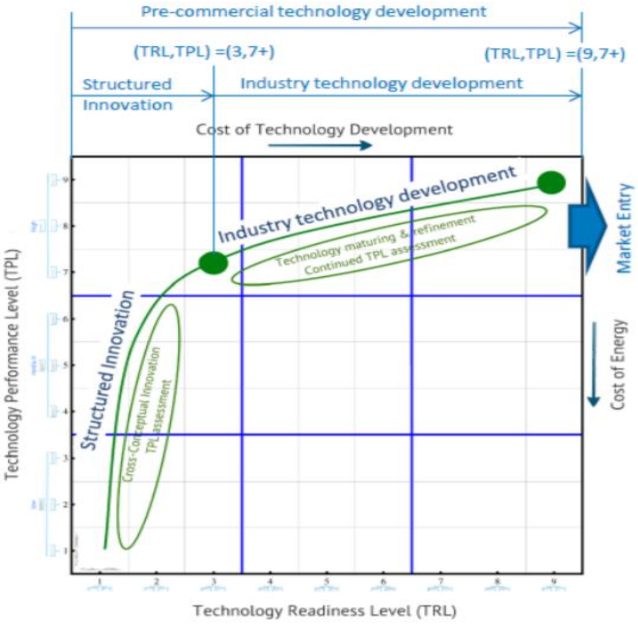


Figure 4.1: System Engineering Approach from a concept to market entry [272]

A more detailed explanation of the adaptation of the combined tools: QDF, TRIZ and FMEA as a Structured Innovation approach is shown in the following subsections of this chapter.

4.2. Structured Innovation Approach

The methodological process is outlined as follows: First, a design using the QFD to identify the stakeholders’ needs through Qualitative survey and obtain potential solutions to these requirements; Second, the integration of TRIZ into QFD for conflict assessment and impact analysis; Third, the extension of QFD analysis to assess the organisational impacts and deviations from the state-of-the-art technologies, and finally the integration of the FMEA method as input or output to the QFD/TRIZ process to mitigate the technical risks.

The process methodology for deriving and solving design conflicts by implementing the Structured Innovation approach is presented in the process diagram shown in Figure 4.2.

The reasoning behind the integrated approach was that the user might be tempted only to assess those solutions that they might come across quickly, or perhaps pre-meditating the solutions by only considering the advantages of their competitors’ products. Hence, one step is fed into the next step, advancing the concepts' quantitative assessment to deliver ‘ideal’ design solutions.

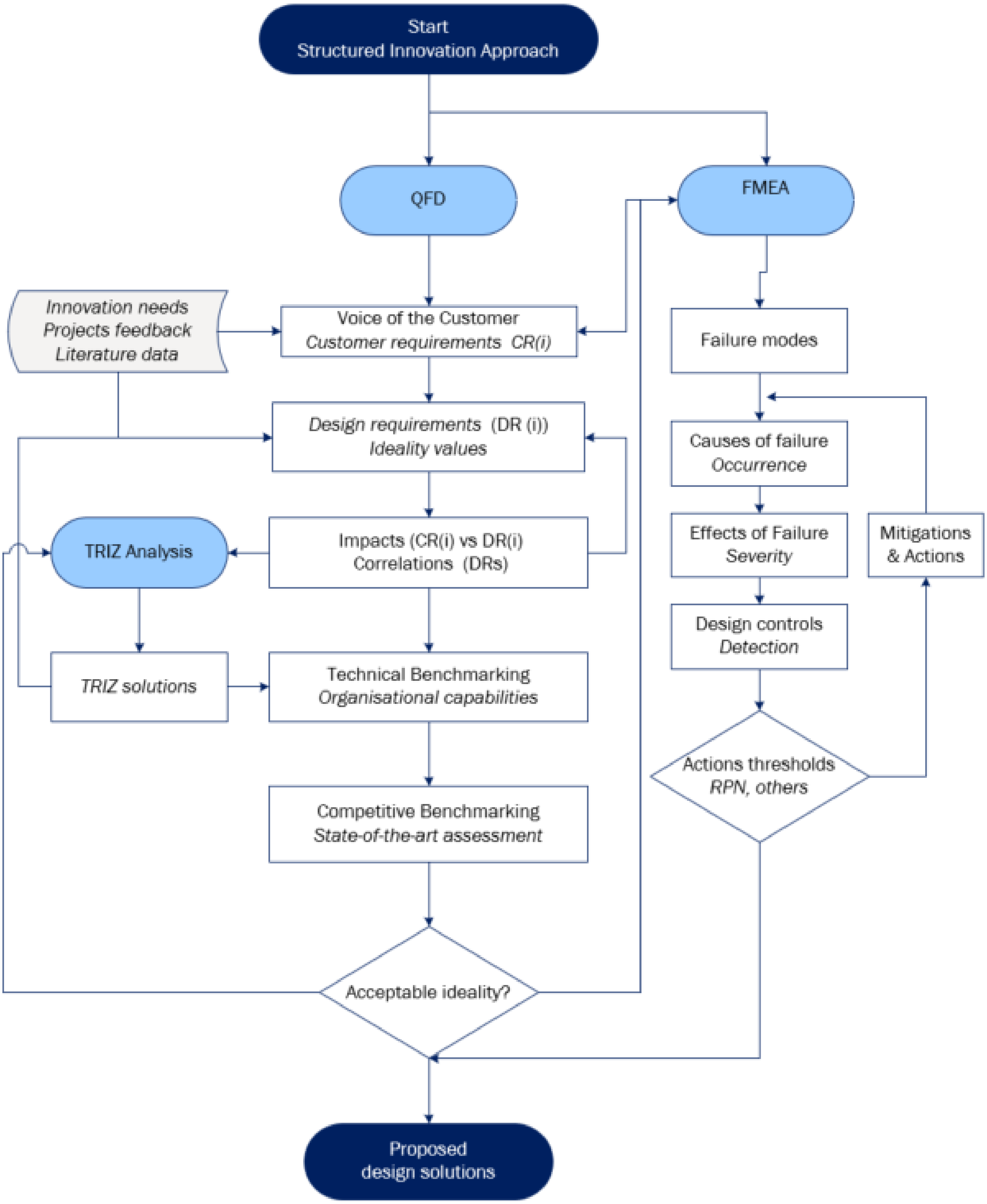
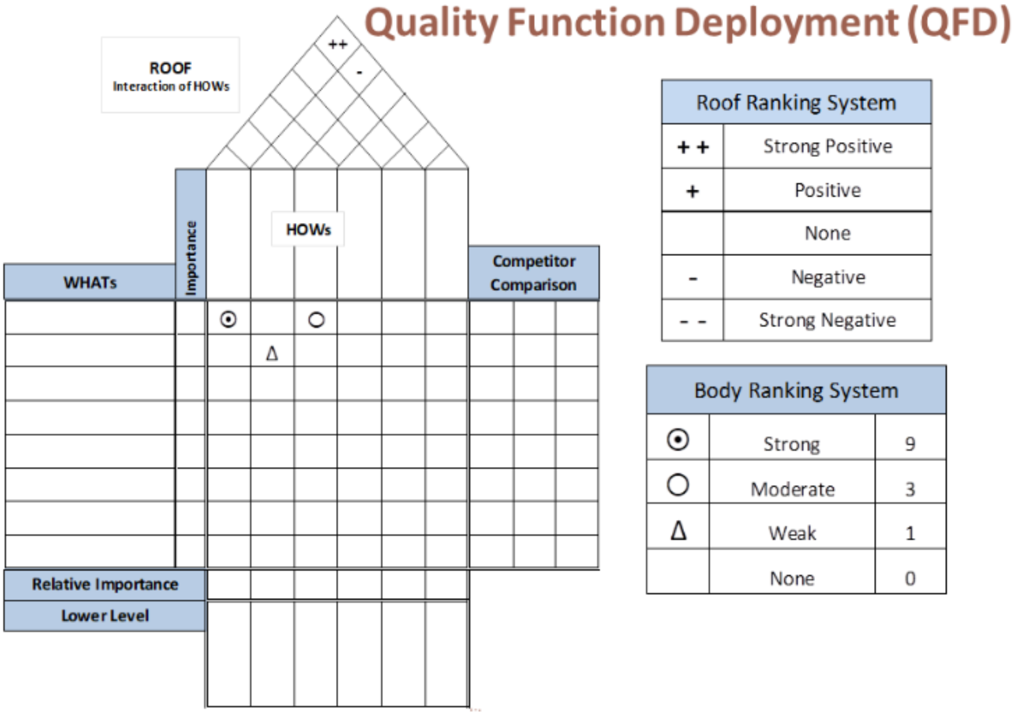


Figure 4.2: Proposed Structured Innovation approach- Process diagram.

4.3. Quality Function Deployment

The purpose of the methodology used was first to validate the Voice of the customers (VOC). The QFD, a structured method, identifies the VOC, prioritises their requirements, and translates them into technical requirements for each stage of product development and production. It is achieved using the House of Quality (HoQ), a matrix used to describe the most crucial product or service attributes or qualities. The HoQ matrix is used to translate the customer needs into design characteristics using a relationship matrix and demonstrates the strength of the relationship between the customer needs (WHATs) and the design parameters (HOWs). This approach allows collaboration between the various teams and the ability to capture and visualise information in one place [200] [273] [274]



Roof Ranking System	
+ +	Strong Positive
+	Positive
	None
-	Negative
- -	Strong Negative

Body Ranking System		
⊙	Strong	9
○	Moderate	3
Δ	Weak	1
	None	0

Figure 4.3: Quality Function Deployment (House of Quality) [200]

The steps to build the HoQ matrix are described below:

WHATs defines the VoC by capturing what the customer needs- the customer requirements. The identification of who the customers are is crucial to the deployment of the tool. This should include customers/stakeholders directly or indirectly involved or affected by the product/service. The multitude of stakeholders' requirements could originate from market research, interviews, laws and regulations, contracts, operational concepts, site conditions, external interfaces and utilities, industrial codes and standards, operator needs, the public interest, and other sources [275].

Importance, also known as a priority, evaluates the importance of each customer's needs relative to the others by generating a ranking scale.

HOWs- describes how to meet the customer' needs using design requirements, also known as technical solutions. These design requirements are translated from refining the customer requirements into parameters that can be achieved, measured, and with measurable target values. Shows how customer needs can derive from various sources (interview, regulations, and references) and are then refined to design requirements that provide parameters and information meaningful to and measurable by a system [276].

The Roof of the HoQ (**HOW vs HOW**) indicates the interactions of design requirements with each other, in synergy or conflict. Different studies use various rating scales to indicate the positive impacts and negative impacts of the correlations of the design requirement with one another (e.g. strong positive interaction (++), strong negative interaction (–), 0- no relationship).

Main Body (WHAT vs HOW) - provides a relationship and correlation matrix to determine each parameter's relative importance against the customer requirement rankings.

HOW-MUCH- also known as target values or metrics, describes the ideal values of each of the design requirements that will potentially trigger innovation. The competitive solutions/ products can then be assessed against these target values competitive to determine if and how close they meet the target criteria and their compliance.

4.3.2. Phases of the House of Quality

The deployment of the QFD is a 4-phase process that uses the HoQ matrix to translate the stakeholder requirements (or VoC) into design requirements. The system of interest's design requirements is then refined into specific requirements for the subsystems and components. The 4 phases, as illustrated in Figure 4.4, are:

- Phase-1 Design requirement phase: defines the stakeholder needs and translates them into high-level design requirements to meet the needs. This level is also known as Top-Level HoQ, and comprises a competitive analysis against the state-of-the-art technologies or processes and ideal target values.

- Phase-2 Product or Part requirement phase uses the technical requirements defined in the top-level HoQ as requirements that need to be met. These technical requirements are refined into product or part characteristics of the sub-systems.

- Phase-3 Process or Manufacturing phase defines manufacturing or assembly requirements for the product or part characteristics defined in the HoQ phase-2.

- Phase-4 Production or Quality Control phase: identifies the critical elements of the subsystems or components and the specific requirements for production or deployment. This step could include inspection for quality assurance, condition testing.

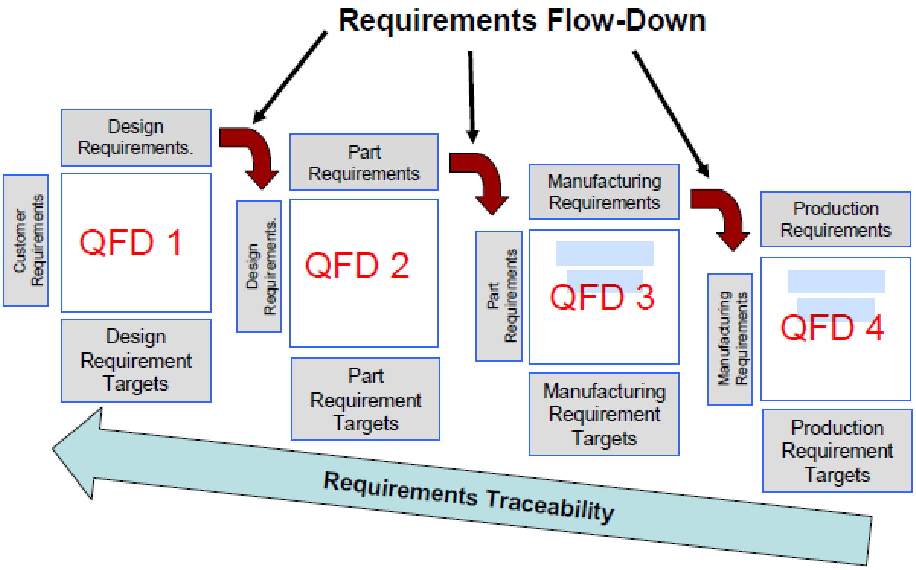


Figure 4.4: QFD 4-phase process [277]

4.3.3. Building a House of Quality

Step 1. Define the VOC.

Nothing happens without people. The ‘voice of the customers’ needs to be captured and translated into the system's designs. The VOC can be captured directly from customer engagements (e.g. questionnaires, interviews, feedback surveys) or indirectly (e.g. market research, fault monitoring). Capturing customer requirements accurately will ensure customer satisfaction and, in turn, the sector's growth and competitiveness.

In this research, an expert qualitative questionnaire was designed to capture the experts' knowledge in the field. The methodology proposed for this study is an expert Delphi process, which means the study relied on expert input captured via a questionnaire survey. The survey was designed and conducted by contacting ‘the expert’ via emails. These experts were selected to include a wider spread from the industry's various actors: from offshore wind developers, government bodies, strategic energy consultants to the Original Equipment Manufacturers (OEMs).

The research method applied for this survey was the Grounded Theory, which involves collecting and analysing data with no preconceived theories. Grounded Theory aims to uncover emerging patterns in data collected and successively develop a theory. A mixture of open- and closed-ended questions was used in the survey, focusing on avoiding any leading questions, or framing bias. Furthermore, a Likert scale was employed in the questions. The scope of the survey was to:

- Identify the stakeholder's requirements to maintain a strong and sustainable offshore wind sector in the UK.
- Highlight the importance of these requirements in their specific industries.
- Gather feedback and results on the methods and approaches to inform further surveys.

The Voice of the Customer captured is presented in Table 4.1 as an example, obtained from combined information from expert survey results, Government industrial strategy reports, previously documented surveys, patent landscaping analysis, and the ETI Wind Programme objectives. Highlighted in this example is the additional information that the customer may or may not provide (unspoken needs), offering more clarifications on their satisfaction measures. In some cases, capturing the VOC can be done using statements and observations from other sources (e.g. literature review, patent landscaping, past projects).

Various data collection methods are recommended to achieve an efficient capture of the VOC, and where appropriate, data processing tools (such as Analytic Hierarchy Process) are recommended to use.

Table 4.1: Sector's expert knowledge data from Questionnaire

Voice of the Stakeholders	How to measure?	Who judges success?
Stimulate Economic Growth in the UK	Increase in workforce and GDP Net Value Added for Local Authorities Energy Savings	UK Gov. Local Authorities Energy Members
Develop advanced technology to support climate change targets	Adoption Tech that reduces CO_2 Reduced Fossil Fuel Usage Energy management Supply Chain Measures	UK Government
Develop technology solutions to support whole energy systems and security	Capacity Margin on the grid Minimisation over capacity Peak loads vs Capacity Weeks of reserves of energy	Public & Private National Grid Distribution Network Operators (DNO)
Provide affordable and competitive Energy for the UK	Reduced energy bills Affordable Infrastructure Costs Increased UK Investment Need more Supply Chain Measures	Local Authorities Public
Maintain a sustainable energy supply for the UK	Net Present Value of Future Energy supply<= to current models Subsidies to encourage sustainable energy	Supply Chain Public/ Private Members NGOs
Ensure competitive energy generation(High Return on investment with Low Investor Risks)	ETI Increase Revenues Clear Legislation/ Policy ETI Enhance Public/ Industry perception of Members	ETI Members Shareholders

Once the customer requirements are captured, obtaining their importance is critical. In this research, the customer importance responses were captured, as shown in Table 4.1 and ranked from 1-Least important to 10- highly important. After that, the responses were coded and formed the input data for the QFD matrix representing the customer requirements (CR).

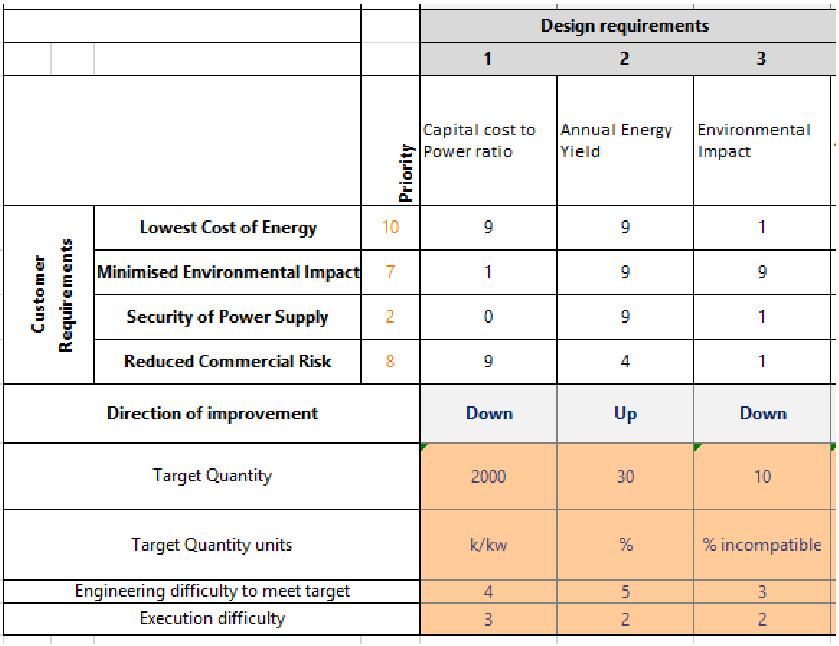
Table 4.2: Customer Importance ratings

	Minor										Major
What the Customer wants	0	1	2	3	4	5	6	7	8	9	10
Affordability										x	

Step 2. Define the design requirements.

The next step in the HoQ is to derive design requirements to meet the customers' needs, as defined in Step 1. A team effort is key to executing this step by involving multi-disciplinary teams, professional contributions, and innovation. These design requirements must be measurable, providing a means of assessing progress objectively. These design requirements contain a degree of technical difficulty, target value, and absolute and relative weights, as shown in the example in Table 4.3. More details on target values, degree of difficulty and weights are provided in the subsequent steps.

Table 4.3: Example Functional requirements in HoQ



			Design requirements		
			1	**2**	**3**
		Priority	Capital cost to Power ratio	Annual Energy Yield	Environmental Impact
Customer Requirements	**Lowest Cost of Energy**	10	9	9	1
	Minimised Environmental Impact	7	1	9	9
	Security of Power Supply	2	0	9	1
	Reduced Commercial Risk	8	9	4	1
Direction of improvement			**Down**	**Up**	**Down**
Target Quantity			2000	30	10
Target Quantity units			k/kw	%	% incompatible
Engineering difficulty to meet target			4	5	3
Execution difficulty			3	2	2

For this research, teams within the ETI wind programme, marine and transport were consulted to develop a list of potential solutions for offshore wind. Additionally, various solutions were extracted from other projects and literature review.

Step 3. Define Impacts and Correlations

This step reviews the relationships between the customer requirements and design requirements to indicate the impacts between the customer's quality and the quality of engineers' products. This is the first step in identifying the essential design requirements that require further investigation and significantly impact the customers. The example, shown in Table 4.3, used a quantitative rating scale of 9 for High, 4 for Medium, 1 for Low, and 0 for

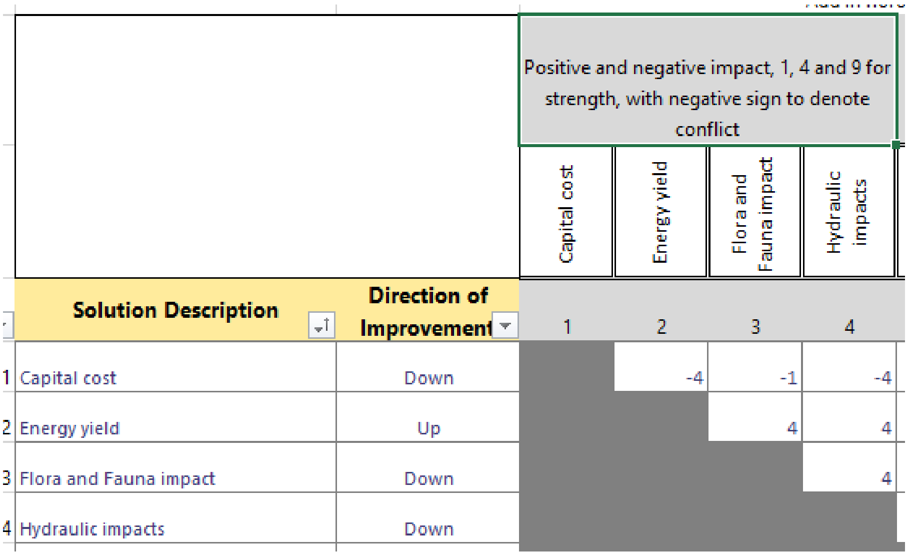
None. This rating is decided by the team and can be qualitative or quantitative to indicate the relationships' strengths.

This step also allows the organisation to prioritise the organisation's needs and further analyse the conflicts associated with implementing specific processes or functions. The correlation matrix, traditionally the roof of the HoQ, allows the designers to determine how design requirements help or impede each other, highlighting areas of further development and investigation to determine trade-offs or alternative solutions.

Numerical ratings (e.g. ± 9, ±4, ±1,0) or symbols (e.g. ++,+, 0, -, --) can be used to indicate the direction of the correlations (i.e. positive or negative), enabling the designer to specify which specific design requirements support each other or are in conflict.

Note that the customer requirements are essentially met by proposing several design requirements to satisfy their needs. However, it is not always possible to meet these requirements without compromises. The term used in QFD is a contradiction or trade-off between the design requirements. Analysing these contradictions to obtain optimal solutions can be done using the TRIZ contradiction matrix. Contradictions exist when a system, service or component require technical and physical improvements; with one of its properties or characteristics (weight, cost, reliability). Systematic innovation using TRIZ enables the removal of the barriers of contradictions to increase ideality.

Table 4.4: Example of the Correlation matrix to identify contradictions

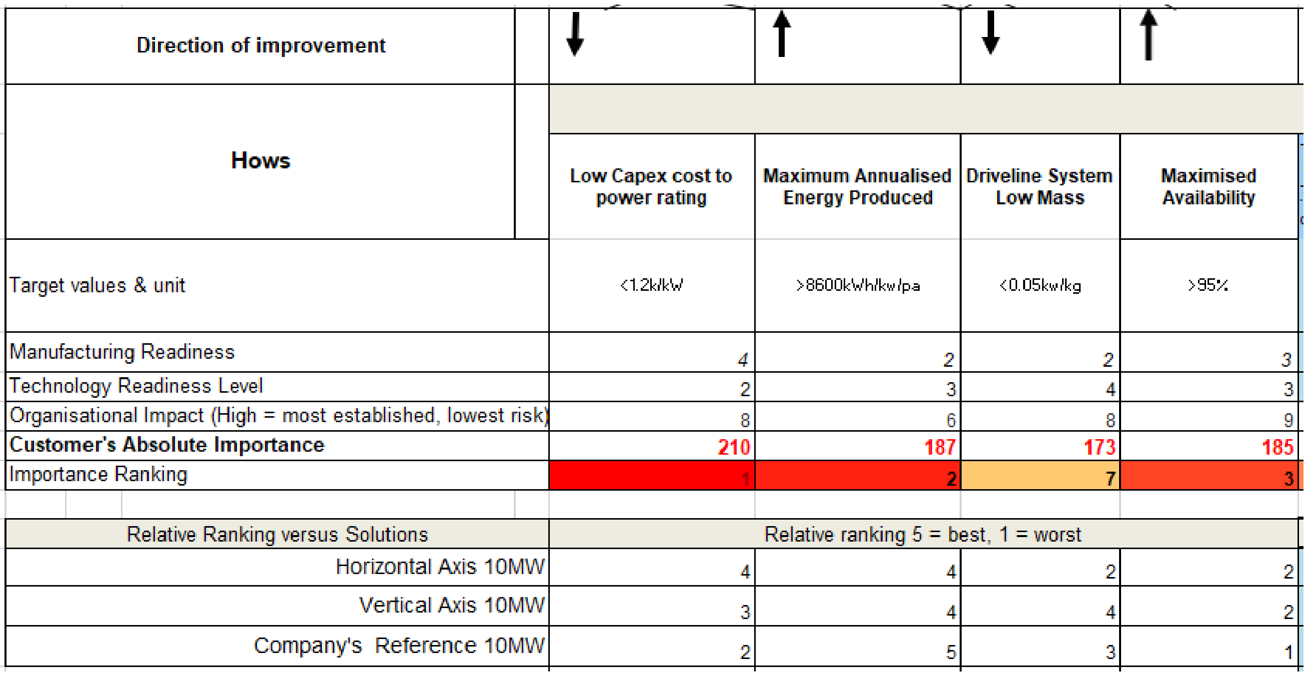


			Positive and negative impact, 1, 4 and 9 for strength, with negative sign to denote conflict			
			Capital cost	Energy yield	Flora and Fauna impact	Hydraulic impacts
	Solution Description	**Direction of Improvement**	1	2	3	4
1	Capital cost	Down		-4	-1	-4
2	Energy yield	Up			4	4
3	Flora and Fauna impact	Down				4
4	Hydraulic impacts	Down				

Step 4- Determine technical & competitive benchmarking.

The technical benchmarking assesses the competitor current state-of-the-art technologies achievements against the organisation's and the target values proposed for each design requirement to determine how well the organisation meets the customer needs with respect to the design requirements.

Table 4.5: Example of illustrating technical and competitive benchmarking.



Direction of improvement	↓	↑	↓	↑
Hows	**Low Capex cost to power rating**	**Maximum Annualised Energy Produced**	**Driveline System Low Mass**	**Maximised Availability**
Target values & unit	<1.2k/kW	>8600kWh/kw/pa	<0.05kw/kg	>95%
Manufacturing Readiness	4	2	2	3
Technology Readiness Level	2	3	4	3
Organisational Impact (High = most established, lowest risk)	8	6	8	9
Customer's Absolute Importance	**210**	**187**	**173**	**185**
Importance Ranking	1	2	7	3
Relative Ranking versus Solutions	Relative ranking 5 = best, 1 = worst			
Horizontal Axis 10MW	4	4	2	2
Vertical Axis 10MW	3	4	4	2
Company's Reference 10MW	2	5	3	1

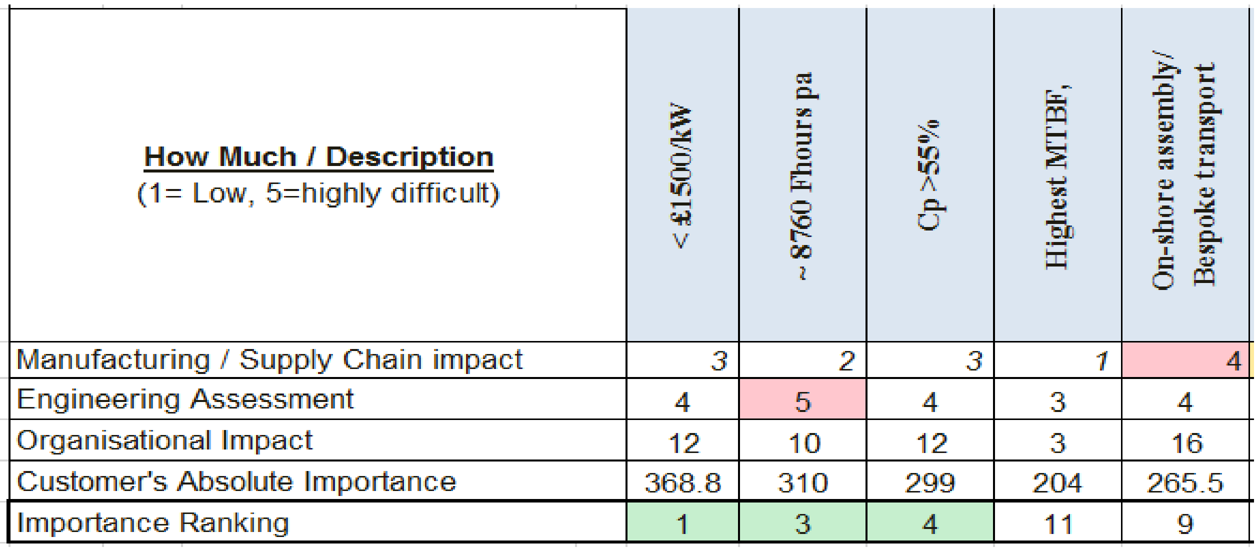
This step enables the team to quantify design targets for each design requirement based on 'ideality' beyond the competitors' achievements and based on the solutions' priority to meet the customer requirements. Establishing these target values is critical to identifying where improvement or innovation are needed for each design requirement. The collaboration of multidisciplinary teams must establish these concrete goals to satisfy the customer and the business. These values can be commercial targets, ideal values (beyond design limits), historical records, or experiments.

This step also enables the team to compare the company's performance and the competitors' against the target values to identify the areas that require further development to satisfy the customer requirements.

Step 4. Establish Organisation impact

This final step assesses the organisation's difficulty to execute the design requirements in terms of the engineering characteristics needs (Engineering, manufacturing, technical readiness level and overall organisation difficulties) of implementing these technical characteristics on the organisation. An example of the organisation impact is shown in Table 4.6. In the thesis, the term organisation impact is defined as the product of engineering difficulties and manufacturing difficulties. A rating of 1 to 5 was used to score how difficult it is for the organisation to implement each design requirement.

Table 4.6: Technical Assessment of a QFD matrix



How Much / Description (1= Low, 5=highly difficult)	< £1500/kW	~ 8760 Fhours pa	Cp >55%	Highest MTBF,	On-shore assembly / Bespoke transport
Manufacturing / Supply Chain impact	*3*	*2*	*3*	*1*	4
Engineering Assessment	4	5	4	3	4
Organisational Impact	12	10	12	3	16
Customer's Absolute Importance	368.8	310	299	204	265.5
Importance Ranking	1	3	4	11	9

4.4. Theory of Inventive Problem Solving

TRIZ is a systematic innovation problem-solving tool that goes beyond intuition, used logic, data, and research derived from studying patterns of invention in the global patent literature.

The tool makes use of the past inventions, problems and solutions, evolution trends and patents in areas of science and technology and across different industries to define a knowledge-based database of 40 inventive principles, a contradiction matrix, 76 standard solutions, and trends of evolution that can be used to solve any contradiction and incremental problems. As a systematic innovation tool, TRIZ attempts to eliminate the compromises and trade-offs usually accepted in a system or process at the early stages of the design. The specific problems or innovation needs are simplified to TRIZ conceptual problems using the TRIZ knowledge database (the inventive principles and standard solutions), and the solution is then evaluated with the specific problem.

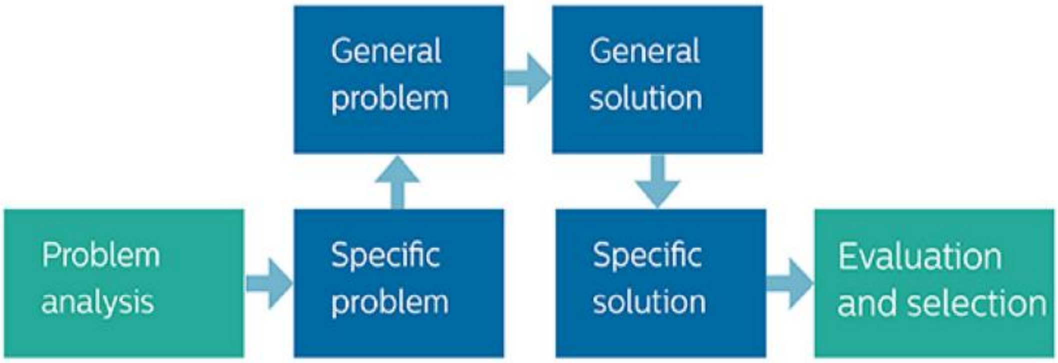


Figure 4.5: Solving technical problems using TRIZ [173]

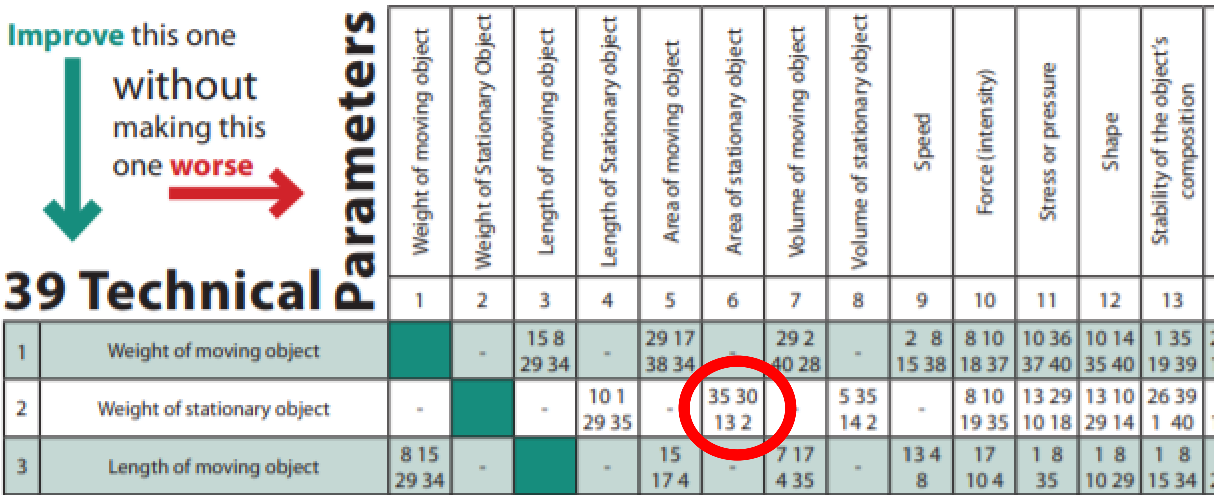
As shown in Figure 4.5, the TRIZ process is executed in two stages: the first step analyses the specific situation, formulates generic problems to resolve solutions, and again translates the generic solutions from the TRIZ library to relevant solutions to the initial problems. The second stage makes use of the TRIZ database representing the best innovation practices. The TRIZ database consists of various tools, such as the 40 inventive Principles, the technical contradiction matrix, the separation principles, the 76 standard solutions, effects, evolution patterns, and substance-field analysis.

The steps, shown in Figure 4.5, are described below,

1. Identify the problem and limitations: What is required? What is not met? And Why?
2. Translate the problem into a TRIZ generic problem common for all fields of technology.
3. Use the TRIZ database (40 inventive principles, 76 solution standards, effect database and knowledge tools) to determine the TRIZ generic solutions.
4. Translate the generic solution to a solution specific to the design problem.

TRIZ general methodology provided a systematic approach for removing contradictions in a system; traditionally, trial and error problems were resolved from the problem analysis to a problem solution obtained. Table 4.7 and Table 4.8 illustrates an example of directing the user to inventive principles.

Table 4.7: TRIZ contradiction Matrix [173]

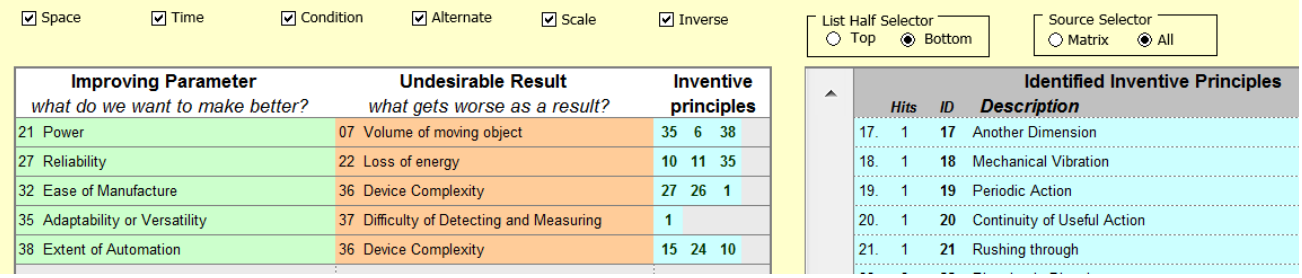


Improve this one without making this one worse

39 Technical Parameters

		1	2	3	4	5	6	7	8	9	10	11	12	13
		Weight of moving object	Weight of Stationary Object	Length of moving object	Length of Stationary object	Area of moving object	Area of stationary object	Volume of moving object	Volume of stationary object	Speed	Force (intensity)	Stress or pressure	Shape	Stability of the object's composition
1	Weight of moving object	🟩	-	15 8 29 34	-	29 17 38 34	-	29 2 40 28	-	2 8 15 38	8 10 18 37	10 36 37 40	10 14 35 40	1 35 19 39
2	Weight of stationary object	-	🟩	-	10 1 29 35	-	35 30 13 2	-	5 35 14 2	-	8 10 19 35	13 29 10 18	13 10 29 14	26 39 1 40
3	Length of moving object	8 15 29 34	-	🟩	-	15 17 4	-	7 17 4 35	-	13 4 8	17 10 4	1 8 35	1 8 10 29	1 8 15 34

Table 4.8: TRIZ Oxford Contradiction matrix representing TRIZ generic solutions to conflicting requirements [278]



☑ Space ☑ Time ☑ Condition ☑ Alternate ☑ Scale ☑ Inverse

List Half Selector: ○ Top ● Bottom

Source Selector: ○ Matrix ● All

Improving Parameter *what do we want to make better?*	Undesirable Result *what gets worse as a result?*	Inventive principles
21 Power	07 Volume of moving object	35 6 38
27 Reliability	22 Loss of energy	10 11 35
32 Ease of Manufacture	36 Device Complexity	27 26 1
35 Adaptability or Versatility	37 Difficulty of Detecting and Measuring	1
38 Extent of Automation	36 Device Complexity	15 24 10

Identified Inventive Principles

	Hits	ID	Description
17.	1	17	Another Dimension
18.	1	18	Mechanical Vibration
19.	1	19	Periodic Action
20.	1	20	Continuity of Useful Action
21.	1	21	Rushing through

In this thesis, TRIZ was integrated into QFD to create innovative solutions using the TRIZ library of problem-solutions after identifying the QFD process's contradictions. The steps of the approach are shown in Figure 4.2. The conflicting design requirements outputs from the QFD were used as input into TRIZ to propose alternative solutions to lead to 'ideal' solutions with no trade-offs. The QFD/TRIZ outputs were then inputted into the FMEA to assess and mitigate any technical risks of the proposed design requirements.

4.5. Failure Mode and Event analysis

FMEA is a systematic analysis method that identifies potential problems by detecting failures that may affect the design at different severity levels. This method helps to raise potential failure modes in the process of product design. Using various threshold limits (e.g. RPNs, Severity or Occurrence limits), the analysis assesses failure modes to identify weak design elements in the early design stage.

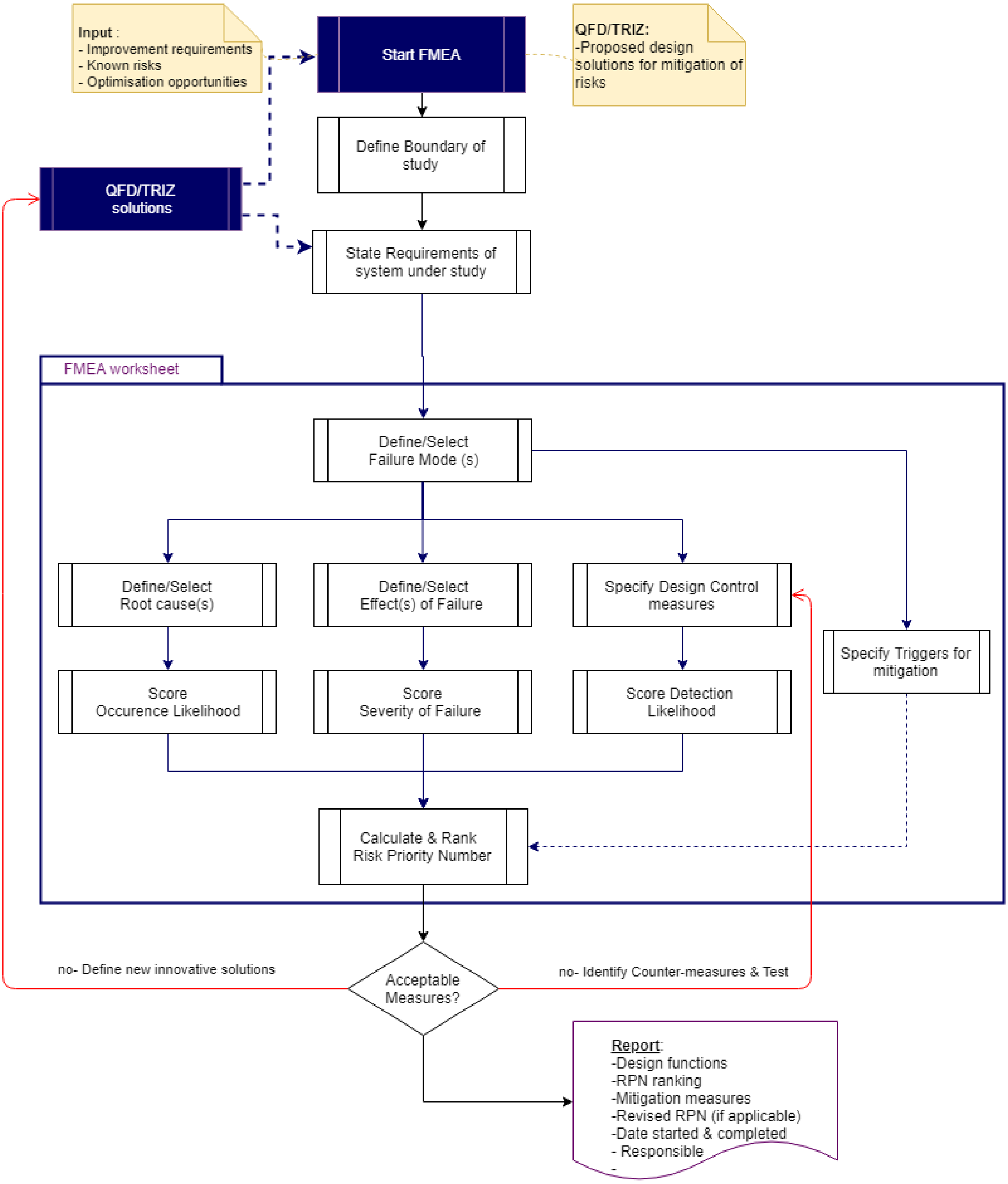


Figure 4.6: Proposed FMEA methodology integrating QFD & TRIZ.

In this thesis, the FMEA was integrated into QFD to evaluate the proposed designs at the earliest stage of the design, concept or design stage to ensure that the customer requirements are met. The global proposed methodology is presented in Figure 4.2, with the detailed FMEA methodology in Figure 4.6.

The purpose is to identify any potential failures at the concept stage, where design changes are still less costly. The methodology was adapted as follows:

- As QFD output, the FMEA was used to assess and mitigate the proposed designs' technical risks.
- As QFD input, the FMEA was to help to define and prioritise the Voice of the Customer and translate to design requirements.

In FMEA, three evaluation criteria are used to determine the potential functional failure modes. These evaluation criteria form the basis of the FMEA in which the Risk Priority Number (RPN) is evaluated as the product of the Severity (S), Occurrence(O), and Detection (D) ratings assigned to each failure mode.

Implementing an FMEA requires multidisciplinary teams' inputs to extend the knowledge in defining the system of interest, the design requirements, engineering characteristics throughout the process, enabling an interaction between the various failure modes and degree of satisfaction of the customer concerning the product performance and services.

The detailed methodology, following the steps given in Figure 4.2, is detailed below:

1. **Determine the system of interest**: In preparation to deploy an FMEA, the system boundary needs to be defined to aid the focus of the analysis by specifying all the functions and the interfaces of the system of interest. Functional diagrams are a way to represent the functions of the systems and the interactions.

2. **Determine the design requirements to assess**: The designers will define which requirements to evaluate. These derive from the design, the team's focus, feedback from quality control, or fed from QFD in an integrated mode.

3. **Identify the potential failure modes** in which the functions of the system may fail. These failure modes can be obtained from various sources such as theoretical or numerical data analysis, complaints, expert inputs, predefined data, and project data. In this research, where expert opinion was not available, pre-defined generic failure modes covering all possible failure modes were obtained from the ETI reports and literature. An example of generic failure modes is provided below in Table 4.9.

However, identifying failure mode for the relevant design requires significant effort from the teams.

Table 4.9: Example of generic failure modes

Generic Failure modes
Failure mode due to premature operation
Failure to operate at a prescribed time (complete loss of function)
Intermittent operation
Failure to cease operation at the prescribed time
Loss of output during operation (reduced performance)
Degraded operation (loss of performance over time)
Performing an unintended/undesired function

4. **List the effects of the potential failures**, noting that there may be more than one effect for each failure. These effects of failure relate to the specific function's ability to perform its intended function (i.e. operation, or status). The consequence of the failure may have impacts on:
    - Design performance
    - Customer satisfaction
    - Personal safety
    - Environmental impact
    - Organisation brand and reputation
5. **Assign severity rating** using a severity classification definition. The team is required to categorise all the foreseen effects into different classes. For this thesis, a pre-defined severity rating was used, adapted from the British Standard BS EN 60812 [248], and shown in Table 4.10. Pre-defined ratings were used for this thesis; it is recommended to classify all the consequences of failures based on all relevant factors being affected. Some examples of classifications can be found in [248] [279] [280].

Table 4.10: Pre-defined severity rating (adapted from [204] [248])

Ranking Values	Severity description	Rating
1	No effect	Minor
2	Minor performance loss, defect noticed only by close inspection	Low
3	Minor performance loss, defect noticed only by most observers	
4	Minor performance loss, defect apparent	Moderate
5	Device operable, but minor performance loss, end-user experience some dissatisfaction	
6	Device operable, but auxiliary performance lost	
7	Device operable, but with reduced performance level, end-user dissatisfied	High
8	Device inoperable, primary function lost	
9	Device inoperable, safe function lost with warning	Very High
10	Device inoperable, safe function lost without warning	

6. **Identify the causes of the potential failures** is critical to assess the criticality of each failure mode adequately. A failure mode may have more than one cause, and these should be identified. A generic library of failure causes can be provided to support the analysis. In this thesis, the generic causes were obtained from various literature and ETI internal projects [233] [190] [281]. Some of the literature reviewed provided assigned failure rates for known causes more specific to components, whereas others provide occurrence rating options such as time-bases, event-based based, piece-based [282].

7. **Assign the probability of occurrence** for each failure mode as the frequency or likelihood that the cause will occur. The organisation needs to involve a multidisciplinary team to define and agree on the occurrence ratings at different system complexity levels. A high Occurrence rating means a high probability of the cause to occur. A generic library containing failure causes is used in the thesis; however, these ratings might not apply to every FMEA system. Table 4.11 presents the pre-defined occurrence ratings used in the thesis.

Table 4.11: Pre-defined Occurrence rating (adapted from [226])

Ranking Value	Occurrence Description	Event occurrence – e.g. 1 in 1000 hours/ days.	Occurrence Rating
1	Failure unlikely	1 in 1000000	Remote
2	Relative few failures	1 in 250000	Very Low
3	Relative few failures	1 in 20000	Low
4	Occasional failures	1 in 1000	Moderate
5	Occasional failures	1 in 400	
6	Occasional failures	1 in 80	
7	Repeated Failures	1 in 20	High
8	Repeated Failures	1 in 8	
9	Failure inevitable	1 in 4	Very High
10	Failure inevitable	> 1 in 2	

8. **Define current Design controls:** This step is conducted to verify that the design controls can safely and easily detect probable failures. These evaluations intend to prove that the proposed design can identify the failure modes due to the several causes identified in the previous step. The higher the effect of the risk, the more critical it is for any design to have measures in place to detect these risks. Agreeing to these criticalities is paramount at the outset of the project, and a team of experts with different background should be involved.

9. **Assign a detection rating:** The detection ranking is based on the likelihood of existing design controls to detect that a failure has occurred. A scoring scale of 1-10 defines how likely the controls will detect the failure or defect's existence and at the design stage and will prevent the cause of the failure from occurring. Table 4.12 presents the pre-defined occurrence ratings used in the thesis.

Table 4.12: Pre-defined Detection rating (adapted from [226])

Ranking	Description FMEA	Rating
1	Design controls will detect a potential cause and failure mode	Very High
2	Very high chance that DC can find the failure mode and cause	
3	high chance that DC can find the potential failure mode and cause	High
4	Moderately high chance	
5	Moderate chance	Moderate
6	low chance	
7	Very low chance	Low
8	Remote chance	
9	Design control is unlikely to predict failure mode or cause	Very low
10	Design control cannot detect the potential cause and failure mode, or there is no design control	No Detection

10. **Obtain the Risk Priority Number (RPN):** a product of the three previously selected rankings: Severity, Occurrence, and Detection ranking associated with each failure mode and effect (RPN= OCC*SEV*DET). This RPN was used to prioritise risks and give a relative risk ranking. Emphasis is made here that the RPN guided the risks' prioritisation activity but should not solely be used to determine the need for actions, as the RPN might not always represent relative risks. The designer objectives should be to:
    - Implement actions for RPN over the threshold given.
    - Reduce the individual ratings as low as possible, even within acceptable RPN.
    - Improve Detection and Prevention controls
11. **Recommend an action plan**: The action plan presents recommended actions to mitigate the higher risk elements. From the calculated RPN, suitable follow-up corrective actions were proposed to reduce potential failures' criticalities by implementing preventing or corrective design actions. These actions aim to reduce the RPN of the three rankings:
    - Lowering the detection ranking by improving the detection or prevention controls
    - Reducing the severity ranking by considering design improvements (e.g. redundancy of the system) improves the design.
    - Lowering the occurrence ranking by tackling the cause of the failure and finding ways to control or remove them.
12. **Re rank the RPN:** Considering the recommended actions, the RPN was re-ranked to establish the revised RPN (rRPN) and the impact of the corrective actions on the elements with critically high risks. It should be noted that the recommended actions are meant to be implemented at the concept or design stage rather than later at the manufacturing or process stage.
13. **Continue to improve:** The FMEA is a continuous living process. The team’s primary goal should be to reduce the risks as low as possible continuously. If risks are still too high after actions have been taken, further mitigations are required until acceptable risks are achieved.
14. **Propose innovative solutions using QFD & TRIZ**: If further mitigations are required to lower the risks in FMEA, the integration of the QFD and TRIZ enable the designer to assess design requirements that would achieve acceptable RPN and still satisfy the customers. With the solutions from QFD& TRIZ, the RPN should be re-calculated.

The FMEA is an engineering analysis method for the identification and mitigation of known and imaginable problems. The FMEA lists failure modes and analyses them for their potential effects, giving mitigation routes. This research proposed implementing concept and design FMEA with QFD and TRIZ to allow the concept designer to assess risk during the concept generation process. Other more advanced methods (e.g. RAMS) become valuable once into detailed design since they involved much more analysis.

4.6. Implementation of the Structured Innovation approach

The health sector's development trend is fast and very competitive, responding to the numerous needs and added values. With continuous technological developments in information and communication and the increasing demand for sophisticated healthcare services, medical companies always investigate ways to design sophisticated, light, accurate and cost-effective healthcare devices. Therefore, creative and innovative thinking is the key to staying ahead of the competition and meeting user needs by breaking through the unending design limitations [163] [234].

Due to an ageing population needing more healthcare support, a study looked to design a concept for mobile healthcare devices to respond to the increasing need for medical care. A structured approach was applied to conceptualise medical devices that provided users' functions and requirements whilst maintaining the level of accuracy, monitoring, and sophistication all medical devices needed to adhere to [234].

The design process proposed a combined QFD/ANP and TRIZ method to provide devices that meet the users' growing needs and support the healthcare industry's new direction. QFD was proposed to integrate the various user needs into the new device design from phase development to product and component deployment. Combined with applying the Analytical Network Process (ANP) to rank and prioritise user needs for their importance and inter-dependence. And contradictions from the different characteristics are solved using TRIZ.

The User requirements and technical requirements were obtained from interviews, questionnaires, and scenario analysis. These were the Customer requirements inputs in the House of Quality (Top HoQ). The functional or technical characteristics to meet these requirements were then inputted at the top row of the HoQ.

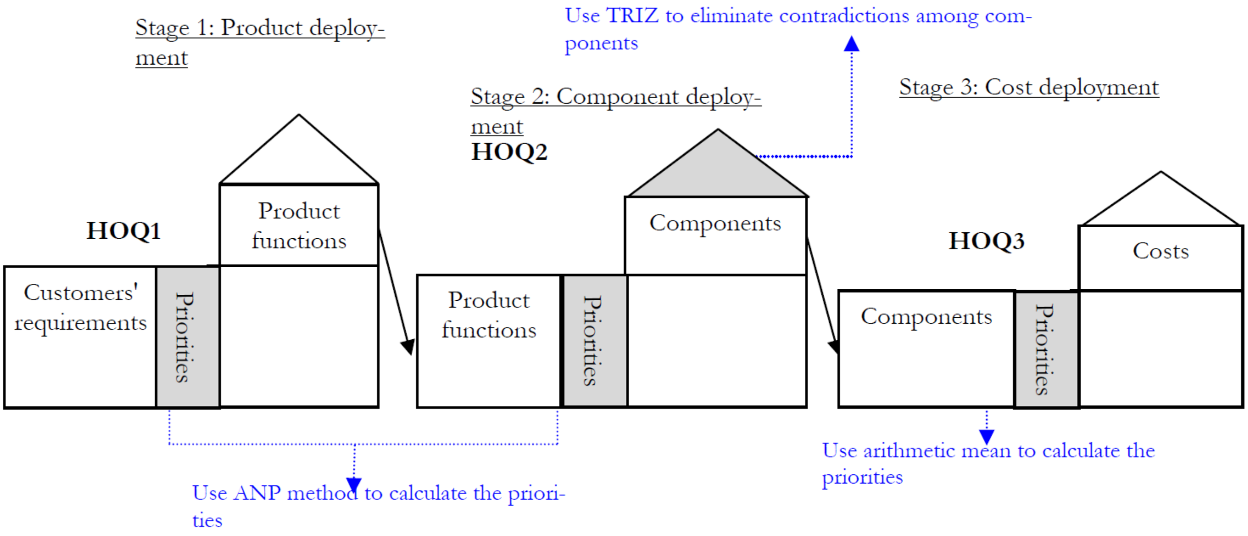


Figure 4.7: Proposed 3-stage House of Quality QFD methodology

In this example, the customer requirements were inputted in the HoQ to determine how to meet these requirements (product functions). Each requirement's importance rating was determined, and the what-how relationship between the customer requirements and the design requirements was determined using the Strong-Moderate-Weak relationship rating. These steps were as followed:

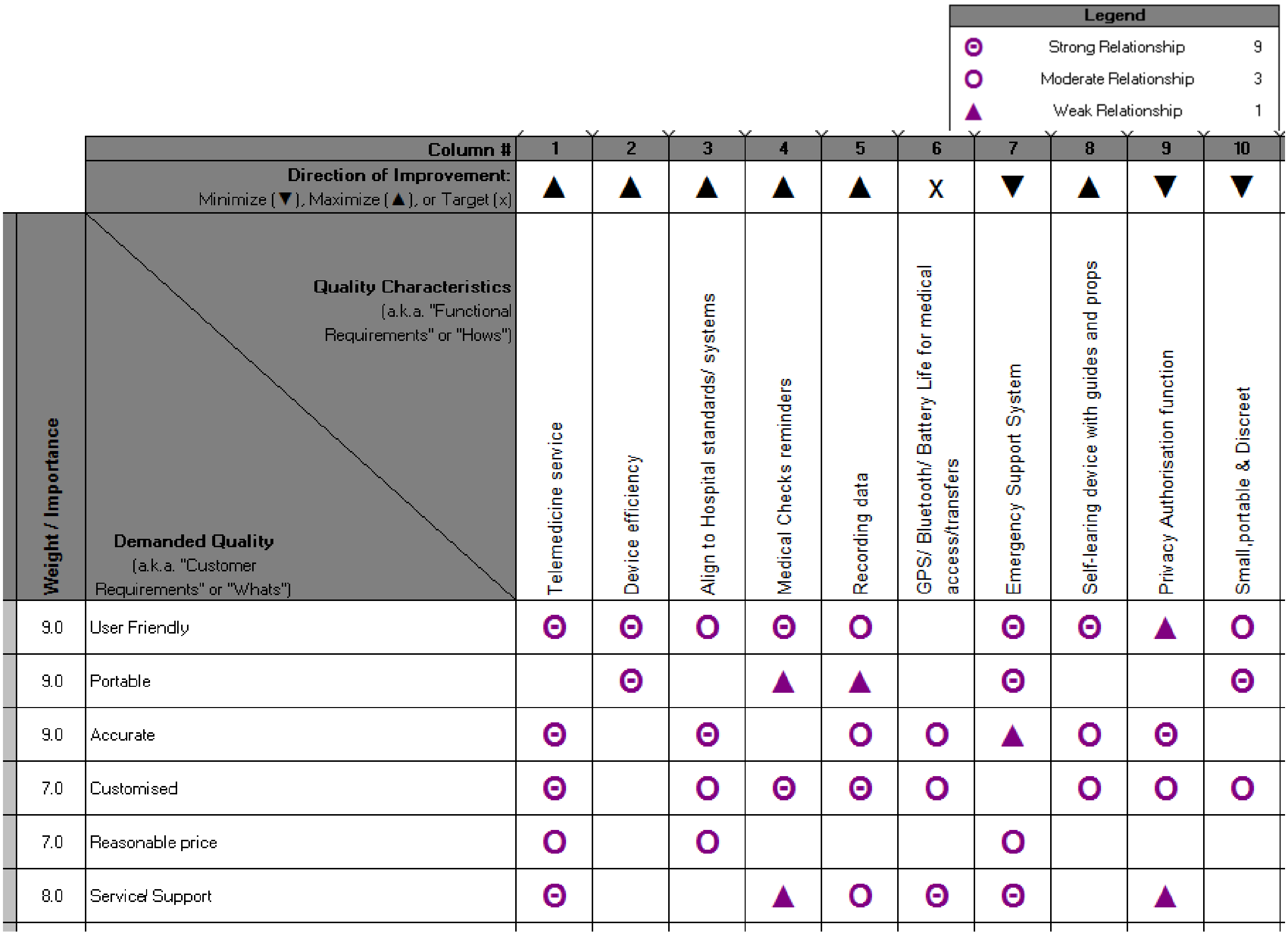
1. The voice of the customer was established using expert knowledge, surveys, questionnaires, and gap analysis.

Table 4.13: Captured customer requirements

Primary	Secondary	Tertiary
Analyse and report. Compatible to send/receive data.	Detect • Blood glucose meter • Blood pressure • Heartbeat Record	Accessible Sophisticated & Simple Easy to carry. Mobile (light & small) Personal use (User-friendly)

2. The customer requirements were then inputted into the HoQ-1 and the design requirements determined to meet these requirements. These design requirements will feed into the HoQ-2 as second-level customer requirements for the components.
3. These requirements were ranked concerning the user's needs, and the What-How' relationships between a customer requirement and design requirement were

established ‘. e.g. If the users want portable and efficient devices, this can be translated as a device light in weight that provides support and telemedicine services, records, reminds and transfers data to the NHS database, and still aligns with the hospital’s standards. Some design requirements will have a stronger relation to the customer requirements than others, and some will have none.



Legend

⊖	Strong Relationship	9
○	Moderate Relationship	3
▲	Weak Relationship	1

	Column #	1	2	3	4	5	6	7	8	9	10
	Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▲	▲	▲	▲	▲	X	▼	▲	▼	▼
Weight / Importance	**Quality Characteristics** (a.k.a. "Functional Requirements" or "Hows") / **Demanded Quality** (a.k.a. "Customer Requirements" or "Whats")	Telemedicine service	Device efficiency	Align to Hospital standards/ systems	Medical Checks reminders	Recording data	GPS/ Bluetooth/ Battery Life for medical access/transfers	Emergency Support System	Self-learing device with guides and props	Privacy Authorisation function	Small,portable & Discreet
9.0	User Friendly	⊖	⊖	○	⊖	○		⊖	⊖	▲	○
9.0	Portable		⊖		▲	▲		⊖			⊖
9.0	Accurate	⊖		⊖		○	○	▲	○	⊖	
7.0	Customised	⊖		○	⊖	⊖	○		○	○	○
7.0	Reasonable price	○		○				○			
8.0	Service/ Support	⊖			▲	○	⊖	⊖		▲	

Figure 4.8: HoQ-1 Whats- How relationship

Hence the relationship between CR(i) and QC(i) will determine the cumulative importance of each QC in relation to QC(i)- the total score of HOWs.

$$QC(i) = \sum (CR(i) * Relationship\ score\ of\ What - How$$

4. The roof of the HoQ enables to determine the interrelationship between design requirements (or QCs). In the case of portability and efficiency of the devices as an example, some of the QCs will record data (e.g. sleep, blood pressure), receive

support and services needed, and still keep the device light, portable and user-friendly. If the device's ability to record, measure and analyse all the data brings a high level of complexity to the device and is not user-friendly, then a negative correlation occurred, restricting the deployment of both design requirements without a compromise. These contradictions were solved using TRIZ to identify possible developments and ideas.

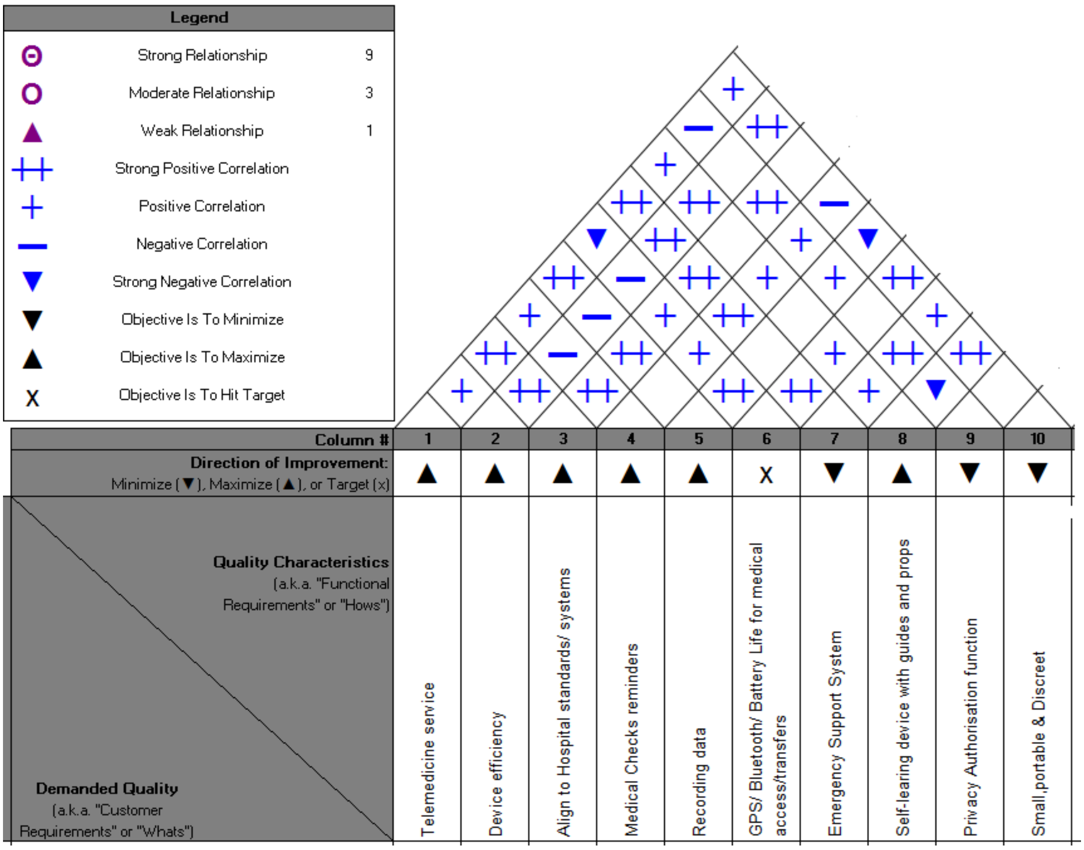


Figure 4.9: Correlation between the design requirements QCs-Positive, Negative, or neutral, strong or weak

According to its definition, TRIZ is a systematic approach that solves conflicts by introducing new solutions [278]. These contradictions were solved using TRIZ forty inventive principles and the 39X39 Contradiction matrix. For the example above, the three negative correlations between the quality characteristics are presented in Table 4.14.

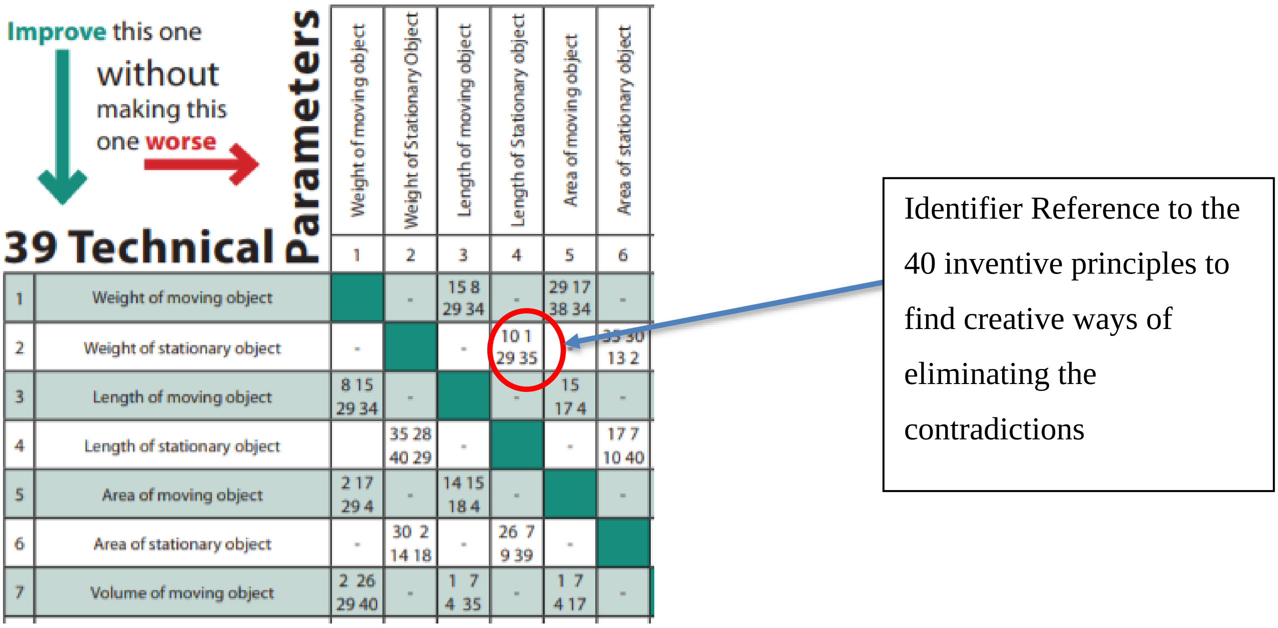
Table 4.14: Highlighted contradictions from Function relationship on the Roof of the HoQ

Contradictions		**Description**
Telemedicine Services	GPS/ Bluetooth/ battery	The ability to remotely diagnose patients meant the patients needed telecommunication technologies advanced such as Bluetooth, GPS tracker, stronger batteries. The addition of these features made the design of the device more complex for some users, such as elderlies and requiring more support for setup
Medical Checks Reminders	Device Efficiency	The more the device's functions, the less efficient it might be in speed, storage capacity and IT capabilities…
Recording Data (larger capacity)	Small, Discreet and Portable	The more the features, the bigger the storage and capacity was

As previously discussed in Section 4.4, the process of solving the contradictions using TRIZ requires translating the contradictions above into TRIZ generic problems, finding the TRIZ generic solutions using the TRIZ 39X39 Contradiction Matrix, and obtaining a specific solution(s) using the 40 inventive principles. In *Table 4.15,* the example presents the contradicting requirements and the closest related TRIZ generic problems. The number in brackets refers to the specific TRIZ inventive principles identifiers.

Table 4.15: Contradictions of technical requirements. Black- Improved - and Red- Worsening

Improving/ Worsening	Generic Problems & Innovative Principles (identifiers)
Telemedicine services	Measurement Accuracy (28) Device complexity (36)
GPS/ Bluetooth/ Battery Life	Measurement Accuracy (28) Use of Energy by moving object (19)
Medical Checks Reminders	Reliability (27) The extent of Automation (38)
Device Efficiency	Measurement Accuracy (28) Productivity (39) Speed (9)
Recording Data (larger capacity)	Volume of moving object (7) Quantity of substance (26)
Small, Discreet and Portable	Volume of moving object(7) Weight of moving object (1)



		Weight of moving object	Weight of Stationary Object	Length of moving object	Length of Stationary object	Area of moving object	Area of stationary object
		1	2	3	4	5	6
1	Weight of moving object	🟩	-	15 8 29 34	-	29 17 38 34	-
2	Weight of stationary object	-	🟩	-	10 1 29 35	-	35 30 13 2
3	Length of moving object	8 15 29 34	-	🟩	-	15 17 4	-
4	Length of stationary object		35 28 40 29	-	🟩	-	17 7 10 40
5	Area of moving object	2 17 29 4	-	14 15 18 4	-	🟩	-
6	Area of stationary object	-	30 2 14 18	-	26 7 9 39	-	🟩
7	Volume of moving object	2 26 29 40	-	1 7 4 35	-	1 7 4 17	-

Identifier Reference to the 40 inventive principles to find creative ways of eliminating the contradictions

Figure 4.10: Screenshot of the contradiction Matrix with technical parameters

In the above example, to achieve the proposed technical parameters, the following principles were suggested to enable the implementation of all the technical characteristics without the need for trade-offs:

Table 4.16: Table of contradictions with the possible inventive principles

Generic Problems (39x39 Matrix)	Measurement Accuracy (28)	Use of Energy by moving object (19)
Measurement Accuracy (28)		Local Quality [3] Universality [6] Optical Changes [32]
Device complexity (36)	Separation or extraction [2] Copying [26] Preliminary action [10] 34 Discard & Recover [34]	Cheap Disposable [27] Separation or Extraction [2] Pneumatics or Hydraulics [29] Replace a mechanical system [28]

The proposed principles offered innovative ideas for possible conceptual design stages. The appropriate principles were chosen based on the relevance to the current design to produce the changes required to implement these innovations. In this case, implementing Telemedicine services (Device Complexity) without impacting the efficiency of the GPS/Bluetooth or battery life of the device (Use of Energy by moving object):

- [10] Preliminary Actions:
    - Allowing the device to be pre-tested (Bluetooth, GPS),
    - The device can close irrelevant windows or actions when not in use
    - Recharging options at a certain percentage to avoid loss of battery strength.
- [34] Discard / Restore:
    - Discard information no longer required (stored data) saved on NHS server.
    - Close applications or windows on the device no longer needed.
    - Recover reminders/ checks when needed.
    - Ability to change device battery (spare) to swap between charging.

5. These inventive principles fed back into the HoQ, providing technical solutions to meet the user needs, as shown in Figure 4.9. These solutions provided quality characteristics for the conceptual design of the medical devices.
6. A Failure Mode Effects Analysis (FMEA) will provide a risk rating for severity, occurrence, and detection in the case of failure or parameter/defect associated with implementing these proposed solutions.

4.7. Summary

This chapter summarises how the selected design methodologies identified in Chapters 3 were applied for this research approach. The QFD’s House of Quality was adapted to include aspects of organisational and technical benchmarking and extend the Customer's Voice to include factors such as costs and the environment as inputs. The outputs of each design method produced inputs for the next, creating a set of inputs and outputs to support each stage for conceptual design solutions.

The application of the selected design methodologies, QFD, TRIZ, FMEA, is fairly old and well established. The novelty is in their integration, the Structured Innovation Approach. to support problem-solving and inventive solution exploration at conceptual stages of offshore wind designs.

5. Structured Innovation Case studies

This chapter aims to validate the proposed Structured Innovation approach described in Chapter 4 and applied to this research thesis. The validation was performed by applying the approach to various case studies within the offshore wind industry at the systems or sub-system level for concept creation and selection.

The case studies chosen were based on ones impacting the sector's key market drivers such as: Enabling the design of bigger turbines for greater energy capture with enhanced reliability, Improving innovation of services for operation and maintenance over the lifecycle of the wind farms, Optimising concepts for offshore wind station keeping for further offshore applications, and Integrating storage options to the future energy systems. These case studies investigate ways of optimising these sub-systems and processes using the Structured Innovation Approach to explore design topologies, functions and materials used following the industry needs.

This chapter is divided into two sections: Section 5.1 introduced the direct-drive generator case study and presented the Structured Innovation Approach application. Section 5.2, the station keeping case study is performed, assessing the potential innovative solutions for floating wind concepts.

5.1. Development of the next generator for the Top Head units

Realising cost efficiencies across the offshore wind turbine system is essential to encourage competitiveness and continued investment in offshore wind. The industry has objectively done this by adopting bigger turbines with gearless direct drive machines, contributing significantly to the overall wind turbine system's reliability and efficiency. However, with gearbox-less drivelines, the direct-drive generators must cope with large torques whilst producing electricity at low speed, which means these are often bigger, heavier and more robust than conventional high-speed generators [283].

5.1.1. Principles of direct drive generators and Statement of the problem

From constant speed multistage gearboxes with squirrel-cage induction generators in the early 1990s to standard variable-speed machines with double-fed induction generators (DFIG) in the late 1990s, the industry has evolved into manufacturing more gearless generator systems mainly to reduce failures and maintenance issues which accounts for over 26% of turbine downtime [284] [88]. Figure 5.1 shows a transition from high-speed three-stage geared generators to low speed geared and direct-drive generators.

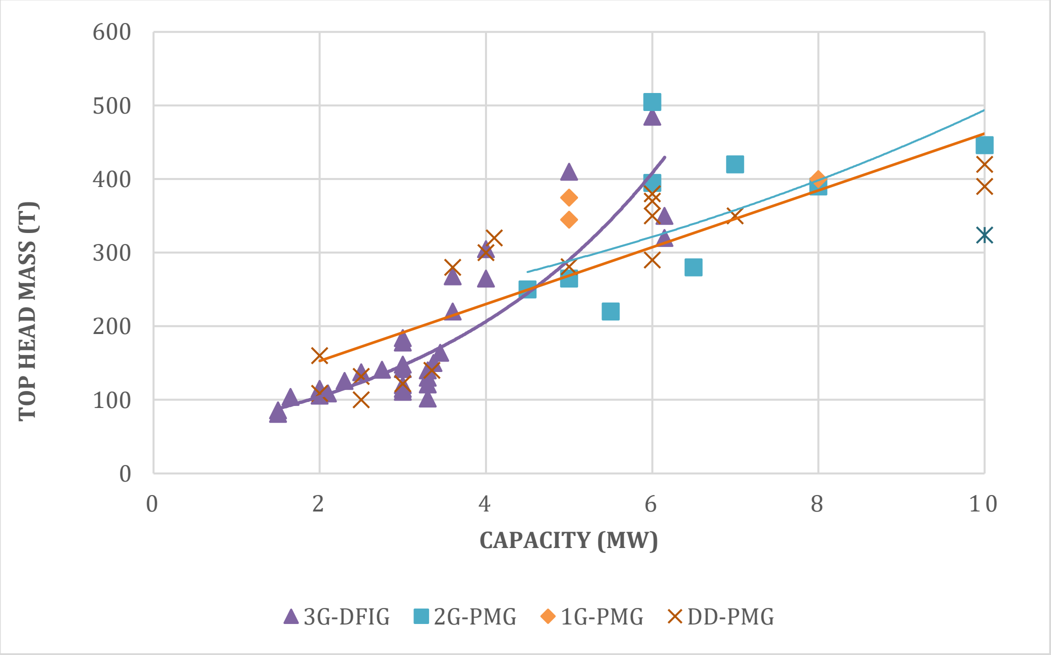


Figure 5.1: Trend of geared and direct drive generators. THM stands for the Top head mass of the top head unit.

This trend shows an increase in the turbines' top head mass due to their power rating and the nacelles' size.

In direct-drive machines, the generators are coupled directly to the main rotor, generating power at low rotational speed, compared to geared machines in which generators are indirectly coupled to the rotor via a gearbox to achieve higher rotational speed. Hence, for these machines to produce higher capacity power at low speed, an increase in the machine diameter will produce higher torque at reduced voltage, making machines larger and heavier to construct and deploy.

Since the torque is a function of the power$^{3/2}$, to achieve high torque and power, synchronous machines that are either electrically excited or use permanent magnets as excitation fields allow high inductor field with low iron losses. According to [285] [281] [286], permanent magnet generators were found to be more cost-effective and with lower excitation losses and improved efficiency at part-load compare to electrically excited generators such as the Enercon machines; however, as machines are scaled up to over 10MW, the generator's length or diameter increases, increasing the mass, which, in turn, increases the machine’s overall cost [262].

5.1.2. The applications of the Structured innovation methodology

According to the above functionalities of direct drive generators, it was understood that direct-drive machines were solutions to reliability and maintainability; however, resolving functions result in heavier and more expensive machines. The Structured Innovation Approach was tested in this case study to improve the concept design of the direct-drive machines, mainly serving the purpose of analysing how the methodology implemented in the early stage of design could improve the design, production, and operation of the designed product.

This case study used data from one of the ETI’s wind projects, the Glosten’s floating platform system [60] [287], which comprises a 6MW direct-drive generator. The project looked to evaluate a floating Tension Leg platform's design potential with an Alstom 150-6MW Haliade turbine. For confidentiality, some of the data were normalised. Table 5.1 and Table 5.2 presents to turbine and operation data, and Figure 5.2 summarises the methodology implemented.

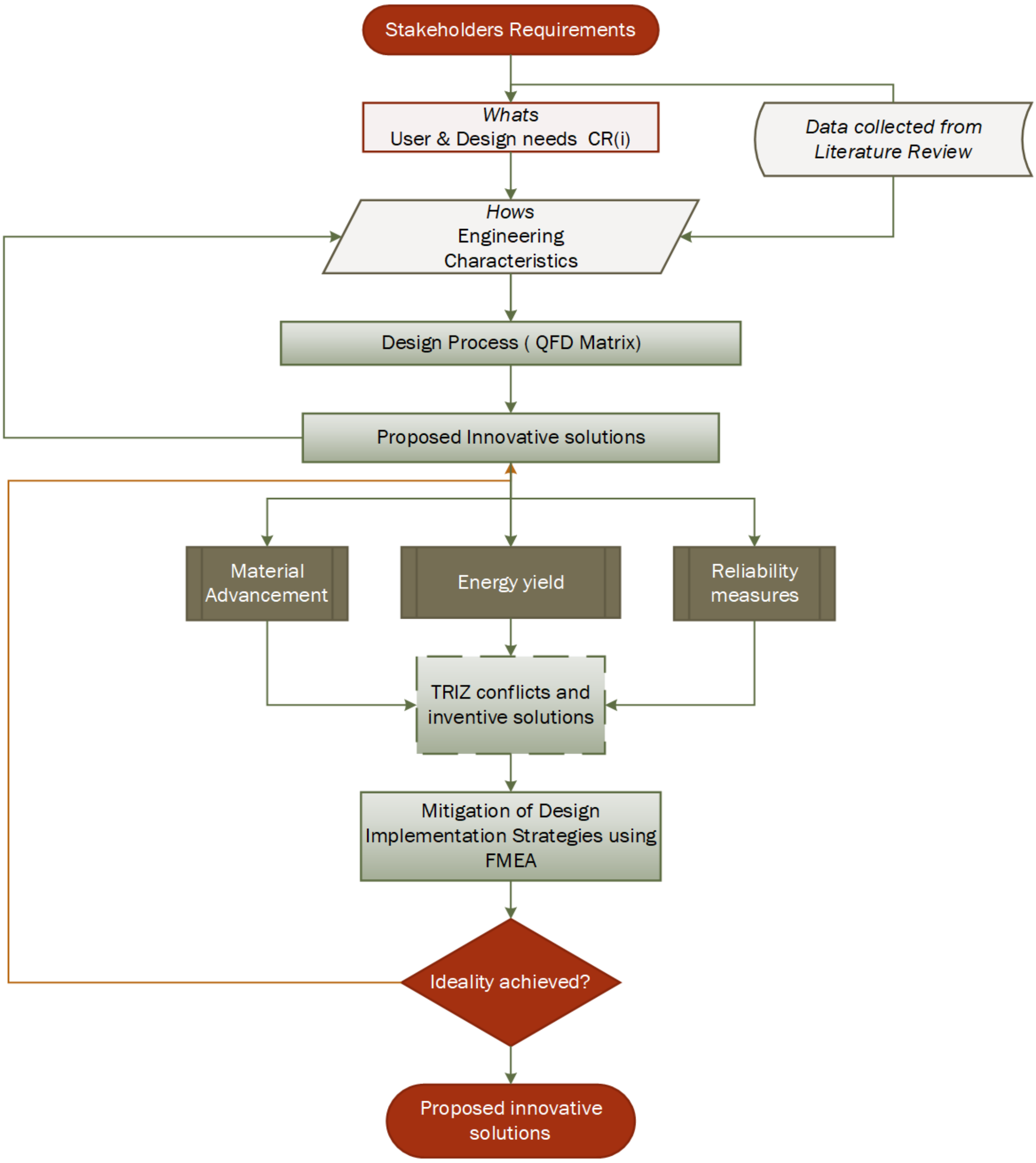


Figure 5.2: Electrical machines- Use case methodology

The 6MW machine ‘specifications are as follows [60] [287]

Table 5.1: 6MW Alstom Haliade Direct drive generator – turbine data

Turbine Data	6MW- Machine
Capacity (MW)	6
Rotor Diameter (m)	150
Blade length (m)	73.5
Hub height (m)	100
THM (tons)	410
Tower type	Tubular steel
Tower mass (tons)	372
Tower length	72.8
Primary Steel weight (MT)	1174
Turbine & Tower (£)	£6,793,000
Total Installed CAPEX cost (£/kW)	£2,534

Table 5.2: 6MW Alstom-Haliade operation data

	OPERATION
Class	I-B IEC-61400-1 / IEC-61400-3
Cut-in/out (m/s)	3-25
Rotor speed range (rpm)	4-11.5
Tip Speed (m/s)	90.8

Table 5.3: 6MW Alstom Haliade generator information

GENERATOR	
Generator type	Direct Drive PMG
Rated Voltage	900V/ phase
Cooling system	Air-cooled & pressurised
No of phases	3x3
Protection class	IPP55
Features	Advanced High-density Direct Drive PMG GE Pure Torque technology Turbine rotor and generator separated to allow a minimum air gap Permanent Magnet reliability= greater efficiency & mechanical reliability Advanced High-Density features= compact, lighter weight Elastic coupling= pure torque system that avoids undesired loads to the generator

The Structured Innovation approach was implemented to explore innovation paths in direct-drive generators, focussing on “the art of the possible within innovation” by seeking to understand and translate the stakeholder’s needs into system functions using Quality Function Deployment (QFD) analysis, describe and solve design problems in TRIZ, and propose mitigation measures of the potential technical risks associated with the reliability and quality of the proposed designs and processes using the Failure Modes Effects Analysis (FMEA) tool.

5.1.3. Capturing the stakeholders’ requirements

QUESTIONNAIRE DETAILS

A survey questionnaire was designed to help understand the stakeholders' needs within the offshore wind sector and the top head units of turbines. The survey included questions on understanding the importance of the specific needs of the sector. These questionnaires were circulated among the ETI members and internal staff.

This questionnaire was developed in association with the ETI Wind Programme, and the format was made of 5 questions covering: the stakeholder’s details (industry and name), open questions asking the user to specify the offshore wind industry needs from their perspective and a one-to-ten rating question enabling the user to determine the importance rankings of these needs, and free text input boxes to add in additional comments. The results were anonymised and grouped into five sectors representative of the industry, and these requirements were ranked from 1-10 in terms of their importance, with 10 being the most important/relevant needs.

A 10-point scale was selected for this questionnaire because it was straightforward, simple, and it highlights the importance of the responses without introducing vagueness in the survey.

Table 5.4: One-to-ten scale used for validation of the questionnaire.

Minor										**Major**
0	1	2	3	4	5	6	7	8	9	10

It was anticipated that this scale would highlight the major requirements from the stakeholders' minor to extremely minor needs. It should be noted that the questionnaire did not consider whether the views of the respondents were based on short- or long-term views of the sector and their industries, and all the respondents were treated as equals.

ANALYSIS OF SURVEY RESULTS

Due to the questionnaire output ‘sample size, the results of the survey were analysed in Excel. Two of the survey responses were excluded, as the participants did not rank their requirements, and no comments were added to their surveys. The rest of the cleaned data and presented are below:

Table 5.5: Stakeholder requirements’ responses- average ranking

Stakeholders Requirements	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**	Average Ranking
Lowest Cost of Energy	10	10	8	10	10	10	10	10	**9**
Flexible Deployment Capability	3	6	2	7	6	6	3	2	**1**
Minimised Environmental Impact	7	7	1	3	5	7	4	5	**2**
Maximum Operating Safety	8	8	6	9	8	8	9	9	**6**
Security of Power Supply	5	5	5	5	8	5	5	7	**4**
Scalable Technology	6	3	6	7	6	3	6	4	**3**
Effective Grid Integration	4	4	7	8	9	4	7	6	**5**
Reduced Commercial Risk	9	9	10	3	8	9	8	9	**6**

The responses were grouped into the following categories based on the type of companies the stakeholders represented: 1) Consultancies, 2) Regulators, 3) Project developers, 4) Public/Private bodies and 5) Government bodies.

The stakeholder responses presented in Table 5.5 indicated the top three most important stakeholder requirements lies in achieving the ‘Lowest Cost of Energy’ with ‘Reduced Commercial Risks’ and with a ‘resilient system with maximum operating safety’. The respondents' views were more varied for the less ‘important’ requirements of the stakeholders, such as maintaining ‘Minimal Environmental Impact’. The lower scoring of some of these requirements did not necessarily mean less interest in the stakeholders to achieve these needs. Nevertheless, their views at the time of the questionnaire completion based on their company’s vision in the short or long term. For this particular requirement, the average ranking was 1, yet this was seen in follow-up comments provided by respondents that at the time of completion of these surveys, some of the requirements might not have been on the top of their agenda but implemented in other requirements (e.g. "*Environmental impact is not high on our agenda except for installation and decommissioning for cases like oil leaking oil, which is statutory*" from a regulator).

Table 5.6: Average Stakeholder importance from survey & stakeholder requirements from literature

Electrical Generators	Minor										Major	**Avg. Score**
Top Level Objectives	0	1	2	3	4	5	6	7	8	9	10	
Optimum Power Output											X	10
Grid Compliant						X						5
Greater Reliability										X		9
Cost Effective								X				7
Interoperability							X					6

The stakeholder requirements associated with the electrical generators were mainly to deliver optimum power output, with the low maintenance cost, high efficiency, and longer lifespan. However, the bigger the machines' size, the higher the amount of rare earth permanent magnet materials was needed, and the larger the structures became. These were the main challenges for designers of direct-drive permanent magnet generators. Several studies have looked into these challenges; a summary of the literature and current research areas are presented in Table 5.7. These findings constitute the stakeholder requirement inputs for this study, as presented in Table 5.6.

5.1.4. Application of the QFD matrix and TRIZ

The Quality Function Deployment methodology, described in section 4.3, is validated in this section. Using a 6MW permanent magnet direct drive generator example, the study mitigates and proposes potential innovative design concepts to meet the stakeholder's requirements. The following steps were applied to achieve the above.

Step 1: Identify Stakeholder requirements

Having obtained the stakeholders 'requirements from the questionnaires (in Section 5.1.3) and validated their average importance, these were transferred to the House of Quality (HoQ) to work out innovative conceptual solutions to these requirements. The Structured Innovation Approach is intended to help represent the Voice of the stakeholder through the design process, and therefore produce concepts that meet their requirements by exploring the “art of the possible”. By incorporating the industry players’ needs into these machines' early design requirements using the Quality Function Deployment (QFD) innovation tool, this case study establishes steps required to achieve these needs.

This example examined the areas of great potential for cost reductions by identifying the critical components and process characteristics and determining the impact of deploying these characteristics to achieve maximum impact in the system's top head unit.

For this study's scope, only level 1 of the House of Quality (HoQ) was analysed to determine the potential innovative solutions in offshore wind turbines' top head unit. However, for studies looking to implement the information into their production lines, detailed and more specific levels of the HoQ should be explored, looking at sub-system and component levels.

Step 2: Propose solutions to the stakeholder requirements.

A wind turbine generator main function is to convert all or most of its mechanical power from the rotor blades to generate useful electricity at a low rotational speed. From Faraday’s law of electromagnetic induction, the main requirements can be met by these parameters: a set of coils or conductors (electron flow through electrical coils), a magnetic field (as a result of a flow of electrons) and the voltage induced by motion (as a magnetic field moves past the coil of wire). The second main requirement of these electrical machines is to operate efficiently to maximise the output capacity, meaning that the machines' design should be reliable with a longer lifespan and maximum availability.

Table 5.7: Possible technical solutions to meet the design requirements- From literature Appendix Table 9.5

Level 1 (design requirements)	**Level 2**	**Level 3**	**Level 4**
Maximising Conversion i/p torque, speed to Power	Increased part-load efficiency (losses in friction.)	**Machines with increased force densities**	Transverse flux machines
Grid compliant	Reduced noise/Vibration		Vernier hybrid machines
Simple Manufacturing process/ requirement	Minimum iron losses		Variable reluctance machines
Efficient Installation and Transport time	Minimum copper losses (windings)	**Optimisation of support structure (weight ~80%)**	Use of magnetic bearing
Longer lifetime (less part/less failure) =Reliable	Lowering mechanical losses		A buried magnet in the iron structure of the rotor (bigger flux density in air gap)
Easy access, repairs, and maintenance	Flexibility in air gap clearance limit		Dynamics of Mechanical design
Improved Return-on-Investment	Optimum material (cost/ weight/ availability, complexity)		Force reduction by use of air gap windings/
Smaller in Size	Stiffness		Force reduction by use of air-cored machines (with no iron in stator)
	Lowering the use of PM due to unstable prices)		Force reduction- machines without iron behind stator coils
	Reduction in mass (diameter/mass)- practical limitations	**Operation and Maintenance**	Failure rate analysis Vs Optimum availability
	Optimum machine topology choice		Improved manufacturing process & protection
	Ways to avoid the large attractive forces		Repairs strategies (CM, condition-based O&M, fault tolerance
		Cost reduction	fractional pitch concentrated windings
			Different configuration of poles & slots for minimum eddy current losses & back iron
		Superconducting (HTS) machines	Smaller/ Higher magnetic field
		Grid connection	Grid voltage, Fault ride through/ Power factor/ frequency
			Reliable power electronic converters (VSC)
			Variation in the number of series/ parallel connected coils= change of voltage level
		Windings distribution (compact machines)	Maximising number of slots per pole per phase, fractional pitch concentrated windings

The stakeholder requirements obtained from the questionnaire (section 5.1.3) were then captured into the HoQ, as shown in Table 5.6. Against these requirements in the conventional QFD layout (Y-axis), design requirements were generated into the vertical section of HoQ (X-axis) as shown, overleaf, in Table 5.9. These design requirements (DRs) were critical to the satisfaction of the stakeholder needs and were obtained from the literature and industry's expert knowledge to determine a potential list of solutions that meets the stakeholder's objectives [204] [272] [288]. This list of solutions was the result of captured potential solutions in the research and academic literature. Weighted scores were used to determine the strength of relationships between the stakeholder requirements and the respective DRs; and ranked using *Strong-9, Medium-4 to Weak-1* metric.

Table 5.8: Innovative solutions impact Quality.

Product for quality check	Product Rank	Priority Rank (should be)	Error, if the result is NOT zero, then solutions need improvement
71	**1**	**1**	**0**
38	**4**	**4**	**0**
70	**2**	**2**	**0**
42	**3**	**3**	**0**
Quality Check Flag			**0**

The Quality impact section of the HoQ, as illustrated in Table 5.8, ensured that the design requirements proposed were as impactful as initially defined by the stakeholders, meaning that each top-level objective's relative priorities matched the overall strength of the solutions to the needs.

Table 5.9: Defining innovative solutions and strength of relationships between requirements and solutions.

Improvement			**Down**	**Up**	**Down**	**Up**	**Down**	**Up**	**Down**	**Up**	**Up**	**Up**
		Priority	Low Capital cost to Power rating	Maximum Machine efficiency	Low Mass to power ratio	Maximum Availability	Short lead time to manufacture. and deploy	Autonomous operations/ self-healing.	Graceful degradation (N+1 redundancy measures)	Grid code compliance (Resistance to disturbance, faults, frequency, LVRT)	System adaptability	Proven- Back-to-Back Full-scale testing (NOAK)
Requirements	Optimum Power Output	**10**	9	9	0	9	4	9	9	4	9	9
	Grid Compliant	**5**	4	1	1	4	9	0	9	9	1	
	Cost Effective	**7**	9	9	9	9	9	4	4	4	4	9
	Interoperability	**6**	9	4	4	4	4	4	4	4	1	4

Table 5.10: Assessing the deployment impacts to organisation (target values vs engineering, manufacturing, and organisation difficulties)

Target Values	2000	98	10	95	8	0.50	1	1	100	5000
Target Quantity units	cost (£/kW)	% Full load	kg/kW	%	weeks	Min hrs/ month	operation	Support to Grid	100%- 9 Material audit Rating	Hrs of service recorded
Engineering difficulty to meet target	4	5	4	5	2	4	5	3	4	5
Execution difficulty	3	2	3	3	5	2	3	1	3	2
Organisational Impact (High = most difficult)	12	10	12	15	10	8	15	3	12	10
Organisational Impact Ranking	3	6	3	1	6	9	1	10	3	6
Solution Importance	227	182	92	197	172	142	187	137	129	177
Importance Ranking	1	4	10	2	6	7	3	8	9	5

$$Organisational\ Impact\ to\ implement\ Low\ CAPEX = 227 =$$

$$= \sum (Power\ Output\ 10 * CAPEX - 9) + (Grid\ Compliant\ 5 * 4) + (Cost\ Effective\ 7 * 9) + Interoperability\ 6 * 9)$$

Step 3: Determine and compare engineering target values to the existing technologies.

In the 6MW case study, the targets values set were obtained from the benchmark and threshold values in literature and ETI internal reports and are shown in Table 5.10 and Appendix Table 9.6. A compliance assessment was conducted to investigate if the proposed solutions were already implemented in the state-of-the-art designs. The assessment also ascertained if the competition met the engineering targets set: too tight targets may eliminate the chances for innovation, too broad it might be unachievable due to the organisation’s impacts on implementing these concepts.

A comparison was made using the target values as a benchmark to assess existing technologies' proposed design solutions against existing technologies' characteristics with similar features. In this case study, some offshore wind electrical generators were assessed against the high-level target values. This provided visibility of the improvement needed for some design requirements to be implemented. Moreover, this exercise enabled the strategic planning of the priority’s technologies or design requirements based on competitive market assessment and desired outcomes more widely.

Table 5.11: Relative Ranking of existing technologies against technical solutions(higher=better)*

Solutions comparison (Qualitative)	**Relative ranking** being 1=worst to 5=Best									
Siemens 3.6MW	1	1	4	3	5	3	2	4	4	3
Siemens SWT6.0-154	3	3	5	4	4	4	3	5	3	5
Alstom-Haliade 150	4	3	3	4	3	5	5	5	2	5
DD 10MW Reference	4	4	3	2	2	4	3	3	1	2

Relative Comparison										
Siemens 3.6MW	**227**	**182**	**368**	**591**	**860**	**426**	**374**	**548**	**516**	**531**
Siemens SWT6.0-154	**681**	**546**	**460**	**788**	**688**	**568**	**561**	**685**	**387**	**885**
Alstom-Haliade 150	**908**	**546**	**276**	**788**	**516**	**710**	**935**	**685**	**258**	**885**
DD 10MW Reference	**908**	**728**	**276**	**394**	**344**	**568**	**561**	**411**	**129**	**354**

*The green highlighted cells represent the best requirements among competitors. Refer to detailed qualitative assessment in Appendix 9.4.1

Table 5.12: Assessment of competitive solutions against target criteria and their compliance

Solution comparison (Quantitative)										
Siemens 3.6 MW	4200	87	19	92.0	48	0	0.0	1	40	2500
Siemens SWT6.0-154	2880	96	8.67	99.0	26	0.5	0.5	1	50	5000
Alstom Haliade 150	2534	97	13.33	99.2	33	0.75	1.0	1	65	7500
DTU-10MW Reference	2600	98	15.00	98.0	38	0.75	1.0	1	70	2500

Compliance with target values (Red- unachieved, 0%- achieved, Green-Overachieved)										
Siemens 3.6 MW	**-110%**	**-11%**	**-87%**	**-3%**	**-500%**	**-100%**	**-100%**	**0%**	**-60%**	**-50%**
Siemens SWT6.0-154	**-44%**	**-2%**	**13%**	**4%**	**-225%**	**0%**	**-50%**	**0%**	**-50%**	**0%**
Alstom Haliade 150	**-27%**	**-1%**	**-33%**	**4%**	**-313%**	**50%**	**0%**	**0%**	**-35%**	**50%**
DTU-10MW Reference	**-30%**	**0%**	**-50%**	**3%**	**-375%**	**50%**	**0%**	**0%**	**-30%**	**-50%**

Step 4: Defining the difficulties to achieve innovative solutions.

The offset section at the bottom of HoQ (Table 5.10) provided the difficulties in implementing the technical solutions, considering manufacturing capabilities, the maturity of the supply chain, procurement, technology readiness, business risks, and engineering implementation difficulty. A ranking system used for the offset section allowed to determine which characteristics were the most important for the organisation concerning the weighted customer requirements. An assessment of the difficult/high-risk characteristics is crucial to determine the likelihood of the innovative product development meeting the customer’s needs. These characteristics can also point out contradictions or need to assess further or alternative solutions that can be accomplished within a given project budget and schedule. The difficulty rating used was a *1 to 5 point scale with 1- being the easier or less risky* to achieve and *5- very difficult or riskier* to implement each design requirement.

According to the Level 1 HoQ (as shown in Table 5.10), at a high level, the most impactful innovative solutions were most likely from functionalities in electrical machines that reduce the capital cost per unit power ratio and the need for electrical machines with higher reliability, efficiency, and maximum availability. These machines will most likely be Nth-of-a-kind (NOAK) as they will have been tested and their technical and commercial risks reduced.

Step 5: Identifying synergies and contradictions (roof of the HoQ)

As discussed in Section 5.1.4, the traditional QFD process mainly identifies the stakeholder needs, the WHATs, translates their needs into design requirements, HOWs, determines the strength of the relationships between the WHATs and HOWs, and for completeness, defines target values to specify HOW MUCH the design targets of each technical requirements should be, to satisfy the stakeholder needs. The QFD process in this case study is enhanced by identifying the synergies and conflicts between the technical requirements (HOWs correlations). At the roof of the HoQ, the relationship grid establishes the relationship between the engineering solutions (the HOWs). The purpose of this roof is to identify those design requirements that potentially support or are in conflict with each other. The design requirements in conflicts highlight the need for compromise in the stakeholder's total satisfaction or further assessments to achieve satisfactory alternative solutions.

In this case study, the strength of the coupling was indicated using the following symbols: (--) strong negative (-) weak negative, (+) weak positive and (++) strong positive. Table 5.13 highlights the correlations matrix between the design requirements.

Table 5.13: Correlation Matrix between design requirements (Roof of HoQ)

Legend

++	Strong Positive
+	Positive
-	Negative
--	Strong Negative

	Synergies/Conflicts between solutions									
10	++	++		++		++	++	++	++	
9	-	+	+	++		+		++		++
8	--	+	+	+		+	-		++	++
7	-	++	++	++		++		++	-	
6	--	++		++			++	++	+	
5	++	+	++	++						++
4		++			+	++	++	++	++	++
3	++			++	++		-	-		+
2	-			++		+	++	++	+	++
1		-	--		++	-	-	-	+	++
	Solutions from Picking List									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Improvement	**Down**	**Up**	**Down**	**Up**	**Down**	**Up**	**Down**	**Up**	**Up**	**Up**
Priority	**Low Capital cost to Power rating**	**Maximum Machine efficiency**	**Low Mass to power ratio**	**Maximum Availability**	**Short lead time to manufacture and deploy**	**Autonomous operations/ self-healing.**	**Graceful degradation (N+1 redundancy measures)**	**Grid code compliance (Resistance to disturbance, faults, frequency, LVRT)**	**System adaptability**	**Proven- Back-to-Back Full-scale testing (NOAK)**

Step 6: Solving the conflicts using TRIZ.

TRIZ was used to understand which parameters had improving or worsening features. Using the TRIZ 39X39 contradiction matrix, Appendix Table 9.24, the specific parameters were translated into generic problems and followed the TRIZ's solution process to determine specific solutions deployed without worsening some features of the system. The strength of the coupling was indicated by whether multiple sources confirm that coupling exists.

The most relevant inventive principles were generated using the 40 TRIZ inventive principles to help achieve innovation during the conceptual design stage, a list of TRIZ solutions to solve similar generic problems or contradictions.

In Table 5.14, all the possible inventive principles were chosen to help obtain the most suitable design requirements for solving the conflicts and meeting the stakeholder's needs. The design requirements in the HoQ were translated into TRIZ generic problems and followed the TRIZ process to determine specific solutions that can be deployed with minimal trade-offs.

The potential inventive design solutions for the floating substructures use case are presented in Table 5.14 to summarise the conflicts and their applicable inventive principles.

Table 5.14: Collation of the contradictions in TRIZ

Feature to improve.		Worst conflicts	Inventive Principles
Design requirements	**TRIZ generic problem**		
Low Capital cost to Power ratio	26 - Amount of substance	19 - Energy spent by moving object	34, 29, 16, 18
Maximum Machine efficiency	22 - Energy Losses	37 - Complexity of control	35, 3, 15, 23
Low Mass/Energy conversion	5 - Area of moving object	26 - Amount of substance	29, 30, 6, 13
Maximum Availability	27 - Reliability	34 - Reparability	1, 11
Quick and simple to Install and Commission	36 - Complexity of device	32 - Manufacturability	27, 26, 1, 13
Autonomous operations/ self-healing.	38 - Level of automation	37 - Complexity of control	34, 27, 25
Graceful degradation (N+1 redundancy measures)	30 - Harmful factors acting on object	37 - Complexity of control	22, 19, 29, 40
Grid code compliance (Resistance to disturbance, faults, frequency, LVRT)	32 - Manufacturability	26 - Amount of substance	35, 23, 1, 24
Control System adaptability	35 - Adaptability	30 - Harmful factors acting on object	35, 11, 32, 31
Proven & standardized technology (NoAK)	32 - Manufacturability	39 - Productivity	35, 1, 10, 28

This process attempted to apply TRIZ to capital cost-related functions to enable more reliable generators with high efficiency and safe operation with the appropriate principles to help achieve low capital cost for the machines.

Step 7: Ideality assessment and detailed design

The proposed technical solutions described in the top-level HoQ provide a list of percentage importance scores and indicate parameters that conflict with each other. The benchmarking exercise highlighted the existing direct-drive generator gaps, which can feed into a product development strategy. These technical requirements are refined into product or part characteristics of the sub-systems. Having translated the stakeholder needs into design requirements in phase-1 of the HoQ, an overview of phase 2 of the QFD is presented below.

Table 5.15: Set Engineering Targets for the part specifications.

	Design Requirements	Target Values
System characteristics	Highly power-dense rotor giving best energy capture Low Loss of electrical machines and drives Minimum Reactive Materials (Support Structure) Minimum Active Materials (Windings, power electronic) Low Component Count Multiple Redundant Levels and systems Optimised Foundation installation method and costs	cp = >0.4 peak CI II <2.8% loss <100kg/kW <2kg/kW <25 Bill of Materials Line 1 >2 levels for BOM Line 2 <8hrs
	Lowest cost of transport to site costs Modular Component Structure Low-Cost reliable power transmission & distribution Component and system HAL testing facilities Effective Electrical control systems for pitch, yaw, other control Effective mechanical control systems for cooling, position Optimised power rating, voltage, and quality Effective site survey of seabed conditions and foundation conditions Standardisation of common components and installation methods Decommissioning costs are converted to revenue Clear and Robust Social and Government Support, national and local Wind Farm Array optimisation for greatest wind energy yield Lowest cost materials (abundant, recyclable, robust) Self-healing structures and components Remote control inspection and Intervention apparatus	<£10k/kW Generator, converter, tower, blades <0.9p/kW >20yrs life HALT equivalent <10mS turn to turn <1Deg C control float MV, THD = 0.5% >5m/s >10m resolution BSI, IEC LRS >75% recyclable content RoCs, EIS, CFD etc…. Increase by 5% AEP <£7/kg. Repairs self if overstrained or heated, or overvoltage
	Increased durability structures and assembly methods HALT guidelines and rules Operators Knowledge Network, facilitating CIP and operational data Remote control inspection and Intervention apparatus	From Shore, From Ship Towards <30years lifetime Rules accepted and adherence noted Sharing best practices (DTOCean/ WES model) 80% of operators contribute and exploit network

5.1.5. Risks Mitigation using FMEA.

As defined in Section 3.4.1, the FMEA is a systematic reliability method used in concept and design phases to help raise potential failure modes and, by doing so, identifies technical risks associated with the proposed designs or processes.

The proposed design criteria were evaluated in terms of the technical risks, having captured and converted the stakeholder requirements into technical solutions for the electrical machines. The outcome of FMEA analysis identified potential failure modes with the highest technical impacts on the electrical system (RPN exceeding 72). Some of these failures' requirements are highlighted in Table 5.16 and Table 5.17 with design recommendations. A sample of the FMEA is presented in The full FMEA analysis is presented in Table 5.18, with the full FMEA presented in *Appendix* Table 9.21

Table 5.16: Electrical machine causes of failure with high RPN (exceeding 72)

Causes of Failure	Recommended design controls & actions
Slippage in coupling locking mechanism due to under-torqued bolts on keyless device	Provide instructions to check torque regularly
Internal motor fault	Provide adequate motor thermal protection
Failure to control temperature rise or failure of the cooling system	Ensure alarm and other measures are fitted and are included within the critical maintenance schedule
Pump failure, hose failure, lose connection	Design review, establish PLC interface
Drive failure, encoder failure, controller failure, mechanical	A health monitoring system, including vibration, temperature, stress, and displacement measurements. Failsafe design, using redundancy (Critical parameter measurements), simulation
Damage to equipment during installation and set-up which leads to failure	Schedule of standards for safety-critical subsystem components and develop compliance in supply- Appropriate maintenance and diagnostics procedures

Table 5.17: Electrical driveline causes of failure with high RPN (exceeding 72)

Causes of Failure	**Recommended design controls & actions**
Improper material selection	Use design guidelines
Failure of the control system to monitor timed overload, Failure of the protection system	Design to ensure timed overload monitoring and use design guideline for protection
Driveline system components are in a fault condition	Develop a fault annunciation system
Incorrect sizing of cooling and lubrication system	Implement a monitoring system, provisions to increase cooling capacity, increase design safety margins
Salt in the air	Use of internal heaters, air-conditioned room for drives, protective coating of PC boards, totally enclosed motors
Grid Voltage drop	VFD/VSD detects and protects against low voltage and will initiate a system shutdown
Unreliable system components	Verify all major components have service life to provide overall required system reliability
Critical components life check	Verify all major component life/Run accelerated testing on critical COTS components
Lack of accessibility to tools and operators	Check design for accessibility to tools and operators
Excessive thrust loads; insufficient bearing lubrication	Design review with the suppliers

Table 5.18 A sample of the Direct-drive generator FMEA

Customer Requirements (CR)	Failure Mode(s)	Effect(s) of Failure	SEV	Cause(s) of Failure	OCC	Current Design Controls Detection & Prevention	DET	RPN	Recommended Actions	SEV	OCC	DET	RPN
To Maximise the Reliability of the system	Partial to Complete failure of the system	Prolonged downtime, loss of profit, Operational (repair or replacement) costs	8	stator core: High load causing thermal/mechanical stresses in winding due to Emergency shutdown, start/stop & other switching events	5	GCSA+ recovery, roughness measured from sensor information to determine wear. Temperature and UMP	4	160	Load and thermal monitoring- Thermal sensor, Appropriate current frequency, and amplitude demodulation algorithm and 1P invariant power spectrum density algorithm - Use of air-core machines (no iron in stator)- for stresses reduction	8	3	3	72
				Windings: Faults in cooling hoses (cracks, leaks, burst, blockage.) during manufacture, installation, material defects or design faults: overheat, leakage to electrical breakdown due to conductors	5	Temperature monitoring, current and power performance monitoring	4	160	Rigorous testing before/after installation. Improved early state NDT and maintenance visits -QFD- Improved Condition Monitoring O&M - Exploring fraction pitch concentrated winding (for minimum losses)	8	2	3	48
				Stator Winding failure of conductor cooling hoses- Manufacture defects, overheat, excessive dielectric stress due to high voltage, vibration, debris contamination	3	Temperature monitoring, current and power performance monitoring	5	120	Monitoring overload condition, operating within voltage and temperature limits. Bump test for new/ reworked windings [QFD- Variation in # of series/ parallel connected coils (change in voltage level…	8	3	3	72
				Deformation of stator core (frame) due to magnetic pull imbalance of field flux- cracks or permanent deformation	3	Monitoring during construction and installation to avoid deformation of stator frame due to vibration of core outside diameter. Careful packing- filling spaces to avoid vibration. UMP analysis	3	72	Corrective action- repair by removing & re-insulation of side-pressure spring? QFD- Embedded sensors/controllers. Rigorous onshore testing before deployment	8	3	2	48

5.2. Development of next-generation Station keeping.

This second case study presents the Structured Innovation Approach in offshore wind stationkeeping design, specifically fixed and floating substructures. The process began with establishing the need for innovation, leading to defining who the stakeholders are and their requirements, using data from the literature. The Structured innovation approach was tested using: the QFD module to establish the potential areas of innovation, TRIZ to resolve conflicts and the FMEA to mitigate the potential technical risks.

5.2.1. Status of the floating offshore wind sector

According to the 2018 Wind Europe statistics, 18.5MW of offshore wind was installed in European waters accounting for 4543 grid-connected turbines across 11 countries. Monopiles remain the most popular substructures, representing 74.5% of all installed foundations, with 24.5% jacket foundations [21]. However, as more projects are brought online, the question remains: How deep can monopiles or fixed-bottom foundations go? Initially estimated to 50-meter water depth restrictions, the monopile foundations have pushed their theoretical limits to provide services to turbines of over 7MW and 60+ water depth [21] [289]. These limitations are based on achieving the least capital expenditure costs, whilst designing for higher loads, manufacturing (larger diameter longer units), transporting and installing (existing fleet, lifting units, driving hammer), as well as the site characterisation and the turbine specifications [289]. However, as seen in the heat maps in Figure 5.3, there is significant wind resource in European deeper waters, particularly off the coast of Scotland and England, and also in the west of France and off the coasts of Portugal and Spain, where fixed-bottom foundations deep water are not suitable [21].

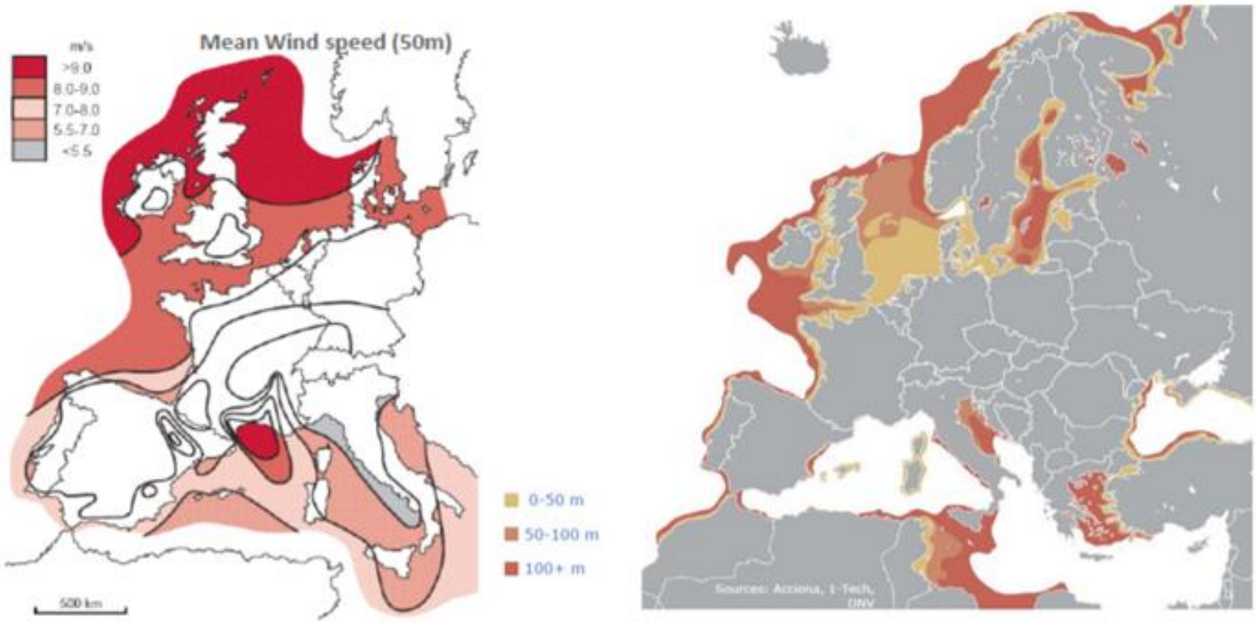


Figure 5.3:European Offshore Wind resource: L- Wind speed, R- Water depth [290]

According to the CCC report [29], the United Kingdom is “aiming for 75 GW of offshore wind by 2050, compared to 8 GW today and 30 GW targeted by 2030” [24] [29]. Across Europe, the offshore wind target is set at 40 GW by 2020 and 150 GW by 2030 achievable by predominantly using conventional fixed-bottom foundations in water depths under 50m. However, by 2050, offshore wind capacity in Europe could reach 460 GW, which can only be achieved by accessing those deep-water water depth sites over 50m using floating technology. “Floating foundation could thus be used to exploit deepwater locations closer to shore, and the added flexibility of floating structures means that it has the potential to be highly scalable” [75]. The Energy Technologies Institute (ETI) estimated that deploying floating wind in these locations to access this stronger wind resource could result in a lower levelised cost of energy (LCOE) compared with some fixed-bottom UK Round 3 sites due to more consistent wind resource, which in turns means higher capacity factor [31] [291].

Globally, floating offshore wind is evolving fast, and there are several floating wind substructure concepts under development. Across Europe, Japan, Korea, and the US, thirteen floating projects were announced, with nine projects in Europe (UK, Portugal, and France), three in Asia (Japan and Korea) and one in the United States [292] [293]. Of all the projects, the only operating floating project to date is the Hywind project in Scotland with a total capacity of 30MW and the 2MW Floatgen demonstrator project in Le Croisic in France [294] [290].

This sector is still infantile, but the success of the demonstration projects, the attractiveness of their higher capacity factors well above the fixed offshore winds and attractive deepwater wind resource means that the sectors need to seek out the best ways for the industry to scale by identifying the right ways to innovate and de-risks the floating concepts. The Structured innovation process is used in this case study to systematically identify, develop, and validate the novel technology concepts.

5.2.2. The application of the Structured Innovation Approach

Defining the stakeholder requirements:

Several offshore wind projects have adopted stakeholder engagements as an integral part of their development process, allowing interested parties to directly or indirectly impact the project by providing a valuable contribution to the project (positive or opposing views). As such, capturing the stakeholder requirements is key to balancing projects' development with the people's needs for the optimal outcome. Some of the key stakeholders captured were:

Table 5.19: Defining the stakeholders.

Local communities	**Local authorities (council & other organisations)**
Local council	National Grid
Fishing communities	Environmental organisations (Natural England and Scottish Natural Heritage)
Other sea users	The Crown Estate (leaseholder)
Ministry of Defence	Road and rail transport authorities,
Aviation, Air Traffic Service	Oil and gas companies
Coastal communities	Supply chain bodies
General public	Statutory bodies Landowners Private equity firms

The responses from the various surveys and consultations inform project developments; some of these responses were captured as shown in Table 5.19 and prioritised in Table 5.21

Table 5.20: Functional requirements to meet stakeholder needs.

Receptors	Consultation	Functional Requirements
Socio-economic impacts	Occupation- Evidence from landowner's preference	Market strategies, Resource assessment Testing at full scale (de-risking)
	Small-to-Medium businesses (SME)- funding issues and valley-of death	Resource/funding for commercialisation (>TRL6) Proof of Return-of-Investment at design/concept level Consortium/ collaboration & risk taking
	Supply chain (Manufacturers, owners, operators, service providers, governmental agencies, workforce agencies, investors, ports)	Risk-sharing with the introduction of new technologies, "pre-commercial projects." Introduction of paid services for floating technologies
Environmental Impacts		Minimal disturbance effects and avoidance responses to installation, operation, and decommissioning
Standardisations	Technology/ Project developers Policy and regulation bodies O&M service providers	De-risking technologies (TRL 9) Adaptability to various design considerations Accommodate innovation & ensure international harmonisation of technical requirements for scale-up.

The average ranking of responses, combined with ETI’s expert survey responses (described in Section 4.3 – Step 1), highlighted the need to deploy offshore wind at the least lifetime costs and with standard technologies adaptable for global scale-up. The stakeholders defined each objective, as shown in *Table 5.21*.

Table 5.21: Stakeholder top level objectives and relative priority

Substructure for Offshore wind	Minor										Major	**Avg. Score**
Top Level Objectives	0	1	2	3	4	5	6	7	8	9	10	
Lowest lifetime cost											x	10
Highest supply and safety										x		9
Lowest Environmental impact								x				7

The design requirements were determined to satisfy the customer requirements using data extracted from the literature summarised in Table 5.20. The requirements associated with the least lifetime cost were mainly instruments to mitigate the technical and commercial risks associated with first-of-a-kind floating designs that were not standardised and deployed globally. This means that the technologies proposed to deliver optimum power output, with the minimal maintenance required, at high efficiency and longer lifespan.

5.2.3. Application of the House of Quality (QFD)

Step 1: Identify Stakeholder requirements

Having identified the stakeholders ‘requirements and validated their average importance in Section 5.2.2 and summarised in Table 5.21, the House of Quality (HoQ) visually represents the innovative conceptual solutions' impacts on these requirements. As described in Section 4.2, this Structured Innovation Approach is intended to help represent the voice of the stakeholder through the design process, and therefore produce concepts that meet their requirements by exploring the “art of the possible”.

Step 2: Propose solutions to meet stakeholder needs.

These requirements define what the offshore wind floating substructure should do to satisfy the industrial players. By incorporating these needs into these offshore wind substructures' early design requirements using the Quality Function Deployment (QFD) tool, this case study established steps required to achieve these needs. The HoQ, as shown in Table 5.22, is a matrix providing a conceptual map for the design process; that is used to understand stakeholder requirements and establish priorities of technical requirements to satisfy them [295] [277] [296].

The stakeholder top objectives were presented against the functional requirements in the HoQ. The relationship matrix defined the strength of the relationship between stakeholder needs and the design requirements, highlighting if the relationship is strong-9, medium-4, or weak-1. An example would be: “minimising the environmental impact” with a weak-to-no link to “having a low substructure cost”, whereas “mass production and economies of scale” have a strong impact on the “lifetime cost of the substructure”.

The direction of improvement for each functional requirement showed that increasing reliability, accuracy in site measurements, mass production, de-risking are all needed to better the technology whist reducing factors associated with commercial risks such as capital costs, operational costs, manufacturing, and installation/decommissioning processes. This highlights that the industry was not yet at its target best to maintain its services and processes, but improvements are still needed, and that is where innovation fills this gap.

As shown in Table 5.23, the Quality Impact assessment section of the HoQ was added to provide a way of carrying out a quality impact assessment of the proposed solutions by supporting the user to know if the solutions to the needs were impactful initially defined by the stakeholders. This means that each top-level objective's relative priorities must match the solutions' overall strength to the needs. Among the challenges of meeting the stakeholder requirements, the floating platform size and weight were seen as some of the most critical technical barriers (Table 5.22). Besides, having simple manufacturing and installation methods was highlighted as another area that could have great potential for cost reduction. From the operation side, potential cost reductions could be achieved from standardised platforms that have been tested and with high Technology Readiness Level (TRL) and onshore repairs to enable robust and time-efficient maintenance procedures.

Table 5.22: HoQ Top level- Assessment of innovative solutions in floating substructures (Relationship matrix: 9-Strong, 4-Medium, 1-Weak)

Improvement			Up	Down	Down	Up	Down	Down	Down	Up	Up	Up
		Priority	Advanced Control Systems	Minimal Operating Costs	Lighter structural size & weight	Economies of Scale/Mass Production	Simple and Quick Manufacture and installation methods	Substructure costs per unit	Minimal footprint (navigation, seabed disruptions.)	Energy yield	Flexibility (adaptable to sites, soils, loads)	Standardised floating types for higher TRL
Requirements	**Lowest lifetime cost**	10	9	9	9	9	9	9	4	9	4	9
	Highest effectiveness	9	9	9	9	4	4	1	4	9	4	9
	Lowest environmental impact	7	1	1	4	4	4	1	9	4	9	4

Table 5.23: Assessing impacts of technical solutions.

		Priority	Advanced Control Systems	Minimal Operating Costs	Lighter structural size & weight	Economies of Scale/Mass Production	Simple and Quick Manufacture and installation	Substructure costs per unit	Minimal footprint (navigation, seabed disruptions.)	Energy Yield	Flexibility (adaptable to site, soils, loads)	Standardised floating types for higher TRL	Product for quality check	Product Rank	Priority Rank	Error, if the result is NOT zero, then solutions need improvement
Requirements	**Lowest lifetime cost**	10	9	9	9	9	9	9	4	9	4	9	**80**	**1**	**1**	**0**
	Highest effectiveness	9	9	9	9	4	4	1	4	9	4	9	**62**	**2**	**2**	**0**
	Lowest environmental impact	7	1	1	4	4	4	1	9	4	9	4	**41**	**3**	**3**	**0**

Step 3: Determine and compare engineering target values to the existing technologies.

For each design requirement obtained in Step 2, engineering target values were required to establish the degree of innovation or improvement of floating technologies. These are target quantities that will satisfy the stakeholder's needs if achieved. In this case study, the following target values were obtained from literature and ETI internal reports and shown in Appendix Table 9.10 and Table 9.11. It should be noted that the references and comparisons outlined in this section relied on the existing publicly available data. For this reason, cost data from floating wind foundations have not been validated and carry greater uncertainty.

A compliance assessment was conducted to investigate if the proposed solutions were already implemented in the existing technologies, such as semi-submersible design or the tensioned leg platform. This step established how much the competition met or deviated from the engineering targets: too tight targets may eliminate the chances for innovation, too broad values might be unachievable due to the organisation's impacts to implement these concepts [219]. This provided visibility of the improvement needed for some of the design requirements, and more broadly, this enabled strategic planning of the technologies/functions to prioritise based on the competitive market assessment and desired outcomes.

Table 5.24: Floating platform target values

Improvement	Up	Down	Down	Up	Down	Down	Down	Up	Up	Up
Priority	Advanced Control Systems	Minimal Operating Costs	Lighter structural size & weight	Economies of Scale/Mass Production	Simple and Quick Manufacture and installation methods	Substructure costs per unit	Minimal footprint (navigation, seabed disruptions.)	Energy Yield	Flexibility (adaptable to sites, soils, loads)	Standardised floating types for higher TRL

Target Values	**90**	**90**	**1400**	**2.5**	**150**	**600**	**1000**	**95**	**95**	**7**
Target Quantity units	**% Efficiency**	**£k/MW/year**	**tonnes- Average Platform weight, Pre-ballast**	**% Learning rate**	**£k/unit Installation costs**	**£k/MW**	**Cost per Unit**	**% Available (Capacity factor)**	**% application for over 50 m water depth sites**	**or higher TRL**

Table 5.25: Defined target values for ideal assessment

Improvement		**Up**	**Down**	**Down**	**Up**	**Down**	**Down**	**Down**	**Up**	**Up**	**Up**
	Priority	Advanced Control Systems	Minimal Operating Costs	Lighter structural size & weight	Economies of Scale/Mass Production	Simple and Quick Manufacture and installation methods	Substructure costs per unit	Minimal footprint (navigation, seabed disruptions.)	Energy Yield	Flexibility (adaptable to sites, soils, loads)	Standardised floating types for higher TRL
Target Values		**90**	**90**	**1400**	**2.5**	**150**	**600**	**1200**	**50**	**95**	**6**
Target Quantity units		% Efficiency	£k/MW/year	tonnes- platform weight, Pre-ballast	% Learning rate	£k/unit Installation costs	£k/MW	Cost per Unit	% (Capacity factor,)	%application for over 50 m water depth sites	or higher TRL
Relative Ranking versus Solutions		**Relative ranking with 1=worst to 5=Best**									
Semi-Submersible platform		2	4	1	0.50	4	2	3	2	2	3
Tensioned Leg Platform (TLP)		2	3	3	1.25	3	3	4	4	4	4
Spar-buoy platform		3	3	2	0.50	1	3	2	5	2	2
Hybrid/Multi-Platform		1	1	1	0.00	1	1	1	2	1	1
Concrete platform		3	3	2	2.00	2	2	2	3	3	2

Table 5.26: Relative Ranking of existing technologies against technical solutions (Qualitative)

Relative Ranking versus Solutions	**Relative ranking with 1=worst to 5=Best**									
Semi-Submersible platform	2	4	1	0.50	4	2	3	2	2	3
Tensioned Leg Platform (TLP)	2	3	3	1.25	3	3	4	4	4	4
Spar-buoy platform	3	3	2	0.50	1	3	2	5	2	2
Hybrid/Multi-Platform	1	1	1	0.00	1	1	1	2	1	1
Concrete platform	3	3	2	2.00	2	2	2	3	3	2

Relative Comparison										
Semi-Submersible platform	**356**	**712**	**199**	**77**	**616**	**212**	**417**	**398**	**278**	**597**
Tensioned Leg Platform (TLP)	**356**	**534**	**597**	**193**	**462**	**318**	**556**	**796**	**556**	**796**
Spar-buoy platform	**534**	**534**	**398**	**77**	**154**	**318**	**278**	**995**	**278**	**398**
Hybrid/Multi-Platform	**178**	**178**	**199**	**0**	**154**	**106**	**139**	**398**	**139**	**199**
Concrete platform	**534**	**534**	**398**	**308**	**308**	**212**	**278**	**597**	**417**	**398**

Table 5.27: Assessment of competitive solutions against target criteria and their compliance (Quantitative)

Relative Ranking versus Solutions										
Semi-Submersible platform	40	87.22	1800	5.00	122	1063	1800	50.00	50	5
Tensioned Leg Platform (TLP)	50	93.00	1100	1.50	201	620	1100	51.72	80	7
Spar-buoy platform	65	99.50	1400	2.00	135	530	2200	45.50	50	3
Hybrid/Multi-Platform	30	150.00	2400	0.00	350	850	2200	40.00	45	3
Concrete platform	30	120.00	2000	1.00	270	1100	1950	45.00	60	4
Compliance with target										
Semi-Submersible platform	**-56%**	**3%**	**-29%**	**100%**	**18%**	**-77%**	**-50%**	**0%**	**-98%**	**-17%**
Tensioned Leg Platform (TLP)	**-44%**	**-3%**	**21%**	**-40%**	**-34%**	**-3%**	**8%**	**3%**	**-16%**	**17%**
Spar-buoy platform	**-28%**	**-11%**	**0%**	**-20%**	**10%**	**12%**	**-83%**	**-9%**	**-47%**	**-50%**
Hybrid/Multi-Platform	**-67%**	**-67%**	**-71%**	**-100%**	**-133%**	**-42%**	**-83%**	**-20%**	**-53%**	**-50%**
Concrete platform	**-67%**	**-33%**	**-43%**	**-60%**	**-80%**	**-83%**	**-63%**	**-10%**	**-37%**	**-33%**

Step 4: Defining the difficulties to achieve innovative solutions.

With the engineering targets set and current floating substructure trends assessed against those target values, the next step was to establish how difficult it would to implement the proposed solutions. The offset section at the bottom of HoQ (Table 5.28) provided a sense of the difficulties of implementing the technical solutions, considering the manufacturing's capabilities, the maturity of the supply chain, the procurement, the technology readiness, the business risks, and engineering implementation.

A ranking system used for the offset section determined which design requirements were the most important for the organisation regarding the weighted stakeholder requirements. An assessment of the difficult/high-risk design requirement was crucial to determine the likelihood of innovative product development. These requirements can also point out to the contradicting requirements or needs for further assessment of alternative solutions. The difficulty rating used was a *1 to 5 point scale with 1- being easier or risky* to achieve and *5- being very difficult or riskier* to implement each technical solution.

In this case (Table 5.28), reducing the substructure platform weight and size were highlighted as some of the most impactful innovative solutions with the greatest organisational impact. Keeping minimal operational costs was also seen as an impactful way to deliver great cost saving to the substructure and the overall turbine by implementing simple manufacturing and installation procedures, providing redundancy measures, and allowing the most efficient maintenance procedures.

As explained in Section 4.3, the technical solutions defined in the top-level HoQ (phase 1) are generally vague and intentionally general to define how the system has to perform to meet the stakeholder needs. The intention is to stop the innovators from jumping to specific and known solutions before thinking of the process needed and potential solutions. These set of design requirements are further translated into sub-function, manufacturing, and production requirements to achieve detailed specific design solution(s) that meet the stakeholder requirements into the Level-2 through to Level-4 HoQ.

Table 5.28: Definition of difficulties to achieve solutions.

Improvement		**Up**	**Down**	**Down**	**Up**	**Down**	**Down**	**Down**	**Up**	**Up**	**Up**
	Priority	Advanced Control Systems	Minimal Operating Costs	Lighter structural size & weight	Economies of Scale/Mass Production	Simple and Quick Manufacture and installation methods	Substructure costs per unit	Minimal footprint (navigation, seabed disruptions.)	Energy Yield	Flexibility (adaptable to sites, soils, loads)	Standardised floating types for higher TRL
Target Values		**90**	**90**	**1400**	**2.5**	**150**	**600**	**1200**	**50**	**95**	**6**
Target Quantity units		% Efficiency	£k/MW/year	tonnes- Platform weight, Pre-ballast	% Learning rate	£k/unit Installation costs	£k/MW	Cost per Unit	% Capacity factor	% application to > 50 m	or higher TRL

ASSESSING DEPLOYMENT IMPACT(S) TO ORGANISATION

Engineering difficulty to meet the target	3	4	5	3	3	4	4	3	5	4
Execution difficulty	3	4	4	4	5	3	3	5	2	2

Organisational Impact (High = most difficult)	9	16	20	12	15	12	12	15	10	8
Organisational Impact Ranking	9	2	1	5	3	5	5	3	8	10
Solution Importance	178	178	199	154	154	106	139	199	139	199
Importance Ranking	4	4	1	6	6	10	8	1	8	1

Step 5: Identifying synergies and contradictions (roof of the HoQ)

The roof of the HoQ is used to define the interrelationships between the design requirements, allowing the designer to identify those requirements that potentially support or are in conflict with each other. The conflicting design requirements highlight the need for either compromise in the stakeholder ‘total’ satisfaction or the need for further assessments for alternative solutions.

The symbols used in Table 5.29 indicate the strength of the technical solutions’ couplings: strong negative (--), weak negative (-), weak positive (+), and strong positive (++).

Table 5.29 presents the roof of the HoQ with the strength of the design requirements identified by pairwise comparison. The positive couplings out ways the negative ones considering some of the parameters with the greatest impacts on the Capital expenditure, for instance: (1) reducing the floating platform size and weight would positively impact the manufacturing and installation procedures by removing the needs for expensive, heavy-duty, and bespoke equipment. However, this might mean that sophisticated and complex control systems were required to minimise the turbine's acceleration by damping the motion. This highlights potential conflicts between the platform size and the control systems. From an operation expenditure point of view, the designer might consider minimising the seabed footprint to achieve minimal environmental impact. Minimal disruption could result in a less complex and cheaper lease consenting process. Nevertheless, this might not be suitable for catenary mooring lines due to the challenges of forming proper catenary configuration or due to wake effects for array configurations [290].

Table 5.29: Roof of HoQ displaying conflicts and synergies between technical solutions for floating substructures.

Legend

++	Strong Positive
+	Positive
-	Negative
--	Strong Negative

Synergies/Conflicts between solutions

	1	2	3	4	5	6	7	8	9	10
10										
9										++
8									++	+
7								+	+	--
6							-			++
5							+	++		++
4					++	++			+	++
3				++	++	+	-	+	++	+
2			--	+		-	+	++	+	++
1		++	+	-	-	--		++	++	++

Solutions from Picking List

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Improvement	**Up**	**Down**	**Down**	**Up**	**Down**	**Down**	**Down**	**Up**	**Up**	**Up**
Priority	**Advanced Control Systems**	**Minimal Operating Costs**	**Lighter structural size & weight**	**Economies of Scale/Mass Production**	**Simple and Quick Manufacture and installation methods**	**Substructure costs per unit**	**Minimal footprint (navigation, seabed disruptions.)**	**Energy Yield**	**Flexibility (adaptable to sites, soils, loads)**	**Standardised floating types for higher TRL**

Step 6: Solving the conflicts using TRIZ.

The TRIZ problem-solution database was used to solve the conflicts highlighted in Table 5.29. The technical solutions in the HoQ were translated into generic problems and followed the TRIZ's process (described in Section-4.4) to determine specific solutions that can be deployed with minimal trade-offs.

Of all the couplings highlighted in Table 5.29, four of the technical solutions were found to have the strongest contradictive couplings, as shown in Table 5.30 based on the author and ETI subject expert matter weighing score.

Table 5.30: Tally of technical solutions with contradictions

Technical solutions	Sum of Positives	Sum of Conflicts
Control Systems	5	**3**
Operating Costs	5	**2**
Platform weight and size	6	**2**
Economies of Scale	4	1
Manufacturing installation methods	1	1
Platform capital cost	2	1
Footprint	2	**3**
Energy yield	1	0
Flexibility/ Adaptability	6	0
Standardisation	9	1

These design requirements were translated into TRIZ generic problems in Table 5.31. Using the TRIZ 39X39 contradiction matrix, the relevant inventive principles were proposed in Table 5.32 as alternative solutions to meet the stakeholder requirements using the TRIZ inventive principles database.

Table 5.31: Substructure desired parameters converted to TRIZ generic problems.

TRIZ Generic Problem (39x39 Contradiction Matrix)			
Technical Solutions	**Improving features**	**Conflicting features**	**Description**
Advanced Control Systems	28 - Accuracy of measurement	36 - Complexity of control	Advanced to maximise yield, reduce fatigue, and dampen floater motion
Minimal Operating Costs	34 - Reparability	25 - Time Losses	For port-side major repairs, rapid mobilisation but slower repair process (site dependent)
Lighter structural size & weight	26 - Amount of substance	38 - Complexity of control	Larger substructure cost more and require more material
Economies of Scale/Mass Production	32 - Manufacturability	35 - Adaptability	Mass production and increase reliability, bespoke control systems
Simple and Quick Manufacture and installation methods	25 - Time Losses	28 - Accuracy of measurement	Manufacturing-Less complex substructure with minimal substance;
Substructure costs per unit	1 - Weight of moving object	14 - Strength	Reliability and strategic O&M plans help with lower capital cost and energy yield
Minimal footprint (seabed disruptions.)	13 - Stability of object	5 - Area of moving object	Based on mooring concepts, high stability of device with minimal seabed disruption
Energy Yield	27 - Reliability	5 - Area of moving object	Energy conversion a function of deflection and frequency (water plane)
Flexibility (adaptable to sites, soils, loads)	33 - Convenience of use	27 - Reliability	Adaptable control system without the need for changes in technology/material. Accelerated testing for all possible scenarios
Standardised floating types for higher TRL	35 - Adaptability	45 - Complexity of control	Standardisation of some components of the platform

Table 5.32: Floating substructure potential inventive design solutions from contradictive parameters

Feature to improve		Worst conflict	Inventive Principles
Advanced Control Systems	28 - Accuracy of measurement	36 - Complexity of device	27, 35, 10, 34
Minimal Operating Costs	34 - Reparability	25 - Time Losses	32, 1, 10, 25
Lighter structural size & weight	26 - Amount of substance	38 - Level of automation	8, 35
Economies of Scale/Mass Production	32 - Manufacturability	35 - Adaptability	2, 13, 15
Simple and Quick Manufacture and installation methods	25 - Time Losses	28 - Accuracy of measurement	24, 34, 28, 32
Substructure costs per unit	1 - Weight of moving object	14 - Strength	28, 27, 18, 40
Minimal footprint (navigation, seabed disruptions.)	13 - Stability of object	5 - Area of moving object	2, 11, 13
Energy Yield	27 - Reliability	5 - Area of moving object	17, 10, 14, 16
Flexibility (adaptable to sites, soils, loads)	33 - Convenience of use	27 - Reliability	17, 27, 8, 40
Standardised floating types for higher TRL	35 - Adaptability	36 - Complexity of device	15, 29, 37, 28

5.2.4. Risks Mitigation using FMEA.

The floating system was represented as a function tree in Figure 5.4. This system (the substructure) represented by its functions allows the design to review what the system must do to meet the stakeholder requirements before considering the system's specific components, such as the anchors, the yaw system.

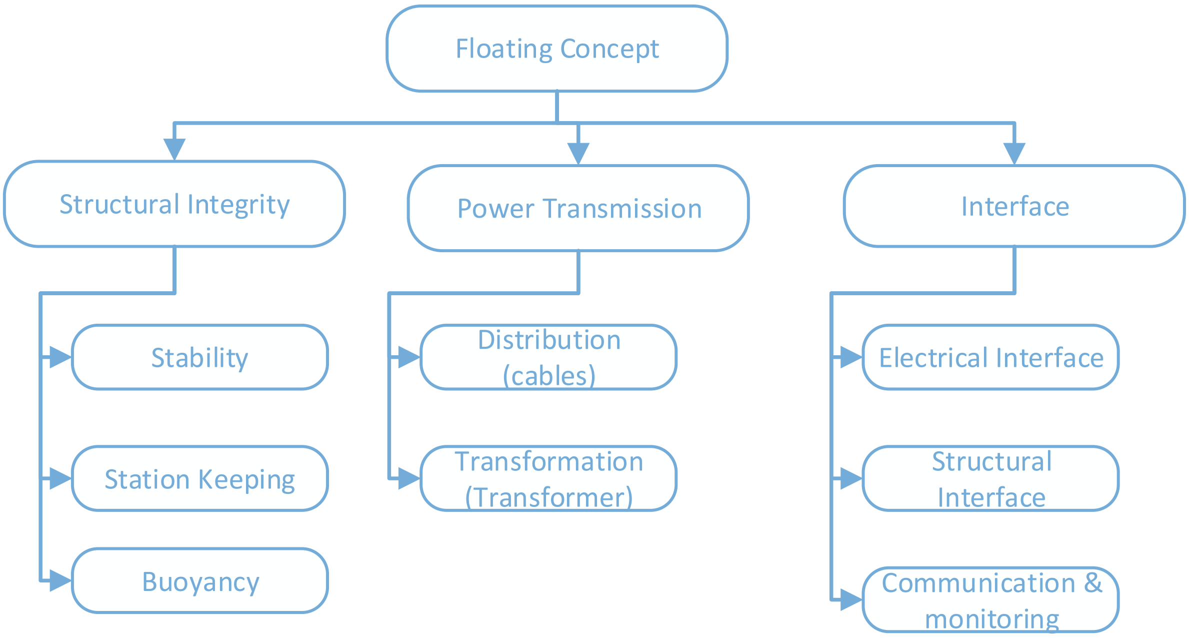


Figure 5.4: Floating concepts- functional analysis

A design FMEA was used to explore the different concepts defined in the QFD/TRIZ stages (Section 5.2.3). The first stage identified and assessed the floating system's high-risk functions and areas using their risk priority numbers (RPN).

Research in the subject [292] [297] found that the mooring systems are the most failure-prone components due to the amount of stress on them, potentially causing line breakage. Kang in [298] found that “anchor and fairlead failures are the second and third largest contributors to mooring system malfunction”, and due to the hard-environmental conditions causing strong winds, storms and lightning strikes, there may be events of tower and foundation failures with damaged piles.

The RPN values obtained for the floating substructures are shown in Figure 5.5, and the full FMEA analysis is presented in *Appendix* Table 9.21.

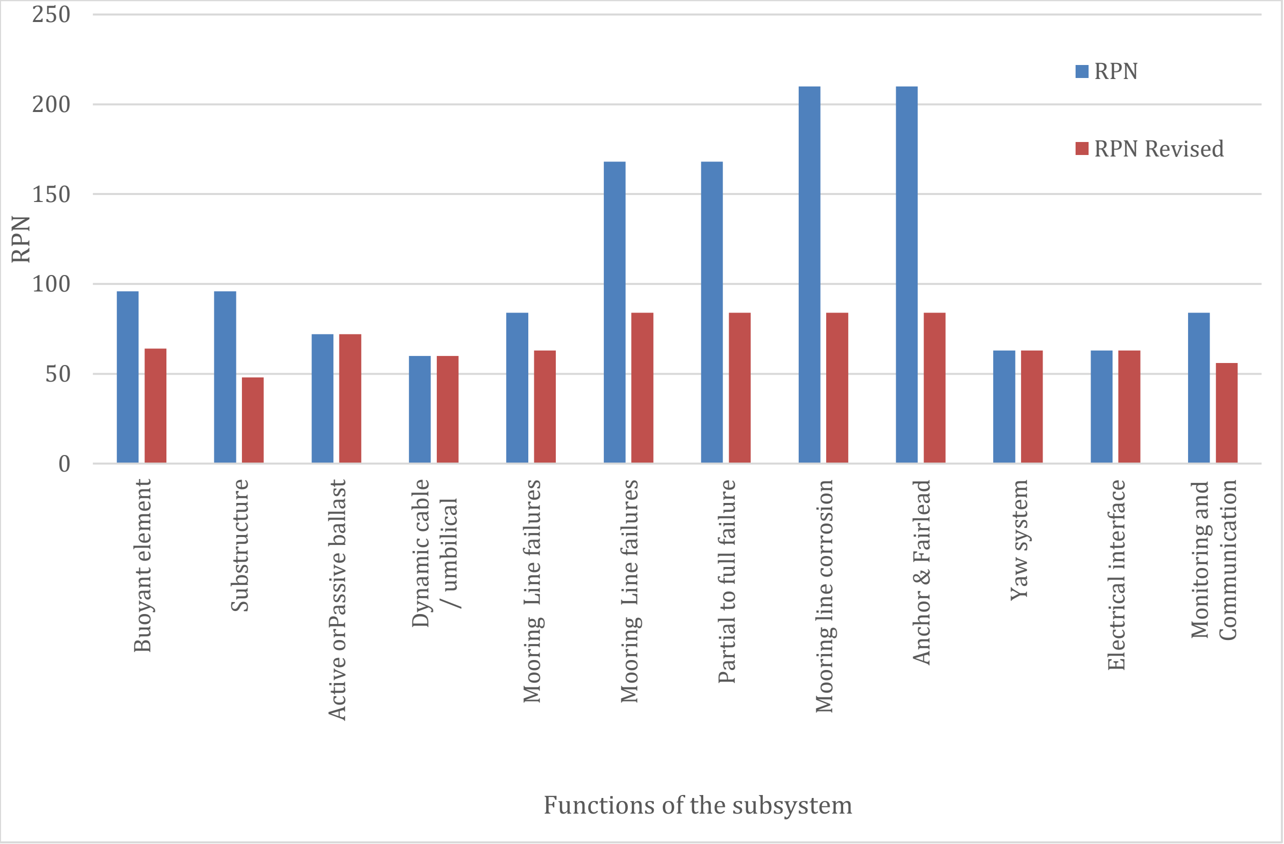


Figure 5.5: Floating substructures RPN data

6. Analysis of results

The chapter is the first step towards presenting the discussion and concluding remarks. Chapter 6 presents the analysis of applying the Structured Innovation Approach to the case studies in the order in which they were presented. The discussion is divided into two parts: Section 6.1 corresponds to the direct-drive generators' results, and the second part to the floating substructure analysis is presented in Section 6.2.

6.1. Direct drive generator

As discussed, wind turbines' capacity has increased significantly in the last decade and can get to a 15-20MW capacity wind turbine in the next decade. The sector has already adopted direct-drive generators; however, innovation is still needed to achieve further costs savings due to their large size and reliance on volatile rare earth materials. This section discusses the outputs obtained from applying the Structured Innovation Approach in Section 5.1.2 to 5.1.5.

6.1.1. QFD analysis

The QFD analysis was carried out to assess the potential innovative concepts that the offshore wind turbine's top head unit could adopt to achieve the least cost of producing electricity. The stakeholder requirements were at the heart of the innovation process. These requirements were captured from the literature review as well as from questionnaires completed by offshore wind experts. Figure 6.1 shows the top-level design requirements that the direct generator must perform to remain cost-competitive, reliable and improve the overall power output.

6.1.1.1. Requirements and Priority Assessments

Maximising the power output while keeping the cost low was described as the most important stakeholder requirement. The Adoption of direct-drive generators over geared machines met the stakeholder's needs for a higher standard of reliability and cost-effectiveness due to the reduced maintenance requirements. The fact that direct-drive generators were compact and structurally integrated made them easy to install, access, and maintain. The low-speed rotor design with an integrated cooling system resulted in minimum wear, reduced maintenance requirements, lower life cycle costs, and a long lifetime. So why do these machines need more innovation? The bigger these machines get, the large they become to generate higher capacity.

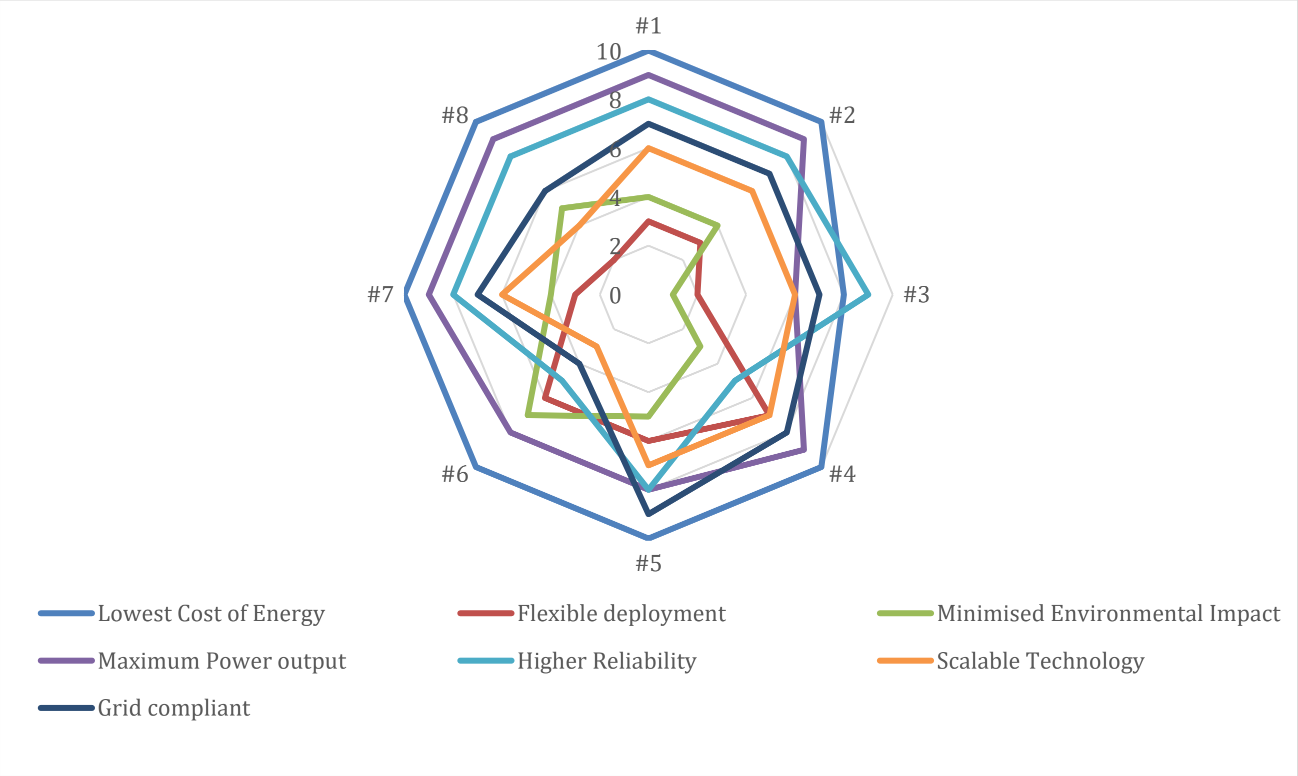


Figure 6.1: Radar chart of QFD Top Objectives and Priorities for each stakeholder

Figure 6.1 highlighted the patterns observed in the stakeholders' responses, bearing in mind that the respondents represented different companies/interests in the sector. This chart, although quite busy, attempted to show agreements in the priority areas between stakeholders. These are: maintaining the lowest cost of energy, maximising power output, and maintaining the machines' high reliability.

In Figure 6.2, the skewness in the higher reliability ranking is more distinct. Some of the comments left by the respondents were "… *where the best way to improve is by higher reliability, lowering the overall system cost of generation will always be the main priority to attract investors*".

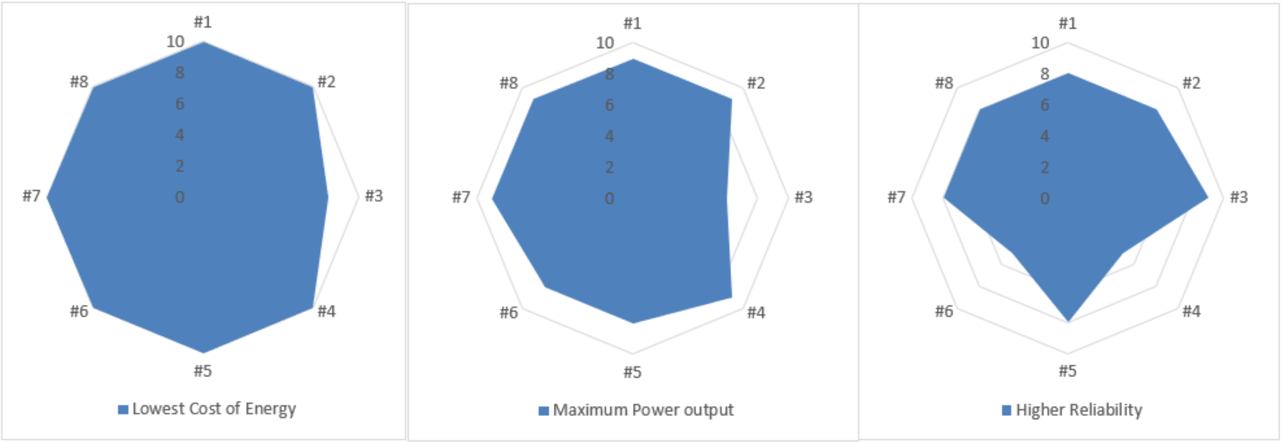


Figure 6.2: Top three stakeholder objectives

Due to how dependent these requirements, some of the needs, such as improving grid compliance, were more skewed between the scores as potentially seen as non-crucial to implement at the current state of projects for some of the respondents. Another comment by a stakeholder on Flexible deployment capabilities was, *"…Offshore resources are fairly high wind speed with low turbulence, and building anywhere else would not be cost-effective".*

One of the Structured Innovation approach's novelties is integrating the stakeholder needs throughout the design process. Those needs are translated into detailed design requirements to focus the development effort based on the gap or shortfall identified in the analysis between the current state-of-the-art tools and identified stakeholder needs.

6.1.1.2. Design requirements for Technical solutions

The QFD approach systematically translates the stakeholder needs into measurable design requirements to facilitate structured technology development, identifying all the proposed solutions' unique attributes. This allows the design team to move away from cognitive fixedness, where the technology development is perceived in specific ways based on individual components or sub-systems, but rather develop the functions and capabilities that the system or subsystem must perform to reach innovative technical solutions. The QFD exercise should bring all the potential stakeholders to discuss their needs and use a team of subject matter experts to translate the needs in as many ways as possible to measure those requirements.

Table 6.1 summarises the proposed top-level functions and capabilities that electrical machines must perform to obtain innovative technical solutions that are competitive and lower the offshore wind turbines' overall commercial risks.

Table 6.1: Top Head Mass QFD Analysis- Quality requirements

	Primary	**Secondary**
Size & Mass reduction	low component count	Number of components with lower mass
	Low Volume	Optimum winding and PM types/arrangement
	Proven/tested designs.	Torque to Weight Ratio, kNm/tonne
		Embedded Power electronics/controllers
Cost reduction	High-Efficiency drivetrain	Condition-based maintenance
	Modular design	Redundant and bypass systems
	Optimised load	Full power conversion
		Minimisation of the support structure (active material.)
	Lower through life costs	Manufacturing, Installation, Decommissioning, Design for maintenance
Increased availability	Modular	High-Performance controller
	Degradation	Redundancy measures
	Improved drive efficiency	Frequency optimised components
		Reduced Switching losses
		Reduced conduction losses
Improved System Compatibility	Modular in design	Frequency optimised components
	Mechanical Design Flexibility	Modular construction philosophy
	High Torque Rating range	

A Solution Impact check was added to the traditional QFD approach to evaluate if the technical solutions are impactful, as defined by the stakeholders. Any errors will point the designer (or team) to reconsider the proposed solutions and improve them, so they still relate to the stakeholder requirements and priorities.

6.1.1.3. Set and Compare Target values

The set engineering targets allowed to assess the potentials for innovation of the concepts. These target values support comparisons and provoke innovation and inventive processes. Depending on the technology readiness level of a concept, not all design data will be available; therefore, the use of literature data, state-of-the-art data from other sectors can support the assessment.

In this case study, literature data was used, and the target values were also be obtained from commercial targets (KPIs, Roadmaps) and state-of-the-art trends in other sectors. These values enabled a subjective assessment of the design requirements by evaluating existing technologies' compliance against the targets, giving the designer better insight into their innovation value. This subjective assessment measures expert knowledge and subjective estimates; it enabled understanding the existing generators' relative achievements against the ideal targets.

In Section 5.1.4, Table 5.11 and Table 5.12 showed the relative comparisons, based on how best or worst (5 to 1 rating) current technologies meet the target values are shown. Generators such as the 3MW direct-drive generators have been in service since early 2011 (e.g. Siemens SWT 3.0-113, GoldWind GW3000, Envision E128-3.6MW), and understandably have already met the ‘lead time to make and deploy’ targets with proven back-to-back testing at full scale. However, in terms of their efficiency and redundancy measures, being one of the first direct-drive generators for the offshore wind, these machines deviated significantly from the set ideal target values.

These results also showed that the most impactful technical solutions, (1) Lowering capital cost, (2) Increasing Availability, and (3) Increased graceful degradation, deviated less from the targets, i.e. as advanced technologies are brought online (e.g. Haliade 6MW and potentially the commercial version of the DTU-10MW reference unit), the proposed design requirements are implemented into their designs.

The quantitative assessment in Table 5.12 highlighted how far the same generators deviated from the conformance targets. Considering the top three solutions, although new to market generators such as the Alstom Haliade 6MW were the most cost-competitive, none of the generators assessed met the target according to the figures used. The same applies to 'maximising efficiency' and reducing 'lead time to make and deploy'. Nevertheless, the Siemens SWT6.0-154 overachieved the targets with a 99% availability and the Halide-150, a 99.2% availability. This stage of the QFD enabled the designer to evaluate the potential areas of innovation of focus. Some were easier to achieve but less important to the stakeholder needs, where some were harder due to their significant deviations from the ideal targets. It should be noted that where quantitative data are not available, qualitative assessments were provided to indicate the areas of innovation of focus.

6.1.1.4. Organisational Impacts

The Organisational impacts defined how difficult it was to implement the potential innovative concepts considering the many obstacles of the organisation or the sector. The organisational impacts group the difficulties into engineer difficulties (concepts, design) and difficulties to delivery (supply chain elements- manufacturing, transport, packaging, procurement).

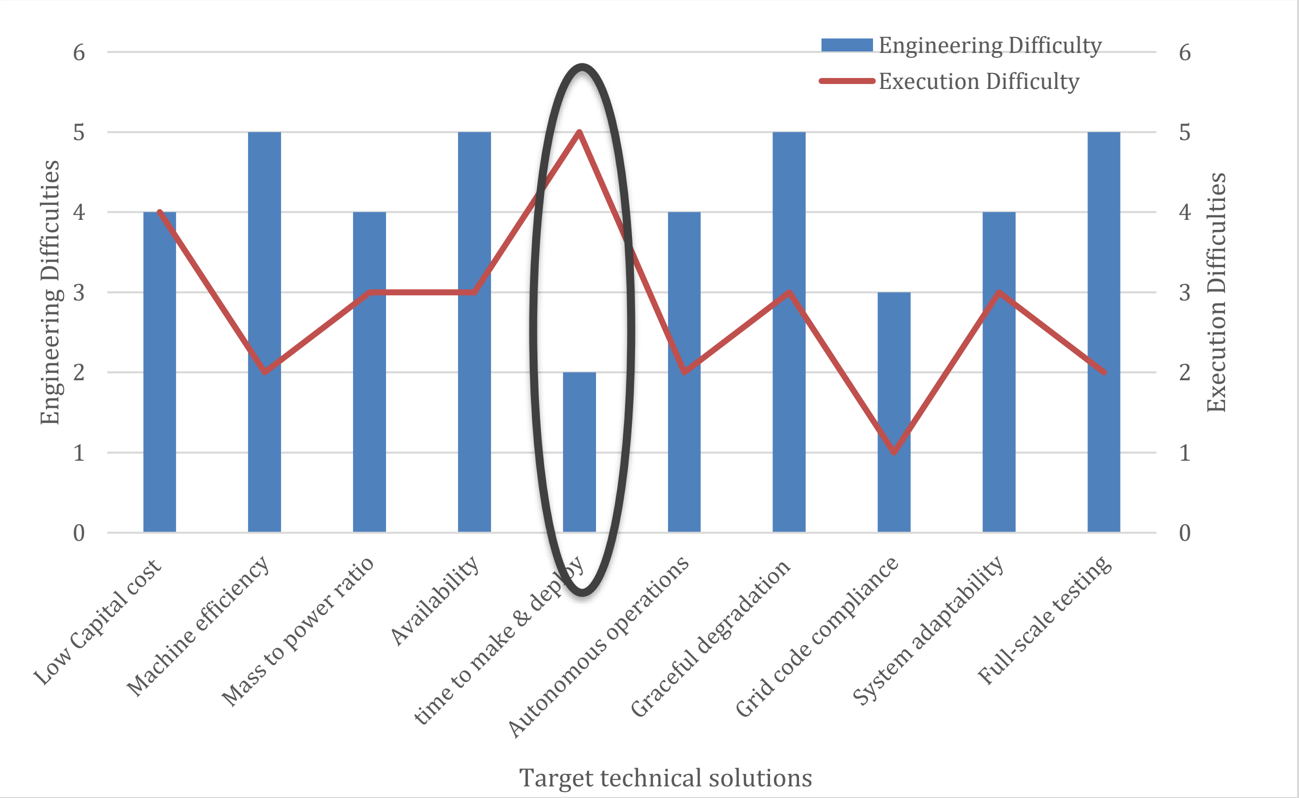


Figure 6.3: Assessing difficulties to achieve targets (1=low, 5-high)

Where short lead time to manufacture and deploy was less complex to design and engineer, the execution difficulty was more difficult due to the complexity of achieving commercial development (financing mechanisms, investment, consenting, commercial risks). Learning-by-doing improved the supply chain, increasing mass production and competitiveness and enabling economies of scale.

Grid integration and compliance were seen as fairly challenging engineering issues and less of execution ones. With the rise in energy demand and the rise in the integration of intermittent renewable energy projects (e.g. wind, solar), the grid must remain stable, reliable, and compliant to various grid codes such as frequency control and fault ride-through requirements. Direct drive generators are fully variable speed machines with full-scale power electronic converters that connect the variable frequency outputs to match the grid's fixed frequency. Being grid compliant, the direct-drive machines must be grid friendly over their entire speed range. However, as more challenging sites are being explored for floating concepts, suitable grid infrastructure must enable smooth transmission to either onshore or offshore grids.

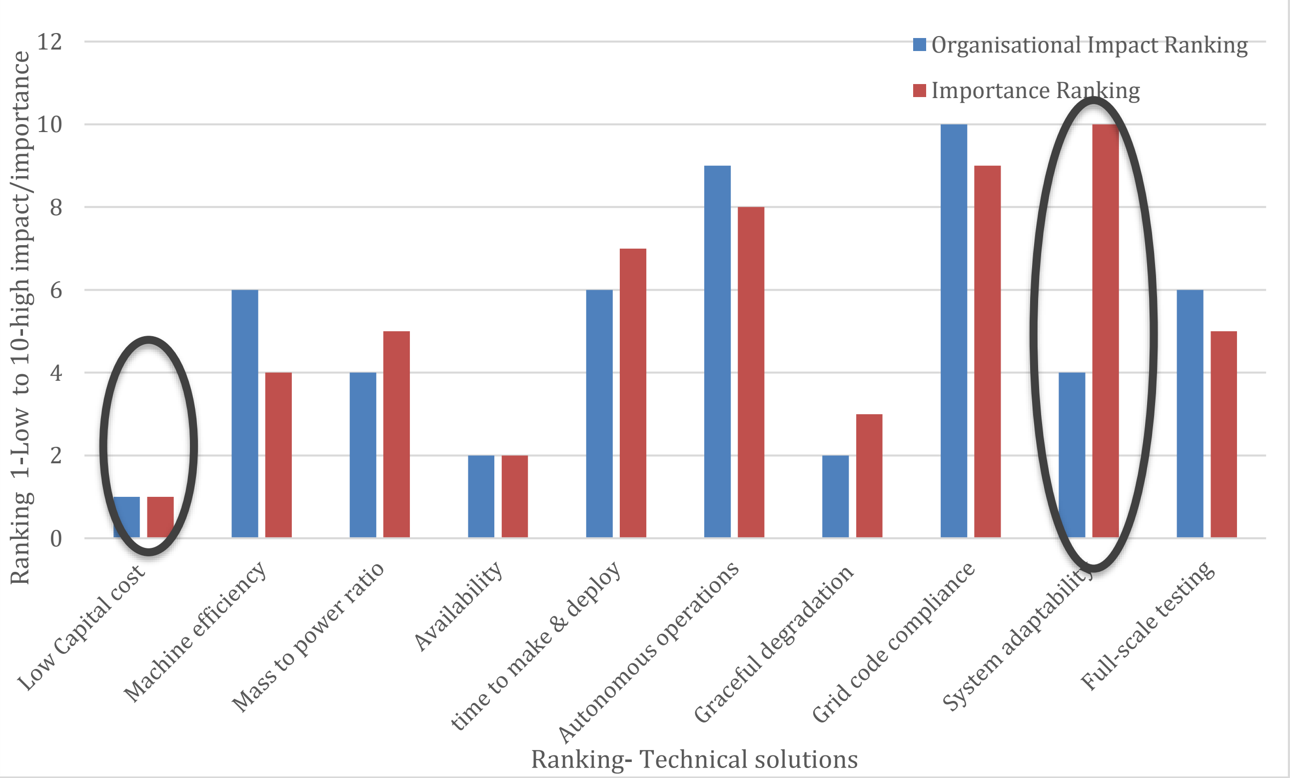


Figure 6.4: Organisational difficulties ranking against ranking of technical solutions importance (1-highest to 10- lowest ranking)

Where lowering the machines' capital cost was seen as one of the most important design requirements to achieve and the most impactful factor to the organisation, mass reduction of the generators was less impactful. Yet, cost reduction could be achieved through mass reduction of the generator active and inactive structures. It was pointed out in Section 5.1.1 that as more capacity is required, the direct-drive generators require larger diameter and stiffer structures to withstand the excessive forces whilst still maintaining a small air gap clearance between their stator and rotor. The contradiction here pointed out the needs for alternative solutions discussed in the next section 6.1.2 and the need to analyse the top-level design requirements to the next Phases of the QFD (Phase 2 to Phase 4) detailed and impactful deployment components.

Some technical solutions will be easier and impactful for the organisation but not important enough for the overall innovation. An example here is the System adaptability that is seen as fairly impactful for the organisation as easy enough to engineering and delivers but with low importance as an overall solution.

6.1.2. Conflicts assessment TRIZ

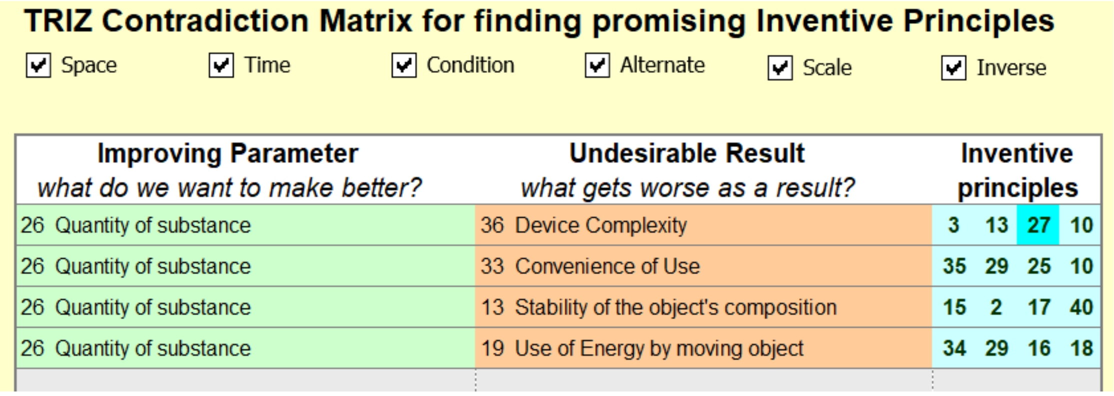
Three of the conflicts identified in Table 5.14 are discussed in this section, with the highest total conflicts. The proposed TRIZ inventive principles were analysed to determine the most relevant innovative concepts for each design requirement.

6.1.2.1. Low capital cost

Lowering the capital costs of direct drive generators whilst increasing autonomous operations at the assembly or manufacturing stage can positively impact the cost. However, self-healing and other operations might result in the need for advanced control systems, increasing the overall capital expenditure.

Lowering the capital costs can be achieved by using larger generators to harness more capacity; this was seen as a key advantage to cost reduction for the sector. However, the larger the direct drive generators becomes, the higher their mass-to-power ratio is. Implementing both parameters highlights conflicts.

These two factors highlighted the need to consider alternative solutions to achieving the least capital cost. These were explored using the TRIZ tools that are intended to raise ideas, test, and propose solutions. Here, the TRIZ 40 inventive principles were used. Figure 6.5 highlighted the possible TRIZ solutions derived from the TRIZ generic parameters. More details on the TRIZ steps taken can be seen in Section 5.2.3.



TRIZ Contradiction Matrix for finding promising Inventive Principles

☑ Space ☑ Time ☑ Condition ☑ Alternate ☑ Scale ☑ Inverse

Improving Parameter *what do we want to make better?*	Undesirable Result *what gets worse as a result?*	Inventive principles			
26 Quantity of substance	36 Device Complexity	3	13	27	10
26 Quantity of substance	33 Convenience of Use	35	29	25	10
26 Quantity of substance	13 Stability of the object's composition	15	2	17	40
26 Quantity of substance	19 Use of Energy by moving object	34	29	16	18

Figure 6.5: Oxford TRIZ template- TRIZ proposed inventive principles.

TRIZ Inventive Principle 10- Prior Action: *Carry out the required action in advance, in full or part, arrange objects so that they can go into action without time loss while waiting for the action.*

The ability for the machines to increase the energy production, to achieve maximum conversion efficiency and to deliver quality electricity to the grid is realised with advanced control systems such as pitch control, machine-side and grid-side converters to control the speed of the electromagnetic torque whilst maintaining constant voltage and power delivered to the grid.

In this context, although the control systems' complexity might impact the turbine's capital expenditure, prior actions such as carrying out back-to-back testing of these machines at full scale before deployment will ensure their reliability and standardisations. In terms of the design, the top head unit could be designed to enable easy access for repairs and maintenance: on-site maintenance such as filter cleaning, connection checks, air-vent cooling systems, and near port onshore for major repairs (easily accessible).

TRIZ Inventive Principle 29- Pneumatics and Hydraulics: *Replace solid parts with gas or liquid or use flexible influences instead of solid rules (air or water for inflation, use of air or hydrostatic cushions…)*

Introducing structural flexibility in direct drive generators by using magnetic bearing technology has been proposed as one way to reduce the mass of these machines [71] [299] better cooling methods, the use of superconducting machines and transverse flux machines. Exploring further these size reduction options can indeed lower the cost of the machines.

However, a system impact should also be assessed to ensure the positive impacts of the cost reduction on the direct drive machines do not impact the rest of the turbine and array.

6.1.2.2. Low Mass

As mentioned above, **Principle 29** can introduce flexibility to the design of the direct-drive generators. These machines' large weight is mainly caused by the stiffness required as a more structural material is required. The larger the diameter of the generator, the higher the efficiency of the electromagnetic field will be. The design and construction of permanent magnet direct drive generators require the air gap between the rotor and the stator to be small enough with limited motion to avoid large deflection and consequently collision between the rotor and stator. Various topologies have been proposed, such as large diameter bearings, contactless (magnetic) bearings, ironless stator to support no attractive forces. The proposed options are not explored further in this work, but further information can be found in [71] [299] [300] [301] [302].

6.1.2.3. Degradation

As more wind farms are deployed further offshore, and in deeper waters, the need for more reliable direct-drive generators and wind farms as a whole is crucial as access becomes even more challenging, impacting the costs of repairs and downtime. Achieving high reliability might be obstructed by the speed of degradation of these machines due to factors such as corrosion, fatigue, creep. According to the TRIZ contradiction matrix, the following inventive principles were proposed:

Inventive Principle 22: Blessing in Disguise: *Utilising a harmful factor to obtain a positive effect.*

Degradation of sub-systems or components happens gradually and usually in a predicted and progressive way. Maintenance is planned around these predicted degradation curves to repair and replace these components as and when required. This TRIZ principle suggests using the harmful factor(s) to better the system. By introducing redundancy measures, the generator's critical elements can be duplicated so that the system tolerates single failures. This is used for direct-drive generators and is well adopted in other sectors (e.g. redundancy for filters and other critical components).

The use of the inventive principle 22 can also be applied to reduce corrosion impacts on the components using the oxidation process to solve components' failure. The contact of the components within the generator and most metals in general results in oxidation due to air and water (humidity), amplifying this harmful factor using material (e.g. Aluminium Oxide) to produce oxide and help protect the components.

Inventive Principle 10- Prior Action: *Pre-arrange objects such that they can come into action from the most convenient place and without losing time for delivery* and **Inventive Principle-11: Cushion in advance:** *Prepare emergency means to compensate for the relatively low reliability of an object.*

These two principles point to redundancy measures for components prone to fail by enabling components or sub-systems to be designed in parallel so that the failure of one part of the system will not necessarily lead to the failure of the entire system (e.g. power electronic modules, surge protections to limit the induced voltage). Torque splitting (segmentation or modularity), multiple generators (Multi-MW rating) can also be a potential solution to eliminating generator design' complexity and capital cost. This means that the smaller capacity generator stack will produce the same capacity as a larger generator to isolate those that fail without impacting the system.

6.1.3. FMEA analysis

After obtaining the design requirements to the stakeholder needs, the FMEA assessed the potential conceptual risks associated with the proposed solutions. The RPN was used to indicate the critical failure modes and enable the designer(s) to warrant the most attention to the system's highlighted functions. It should be noted that not all high RPN is critical; the severity of the failure and the likelihood that a failure would occur can determine how critical the failure mode is and the need for mitigation. Hence the RPN alone would not give a complete picture of the failure's severity and trigger mitigation.

For the direct-drive generator case study, the RPN threshold value was set as 70 to trigger mitigation measures and an occurrence of 4, based on a commonly used threshold in the energy, shipping, and automotive industry[5]. However, the organisation set these thresholds to prioritise the corrective actions based on current design controls. Nevertheless, failure modes with lower RPN could still be mitigated to reduce the risks as low as reasonably possible. The lower the RPN, in this case, study, the closer the design is to meet the

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[5] This was proposed by ETI's maritime and marine team

requirements of the stakeholder was proposed and Remedial action proposed for the triggered failure modes.

Looking at the design requirement ‘reduce to the overall cost of the machine’ could result in complex instrumentation, specialised material selections and embedded power electronics that would make the manufacturing more complex and less standardised. The ability to standardise some critical components within the machine will increase the reliability and the organisational ability to implement tested and proven system elements.

Critical components such as air gaps are prone to fail by deformation due to excessive loads. These failures are likely to happen during manufacturing and early installation stages; hence, improved and rigorous system testing and extended warranty programmes are suggested. A design for manufacturing and assembly (DFMA) could potentially minimise costs by determining each component’s efficiency, opportunities to reduce secondary operation and analyse the improved design for windings, bearing and rotor core.

Good practice would be to loop back to the QFD to ensure all the requirements are met with the existing designs or proposed FMEA measures. Due to the exercise's complexity, this is recommended by a team of experts from multiple disciplines. An attempt is shown in Table 6.2.

Table 6.2: QFD Requirements Vs Mitigation measures (Specific hows)

CUSTOMER NEEDS	HOWs	RISKY EVENTS	RISKS	SPECIFIC HOWs
Easy & Flexible deployment	Standardisation of components and structure/ Supply chain	Long time to repair/replace	Output Inaccuracy	Rigorous Testing facilities/ certifications
Scalable and Integrable to system		Full system upgrade	Intermittent output	Design for assembly
Safe operation		Defective	Mechanical Failures	Beyond the prototype stage
		Non- conformance	Damage to components	Vessels/ Be-spoke transports
Reliable			High repair costs	Advanced local manufacturing facility- allowing modularity
			Fatigue	More integrated value chain players
Low Capital Cost (£/kW)	Low mass units	High failure rate (Low TRL)	Material defects	Torque to weight ratio
Easy & Flexible deployment		High cost for advanced designs	Misalignment	Embedded power electronics/ controllers
Reliable			Electrical failure	Optimum winding and Permanent magnet arrangements
Maintainability of components				Higher MTBF due to fewer components
Scalable and Integrable to system	Advanced material quality control (GRP, superconducting material, matrix, supporting structure)	Thermal failures	Deformation	Improved sensing and monitoring system
Safe operation		Fatigue	Loss of power	Advanced material testing (modular & integral)
Reliable		Insulation failures	Intermittent output	Higher yield strength material
Maintainability of components		Structural failure		Rigorous testing of material strength for lifecycle
Long warranty period		Long time to repair/replace		High-Performance Controller
Safe operation		Overload		Frequency optimised devices
Robust Storage and interconnection system				Use of active materials as a support structure

6.2. Innovative design concepts- station keeping

The offshore wind sector has seen significant cost reduction since the Contracts for Difference (CfD) auctions in 2017, and now, fast forward to 2019, the Crown Estate is finalising the leasing of 7GW of new seabed for the round 4 leasing seabed. “This round will see a new opportunity for the industry to propose projects with up to 10% of the capacity deemed to integrate a “qualifying innovation” [15] [77]. As more sites are becoming available in deeper water, the floating concepts are becoming more attractive for sites with water depths in the range of 50 meters or deeper. This section discusses the outputs obtained from applying the structured innovation approach in Section 5.2.2-5.2.4.

6.2.1. QFD Analysis

In the top Level of the QFD, the case study highlighted design requirements that floating concepts could adapt to achieve potential innovative solutions and meet the stakeholders' needs.

Organisational impact and Solution importance

Table 6.3: Summary of proposed functional requirements for floating concepts

	Advanced Control Systems	**Operating Costs**	**Structural size & weight**	**Economies of Scale**	**Manufacture & installation methods**	**Substructure costs per unit**	**Footprint)**	**Energy Yield**	**Flexibility & adaptability**	**Standardised floating concepts**
Solution Importance	178	178	199	154	154	106	139	199	139	199
Organisation Impact	9	16	20	12	15	12	12	15	10	8

As highlighted in Table 6.3, achieving a lower structural size, a smaller weight of the platform, a higher energy yield and reaching maturity of technology (Nth-of-a-kind) or standardised components were seen as the most impactful paths to innovative optimal solutions.

Compared to the traditional QFD tool, this approach's novelty includes a development impact- this is the organisational effort to implement the optimal solutions proposed. The organisational effort rate is based on the level of difficulty to engineer and deliver these solutions.

In this case, study, where, for example achieving a lighter structural size platform was seen as an impactful design requirement, the organisation's difficulties implementing that requirement are the most difficult, requiring more effort and resources. In contrast, the standardisation of critical parts of the floating substructure, although seen as very impactful for innovation, requires less organisational effort to implement. These low hanging fruits can be developed first before tackling the more challenging innovative concepts from a strategic view. Obtaining this ranking allowed the designer to understand the impacts between proposed solutions, so one lower-ranked solution might be key to more impactful solutions.

Ideality Assessment

The concept of ideality assesses the properties of an ideal solution without any restriction within or outside the design. Here, target values were assigned to these designed requirements as ‘ideal’ metrics to achieve. It should be noted that these target values can be obtained from research studies, commercial Key performance indicators (KPIs), accurate modelling tools such as the ETI’s internationally peer-reviewed Energy System Modelling Environment (ESME), and state-of-the-art technologies. In this study, these metrics were obtained from these studies [76] [294] [87] [303]. The target values allow to assess the potentials for innovation of concepts and compare existing technologies against ideality.

The qualitative assessment in Table 5.11 and quantitative assessment in Table 5.12 offered both subjective and objective measures to these solutions. Finding data is not always possible due to Intellectual property issues, the originality of the technology, competition and many other factors. Although subjective, qualitative assessment gives an insight into how much a current design can deviate from the ideality. In this case, the higher the qualitative value was for a design requirement, the closer that existing state-of-the-art technologies were close to meeting the targets. This is the case for the Tensioned Leg platform (TLP) that is the closest or the best to meet the target value for lighter platform size and weight. Another novelty of this method is the additional Solution importance Ideality section. This section assesses the existing designs gap and determines how impactful the solutions will be to meet the stakeholder needs. The radar chart, shown in Figure 6.6, displays each state-of-the-art product's importance to achieving a design requirement and its deviation from ideality. The chart highlights the outliers which correspond to the most impactful design requirements for the current designs. The legend's colours correspond to the ten proposed innovative solutions, as highlighted in Table 6.3.

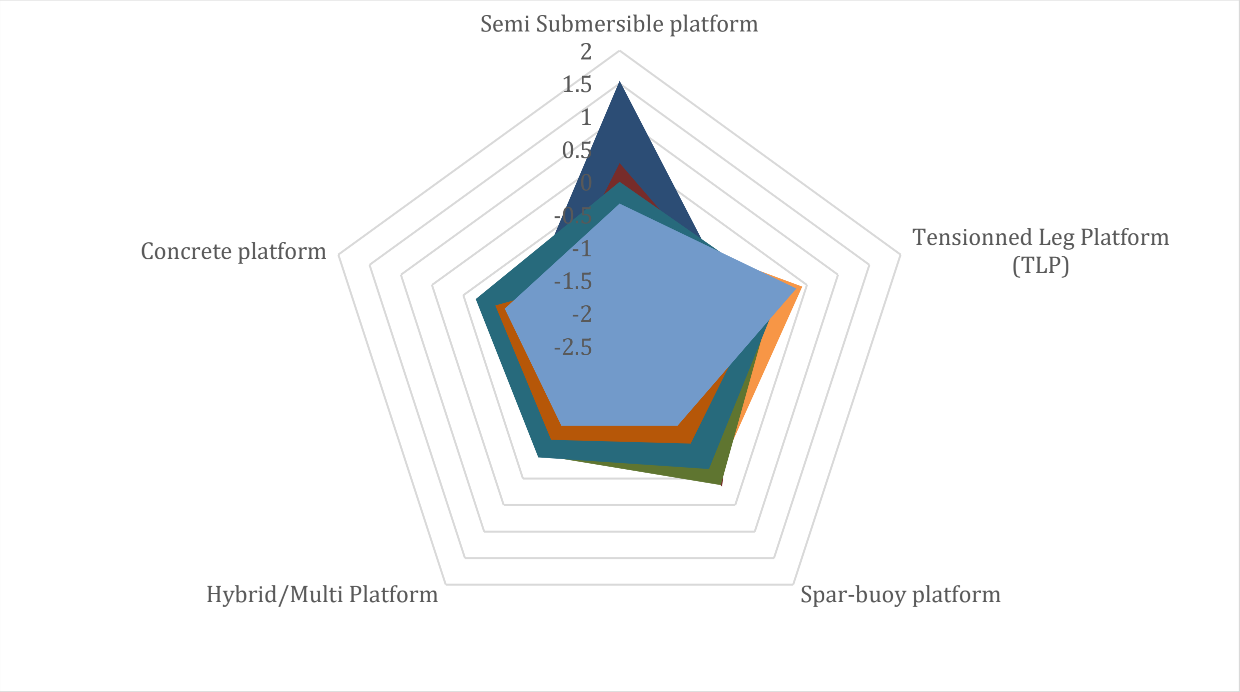

Figure 6.6: Solutions impact ideality assessment of existing floating concepts against target values

Assessing the design requirement impact ideality of the Tensioned Leg Platform against the Hybrid/Multi-platform in Figure 6.7 highlights how close the TLP is to achieve ideality (i.e. the target values) compare to the hybrid/Multi-platform, as well as how important it is for the design to achieve the target criteria.

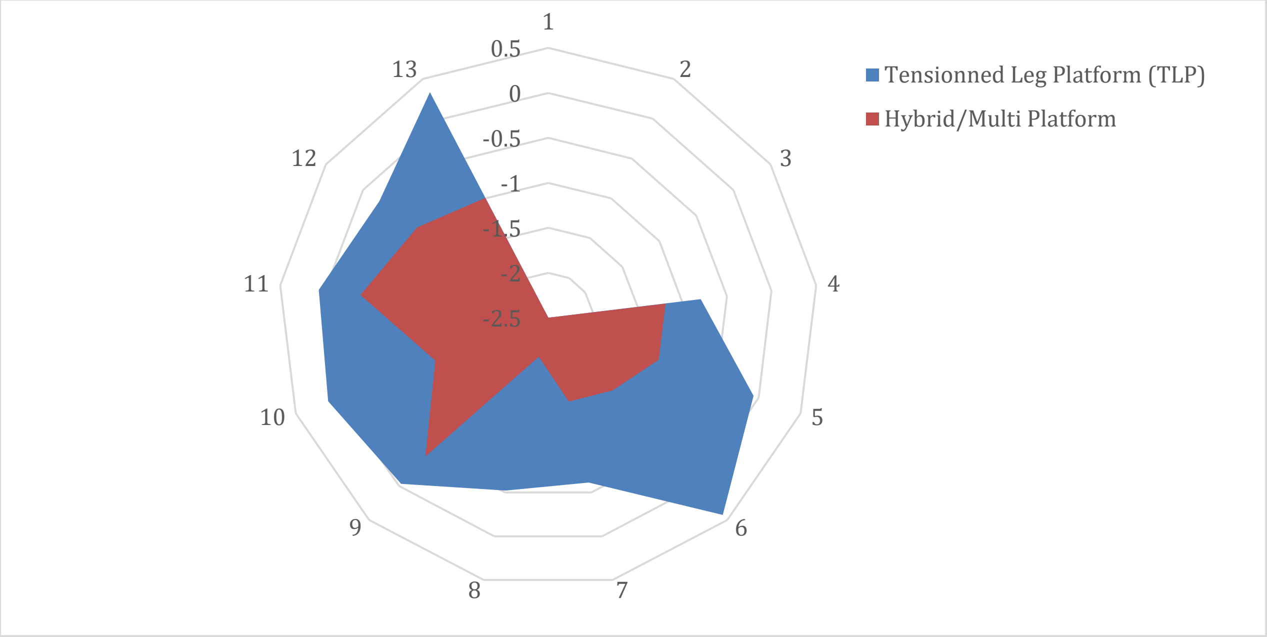

Figure 6.7: TLP vs Hybrid platform Solution impact ideality

6.2.2. TRIZ alternative solutions

Having obtained and assessed the requirements to potential innovative solutions in the QFD’s HoQ, the designer(s) might be tempted only to assess those solutions that they might come across quickly from roadmap studies or the common innovation path or by only considering the advantages of their competitors or current market designs. This might lead to cognitive fixedness, as described in 6.1.1.2, and prevent breakthrough inventions.

The roof of the HoQ enables the designers to specify the relationships between stakeholder requirements and design requirements. For any conflict identified, TRIZ is triggered to explore the most appropriate alternative innovative solutions. In Step 5 of Section 5.2.3, the conflicts arising from implementing technical solutions for floating concepts were assessed.

Some of the highest conflicts are discussed below:

6.2.2.1. Advanced control systems

In floating platforms, given the need for higher reliability, the control systems need to support the turbine to maximise energy yield, reduce fatigue, and dampen floater motion. However, the more advances the control system becomes, the more complex and costly they become.

Inventive Principle 26-Coping: *"Instead of an unavailable, expensive or fragile object, use simpler, inexpensive copies".*

This could mean that some of the control systems' standard elements can be standardised and produced in mass. This will, in turn, increase the manufacturing readiness level of the products and reduce the costs. The most critical elements specific to site conditions or technology could be designed for specific conditions. The same principle could extend to the mooring lines, the anchors. The modularity of these elements would enable elements less prone to failure to be built in mass.

Inventive Principle-13 The other way round: *Invert the action(s) used to solve the problem. Make movable parts fixed and fixed parts movable".*

This principle is already implemented in most substructures, where moorings are either in tension or not, depending on the need for stability or repairs.

6.2.2.2. Operational costs

An advanced control system shows high synergy with the standardisation of components to achieve lower operational and maintenance costs. The more the components/substructures are designed and manufactured to standard specifications, the higher their reliability and hence availability. This, however, means that for such a less mature technology, the capital cost will be high with potential reluctance from investors.

Inventive Principle-1 Segmentation: *Divide an object into independent parts or make an object sectional.*

This principle has already been adopted in many floating concepts developing modular designs suitable for serial fabrication with the hull fabricated and assembled in multiple sections. Some examples are the IDEOL damping pool, the semi-submersible DCNS SeaReed (now Naval Energies), the Tensioned Leg platform Glosten Pelastar, and many more. The benefits of this principle enable design standardisation and consequently cost savings.

Inventive Principle-11 Coping is also mimicked as modularity will result in mass production.

The ability to quickly assemble and disassemble part of the whole structure for major repairs makes the operational costs cheaper as units can be towed by tugboats and repair onshore.

Some of the TRIZ principles have already been implemented in the floating offshore wind sector; some approaches could be considered from other industries. One example is **Principle-15 Dynamics:** *change the object for optimal performance for every stage of operation.* The transmission of electricity from the floating platform back to the grid onshore is crucial for electricity production. Adjusting the current infrastructure to accommodate sites further offshore might require artificial grid islands, floating transformers, and dynamic transmission cables to optimise operation.

6.2.3. FMEA Analysis

Mitigating the technical risks associated with adopting floating concepts requires bringing together stakeholders such as financing bodies, developers, certification bodies, Original Equipment Manufacturers (OEM) at the concept and design stage.

As discussed in Section 5.2.4 and seen in Figure 5.5, some failure modes are more likely to happen than others. The RPN indicates the design controls in place and remedial measures.

The buoyancy element within the subsystem may fail due to collision compromising its function and impacting the whole turbine's stability. The ability to design and fully test such components to survive collision or resist high impact load (ultimate accidental load) could extend these elements' lifespan.

Failures associated with the mooring system are also high: the ability to design a mooring system that maintains its defined position. Mooring systems are designed for ultimate limit state load and tested at maximum load to ensure their integrity. The need for accuracy in site characterisation and better weather monitoring is also crucial for selecting the most efficient anchor type, material and installation methods and tools. As proposed in the QFD, standardisation of the components, improved condition monitoring and maintenance schedules, and testing at full-scale are the recommended solutions to maintain the floating platform's structural integrity.

7. Discussion

The preceding chapters 5 and 6 presented the design methodologies' results that evaluated wind turbines' innovation process in the direct drive generator and floating wind concept case studies. This chapter describes the implications of the results presented in this research and how these can be used alongside the offshore wind industry's developed Structured Innovation Approach to design wind farms more effectively. Each of the individual tools created, the Quality Function Deployment, the Theory of Inventive Problem-solving, and the Failure Mode and Effects analysis, have helped advance the understanding of how a structured approach to innovation can impact an organisation's advancement offshore wind farm project.

The chapter is presented in four sections. In the first three sections, key aspects of the three main methodologies are discussed, and the final section compares or reflects on the integrated approach and impacts on the offshore wind market drivers.

7.1. Quality Function Deployment

QFD is an internationally recognised design methodology to consolidate customer needs and develop, as a result, new or improved solutions to avoid negative customer satisfaction. The needs of customers are central to this methodology to design products of value that evolve.

7.1.1. The Voice of the Customer and Stakeholder

The first step to QFD analysis is to identify the Voice of the Customer, their needs and wants, known or unknown. The preceding chapters described how these needs or requirements could be captured in various ways such as surveys, interview, quality control feedback, discussions, focus groups, customer specifications, observation, warranty data, field reports.

However, the customer voices are diverse and have different roles and impacts on product development; it is; therefore, important to identify the chains of customers, their needs, and who ultimately determine the success of the product and the business. The customers' desired outcomes are included in the business's voice, internal functions and focus, supply chains, customers, and stakeholders. Sections in the ISO 16355, the QFD standard, address important questions to ensure these needs are captured fully.

This research utilised some of these approaches to capture these requirements. In the first case study, the direct-drive generator assessment, various stakeholders were consulted to capture their needs via questionnaires, interviews, and focus groups. These stakeholders highlighted “why” they wanted their organisation's specific needs, rather than “how” they wanted the needs, which would have limited the opportunities to innovate. Literature was also used for landscaping the state-of-the-art technologies and design requirements sought to improve.

The second case study defined the stakeholder requirements from the literature review for statements about what an ideal direct-drive generator needs to be designed and operate optimally. In this case, the criteria were validated by subject matter experts in the field (ETI team), as described in the method.

The detail in which the stakeholders provide their needs varies significantly from vague and very general requirements to more specific detailed requirements. Once the stakeholder needs are gathered, categorising into related needs or logical groups, or listing these requirements into a hierarchy of requirements (e.g. primary, secondary, tertiary) would accurately capture dependable requirements.

As a critical part of this process, it is crucial to identify the stated or non-stated, spoken or non-spoken needs of the stakeholder and continuously validate these with the stakeholder recognising opportunities for changes.

Due to the small sample size from the questionnaire, validation, and literature gathered, an Excel spreadsheet was utilised to distil the various statements into key customer requirements. For larger analysis with significant inputs from the various stakeholders, useful tools (e.g. Affinity diagram, hierarchy diagram) can support these tasks.

In a fast-growing sector such as offshore wind, the customers' needs will differ significantly for the various stakeholders and in time. For instance, in terms of the time, the offshore wind task force was set up in 2012 to produce a path and action plan to get the cost of energy down to £100/MWh by 2020; The most important challenge then was cost reduction [50]. Fast forward to the mid-2020s with over 9.8GW installed capacity, and record low prices of £39.65/MWh– around 65% lower than projects in the 2015 auction [304], cost competitiveness remains a challenge; however, the net-zero target brought additional needs for the sector to deploy higher volumes of offshore wind to meet the greater levels of electrification across the economy [304] [34] [93].

In terms of the stakeholders, offshore wind developers will have better knowledge and insights about deployment and operations' strategic planning. Their needs will differ from wind turbine Original Equipment Manufacturers (OEM), whose needs might be more focussed on specific subsystem and operation planning. Continuous integration of stakeholders' chain is crucial to this process and establishing who will be directly impacted by any changes.

7.1.2. Prioritisation of customer requirements

Achieving customer satisfaction commences with effectively recognising and understanding customer requirements and determining their precise importance ratings in product design or improvement. Determining these ratings is an essential step in QFD application and will affect product design and improve quality. These ratings can be obtained through customer activities such as surveys or focus groups using Likert scales such as 1 (Less important) to 10 (extremely important).

In this study, the 1-10 scale was used to achieve greater variation in the stakeholder responses, using paired comparisons to develop the customer requirement priorities. Group decision-making techniques (such as the Analytic Hierarchy Process (AHP)) are recommended when dealing with large and complex data to compare relative importance between two customer requirements and derive more precise importance ratings.

As the direction of travel moves, as mentioned in Section 7.1.1, the needs and priorities should be adjusted to reflect an accurate view of the stakeholder at a point in time.

7.1.3. Definition of the design requirements

This is the stage of the QFD where the customer requirements are translated into design requirements describing performance characteristics and capabilities that the new product must achieve and, in turn, meet the customer needs. These requirements, also known as “the voice of the engineer”, need to be measurable, meaningful, technology-independent, function-based, and cascaded down the development process until a final product or service is produced. Diagrams such as cause-to-effect and effect-to-cause are useful techniques as defined in ISO 16355 [206].

Establishing the design requirements relies on the inputs of cross-functional teams of multiple disciplines who must translate the customers' needs into design requirements that will meet or exceed customer expectations. The team's challenges are to have a comprehensive understanding of all the customer requirements and consider multiple functions with the potential for ideality, innovation, and thoroughness.

In [305] [306], Duncker and Welling defined functional fixedness as “A category or cognitive set or mental structure that manifests in rigidity or lack of flexibility in disembodying components from a given field”. With a natural tendency to look at problems, people are trapped in seeing and resolving problems in conservative ways, following patterns, trends, habits already known. This fixedness can cause an intellectual block to a problem solver (e.g. inability to use an object in a new function) and prevent innovation.

The team must identify leading-edge opportunities to exceed competitors' capabilities, areas for improvement, and strategies to focus on development efforts with the greatest payoff.

7.1.4. Relationship between customer and design requirements

Organisations, mostly having limited time and resources, will need to specify design requirements to prioritise their efforts. This step enables the determination of the design requirements having the most impact on meeting the stakeholder needs. In the case study, weighted scores were used to determine the strength of relationships between the stakeholder requirements and the respective design requirements; and ranked using *Strong-9, Medium-4, Weak-1*, or no-0 rating.

The cause-and-effect relationship between the stakeholder requirement and the design requirement was dependent on data obtained from expert knowledge and the literature. Based on the frequency of mention of the cited references' interactions, a decision was made about the relationship's strength.

This step required significant time and team effort to carefully define each relationship, ensuring that all the needs and requirements were addressed. A recommendation to involve the team as early in the development process as possible is critical to minimise the need for future changes and to shorten the development cycle. In the past, companies such as Ford Motor found that internal teams were willing to support early in the QFD process; however, commitment from external suppliers was harder to secure without a strategic approach from organisations from the start. According to [219], “Within Ford Motor Company, (1995) there is now a growing emphasis on earlier sourcing commitments with single source suppliers, which will overcome past reticence to join QFD, or FMEA teams internally within the company, or share FMEA material produced by the suppliers”.

A Solution Impact check, shown in Table 5.8, was added to the QFD approach to evaluate if the technical solutions are impactful, as defined by the stakeholders. Any errors point the designer (or team of) to reconsider the proposed design requirements and improve them, so they still relate to the stakeholder requirements and priorities.

This process leads the team to address the weak relationships or those design requirements that do not relate to the customer needs, highlighting customer requirements that have not been met. The whole team requires scrutiny to address any shortcomings at this stage. Questions such as: Are the proposed design requirements suitable to meet the customer needs? Should other design requirements be considered to meet customer needs?

In Section 3.3.6, the ISO 16355 was described, and how the application of QFD has evolved significantly from the traditional to a modern QFD. In the modern QFD, a combination of a Maximum Value Table is used to only focus on the top 3 most important customer needs and require the amount of time and effort required for this exercise.

The framework and basic principles of the QFDs remain fairly the same, but the modern QFD emphasises on maximising the results with minimum effort on businesses. The reader is recommended to refer to [234] [206] [307] for more details.

7.1.5. Technical Competitive benchmarking

Setting target values

In Sections 5.1.4 and 5.2.3, target values for all the design requirements were set to establish concrete goals for the designs. The target values are the objective measures defining values that must be obtained to achieve the design requirement and meet or exceed customer needs. Is the final product to be kept unchanged? Is the final product be improved by maximising or minimising design requirements? These target values need to be measurable. For the two case studies, the values were developed from the literature review and past ETI projects. However, these values can also be derived from commercial targets, organisation vision, competitor's advantage, or ideal values.

Careful consideration is needed when setting the target values: too high, and it may not be realistic to achieve; too low a value might not bring innovation required by the organisation.

In the offshore wind sector, various hubs (e.g. Offshore wind Innovation Hub [66] [86]), research landscape (e.g. SuperGEN [308]), energy systems organisations (e.g. Energy Systems catapult, ETI), was set up to support the acceleration of the UK's energy systems by coordinating the entire innovation landscape, present the innovation priorities, and support the sector growth. The data, such as innovation roadmap, market competition, technology cost, and performance, tend to be publicly available and can be sources for target values.

The set engineering targets allowed to assess the potentials for innovation of the concepts. These target values support comparisons and provoke innovation and inventive processes. Depending on the technology readiness level of a concept, not all design data will be available; therefore, the use of literature data, state-of-the-art data from other sectors can support the assessment.

Competitive benchmarking

In Section 5.1.4 and 5.2.3, Step 3 described how the 6MW direct drive and the station keeping case studies assessed the proposed design requirements' technical competitiveness against state-of-the-art technologies. The state-of-the-art data referred to leading-edge technologies, including the newest ideas, concepts or designs. A relative ranking (1-worst to 5-best) was used as an initial assessment providing a view of how well the proposed ‘design’ compares to the competitors.

As a subjective exercise, an understanding of the competitors’ advancements required completing this exercise as objectively as possible. The relative ratings were validated with the team at ETI. Table 5.11 uncovered which of the four direct drive generators were designed “better” to customer’s satisfaction. Unsurprisingly, the newest and more advanced technologies, such as the 6MW Haliade machine, performed better than the Siemens SWT 3.6MW machines. Comparing competitors' technologies in time or space might not necessarily represent their products or designs against the proposed ones. Understanding and evaluating the features and functionalities of the technologies and how they relate or differ from the proposed design is critical to select the state-of-the-art. The knowledge and involvement of the wider team are again crucial to this exercise.

The state-of-the-art achievements were assessed against the design requirement target values to determine if the competitive technologies met the target criteria and compliances. ETI’s database of offshore wind technologies and components was adapted and used for this study. Table 5.27 shows the floating wind concept examples, where design specifications were required. Finding technology data was proven difficult beyond publicly available sources. Several government initiatives have proposed adopting digitalisation requiring data sharing to further growth in the sector [309]. In an effort to advance the sector, organisations such as the Floating offshore wind centre of excellence [310], Offshore wind industry hub [86], encourages collaborative programmes between industries, stakeholder partners and academia. These approaches will support activities such as these to enable teams to drive innovation where design gaps are uncovered.

7.2. TRIZ integration to resolve contradictions.

TRIZ, the theory of inventive problem-solving, can help designers find alternative engineering parameters for their designs, meet their customer needs and eliminate conflicts. This tool provides guidelines for the designers to ‘think outside the box’ and lead to innovative solutions. In Section 7.1.1, cognitive fixedness was discussed as an inhibiting factor of innovation. TRIZ attempts to remediate that by proposing generic ways to resolve problems, allowing the design to think in time, space, condition, and between parts and the whole.

The direct-drive generator case study highlighted, in Table 5.13, three contradictive requirements (the Low capital cost, Low mass, and degradation) with the highest conflicts. The integration of TRIZ into the QFD methodology allows the user to think of impactful alternative solutions by referencing the TRIZ toolkit – thinking of past, present and future inventions that meet a similar problem, or perhaps with a difference of scale. In section 6.1.2, various interpretations of the TRIZ generic inventive principles for direct-drive generators were discussed.

TRIZ has no formal rout as to how to proceed at this stage. Thus, of the proposed generic solutions, prioritising a single design to implement, one at a time, would be recommended to enable the designers to loop back into QFD and ensure that the alternative solution has enough or better impacts on meeting the customer requirements and is within an acceptable organisational impact. Implementing all the proposed inventive solutions into the design at once might result in further design contradictions that did not previously exist.

Some of the alternative design solutions proposed, Inventive Principle 10, were: (1)- testing, demonstrating and standardising all or parts of the machines to reduce the overall cost of the machine, (2)- considering radical changes into the design, Principle 29, i.e. is the direct drive generator a function or can another machine satisfying the stakeholder requirement be considered? Can introducing redundancy measures positively impact the three contradicting requirements (i.e. overall cost of the machine, their mass, and degradation)? What about redundancy measures with smaller and multiple generators?

Therefore, TRIZ directed the team to consider alternative solutions and decide on the design requirement (s) to take forwards in the QFD to further assessment against the technical and competitive benchmarking.

In Section 3.3.4, the literature review showed that TRIZ was widely used, but some of its application limitations were around the need for intensive training. The author agrees with these observations; however, once familiar with the set of tools, the designers will be able to apply an innovative systematic methodology to resolving problems.

7.3. Failure mode and effects analysis

Concept and design FMEAs provide an opportunity for designers to identify the potential risks introduced in a new or improved concept or design, take countermeasures, and prevent failures in the early stages of product development. As opposed to process FMEAs where specific components or systems' elements are assessed, design FMEA considers design functions or requirements of a system, identifies the potential failure modes, effects and occurrences, to indicate where mitigative actions are required to prevent failures. Section 3.4.1 detailed the primary steps to perform an FMEA. Of the five main steps of the process, key aspects of the following steps are discussed below:

7.3.1. Design requirements

Once the designers have defined the system's function(s) to investigate (scope and objective), the design requirements are described, either provided by the team or converted from the QFD. As explained in Section 8.1.3, these requirements need to be measurable, meaningful, technology-independent, and function-based.

Involving a multi-functional team of experts as early as possible in this process from various background and roles will significantly support the definition of these requirements, expanding the knowledge of the system being considered. A point was made, in Section 7.1.3, to involve both internal and external teams (e.g. supply chain).

Both the QFD and FMEA are systematic approaches developed to address customer needs, requiring what/how or cause/effect processes to define, assess and prioritise the design requirements.

The design requirements were obtained from previous ETI documentation and reports and literature review in both case studies. There is a need for publicly available databases to provide comprehensive data in maintenance, reliability and potential failure modes and causes. Integrating FMEA into QFD will enable the designer to consider the defined design requirements for the FMEA analysis.

7.3.2. Failure modes

At its core, the design FMEA determine what might go wrong (failure modes), how bad the effect might be (severity), and how it can be prevented (Design control and mitigation measures). Defining the potential failure modes helps identify the design's weak points as early in the process as possible.

The FMEA team identifies the potential failure modes by exploring questions such as “what are the ways the intended function X is not achieved?” “How can this design fail”. Generic failure requirements can be considered such as performing an unintended or undesired function, failure to operate at a prescribed time, intermittent operation, failure to cease operation at a prescribed time, loss of output during operation, degraded operation, premature operation, complete loss of function. Identifying all possible failure modes is critical to this process to ensure all possible weak points of the design are considered.

Although It is recommended to capture all possible failure modes, careful consideration must identify and only list the potential failure modes relevant to the system considered and areas of concern.

Once all the failure modes identified, the failure effects, causes and severity are determined to allow the RPN to be calculated. The RPN values enable the designers to define what is acceptable or unacceptable for each failure. The expertise of the team will enable this. So, it is fair to say that FMEA, or any design process, is only as good as the team conducting it; (i.e. inexperienced, demotivated, or wrong team).

7.3.3. RPN and mitigations

The risk priority number comprises severity, occurrence and detection rating and is used to determine the need for action. As described in 6.1.3, although the RPN indicates the critical failure modes that warrant the most attention, it should be not be used as a threshold. Rather, the RPN should be used as an indicator of priority actions for the design requirements. Since not all high RPN is critical, the severity of the failure and the likelihood that a failure would occur can determine how critical the failure mode is and the need for mitigation. Hence the RPN alone would not give a complete picture of the failure's severity and trigger mitigation.

For instance, In the direct-drive generator example in Table 5.18, the severity was rated 8, a critical level as defined in Table 3.19, a very high rating because of the “loss of system capability or may cause a serious health hazard or serious injury to the user”. The occurrence was rated at five and detection at four, which means that with appropriate design control, the probability of occurrence can reduce with easier ways to detect the failure mode. However, it is harder to reduce the severity rating without the need for design changes.

One of the FMEA limitations highlighted in Section 3.4.1 was how close the definition of the three evaluation criteria classifications was to facilitate each failure mode’s RPN analysis. As a team effort, the definition of these criteria should be established and agreed upon by the team before starting the analysis. Each assigned value and description should be distinctive and clear enough to avoid confusion or misconception. As the FMEA is intended to be a living tool, updating these definitions as and when required is necessary to maintain the process as accurately as possible.

In both case studies, the ratings used were adapted from BS EN 60812. However, studies such as [279] [280] have provided alternative definitions of the ratings, including using a three-dimensional risk matrix as an indicator of criticality, allowing the analysis of failure detectability components.

In summary, design FMEA is a valuable tool for identifying potential risks introduced in a new or improved product design. The systematic approach mainly relies on teamwork to support technology development from the early stages of design to deployment. The involvement of multidisciplinary teams and the supply chain as early as possible is recommended, including training sessions when required. As a quality tool, incorporating FMEA into the organisation quality and design operations is crucial for continuously implementing its recommendations.

Integrated, the FMEA and QFD will enable organisations to design their products more objectively, tackling planning and problem-solving issues. These will result in improved, reliable and robust innovative designs and bring the voice of the customer and the voice of the engineer closer together along the “performance quality line” [219]. The unresolved failure modes can be analysed in the QFD & TRIZ to assess the customers' alternative functional requirements and the engineering specifications.

7.4. Integrated Structured Innovation approach

The discussion of finding design methodologies to support the offshore wind's future growth by impacting its market drivers (such as technology development, cost competitiveness, and innovation) has led to developing the integrated Structured Innovation approach for design quality development.

The amount of primary research data and exceeded benefits has led to the incorporation of the customer-driven QFD methodology, with the concept or design FMEA to support systematic product development. Integrating the QFD and FMEA ensures the voice of the customer is translated into a product design through the voice of the engineer. The customer's satisfaction is achieved by delivering high and performance quality (QFD) and robust products at the same time (FMEA). If implemented in the early stages of development, the QFD will help validate the customer requirements' continuous integration into the component specifications. Merging both methods forms a decision tool that identifies the most suitable design solutions and mitigation measures for the associated risks. Combining the tools also provide a way to prioritise the order of mitigation actions beyond the RPN values.

Teamwork is a key enabler for both QFD and FMEA. It requires experts from multidisciplinary teams to extend the customer requirements and engineering characteristics throughout the product or process, enabling an interaction between the customer's various failure modes and degree of satisfaction concerning the product performance and services. Involving external supply chains from the early stage of development will ensure continued commitment throughout product development.

As a continuous improvement process, good practice would be to loop back to the QFD to ensure all the requirements are met with the existing designs or proposed FMEA measures.

The integration of QFD and TRIZ is another popular product planning combinations. The fundamental concept of the QFD is the ability to capture and convert the customer requirements into design characteristics, to define organisational impacts, interrelationships, and target values of the design, to satisfy the customer demand. The contradictions that may arise from the interrelationships between the design requirements can be resolved using TRIZ by proposing innovative solutions that meet the customer demands. These tools can be used in isolation. However, the lacking input information is replaced with assumptions instead of complemented by the other tools.

Both QFD and TRIZ require the designers to identify the customer's spoken and unspoken needs; these needs can relate to completely new design or improvement of existing designs. The slight difference is that the QFD seeks to develop and deliver a design that meets the customer needs. In contrast, TRIZ looks to innovate due to a problem (or contradiction) within an existing design. The integration of TRIZ into QFD can be initiated for solution exploration- when defining functional requirements, during the conflict assessment- where a solution is seen as a block, and during impact analysis. When TRIZ is used, the integrated process will allow the designer to quickly create innovative solutions using the TRIZ tools and inventive solutions within the QFD process. For example, suppose there is a lack of impact on the user's solutions. In that case, TRIZ might allow the user to think of impactful alternative solutions by reference to the TRIZ toolkit – thinking of past, present and future inventions that meet a similar problem, or perhaps with a difference of scale – micro or macro.

Significant updates have since been made in the QFD Framework to integrate policy deployment (Hoshin Kanri) and adapt the new modern QFD into the ISO16355. The core objective of the QFD remains the same, i.e., to create a powerful, sustainable new product quality system critical to customer satisfaction. However, modern QFD is tailored to support businesses with limited time and resource and aims for speed and efficiency by using a pre-matrix voice of the customer analysis, a customer voice table to obtain the customer requirements, ratio scale values, and a Maximum Value Table to define interrelationships to select only the top customer needs for the analysis. Despite these differences, the similarities and complimentary benefits of the QFD approach should be the designer's focus. More information can be found in [202] [234] [206] [307].

While the application and adaptation of the QFD, TRIZ and FMEA tools bring significant values to the design and development of innovative technologies, the real value of integrating these tools into the Structured Innovation approach was found in the process of communicating, problem-solving, and decision-making to develop beyond the current state-of-the-art innovative design for product development. The active involvement of multi-disciplinary departments (such as marketing, design, Quality Assurance, manufacturing, Finance, certification) can lead to a balanced consideration of the requirements at each stage of this translation process and provide a mechanism to communicate hidden knowledge of individual or department. In turn, this will a whole organisation buy-in, enabling the teams to understand critical requirements, internal capabilities, constraints and design the product that satisfies the customers.

8. Concluding Remarks

The following section presents the thesis findings in order of the research objectives. The contribution to knowledge and broader implications are stated.

8.1. The Approach to the Problem

This thesis presents conceptual design methodologies and the development of a Structured Innovation approach for design creation and selection and demonstrates its application in offshore wind. In the literature review, existing design methodologies for conceptual designs are presented and are analysed to identify the major areas of improvement from a growing market perspective. Previously developed conceptual design methodologies have often omitted many real constraints and considerations important to drive innovation in the early design stages of technology development. The principal aim of this thesis has, therefore, been to:

> Develop a design innovation method to support the creation and development of innovative conceptual designs and enable a structured approach to achieving competitive, robust and reliable design options from concept to commercialisation.

The review of the current state of the art in design theory and methodologies has identified the need for design methodologies that encapsulate ways to solve design conflicts, manage customer expectations to drive the design process effectively, and establish robust, leading-edge technologies.

The following design methodologies have been identified and integrated a Structured Innovation approach comprising: Quality Function Deployment– to capture and translate the customers’ requirements in the design process for product development, quality management and customer need’s analysis, TRIZ– to generate innovative solutions from conflicting requirements, and Failure Mode and Effects Analysis– to identify and mitigate potential risks within a system.

In the UK, offshore wind has been identified as one of the fastest-growing power markets globally. One of the major drivers behind this growth is the Government long-term support boosting innovation and investment in the sector. As a sector that is still growing and that encourages innovation, offshore wind has been selected to demonstrate the feasibility and application of the Structured Innovation approach.

Deploying the integrated structured innovation tool using two case studies: The assessment of innovation in direct-drive generators and floating substructures highlights the advantages of this holistic, structured approach of generating a detailed list of design requirements and engineering targets to drive innovation and meet the stakeholder needs. Applying these case studies' approach highlights how the tool's implementation can strategically support future offshore wind designs.

8.2. Contribution to knowledge

This research's main contribution to knowledge is the assessment, the development and the demonstration of conceptual design methodologies for the creation or improvement of offshore wind design concepts. These design methodologies, referred to as the Structured innovation approach, are based on the synthesis, the combination and demonstration of well-established approaches of previous studies, which have combined problem-solving, innovative and creative thinking, and design for six sigma approaches. The specific contributions are:

- The development of a coordinated approach to capture, translate and present the stakeholder needs and design requirements to enable good communication and initial discussion with the teams.
- The ability to detail a list of design requirements and engineering targets and assess their feasibility concerning the organisational, competitive benchmark.
- The assessment and presentation of the potential alternative solutions to the conflicting requirements
- The application of methods routinely used to identify and assess mitigation measures to potential risks in conceptual design.
- The development of a structured approach to strategically support the design of new or improved offshore wind concepts.

8.3. Research Limitations

Some of the limitations encountered during the research are discussed below:

- Team expertise and stakeholder engagement are critical to deploying the design methodologies to test, assess, evaluate, and validate the needs, design requirements, and proposed solutions more accurately. These engagements were limited due to the internal restructuring, among other factors, making the results and outputs less reliable. The use of literature data and previous projects, the development of survey questionnaires, and access to modelling tools were used instead to validate the required parameters.
- Data sharing: a multi-disciplinary team of experts should define the inputs data required for the tool. As a single researcher, this was not possible. Instead, these data were obtained from the various ETI database and expert knowledge within the offshore wind programme for mature technologies. The survey questionnaires allowed to capture stakeholder inputs for this exercise. However, to assess less mature and novel technologies, with little to no viable products to validate against, the data were obtained and adapted from other sectors, with a generalised approach to obtaining them explained.
- Adapting to quick changes: During the duration of this research, the energy sector, and the offshore wind sector, in particular, evolved so rapidly that thresholds, targets and objectives of the research were adjusted and adapted to maintain some relevance to the sector's need. It was impossible to amend all the research literature; the demonstration of the tool and analysis was conducted using the sector's current knowledge.
- Collaboration and knowledge-based pool: Several hubs and research centres have common research goals (e.g. OREC, SuperGEN Offshore Renewable, Offshore Wind Industrial Hub, EINA offshore wind, ESC). However, access to the data, the results and their approaches are still challenging. Recent initiatives such as the Energy data taskforce are looking to increase cross-collaboration and data sharing, which will support research projects like this one.

9. Scope for future work

This thesis has focused on the development of the Structured Innovation approach, and further work will need to explore the application of this approach to further case studies and sensitivity studies to understand the relationships between engineering and non-technical requirements and between the novel and advanced sectors. With this in mind, further work can explore improvements in the developed approach and methodology and explore this methodology's application in other sectors.

With the project's timeline, it was not possible to fully validate all the presented case studies. Validation and refinements of the tool are proposed. Also, some of the areas of the thesis that could lead to further work are:

- To carry out a complete analysis of the potential innovative concepts by taking the functional requirements defined in Level-1 of the QFD and further refine design requirements up to Level-4 detailed process characteristics of specific innovative designs. To understand further the relationship between the extended QFD and the modern QFD approach and draw some conclusions on their comparability.
- The ability to integrate the alternative solutions obtained in TRIZ and the mitigation measures from the FMEA back to the QFD to assess if the stakeholder's requirements are met and if further conflicts and development impacts issues arise.
- Develop an integrated structured innovation tool that integrates a technology development assessment process (stage gating) and a common database with the reference data, state-of-the-art, and ideality scenarios.

In addition to the points above, further analysis to understand the impacts of potential backup systems (storage) on the overall cost of generating electricity from offshore wind would inform future offshore wind generations' market strategies.

10. References

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11. Appendices

11.1. Types of electricity markets

There are different types of electricity markets that enable short and long-term trading and balancing agreements between market participants: the generators, the distributors, transmission system operators (TSO), the investors, policy-makers, the retailers. Some of these market types are illustrated below [3] [37]

- **Wholesale transactions**: Overseeing market bids and offers to maintain generation and load balance.
- **The market for power-related commodities**: ensures reliability of the generation with consideration of ancillary services (spinning reserves, baseload, responsive reserve) and installed capacity.
- **The market for energy-related commodities**: net generation output traded for various time intervals (5,15, 60 minutes increments)
- **The market for transmission congestions**: for future electricity generation options and restructuring of the power system.
- **Wholesale electricity Market**: Buying electricity directly from the generators. Companies or suppliers (e.g. the big 6 in the UK- Npower, Eon, British Gas, Edf, Eon…) will enter into contracts with the generators to provide the required electricity for their customers. The generators will have to ensure smooth delivery of electricity needed considering the losses in transmission.
- **Capacity Market:** "… ensures the security of electricity supply by providing a payment for reliable sources of capacity, alongside their electricity revenues, to ensure the delivery of energy when needed. This encourages the investment needed to replace older power stations and provide backup for more intermittent and inflexible low carbon generation sources" [37].

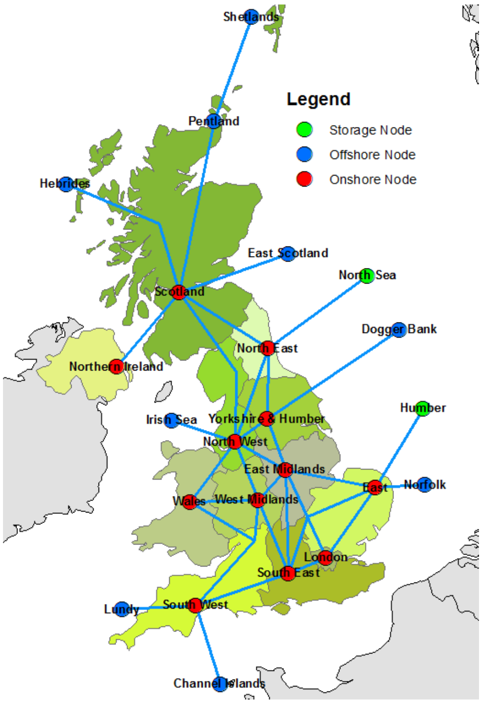
11.2. Wind resources: Introduction to ESME

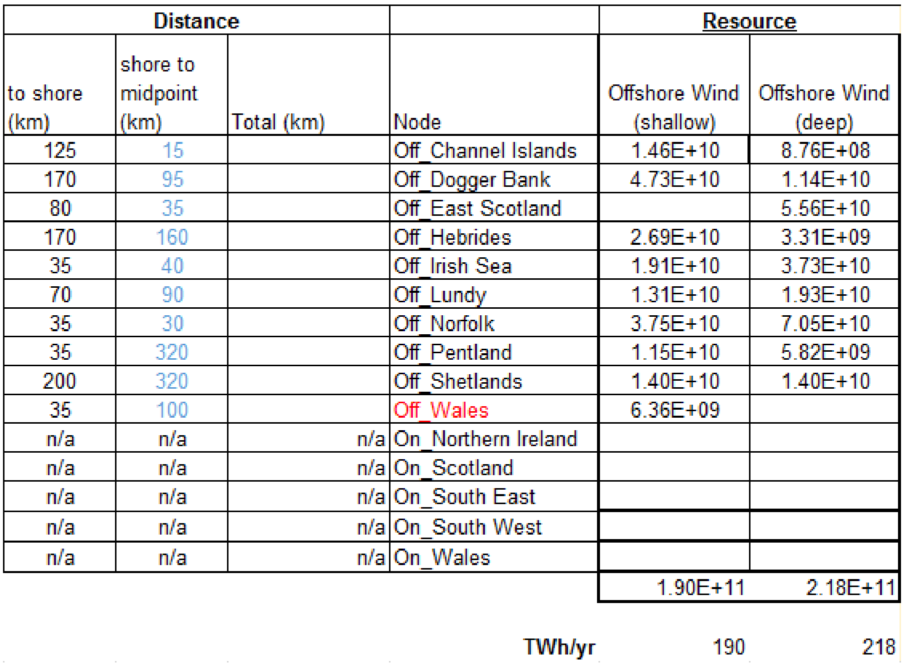
To gain insight into the quality and accuracy of wind data, spatial mapping of the UK renewable energy zone's offshore wind resources was generated using a geographical information system tool (ArcGIS 10.4 or QGIS). This enabled an assessment of economically feasible sites for production.

This section of the report summarises work done to update current UK offshore wind resource data in the ETI whole energy system modelling tool (ESME); This will be the basis of the Met-ocean tool that will be exploited in Q4 this year and Q1 next year.

ESME, a peer-reviewed least-cost energy system design and planning tool, enables identifying pathways towards lowest-cost decarbonisation for the UK energy system. The model runs Monte Carlo simulations, exploring the variation in cost-optimal designs within sets of assumptions and constraints to obtain strategies against a range of uncertainties [303] [33].

Table 9.1: ESME On- and off-shore Regions and updated resource (Transmission distances are indicated as shore distance- from nearshore node to off-shore node and shore-midpoint is point from shore to network onshore node)





Distance				Resource	
to shore (km)	shore to midpoint (km)	Total (km)	Node	Offshore Wind (shallow)	Offshore Wind (deep)
125	15		Off_Channel Islands	1.46E+10	8.76E+08
170	95		Off_Dogger Bank	4.73E+10	1.14E+10
80	35		Off_East Scotland		5.56E+10
170	160		Off_Hebrides	2.69E+10	3.31E+09
35	40		Off_Irish Sea	1.91E+10	3.73E+10
70	90		Off_Lundy	1.31E+10	1.93E+10
35	30		Off_Norfolk	3.75E+10	7.05E+10
35	320		Off_Pentland	1.15E+10	5.82E+09
200	320		Off_Shetlands	1.40E+10	1.40E+10
35	100		Off_Wales	6.36E+09	
n/a	n/a	n/a	On_Northern Ireland		
n/a	n/a	n/a	On_Scotland		
n/a	n/a	n/a	On_South East		
n/a	n/a	n/a	On_South West		
n/a	n/a	n/a	On_Wales		
				1.90E+11	2.18E+11
			TWh/yr	190	218

A Geographical Information System (GIS) tool is inbuilt into the model to assess the wind and other energy resources within the renewable energy zone (12nm) using wind speed, water depth, distance to/from shore and transmission and distribution lines. These wind characteristics are specified for each region as specified by ESME areas and nodes.

The above datasets constituted the layers in GIS of UK water maps allowing ranking and quantification of wind resources in “regions and at nodes” and defined the extent of magnitude and distribution of wind speed, water depth, seabed conditions, wave characteristics and other factors.

Rating Schemes were generated as a combination of each parameter ranking level, and preliminary analysis has drawn from this, providing an assessment of the offshore wind survey area. As a user-friendly tool with inbuilt datasets, ArcGIS will be used for the analysis and GIS maps will be generated for siting and analysis. [311] [312].

Post-processing using ESME will then use engineering input such as capacity factor, economic and technical life, construction period, and build rate specified for each technology.

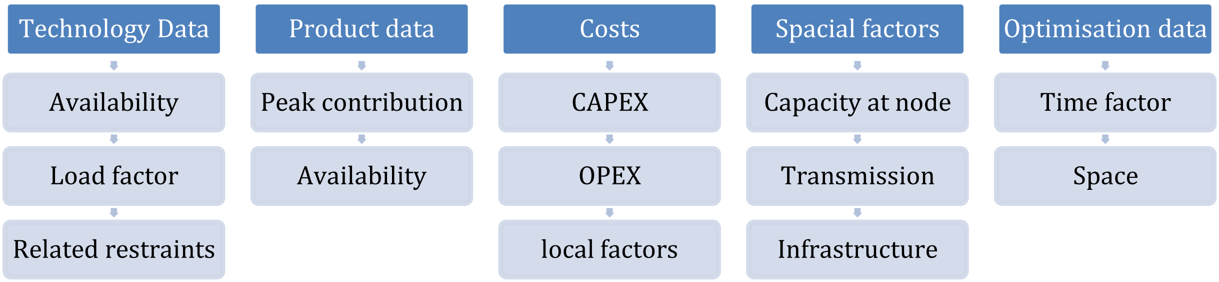


Figure 9.1: Additional Engineering and financial data input in ESME

11.3. Direct drive generator innovations

Table 9.2: Engineering specifications to meet stakeholder requirements for DD machines (Part-1)

Author	Reference	Aim	Report Summary	Methods				Conclusion
Polinder & A McDonald		* PM topology (surface mounted (high Bhmax) or flux concentrating variant- (Low magnetic flux) * 4 Objective functions: * Impact of magnetic material cost (double PM= Euro 1.1/MWh increase) & generator diameter limits (from 6-8m= 0.9% cost drop).						
Polinder & Dubois		Minimise the cost of active materials (magnet, Cu, Fe) and generator losses	* Requirement of PM generators for DD * Material choices * Topology and design calculations	High Efficiency @ high part load Torque or force Speed of the DDPM Cogging torque minimal High efficiency- optimisation	Cost: * Material cost C=CfeMfe+CcuMcu+CpmMpm-PCeEy * Manufacturing cost * Transport *O&M	Material choices Steel- highest saturation flux density & lowest iron losses (Insulation techniques) Magnet: demagnetisation, reversible magnetisation, resistivity	Losses calculation (stator windings & laminations: Cu losses= 3*R*I^2 (current and res) Iron Losses= hysteresis & eddy losses	<u>Increased force density (limitation?) machines:</u> *Transverse flux (Dubois 2004, Bang et al 2008) *Vernier Hybrid (Muller and Baker 2003) <u>Reduction of large forces in the air gap</u> * air gap winding machines * without iron behind stator coils (Spooner et al. 2005, McDonald 2008, Muller et al. 2009)

Table 9.3:Engineering specifications to meet stakeholder requirements for DD machines (part-II)

Author	Aim	Report Summary	Methods			Conclusion
A McDonald & A. Bhuiyan	Optimisation of DDPM design to reduce CoE	surface mounted PMG- lowest CoE * Use of simplified metric (generator costs & losses similar as full scale CoE calculation * Impact of magnetic material costs (2x equals to 1.1/MWh Euros increase in CoE) Increase of generator diameter limit (6 to 8m leads to 0.9% drop in CoE)	Parametric electromagnetic and structural generator model for * surface mounted PMG (Nd-Fe-B magnet with high BHmax) * Flux-concentrated arrangement (ferrite magnet with low BHmax) Optimisation - hybrid genetic algorithm and Pattern search processes (ref-12)	<u>Objective functions</u> aiming to minimise the use of magnet material Nd-Fe-B : * Rated generator Torque per magnet mass (reduce magnet material amount) F1= T/mpm *Minimise cost of all electromagnetically active materials instead of the magnet mass only- Cpm, Ccu, Cfe F2= T/ (Cpm+Ccu+ Cfe) * 3rd Function: Min cost of active materials and maximise revenue Ce over several years Py=5,10,15yrs. F3=Cpm+Ccu+Cfe- PyCeEy * Lowest LCOE **F4= [(FCR*ICC)+AOM]/ Ey**	Results F3(iii)- Min cost of active materials and Max revenue over 15 years: Highest airgap diameter, largest axial length (m), medium magnetic pole, highest magnetic height, the lowest number of pole pairs * F1= highest torque/ magnet mass * F2= highest torque/ cost of all active materials & F3(iii) lowest *F3(iii)- lowest cost of active materials over 15-year revenue period *F4-Lowest LCOE (F3 (all years) and F4)	<u>Easy Repair/Maintenance:</u> * Modularity (Spooner et al. 1996) *Modules with magnets and coils * Optimum combination of # of poles/slots

Table 9.4: Engineering specifications to meet stakeholder requirements for DD machines (part-III)

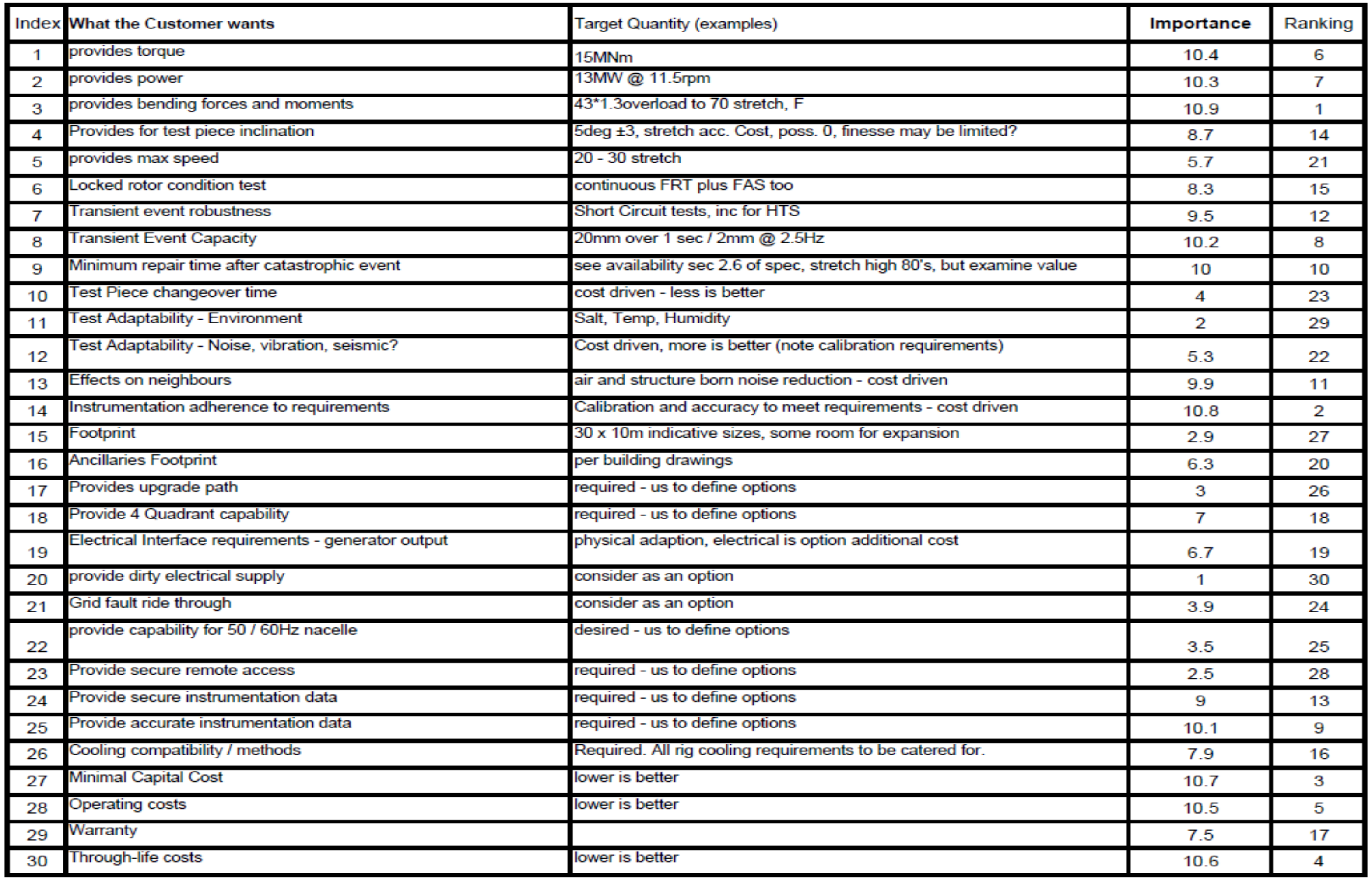
Author		**Aim**	**Report Summary**	**Methods**			**Conclusion**
Polinder, H et al	Comparison of DD and geared Generator concepts for WT	Comparison of 5 diff generator systems - based on cost and Annual energy yield	* Excitation losses in EESG Risks of demagnetisation in DDPMG- hence doubling the pole pitches compared to DDSG- EE) DFIG3G not suitable for increased power levels and reduced speed PMG1G (multigrid: Complex, compact & expensive. Fully rated converter	Defined WT characteristics & modelling (generator materials, losses, costs) Gearbox & converter modelling _ gear ratio (studies ref), cost estimate & losses. Calculation of Pgear- losses in gear 3. Generator modelling= parameters of equivalent circuits	Equivalent circuit calculations for generator Slot, air gap, end-winding leakage inductance The magnetic inductance of AC machine= function (stator radius, number of turns of phrase windings, winding factor, pole pairs, effective air gap, stack length in axial direction…) Where the effective airgap is a function (reluctance of iron in the magnetic circuit, carter factor of stator slots, mechanical air gap, recoil permeability of magnets	effective air gap larger due to low permeability of magnets (carter factor is smaller) *BH characteristics, *Harmonics of flux density, * No-load voltage induced by flux density * Copper losses (form current and resistance) * Phase resistance. Main dimensions of the five generators with parameters, material weights, costs, and annual energy	DFIG3G- lighter, low cost, standard components but low energy yield due to high losses in the gearbox DDSG- heaviest, most expensive- Enercon (Stander et al. 2012) DDPMG- less heavy than DDSG (EE), half the active material. More expensive, less standardised. Cost a function of PM material costs and converter/ power electronics costs (* McDonald et al. 2008) No brushes or gearbox= more reliable Fully rated converter DFIG1G- highest energy yield/ cost due to (*Shrestha et al. 2010 (magnetic bearings): Rating of converter= low costs/ losses Less standardise, so higher risk, less will to invest improvements with DDPMG) * Variable reluctance

Table 9.5: Summary Potential technical solutions from Literature reviews

Needs CR (i)	**Tech requirements to meet CR(i)**			
	QC- Top Level	**Level-2**	**Level 3**	**Potential solutions**
Increased Power Output	Cost Effective:			Transverse flux machines
	Economies of scale (mass production)	Improved material properties (resistance, weight, availability, complexity)		
Maximise availability			Optimum Winding type and arrangement	Vernier hybrid machines
Greater Reliability	Lower WACC- shared risks	Standardisation of sub-elements	Efficient cooling system (optimum insulation materials	Variable reluctance machines
	NOAK (de-risked technology) & higher MRL/TRL			
		De-risking/ Testing facilities (TRL & CRI increase)		
Cost Effective			B Max (maximum saturation flux)	
Simple design, manufacture,		Smaller air gap clearance		
	Low capital cost per MW		Optimum Stator/Rotor configuration (Inner or Outer)	Use of magnetic bearing
Easy access, maintain & Monitor	Performance & Reliability	Lamination filling factor (Cu Vs Steel)		The buried magnet in the iron structure of the rotor (bigger flux density in the air gap)
			Maximise rated torque/ active material	
Longer life span	Increased Efficiency	Insulation	Low turbine cost overall	Dynamics of Mechanical design
	Longer MTBF	Availability (less failure- fatigue Vs Stress and Strength applied)	Increased Shear stress= Power density (fun(torque, variable rot speed))	
Easy Integration				Force reduction by use of air gap windings/
Grid Compliant	Reduced losses (Fe, Cu, Thermal)	Dimensions/ choice of materials	Bearing types and properties	Force reduction by use of air-cored machines (with no iron in stator)
	Minimum number of materials/ components	Optimisation of electromagnetic parameters (torque ripple, cogging torque, vibration, noise)		
			Magnet with high/low Hbmax	Force reduction- machines without iron behind stator coils
	Robustness (longer life	Cooling system- thermal insulation	Minimise the cost of support material	Failure rate analysis Vs Optimum availability
	Minimisation of losses	I^2R resistance losses ~ temperature (hence reducing losses)		
			Embedded Power electronics in structural material	Improved manufacturing process & protection
	Graceful Degradation & Redundancy measures	Mass reduction	Ancillary equipment (cooling system, breaking, Hex)	Repairs strategies (CM, condition-based O&M, fault tolerance
		Maximise air gap clearance limit & minimise airgap radius (reduced load-path)		
	Easy access and maintenance-CBM		Inner Vs Outer rotor configuration	fractional pitch concentrated windings
				Different configuration of # poles &slots for minimum eddy current losses & back iron
	Optimum Manufacture			
	Simplified designs			Smaller/ Higher magnetic field
	Modular/ smaller units			Reliable power electronic converters (VSC)
	Less strict tolerance			Maximising the number of slots per pole per phase
	Meeting Grid Code			fractional pitch concentrated windings

11.3.1. Data Input

Table 9.6: QFD Report- Offshore Wind turbine drivetrain- Output ETI report



Index	**What the Customer wants**	Target Quantity (examples)	**Importance**	Ranking
1	provides torque	15MNm	10.4	6
2	provides power	13MW @ 11.5rpm	10.3	7
3	provides bending forces and moments	43*1.3overload to 70 stretch, F	10.9	1
4	Provides for test piece inclination	5deg ±3, stretch acc. Cost, poss. 0, finesse may be limited?	8.7	14
5	provides max speed	20 - 30 stretch	5.7	21
6	Locked rotor condition test	continuous FRT plus FAS too	8.3	15
7	Transient event robustness	Short Circuit tests, inc for HTS	9.5	12
8	Transient Event Capacity	20mm over 1 sec / 2mm @ 2.5Hz	10.2	8
9	Minimum repair time after catastrophic event	see availability sec 2.6 of spec, stretch high 80's, but examine value	10	10
10	Test Piece changeover time	cost driven - less is better	4	23
11	Test Adaptability - Environment	Salt, Temp, Humidity	2	29
12	Test Adaptability - Noise, vibration, seismic?	Cost driven, more is better (note calibration requirements)	5.3	22
13	Effects on neighbours	air and structure born noise reduction - cost driven	9.9	11
14	Instrumentation adherence to requirements	Calibration and accuracy to meet requirements - cost driven	10.8	2
15	Footprint	30 x 10m indicative sizes, some room for expansion	2.9	27
16	Ancillaries Footprint	per building drawings	6.3	20
17	Provides upgrade path	required - us to define options	3	26
18	Provide 4 Quadrant capability	required - us to define options	7	18
19	Electrical Interface requirements - generator output	physical adaption, electrical is option additional cost	6.7	19
20	provide dirty electrical supply	consider as an option	1	30
21	Grid fault ride through	consider as an option	3.9	24
22	provide capability for 50 / 60Hz nacelle	desired - us to define options	3.5	25
23	Provide secure remote access	required - us to define options	2.5	28
24	Provide secure instrumentation data	required - us to define options	9	13
25	Provide accurate instrumentation data	required - us to define options	10.1	9
26	Cooling compatibility / methods	Required. All rig cooling requirements to be catered for.	7.9	16
27	Minimal Capital Cost	lower is better	10.7	3
28	Operating costs	lower is better	10.5	5
29	Warranty		7.5	17
30	Through-life costs	lower is better	10.6	4

Table 9.7:Current trend Offshore wind turbines (1/3)

Make	Model	First in Service	Nominal Max Power, MW	Speed, rpm	Torque, MNm	Top head mass	Bladed diameter	Swept area	Drivetrain	Generator	Converter	Nominal Current, A	Torque to THM ratio, Nm/kg.
GoldWind	2.5/109	2012	2.5	13.5	1.77	100	109	1076	DD	PMG	690	3623	17.7
Siemens	3.0-113	2011	3	14.9	1.92	122	113	1115	DD	PMG	690	4348	15.8
Mervento	4.0-118	2016	4	12.6	3.03	300	118	1165	DD	PMG	690	5797	10.1
GE	4.1-113	2010	4.1	11.5	3.40	320	113	1115	DD	PMG	690	5942	10.6
XEMC / DarWind	5MW Offshore	2010	5	12.2	3.91	281	115	1135	DD	PMG	690	7246	13.9
GoldWind	Concept	2016	10	10	9.55	420	190	1875	DD	PMG	690	14492.75	22.73
Siemens	D10	2019	10	8.8	10.85	390	206	2033	DD	PMG	690	14493	27.8
Siemens	D6-150	2013	6	9.9	5.78	350	154	1520	DD	PMG	690	8696	16.5
Siemens	D7-154	2014	7	9.6	9.43	350	154	1520	DD	PMG	690	10145	26.9
Envision	E128-3.6MW	2012	3.6	15	2.29	280	128	1263	DD	PMG	730	4932	8.2
GoldWind	GW3000	2011	3.35	15.3	2.09	140	110	1086	DD	PMG	690	4855	14.9
GoldWind	GW6000	2012	6	11	5.21	380	150	1480	DD	PMG	690	8696	13.7
GE	Haliade 150	2013	6	11.5	4.98	370	150	1480	DD	PMG	900	6667	13.5
AMSC	Sea Titan	2020	10	10	9.55	324	190	1875	DD	HTS	4160	2404	29.5

Table 9.8: Current trend offshore wind turbines (2/3)

					CAPEX Estimates by materials and topology				
Make	**Model**	**Tip Speed, m/s**	**Rotor Power Density, W/M^2**	**THM Power Density kW/kg**	**Nacelle, Tower, foundation**	**Blades**	**Converter (Price per current, third for part converter)**	**Total**	**CAPEX £/kW)**
GoldWind	2.5/109	77.0	2323.88	0.025	1645000	185300	70833	1901133	760.4533333
Siemens	3.0-113	88.2	2689.94	0.025	2006900	192100	85000	2284000	761.3333333
Mervento	4.0-118	77.8	3434.62	0.013	4935000	200600	113333	5248933	1312.233333
GE	4.1-113	68.0	3676.26	0.013	5264000	192100	116167	5572267	1359.089431
XEMC / DarWind	5MW Offshore	73.5	4405.27	0.018	4622450	195500	141667	4959617	991.9233333
GoldWind	Concept	99.48	5332.69	0.02	6909000	323000	283333	7515333	751.53
Siemens	D10	94.92	4918.50	0.03	6415500	350200	283333	7049033	704.90
Siemens	D6-150	80.00	3947.58	0.02	5757500	261800	170000	6189300	1031.55
Siemens	D7-154	77.41	4605.51	0.02	5757500	261800	198333	6217633	888.23
Envision	E128-3.6MW	100.53	2849.66	0.01	4606000	217600	96411	4920011	1366.67
GoldWind	GW3000	88.12	3085.69	0.02	2303000	187000	94917	2584917	771.62
GoldWind	GW6000	86.39	4052.85	0.02	6251000	255000	170000	6676000	1112.67
GE	Haliade 150	90.32	4052.85	0.02	6086500	255000	130333	6471833	1078.64
AMSC	Sea Titan	99.48	5332.69	0.03	4416120	323000	46995	4786115	478.61

Table 9.9: Electrical machine power and torque density- data machine studies [ETI - marine and power] (3/3)

Maker	Application	Machine type	Topology	Excitation	Mass, kg	Peak Power, kW	Speed, rpm	Peak Torque, Nm	Power / weight ratio kW/kg	Torque/ weight ratio
Cummins	Power	Generator	Radial	PM	5	10	80000	1.2	2.0	0.24
Lynch Motor	Marine	motor	Axial	PM	25	15	3700	38.7	0.6	1.55
Xinda	Power	Generator	Radial	PM	140	300	1500	1909.8	2.1	13.64
TPS	Power	Generator	Radial	PM	350	1200	11500	996.4	3.4	2.85
Siemens	Power	Generator	Radial	PM	56000	3000	15	1909760.0	0.1	34.10
GE	Power	motor	Radial	PM	8000	3000	1500	19097.6	0.4	2.39
Arreva	Power	Generator	Radial	PM	45000	5000	340	140423.5	0.1	3.12

11.4. Fixed Vs Floating Trends

Table 9.10: Fixed vs floating substructures

	Monopile	Gravity Base	Tripod	Braced Lattice Frames	Floating
Depth (m)	0-30m	0-40m	0-50m	0-50m (deeper water)	>60m
Accounts for:	>90%	c2%		c6%	0%
Configuration	Simple Large steel pipes Guyed Monopile (>30m) Monopile with tensioned guy wires	Overturn load by its gravity	Triangular frame of steel. Jacket leg at e/corner braced to the transition piece.	Tripod modified frame More structural members- jacket has 3-4 leg structure to increase stiffness	TLP-Glosten Hywind-Norway WindFloat-US Blue high tension TLP-Hollande
Soil condition	Variety of soil conditions Sands, cobbles & boulders, dense sands	Hard rock ledge or glacial soil in shallow waters			
Installation Methods	Piles grouted into sockets drilled into rocks. Or vibratory hammers	Gravity caisson (concrete shell structures)			
Pros	Most economical Low Environmental Impact Low water depth (	Cost-effective (for low environmental Load)	Avoid deflection of the tower. Onshore construction No seabed prep.	More stability via stiffness	
Cons	Stiffness issues- deeper waters	Requires significant dead load (ballast)		More material, higher cost	

11.5. Floating concepts Data Inputs

Table 9.11: Floating Structure Current trends of floating substructure platforms. Data inputs from Literature [76] [60]

	Concepts	Mooring weight per metre (tons) Vs Cost per metre (£)		Mooring length (m) and cost per unit (£m)		Platform	Number	Length (m) Vs Weight (tons)	Radium of Mooring Footprint (m) Vs Cost per meter (£) Vs Cost per unit (£m)		
Catenary	Chains	0.20	520	750	0.5	Semi-Sub, Spar	3-4	710 - 155	610	500	2200
	Chains & wires	0.20	300	500	0.175	multi/hybrid					
	Synthetic fibre	0.025	2000	80	0.16						
Taut Leg	Wires	0.36	2100	50	0.13	TLPs	TLP (5-6)-	80 -10	30	2200	1100
	Steel pipes										
Semi-taut	Synthetic fibre and chains & Wires					Semi-sub		600- 60	580	490	1800

Table 9.12: Data input to case study [76]

Platform weight	Semi-Sub	Spar Buoy	TLP	Hybrid/Multi	Concrete based
Pre-Ballast	1800	1400	1100	2400	2000
Post-ballast	6000	8100	1500	9000	

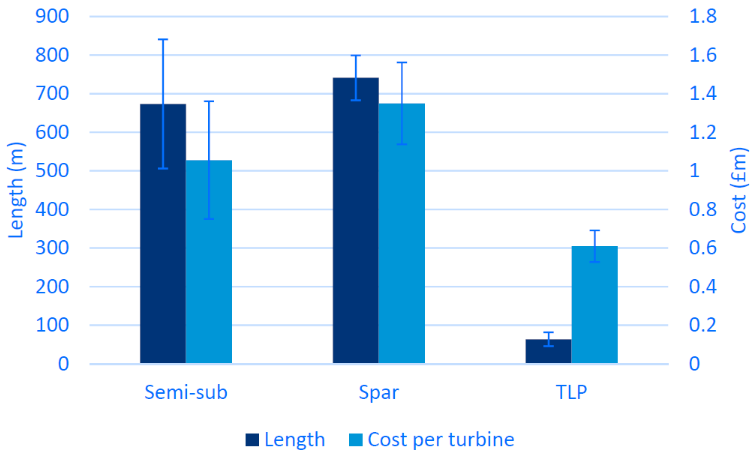


Figure 9.2: Mooring Length and cost per turbine, by floater typology [76]

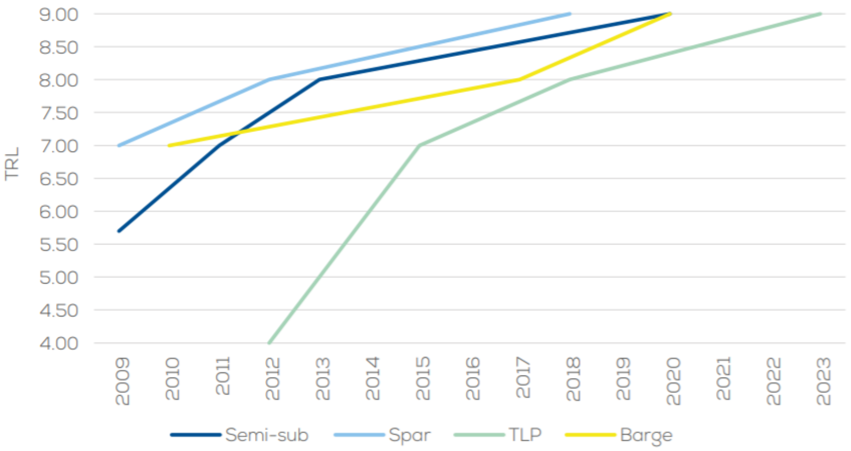


Figure 9.3: TRL Floating substructures in development [76]

Operational costs:

Data from ETI cost model (Glosten Project)

Table 9.13: Operational Costs- Glosten Pelastar project ETI

OPEX (£m typical annual)		
Scheduled Maintenance	Turbines	**0.79**
	Floating support structure	**0.52**
	Floating active elements	**0.00**
Unscheduled Maintenance	Turbines	**18.93**
	Floating support structure	**0.00**
	Floating active elements	**0.00**

11.6. FMEA definitions and analyses

Table 9.14: FMEA- definition of Severity

Severity	
1	No effect
2	Minor performance loss, defect noticed only by close inspection
3	Minor performance loss, defect noticed only by most observers
4	Minor performance loss, defect apparent
5	Device operable, but minor performance loss, end-user experience some dissatisfaction
6	Device operable, but auxiliary performance lost
7	Device operable, but with reduced performance level, end-user dissatisfied
8	Device inoperable, primary function lost
9	Device inoperable, safe function lost with warning
10	Device inoperable, safe function lost without warning

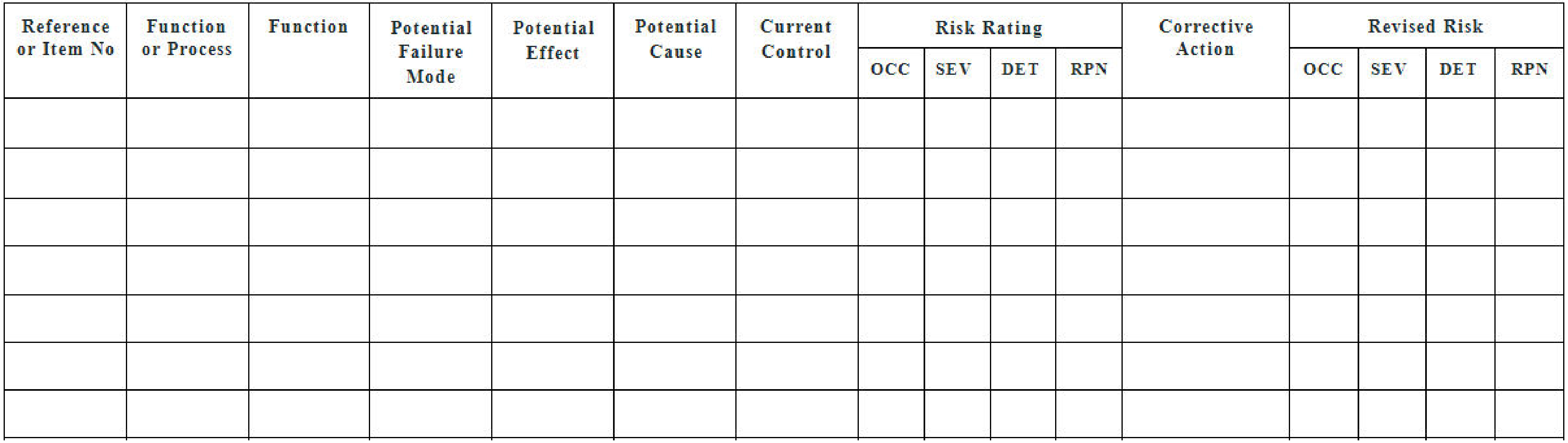
Table 9.15: Definition of likelihood of failure (Occurrence)

Occurrence	Description	Event occurrence – e.g. 1 in 1000 hours / days
1	Failure unlikely	1 in 1000000
2	Relative few failures	1 in 250000
3	Relative few failures	1 in 20000
4	Occasional failures	1 in 1000
5	Occasional failures	1 in 400
6	Occasional failures	1 in 80
7	Repeated Failures	1 in 20
8	Repeated Failures	1 in 8
9	Failure inevitable	1 in 4
10	Failure inevitable	> 1 in 2

Table 9.16: Definition of level of detection

Detection	Process FMEA	Design FMEA
1	Detection is almost certain	Design controls will detect a potential cause / mechanism and failure mode
2	Detection is highly likely	Very high chance that DC can find the failure mode and cause
3	High chance that the defect can be found	High chance that DC can find the potential failure mode and cause
4	Moderately high chance that the defect will be detected	Moderately high chance
5	Moderate chance that detection is possible	Moderate chance
6	Low chance of detection	low chance
7	Very low chance of detection	Very low chance
8	Remote chance of detection	Remote chance
9	Very remote chance of detection	Design control unlikely to predict failure mode or cause
10	Total uncertainty of detection	Design control cannot detect the potential cause and failure mode, or there is no design control

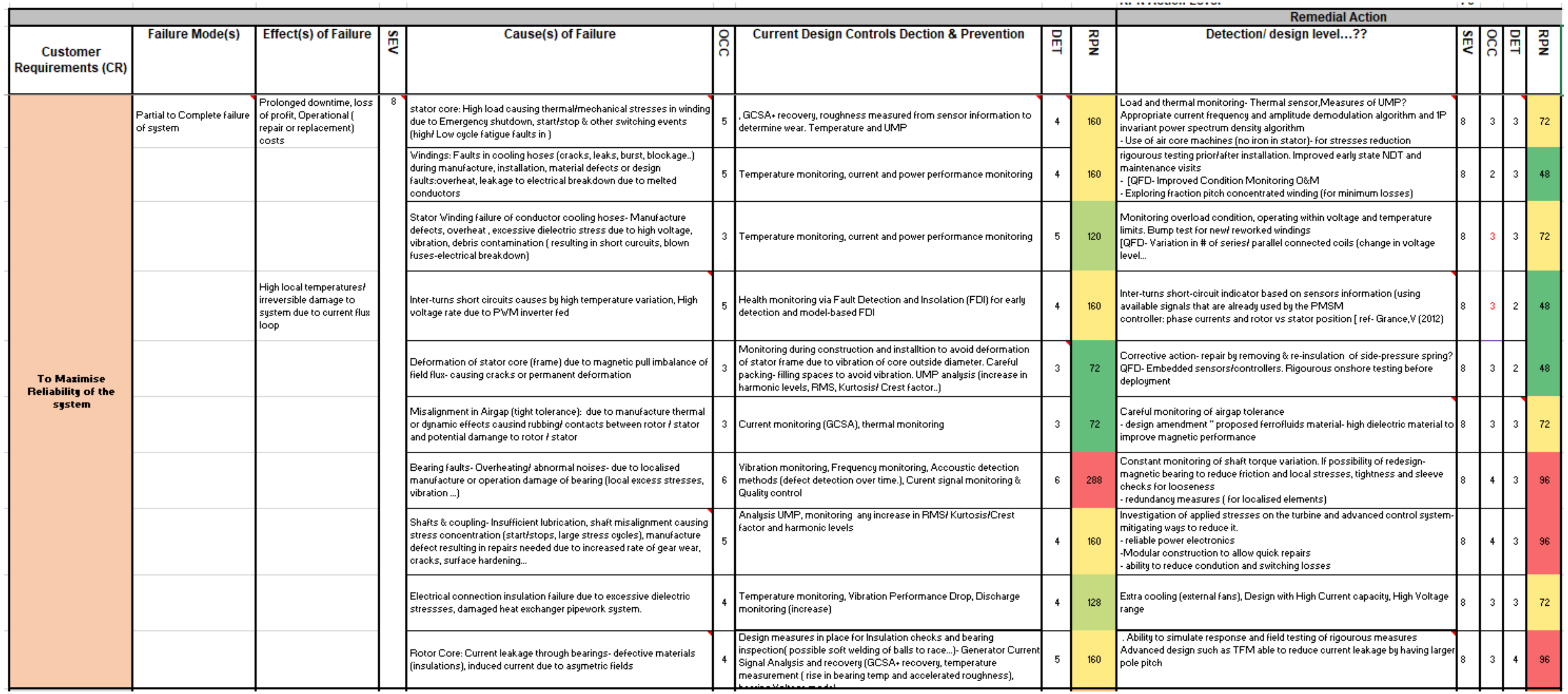
Table 9.17: Example FMEA Worksheet- BS En 60812 FMEA



Reference or Item No	Function or Process	Function	Potential Failure Mode	Potential Effect	Potential Cause	Current Control	Risk Rating				Corrective Action	Revised Risk			
							OCC	SEV	DET	RPN		OCC	SEV	DET	RPN

FMEA of Direct-drive generator

Table 9.18: FMEA of direct drive generator based on Stakeholder requirements (1/3)



										Remedial Action				
Customer Requirements (CR)	**Failure Mode(s)**	**Effect(s) of Failure**	**SEV**	**Cause(s) of Failure**	**OCC**	**Current Design Controls Dection & Prevention**	**DET**	**RPN**	**Detection/ design level…??**	**SEV**	**OCC**	**DET**	**RPN**
To Maximise Reliability of the system	Partial to Complete failure of system	Prolonged downtime, loss of profit, Operational (repair or replacement) costs	8	stator core: High load causing thermal/mechanical stresses in winding due to Emergency shutdown, start/stop & other switching events (high/ Low cycle fatigue faults in)	5	, GCSA+ recovery, roughness measured from sensor information to determine wear. Temperature and UMP	4	160	Load and thermal monitoring- Thermal sensor,Measures of UMP? Appropriate current frequency and amplitude demodulation algorithm and 1P invariant power spectrum density algorithm - Use of air core machines (no iron in stator)- for stresses reduction	8	3	3	72
				Windings: Faults in cooling hoses (cracks, leaks, burst, blockage..) during manufacture, installation, material defects or design faults:overheat, leakage to electrical breakdown due to melted conductors	5	Temperature monitoring, current and power performance monitoring	4	160	rigourous testing prior/after installation. Improved early state NDT and maintenance visits - [QFD- Improved Condition Monitoring O&M - Exploring fraction pitch concentrated winding (for minimum losses)	8	2	3	48
				Stator Winding failure of conductor cooling hoses- Manufacture defects, overheat , excessive dielectric stress due to high voltage, vibration, debris contamination (resulting in short curcuits, blown fuses-electrical breakdown)	3	Temperature monitoring, current and power performance monitoring	5	120	Monitoring overload condition, operating within voltage and temperature limits. Bump test for new/ reworked windings [QFD- Variation in # of series/ parallel connected coils (change in voltage level...	8	3	3	72
		High local temperatures/ irreversible damage to system due to current flux loop		Inter-turns short circuits causes by high temperature variation, High voltage rate due to PWM inverter fed	5	Health monitoring via Fault Detection and Insolation (FDI) for early detection and model-based FDI	4	160	Inter-turns short-circuit indicator based on sensors information (using available signals that are already used by the PMSM controller: phase currents and rotor vs stator position [ref- Grance,V (2012)	8	3	2	48
				Deformation of stator core (frame) due to magnetic pull imbalance of field flux- causing cracks or permanent deformation	3	Monitoring during construction and installtion to avoid deformation of stator frame due to vibration of core outside diameter. Careful packing- filling spaces to avoid vibration. UMP analysis (increase in harmonic levels, RMS, Kurtosis/ Crest factor..)	3	72	Corrective action- repair by removing & re-insulation of side-pressure spring? QFD- Embedded sensors/controllers. Rigourous onshore testing before deployment	8	3	2	48
				Misalignment in Airgap (tight tolerance): due to manufacture thermal or dynamic effects causind rubbing/ contacts between rotor / stator and potential damange to rotor / stator	3	Current monitoring (GCSA), thermal monitoring	3	72	Careful monitoring of airgap tolerance - design amendment " proposed ferrofluids material- high dielectric material to improve magnetic performance	8	3	3	72
				Bearing faults- Overheating/ abnormal noises- due to localised manufacture or operation damage of bearing (local excess stresses, vibration ...)	6	Vibration monitoring, Frequency monitoring, Accoustic detection methods (defect detection over time.), Curent signal monitoring & Quality control	6	288	Constant monitoring of shaft torque variation. If possibility of redesign- magnetic bearing to reduce friction and local stresses, tightness and sleeve checks for looseness - redundancy measures (for localised elements)	8	4	3	96
				Shafts & coupling- Insufficient lubrication, shaft misalignment causing stress concentration (start/stops, large stress cycles), manufacture defect resulting in repairs needed due to increased rate of gear wear, cracks, surface hardening...	5	Analysis UMP, monitoring any increase in RMS/ Kurtosis/Crest factor and harmonic levels	4	160	Investigation of applied stresses on the turbine and advanced control system- mitigating ways to reduce it. - reliable power electronics -Modular construction to allow quick repairs - ability to reduce condution and switching losses	8	4	3	96
				Electrical connection insulation failure due to excessive dielectric stressses, damaged heat exchanger pipework system.	4	Temperature monitoring, Vibration Performance Drop, Discharge monitoring (increase)	4	128	Extra cooling (external fans), Design with High Current capacity, High Voltage range	8	3	3	72
				Rotor Core: Current leakage through bearings- defective materials (insulations), induced current due to asymetric fields	4	Design measures in place for Insulation checks and bearing inspection(possible soft welding of balls to race...)- Generator Current Signal Analysis and recovery (GCSA+ recovery, temperature measurement (rise in bearing temp and accelerated roughness),	5	160	. Ability to simulate response and field testing of rigourous measures Advanced design such as TFM able to reduce current leakage by having larger pole pitch	8	3	4	96

Table 9.19: FMEA of direct drive generator based on Stakeholder requirements (2/3)

									Remedial Action				
Customer Requirements (CR)	Failure Mode(s)	Effect(s) of Failure	SEV	Cause(s) of Failure	OCC	Current Design Controls Dection & Prevention	DET	RPN	Detection/ design level...??	SEV	OCC	DET	RPN
Decrease excepted system cost	Higher than expected cost of material and key components to realise optimum LCOE	Reduced Market acceptance and investor confidence due to high capital costs and increased paypack period	7	material costs higher than expected due to advanced materials required to provide lightweight properties, higher yield strength and more efficient properties (reduction of losses)	5	Design, build and demonstration projects to eliminate as many "potential failures" and know how to migitate them.	5	200	Increase of TRL and MRL for individual compoents and system integration through testing (pre production Accelerated life & prototype Testing) & standardisation. Demonstration projects- simulation, testing and buidling	7	4	3	84
		Higher Cost for Improving performance and efficiency of machine	7	Complex instrumentation system design- Low TRL (insulation, cooling, optimum magnetic field, air gap tolerance, Conduction/ switching losses)	6	Sensors and measurement data- SCADA and robust control system/ more CBM	5	240	More design, build and demonstration projects to increase voltage range, current capability and reduce switching/conduction losses More data measurement analysis (remotely and online systems)	8	4	4	128
			8	Higher risk and low reliability due to Higher grade controls and sensors needed for harsher operating conditions (deeper water-floating technologies...)- less tested	6	Expertise in electronic system in the sector, simulation and testing capabilitites,	5	240	More R&D in control system, Design and process review and validation Provide mechanical/electrical/hydraulic mechanisms to meet requirements and implement advanced monitoring algorithm to detect abnormal response	8	4	3	96
			7	High cost of support structure due to over-engineering to contain high torque & supporting structure	5	-Embedded power controllers -Advanced materials for windings, airgap design, core	4	160	-Embedded power electronics. - Use of active material as support structure - Testing of advance materials (ferrofluids or other PM materials)	8	3	3	72
			8	Heavy support structure to contain hgih torques for large direct drive machines (over engineering)	7	Selection and design of most efficient support structures (floating or fixed) taking into consideration sites/ cost and reliability	3	168	More testing of floating and other alternative support stucture for supporting WT based on geographical location, loads...	5	3	3	45

Table 9.20: FMEA of direct drive generator based on Stakeholder requirements (3/3)

									Remedial Action				
Customer Requirements (CR)	Failure Mode(s)	Effect(s) of Failure	SEV	Cause(s) of Failure	OCC	Current Design Controls Dection & Prevention	DET	RPN	Detection/ design level...??	SEV	OCC	DET	RPN
To reduce the mass of the machine	Excessive time to install	Delay in installation due to lack of appropriate vessels/ cranes... High MTTR, Cost over-run	7	Increased Operational costs due to need for be-spoke equipments & skills Time to install is excessive	6	Maximise onshore assembly & onshore maintenance	3	144	Mitigation into the design of lightweight inactive support materials to maximise active material as support: - Nacelle cover : replace GRP and inner steel beam with a self-supporting outer housing without the need for the inner beams - Embedded power electronics - Standardisation of cranes, vessels, installation equipment and design according to them Advanced designs (Superconductors, back to 1G)	7	3	3	63
	Cooling system failure	Damage to equipments, loss of function resulting in Low- to-loss of power generated	8	Insufficient cooling or damage of cooling system (lose connection, hose and/or pump failure)	3	Comply with design standards:Cooling system design specification (Temperature sensor (thermostats) & Auto-shut down & thermal protection)	8	192	Design review, establish PLC interface Further testing of impacts of liquids cooling systems such a 2-phase evaporative cooling to improve thermal losses, efficiency....	8	2	4	64
	Low Performance of machine	Low Efficiency	7	Significant current leakage causing degradation of machine performance with diameter >1m	4	detection control measures to Generator Current Signal Analysis and recovery (GCSA+ recovery, temperature measurement (rise in bearing temp and accelerated roughness), bearing Voltage model	5	160	. Ability to simulate response and field testing of rigourous measures Advanced design such as TFM able to reduce current leakage by having larger pole pitch	7	2	3	42
	Higher than expected cost of material and key components to realise optimum LCOE	Higher Cost for Improving performance and efficiency of machine	7	material costs higher than expected due to advanced materials required to provide lightweight properties, higher yield strength and more efficient properties (reduction of losses)- over engineering	7	Use of steel- cheaper yet heavier. Selection of appropriate materials and protection- coating , build-in fire protection, and other properties (thermal conductivity, surface treatments...)	2	112	Exploitation of advanced materials such as Aluminium alloys and composites in more components such as nacelle cover and others to reduce weight of the system and improve its efficiency. Further analysis and optimised alloys composition for cost saving ferro fluids.. ref and what it does	7	3	2	42
	Bearing damage	Permanent deformation due Inability to handle radial, axial and/ or tilting moments	8	Overload or innapropriate specs Corrosion- accelerated condensation Fatigue- Load spectrum over lifetime	7	Testing monitoring system to complete failure & degradation. inc vibration monitoring & analysis, temperature, composition & ways to monitor contamination of oil & determine replacement and inspection intervals	4	224	Advanced design of bearing to minimise losses, maintain high reliability and low bearing weight without increasing bearing diameter. (magnetic bearing / reduction of the support structural structure, possibility of keeping bearing near airgap and still retain the strict tolerance requirements and monitoring the lubrication.	8	3	4	96
	permanent damage of machine	Deformation/ decrease of aerodynamic efficency	8	Mechanical unstability due to the need for lighter construction Deformation of stator core (frame) due to magnetic pull imbalance of field flux- causing cracks or permanent deformation	3	Monitoring during construction and installtion to avoid deformation of stator frame due to vibration of core outside diameter. Careful packing- filling spaces to avoid vibration. UMP analysis (increase in harmonic levels, RMS, Kurtosis/ Crest factor..)	3	72	R&D into reliability of ironless stator and/or C-core machines & how to overcome issues of decrease aerodynamic efficiency and large amount of magnet QFD- Embedded sensors/controllers. Rigourous onshore testing before deployment	8	3	2	48
	Poor prediction of turbine Performance & blade damage	Rotational decrease (impact on lift coefficient) on blade boundary layers leading to higher Rossby number- lower Pout and wake development	6	Increased complexity of inner part of blades (on the boundary layer development under highly separated flow at the post-stall regime)	7	Pitch control and sensors. Ability to increase lift coefficient & reduce stall. Load and performance monitoring	3	168	Rotation augmentation is airfoil dependent- hence addional R&D to understand overall Boundary layer of longer and thinner blades on wake development and impact on power performance.	6	5	3	90
	Hub/ Blade detaching due to increased impact of modularity due to larger sizes	No power, recovery of unit for maintenance	8	Assembly error, Loosening of nuts and/or overload	3	Torque tests, testing assembly procedutes & full scale testing	3	72	Design standardisation and certification. Full scale testing	8	3	3	72

FMEA for floating concept

Table 9.21: Floating substructure concept FMEA

										Remedial Action				
Requirements	**Item/Function**	**Failure Mode(s)**	**Effect(s) of Failure**	**SEV**	**Cause(s) of Failure**	**OCC**	**Design & Process Control(s)**	**DET**	**RPN**	**Recommended Solution(s)**	**SEV**	**OCC**	**DET**	**RPN**
Buoyancy	Buoyant element	Flooding of the main body	Compromised buoyancy	8	Collision	3	Quality control Design to avoid collision (compartmentalisation) Design for vessel impact resistance Signalling Periodic inspection	4	96	Full-Scale testing at ultimate and Accidental limit state	8	2	4	64
Stability	Substructure	Insufficient material	Collapse of structure	8	Excessing loading Design or manufacturing errors	3	Simulation modelling at the design stage, FAT testing during and after assembly	4	96	Systems integration approach (OEM collaborative work). Full-scale testing of the whole system	8	2	3	48
	Active or Passive ballast	Unequal distribution of ballast	Structure collapse	6	Misalignment during installation	4	Accelerated full-scale testing Quality control	3	72	Monitoring and inspection	6	4	3	72
Power transmission	Dynamic cable / umbilical	Damage to dynamic cable / umbilical	Loss of power production	5	Unintended interaction / collision with foreign objects (e.g. vessels, debris)	4	Collaboration with OEMs • Layout redundancy • Experience from other industries	3	60	Redundancy as part of the design	5	4	3	60
Station Keeping	Mooring systems	Mooring lines failure	Compromised capabilities	7	Manufacturing errors Malfunction	4	Quality control Component testing Inspection planned	3	84	Standardisation of component, testing	7	3	3	63
			Line breakage or line fatigue	7	Wear or excessive stress	6	Design for Ultimate limit state, full testing at maximum loads	4	168	Standardisation of component, testing	7	4	3	84
			Line wear or breakage	7	Collision, Severe sea conditions, or during installation	6	Pre-install: sophisticated weather forecast tools. Collision protection measures, Sensors for periodic detection	4	168	Standardisation of component, testing	7	4	3	84
		Anchor & Fairlead	Corrosion	7	Seabed conditions	6	Accuracy in site characterisation Anchor material & testing	5	210	Strategic operation and maintenance strategies. Remote testing	7	4	3	84
			Limited function due to Fatigue & strength capacity	7	Excessive load	6	Design for Ultimate limit state, full testing for maximum tendon loads	5	210	Strategic operation and maintenance strategies. Remote testing	7	4	3	84
Rotor Nacelle Assembly interface	Yaw system	Misalignment with wind direction	Yaw motor fault or meteorological unit faults	7	Load fluctuation and abnormal vibration to the blades, tower, and nacelle. Or anemometer damage	3	Regular inspection Remote monitoring	3	63	Regular inspection Remote monitoring	7	3	3	63
	Electrical interface	Excessive motions (Rotor Nacelle Assembly towers)	Damage to RNA	7	Underestimation of inclinations, accelerations and vibrations	3	Independent third-party review and certification • Monitoring • Inspection	3	63	Design to standard • Use of proven numerical simulation tools • Wave tank experiments • Collaboration with OEMs • Independent 3rd party review and certification • Monitoring • Inspection	7	3	3	63
Monitoring and Communication		Partial or complete loss of structural hull stress monitoring information	Collapse of the structure	7	Expected failure of sensors during operation	4	Sensor redundancy • Monitoring • Inspection	3	84	Strategic operation and maintenance strategies. Remote testing	7	4	2	56

Table 9.22: Potential technical solutions- Direct drive generators (ETI survey results with literature data)

Function	Features	Operations
Cost Effective	Standardisation	Optimum Winding type and arrangement
Economies of scale (mass production)	De-risking/ Testing facilities	Efficient cooling system (optimum insulation materials
Performance	Smaller air gap clearance	B Max (maximum saturation flux)
Increased Part load Efficiency	Lamination filling factor (Cu Vs Steel)	Optimum Stator/Rotor configuration (Inner or Outer)
Longer MTBF	Insulation	Maximise rated torque/ active material
Reduced losses (Fe, Cu, Thermal)	Availability (less failure- fatigue Vs Stress and Strength applied)	Low turbine cost overall
A minimum amount of materials/ components	Dimensions/ choice of materials	Increased Shear stress= Power density is a function (torque, variable rot speed
Reliability	Optimisation of electromagnetic parameters (torque ripple, cogging torque, vibration, noise)	Bearing types and properties
Robustness (longer life	Cooling system- thermal insulation	Magnet with high/low Hbmax
Minimisation of losses	I^2R resistance losses ~ temperature (hence reducing losses)	Minimise the cost of support material
Optimum Manufacture (simplified/modular/ less strict tolerance)	Higher temp= higher magnetic loading (BH)…	Embedded Power electronics in structural material
Simplified designs	Standardisation	Ancillary equipment (cooling system, breaking, Hex)
Modularisation	De-risking/ Testing facilities	Inner Vs Outer rotor configuration
Less strict tolerance	Smaller air gap clearance	
Cost Effective	Lamination filling factor (Cu Vs Steel)	
Economies of scale (mass production)		
Performance		
Increased Part load Efficiency		

Table 9.22: Current floating technologies

Name	Classification	Material	TRL
WindFloat	Semi-sub	Steel	4
IDEOL-Damping pool	Caisson/barge	Concrete or steel	3
Vertiwind	Semi-sub	Steel	3
SeeReed	Semi-sub	Steel	3
Tri-floater	Semi-sub	Steel	3
TetraFloat	Semi-sub	Steel	3
VolturnUS	Semi-sub	Steel	3
Compact	Semi-sub	Steel	4
V-shape	Semi-sub	Steel	3
Hywind	Spar	Steel or Concrete	4
Sway	Spar	Steel	3
Wind Crete	Spar	Concrete	3
Hybrid Spar	Spar	Concrete/Steel hybrid	4
Advanced Spar	Spar	Steel	4
SeaTwirl	Spar	Steel	3
Glosten Pelastar	TLP	Steel	3
Blue H	TLP	Steel	3
GICON-SOF	TLP	Steel	3
DBD Eco TLP	TLP	Concrete	3
Iberdrola TLP Wind	TLP	Steel	3
Advanced Floating turbine (AFT)	TLP	Steel	2
Hexicon	Multi	Steel	2
WindSea FORCE technology	Multi	Steel	2
W2Power	Multi	Steel	2
Poseidon P80	Hybrid	Steel	3
MODEC SWID	Hybrid	Steel	3
WindLens	Multi	Steel	3

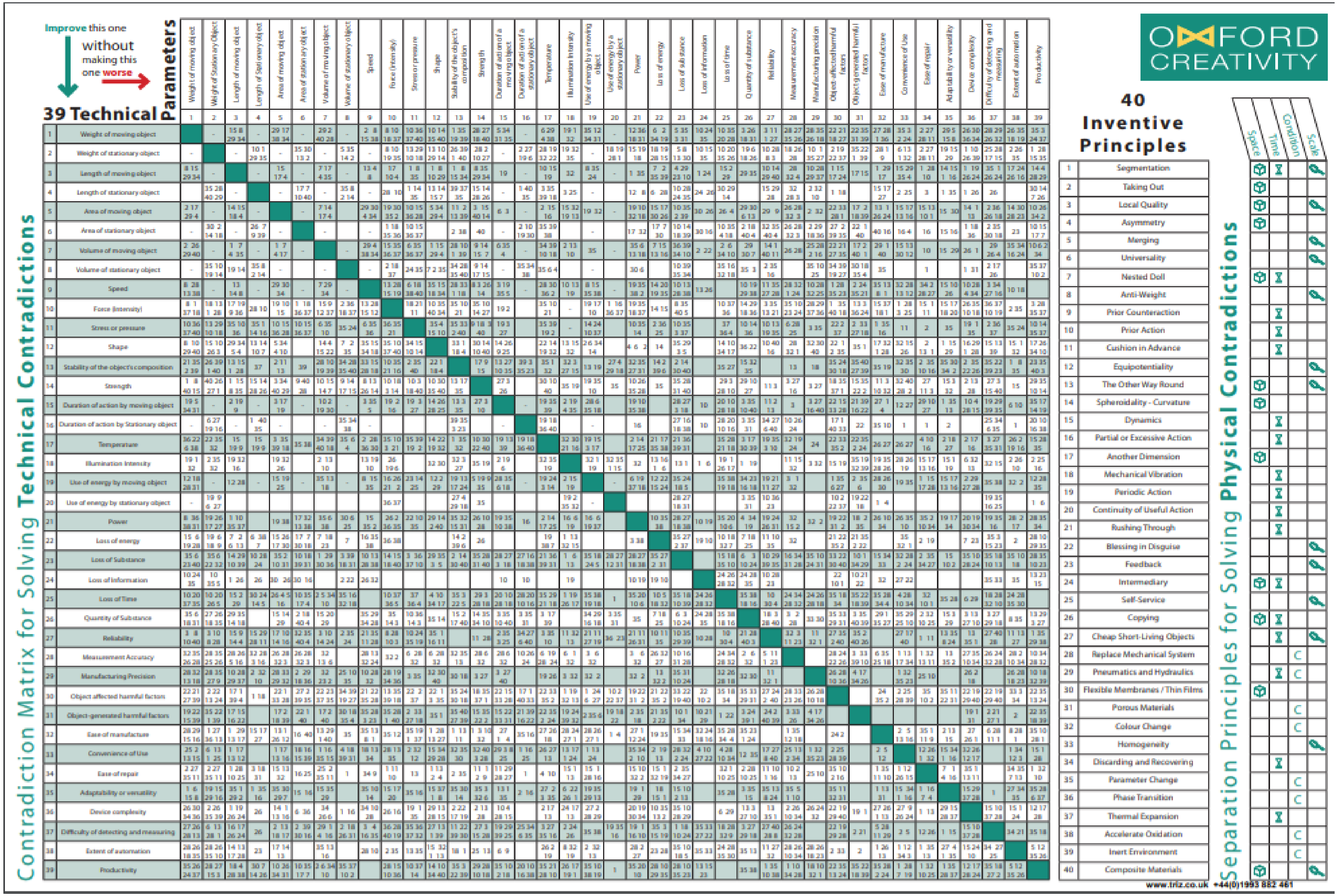
11.7. Qualitative analysis- Direct drive generator

Table 9.23: Amend table above with RAG status or achievable % for target values (qualitative analysis- breakdown)

	Low cost drivetrain (k£)	**High Efficiency**	**Longer MTBF/Reliability**	**Low Mass**		**Minimal Losses (thermal &Mechanical)**	**Grid Compliant EU regulations met**
3-Stage DFIG	200	Higher efficiency at high speed (Brushless BDFIG an option by low TRL)		Reduces generator torque and allow the compact machine	65	Power electronics- 3.3 kV fully/partial rated at tower base= lower tower cable Joule losses, smaller cross-section, lower costs	33kV 50Hz array (high TRL and supply)- Maximum voltage output
3-Stage PMG	350	use of High Voltage		Reduces torque and bring robust design	62	Power electronics- 3.3 kV fully rated at tower base- lower tower cable Joule losses, smaller cross-section, cheaper	33kV 50Hz array (high TRL and supply)- Maximum voltage output
1-Stage PMG	400	Reduced number of mechanical gear stages	Reduced number of mechanical gear stages= lower maintenance		70	Power electronics- 3.3 kV fully rated at tower base- lower tower cable Joule losses, smaller cross-section, cheaper	33kV 50Hz array (high TRL and supply)- Maximum voltage output
DD- PMG	580	Elimination of GB and Power electronics means higher reliability but lead to yield losses	Design accommodating phase /winding failures (partial and not Fully shutdown) = lower maintenance /self-healing system		135	Elimination of Power electronics lead to yield losses	66kV-50HZ output Low TRL but the potentially higher voltage output
Artemis- Hydraulic WRSG	160	High Reliability, torque limitation and elimination of power electronics	Part-fail operation with reduced output with multiple pistons working in parallel		45		Torque smoothing effect- no power electronics
Magnetic DD - Magnomatic Pseudo-DD		Higher reliability due to the elimination of meshing of mechanical gears	Relocation of power electronics and transformers into the tower base				DC Array
DD Superconducting Machines		Higher efficiency with a lighter, more compact design but low TRL	Lower reliability of cryogenic cooling systems				

11.8. TRIZ

Table 9.24: TRIZ Technical contradiction matrix [278]



Improve this one ↓ without making this one worse →

39 Technical Parameters

Contradiction Matrix for Solving Technical Contradictions

1 Weight of moving object
2 Weight of stationary object
3 Length of moving object
4 Length of stationary object
5 Area of moving object
6 Area of stationary object
7 Volume of moving object
8 Volume of stationary object
9 Speed
10 Force (Intensity)
11 Stress or pressure
12 Shape
13 Stability of the object's composition
14 Strength
15 Duration of action by moving object
16 Duration of action by Stationary object
17 Temperature
18 Illumination Intensity
19 Use of energy by moving object
20 Use of energy by stationary object
21 Power
22 Loss of energy
23 Loss of Substance
24 Loss of information
25 Loss of Time
26 Quantity of Substance
27 Reliability
28 Measurement Accuracy
29 Manufacturing Precision
30 Object affected harmful factors
31 Object-generated harmful factors
32 Ease of manufacture
33 Convenience of Use
34 Ease of repair
35 Adaptability or versatility
36 Device complexity
37 Difficulty of detecting and measuring
38 Extent of automation
39 Productivity

OXFORD CREATIVITY

40 Inventive Principles

Separation Principles for Solving Physical Contradictions

		Space	Time	Condition	Scale
1	Segmentation	✓	⧗		✓
2	Taking Out	✓			
3	Local Quality	✓			✓
4	Asymmetry	✓			
5	Merging				✓
6	Universality				✓
7	Nested Doll	✓	⧗		
8	Anti-Weight				✓
9	Prior Counteraction		⧗		
10	Prior Action		⧗		
11	Cushion in Advance		⧗		
12	Equipotentiality				✓
13	The Other Way Round	✓			✓
14	Spheroidality - Curvature	✓			
15	Dynamics		⧗		
16	Partial or Excessive Action		⧗		
17	Another Dimension	✓			
18	Mechanical Vibration		⧗		
19	Periodic Action		⧗		
20	Continuity of Useful Action		⧗		
21	Rushing Through		⧗		
22	Blessing in Disguise				✓
23	Feedback				✓
24	Intermediary	✓	⧗		
25	Self-Service				✓
26	Copying	✓	⧗		
27	Cheap Short-Living Objects		⧗		✓
28	Replace Mechanical System			C	
29	Pneumatics and Hydraulics		⧗	C	
30	Flexible Membranes / Thin Films	✓			
31	Porous Materials			C	
32	Colour Change			C	
33	Homogeneity				✓
34	Discarding and Recovering		⧗		
35	Parameter Change			C	
36	Phase Transition			C	
37	Thermal Expansion		⧗		
38	Accelerate Oxidation			C	
39	Inert Environment			C	
40	Composite Materials	✓			✓

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