Modelling Operations and Maintenance Strategies for Wave Energy Arrays

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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 Pelamis Wave Power and Wave Energy Scotland as a project within the Industrial Doctoral Centre for Offshore Renewable Energy.

Abstract

Wave energy has the potential to be a major contributor to the global energy mix. It is estimated that commercial deployment of wave and tidal energy arrays could meet as much as 20% of the UK's current electricity demand, with an installed capacity of 30-50 GW providing up to 16,000 jobs. However, the wave energy sector has not yet developed into a commercial industry due to several key challenges. One reason private investors have been reluctant to back the sector is that the uncertainty surrounding lifetime costs of wave energy arrays makes it difficult to obtain reliable estimates for overall cost of energy. In order to improve these estimates, a better understanding of the operations and maintenance (O&M) phase of wave energy arrays needs to be gained.

This thesis presents an O&M simulation tool designed for wave energy arrays. The work presented uses the model to assess aspects of O&M strategies for two different types of wave energy converter. Uncertainty in the model inputs is also addressed by undertaking a series of sensitivity analyses.

The methods and results presented in this thesis highlight the importance of using an O&M simulation tool to plan lifetime logistics for wave energy arrays and obtain realistic cost estimates. The work has also shown how an O&M tool can be used to identify critical components in wave energy converters, thereby helping to design the best device possible for the challenging marine environment. Understanding lifetime costs of wave energy arrays will drive the sector towards commercialisation, bringing wave energy a step closer to fulfilling its potential as a major contributor to global energy production.

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Declaration

I declare that this thesis was composed by myself and that the material presented is, except where clearly indicated, my own work. I declare that the work has not been submitted for consideration as part of any other degree or professional qualification. Furthermore, the journal and conference papers listed on the following page are also my own work.

……………………..

Anthony Gray

List of Publications

Journal Papers

Gray, A., Dickens, B., Bruce, T., Ashton, I. & Johanning, L. (2017). Reliability and O&M sensitivity analysis as a consequence of site specific characteristics for wave energy converters. Ocean Engineering. (Under Review).

Conference Papers

Gray, A., Johanning, L. & Dickens, B. (2014). The Modelling of Pelamis Wave Power's Operations and Maintenance Strategy. ASRANet International Conference on Offshore Renewable Energy. 15-17 September 2014. Glasgow, UK.

Gray, A., Johanning, L. & Dickens, B. (2015). A Markov Chain Model to Enhance the Weather Simulation Capabilities of an Operations and Maintenance Tool for a Wave Energy Array. 11th European Wave and Tidal Energy Conference. 6-11 September 2015. Nantes, France.

Gray, A. & Johanning, L. (2016). Identifying key O&M strategy considerations for a wave energy array – a case study on Pelamis. ICOE: International Conference on Ocean Energy. 23-25 February 2016. Edinburgh, UK.

Gray, A., Findlay, D., & Johanning, L. (2016). Operations and maintenance planning for community-scale, off-grid wave energy devices. RENEW Progress in Renewable Energies Offshore. 24-26 October 2016. Lisbon, Portugal.

Nomenclature

AEP - Annual Energy Production

CAPEX - Capital Expenditure

CBA - Cost-Benefit Analysis

CCO - Channel Coastal Observatory

CfD - Contracts for Difference

DECC - Department of Energy and Climate Change

DTOcean - Optimal Design Tools for Ocean Energy Arrays

ECN - Energy Research Centre of the Netherlands

EMEC - European Marine Energy Centre

EngD - Engineering Doctorate

FMEA - Failure Modes and Effects Analysis

Hs - Significant Wave Height

IDCORE - Industrial Doctoral Centre for Offshore Renewable Energy

LCOE - Levelised Cost of Energy

MCM - Markov Chain Method

MTBF - Mean Time Between Failure

MTTF - Mean Time To Failure

NPV - Net Present Value

O&M - Operations and Maintenance

OOP - Object Oriented Programming

OPEX - Operational Expenditure

ORE - Offshore Renewable Energy

OREDA - Offshore and Onshore Reliability Data

P2 - second generation Pelamis wave energy device

P_{fail} - Probability of failure per year

PRIMaRE - Partnership for Research In Marine Renewable Energy

PTO - Power Take Off

PWP - Pelamis Wave Power

SPARTA - System Performance, Availability and Reliability Trend Analysis

SWAN - Simulating Waves Nearshore

Te - Wave Energy Period

Tp - Wave Peak Period

VBA - Visual Basic for Applications

WEC - Wave Energy Converter

WES - Wave Energy Scotland

Chapter 1 - Introduction

1.1. Research Context

The wave energy sector has the potential to be a major contributor to global renewable energy generation. It is estimated that ocean energy as a whole (i.e. wave, tidal current, tidal range etc.) could generate over 885 TWh/year globally from an installed capacity of 337 GW (Huckerby et al., 2012). Gunn & Stock-Williams (2012) estimate that up to 95GW of wave energy devices could be installed in the world's seas and oceans. At a national level, commercial deployment of wave and tidal energy devices could meet 15%-20% of the UK's electricity demand and could provide up to 16,000 jobs (DECC, 2010), with an installed capacity of between 30 and 50 GW (BEIS, 2013). Boud (2012) estimates that the total power capacity of wave energy projects in UK waters could potentially reach 13GW in the future. Scotland in particular has some of the greatest wave energy potential in Europe, with an average annual resource exceeding 60–70 kW/m in mid-depth locations (Lavidas, Venugopal & Friedrich, 2017). However, wave energy is still an early stage technology in comparison to other forms of renewable energy such as offshore wind and solar. The development of wave energy technology has also begun to lag behind that of tidal stream projects in recent years. There are a number of challenges to overcome before wave energy arrays become commercially viable projects.

One such challenge is the lack of certainty relating to lifetime costs of a wave energy array. This uncertainty makes wave energy projects less attractive to private investors. The Levelised Cost of Energy (LCOE) is a useful measure of the viability of projects. For the wave energy sector to attract private investment and succeed in becoming a commercial industry, it is vital that the inputs to LCOE calculations are obtained with more confidence. As shown in equation 1.1, operational expenditure (OPEX) plays a key role in calculating LCOE.

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{AEP_t}{(1+r)^t}} \qquad (1.1)$$

LCOE – Levelised Cost of Energy

CAPEX – Capital expenditure

$OPEX_t$ - Operational expenditure (in year t)

AEP_t – Annual electricity production (in year t)

r – Discount rate

n – Lifetime of the system (years)

t – year from start of project

It has been proven over the course of the commercialisation of the offshore wind industry that Operations and Maintenance (O&M) incurs significant expenditure for any offshore renewable energy development, with O&M costs accounting for approximately one fifth of the total costs of offshore wind farms (BVG Associates, 2013). Initial wave energy arrays are likely to require even higher levels of O&M, given that offshore wind is a much more advanced technology.

The fact that there are multiple types of wave energy converter (WEC) being considered and developed at present (Lewis et al., 2012), such as attenuator, point absorber and oscillating wave surge converter (EMEC, 2016a), makes estimating lifetime O&M costs difficult as developers of WEC technology have very little on which to base their assumptions. The task is made even more difficult due to the limited amount of real-sea experience gained by WEC developers. A cost effective method to estimate OPEX of a wave energy array is to build an O&M simulation model. An O&M tool not only has the benefit of estimating OPEX costs, but it can also provide feedback into the design of WECs by identifying those components and subsystems that have the biggest impact on lifetime profitability of a wave farm. An O&M model can also be used to analyse the impacts of different maintenance strategies, thereby ensuring smooth operation of a wave energy array. WEC developers often focus on performance and survivability of their devices, with O&M considerations coming into the design as an afterthought. Selecting the optimal approach to the O&M strategy, as well as implementing the necessary design changes required to achieve it, is fundamental to ensuring the long term economic benefits of a wave farm.

1.2. Industry Engagement

The research presented in this EngD thesis has been funded by the Industrial Doctoral Centre for Offshore Renewable Energy (IDCORE) in collaboration with three industrial partners over the course of the three year project; Pelamis Wave Power (PWP), Wave Energy Scotland (WES) and Albatern Ltd.

The research project was initiated by Pelamis Wave Power, with the Research Engineer starting at the company in June 2013. The company had the objective of bringing the Pelamis articulator-type WEC to the commercial market, thereby forming the basis for a wave energy industry in the UK. Formed in 1998, the company carried out successful deployment, retrieval and decommissioning of a full scale pre-production prototype device at the European Marine Energy Centre in 2004 (EMEC, 2016b). PWP also built the world's first wave farm, with three of the first-generation attenuator WECs deployed at Aguçadoura, off the coast of Portugal, in 2008 (Eco Green Globe, 2016). However, the project was short lived due to financial issues involving the primary investor. Despite this setback, PWP secured further funding to develop a second generation of Pelamis devices; the P2. Two P2 devices (Figure 1.1) were manufactured and deployed at EMEC (EMEC, 2016b). The two devices achieved over 11,000 hours of grid connected operation between 2010 and 2014. At the time, this made PWP the world's most advanced wave energy developer. A number of potential design improvements were identified over the course of the P2 testing programme. The third-generation of Pelamis device, the P3, was in the design phase when Pelamis Wave Power entered administration in November 2014 due to a lack of additional investment.

Figure 1.1. The two Pelamis P2 devices operating at EMEC in 2012 (Source: R.Ionides)

Wave Energy Scotland (WES) was set up by the Scottish Government in late 2014 (Scottish Government, 2014) and bought the assets of Pelamis Wave Power after the company entered administration. The EngD research project presented in this thesis was sponsored by WES from January 2015 until its completion.

Albatern Ltd. is a developer of wave energy technology based in Midlothian, Scotland. The company is the manufacturer and operator of its Squid device, a form of articulated WEC, several units of which can be connected together and deployed in a WaveNET array (see Figure 1.2). Formed in 2007, Albatern Ltd. have since carried out several sheltered-sea trials of their 6-series Squid device, such as testing at the Isle of Muck in 2014. The devices are intended to supply clean energy to fish farms and off-grid communities as a replacement for diesel generated power. Albatern is working towards developing a larger Squid device, the 12-series, to move towards grid connected WaveNET arrays. The research engineer was based at Albatern from March 2016 through to October 2016.

Figure 1.2. Albatern's 6-series WaveNET array being tested at the Isle of Muck, 2014 (Source: D. Findlay)

1.3. Prior Work

The work presented in this thesis builds upon an O&M model first created by Pelamis Wave Power in 2007. The O&M model was built for two key purposes. The first was to create a bottom-up process of estimating OPEX costs which could be applicable to future Pelamis devices. The second was to find the level of reliability that certain components needed to have in order for a Pelamis wave farm to achieve the required performance targets.

A Monte Carlo analysis is the fundamental principle of the O&M tool, where a random number is generated and compared with a value for probability of failure in order to simulate the occurrence of faults on a Pelamis machine. In the original model, all the components and subsystems of the Pelamis device were represented by sixteen different failure categories. Each category was assigned a failure probability, associated power loss, costs of repair and time required off site for repair. This process was achieved by carrying out a Failure Modes and Effects Analysis (FMEA), enabling each failure mode to contribute to the appropriate fault category or categories. Monthly statistical data was used to calculate weather windows and revenue. The model had an Object-Oriented Programming (OOP) structure and was built using spreadsheet software. A cost-benefit analysis was designed to simulate a decision making process of when to remove and repair faulty Pelamis devices. This reactive maintenance approach was accompanied by proactive scheduled maintenance. The user could define universal parameters such as the number of devices in the farm, the design lifetime and vessel hire cost. The results of the O&M model provided a breakdown of the operational costs, as well as availability and revenue of the farm, for every year and for every machine. Costs were also attributed to each fault category.

Chapter 3 of this thesis goes into much more detail about the algorithms and functionality of the O&M model. The tool has been modified significantly over the course of the EngD research project. A clear distinction is made between the original O&M model designed by Pelamis Wave Power (to be referred to as the ‘pre-EngD model’), and the work undertaken in this EngD.

1.4. Contribution to Knowledge

This EngD thesis makes the following contributions to knowledge in the field of operations and maintenance strategies for wave energy arrays:

- Detailed methodology of O&M modelling for wave energy arrays

- Identification of realistic weather conditions for undertaking marine operations on wave energy arrays

- Assessment of potential O&M strategies for commercially viable wave farms

- Inclusion of detailed aspects of O&M for wave energy arrays previously not presented, including labour considerations and vessel arrangements

- Realistic estimation of the OPEX for wave farms, both grid-connected and off-grid

- Identification of generic WEC components which will have the biggest impact on wave farm profitability

- Identification of the development steps required by a developer of WEC technology to achieve greater confidence in LCOE estimates

1.5. Aims of the Research

The motivation for the work presented in this thesis comes from the need to improve investor confidence in wave energy arrays in order for them to become commercially viable projects in the future. Wave energy is still in its infancy as a renewable technology, and will require private investment for it to become a commercial industry and rival the likes of the offshore wind sector.

The initial objective when the work was sponsored by Pelamis Wave Power was to review and upgrade their existing O&M simulation tool to derive realistic lifetime cost estimates for a Pelamis wave farm, utilising the real world experience gained during the P2 testing programme. Using this experience is vital as it is widely acknowledged that increased confidence in OPEX estimates can be obtained if the inputs to an O&M tool are device-specific. The enhanced model could then be used to test hypotheses relating to O&M strategy decisions and the potential improvements they could have on a Pelamis wave energy array. The tool could also be used to identify the development steps required to achieve the optimal O&M strategy for specific wave farms.

Finding realistic OPEX estimates and the optimal O&M strategy for Pelamis wave farms is no longer necessary due to the collapse of the parent company. However, Wave Energy Scotland recognise that the O&M simulation tool can still serve an important purpose in advancing the wave energy sector. The partnership with Albatern Ltd. seeks to build the O&M model around their WaveNET array. Therefore, the aims of the research presented in this project are threefold:

1. to provide a blueprint for building O&M models for wave energy arrays
2. to use an O&M tool to analyse strategy decisions that could be employed in future wave energy arrays

3. to identify the development steps required for achieving greater confidence in OPEX estimates for wave energy arrays

This thesis aims to make a significant contribution to the engineering knowledge that will enable the commercialisation of the wave energy sector. It is hoped that other wave energy developers will benefit from the detailed dissemination of O&M-related information from the Pelamis endeavour, as well as from the described methodology of creating an O&M simulation tool.

1.6. Content and Structure

In order to achieve the aims of the research, a systematic approach has been employed whereby a realistic O&M simulation tool has been created, followed by thorough analysis on model uncertainty and O&M strategies using case studies. This thesis is composed of six distinct chapters to address the issues of operations and maintenance strategies for wave energy arrays. These are represented graphically in Figure 1.3.

Chapter 1 has outlined the research questions that this thesis seeks to address and has provided details of the work’s funding bodies. The methods and justification of presenting the results in this thesis are also highlighted.

Chapter 2 provides a review of the literature and ongoing activities in the field of operations and maintenance across the offshore renewable energy sector.

Chapter 3 details the methodology of building an O&M simulation tool for wave energy arrays, and includes descriptions of the inputs, outputs and functionality of the model, justifying decisions made where appropriate.

Chapter 4 describes the inputs to the O&M tool that are specific to the Pelamis wave energy converter. The chapter explores different options for an O&M strategy that could be employed for a commercial scale wave farm, and assesses the merits of each using the results of the Pelamis-based O&M tool. A discussion surrounding the optimal O&M strategy for grid connected wave farms is given.

Chapter 5 follows the same structure as the previous chapter, but carries out the assessment using an Albatern-specific O&M model. The discussion focusses on strategies for off-grid, community-scale wave energy arrays.

Chapter 6 presents results of a series of sensitivity analyses in an effort to address areas of uncertainty within the O&M model. A sensitivity analysis of the failure rate inputs to the model will identify those components and subsystems within a Pelamis WEC that have the biggest impact on wave farm profitability. A discussion on how to increase confidence in OPEX estimates is provided.

The thesis then concludes with Chapter 7, where the main findings are discussed, including a comparison of grid-connected and off-grid wave energy arrays. Areas suitable for further investigation are also identified.

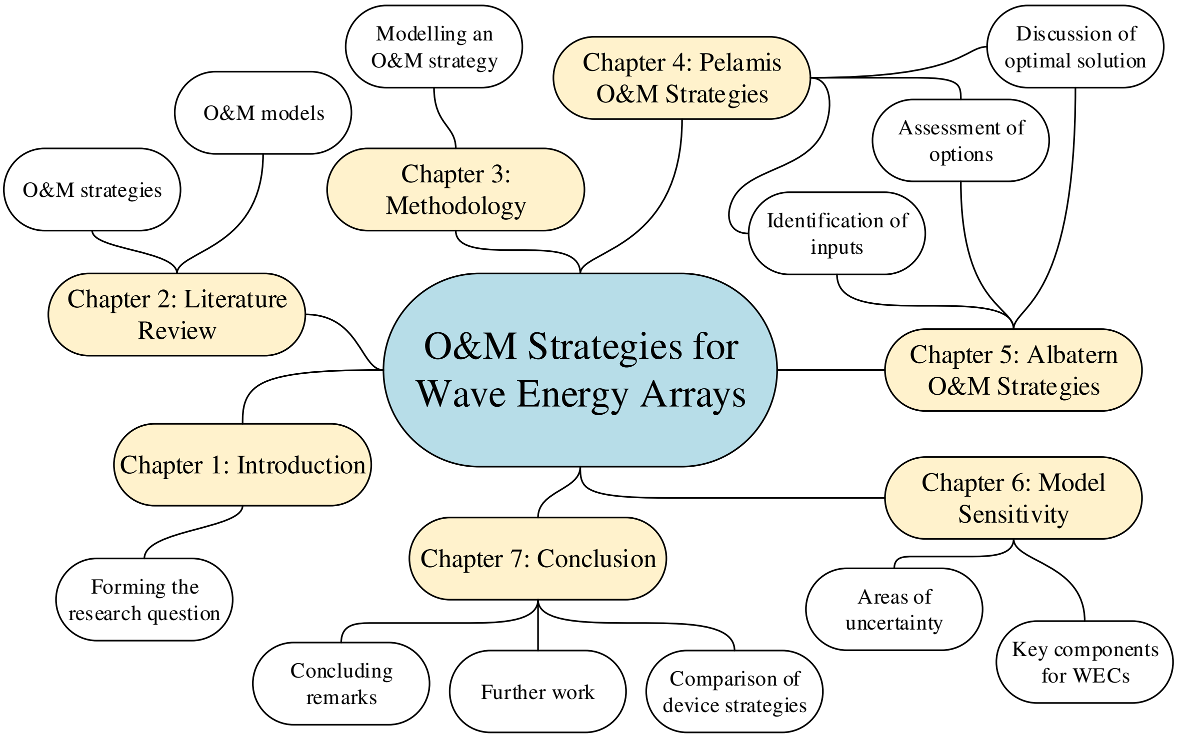


Figure 1.3. Thesis structure mind map

1.7. Presentation of Results

Key information in this thesis, particularly from O&M tool simulations, will be presented numerically and graphically in a number of different ways. This section will act as a reference for clarity.

1.7.1. Weather windows

A weather window is a given period of time when the sea and wind conditions do not exceed the limits placed on marine operations.

1.7.1.1. Average wait time

One method of assessing weather windows is by calculating the average time to wait; e.g. once a Pelamis WEC is ready to be installed, this is the average amount of time (in that month) the installation crew need to wait for weather conditions suitable for carrying out the marine operation. Average wait times for each month are calculated using the equation described by Martins, Muraleedharan & Guedes Soares (2015):

$$wait\ time = \frac{1}{P} - 1 \quad (1.2)$$

Where P = the probability of any window being 'open' in the given month

Where the thesis discusses seasons, this refers to the meteorological definition:

- Winter - December, January, February
- Spring - March, April, May
- Summer - June, July, August
- Autumn - September, October, November

1.7.1.2. Wait time charts

Another method of presenting the time required to wait for a weather window suitable for marine operations is by using persistence charts. These graphs are created using a time series of weather conditions. Firstly, the persistence of non-accessible weather conditions at each time step is calculated. The number of occurrences of each persistence time in every month of the year is then recorded, along with the total number of time steps in that month. This enables the probability of the non-accessible weather conditions not exceeding each cumulative period of time, up to a maximum of 30 days, to be calculated. The best way to interpret these graphs is by thinking in terms of weather wait times. For example, from Figure 1.4 it can be determined that there is approximately a 63% probability of having to wait less than 5 days for a 2m Hs weather window during the winter months at the given site.

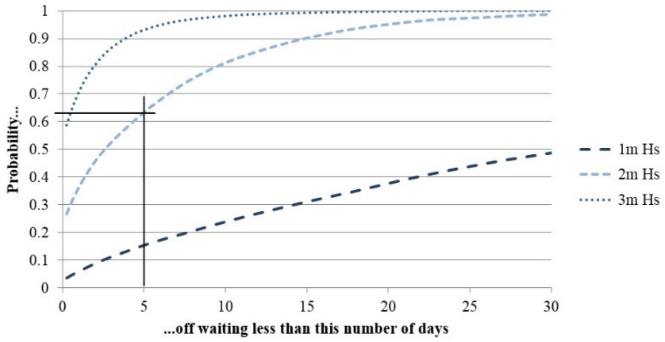


Figure 1.4. Example of a weather wait time graph for December-February

1.7.2. Availability, revenue and OPEX

The most useful results produced by the O&M model are in terms of wave farm availability, revenue and operational expenditure (OPEX). Availability is the average power capacity of all the WECs in the farm throughout the year; i.e. 100% availability would mean that there are never any failures and WECs do not undergo maintenance at any point. Revenue is the total amount of income generated by the wave farm from the sale of electricity, taking WEC downtime into account. OPEX is the total cost of maintaining the wave farm, including parts costs for repairs, labour, vessel fees and fuel, inspection costs and other expenses such as pilot fees. These parameters are usually presented as annual averages. By using these three parameters, the impact that any changes to the O&M strategies have on the wave energy arrays can be assessed critically.

1.7.3. Net operational income

A fourth parameter is used to present the outputs of the O&M model, described in the figures and tables of this thesis as ‘profit’. This value is calculated as simply the revenue generated by the array minus the incurred operational expenditure. The ‘profit’ does not account for other ongoing costs, such as site leasing fees, nor does it take capital expenditure into consideration. As such, the values of ‘profit’ presented in this thesis are better referred to as ‘net operational income’.

1.7.4. Confidence bounds

Several simulations are carried out using the O&M model for each analysis in this thesis. The mean values from these simulations are presented. The fact that WEC failures are simulated using a Monte Carlo analysis means that no two runs will ever be exactly the same. Therefore, where relevant, 95% confidence bounds are applied to the presented results. If the results are normalised then the confidence bounds are modified accordingly. Following the application of equation 1.3, it can then be said with 95% confidence that the true mean of the results lies within those boundaries.

$$95\%\ confidence\ bounds = \bar{X} \pm \frac{z * \sigma}{\sqrt{n}} \qquad (1.3)$$

Where a $\bar{X}$ = mean, z-value = 1.96 (for 95% confidence), σ = standard deviation, n = population size

The convergence study presented in Appendix A demonstrates that 50 simulations of the O&M model obtains mean results with a sufficiently low level of variance.

Chapter 2 - Literature Review

This chapter reviews the literature in the field of modelling operations and maintenance (O&M) for wave energy arrays, utilising research undertaken in more established sectors such as offshore wind. Section 2.1 provides a brief history of the development in the wave energy sector since the 1970s. Section 2.2 identifies the practices and techniques used in undertaking operations and maintenance on offshore renewable energy projects. Section 2.3 discusses the different methods of modelling operations and maintenance in the offshore wind industry, and identifies the efforts being made to develop similar tools and techniques for the wave energy sector. Section 2.4 explores the field of obtaining reliability data as an input to O&M simulation tools. Section 2.5 then reviews research undertaken in the field of accessing offshore renewable energy arrays for O&M activities.

2.1. Wave Energy Development

The challenge of harnessing the power of the waves to generate energy has considered by engineers for many decades. Some of the first articles on the potential of wave energy converters (WECs) were published following the global oil crisis in the 1970s. These include work by Salter (1974), Evans (1976), Mei (1976) and Budal (1977). One of the earliest WECs to be analysed was the ‘Edinburgh Duck’ (a.k.a. ‘Salter’s Duck’, Figure 2.1); a floating, gyroscope-based device designed by the Edinburgh Wave Power Group (Salter, Jeffrey & Taylor, 1976).

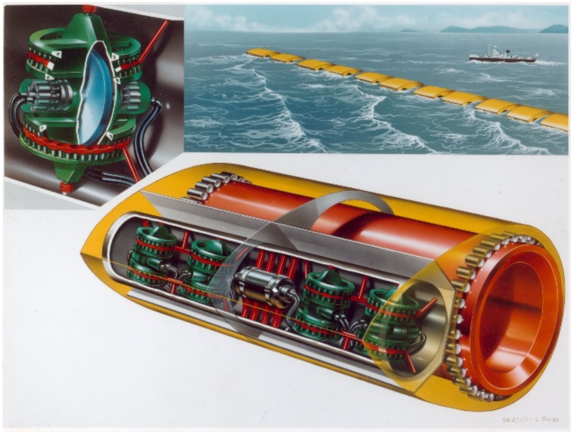


Figure 2.1. The 'Edinburgh Duck' wave energy device concept (Taylor, 2009)

Political interest in wave energy dropped as the North Sea oil and gas industry gained momentum (Baldwin & Power, 1988), resulting in the Edinburgh Wave Power Group being disbanded in 1982 (EMEC, 2015). By the 1990s, the issue of greenhouse gases and manmade climate change was becoming widely acknowledged (Oreskes, 2004), thereby re-engaging political will on the topic of renewable energy. One example of the resurgence of interest in wave energy is the construction of the onshore 'LIMPET' device (Figure 2.2) on the Scottish island of Islay in 1999, based on the oscillating water column principle (Whittaker et al., 1997). The Islay project demonstrated the benefits of onshore WECs, most notably ease of access, inspiring other projects such as the Mutriku power plant (Figure 2.3), contained within a breakwater in Northern Spain (Bahaj, 2011).

Figure 2.2. The Islay LIMPET wave energy device (Apland-Hitz, 2010)

Figure 2.3. Mutriku breakwater wave power plant (Ente Vasco de la Energía, 2017)

However, it was clear that the true potential of wave energy could only be exploited by moving WECs offshore. Following on from the work undertaken on the 'Edinburgh Duck', the 'Pelamis' wave energy converter (Figure 2.4) was developed as an offshore, floating, articulator-type WEC (Thorpe, 2004), with a hydraulic power-take off system (Henderson, 2006). This was the first in a new series of offshore WEC designs, including the flap-type 'Oyster' (Figure 2.5) developed by Aquamarine Power Ltd. (Folley, Whittaker & van't Hoff, 2007), AWS' 'Archimedes WaveSwing' (Polinder, Damen & Gardner, 2004) also shown in Figure 2.5, and the overtopping-WEC 'Wave Dragon' (Tedd, 2007) seen in Figure 2.6.

Figure 2.4. The 'Pelamis' WEC (Yemm et al., 2012)

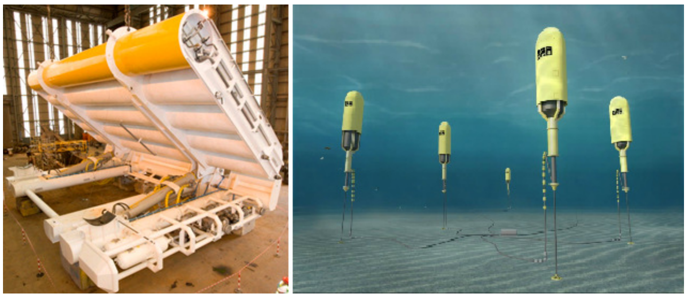


Figure 2.5. Left: Aquamarine's 'Oyster' WEC prior to deployment (Ramboll, 2010). Right: AWS' Waveswing WEC (AWS, 2017)

Figure 2.6. 'Wave Dragon' WEC (Tedd, 2007)

The 1990s and 2000s saw several different types of wave energy devices being tested at small scale, as well as in real sea environments (Falcão, 2010). Significant advances were made in terms of understanding the hydrodynamic behaviour of WECs in the marine environment, as well as in other areas such as estimating power capture (Borthwick 2016). However, the early part of this decade has seen several of the major companies in the sector go out of business, including Pelamis Wave Power Ltd. and Aquamarine Power Ltd. Interest in tackling the wave energy challenge is still strong, with governments around the world funding initiatives such as Wave Energy Scotland (Highlands and Islands Enterprise, 2016) and the Wave Energy Prize (EERE, 2017). A recent report by the European Commission (Magagna, Monfardini, & Uihlein, 2016) states that up to 37 MW of wave energy projects could be operational within the European Union (including the United Kingdom) by 2020.

In stark contrast, there was a total 14,384 MW of installed offshore wind projects globally by the end of 2016, with nearly 88% located off the coasts of European countries (GWEC, 2017). Therefore, a significant amount of experience in operating and maintaining wind turbines offshore has been accrued over recent decades, which can aid the development of wave energy. The wave energy sector is also falling behind tidal stream in terms of development, with major projects, such as the Meygen array in Scotland's Pentland Firth (Atlantis Resources Ltd., 2016), contributing to the estimated 71 MW of tidal stream projects to be operational by 2020 (Magagna, Monfardini, & Uihlein, 2016).

2.2. Operations and Maintenance

The operations and maintenance (O&M) phase of offshore renewable energy projects accounts for a significant part of the total lifetime costs. Experience in the offshore wind sector indicates that O&M costs account for approximately one fifth of the total costs of offshore wind farms (BVG Associates, 2013). Other estimates put the operational expenditure (OPEX) as high as 30% of the total lifecycle cost (Musial & Ram, 2010). In 'The economics of wave energy: A review', Astariz & Iglesias (2015) state that this proportion of OPEX relative to total lifecycle costs is likely to also be seen in wave energy arrays.

2.2.1. O&M in Other Industries

The oil and gas sector has built up several decades of experience in operating and maintaining mechanical equipment, subsea electrical cables and mooring lines offshore. The majority of the mechanical pieces of equipment on oil and gas rigs are located on the platforms themselves, such as pumps and heat exchangers (Telford, Ilyas Mazhar & Howard, 2011). Such components can therefore be accessed easily by the technicians living and working on the platform. Other components, such as mooring lines, lie beneath the water surface and were historically accessed by divers. As the oil and gas sector developed and platforms moved into deeper water, other alternatives for undertaking subsea maintenance tasks were required (Webb, 1981). This led to the enhancement of technology such as Remote Operated Vehicles (ROVs, Figure 2.7) so that the use of divers could be phased out (RovMarine Technologies, 2017), thereby greatly reducing the health and safety risks involved. Personnel transit to and from offshore oil and gas platforms is commonly undertaken with the use of helicopters (Silva, Martins & Bahiense, 2014).

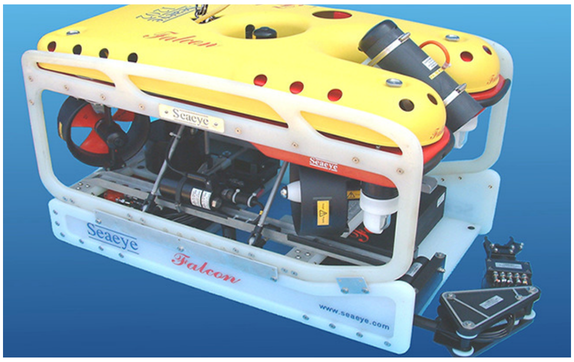


Figure 2.7. A Remote Operated Vehicle (ROV) (RovMarine Technologies, 2017)

The experience that the oil and gas sector has built up in the field of operations and maintenance translates directly to the offshore wind industry. For example, jack-up vessels which were first developed as shallow-water oil and gas platforms (Scot Kobus & Fogal, 1989) are now used extensively for installation of offshore wind turbines, as well as for major O&M activities such as blade replacement (Dalgic et al., 2015). ROVs are used in the offshore wind sector for O&M activities such as foundation inspections (Taylor, 2013). Helicopters are also utilised for far-offshore wind farms (GL Garrad Hassan, 2013).

Other aspects of operating and maintaining offshore wind turbines have been transferred from the onshore equivalent. This includes personnel being able to gain access to the inside of the nacelle, thereby being able to undertake repairs and inspection in a relatively sheltered environment (Figure 2.8).

However, there are clearly greater challenges in accessing wind turbines located offshore rather than on land (Scheu et al., 2012). Onshore turbines can be accessed by car for minor repairs and inspection, or even helicopter in the case of large wind farms, whilst some major repairs only require the use of readily available mobile cranes (Bertling-Tjernberg & Wennerhag, 2012). When the turbines are placed offshore, marine vessels must be used and weather conditions have a much more significant role in determining accessibility. These aspects lead to the increased operational expenditure of offshore wind farms. On the other hand, technology advancements in recent years have seen the size of wind turbines increase dramatically, as stated by Ederer (2014), meaning that a well-run offshore wind farm could offer substantial financial returns to investors.

Figure 2.8. Technician inside the nacelle of a wind turbine (www.alamy.com)

Several innovative techniques and new pieces of equipment have been developed solely for operations and maintenance of offshore wind farms. One example is the fenders attached to the base of monopile offshore wind turbines (Figure 2.9) which allow technicians to reach the access ladder. Further research is going into motion-stabilising gangways to make this access method safer for the personnel involved (Guanche et al., 2016). Wind farms are now being developed even further offshore requiring more complex O&M strategies to be planned, such as ‘mother ships’ (i.e. vessel-based technician accommodation), offshore storage of spare parts and advanced condition monitoring systems (Maples et al., 2013).

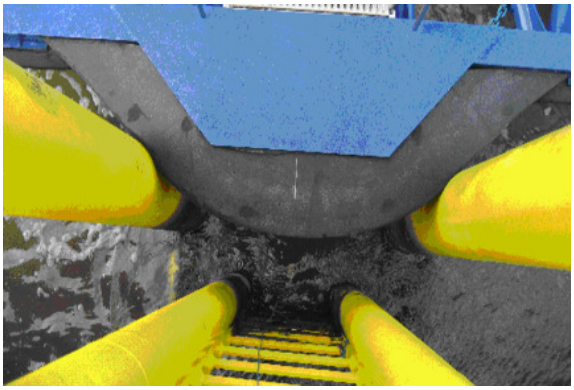


Figure 2.9. Top view of small service vessel engaging with fenders on an offshore wind turbine (Wu, 2014)

2.2.2. Wave Energy O&M

Understanding the development of operations and maintenance in offshore wind farms is vital when considering marine energy arrays (wave and tidal), as many of the techniques and strategies are directly applicable.

The tidal stream sector has gained significant experience in installing, operating and maintaining devices offshore in recent years. Projects include the OpenHydro device (OpenHydro, 2017), Alstom's TGL turbine (EMEC, 2017) and Tidal Energy Ltd's DeltaStream technology (TEL, 2017). All three devices required the use of a heavy-lift vessel, similar to those used in offshore wind, for installation and retrieval. This method is also being used at the ongoing Meygen array in Scotland's Pentland Firth, where four turbines have been installed (Atlantis Resources Ltd., 2016). Segura et al. (2017) identify the significant cost of these specialist vessels as a potential barrier to the economic viability of tidal stream projects. Other developers of tidal stream technology seek to reduce the operational expenditure by utilising cheaper workboats. One example is the seabed-fixed, surface-piercing Marine Current Turbines device tested in Northern Ireland's Strangford Narrows in 2008 (MCT, 2017a). The turbines could be raised out of the water enabling maintenance to be carried out onsite using small, low-cost vessels (MCT, 2017b). Two examples of using low-cost vessels to retrieve a tidal energy converter in order to undertake repairs and inspection offsite (i.e. at a sheltered or onshore O&M base) are Sustainable Marine Energy's Plat-o technology (SEM, 2017) and ScotRenewables' SRTT device (ScotRenewables, 2017). In both cases, the main body of the device is buoyant and can therefore be towed easily using readily available workboats, such as the multicat vessel shown with the SRTT device in Figure 2.10.

Figure 2.10. ScotRenewables Tidal Turbine (SRTT) installation (www.greenmarineuk.com)

Maintenance of onshore or breakwater-based wave energy converters, such as LIMPET (Figure 2.2) and Mutriku (Figure 2.3) is relatively straightforward, as access is rarely limited by adverse weather conditions (Whittaker et al., 1997). The mechanical components can be repaired without needing a vessel (in most cases), as can inspections of structural and civil works, thereby reducing downtime of the devices. Major repairs can be undertaken with readily available mobiles cranes, thus minimising OPEX costs (Mustapa et al., 2017). Clearly, the operational expenditure of onshore WECs will be lower than the offshore equivalent, following the trends of the wind energy industry.

Several lessons on operating and maintaining wave energy arrays can be taken from the more advanced offshore wind sector. This includes the application of condition-based monitoring systems to identify failures (Mérigaud & Ringwood, 2016), as well as the importance of minimising operational expenditure as a means of improving the economic viability of projects. Many of the WEC concepts studied in recent years involve a floating or buoyant design with the maintenance strategy being to undertake repairs and inspections offsite. This is true of the Pelamis articulator-type WEC (Figure 2.4), Carnegie Clean Energy's CETO heaving-buoy device and Wello Oy's rotating-mass Penguin machine (Figure 2.11). Low-cost multicat vessels as shown in Figure 2.10 were used to install and retrieve all three devices. This is widely acknowledged as the best method of accessing wave energy converters, with even previously seabed-fixed WECs changing their design to incorporate the low-cost vessel approach (see Figure 2.12). Downtime can be reduced with WECs that can be easily accessed for maintenance (Davidson, 2012).

Figure 2.11. Left: Carnegie Clean Energy's CETO wave energy device (www.carnegiewave.com). Rght: Wello Oy's Penguin wave energy device (www.wello.eu)

Figure 2.12. Left: Oyster 1 installation using a jack-up barge. Right: Oyster 800 under tow by a multicat vessel for installation (Davidson, 2012)

2.3. O&M Simulation Tools

Creating simulation tools to estimate operational expenditure (OPEX) and optimise the maintenance strategy of offshore renewable energy projects plays a vital role in driving down the cost of these technologies, which is currently far greater than the cost of energy produced by coal or gas-fired power stations (DECC, 2013a). The wave energy sector has benefitted from the lessons learnt in the offshore wind industry with regards to practical offshore O&M techniques. The experience gained in offshore wind in the field of modelling O&M strategies can also be utilised by the wave energy sector.

2.3.1. Offshore wind models

Hofmann (2011) found that there is a plethora of O&M models in the offshore wind industry which have been developed by many different organisations within the last 20 years. This section highlights the techniques used in some of the offshore wind O&M models which are available or described in the public domain. O&M models have also been developed for analysing onshore wind farms, such as that presented by Poore & Walford (2008). However, only those developed for offshore wind farms are discussed here, due to the clear applicability to the wave energy sector.

Some of the earliest work into the field of analysing O&M for offshore wind farms was undertaken by Van Bussel & Schöntag (1997) at Delft University of Technology in the Netherlands. This paper presented a Monte Carlo approach to simulate the occurrence of faults on an offshore wind farm, utilising limited failure rate data obtained from onshore turbines. Weather conditions were incorporated stochastically. The work was developed further to become the CONTOFAX model (Van Bussel, 1999 and Van Bussel & Zaaijer, 2001). The model was used to analyse different access methods of offshore wind farms, as well as the consequential effects on OPEX, as described by Van Bussel & Bierbooms (2003). The tool is a discrete-time model with a resolution of one hour.

A similar model to CONTOFAX is the ECN O&M Tool developed at the Energy Research Centre of the Netherlands and is described by Eecen et al. (2007). The tool was utilised by Van Der Pieterman et al. (2011) to explore the optimisation of O&M strategies for offshore wind farms. The ECN O&M Tool uses similar modelling principles as the CONTOFAX model, as shown in Figure 2.13, with some key differences. Rademakers et al. (2003) compare the two models, describing how the ECN O&M Tool is more deterministic than stochastic, particularly with regards to weather window assessment. Both tools incorporate a probabilistic element in terms of characterising failure behaviour of wind turbine components, as described by Koutoulakos (2008).

A commercial tool for analysing O&M strategies in offshore wind farms is the O2M model developed by DNV GL, as used by Phillips, Morgan & Jacquemin (2006). The O2M model was also used to investigate serial failures in offshore wind farms by Redfern & Phillips (2009). Only a reactive maintenance strategy is modelled in the O2M tool, without incorporating the scheduled inspection activities which occur in real life. The flexibility of the O2M model, and indeed the applicability of offshore wind tools to other forms of marine energy, is demonstrated by Smith, Thomson & Whelan (2010) with the analysis of a tidal stream array. As with many commercial software tools, the O2M model is not available in the public domain. Another example is the O&M model developed for Iberdrola, which also incorporates electrical array layouts, as described by Hofmann et al. (2011).

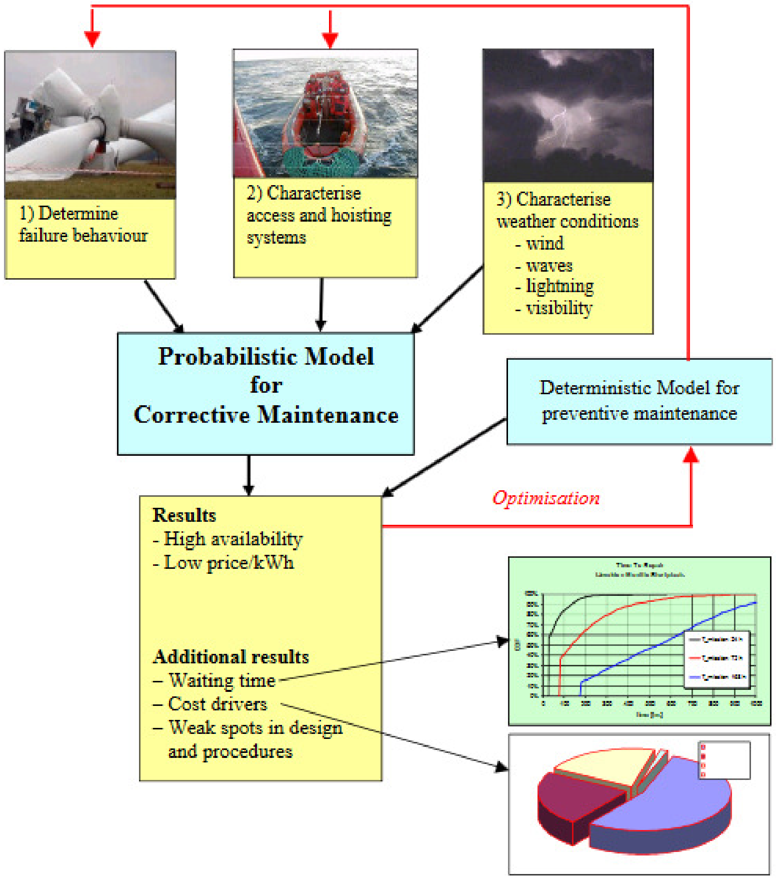


Figure 2.13. Approach for modelling and optimising O&M strategies of offshore wind farms (Rademakers et al., 2003)

The review of offshore wind O&M simulation models undertaken by Hofmann (2011) resulted in the development of the NOWIcob tool at the SINTEF Energy Research Centre in Norway. Hofmann & Sperstad (2013) describe the tool as a holistic means of estimating and 'reducing the maintenance costs of offshore wind farms', in that it incorporates aspects of meteorology, reliability, power production and economics. It is a discrete time-based model with stochastic elements of weather representation and failure simulation. Hofmann & Sperstad (2013) highlight the option to model failure rates flexibly with a Weibull distribution as a key attribute which distinguishes NOWIcob from other offshore wind O&M tools.

Another well-documented O&M tool for offshore wind farms has been developed at the Wind Energy CDT at the University of Strathclyde, based on a probabilistic climate model (Feuchtwang & Infield, 2013). Dinwoodie et al. (2013) describe the O&M tool as utilising Weibull distributions, Bayesian belief networks and Monte Carlo simulations to model the lifecycle logistics of an offshore wind farm as realistically as possible. The Wind Energy CDT O&M model is utilised for the offshore wind farm analysis described by Dalgic, Lazakis & Turan (2015) and

Dalgic et al. (2015). Dinwoodie et al. (2015) identify that obtaining sufficient reliability data is vital in order to increase the confidence in outputs of offshore wind O&M simulation tools.

The O&M simulation tool developed at the University of Stravanger in Norway is another discrete time-based model, as described by Van Endrerud, Liyanage & Keseric (2014). The modelling approach is similar to the NOWIcob and Wind Energy CDT tools described previously. The key difference is the incorporation of a synthetic time series of weather conditions generated with a Markov Chain process (Hagen et al., 2013).

Many of the O&M tools developed for the offshore wind industry are difficult to validate due to the lack of failure rate data available in the public domain (Dinwoodie et al., 2015). Large utility companies have now achieved a significant amount of operational experience in the offshore wind sector. One example is the EDF Group, where the ECUME tool for analysing O&M aspects of offshore wind farms has been developed. Douard, Domecq & Lair (2012) state that the ECUME tool is based on the ECN O&M cost model (i.e. with the same principles shown in Figure 2.13), whilst benefiting from the experience the organisation has gained in the offshore wind industry. Martin et al. (2015) and Martin et al. (2016) make use of the ECUME tool by analysing the key factors in operating an offshore wind farm successfully.

In reviewing the literature in the field of O&M modelling of offshore wind farms, the following conclusions can be drawn:

- Models are created using a range of computer languages, but many use Microsoft Excel or Matlab.
- Monte Carlo simulation of failures is the standard
- Development is improving with regards to modelling failure rates (e.g. Weibull, Bayesian) and maintenance tasks, as more data is made available
- Validation of tools is now becoming possible

2.3.2. Marine Energy Tools

Whilst there are a large number of O&M models in existence for the offshore wind industry, there are a limited number of fully functioning tools in the wave and tidal sector. Known O&M simulation tools for marine energy are summarised in Table

2.1. Other methodologies have been used for estimating operational expenditure incurred by future wave energy arrays. These include taking OPEX to be a percentage of capital expenditure (CAPEX), as demonstrated by O'Connor, Lewis & Dalton (2013a). Another example is the top-down approach incorporated into the ExceedenceFinance tool (www.exceedence.com), developed following a wave energy feasibility study by Dalton, Alcorn & Lewis (2010). Discrete time-based models clearly offer a significant advantage over such methods in terms of obtaining more realistic lifecycle cost estimates.

Table 2.1. Known simulation tools for analysing OPEX and O&M strategies for wave and tidal arrays

Model Name	**Organisation**	**Currently in Development?**	**Reference**
'Availability model'	Aquamarine Power Ltd.	No	Abdulla et al., 2011
DTOcean	Various (European Project)	Yes (open source)	Teillant et al., 2014
Mermaid	Mojo Maritime	No	Morandeau et al., 2013
O2M	DNV GL	Yes	Smith, Thomson & Whelan, 2010
'Simulation tool'	Wave Star	Unknown	Ambühl et al., 2015
'Techno-Economic Model'	CorPower Ocean AB	Yes	De Andres et al. 2016

The techno-economic model for the CorPower Ocean WEC uses two approaches to incorporate OPEX into calculations of Levelised Cost of Energy (LCOE), as described by De Andres et al. (2016). The first approach simply takes OPEX to be a percentage of CAPEX (8% in the case study). The second method is a top-down approach of estimating the real cost of repairs throughout the lifecycle of the WEC. This is based on assumptions of one major repair being undertaken every two years but does not take more detailed component failure rates into account. The authors concede that this approach to estimating OPEX is 'partially inaccurate' due the uncertainties involved and state that future studies will incorporate a Monte Carlo analysis.

As previously discussed, the O2M model was originally developed by DNV GL for analysing offshore wind farms (Phillips, Morgan & Jacquemin, 2006). It was used to analyse a hypothetical tidal stream array in Scotland's Pentland Firth by Smith, Thomson & Whelan (2010). The tool undertakes time domain Monte Carlo simulations, utilising reliability data in the form of Mean Time Between Failure (MTBF) of single turbines. The simulations do not extend to the component level, meaning that if a failure is simulated to have occurred then the turbine ceases to operate and is set to be repaired. Marine operations are constrained in the tool using the parameters of significant wave height (Hs) and tidal current speed. The maintenance strategy of the O2M model sees the faulty turbine get retrieved once accessible weather conditions are found (in a modelled harmonic time series), thereby allowing repairs to be undertaken at the O&M base. Vessel crews and technicians are assigned shift working hours and operations are limited to daylight hours only. As well as describing the O2M tool, the initial analysis by Smith, Thomson & Whelan (2010) indicates that the strategy of having spare devices at the O&M base ready for rapid replacement of faulty machines could be a viable option for tidal stream arrays. Outputs of the O2M model include costs of lost production, cost of service crews and average price per repair.

The Mermaid tool (Marine Economic Risk Management Aid - Mojo Maritime, 2016) has been developed by Mojo Maritime (now part of James Fisher and Sons plc) following research into weather windows for marine operations undertaken by Walker, Johanning & Parkinson (2011). The tool was used by Morandeau et al. (2013) to investigate the optimisation of a tidal stream array installation procedure. Whilst Mermaid is not designed to estimate OPEX of marine energy projects, it offers a detailed method of planning marine operations, which is a vital part of O&M simulation tools. This is demonstrated by Rinaldi et al. (2016), where the Mermaid operations planning software is implemented into an O&M model with the focus on the Pelamis P1 wave energy converter. The authors admit that the O&M model could be improved substantially once better reliability data and operational experience can be accessed.

The DTOcean project has been funded by the European Commission and has been a collaboration between 18 partners spread across 11 European nations

(DTOcean, 2016). The project has produced an open source suite of software tools intended to allow developers of marine energy technology to plan and optimise their arrays. One of the five work packages involved in the project focusses on lifecycle logistics of the array (DTOcean, 2014) and is described by Teillant et al. (2014) and Teillant et al. (2015), following earlier work by Teillant et al. (2012). Operations and maintenance is incorporated into the lifecycle logistics package with a detailed and complex top-down modelling approach. The studies state that the inputs to DTOcean should be reviewed and upgraded as the marine energy sector matures and gains more operational experience, thereby obtaining results with greater confidence. Another key message from Teillant et al. (2014) is that incorporating a reliable estimator of weather windows into lifecycle analysis tools is of significant benefit to the sector.

Two studies have been found that use O&M simulation tools for specific wave energy converters, created in close collaboration with the companies developing the devices. An O&M model built for the nearshore, flap-type WEC, ‘Oyster’ (Figure 2.14), developed by Aquamarine Power Ltd., is described by Abdulla et al. (2011). It uses failure rate estimates for the offshore components of the Oyster WEC and undertakes a Monte Carlo analysis to simulate device faults. The study assesses the availability (but not costs) of a 3-Oyster array for a series of different strategy considerations, such as being able to undertake diving operations at night. Aquamarine Power entered administration in October 2015. Ambühl et al. (2015) use an O&M tool to explore several different O&M strategies for the Wavestar device (Figure 2.15), a fixed offshore structure with ‘floater’ arms to generate electricity, and presents the results in terms of total lifetime repair costs. The study translates failure rate data from the offshore wind industry to incorporate a ‘damage model’ into the analysis, where fatigue of the structural components is taken into account. Only two failure modes are incorporated into the report; the ‘floater’ arms and the generator system housed within the structure. Wavestar announced in June 2016 that the 110kW prototype device was to be scrapped (Renews, 2016). In both studies, the authors concede that the tools are extremely sensitive to the inputs, failure rate estimation in particular, and agree that more real-sea experience by WEC developers would substantially increase confidence in the model outputs. Neither study uses a holistic analysis to include aspects such as labour requirements, nor does either model analyse a wave farm where the entire WEC can be removed from the offshore site and taken to the safety of a sheltered harbour for repairs and inspection.

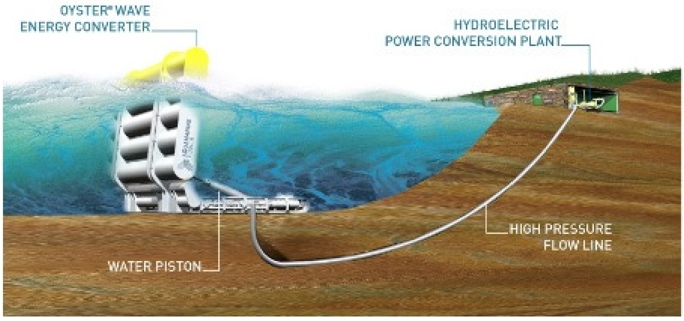


Figure 2.14. Principle of the Oyster WEC (Rühlicke & Haag, 2013)

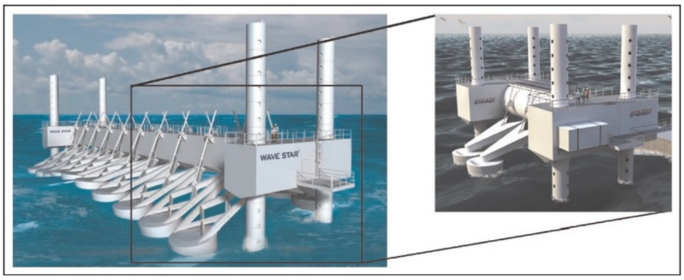


Figure 2.15. Wavestar design concepts (Ambühl et al., 2015)

2.4. Reliability Data

One of the key inputs required to obtain realistic estimates and scenarios from an O&M simulation tool is failure rate data. Early studies by Van Bussel (1999) and Van Bussel & Zaaijer (2001) attempted to estimate availability and OPEX of offshore wind farms by assuming the same failure rates as onshore wind turbines.

Confidence is now growing in the estimates for offshore wind farms due to the increasing amount of operational data available to both academics and industrial researchers. This is demonstrated in a study by Carroll, McDonald & McMillan (2015) where a population of over 2,000 wind turbines was used to assess the reliability of different generator types. Hameed, Vatn and Heggset (2011) recognise the need to develop a common reliability database for offshore wind turbines in order to find optimal O&M strategies for commercial arrays. Such calls have led to the creation of the SPARTA (System Performance, Availability and Reliability Trend Analysis) project; ‘a database for sharing anonymised offshore wind farm performance and maintenance data’ (ORE Catapult, 2016). SPARTA was inspired by the OREDA handbook, first created in 1981, which has contributed to improved safety and cost effectiveness in the oil and gas industry (OREDA, 2015). A similar reliability database for wave energy is not possible at present, in part due to the large variety of WEC concepts currently being explored, as well as the significant lack of operational experience in the sector.

Thies, Flinn & Smith (2009) discussed the challenges facing the wave energy sector in terms of obtaining reliability data. The study looked at well-understood reliability approaches from other industries (i.e. aviation, oil & gas), such as reliability block diagrams and fault tree analyses, and identified that the lack of data is a significant barrier to such methods being applied to the wave energy sector. The study asserts that, whilst some components will be procured alongside manufacturers' specifications (e.g. Voith, 2016), crude adjustments need to be made to account for the fact that they are operating with different loads and in a different environment to their designed application. Destructive testing on generic components, such as the work undertaken by Weller et al. (2014) on mooring lines, is an extremely useful activity for reducing the uncertainty in WEC failure rates, with a detailed testing procedure laid out by Thies, Johanning & Smith (2011). However, many other WEC components are device-specific and therefore require testing to be undertaken by the developer themselves. Such testing can be time consuming and expensive, making it unattractive to WEC developers with tight financial constraints (Wolfram, 2006). As a result, destructive testing is usually only appropriate for key components such as hydraulic ram cylinders, as demonstrated for the Oyster WEC by Rühlicke & Haag (2013). In reality, the best source of reliability information at this early stage of the wave energy sector's development is real sea testing combined with the expert judgement of the engineers involved. There is a significant amount of uncertainty surrounding failure rates obtained in this manner and this needs to be accounted for when used in O&M tools for estimating OPEX and availability of a wave farm.

Many of the existing tools for modelling O&M in offshore wind farms take component failure rates as constant values throughout the project lifetime (e.g. Van Bussel, 1999, Van Bussel & Zaaijer, 2001, Phillips, Morgan & Jacquemin, 2006 and Douard, Domecq & Lair, 2012). Thies, Smith & Johanning (2012) discuss that this method ignores both early 'infant mortality' failures and end-of-life degradation 'wear' of components. Hofmann & Sperstad (2013) built a Weibull distribution into the NOWIcob O&M tool as a means of better representing the failure behaviour of offshore wind turbine components. The increasing amount of operational data of offshore wind farms means that the consequential 'knock on' failures can now also be considered, as addressed by Dawid, McMillan & Revie (2015) with a Markov Chain approach. Thies, Smith & Johanning (2012) suggest that, whilst such complex modelling of failure behaviour for WECs is difficult at present due to the lack of data, a Bayesian methodology could be employed in order to refine initial estimates as more experience is gained.

2.5. Weather Windows

Another major input required to make an O&M simulation tool as realistic as possible is weather information. This is primarily used to evaluate the weather windows for the array; periods when the devices can be accessed by vessels and maintenance crew. In their availability study for the Oyster device, Abdulla et al. (2011) use significant wave height only for defining weather windows but concede that realistic limits on operations are also dependent on wave period and wind speed. O'Connor, Lewis & Dalton (2013b) state that the weather conditions defining these windows generally come through operator experience as well as vessel specifications. A study by Walker et al. (2013) assesses weather windows for marine energy devices and makes it clear that O&M tasks for a wave farm should be scheduled for periods when accessibility is highest and expected revenue is at a minimum. However, this may not always be possible due to unexpected failures. Walker et al. (2013) also acknowledge that, whilst significant wave height tends to be the defining factor, marine operations can also be constrained by wave period, wind speed, tidal current and tidal elevation. Any weather data used as an input to an O&M tool should provide sufficient seasonal variability to enable calculations of detailed weather windows and power output in order to carry out a full analysis of OPEX costs, farm availability and revenue.

Commercial tools are available for complex planning of marine operations. These include Mermaid (discussed previously), as well as the ForeCoast Marine tool developed by JBA consulting. In addition to forward planning of operations, ForeCoast Marine also offers a real-time mode in order to reduce the risk when undertaking vessel operations in the marine environment (JBA Consulting, 2015).

Chapter 3 - Methodology

This chapter details the methodology of the O&M model used for the work presented in this thesis. A generic O&M model is described which can then be tailored to a specific wave energy converter in order to achieve more realistic results. Section 3.1 provides an overview of the O&M model functionality and coding structure. Section 3.2 describes the inputs to the model in detail and provides justification for decisions made. Section 3.3 details the functionality of the generic O&M model, before section 3.4 highlights the outputs obtainable from the tool. Section 3.5 summarises how the model can be modified to suit specific WECs.

3.1. Model Overview and Coding Structure

Corrective maintenance falls into two distinct categories; i) *reactive* or *unscheduled* maintenance, and ii) *proactive* or *scheduled* maintenance (GL Garrad Hassan, 2013). The O&M model accounts for reactive maintenance by using a Monte Carlo analysis to simulate the occurrence of faults on a wave energy device. This involves generating a random number at each time step and comparing it to probabilities of failure. Proactive maintenance is included by having scheduled periods in which to undertake routine servicing and inspections. The user interface allows parameters defining the wave energy array, such as design lifetime and number of wave energy converters (WECs), to be changed for different simulations. Revenue and accessibility are modelled with the inclusion of weather data. The model provides a ‘bottom-up’ means of estimating the operational costs of wave energy arrays, identifying device design changes and optimising O&M strategy planning.

The O&M model operates by taking information stored in Excel spreadsheets and processing the data in Visual Basic for Applications (VBA). The model interface consists of a primary ‘Inputs’ spreadsheet with tables detailing potential failures and scheduled maintenance tasks, as well as other spreadsheets for aspects such as workforce arrangements and vessels available for the array. These parameters allow the array to be defined and are used to constrain operations, thereby dictating the O&M strategy. The processing methodology of the model occurs in VBA and is of an Object-Oriented Programming (OOP) nature. This allows the model to undertake a series of processes at every time step for each year of the array lifetime. Output data is calculated throughout the model processing and the information is printed in a clear way on spreadsheets. A flowchart of the model structure can be seen in Figure 3.1.

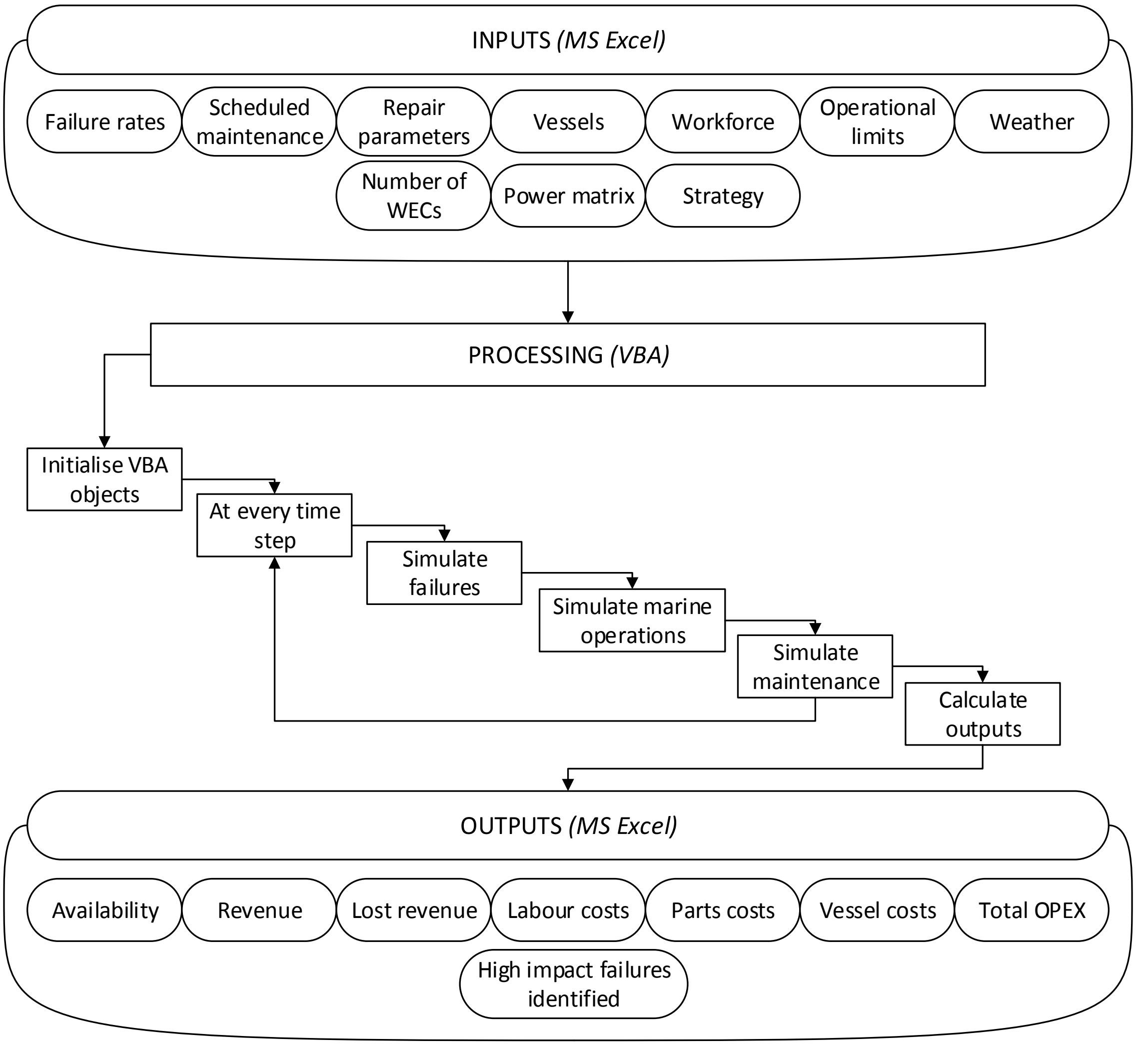


Figure 3.1. O&M Model Structure

3.2. Model Inputs

3.2.1. Failure rate information

In order for the Monte Carlo analysis to be used, the O&M model requires estimates of probability of failure for the components of the WEC under analysis.

This probability of failure is known as *unreliability*. Failure rate data can be obtained in a number of different formats, most notably; annual failure rate, mean time between failures (MTBF) and mean time to failure (MTTF). Failure rate data obtained in different formats can be compared using the following equations:

$$\lambda = \frac{T_f}{t} \tag{3.1}$$

$$MTBF = \frac{1}{\lambda} \tag{3.2}$$

$$F = 1 - e^{-\lambda} \tag{3.3}$$

$$R = 1 - F \tag{3.4}$$

$$F_x = 1 - R^{\frac{1}{N_x}} \tag{3.5}$$

Where:

λ = annual failure rate

T_f = total number of expected failures in design lifetime

t = design lifetime

F = annual probability of failure

R = annual reliability (i.e. probability of not failing)

F_x = probability of failure in time step ‘x’

N_x = number of time steps ‘x’ in a year

A wave energy converter may consist of many hundreds of different components. It is unfeasible to apply the Monte Carlo analysis to each component due to the unacceptable computational time required. Instead, the WEC components can be grouped into fault categories representing the main engineering aspects of a wave energy machine; hydraulics, moorings, structural and electrical. The fault categories also represent the severity of component failure, in terms of cost and time to repair, and are therefore classed as major, intermediate or minor. Data communication components, such as GPS systems, are placed in their own category due to their importance for array safety and fault detection. Figure 3.2 shows thirteen generic fault categories, however, these can be tailored to fit the engineering design of a particular WEC.

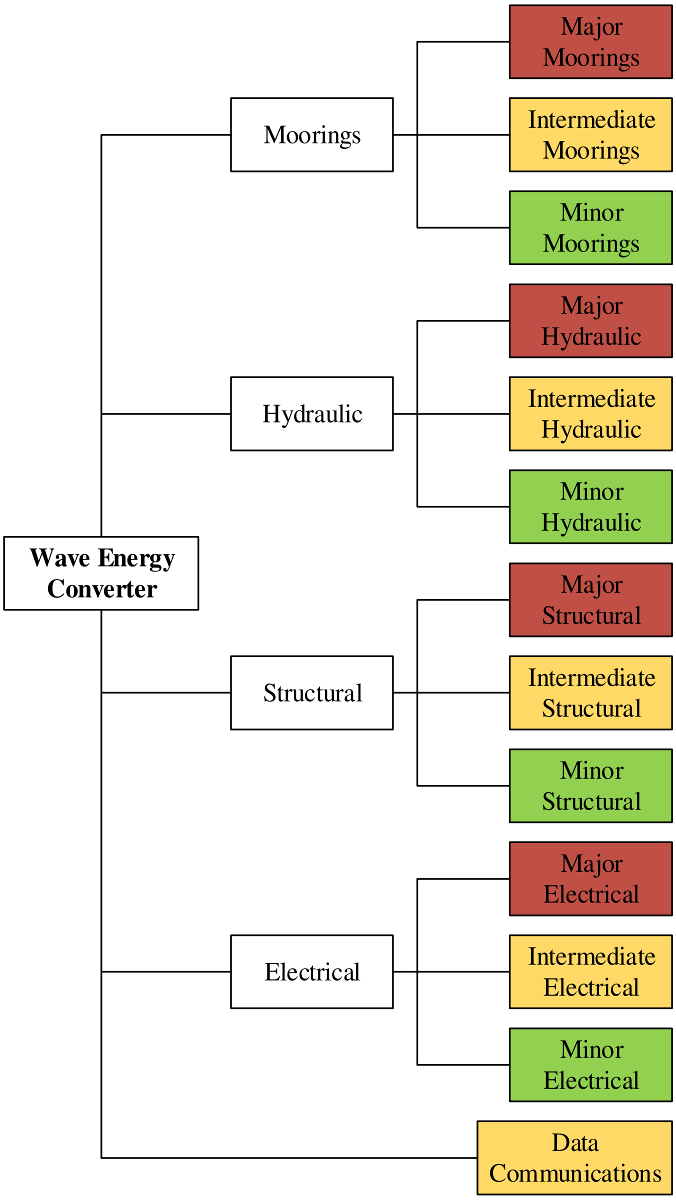


Figure 3.2. Generic fault categories for the O&M model showing classification (red = major, yellow = intermediate, green = minor)

The method of grouping components into these categories means that the best way of obtaining failure rate data for a wave energy converter is by undertaking a Failure Modes and Effect Analysis (FMEA). This design process involves listing all the possible failure modes within a system and evaluating each one in terms of likelihood and consequence in order to identify priority areas that require redesign or mitigation in an effort to reduce risk. It is a well understood process and will be carried out by wave energy developers during the device design stage. This makes it an attractive method of obtaining input data for an O&M model, rather than carrying out extra activities that may be unnecessary, such as creating reliability block diagrams. Each failure mode is placed into a probability band, from very low to very high, for both likelihood and consequence. Expert judgement is used throughout this process, but can be supported by other sources such as reliability handbooks (e.g. US Department of Defense, 1991). The severity bands can be used to determine the classification of component failures. The likelihood bands enable initial estimates for probability of failure for each component to be obtained. From this information, the annual probability of failure for each fault category is calculated using equation 3.6.

$$F = 1 - \prod_{i-1}^{n} Ri^{N_i} \quad (3.6)$$

Where:

F = annual probability of failure of fault category

i = single component i in fault category

n = number of components in fault category

R_i = annual probability of no failure (i.e. reliability) of single component i

N_i = total number of component i in WEC

This method of using fault categories in the O&M model (as opposed to using the full list of failure modes) means that future WEC design changes do not require major modification to the O&M tool, enabling the results to be compared directly in a rapid and efficient manner. The values for probability of failure remain constant throughout the lifetime of the simulated wave farm, as illustrated by the 'bathtub curve' in Figure 3.3. It is assumed that early 'infant mortality' failures are identified and dealt with during the commissioning phase prior to full deployment. Degradation of components is likely to occur in WECs (Thies, Smith & Johanning, 2012), but this effect has not been included in the O&M model at this stage due to the limited amount of knowledge in this area.

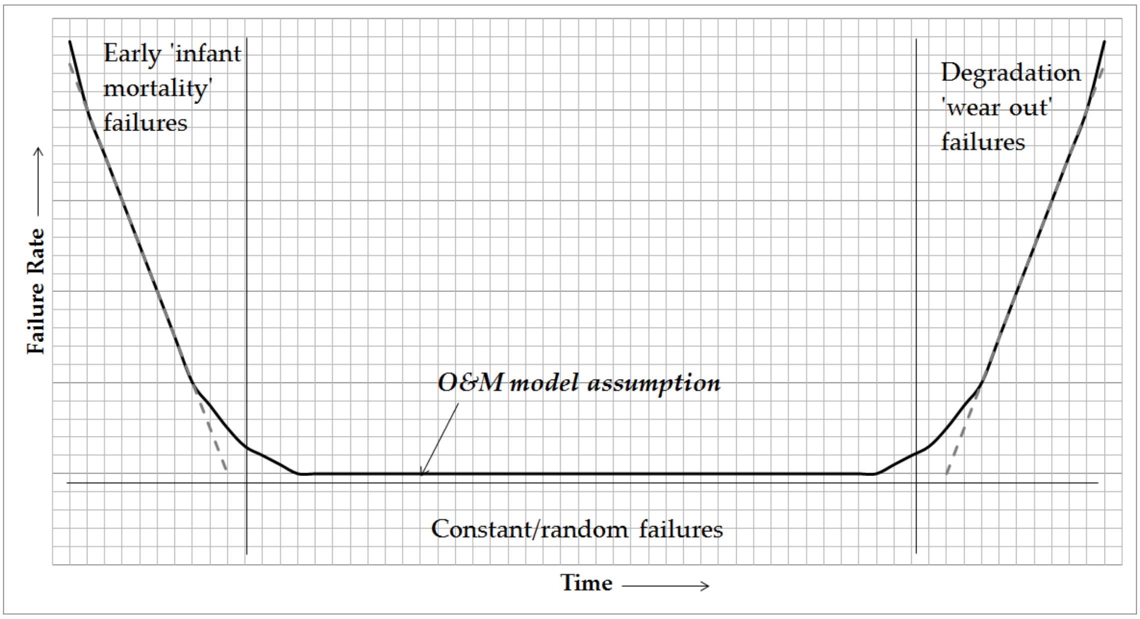


Figure 3.3. Bathtub curve showing O&M model assumption (Gray, Johanning & Dickens, 2014)

3.2.2. Repair parameters

In order to simulate repairs on a WEC, each fault category is assigned the following parameters:

- Parts costs – the average cost of replacement components in that category.
- Other costs – additional costs due to component repairs (e.g. divers for subsea work), as well as an unforeseen costs allowance.
- Time required offshore – if the WEC needs retrieving for onshore maintenance, then this is the time for disconnection. Otherwise, this is the time to carry out an offshore repair.
- Time required onshore – time to repair the WEC once at the onshore O&M base (if required).
- Operational limits – weather constraints for the required marine operation.
- Technicians required – total number of technicians required to undertake the repair.

The estimated times to undertake marine operations and repairs come from the expert judgement of the engineers involved in the O&M of analysed wave energy converters. These estimates will improve as more experienced is gained in operating and maintaining WECs. The estimated number of specialist and non-specialist technicians required for repairs and maintenance will also be improved with experience. Working hours are not modelled explicitly, however, the estimated time to undertake maintenance activities takes such practicalities into account. Operational limits can be specified as they vary between different types and sizes of wave energy converter, as well as between different offshore tasks.

Each fault category is also assigned an assumed power loss, given as a proportion of available power output (i.e. a power loss of 0.5 means full power rating is reduced by 50%). Power loss is associated with the severity of failure, where ‘major’ failures generally result in a 100% power loss. Less severe failures might result in only a part shutdown of a WEC. Major electrical faults, such as failure of a subsea cable, may cause total power loss for the entire array.

3.2.3. Scheduled maintenance

In addition to the fault categories, the model also includes scheduled maintenance categories. This is necessary in order to incorporate the ‘proactive’ maintenance strategy employed by operators of offshore renewable energy developments. Routine service activities could include cleaning biofouling and carrying out non-destructive testing. Major scheduled maintenance could involve replacing certain components whose expected lifetime is lower than the design lifetime of the WEC. Again, each category is assigned parts costs, other costs, time to carry out the task, and labour requirements. Inspection costs are also included, as specialist equipment or personnel may be required for certain tasks. The minimum time interval between maintenance can be specified, as well as the time of year that each task is to be carried out.

3.2.4. Weather conditions

A major input to the O&M model is weather data. This is used for two key reasons; i) to allow or constrain marine operations (such as the installation of a WEC), and ii) to enable revenue to be calculated. The pre-EngD methodology involved using statistics, obtained from a SWAN model for the wave energy test site at EMEC, to calculate the probability of the waves exceeding a certain significant wave height in a given month. Weather windows (i.e. periods of accessibility) were then calculated using a Monte Carlo analysis. The mean power output in each month was also calculated using basic assumptions of capture width of the WEC, allowing an estimate for daily revenue earned (if the WEC was operating at full capacity) to be obtained.

This low-resolution (i.e. month by month) methodology was deemed unsuitable for producing the realistic results required for this thesis, and for more realistic simulations. Therefore, a Markov Chain Model (MCM) has been developed to provide the O&M tool with a time series of weather data, as described by Gray, Johanning & Dickens (2015). Although significant wave height is generally the dominant factor in determining weather windows for marine operations, as stated by Walker et al. (2013), there are other parameters to consider, such as wave period and wind speed. The MCM operates by taking an input of hindcast weather data and calculating the probability of transitioning from one 'sea state' (i.e. a certain combination of weather parameters) to another. By undertaking this process for the full dataset, it is possible to construct a probability matrix (Figure 3.4), whereby the sea state at one time step is dependent only on the sea state at the previous time step. Guidance suggests than hindcast data of at least 10 years in length should be used in order to capture a sufficient range of weather conditions (Equimar, 2011).

		Sea State$_{t+1}$							
		1	2	3	4	5	6	…	n
Sea State$_t$	1	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	P_{16}	…	P_{1n}
	2	P_{21}	P_{21}	P_{21}	P_{21}	P_{21}	P_{21}	…	P_{2n}
	3	P_{31}	P_{31}	P_{31}	P_{31}	P_{31}	P_{31}	…	P_{3n}
	4	P_{41}	P_{41}	P_{41}	P_{41}	P_{41}	P_{41}	…	P_{4n}
	5	P_{51}	P_{51}	P_{51}	P_{51}	P_{51}	P_{51}	…	P_{5n}
	6	P_{61}	P_{61}	P_{61}	P_{61}	P_{61}	P_{61}	…	P_{6n}
	…	…	…	…	…	…	…	…	…
	n	P_{n1}	P_{n2}	P_{n3}	P_{n4}	P_{n5}	P_{n6}	…	P_{nn}

Figure 3.4. Probability matrix representative of the Markov Chain Model process

Probability matrices are created using the hindcast dataset for every month as this enables seasonal variability to be maintained. A consistent sea state ID system is used to enable the MCM to calculate transitions from month to month. In some situations, the final state from the previous month's dataset may not occur in the dataset for the next month. To account for this, a three tier hierarchical system of determining the sea state at the first time step in the next month has been developed, as shown in Figure 3.5.

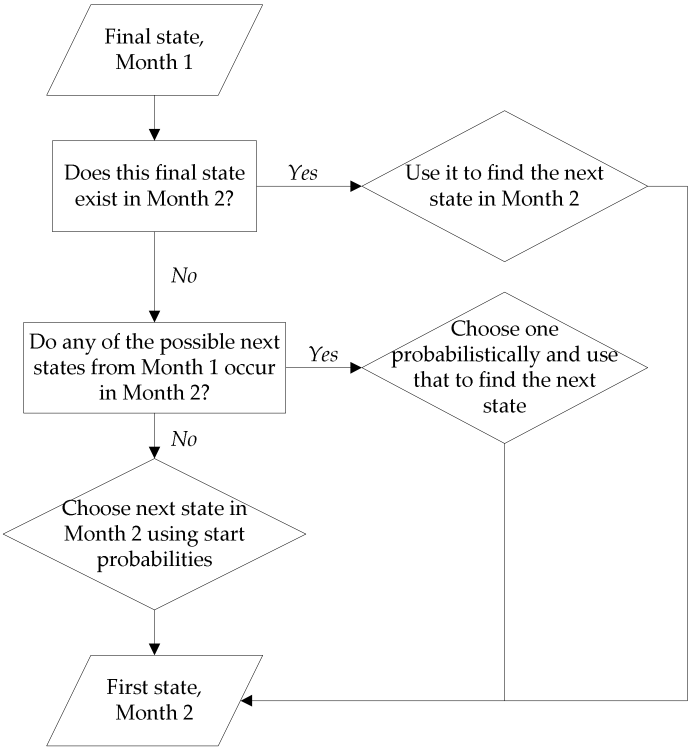


Figure 3.5. Decision matrix explaining the three tier hierarchical system for monthly transitions

To implement the Markov-generated time series' of weather conditions into the O&M model, a virtual store containing generated datasets is created for several different design lifetimes of wave energy arrays. This means that the user can either select a specific time series, thereby enabling the sensitivity of other aspects to be analysed, or can allow the O&M tool to choose one at random in order to test the sensitivity of the model to the weather input data. Throughout this thesis, where one time series' is selected from the virtual store, it has been chosen based on its similarity to the original hindcast dataset using the criteria of mean annual power, percentage of open weather windows, mean annual wait times, and mean monthly wait times.

Using the Markov Chain methodology to provide the weather input to the O&M tool is a significant improvement for many reasons. It allows multiple weather parameters to be accounted for which is vital in defining realistic weather windows. Although significant wave height is the primary factor to consider when assessing a weather window, wind speed and wave period are also important. The MCM retains the ability to simulate both 'good' and 'bad' years (in terms of weather), but goes further than the pre-EngD model by inputting a time series, thus providing visual representation of the weather data and allowing further analysis. The MCM provides this variability whilst also maintaining seasonal trends. Implementing the MCM has also allowed the 24 hour resolution of the pre-EngD model to be increased to 6 hours or 3 hours (depending on the user requirements), thereby enabling simulations to be analysed in greater detail. Another key benefit of the MCM is that the wave height and period values can be matched up with a power matrix for the WEC in order to better represent the electricity generated by the wave farm.

3.2.5. Wave farm logistics

The number of specialist and non-specialist technicians permanently employed at the O&M base is defined by the user. This includes the employment of a site manager. The base salaries are specified and a multiplier is applied to account for overheads such as high-visibility clothing and IT equipment. The overheads multiplier can be defined by the user, but is usually taken to be 1.3. In addition, the user can choose whether or not to allow external contractors to be hired on a short term basis to assist with maintenance.

A wave energy array will require at least one vessel to be available for marine operations. The O&M model allows the user to select the hire or purchase arrangement of the required vessel/s, a ‘hire when required’ scenario for example. Fuel costs are also included for all marine operations. If different types of vessels are used, then the operational limits of each one can be specified.

3.3. Functionality

The O&M model runs for each year of the specified design lifetime and for each time step. The annual probabilities of failure for each fault category are converted using equation 3.5 (page 54) in order for the model to run at each time step. The Monte Carlo analysis then runs for array-based failures, such as subsea cables, as well as for WEC-based failures for each device in order to simulate faults in the wave energy array. If an array-based failure has occurred, then it is repaired as quickly as possible in order to minimise downtime. If onsite repairs are possible (i.e. whilst the WEC is offshore) then these are also repaired as soon as possible. However, if a fault has occurred that requires a WEC to be retrieved for offsite repair (i.e. at a sheltered O&M base), then a cost-benefit analysis takes place to determine whether or not it is worth undertaking the marine operation, or if it is best to leave the WEC onsite operating at reduced power output. If no faults have occurred, then the tool assesses whether any WECs require scheduled maintenance, according to the model input specifications. If any repairs or maintenance activities are required, then the availability of the appropriate vessel required for the task is identified. The minimum operational limits for the task are calculated, along with the length of the required marine operation, in order to determine if the weather window is open. Availability of technicians is also considered. Work is delayed if any of these conditions cannot be met. Otherwise, the repair or maintenance task is simulated to have commenced. At the end of each time step, the model checks if any work is still being undertaken before looping through to the next time step or new year. The algorithm finishes at the end of the specified design lifetime of the array and the results are printed. A flowchart of this described functionality is given in Figure 3.6.

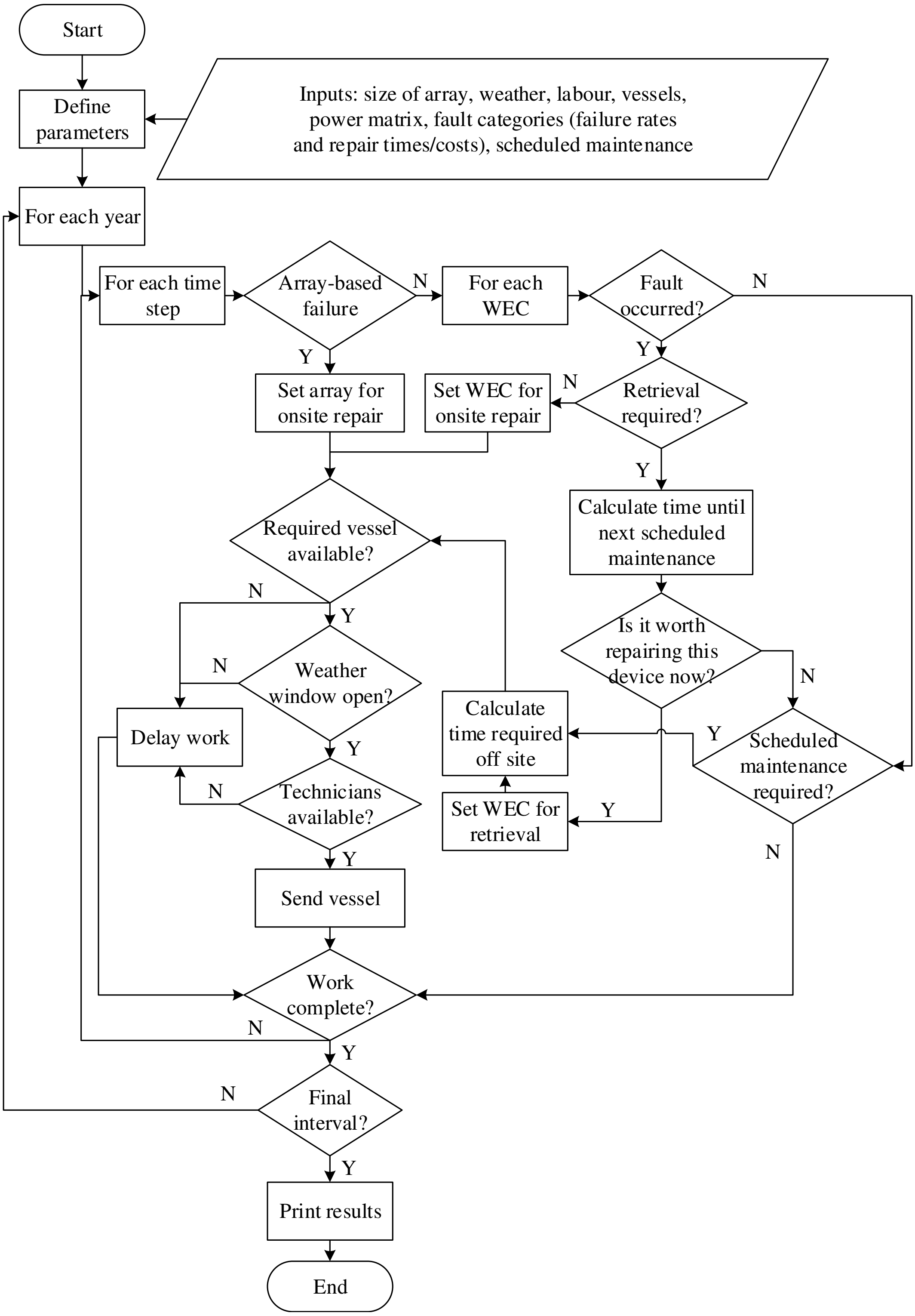


Figure 3.6. Flowchart of generic O&M model functionality

3.4. Outputs

For each year and for each machine, as well as for the annual average, the following results are calculated:

- Availability – a value between 0 and 1. Takes reduced power output due to failures into account, as well as full power loss during maintenance. Average availability is presented.
- Revenue – the sum of revenue earned.
- Parts costs - the sum of parts costs used for repairs and maintenance.
- Other costs – the sum of other costs incurred.
- Inspection costs – the sum of inspection costs for scheduled maintenance.
- Vessel costs – the sum of day hire rates and mobilisation fees (if applicable), plus fuel costs.
- Labour costs – the sum of technician salaries and contractor fees (if applicable).

The annual averages and sum values are contained within a summary table. In addition, there is also a summary table of the fault categories where a proportion of the operational expenditure (OPEX), including lost revenue and vessel fuel costs, is assigned to each category. These costs are assigned when any marine operation is simulated by the model. This enables analysis of the faults which have the biggest impact on OPEX costs. The O&M tool is also capable of producing statistical forms of the results (i.e. minimum, maximum, mean, range and standard deviation) by running simulations several times, using the same time series of weather data if required.

3.5. Creating a WEC-Specific Model

The generic O&M model methodology, as described in this chapter, requires the inputs and functionality to be modified when a specific wave energy converter is analysed. Confidence in the outputs of numerical models is increased when the inputs obtained are as realistic as possible. There is no such thing as a generic and realistic O&M model for wave energy arrays.

In order for the appropriate fault categories to be defined, a Failure Modes and Effects Analysis (FMEA) for the specific WEC needs to be carried out. It may be possible that one or more of the fault categories identified in the generic O&M

model methodology is not relevant, and a new category may be more appropriate. The failure rate data for the specific WEC needs to be obtained.

The ideal location for one type of WEC may not be suitable for another device. This is accounted for in the O&M tool by using an appropriate hindcast dataset of weather conditions as input to the described Markov Chain Model. This also involves identifying the dominant factors in defining weather windows for marine operations for the specific WEC. The generated time series' of weather conditions must be able to be matched to the WEC's power matrix in order for the model to calculate power output and revenue (using an assumed sale price of electricity).

It is useful to have a 'bill of materials' document available for the analysed WEC so that the average cost of spare parts in each fault category can be determined. A level of logistical knowledge for the specific WEC is also required, such as time to undertake installation and retrieval, as well as the number of technicians required for particular faults and maintenance. Logistical knowledge also helps to tailor the O&M model functionality to the specific WEC array. Modifications, such as removing the cost-benefit analysis part of the tool if it is deemed unnecessary, enable the O&M strategy for the WEC array to be modelled as realistically as possible.

Chapter 4 – Pelamis O&M Strategies

In order for a commercial wave farm to reach the maximum level of profitability possible, it is vital that the operations and maintenance strategy is critically assessed. There is no generic strategy that is optimal for each and every wave energy array, due to the complexities involved with site specific details, as well as the various designs of WEC under development. However, it is possible to analyse several O&M strategy options that could potentially be used in a future commercial wave farm using a Pelamis-specific O&M tool, with the P2 device as the case study.

In this chapter, such analysis is carried out and the merits of the presented O&M strategies are assessed. Section 4.1 outlines the principles of operations and maintenance for the Pelamis device. The inputs and functionality modifications that make the O&M model specific to the P2 WEC are described in section 4.2. The base case for the simulations in this chapter is stated in section 4.3. In section 4.4, five possible hire or purchase arrangements for the multicat vessel used for marine operations are assessed. Section 4.5 looks into the effect of constraining marine operations to daylight hours only. Logistical permutations of the number of WECs that can be installed or retrieved in a weather window are analysed in section 4.6. A similar analysis for the weather constraints on marine operations is undertaken in section 4.7. Section 4.8 assesses the viability of keeping a spare WEC at the quayside ready for immediate installation. The final strategy consideration to be reviewed is the workforce available for operations and maintenance in section 4.9. A discussion of the key results and outcomes of the chapter is provided in section 4.10.

4.1. Pelamis O&M

The O&M strategy of the Pelamis P2 device (Figure 4.1) has been modelled in the O&M tool. The articulator-type WEC was rated at 750kW, had a total length and mass of 180m and 1300 tonnes respectively, and was tested in real sea conditions at EMEC from 2010 to 2014 (i.e. the P2 testing programme).

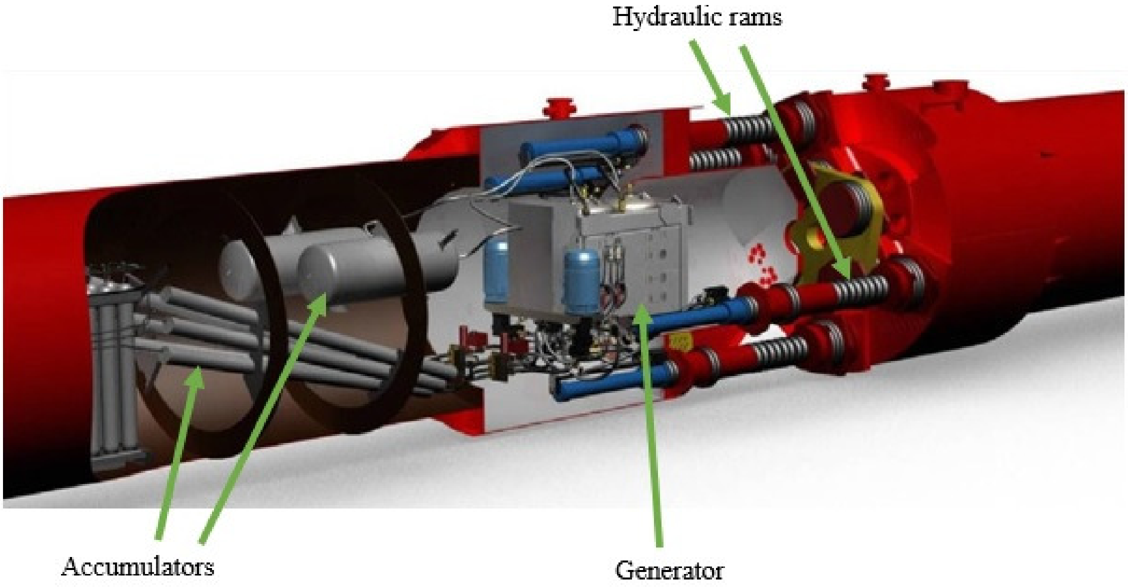


Figure 4.1. P2 joint and power take-off (PTO) system (Yemm et al., 2012)

The P2 device was designed with a ‘plug in and play’ system, whereby the machine could be installed and removed from its electrical and moorings connection point remotely using controllers on board the installation vessel. The maintenance strategy was to remove the WEC from its offshore location to the safety of a sheltered harbour where spare parts could be readily available and adverse weather conditions were not a concern. No maintenance was to be carried out whilst the device was offshore, regardless of weather conditions. A P2 installation operation could be carried out in less than one hour once the machine was on site, using two small, low cost, multi-purpose workboats (i.e. multicat vessels). A removal operation could be carried out ‘in a matter of minutes’ (Yemm et al., 2012) and in rougher seas using only one workboat.

4.2. Pelamis-Specific O&M Model

The generic O&M tool described previously has been tailored to be specific to the Pelamis P2 device. This process involved utilising the experience gained during the P2 testing programme in order to obtain realistic results with an acceptable level of confidence. The time step resolution of the model is six hours.

4.2.1. Inputs

The inputs to the P2-specific O&M tool have primarily come from the expert judgement of the engineers involved in the Pelamis endeavour. Operational experience with the P2 device, as well as with earlier designs, informed the estimates for maintenance parameters, such as the time required offsite to repair particular faults. Inputs requiring further description are discussed in the following subsections. The information for the fault categories and scheduled maintenance tasks is displayed in tabular form in the appendices (Table A.1 and Table A.2). The fault categories have been modified from the generic O&M model, in order to better represent the components of the Pelamis P2 device. This includes introducing a ‘half circuit failure’ category to account for the redundancy built into the electrical circuitry of each joint module in the device. All the fault categories are applicable only to the WECs, rather than the array. The assumption is that subsea, array-based components have higher reliability and are better understood than the WEC-based systems, and are therefore not included in the Pelamis-specific O&M model fault categories. The scheduled maintenance categories are made up of an annual routine service, as well as an overhaul of major components taking place at the halfway point of the wave farm lifetime.

4.2.1.1. Failure rate data

A Failures Modes and Effects Analysis (FMEA) was first carried out by Pelamis Wave Power in 2008 during the design phase of the P2 wave energy converter. At that time, the initial estimates for the failure rates of the P2 components (prior to deployment) came from four main sources; i) manufacturers’ specifications for off-the-shelf components, ii) a US military handbook on reliability prediction (US Department of Defense, 1991), iii) destructive testing on several components (Pelamis Wave Power, 2013), and iv) the limited operational experience with the Pelamis prototype and P1 devices. These estimates were updated over the course of the P2 testing programme, as staff at Pelamis Wave Power learnt more about their device through operational experience.

4.2.1.2. Operational limits

The Pelamis-specific O&M tool is supplied with a time series of weather conditions containing significant wave height (Hs), wave energy period (Te) and wind speed using the Markov Chain Model (MCM) described previously. The simulated time series' contain these three parameters in order to define a weather window for the Pelamis device, as defined over the course of the P2 testing programme. It was found that although significant wave height was the primary factor in accessibility, operational limits of Hs were also dependant on wave energy period. In addition to Hs and Te, wind speed has also been included because multicat vessels and tug boats are typically restrained to working in wind speeds of 20kts or less. The P2 testing programme also proved that the operational limits for an installation of the WEC were more restrictive than for a device retrieval, as shown in Figure 4.2.

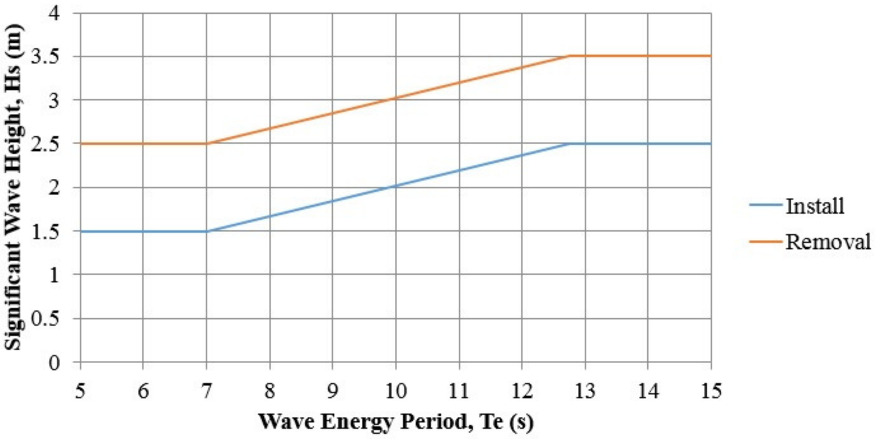


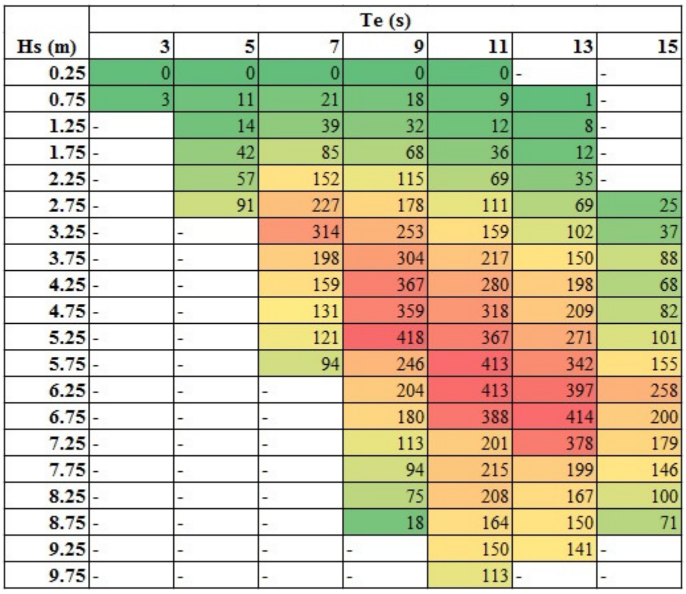
Figure 4.2. Operational limits defined during the P2 testing programme and used in the O&M tool for this study (Gray, Johanning & Dickens, 2015)

Where the hindcast dataset used as the input to the MCM contains wave peak period (Tp), an equation is required to convert it into wave energy period (Te) in order to match the P2 power matrix described in the next subsection. Equation 4.1 was empirically calculated by Pelamis engineers who analysed wave buoy data at EMEC for the period 10/12/2006 to 30/09/2014:

$$Te = 0.5764\, Tp + 2.5317 \quad (4.1)$$

4.2.1.3. Power matrix

The Pelamis P2 power matrix used in the O&M tool (Figure 4.3) has been inferred from the contracted targets that Pelamis Wave Power had during the P2 testing programme. It should be noted that this power matrix is not indicative of the true potential of a commercial attenuator WEC. The sell price is assumed to be 30.5p/kWh, in line with the UK's 'Contracts for Difference' model (DECC, 2013b).



Hs (m)	Te (s)						
	3	5	7	9	11	13	15
0.25	0	0	0	0	0	-	-
0.75	3	11	21	18	9	1	-
1.25	-	14	39	32	12	8	-
1.75	-	42	85	68	36	12	-
2.25	-	57	152	115	69	35	-
2.75	-	91	227	178	111	69	25
3.25	-	-	314	253	159	102	37
3.75	-	-	198	304	217	150	88
4.25	-	-	159	367	280	198	68
4.75	-	-	131	359	318	209	82
5.25	-	-	121	418	367	271	101
5.75	-	-	94	246	413	342	155
6.25	-	-	-	204	413	397	258
6.75	-	-	-	180	388	414	200
7.25	-	-	-	113	201	378	179
7.75	-	-	-	94	215	199	146
8.25	-	-	-	75	208	167	100
8.75	-	-	-	18	164	150	71
9.25	-	-	-	-	150	141	-
9.75	-	-	-	-	113	-	-

Figure 4.3. Pelamis P2 power matrix inferred from contracted targets during testing programme 2008-2014, values in kW

4.2.1.4. Vessel arrangements

Two multipurpose workboats (a.k.a. multicats) were required for the installation of a P2 device during the testing programme. However, it was always the plan that this level of redundancy would no longer be required in a commercial wave farm. Therefore, the P2-specific O&M tool assumes that only one multicat is required for both installation and removal operations. The pre-EngD O&M tool assumed the multicat vessel was hired on a 'hire when required' basis. There are several more options that would be available to operators of a wave farm. The four further options built into the P2-specific O&M model are: 'long term lease', 'long term standby rate', 'hire to purchase' and 'outright purchase'. With 'long term lease', a flat rate is paid for the vessel, whereas 'long term standby rate' means that a reduced fee is paid when the vessel is not being used. The 'hire to purchase' scheme sees a long term lease in effect until such a point where the total fee covers the cost of the vessel purchase; a fee which would be higher than buying the vessel with an 'outright purchase'. The 'hire when required' arrangement has been made more realistic by using a probability of boat availability and also incurs a mobilisation fee. All five boat arrangements also include a fuel cost for each marine operation carried out. If two or more vessels are required then this can be accounted for in the costs.

4.2.1.5. Offshore logistics

In the interest of computational run speed, the Pelamis-specific O&M tool does not calculate the length of each marine operation at the point it is required. Instead, the model uses pre-defined logistical inputs of the number of Pelamis P2 devices that can either be installed, retrieved, or both, in a given period related to the model's time step resolution. These inputs are stored in a vessel permutations table in the main user inputs sheet.

4.2.1.6. Onshore facilities

It is assumed that there is no limit on the number of P2 WECs that can be kept at the quayside at any one time. Quayside fees are included as an input, both as a base rate for items such as shed hire, as well as an additional fee for when a WEC is berthed at the quayside to cover additional costs such as layage.

4.2.1.7. Labour requirements

There are four primary subsystems in the P2 WEC; moorings, hydraulics, structural and electrical. Each fault category in the P2-specific O&M tool is assigned labour requirements to one of these categories, plus any extra non-specialist personnel that may be needed. Repairs and maintenance tasks are delayed if the required specialist (or other personnel) is not available, although if the short term contractor approach is enabled then the model assumes that the required specialist can be selected.

4.2.1.8. Spare machine

The option has been built in to the P2-specific O&M tool to keep one or more WECs in harbour, fully maintained and ready to replace machines that are removed from site for repairs or maintenance. This is seen a very real option for wave farm operators in the future. The farm availability is calculated as the sum of the availability of all machines (including spares), divided by the number of site berths.

4.2.2. Functionality

The decision making process of when to retrieve a P2 device from the offshore site and take it to a sheltered harbour for repair is represented graphically in Figure 4.4. If a WEC suffers either one major fault or two intermediate ones, then it is retrieved for repair as soon as weather permits. If the device has exceeded the maximum allowable time between two scheduled maintenance events then it is also retrieved. If none of these conditions are met, then the tool runs through a cost-benefit analysis (CBA) to decide whether or not to send a vessel to remove that machine from site (provided the weather window is open). Groups of an increasing number of machines are assessed in turn to enable multiple devices to be removed in the same window if logistics allow. In the pre-EngD model, this calculation compared the cost of repairing the device against a user-defined value known as ‘cost per machine’. It was recognised, however, that this equation could be redesigned to be quantifiable due to the proactive maintenance strategy of undertaking a routine inspection on each device every summer. Therefore, the modified analysis weighs up the cost of retrieving and repairing the device/s against leaving it/them to operate at a reduced power output. Estimates for potential revenue and time spent waiting for a weather window in a given month are provided as an input to enable the cost-benefit calculations to take place. These estimates come from the hindcast dataset of weather conditions used as input to the described Markov Chain method. An increased level of realism could be achieved if forecasting was built into the cost-benefit analysis.

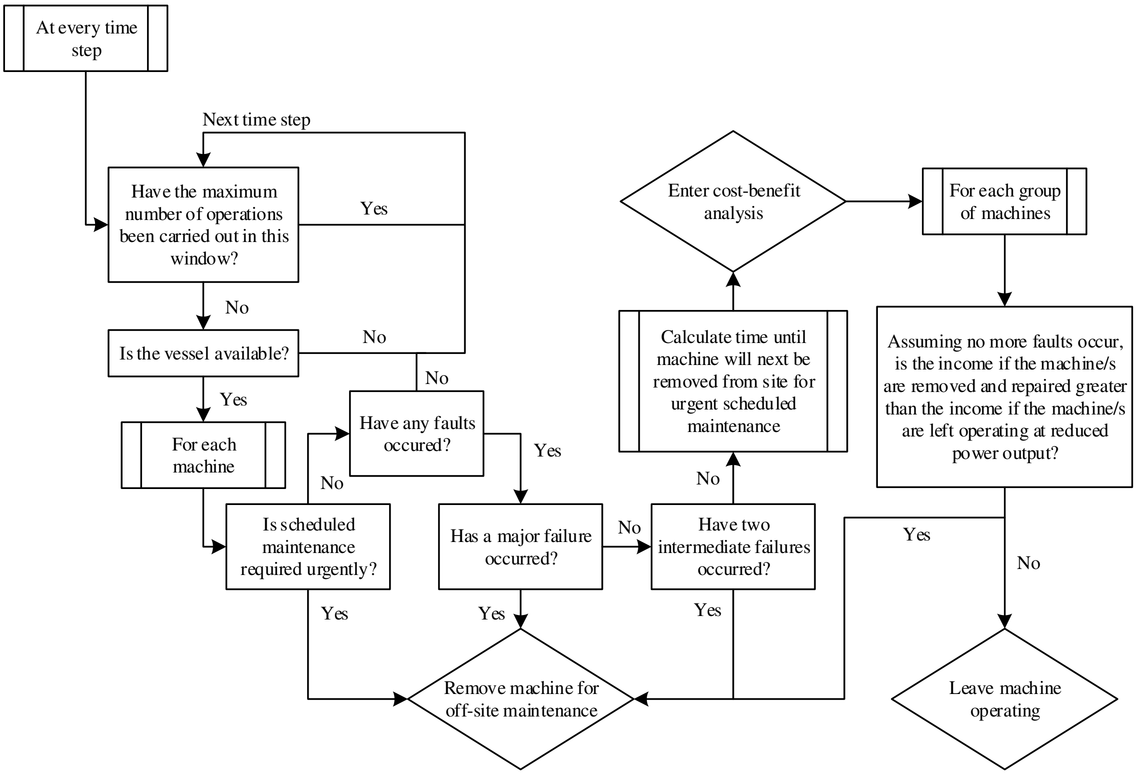


Figure 4.4. P2-specific O&M model decision flowchart for marine operations

4.3. Base Case

The analyses presented in this chapter use the Pelamis-specific O&M model combined with a Markov-generated time series of weather conditions for Farr Point, an area previously being developed as a commercial wave energy site, located off the north coast of Scotland. The simulations in this chapter are for a wave farm consisting of 10 P2 devices, over a design lifetime of 20 years, unless specified otherwise. The base case assumes that one multicat vessel is available for the wave farm, and is paid for on a ‘hire when required’ basis, which includes a mobilisation fee, day rate and fuel costs. The probability of the vessel being available when required is 0.9. Marine operations can be undertaken at night. A 12 hour weather window is used, where the vessel permutations are specified as follows:

- remove a maximum of two P2 devices and bring them both to the quayside
- install one P2 device at the farm
- install one P2 device at the farm, then remove another one and bring it to harbour

There is a total of 12 personnel employed at the O&M base, with the option to bring in external contractors to avoid delays to operations or maintenance. For each analysis undertaken in this chapter, 50 simulations of the O&M model are run, with the mean values presented. Table 4.1 provides the numerical results of the O&M model base case.

Table 4.1. Pelamis-specific O&M model base case results

	Availability	**Revenue (£k)**	**OPEX (£k)**
Annual mean ± 95% confidence	86.61% ± 0.15%	2841.3 ± 6.2	1089.2 ± 8.7

4.4. Vessel Hire/Purchase Arrangements

4.4.1. Scenario inputs

The ‘hire when required’ vessel scenario is similar to the one used by Pelamis Wave Power during the P2 testing programme at EMEC. This arrangement may not be optimal when it comes to operating a commercial-scale wave farm, and is therefore critically assessed in this section alongside the four other scenarios previously described. Table 4.2 provides the costs associated with each of the five scenarios. These costs have been obtained through communications with leading vessel operators who have experience in the marine energy sector.

Table 4.2. Vessels costs for the five scenarios considered

	Hire when required	**Long term lease**	**Long term standby rate**	**Hire to purchase**	**Outright purchase**
Vessel mobilisation cost (£k)	5	-	-	-	-
Vessel day rate (£k)	4	3.5	3	3.5	-
Fuel cost per op (£k)	1	1	1	1	1
Vessel standby rate (£k)	-	-	2	-	-
Vessel purchase fee (£k)	-	-	-	6000	5000
Vessel availability (probability)	0.9	-	-	-	-

4.4.2. Results and discussion

A breakdown of the total operational expenditure (OPEX) of each scenario, calculated by the P2-specific O&M model simulations, is shown in Figure 4.5. The results of the simulations are also represented in terms of annual 'profit' (revenue minus OPEX, i.e. 'net operational income') in Figure 4.6. The numerical results of the simulations are provided in Table 4.3.

Table 4.3. Mean results for the five vessel hire/purchase arrangements

	Availability	**Revenue (£k)**	**OPEX (£k)**
Hire when required	86.6%	2841.3	1089.2
Long term lease	89.9%	2948.7	2156.2
Long term standby rate	90.5%	2986.9	1723.5
Hire to purchase	90.0%	2952.5	1177.6
Outright purchase	90.0%	2952.2	1127.0

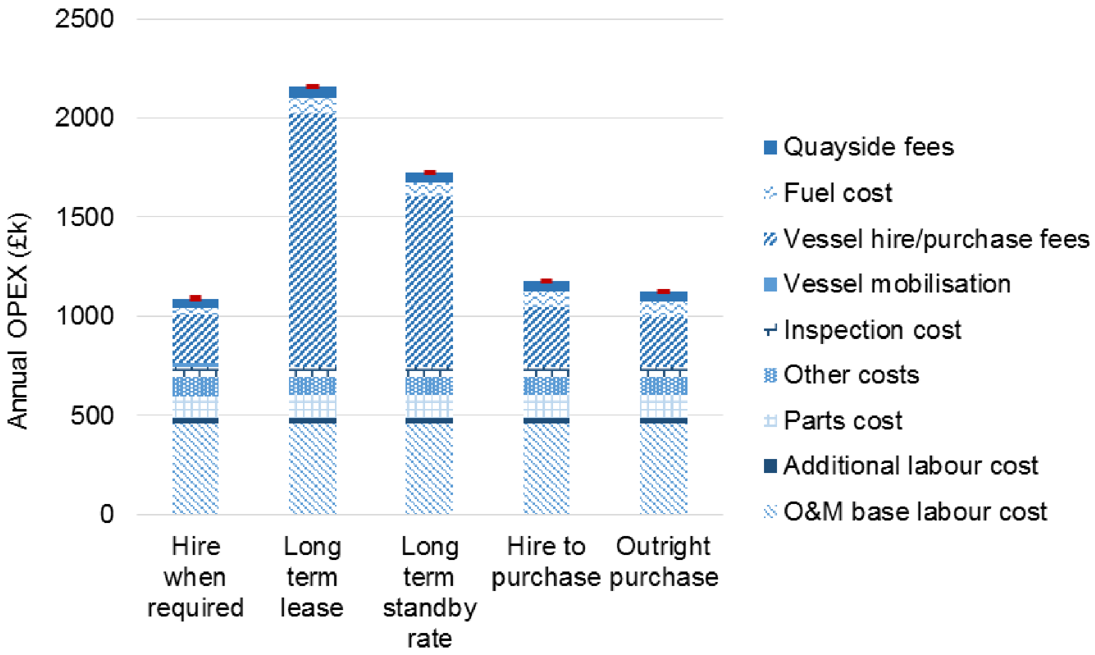


Figure 4.5. OPEX breakdown of the five vessel hire/purchase scenarios, with 95% confidence intervals applied

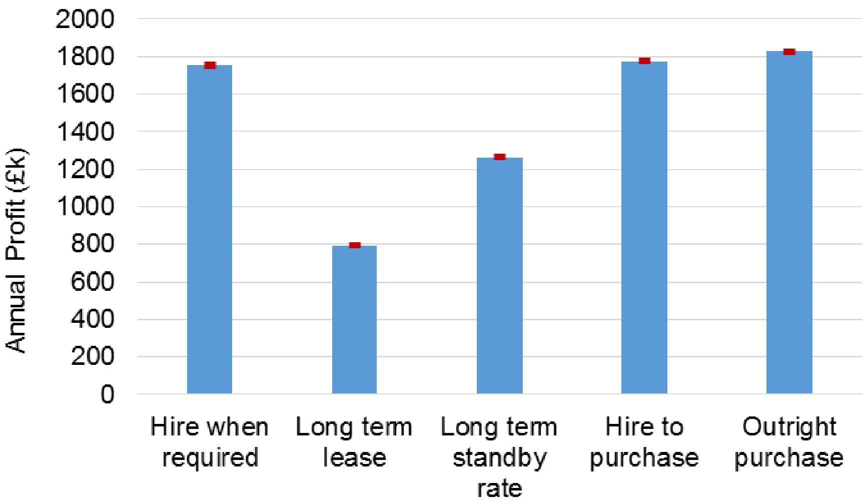


Figure 4.6. Annual profit of the five vessel hire/purchase scenarios, with 95% confidence intervals applied

The results of the O&M model simulations show that both the vessel lease options (‘long term lease’ and ‘long term standby rate’) are the least profitable as they incur the greatest OPEX costs. This increase in OPEX compared to the other scenarios is shown to be due to the vessel hire fees. The costs analysed in this study have been deemed to be realistic by those involved in the offshore industry, and therefore it can be deduced that having a multicat vessel on a long term lease arrangement is not a viable option for a commercial-scale wave farm. The scenario that incurs the lowest annual OPEX in the results is ‘hire when required’.

However, it can be seen that the 'outright purchase' option achieves a slightly higher annual net operational income. This is due to the potential delay in hiring a vessel when it is on a 'hire when required' scheme, rather than having 100% vessel availability when it is owned by the wave farm operator. The 'hire to purchase' scheme also achieves a high annual net operational income. All three scenarios have been shown to be suitable for the 10-WEC commercial wave farm in this analysis.

The presented results do not take Net Present Value (NPV) into account. In the 'outright purchase' simulations, the vessel fee is paid on the first day in year 1. Vessel fees in the other scenarios are paid for throughout the lifetime of the wave farm. Figure 4.7 shows the total OPEX incurred throughout the lifetime of the wave energy array, with different discount rates (r). The discounted OPEX in each year (t) is calculated using the formula: $\frac{OPEX_t}{(1+r)^t}$.

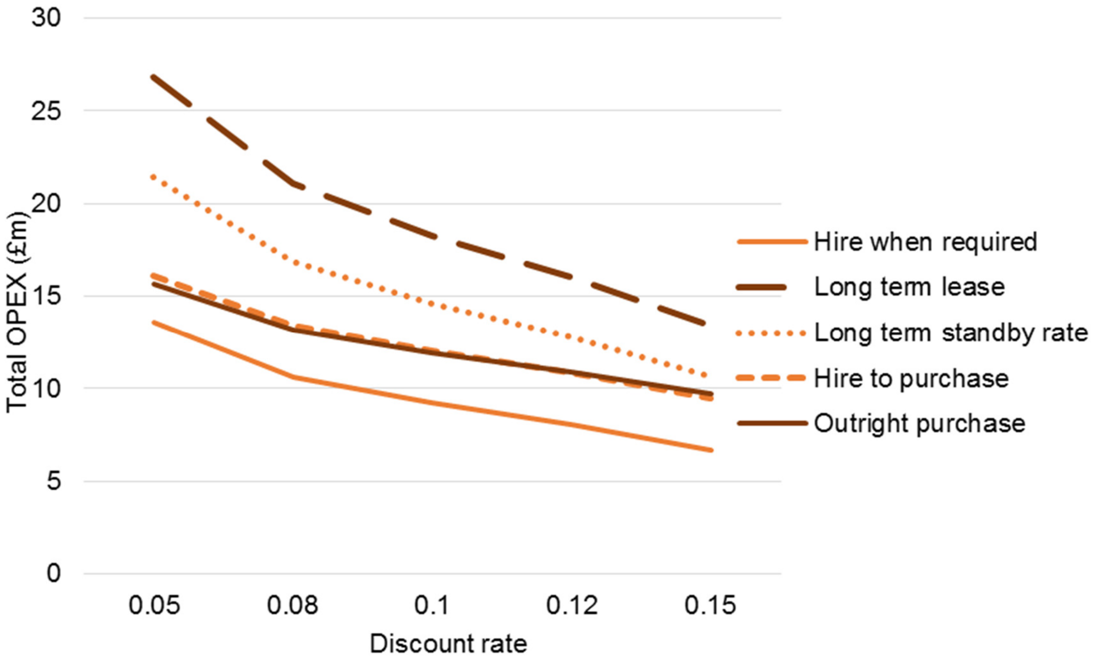


Figure 4.7. Total discounted OPEX the five vessel hire/purchase scenarios

For all the different discount rates used in the analysis, the 'hire when required' scenario incurred the lowest OPEX over the lifetime of the wave farm. The two scenarios where the vessel is eventually owned by the wave farm operator ('hire to purchase' and 'outright purchase') show the second lowest total OPEX. With lower discount rates, the total OPEX for the 'hire to purchase' arrangement is slightly higher than the 'outright purchase'. This seems to be reversed at higher discount rates. This information shows that the terms of finance for the wave farm need to be considered when assessing the optimal O&M strategy.

4.4.3. Design lifetime

Although 20 years has typically been used as the design lifetime by wave energy developers in the past, it is by no means a fixed value. In the UK, subsidies under the Contracts for Difference (CfD) scheme are delivered for 15 years. It is also possible that the design lifetime will be extended if degraded components can be replaced. Two of the most profitable vessel arrangements, ‘hire when required’ and ‘outright purchase’, have been used to compare P2 wave farms with design lifetimes of 15 and 25 years. The scheduled maintenance task involving the replacement of major components in each WEC is undertaken halfway through the design lifetime. A comparison in terms of the mean annual net operational income from 50 O&M model simulations is shown in Figure 4.8. The results are also presented in terms of the total discounted net operational income generated over the farm lifetime in Figure 4.9.

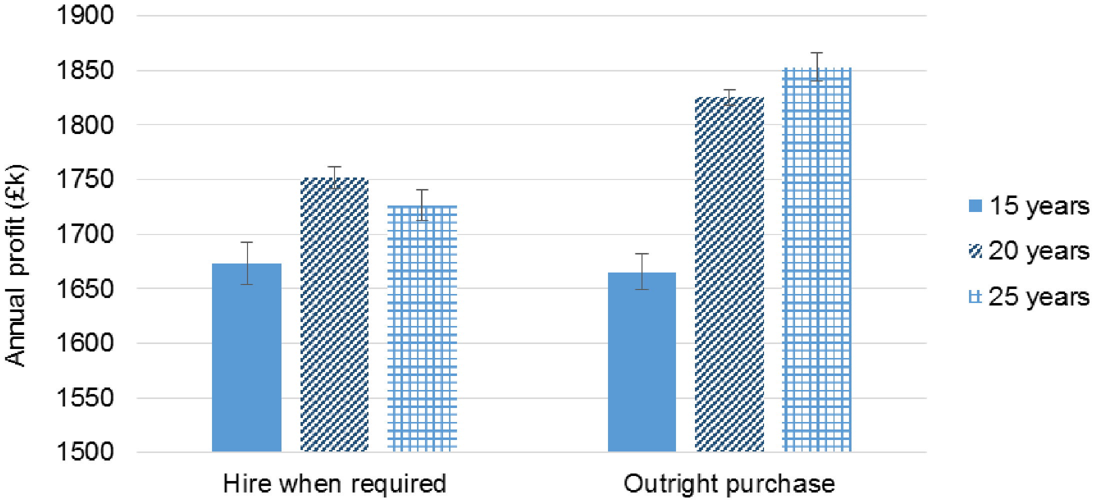


Figure 4.8. Mean annual profit, comparison of differing design lifetimes for two vessel hire/purchase arrangements, with 95% confidence intervals applied

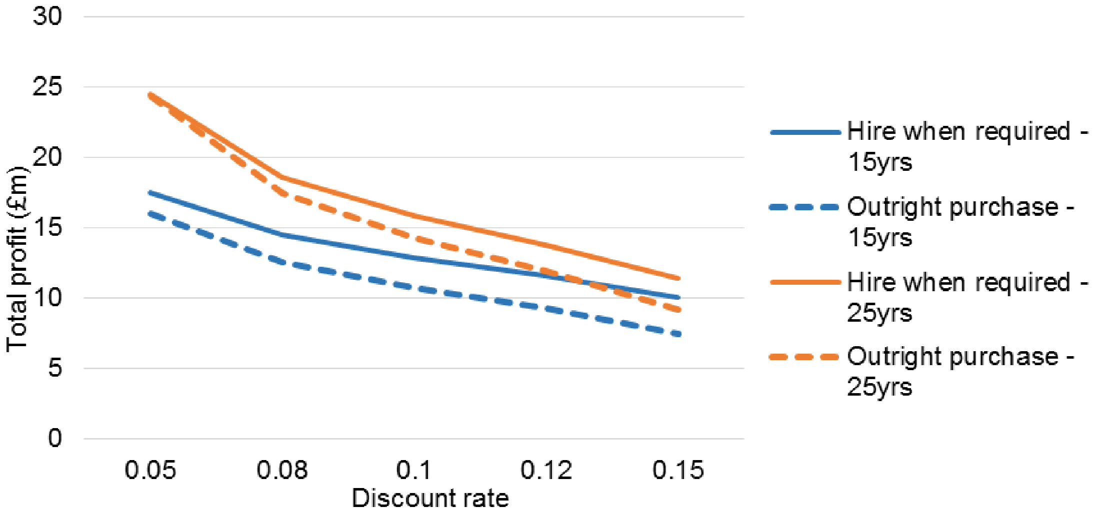


Figure 4.9. Total discounted profit, comparison between 15 and 25 year design lifetime for two vessel hire/purchase arrangements

The results in Figure 4.8 show that the 'outright purchase' vessel scenario has a greater annual net operational income than the 'hire when required' arrangement for a 25 year design lifetime. However, the annual net operational income values are almost matching for the two scenarios when the wave farm lifetime is reduced to 15 years. Therefore, a 'vessel purchase' arrangement should be considered for a wave farm with a longer design lifetime, as the initial fee can be recovered over the course of the project. On the other hand, Figure 4.9 shows that the total net operational income earned over the wave farm lifetime is greater for the 'hire when required' scenario, for all values of discount rate used. The only exception is for the 25 year design lifetime at a discount rate of 0.05, where the total discounted net operational income for the two arrangements nearly match. Figure 4.9 also displays a widening gap between the two vessel arrangements as the discount rate is increased. This is due to the fact that, for the 'outright purchase' scenario, the higher annual net operational income achieved in later years loses value over time, and therefore does not have as much of a negating effect on the initial vessel purchase. Again, this highlights the need to incorporate the terms of finance for the wave farm into any attempts at optimising the O&M strategy.

Net Present Value (NPV) is not included in the calculations presented in the remainder of this thesis as other strategies do not incur the initial capital expenditure (CAPEX) in the same was as the 'outright purchase' of a vessel. Therefore, the trends in NPV will not differ from those seen with the average annual output values.

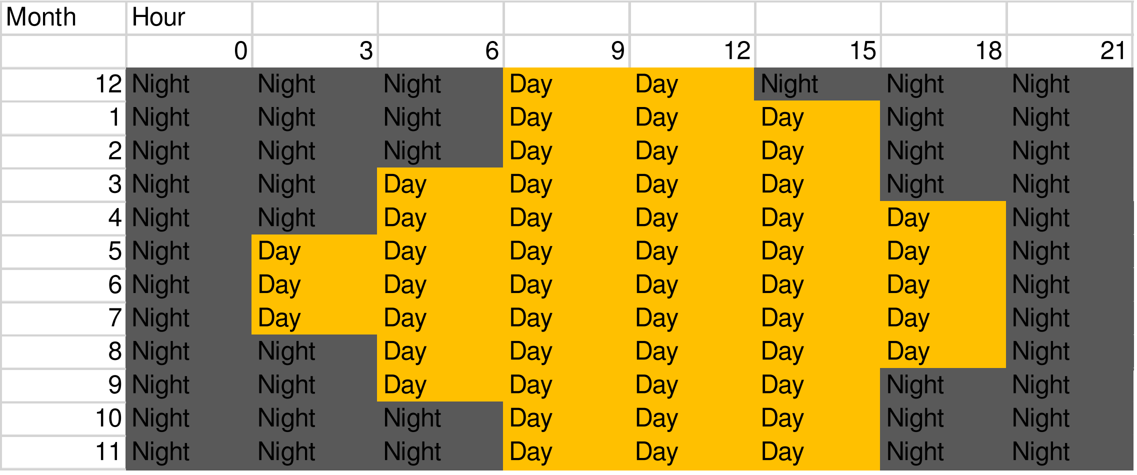
4.5. Daylight Constraints

The base case O&M model simulations assumed that marine operations can be undertaken at any time, given accessible weather conditions. However, the marine environment can be extremely unforgiving, and therefore the P2 WECs were only installed or removed from site in daylight hours during the test programme at EMEC. It will be possible to undertake marine operations at night, as shown regularly with the installation of offshore wind turbines, however, these activities will incur additional costs such as floodlights and other expenses in order to adhere to standards of health and safety and mitigate any identified risks.

This section uses a version of the P2-specific O&M model with a three hour resolution to assess the impact on wave farm profitability if marine operations are limited to daylight hours only. The three hour O&M model has been validated against results of the six hour version used previously.

4.5.1. Daylight hours at Farr Point

Figure 4.10 shows how the three hour O&M model distinguishes between day and night for the Farr Point site off the north coast of Scotland. This information has been inferred from the average time of sunrise and sunset at Thurso in each month of 2013 (www.sunrise-and-sunset.com). When using the O&M model to analyse the effects of restricting marine operations to daylight hours only (i.e. the 'night ops off' case), all periods of darkness have a 3-hour weather window automatically set to 'closed' (thereby saving computational power by not having to go through further calculations in assessing the weather conditions).



Month	Hour							
	0	3	6	9	12	15	18	21
12	Night	Night	Night	Day	Day	Night	Night	Night
1	Night	Night	Night	Day	Day	Day	Night	Night
2	Night	Night	Night	Day	Day	Day	Night	Night
3	Night	Night	Day	Day	Day	Day	Night	Night
4	Night	Night	Day	Day	Day	Day	Day	Night
5	Night	Day	Day	Day	Day	Day	Day	Night
6	Night	Day	Day	Day	Day	Day	Day	Night
7	Night	Day	Day	Day	Day	Day	Day	Night
8	Night	Night	Day	Day	Day	Day	Day	Night
9	Night	Night	Day	Day	Day	Day	Night	Night
10	Night	Night	Night	Day	Day	Day	Night	Night
11	Night	Night	Night	Day	Day	Day	Night	Night

Figure 4.10. Daylight hours at Farr Point (Gray & Johanning, 2016)

4.5.2. Average wait times

As discussed previously, one of the inputs to the Pelamis-specific O&M model is the average time to wait for an installation weather window in a given month. This allows the cost-benefit analysis part of the tool to determine whether or not to retrieve a faulty P2 device for offshore repair. Figure 4.11 compares the average wait times (for a 3-hour weather window) in each month for the two scenarios of 'night ops on' (i.e. the base case, where marine operations are undertaken at night) and 'night ops off'.

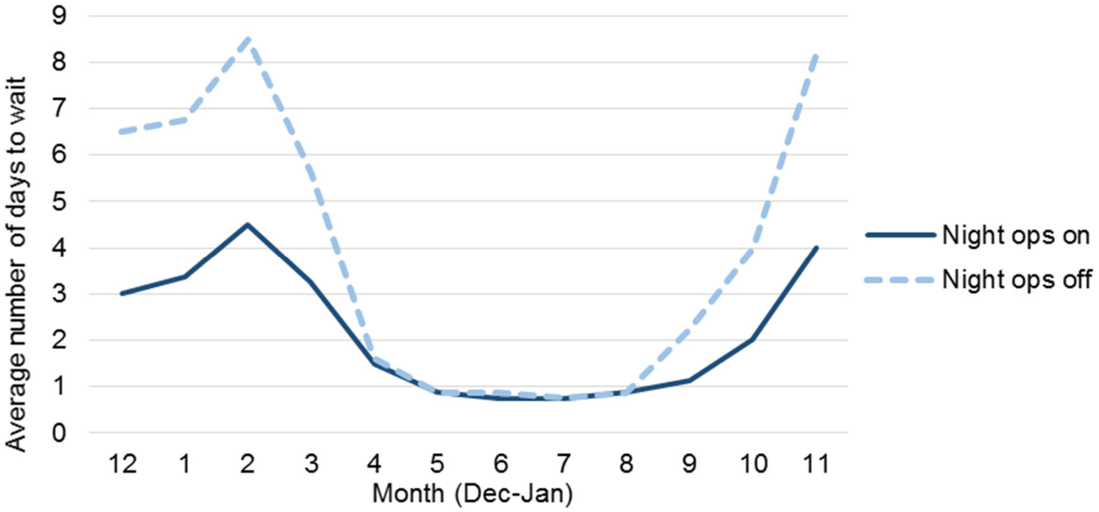


Figure 4.11. Monthly average wait times for a 3-hour weather window the two 'night ops' cases

4.5.3. Results and discussion

The three hour version of the Pelamis-specific O&M model was run 50 times for each 'night ops' case, with the mean results shown in Table 4.4. The mean results for each year of the 20 year lifetime are also presented in terms of availability, revenue and OPEX (Figure 4.12, Figure 4.13 and Figure 4.14 respectively).

Table 4.4. Mean results for the two 'night ops' cases

	Availability	Revenue (£k)	OPEX (£k)
Night ops on	86.2%	2777.6	1110.9
Night ops off	83.0%	2650.9	1176.4

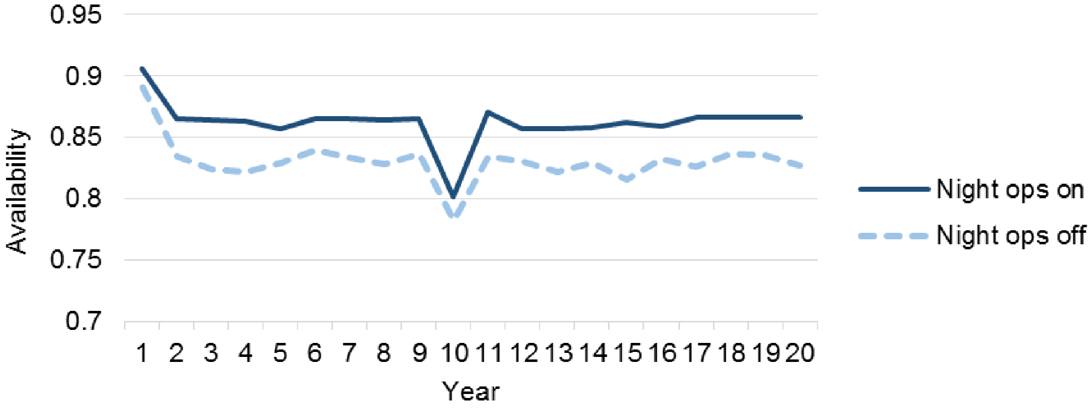


Figure 4.12. Annual mean results for the two 'night ops' cases, in terms of wave farm availability

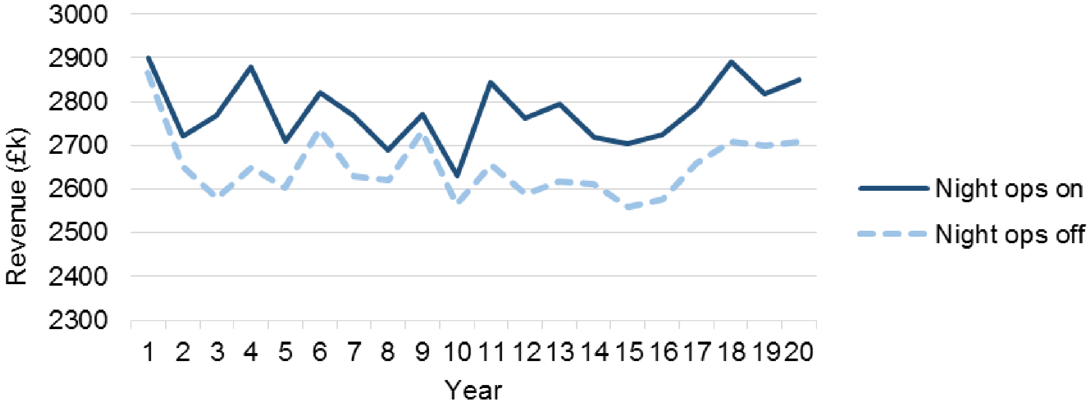


Figure 4.13. Annual mean results for the two 'night ops' cases, in terms of revenue

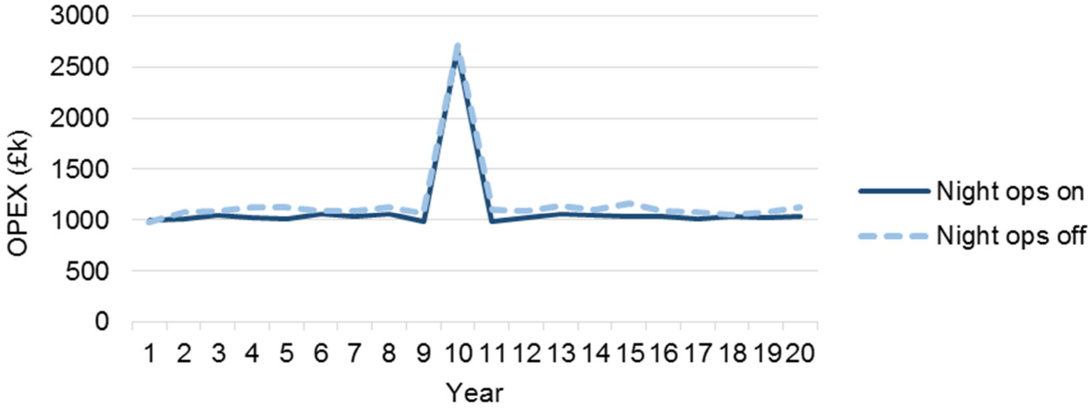


Figure 4.14. Annual mean results for the two 'night ops' cases, in terms of OPEX

The results of the O&M model simulations show that an increase in average wave farm availability of over 3% can be achieved when marine operations are allowed at night, rather than being restricted to daylight hours only. This equates to a 4.8% increase in revenue, from £2.65m per year to £2.78m. There is also a slightly higher annual OPEX incurred when marine operations are constrained to daylight hours, with an average of £1.18m compared to £1.11m, representing a 5.9% increase.

The average wait times of 2.17 days and 3.90 days for the ‘night ops on’ and ‘night ops off’ cases respectively may suggest that allowing marine operations to be undertaken at night would have a much greater impact than seen in the results. The somewhat modest increases in profitability seen can be explained by Figure 4.11, where the average wait times are almost matching for the months from April to August. It is during these months that scheduled maintenance tasks are undertaken, including the half-life refit of major components represented by the spike in OPEX in Figure 4.14 (and matching drop in availability in Figure 4.12). Nevertheless, it is clear that the profitability of a wave farm will increase if marine operations can be undertaken at night. However, achieving this will require further expense in the form of equipment such as floodlights, and will also need engineers to have gained a sufficient level of experience in order to de-risk night-time marine operations.

4.6. Offshore Logistics

It is typical for a wave energy developer to gain consent for an area much bigger than actually required for the wave farm. The exact location of the wave farm will be determined by a number of factors, such as bathymetry. Accessibility will also be taken into consideration. Other aspects of offshore logistics can affect the operability of the wave farm, e.g. selected vessel speed. This section assesses differences in the offshore logistics approach for the Farr Point site by changing the permutations of marine operations using realistic scenarios.

4.6.1. Realistic logistical scenarios

The permutations of marine operations used for the base case O&M model simulations were based on the assumption that the Farr Point wave farm site is located approximately 30km from the O&M base. This distance was calculated to be approximately the centre of the area leased by the Crown Estate, shown in Figure 4.15 as the ‘area of search’. It is therefore possible that a wave farm requiring 3km^2 could be located anywhere inside this 100km^2 area (Aquatera, 2011).

Figure 4.15. 'Area of search' for Farr Point during the consenting phase (Aquatera, 2011)

In addition, although the vessel speed when towing a WEC is limited to 5kts due to safety, it is possible that the vessel speed when not towing could differ from the base case assumption of 15kts. It is also possible that the estimations for installation or removal time, or the time to carry out pre-ops work, could be inaccurate. Taking these possibilities into consideration, two additional scenarios of marine ops permutations have been calculated. Table 4.5 shows the calculated timings and states the permutations (in a 12 hour weather window) used for the analysis.

Table 4.5. Permutations of marine operations

Timings	**Base Case**		**Scenario 1**		**Scenario 2**	
	Value	**Units**	**Value**	**Units**	**Value**	**Units**
Vessel tow speed	5	kts	5	kts	5	kts
Vessel speed (no tow)	15	kts	15	kts	20	kts
Distance to site	30	km	35	km	23	km
Time to site (tow)	3-15	hrs-mins	3-50	hrs-mins	2-30	hrs-mins
Time to site (no tow)	1-5	hrs-mins	1-20	hrs-mins	0-40	hrs-mins
Installation time	1-0	hrs-mins	2-0	hrs-mins	1-0	hrs-mins
Time for installation pre-ops	2-0	hrs-mins	2-0	hrs-mins	1-0	hrs-mins
Retrieval time	0-15	hrs-mins	1-0	hrs-mins	0-15	hrs-mins
Total time for installation	7-20	hrs-mins	9-10	hrs-mins	5-10	hrs-mins
Total time for retrieval	4-35	hrs-mins	6-10	hrs-mins	3-25	hrs-mins
Permutations in a 12 hour weather window	**Base Case**		**Scenario 1**		**Scenario 2**	
	WECs retrieve	**WECs install**	**WECs retrieve**	**WECs install**	**WECs retrieve**	**WECs install**
	2	0	1	0	3	0
	0	1	0	1	0	2
	1	1	0	0	2	1

4.6.2. Results and discussion

The mean results for each scenario are shown in Table 4.6. The normalised results are also shown graphically in Figure 4.16, with 95% confidence intervals applied.

Table 4.6. Mean results comparing scenarios of marine ops permutations

	Availability	Revenue (£k)	OPEX (£k)	Profit (£k)
Base case	86.63%	2840.8	1099.4	1741.4
Scenario 1	84.98%	2782.4	1081.9	1700.5
Scenario 2	87.99%	2886.8	1110.6	1776.2

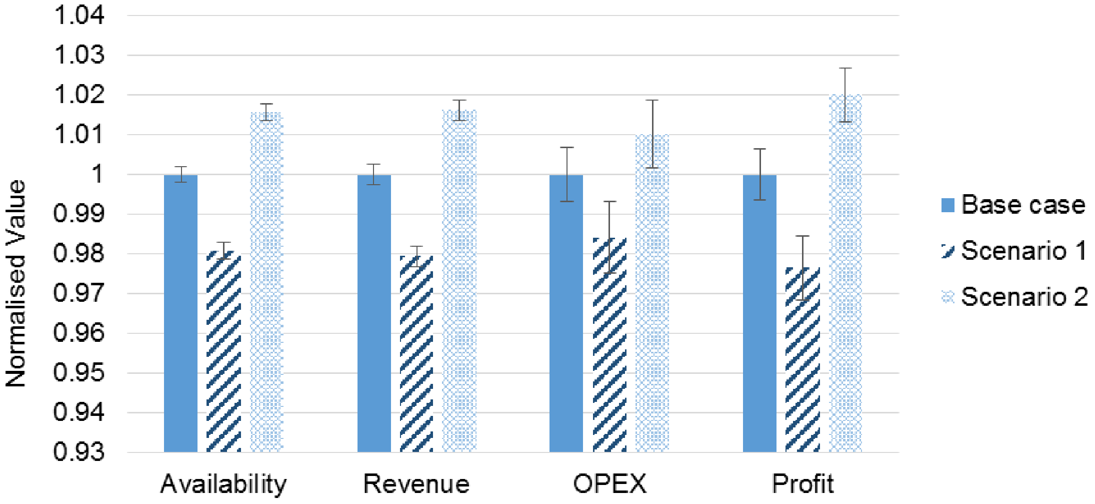


Figure 4.16. Mean results comparing scenarios of marine ops permutations, normalised against the base case, with 95% confidence intervals applied

The results show that, as expected, scenario 2 is the most profitable for the wave farm due to the increased number of marine operations possible in a 12hr weather window. Scenario 2 generates an annual net operational income (i.e. 'profit') of £1.76m, representing an increase on the base case of 2%. In contrast, scenario 1 generates an annual net operational income of £1.7m which is a 2.3% decrease from the base case. In terms of availability, revenue and net operational income, the applied confidence intervals demonstrate that the three cases are sufficiently different. With OPEX however, the confidence intervals overlap for the base case and scenario 2, and are very close to overlapping for the base case and scenario 1. This shows that there is larger degree of variability in the OPEX values than in the other results. Nevertheless, it is clear that during the summer months when all WECs undergo routine servicing, the ability to carry out more marine operations in the same weather window would add significant value to the wave farm. Although care has been taken to ensure the scenarios modelled here are realistically possible, it may well be difficult to achieve the scenario 2 permutations with one multicat vessel. Table 4.7 shows that the profitability of the wave farm drops significantly if scenario 2 requires two vessels (i.e. incurs twice the vessel fees and fuel costs). This makes it clear that offshore logistics need careful consideration when planning the O&M strategy for a wave farm.

Table 4.7. Mean results comparing scenario 2 of marine ops permutations with one and two vessels

	Revenue (£k)	OPEX (£k)	Profit (£k)
Base case	2840.8	1099.4	1741.4
Scenario 2 – one vessel	2886.8	1110.6	1776.2
Scenario 2 – two vessels	2886.8	1423.9	1462.9

4.7. Operational Limits

Weather windows are characterised by the sea conditions that would allow marine operations to be carried out in a safe manner. These operational limits are usually defined by working constraints recommended for vessels, such as maximum speed when towing. The limits can also be laid out by the insurer of the offshore renewable energy project. This section investigates the impact of different operational limits on the profitability of the described P2 wave farm.

4.7.1. Realistic scenarios

The pre-EngD O&M model originally developed at Pelamis Wave Power used weather windows defined by significant wave height (Hs) only. A limit of 2m Hs was assumed for all marine operations, although this was prior to gaining any significant real-sea experience. During the P2 testing programme however, it was found that wave period and wind speed also had an effect on operational limits. The base case limits described previously (see Figure 4.2) were defined during this period. The wind speed limitation of 20kts was applied with the recommendation of vessel operators. Seeing as the P2 testing programme was at a very early stage in the wave energy sector, it is expected that offshore techniques will be improved and streamlined as the industry progresses.

In addition to the base case, two realistic scenarios of operational limits are assessed. Scenario 1 is where a limit of 2m Hs is applied for all marine operations. Wave period and wind speed are not involved in defining weather windows in scenario 1. Scenario 2 has the same constraints as the base case (i.e. 20kts wind speed, Hs varies dependant on Te) except that the Hs limits are increased by 1m (see Figure 4.17).

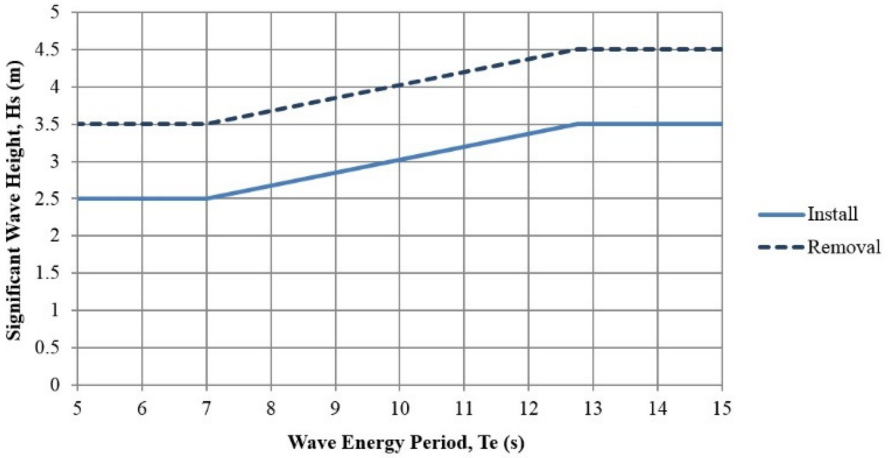


Figure 4.17. Operational limits for scenario 2 (i.e. increased from the base case by 1m)

4.7.2. Analysis of input data

The weather input data to the P2-specific O&M model can be analysed in order to investigate potential differences between the three scenarios of operational limits. The hindcast dataset for Farr Point used as input to the previously described Markov Chain Model is utilised. Firstly, the results of an investigation into the percentage of weather windows for the base case and scenario 2 that were closed solely due to wind speed (i.e. the weather conditions lay within the Hs and Te limits, but wind speed exceeded 20kts) can be seen in Table 4.8. This shows that a wind speed constraint of 20kts becomes more of a limiting factor as the wave-related operational limits increase.

Table 4.8. Weather window analysis of the Farr Point dataset comparing base case ops limits against scenario 2

	Base Case	**Scenario 2**
Percentage of open 12hr windows	46.14%	76.91%
Percentage of closed 12hr windows	53.86%	23.09%
Percentage of 12hr windows closed solely due to wind speed	5.19%	14.38%

The hindcast dataset can also be analysed further by looking at the wait times (i.e. time to wait for a weather window suitable for marine operations). Figure 4.18 (installation) and Figure 4.19 (removal) provide graphical representation of the average wait times in each season by showing the cumulative probability distribution functions of accessibility weather conditions. This information is also presented in terms of the average number of days required to wait for an installation weather window in each month, given the operational limits, in Figure 4.20.

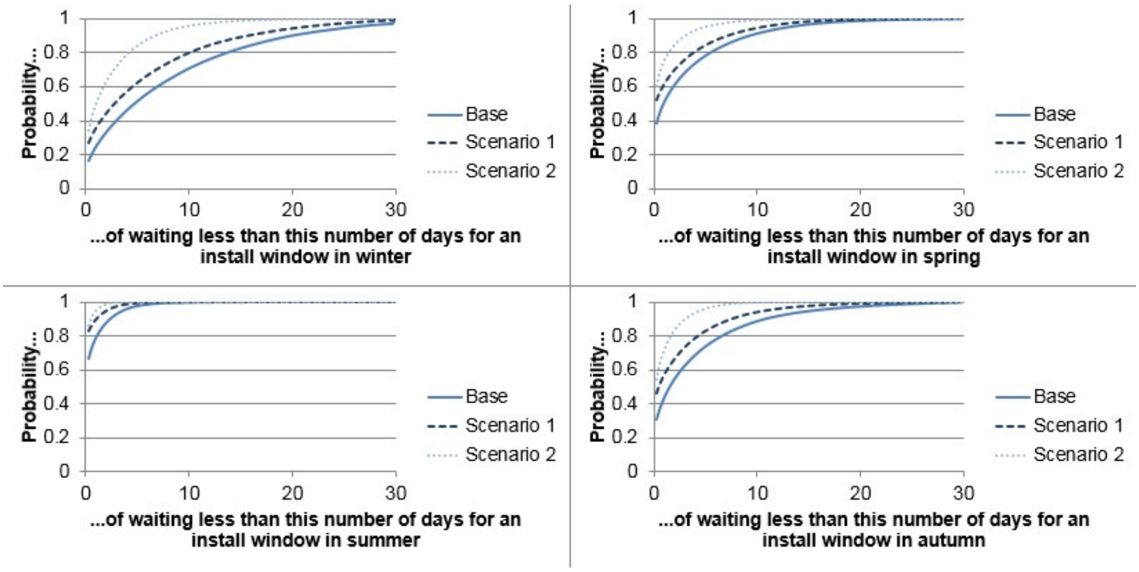


Figure 4.18. Cumulative Distribution Functions of P2 installation accessibility, given the three scenarios of operational limits. Clockwise from top left: winter, spring, summer, autumn

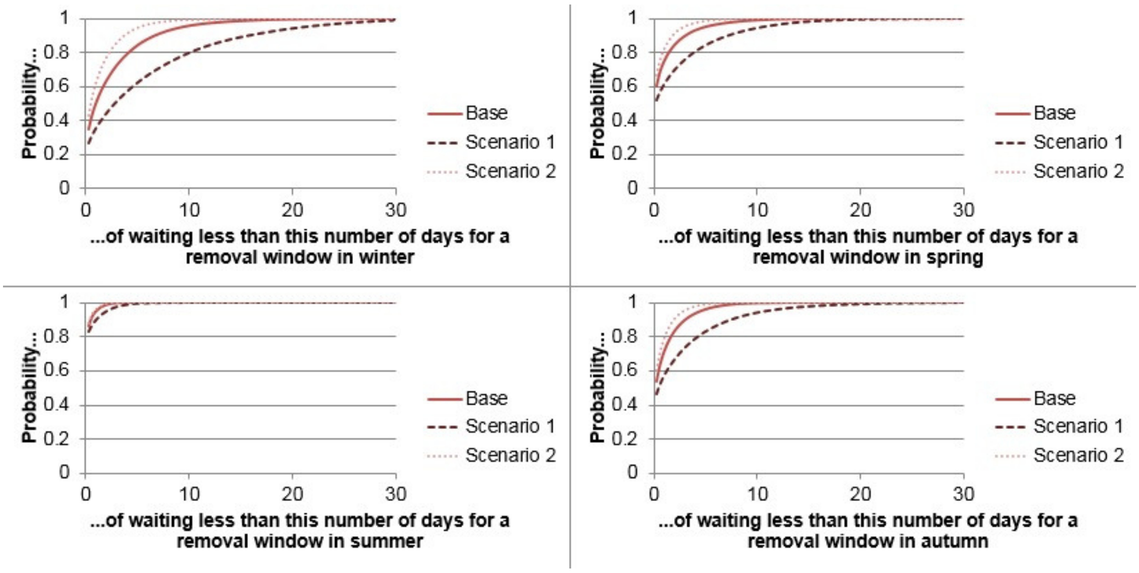


Figure 4.19. Cumulative Distribution Functions of P2 removal accessibility, given the three scenarios of operational limits. Clockwise from top left: winter, spring, summer, autumn

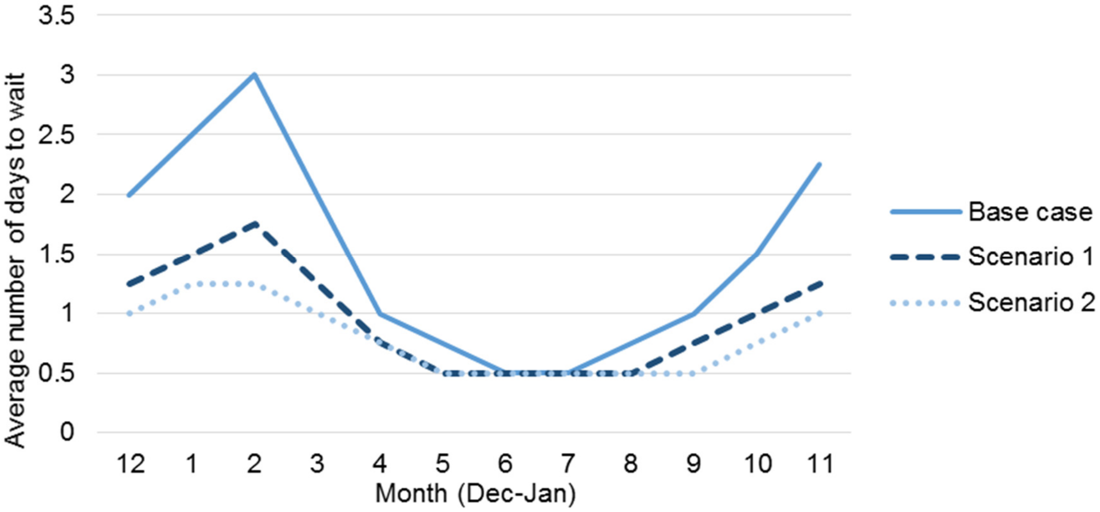


Figure 4.20. Comparison of the three ops limits scenarios in terms of the average number of days to wait for a 12 hour weather window suitable for installation of a P2 device in each month

From Figure 4.18 and Figure 4.19 it can be seen that the highest probability of any weather window being open occurs for scenario 2. Figure 4.19 shows that the constraint of 2m Hs (i.e. scenario 1) is a limiting factor for removal operations, when compared to the other scenarios. However, the base case scenario has the lowest probability of an open weather window for installation through all seasons, as shown in Figure 4.18. This is demonstrated again in Figure 4.20 with the base case having an average annual wait time for installation of 1.48 days compared to 0.96 and 0.79 days for scenarios 1 and 2 respectively.

4.7.3. Results and discussion

The average wait times shown in Figure 4.20 are used as an input to the cost-benefit analysis part of the P2-specific O&M tool in order to produce the results shown in Table 4.9 (i.e. mean results from 50 simulations). These results have also been presented in percentage terms, normalised against the base case (Figure 4.21).

Table 4.9. Mean annual results comparing different scenarios of limits on marine operations

	Availability	**Revenue (£k)**	**OPEX (£k)**	**Profit (£k)**
Base case	86.62%	2840.2	1099.0	1741.3
Scenario 1	87.04%	2859.3	1076.9	1782.4
Scenario 2	87.81%	2880.6	1061.7	1818.9

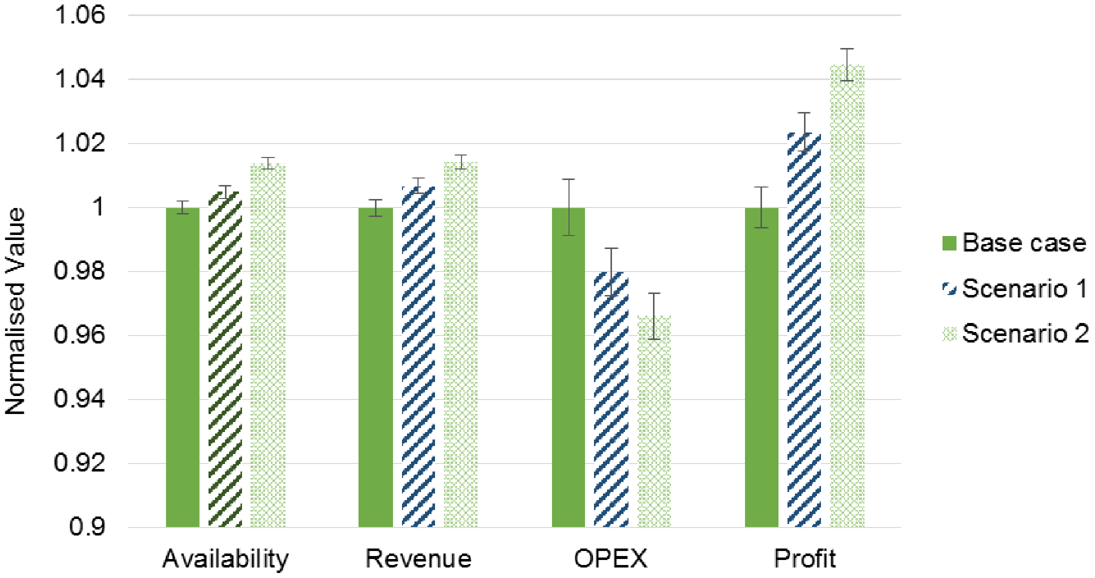


Figure 4.21. Mean results comparing scenarios of limits on marine operations, normalised against the base case, with 95% confidence intervals applied

Scenario 2 is shown to be the most profitable case of operational limits assessed in this study. It generated a mean annual net operational income of £1.82m, representing a 4.5% increase from the base case. Table 4.8 showed that the percentage of open 12hr weather windows increased by 46.1% for the base case up to 76.9% for scenario 2. Figure 4.18, Figure 4.19 and Figure 4.20 show that the time spent waiting for a weather window in much less in scenario 2 than in the base case. By being able to carry out marine operations in more severe weather conditions, faulty WECs are repaired and installed quicker, which improves availability and revenue. In addition, the vessel being on a ‘hire when required’ scheme means that OPEX decreases due the average length of vessel hire being reduced. The 95% confidence intervals applied to the results show that, although there is still a relatively large amount of variance in the OPEX results, the values for mean annual net operational income are sufficiently different.

Scenario 1 has been included to highlight the differences seen when realistic operational limits are applied, developed through real-sea testing of WECs, compared to the pre-EngD model assumptions. Figure 4.18 shows that accessibility for WEC installation when scenario 1 operational limits are applied lies between the base case and scenario 2. However, Figure 4.19 demonstrates that scenario 1 has the longest wait times for a WEC retrieval operation. Nevertheless, all the presented results for scenario 1 lie between the other two cases, with a mean annual net operational income of £1.78m (an increase from the base case of 2.3%). It is therefore vital to use realistic inputs for operational limits in order to obtain the best estimates for wave farm profitability possible.

The base case operational limits have been developed using the experience gained by Pelamis Wave Power during the P2 testing programme, where one multicat vessel has been assumed to be capable of undertaking all marine operations. A larger vessel may be required in order to achieve the operational limits outlined by scenario 2. For example, during the prototype testing, Pelamis Wave Power used an anchor handler vessel, commonly used in the oil and gas industry. The cost of such vessels can fluctuate significantly, depending on market demand. Table 4.10 shows that the profitability of the wave farm drops significantly if vessel mobilisation and daily hire fees are increased (x5 in this example). This makes it clear that wave farm developers should focus more on streamlining their marine operations to allow the use of low cost, readily available boats, rather than utilise larger and more expensive vessels in a bid to increase operational limits.

Table 4.10. Mean results comparing scenario 2 of operational limits if vessel fees are increased

	Revenue (£k)	**OPEX (£k)**	**Profit (£k)**
Base case	2840.2	1099.0	1741.3
Scenario 2 – multicat	2880.6	1061.7	1818.9
Scenario 2 – vessel fees x5 (e.g. anchor handler)	2880.6	1978.0	902.6

4.8. Spare Machine

An O&M strategy that was under consideration by Pelamis Wave Power, and may well be considered by wave farm developers in the future, is the concept of keeping one or two spare WECs at the quayside ready to replace a fault device. The spare machines will be fully maintained and will provide benefits such as technician training and marine operations practice, as well as allowing the rapid replacement of a faulty WEC in order to minimise downtime. This section explores the economic viability of this concept for the base case 10 berth wave farm, as well as for wave farms of a greater number of devices.

4.8.1. Initial results

Two different scenarios are assessed in this study, in addition to the base case: having one or two spare machines ready to be installed at the site. The base case wave farm consists of 10 machines. In this study, the size of the wave farm is referred to as the number of berths. In other words, the base case has 10 berths at the wave farm with a total of 10 machines. The 'one spare machine' scenario means that the wave farm has 11 WECs, with only 10 berths. The spare machine is assumed to undergo the same scheduled maintenance events as the other machines. There are no additional costs to account for the personnel and vessel crew training, although this is seen as a benefit of the spare machine concept. Table 4.11 and Figure 4.22 show the mean results for each of the scenarios assessed in this study. The availability results are for the wave farm in terms of the number of berths, not the number of machines.

Table 4.11. Mean annual results for a 10 berth wave farm comparing different spare machine scenarios, with 95% confidence intervals shown

	Availability	**Revenue (£k)**	**OPEX (£k)**	**Profit (£k)**
Base case	86.62% ± 0.19%	2840.9 ± 7.7	1096.9 ± 9.9	1744.0 ± 13.0
1 spare machine	87.16% ± 0.20%	2857.7 ± 8.2	1058.4 ± 7.2	1799.4 ± 10.2
2 spare machines	87.10% ± 0.20%	2850.8 ± 8.3	1090.8 ± 6.9	1760.0 ± 11.8

Figure 4.22. Mean results for a 10 berth wave farm comparing different spare machine scenarios, with 95% confidence intervals applied

The results show that the scenario with one spare machine is the most profitable, primarily due the low annual OPEX cost. The applied 95% confidence intervals show that there is very little difference between the three scenarios. The ‘base case’ and ‘two spare machines’ scenarios overlap on every result shown in Table 4.11. The 'base case’ and ‘one spare machine’ scenarios are very close to overlapping, particularly for the availability and revenue results. The fact that the ‘two spare machines’ scenario incurs greater OPEX costs than with one spare WEC implies that the cost of scheduled maintenance events begins to outweigh the repair costs of random failures as the number of spare machines increases. Although the ‘one spare machine’ scenario is shown to generate the highest net operational income for this 10 berth wave farm, these results do not take capital expenditure (CAPEX) into account.

4.8.2. CAPEX estimation

In order to gain a better understanding of the economic viability of the spare machine concept, CAPEX must be included in the calculations. CAPEX has not been included in the calculations thus far due to the fact that it does not affect the assessment of the different O&M strategies previously presented. A breakdown of assumptions for various aspects of CAPEX is provided in Table 4.12. This information has been taken from the fabrication costs of the pre-commercial P2 WEC. From these assumptions, the cost of a single WEC is taken to be £6.12m, with an additional £1m added to the OPEX in year 20 to account for decommissioning. The remaining CAPEX of the wave farm, involving aspects such as O&M base development, equates to £24.8m.

Table 4.12. Breakdown of CAPEX assumptions for a wave farm consisting of 10 Pelamis P2 WECs

Item	CAPEX	Notes	Total CAPEX for 10 machine farm
WEC manufacturing cost	£6m per WEC	Based on pre-commercial P2 WEC costs	£60m
WEC insurance	£120k per WEC	2% of device CAPEX	£1.2m
O&M base development	£20m	Quayside, shed, office space	£20m
Licencing and surveys	£0.8m	Farr Point experience	£0.8m
Subsea station	£2m	No prior deployment	£2m
Balance of plant	£1m	Quayside machinery	£1m
Spare parts	£1m	Stored in shed	£1m
Decommissioning	£1m per WEC	Added to OPEX in year 20	£10m (year 20)

4.8.3. Levelised cost of energy

The impact of using the spare machine concept as part of the O&M strategy of a commercial wave farm can be better assessed using levelised cost of energy (LCOE) calculations. Equation 4.2 repeats the LCOE formula stated in chapter 1. The figures for annual energy production (AEP) are calculated by multiplying the annual revenue produced by the O&M model by the electricity sale price. The calculated LCOE for each of the three spare machine scenarios is shown in Figure 4.23 for a range of discount rates. It should be noted that these calculated values are in no way representative of the commercial potential of wave energy devices. Offshore wind turbines can be installed at a CAPEX of around £1m per MW, and achieve capacity factors of up to 40% of rated power. The CAPEX assumptions made for the P2 WEC have come from pre-commercial devices, and are therefore significantly higher (at approximately £8m per MW) than would be expected for commercial WECs. In addition, the power matrix in the P2-specific O&M model has been inferred from the contracted targets that Pelamis Wave Power had during the P2 testing programme. A commercial WEC would achieve a far greater AEP than used for these LCOE calculations. Therefore, the

LCOE values presented here are only used for comparison between different O&M strategy scenarios, and should not be taken out of this context.

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{AEP_t}{(1+r)^t}} \qquad (4.2)$$

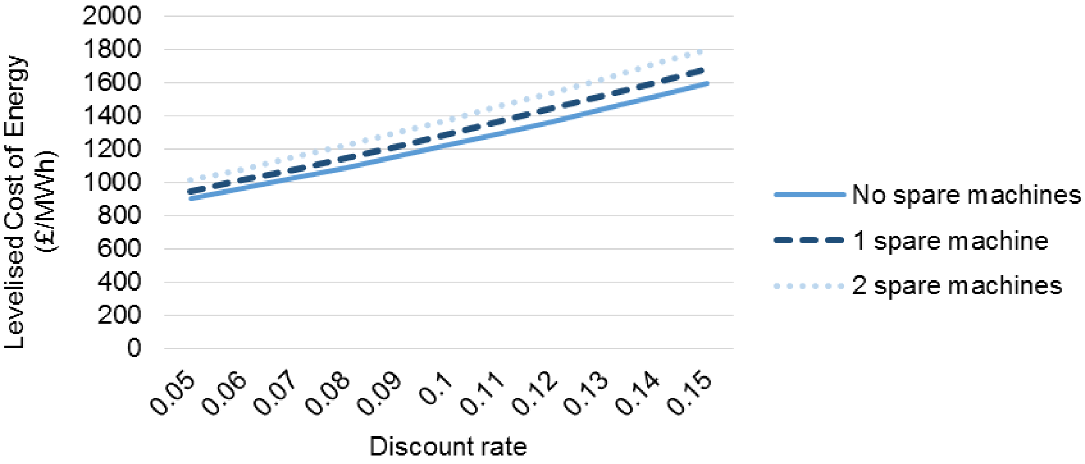


Figure 4.23. LCOE comparison of three different 'spare machine' concepts, using a range of discount rates, if deployed in a 10 berth P2 wave farm

The LCOE calculations show that using the spare machine concept is not economically viable for a 10 berth P2 array, as the increased net operational income does not outweigh the CAPEX of the extra WECs. The 'no spare machine' scenario has the lowest LCOE, regardless of the applied discount rate.

4.8.4. Larger wave farms

Further analysis has been undertaken to attempt to find the 'break-even point' where utilising a spare machine becomes an economically viable option. The Pelamis-specific O&M model was modified to analyse wave farms of an increasing number of berths, from 15 to 40 in steps of 5. For each wave farm, the three 'spare machine' scenarios were assessed. Where 50 simulations were used to obtain the main results for the base case wave farm, 10 simulations were run for each of the analysed scenarios (and wave farms). The LCOE has been calculated for each analysis, with the CAPEX assumptions stated previously. In reality, it is likely that more money would need to be spent on O&M base development for a 40 berth wave farm than for a 10 berth array if the ability to store an unlimited number of devices at the quayside is required (as assumed in the O&M tool). However, this study is focused on the differences between the three 'spare machine' scenarios, rather than the actual LCOE values for different wave farms. Figure 4.24 presents the LCOE results for a discount rate of 0.1. Discount rates of 0.05 and 0.15 are also presented in Figure 4.25. Again, these LCOE values should not be taken out of context as they do not represent the true potential of a commercial wave farm.

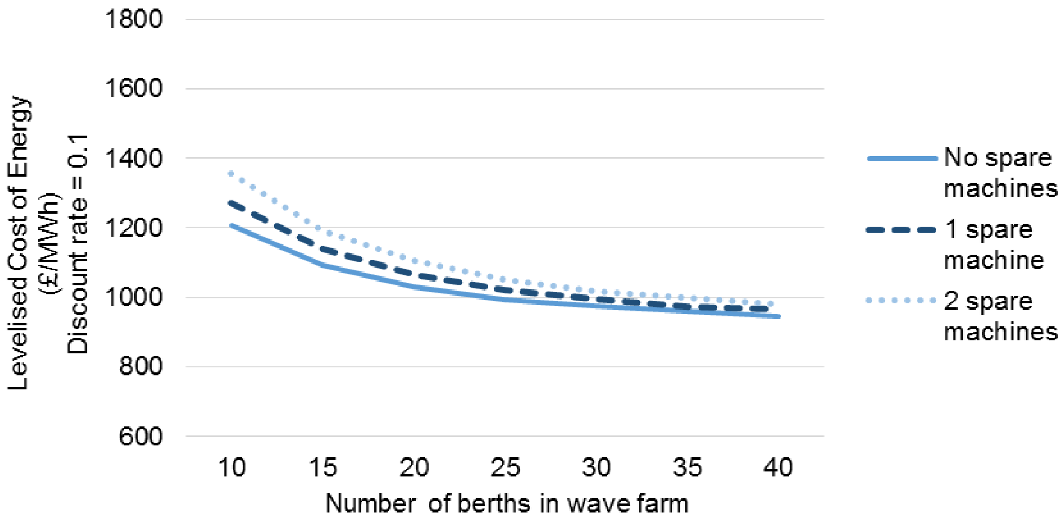


Figure 4.24. LCOE comparison of three 'spare machine' concepts for different sizes of wave farm, with a discount rate of 0.1

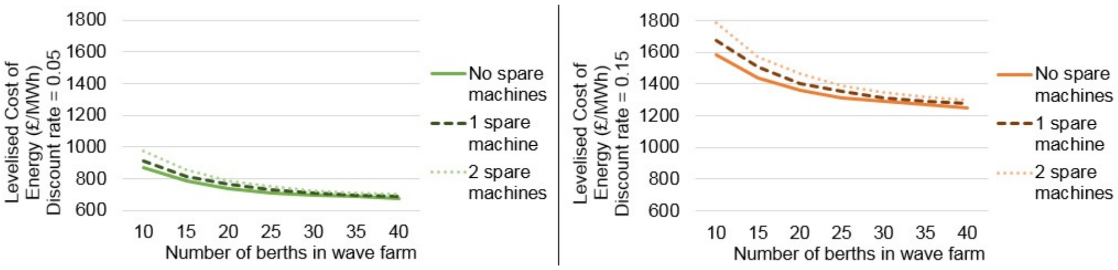


Figure 4.25. LCOE comparison of three 'spare machine' concepts for different sizes of wave farm, with discount rates of 0.05 (left) and 0.15 (right)

In all cases of wave farm size and discount rate, the results show that the 'no spare machines' scenario has the lowest LCOE. The 'two spare machines' scenario has the highest LCOE. This suggests that any increase in annual net operational income is negated by the extra cost of the spare machine/s. In this analysis, at no point do the presented LCOE curves overlap, meaning that the 'breaking point' (i.e. where utilising a spare machine becomes an economically viable option) is never reached. As the wave farm increases in the number of berths, however, the LCOE values of the three scenarios begin to converge. This implies that using one or two spare machines in larger wave farms is a more useful strategy that at the 10 berth level. A much more detailed analysis would need to be undertaken to truly assess the potential of the strategy in larger wave farms due to the number of variable inputs to consider. For example, the base case incurs an external contractor fee (i.e. additional technicians) of £26k p.a. This increases to £134k p.a. for the ‘no spare machines’ scenario in a wave farm with 40 berths. It is not certain that this level of additional labour would be available for the wave farm, meaning that the number of technicians permanently employed at the O&M base would need to be reviewed. Such aspects of an O&M strategy need to be considered when assessing the viability of larger wave farms.

4.9. Labour Considerations

Throughout the previous simulations presented in this chapter, the O&M model assumes that an unlimited number of technicians can be hired as external contractors, in addition to the permanently employed personnel at the O&M base, in order to ensure that repairs and maintenance are not delayed by a lack of available labour. It is possible that this arrangement may not be viable in a commercial wave farm due to external constraints. This section first assesses the impact on profitability of the base case P2 wave farm if external contractors cannot be hired. Taking this scenario further, an analysis on the optimal number of technicians permanently employed at the O&M base has been carried out.

4.9.1. External contractors

The base case used for the O&M model simulations assumed that a total of 12 personnel are employed at the 10 WEC wave farm. The ‘contractor’ scenario (i.e. base case) involves hiring extra personnel at a rate of £200/day whenever maintenance would otherwise be delayed due to a lack of available technicians. The results shown in Figure 4.26, Figure 4.27 and Figure 4.28 compare the base case with a scenario where external contractors cannot be hired. In this ‘no contractors’ scenario, all repairs and maintenance have to be undertaken by the technicians permanently employed at the O&M base. At any given time interval, if the required number of specialist technicians are not available for a new maintenance task, then the work is postponed until the current task/s are completed, thus freeing up the technicians’ time. Working hours are accounted for in the ‘time to repair’ values provided as inputs for each fault category and maintenance event (see appendix Tables A.1 and A.2).

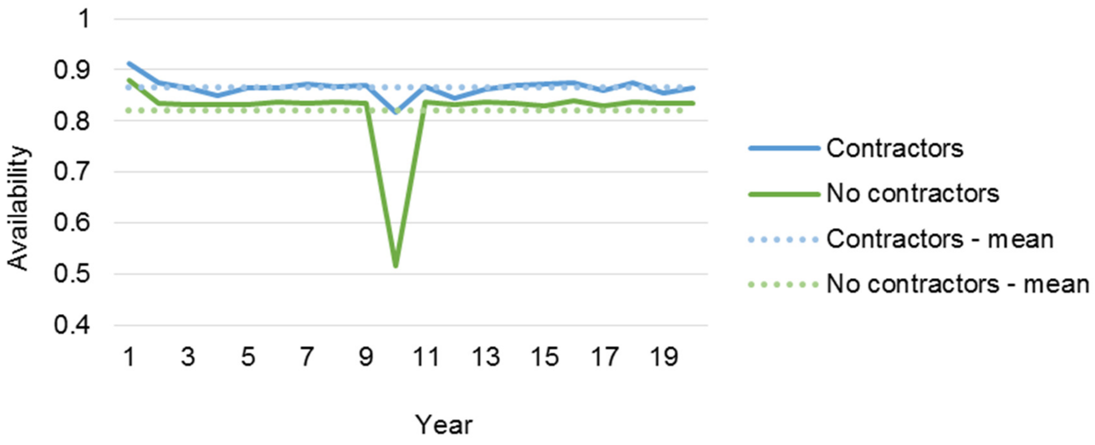


Figure 4.26. Annual mean wave farm availability comparing the two contractor scenarios

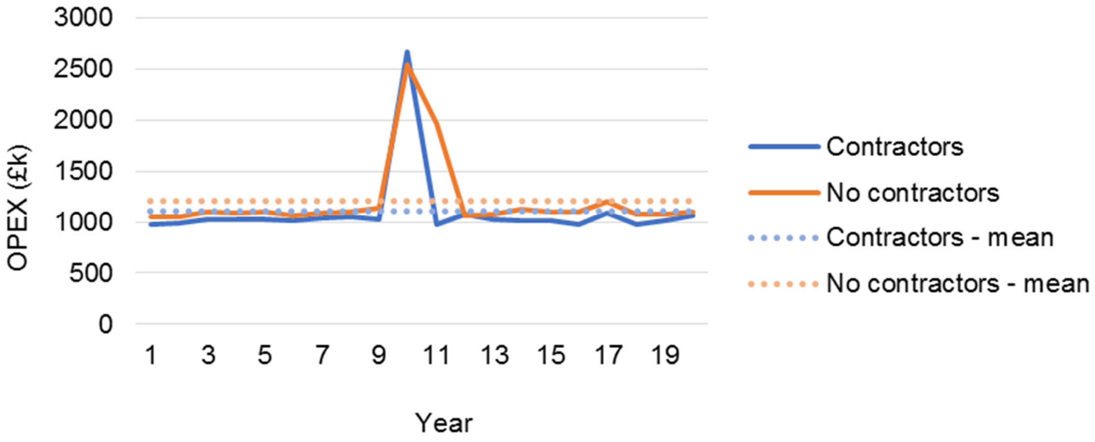


Figure 4.27. Annual mean OPEX comparing the two contractor scenarios

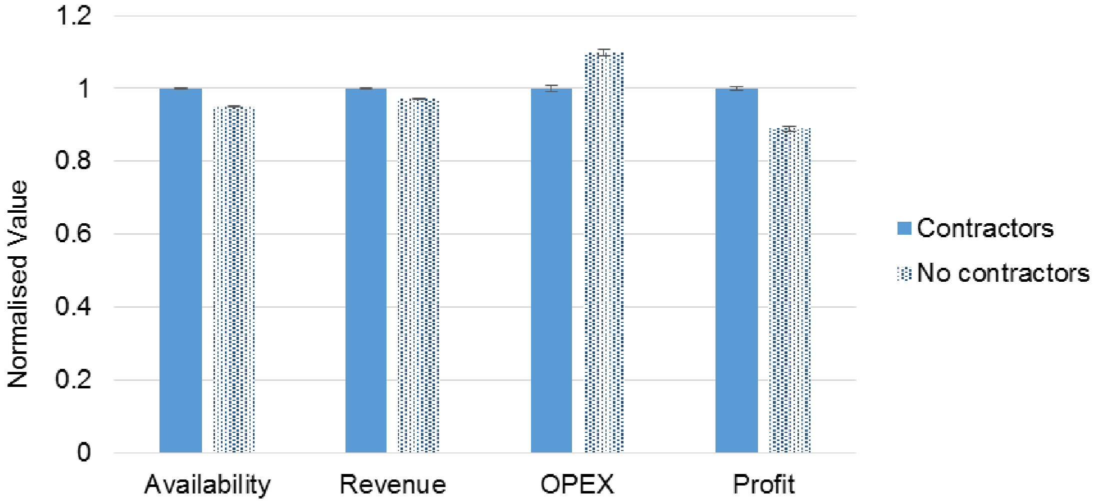


Figure 4.28. Mean results comparing the two contractor scenarios, normalised against the base case (i.e. 'contractors' scenario), with 95% confidence intervals applied

The results show that removing the ability to hire external contractors means that the annual net operational income is reduced by 11% when compared to the base case (Figure 4.28). When contractors are allowed, there are no maintenance tasks delayed due to a lack of technicians, making the availability and revenue of the wave farm increase. In addition, the increased labour cost in the base case is negated by the fact that the vessel stays on hire for fewer days, thereby reducing overall OPEX costs. The impact that the major scheduled maintenance event in year 10 has on profitability is greatly reduced when contractors are allowed. This is shown by the sharp trough in availability in Figure 4.26. In the base case, the availability drops to approximately 82% whereas, for the 'no contractors' scenario, it drops significantly further down to 52%. With external contractors involved, scheduled maintenance can potentially be undertaken on multiple WECs simultaneously, thereby greatly improving average wave farm availability during these periods. Figure 4.27 also shows that the year 10 maintenance event often carries through the winter into year 11 in the 'no contractors' scenario. It is clear that a staggered maintenance approach would be required if the hire of external contractors was restricted in a commercial wave farm.

4.9.2. O&M base workforce

If the ability to hire external contractors as technicians is not an option for the wave farm, then an optimisation of the number of specialist and non-specialist technicians employed permanently at the O&M base would be required to maximise profitability. Table 4.13 details 11 scenarios of labour arrangements at the O&M base, as well as the new base case (i.e. the original base case without the use of external contractors). Scenario 1 is the workforce arrangement with the lowest possible total labour cost, whilst still supplying enough specialist technicians to deal with the most severe failures and the scheduled overhaul of major components in year 10. Each scenario also includes an O&M base site manager who is available to work as a non-specialist technician. The salary of the site manager is included in the total annual salary figure for each scenario.

Table 4.13. Scenarios of different labour arrangements at the O&M base

Scenario ID	**Number of technicians**					**Total annual salary (£k)**	**Notes**
	Moorings	**Hydraulic**	**Structural**	**Electrical**	**Apprent-ice**		
Base Case	2	3	3	2	1	355	Contractors allowed
Base case 2	2	3	3	2	1	355	Base case, no contractors
1	2	2	3	2	0	315	Minimum
2	2	2	3	2	1	325	Minimum + 1 apprentice
3	2	2	3	2	2	335	Minimum + 2 apprentices
4	3	3	3	2	1	385	Base case + 1 moorings
5	2	4	3	2	1	385	Base case + 1 hydraulic
6	2	3	4	2	1	385	Base case + 1 structural
7	2	3	3	3	1	385	Base case + 1 electrical
8	2	3	3	2	2	365	Base case + 1 apprentice
9	2	3	3	2	3	375	Base case + 2 apprentices
10	3	4	4	3	2	485	Base case + 1 all
11	4	5	5	4	3	615	Base case + 2 all

As stated previously, the total labour cost is calculated with an overheads multiplier of 1.3 on top of the annual salary. For each scenario listed in Table 4.13, the P2-specific O&M model was run 50 times, with the mean results of availability, revenue, OPEX and net operational income presented in Figure 4.29, Figure 4.30, Figure 4.31 and Figure 4.32 respectively. The original base case (i.e.

the same arrangement of technicians as 'base case 2', but with external contractors allowed) is shown in the results for reference.

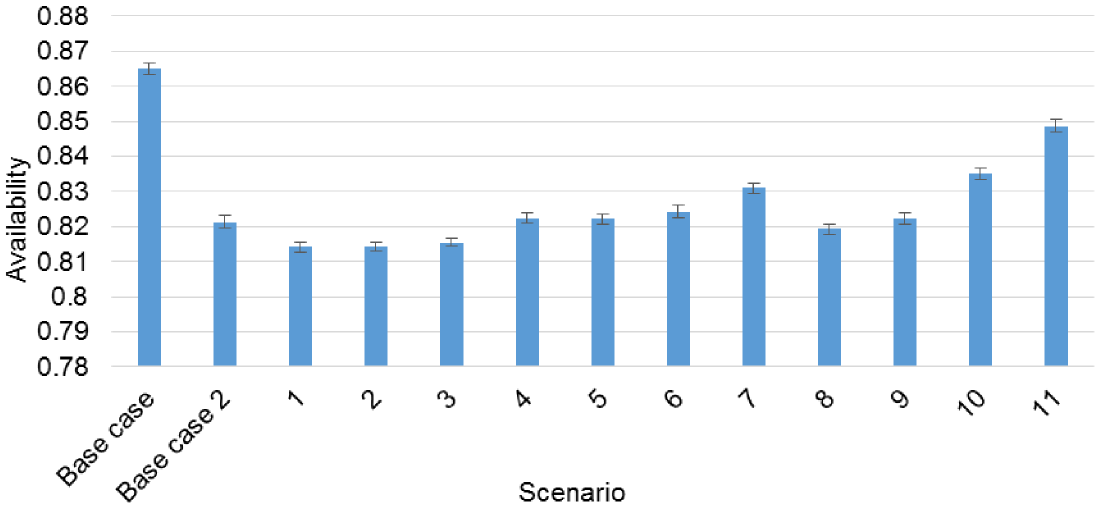


Figure 4.29. Wave farm availability for a series of workforce arrangements, with 95% confidence intervals applied

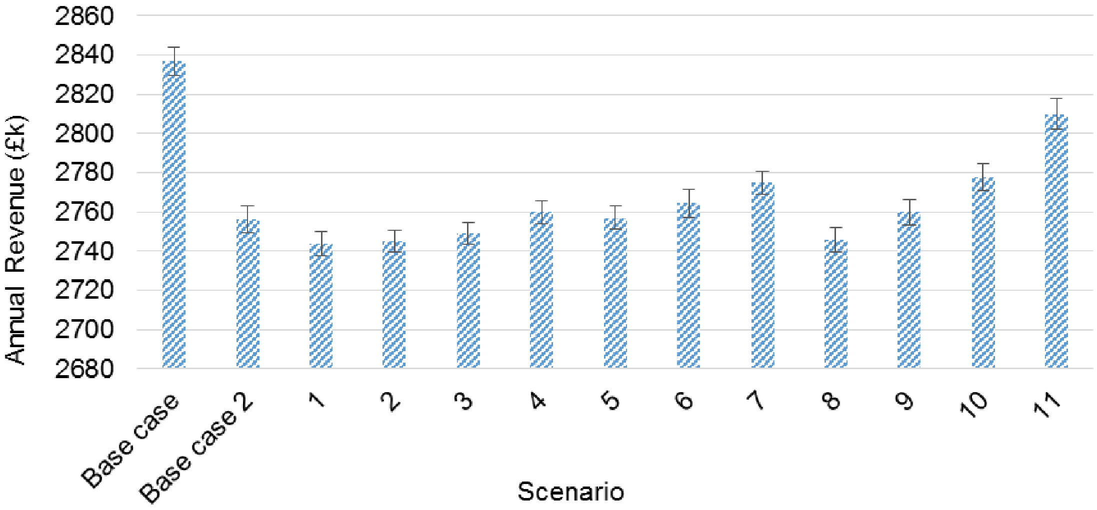


Figure 4.30. Annual revenue for a series of workforce arrangements, with 95% confidence intervals applied

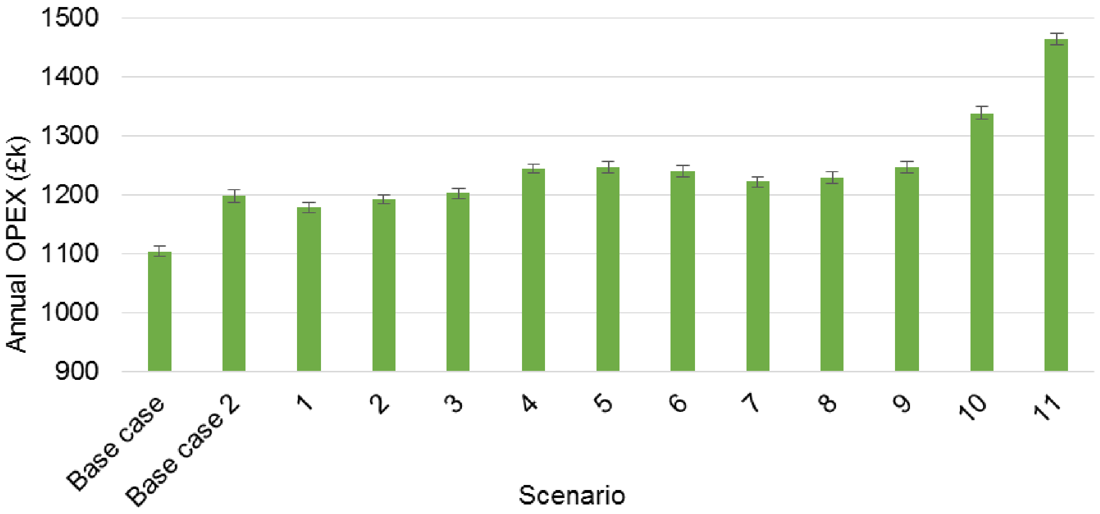


Figure 4.31. Annual OPEX for a series of workforce arrangements, with 95% confidence intervals applied

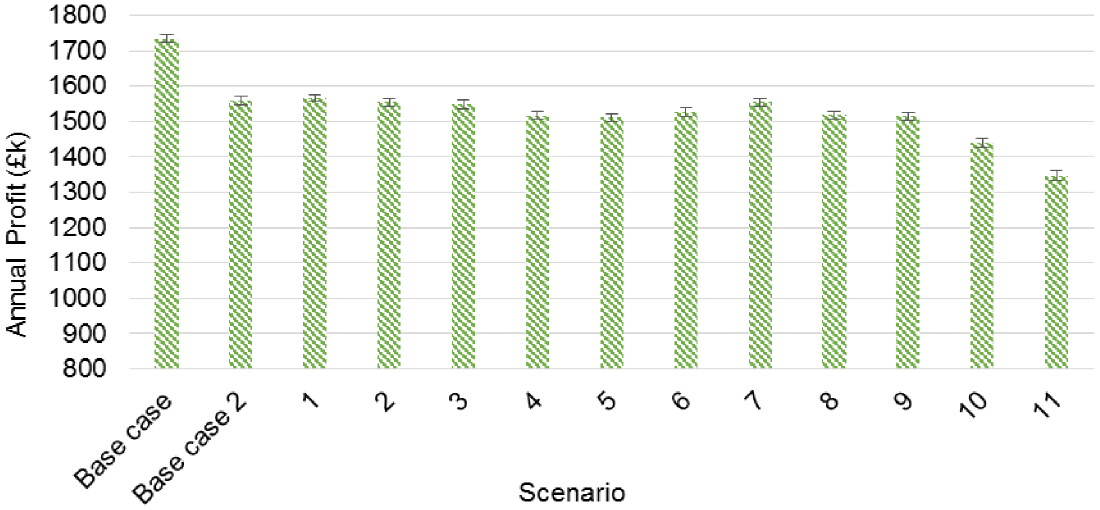


Figure 4.32. Annual profit for a series of workforce arrangements, with 95% confidence intervals applied

Scenario 11 has the largest workforce and therefore shows the best availability and revenue results of the 'no contractor' scenarios in Figure 4.29 and Figure 4.30 respectively. Repairs and maintenance tasks are delayed far less often if more technicians are available. However, this scenario also incurs the greatest OPEX, shown in Figure 4.31, due to the substantial increase in fixed labour costs. This has the effect of completely negating any increase in revenue, with Figure 4.32 showing scenario 11 to be the least profitable of all the arrangement considered. Scenario 10 has the second lowest annual net operational income.

Scenario 7 (defined as the base case plus one electrical technician) shows the third highest results in terms of availability and revenue, after scenarios 11 and 10. This suggests that electrical failures, or maintenance tasks that require an electrical technician, cause the most delays in undertaking repairs or maintenance. This is confirmed when the OPEX for scenario 7 is compared to the results for scenarios 4, 5 and 6. The fixed labour cost is the same for all four scenarios, yet scenario 7 shows the lowest OPEX. This is because the multicat vessel is, on average, on hire for fewer days in scenario 7 when the WECs are repaired and maintained faster. In observing the 95% confidence intervals, it can be seen that there is no clear difference between the average annual net operational income for scenarios 1, 2, 3, 7, and base case 2 (i.e. the ‘no contractors’ base case).

For this particular wave farm (made up of 10 P2 devices), scenario 7 is the most attractive workforce arrangement, with a high availability being achieved, as well as a good net operational income. However, from the slight differences between the results of all the assessed scenarios, it is clear that a different size of wave farm may have a much different optimal workforce arrangement. Nevertheless, in this analysis, none of the assessed ‘no contractors’ scenarios come close to achieving the same level of annual net operational income as the original base case where external contractors can be hired. With labour costs contributing so much to overall OPEX, project developers need to consider the workforce arrangements of their wave farms very carefully. Hiring external contractors to support permanently employed technicians during peak times should certainly be considered.

4.10. Chapter Discussion

A series of sensitivity analyses have been undertaken in this chapter in order to assess various options that could form part of an O&M strategy for a commercial wave energy array. The case study of a wave farm containing ten Pelamis P2 wave energy converters was used. The method of changing certain inputs to the P2-specific O&M model allowed each option to be analysed in terms of the effect on availability, revenue, operational expenditure and annual net operational income of the wave farm. The base case assumptions modelled a ten P2 wave farm with an 86.8% annual availability, £2.85m annual revenue and £1.09m annual OPEX.

Five options for hiring or purchasing a multicat vessel for the P2 wave farm were assessed. The analysis found that long term lease arrangements may not be viable for a ten WEC wave farm. The annual net operational income was highest when the vessel was purchased outright at the beginning of the wave farm's twenty year lifetime. However, this does not take into account the reluctance of a wave farm operator to spend such a large amount on a vessel in year one, nor does it consider net present value (NPV). When NPV is incorporated into the calculations, the highest total net operational income over the lifetime of the wave farm came from the base case 'hire when required' vessel arrangement.

The base case assumption is that marine operations can be undertaken at night. When marine operations were constrained to daylight hours only, the model showed only a slight decrease in profitability of the wave farm. This is because most marine operations are undertaken during the summer months, when routine maintenance is scheduled. The longer daylight hours in the summer, particularly in the north of Scotland, mean that operations are not significantly affected by being constrained to daylight hours only.

Analyses into offshore logistics and operational constraints showed clearly that being able to carry out more offshore operations in the same weather window, or undertake marine operations in more severe weather conditions, increase profitability of a wave energy array. However, achieving this level of confidence in offshore operations requires a significant amount of experience and may incur additional costs which could negate the increase in profitability.

The strategy of keeping a spare WEC at the quayside fully maintained and ready to replace a faulty device was found to be unviable for wave farms of the size considered in this study.

The ability to hire external contractors to support permanently employed technicians was found to be beneficial to the operability of the wave farm, especially during peak maintenance times such as summer months when routine servicing takes place. If this is not an option, then an extra electrical technician would need to be added to the base case assumptions of the workforce employed at the O&M base in order to achieve the highest possible net operational income from the wave farm.

The analysis presented in this chapter has demonstrated how a simulation model can be used to optimise the O&M strategy for wave energy farms, thereby cutting down overall levelised cost of energy (LCOE). The aspects of the O&M strategy considered in this chapter are by no means all encompassing, however, they do provide the foundation for refining the base case assumptions for the O&M strategy of this particular 10 P2 wave farm. Table 4.14 lists the differences between the base case assumptions and the 'optimal' O&M strategy.

Table 4.14. O&M model assumptions for the optimal case compared to the base case

O&M Strategy Consideration	Base Case	Optimal Case
Vessel hire/purchase	Hire when required	Hire when required
Night operations	Allowed	Allowed
Offshore logistics	See Table 4.5	Scenario 2, see Table 4.5
Operational limits	See Figure 4.2	Scenario 2, see Figure 4.17
Spare machine	No	No
External contractors	Allowed	Allowed
O&M base workforce	See Table 4.13	Scenario 7, see Table 4.13

The optimal case described in Table 4.14 has been run 50 times in the P2-specific O&M model, with the results, normalised against the base case, presented in Figure 4.33. The LCOE values have been calculated using the same CAPEX assumptions as described in Table 4.12, with a discount rate of 10%.

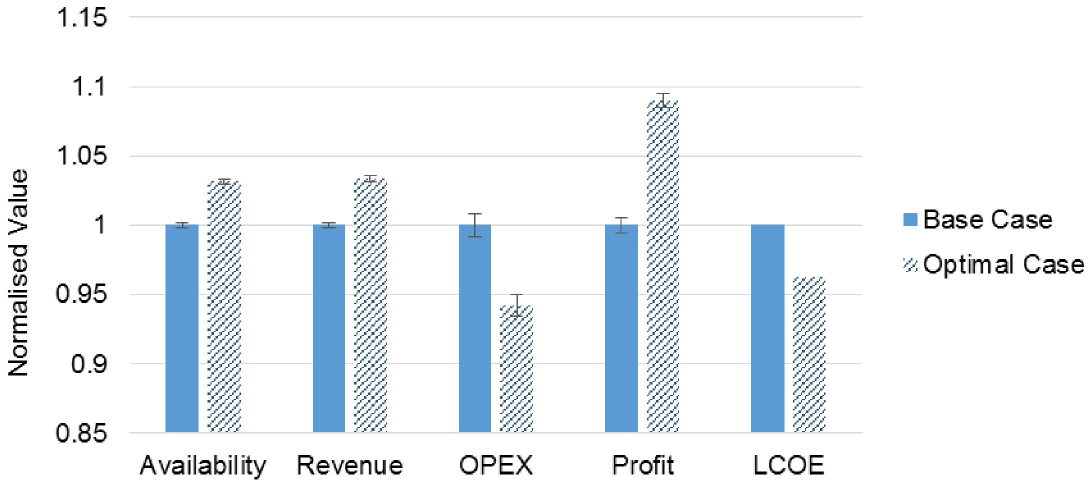


Figure 4.33. Results of the 'optimal' O&M strategy, normalised against the base case, with 95% confidence intervals applied

The optimised O&M strategy gives the modelled wave farm greater operability and profitability than the base case assumptions. Availability increases by nearly

3%, from 86.6% up to 89.3%, with a matching percentage increase in annual revenue. Annual OPEX is reduced by 6%, from £1.09m to £1.03m. This has the effect of increasing annual net operational income by 9%, from £1.75m with the base case assumptions up to £1.91m for the optimised O&M strategy. When net present value is included in the calculations, the Levelised Cost of Energy shows a 4% decrease for the optimised strategy.

These results have been produced for the wave farm consisting of ten Pelamis P2 devices described in this chapter, and therefore, the specific values may not be relevant for all wave energy arrays. In addition, the few aspects of O&M considered in this chapter by no means incorporate all the possibilities for a wave farm's O&M strategy. However, the analysis undertaken in this chapter does show how taking steps to streamline O&M strategies can increase the profitability, and therefore attractiveness to investors, of grid-connected wave energy arrays. The analysis has also shown how useful an O&M simulation model can be in assessing different options in an effort to optimise the O&M strategy.

Chapter 5 – Albatern O&M Strategies

The community-scale, off-grid wave energy array concept needs to be analysed from an operations and maintenance viewpoint to assess the economic impact of different O&M strategy considerations. As with grid connected wave farms, there is no pre-defined optimal O&M strategy for every possible wave energy site. The strategy needs to be tailored to the specific site and selected WEC design. Operations and maintenance aspects of an off-grid wave energy array require close collaboration with the customer (e.g. a fish farm or island community), in order to deliver social benefits as well as providing a financial return on investment. Using an O&M simulation tool tailored specifically to Albatern's 6-series wave energy device, it is possible to analyse O&M options that could be used for a community-scale, off-grid wave energy array.

In this chapter, an Albatern-specific O&M tool is used to assess different O&M aspects of an off-grid WEC array. Section 5.1 outlines the basic O&M principles of the Albatern device. In section 5.2, the inputs and functionality changes that make the generic O&M tool specific to Albatern's device are described. A small wave energy array is assessed in section 5.3, before being scaled up in section 5.4. Section 5.5 states the base case for the subsequent O&M strategy analysis. Section 5.6 investigates different scenarios of O&M base facilities and onshore logistics. In section 5.7, several vessel arrangements for the wave energy array are assessed. Section 5.8 investigates the impact if repairs and maintenance can only be carried out at the onshore O&M base. Employment of technicians and other labour considerations are analysed in section 5.9. Section 5.10 looks into the impact on operability of the wave energy array if it was located further from the onshore O&M base. The initial assumption of sale price of electricity generated by the array is challenged in section 5.11. A discussion of the key results and outcomes of the chapter is provided in section 5.12.

5.1. Albatern O&M

Albatern's 6-series 'Squid' device (Figure 5.1) is a form of articulated WEC, several units of which can be connected together and deployed in a 'WaveNET' array (Figure 5.2). The 6-series (a.k.a. 6s) device is very small in terms of power output, at 7.5kW, especially when compared to the Pelamis P2 WEC. The devices are intended to supply clean energy to fish farms and off-grid communities as a replacement for diesel generated power. The modular nature of the Squid devices means that the main electrical and mechanical components are easily accessible. The power take-off unit (PTO) is located inside one of the anti-nodes and could therefore be replaced whilst offshore (a.k.a. onsite) without having to retrieve the entire Squid device. Other components, such as the instrumentation box, are also easily accessible. However, Squid retrieval is required for some faults and for routine inspections. When a Squid is retrieved, it can be towed using a low cost vessel into the safety of an onshore O&M base, where maintenance can take place independent of adverse weather conditions. The moorings and electrical connections within the WaveNET array have been designed so that a single Squid can be manually disconnected and rapidly placed in transport mode (with the arms folded in) without affecting the other devices in the array. Sheltered sea trials of the 6s Squid have been carried out, however, operational experience is still limited when compared to the Pelamis P2 WEC. This uncertainty is addressed later in this thesis.

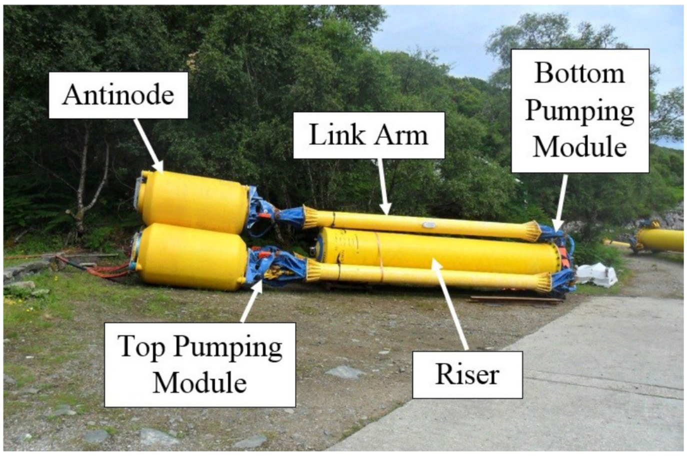


Figure 5.1. Albatern's 6-series Squid device in transport mode (Source: A. Gray)

Figure 5.2. Albatern's 6-series WaveNET array being tested at the Isle of Muck, 2014 (Source: D. Findlay)

5.2. Albatern-Specific O&M Model

The expert judgement of Albatern's engineers has helped modify the generic O&M tool in order to make it specific to the Squid 6s wave energy converter. Albatern began sheltered-sea testing of a six Squid WaveNET array at Mingary Bay, off the Ardnamurchan peninsula in the west of Scotland, in October 2016. The limited experience gained during this test programme, as well as from the brief Isle of Muck testing phase in 2014, adds further valuable information to the Albatern-specific O&M model. The time step resolution of the tool is three hours.

5.2.1. Inputs

With the 6s devices having gained only limited operational experience, obtaining reliable inputs for the Albatern-specific O&M tool is challenging. The inputs have almost all come from the expert judgement of the engineers involved in designing the WEC, including estimates for the maintenance parameters such as time required to carry out specific onsite (offshore) or offsite (at the onshore O&M base) repairs. The base case information for the fault categories can be found in the appendices (Table A.3). In addition, Table A.4 shows the scheduled maintenance categories, consisting of a bi-annual routine service on each Squid device, as well as an annual moorings inspection on the array.

5.2.1.1. Failure rate data

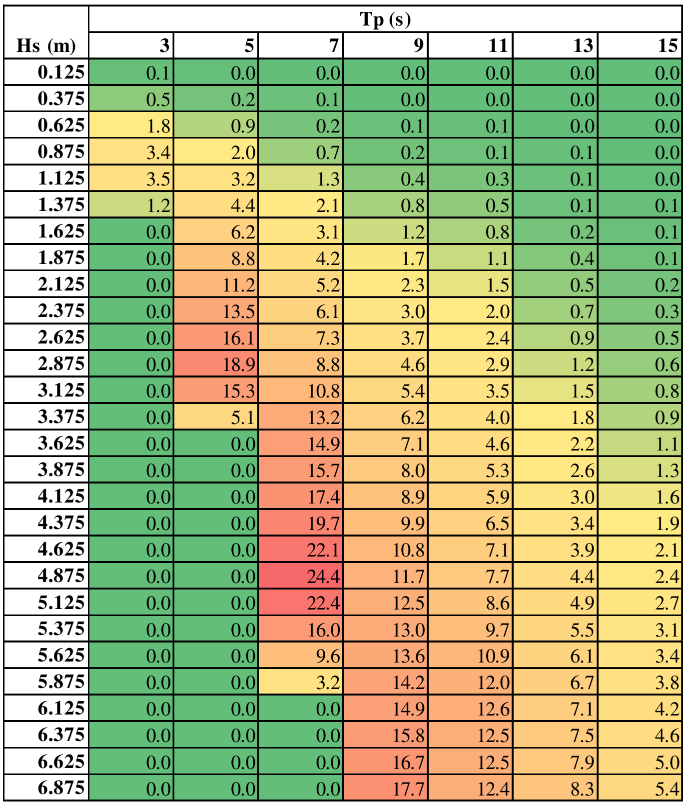
Albatern Ltd. have undertaken a Failures Modes and Effects Analysis (FMEA) for the 6s Squid wave energy converter. The estimates for failure rates of the Squid components have come almost exclusively from the expert judgement of the Albatern engineers. The OREDA handbook (OREDA, 2015) has also been used to inform failure rate estimates where possible, e.g. for generic offshore components such as mooring chains. The consequences of each component failure identified in the FMEA process have led to the creation of the fifteen fault categories detailed in Table A.3. The failure rates of the fault categories are defined by the failure probabilities of all the components that make up each category. The Monte Carlo analysis accounts for the fact that some fault categories are relevant only to the whole array (i.e. moorings), whilst others are relevant only to the Squid WEC units.

5.2.1.2. Operational limits

For the relatively low-energy sites considered suitable for the Squid 6s WEC, wind speed and wave period are not defining factors for accessible weather windows. Therefore, only significant wave height (Hs) is used as the defining constraint for marine operations.

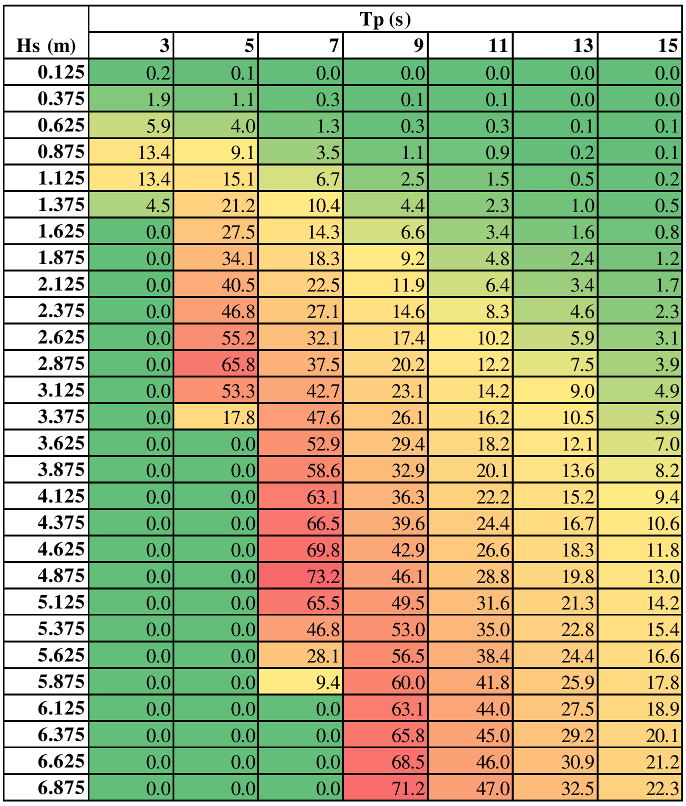
5.2.1.3. Power matrices

To calculate the power output of the WaveNET array, the Hs and Tp (i.e. wave peak period) values at each time step are matched to power matrices, with the array availability taken into account. Revenue is then calculated using a user-defined sale price of electricity. Both model and real-sea tests of the 6s WEC have shown that a higher power generation per unit can be gained when multiple Squid WECs are coupled together in an array. Therefore, the fundamental layout for a WaveNET array is a hexagonal formation, with three devices known as a 1-hex array, and six devices known as a 3-hex array. Power matrices for both these types of array have been created using ANSYS Aqwa (Figure 5.3 and Figure 5.4). A linear relationship of the 3-hex power matrix has been assumed when analysing larger arrays, meaning that the user defines the number of WECs that make up the array as a multiple of three. For example, the power generated by a 15-WEC WaveNET array is calculated by multiplying the relevant value from the 3-hex matrix by two, and adding the appropriate value from the 1-hex matrix.



Hs (m)	Tp (s) 3	5	7	9	11	13	15
0.125	0.1	0.0	0.0	0.0	0.0	0.0	0.0
0.375	0.5	0.2	0.1	0.0	0.0	0.0	0.0
0.625	1.8	0.9	0.2	0.1	0.1	0.0	0.0
0.875	3.4	2.0	0.7	0.2	0.1	0.1	0.0
1.125	3.5	3.2	1.3	0.4	0.3	0.1	0.0
1.375	1.2	4.4	2.1	0.8	0.5	0.1	0.1
1.625	0.0	6.2	3.1	1.2	0.8	0.2	0.1
1.875	0.0	8.8	4.2	1.7	1.1	0.4	0.1
2.125	0.0	11.2	5.2	2.3	1.5	0.5	0.2
2.375	0.0	13.5	6.1	3.0	2.0	0.7	0.3
2.625	0.0	16.1	7.3	3.7	2.4	0.9	0.5
2.875	0.0	18.9	8.8	4.6	2.9	1.2	0.6
3.125	0.0	15.3	10.8	5.4	3.5	1.5	0.8
3.375	0.0	5.1	13.2	6.2	4.0	1.8	0.9
3.625	0.0	0.0	14.9	7.1	4.6	2.2	1.1
3.875	0.0	0.0	15.7	8.0	5.3	2.6	1.3
4.125	0.0	0.0	17.4	8.9	5.9	3.0	1.6
4.375	0.0	0.0	19.7	9.9	6.5	3.4	1.9
4.625	0.0	0.0	22.1	10.8	7.1	3.9	2.1
4.875	0.0	0.0	24.4	11.7	7.7	4.4	2.4
5.125	0.0	0.0	22.4	12.5	8.6	4.9	2.7
5.375	0.0	0.0	16.0	13.0	9.7	5.5	3.1
5.625	0.0	0.0	9.6	13.6	10.9	6.1	3.4
5.875	0.0	0.0	3.2	14.2	12.0	6.7	3.8
6.125	0.0	0.0	0.0	14.9	12.6	7.1	4.2
6.375	0.0	0.0	0.0	15.8	12.5	7.5	4.6
6.625	0.0	0.0	0.0	16.7	12.5	7.9	5.0
6.875	0.0	0.0	0.0	17.7	12.4	8.3	5.4

Figure 5.3. Power matrix for a 1-Hex WaveNET array consisting of three 6s Squid WECs, values in kW



Hs (m)	Tp (s) 3	5	7	9	11	13	15
0.125	0.2	0.1	0.0	0.0	0.0	0.0	0.0
0.375	1.9	1.1	0.3	0.1	0.1	0.0	0.0
0.625	5.9	4.0	1.3	0.3	0.3	0.1	0.1
0.875	13.4	9.1	3.5	1.1	0.9	0.2	0.1
1.125	13.4	15.1	6.7	2.5	1.5	0.5	0.2
1.375	4.5	21.2	10.4	4.4	2.3	1.0	0.5
1.625	0.0	27.5	14.3	6.6	3.4	1.6	0.8
1.875	0.0	34.1	18.3	9.2	4.8	2.4	1.2
2.125	0.0	40.5	22.5	11.9	6.4	3.4	1.7
2.375	0.0	46.8	27.1	14.6	8.3	4.6	2.3
2.625	0.0	55.2	32.1	17.4	10.2	5.9	3.1
2.875	0.0	65.8	37.5	20.2	12.2	7.5	3.9
3.125	0.0	53.3	42.7	23.1	14.2	9.0	4.9
3.375	0.0	17.8	47.6	26.1	16.2	10.5	5.9
3.625	0.0	0.0	52.9	29.4	18.2	12.1	7.0
3.875	0.0	0.0	58.6	32.9	20.1	13.6	8.2
4.125	0.0	0.0	63.1	36.3	22.2	15.2	9.4
4.375	0.0	0.0	66.5	39.6	24.4	16.7	10.6
4.625	0.0	0.0	69.8	42.9	26.6	18.3	11.8
4.875	0.0	0.0	73.2	46.1	28.8	19.8	13.0
5.125	0.0	0.0	65.5	49.5	31.6	21.3	14.2
5.375	0.0	0.0	46.8	53.0	35.0	22.8	15.4
5.625	0.0	0.0	28.1	56.5	38.4	24.4	16.6
5.875	0.0	0.0	9.4	60.0	41.8	25.9	17.8
6.125	0.0	0.0	0.0	63.1	44.0	27.5	18.9
6.375	0.0	0.0	0.0	65.8	45.0	29.2	20.1
6.625	0.0	0.0	0.0	68.5	46.0	30.9	21.2
6.875	0.0	0.0	0.0	71.2	47.0	32.5	22.3

Figure 5.4. Power matrix for a 3-Hex WaveNET array consisting of six 6s Squid WECs, values in kW

5.2.1.4. Vessel arrangements

Using the knowledge from the Mingary Bay testing programme, three vessels are defined in the Albatern-specific O&M model, labelled ‘slow boat’, ‘fast boat’ and the ‘rib’ (i.e. Rigid Inflatable Boat). The ability to carry out both onsite and offsite maintenance is accounted for by the different capabilities of each vessel. The ‘slow boat’ is a small workboat with a strong enough bollard pull to tow Squid WECs to and from site. It is the only vessel of the three suitable for installation and retrieval of Squid devices. The ‘fast boat’ is also a small workboat (specifically, a ‘Fastworker 26’) but can travel at greater speeds. However, it is not capable of towing a WEC. Instead, it can be used for carrying out subsea work or onsite PTO replacements. Other parts, such as the instrumentation box, are much smaller and can therefore be replaced onsite using the ‘rib’ (with a maximum speed of 35 knots).

These vessels are readily available at fish farms or island communities, who would be the customers of the WaveNET array. A free-hire usage arrangement was made for the testing programme at Mingary Bay. Therefore, only vessel fuel costs are accounted for in the operational expenditure of the O&M model, as it is assumed there would be no daily hire rates or mobilisation fees. This assumption is made for the purposes of the studies undertaken in this chapter, however, vessel costs can and should be added when analysing the true economic viability of commercial WaveNET arrays.

5.2.1.5. Offshore logistics

Each vessel, as well as each fault category, has its own user-defined weather constraints for marine operations. The O&M model calculates the safest limits allowed for weather windows each time a marine operation is required. The length of the weather window is also calculated as and when required, based on the travel times of the vessel used and the time to carry out any offshore work, and is rounded up according to the model resolution of three hours.

5.2.1.6. Onshore facilities

A commercially viable 6s WaveNET array would consist of potentially hundreds of WECs. Given that it would not be possible to store hundreds of devices at the onshore O&M base (a.k.a. offsite), the Albatern-specific O&M model has a user-defined limitation on the number of Squid WECs that can be kept offsite at any given time. There is also a limitation on the number of WECs that can be stored offsite specifically for routine maintenance.

5.2.1.7. Labour requirements

Each fault category and scheduled maintenance task is assigned a number of technicians required to complete the task. In addition, there is a minimum number of personnel that need to be on board vessels undertaking offshore work in order to comply with health and safety regulations. The assumption has been made that technicians can be trained to undertake all maintenance tasks and marine operations, and therefore the Albatern-specific O&M model does not need to account for specialist technicians. Contractors can be hired on a short term basis, if selected by the user, to avoid work being delayed through lack of labour availability.

5.2.2. Functionality

The minimal cost of the vessels that will be used for a 6s WaveNET array, as well as the Squid device’s high accessibility, mean that it is not necessary for the Albatern-specific O&M model to incorporate a cost-benefit analysis in terms of deciding whether or not to repair a WEC. Instead, the approach is to repair a fault as soon as weather and logistics permit. Array-based failures are given the highest priority. Onsite repairs on one Squid are prioritised over repairs that require retrieval of another Squid. However, if a Squid suffers multiple failures, one or more of which require retrieval, then all repairs are undertaken at the offsite O&M base.

In addition to the outputs of the generic O&M tool described previously, the results of the Albatern-specific model include the number of days each vessel is utilised in each year, as well as the array downtime associated with periods of inaccessibility (i.e. when the weather conditions don’t allow desired marine operations).

5.3. Initial O&M Strategy Assumptions

5.3.1. Mingary Bay

The testing programme at Mingary Bay (see Figure 5.5) involves operating six Squid 6s devices in sheltered-sea conditions. The offshore site is located approximately 1.5km from the onshore O&M base. A hindcast dataset for Mingary

Bay, for the period 2000-2008, has been used to generate a time series of weather conditions, via the Markov Chain Model described previously. A design lifetime of 20 years is used. Ideally, a hindcast dataset for a period of at least 10 years would have been used in order to represent an adequate range of sea states, as suggested by the Equimar protocols (Equimar, 2011).

Figure 5.5. Location of the Mingary Bay test site, Ardnamurchan, west coast of Scotland

A series of initial assumptions about the modelled O&M strategy have been made using the experience gained with the Squid WECs at Mingary Bay. The three vessels being used at Mingary Bay are modelled with the constraints shown in Table 5.1. The table includes the maximum personnel capacity of each vessel, however, an additional requirement is that there must be a minimum of two personnel on a boat at any time for health and safety reasons. For marine operations, travel time to the site is calculated using the average speeds listed in Table 5.1, with an additional 30 minutes preparation time included.

Table 5.1. Vessel limitations

Vessel ID	Type	Average speed (kts)	Tow speed (kts)	Fuel cost per hour (£)	Personnel capacity
1	Slow boat	6	3	20	3
2	Fast boat	10	N/A	20	2
3	Rib	15	N/A	10	2

Marine operations and onshore maintenance tasks can both be undertaken at night. An installation operation has the limit of 1m Hs and takes one hour once the WEC has been towed to site. Space at the onshore O&M base is assumed to be limited, with a maximum of one WEC allowed at any one time. The bi-annual routine service of Squid WECs is staggered in that half the devices are scheduled to be maintained from year one onwards, whilst the other half are scheduled from year two onwards. This ensures that some routine servicing takes place every summer and reduces delays due to shortage of onshore space. One site manager is employed with an annual salary of £30k and an overheads multiplier of 1.3. In addition, external contractors can be brought in as extra technicians when required, at a day rate of £120. These values are in line with the average wages for the west coast of Scotland (SPICe, 2015).

The sale price of electricity is a point for negotiation with the customer. The initial assumption of 30.5p/kWh, in line with the UK's Contracts for Difference (CfD) strike price (DECC, 2013b), is used in the Albatern-specific O&M model. However, the CfD tariff applies only to grid-connected WECs. Therefore, this assumed sale price of electricity will be analysed later in the chapter.

The numerical results of 50 simulations of the Albatern-specific O&M model using these assumptions are shown in Table 5.2. 95% confidence intervals are applied.

Table 5.2. Results of a six 6s Squid WaveNET array deployed at Mingary Bay

	Availability (%)	**Revenue (£k)**	**OPEX (£k)**	**Profit (£k)**
Annual mean ± 95% confidence	98.37 ± 0.03	5.89 ± 0.003	57.46 ± 0.33	-51.58 ± 0.33

5.3.2. The Minch

It is clear from the results that a six WEC array deployed in the sheltered-sea conditions at Mingary Bay will not be a commercially viable project, as the annual operational costs outweigh income earned from generating electricity. It is not the purpose of the testing programme to be economically viable. However, the O&M strategy developed and tested at Mingary Bay is likely to be equally applicable to more energetic wave energy sites. One site being assessed as a possible location for a WaveNET array in the future is in the Minch, off the west coast of Skye in Scotland (see Figure 5.6). A suitable location for an onshore O&M base is an existing slipway at Meanish Pier in Loch Pooltiel, approximately 7km from the site. Again, the Markov Chain method was used to convert the hindcast dataset for the Minch site into a 20 year time series for use in the Albatern-specific O&M tool.

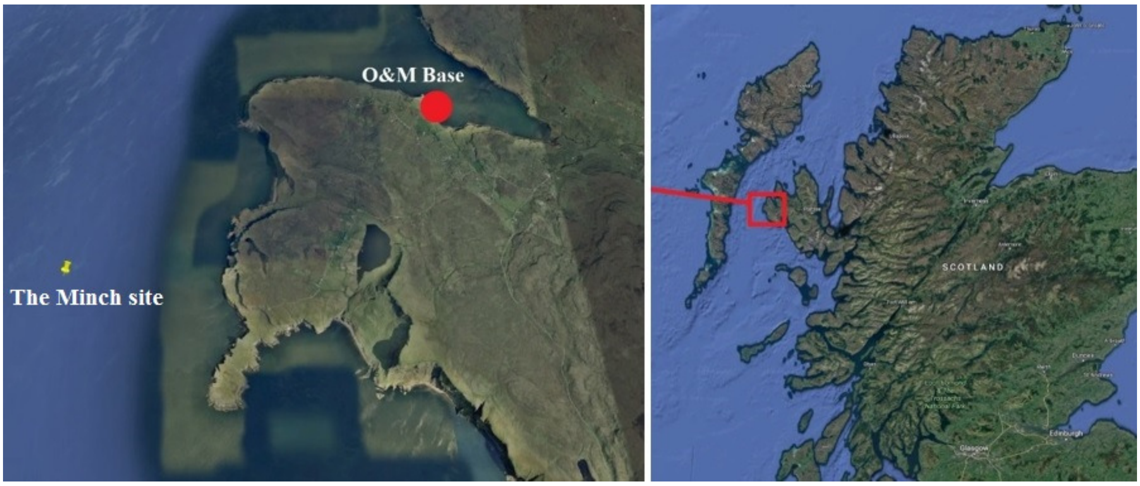


Figure 5.6. Location of the Minch site, Skye, west coast of Scotland

The two sites have been characterised and compared in terms of mean significant wave height (Hs) throughout the year (Figure 5.7) and average power generated by a 3-hex WaveNET array, assuming 100% availability (Figure 5.8). This comparison shows that an array located at the Minch site generates much more power than at Mingary Bay, but will face more periods of inaccessibility in terms of Hs-dominated weather windows.

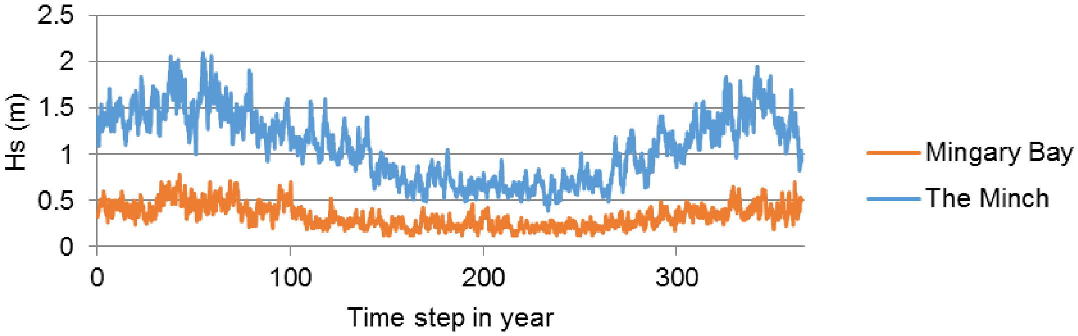


Figure 5.7. Comparison of Mingary Bay and the Minch sites in terms of mean significant wave height (by day in year)

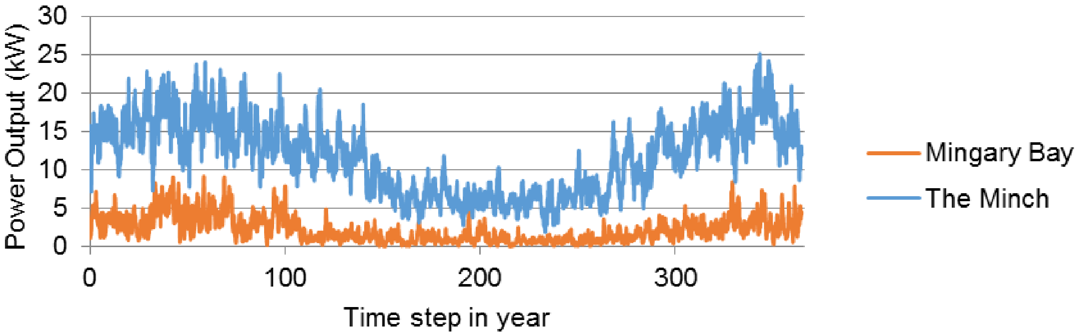


Figure 5.8. Comparison of Mingary Bay and the Minch sites in terms of power generated by a 3-hex WaveNET array operating at 100% capacity (by day in year)

Numerical results of 50 simulations of the Albatern-specific O&M model using the Minch weather dataset, with the previously stated assumptions, are shown in Table 5.3.

Table 5.3. Results of a six 6s Squid WaveNET array deployed at the Minch site

	Availability (%)	**Revenue (£k)**	**OPEX (£k)**	**Profit (£k)**
Annual mean ± 95% confidence	97.73 ± 0.04	30.70 ± 0.03	58.06 ± 0.30	-27.36 ± 0.31

5.4. Defining WaveNET Size

From the results of the O&M model, it can be seen that a WaveNET array consisting of six 6s Squid devices will not generate an annual net operational income at either of the two sites analysed. In order to provide a better illustration of the economic impacts of different O&M strategies, it is useful to identify the size of WaveNET array where the 'break even' point is reached (i.e. when the array begins to make an annual net operational income). It is possible to carry out a more holistic assessment of the economic viability of the 6s Squid WEC by finding the size of array where the project provides a return on capital investment. However, this was deemed unnecessary for the purpose of illustrating different aspects of O&M as it would take too long to run the simulations in this chapter for much larger arrays, as well as requiring an uncertain estimation of CAPEX to be made.

5.4.1. Scaling up inputs

As stated previously, the power matrices used in the Albatern-specific O&M model are applicable to 1-hex (i.e. 3 Squid WECs) and 3-hex (i.e. 6 Squids) arrays. When the number of Squids in the modelled array is increased, a linear relationship with the 3-hex power matrix is assumed, with a 1-hex added for an extra multiple of three if required. Therefore, a modelled WaveNET array must consist of multiples of three WECs.

Another input affected by scaling up the number of WECs is the probability of array-based failures. The possible moorings configurations for a WaveNET array larger than six Squid units are yet to be determined. Therefore, the assumption in the FMEA is that one 'mooring system' applies to six Squid units. This means that the probabilities of failure for array-based fault categories are scaled up with increasing numbers of Squid devices using equation 5.1. The input parameters to this equation for the four array-based fault categories in the Albatern-specific O&M model are given in the appendices (Table A.5).

$$F_A = 1 - (\prod_{i-1}^{n} Ri^{N_i})^{N_m} \qquad (5.1)$$

Where:

F_A = annual probability of failure of array-based fault category

i = single component i in fault category

n = number of components in fault category

R_i = annual probability of no failure (i.e. reliability) of single component i

N_i = total number of component i in single mooring system

N_m = total number of mooring systems in array (i.e. a function of the number of Squid units)

The time and cost of the annual moorings inspection also increases with an increasing number of Squid WECs. It is assumed that the dive team charge £1500 per 12 hour block whilst undertaking the inspections. It is estimated that the dive team could inspect the moorings at a rate of three systems per hour; however, the full operation is constrained to a minimum of 3 hours and a maximum of 24 hours in the O&M model.

Other inputs that change with an increasing number of Squid WECs are the number of technicians permanently employed and the number of WECs that can be located at the onshore O&M base at any one time. The initial assumption is that one technician is permanently employed for every thirty WECs in the array, although external contractors can be hired to assist with repairs and maintenance. It is not necessary to have an onshore O&M base capable of storing all the WECs in the array at once, as initial deployment would be staggered, as would maintenance. Therefore, it is assumed that there is enough onshore space to store one Squid for every ten in the array, rounded up. For arrays larger than ten squids, routine servicing is staggered so that there is always one onshore space reserved for emergency Squid retrieval during scheduled maintenance periods.

5.4.2. Number of Squids

The Markov-generated 20 year time series of weather conditions representing the Minch site is again used for the following analysis. The Albatern-specific O&M model was run for an increasing number of Squid WECs. The model was run ten times for each scenario, in order to minimise variability whilst achieving results within an acceptable time. The mean annual net operational income achieved by each WaveNET array is shown in Figure 5.9.

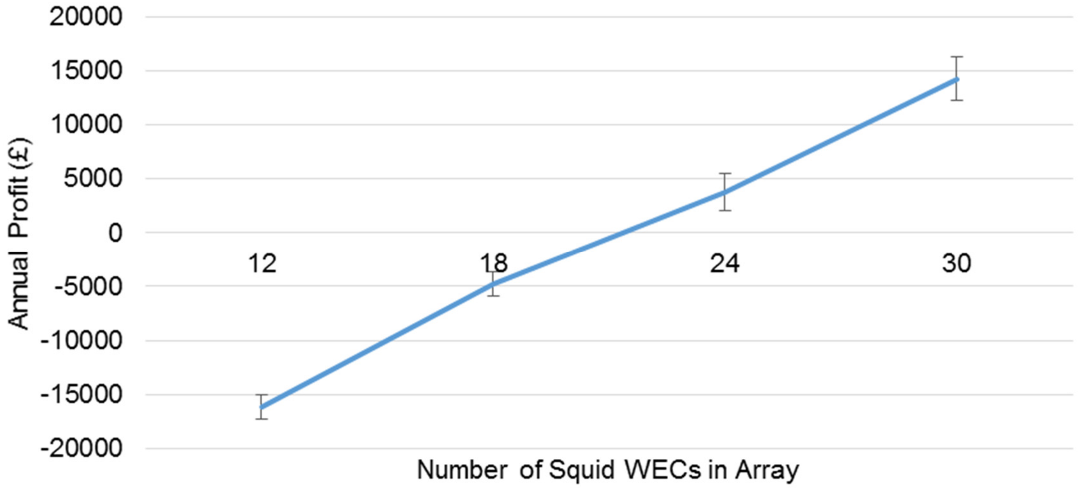


Figure 5.9. Mean annual profit for a WaveNET array containing different numbers of Squid WECs, with 95% confidence intervals applied

From these results, it can be seen that the array which first begins to generate an annual net operational income consists of 24 Squid WECs.

5.5. Base Case

The analysis presented in this chapter uses the Albatern-specific O&M tool combined with a Markov-generated time series of weather conditions for a site in the Minch, an area off the west coast of Skye in Scotland. The simulations are for a WaveNET array consisting of 24 6s Squid devices, over a design lifetime of 20 years, unless specified otherwise. For clarity, the base case O&M strategy considerations are as follows:

- There is enough space at the onshore O&M base to store 3 WECs at any one time.
- Only 2 WECs undergoing routine servicing are allowed at the onshore O&M base at any one time.

- Three vessels are available, one of each type.
- O&M base workforce consists of one site manager with a salary of £30,000 p.a. In addition, external contractors can be hired as technicians at a day rate of £120.
- The array site is located 7km from the onshore O&M base.
- The sale price of electricity is 30.5p/kWh.

The results presented in this chapter are the mean values from 50 simulations of the Albatern-specific O&M model, unless specified otherwise. The numerical results with the base case inputs are shown in Table 5.4. The results for availability, as well as revenue and operational expenditure, are shown graphically in Figure 5.10 and Figure 5.11.

Table 5.4. Base case results for a 24 device WaveNET array deployed at the Minch site

	Availability (%)	**Revenue (£k)**	**OPEX (£k)**
Annual mean ± 95% confidence	97.73 ± 0.02	122.78 ± 0.05	119.18 ± 0.59

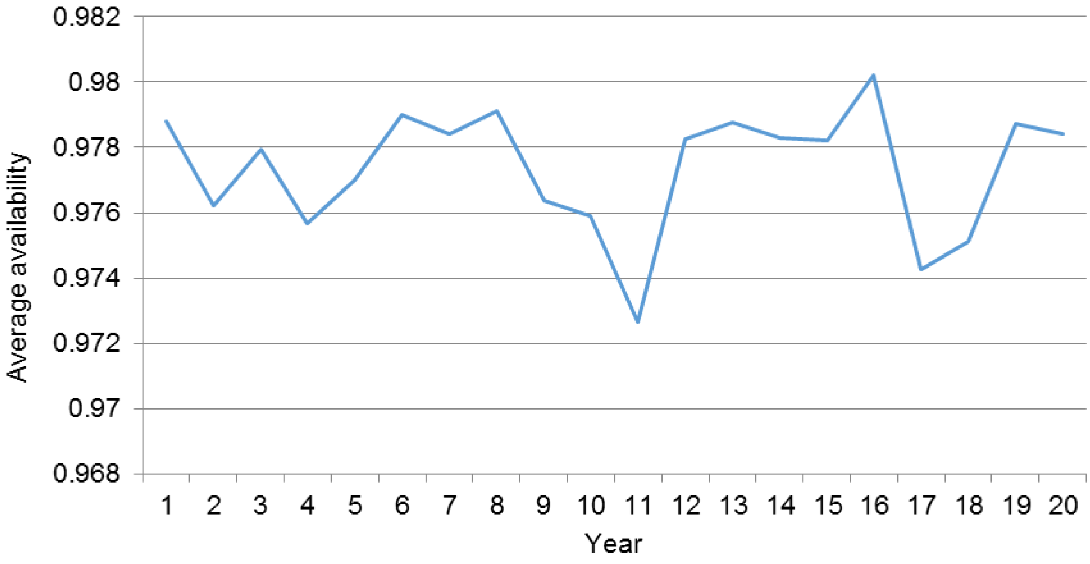


Figure 5.10. Base case average availability in each year of the array lifetime

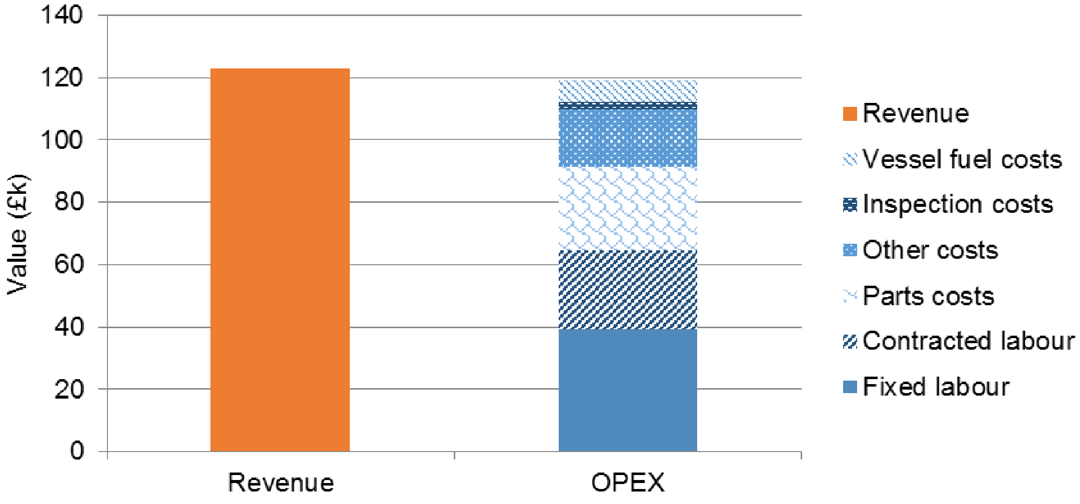


Figure 5.11. Base case average annual revenue and breakdown of annual OPEX

The negligible size of the 95% confidence intervals for availability and revenue shows that there is very little variability between simulations. This is to be expected as the same time series of weather conditions is being used for each run. Figure 5.10 demonstrates the effects of weather conditions, with higher availability seen in years with a greater portion of open weather windows. More variability is seen in the results for OPEX due to the Monte Carlo method of simulating faults, leading to there being many different possible scenarios from one simulation to the next. It is clear from Figure 5.11 that the total labour cost for permanent staff and external contractors is the greatest expense for the project. Costs for repairs (parts and other costs) are also significant, whilst vessel fuel and inspection costs incur the least amount of OPEX.

5.6. O&M Base Facilities and Onshore Logistics

Onshore logistics and available facilities at the O&M base need consideration for a multi-device wave energy array in order to maximise profitability. As stated previously, the Albatern-specific O&M model can limit the total number of Squid WECs allowed at the onshore base at any one time. During periods of scheduled maintenance, one space is always kept available for emergency Squid retrieval due to major faults. This section analyses the impact of changing the space available at the onshore O&M base for the 24 device WaveNET array described in the base case. The analysed scenarios are defined in Table 5.5. The results of the model simulations are shown graphically in Figure 5.12 (availability), Figure 5.13 (revenue and OPEX) and Figure 5.14 (net operational income, i.e. 'profit').

Table 5.5. Onshore logistics scenarios

Scenario	**Number of WECs allowed onshore at any one time**	**Number of WECs allowed onshore for routine servicing at any one time**
1	1	1
Base Case	3	2
2	5	4
3	10	9
4	15	14
5	20	19
6	24	23

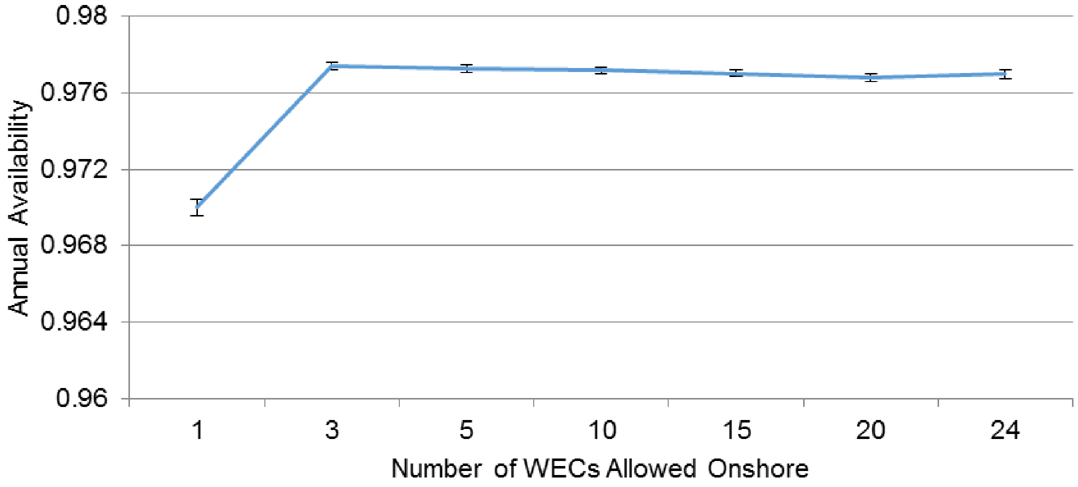


Figure 5.12. Average annual availability of the array for different onshore logistics scenarios, with 95% confidence intervals applied

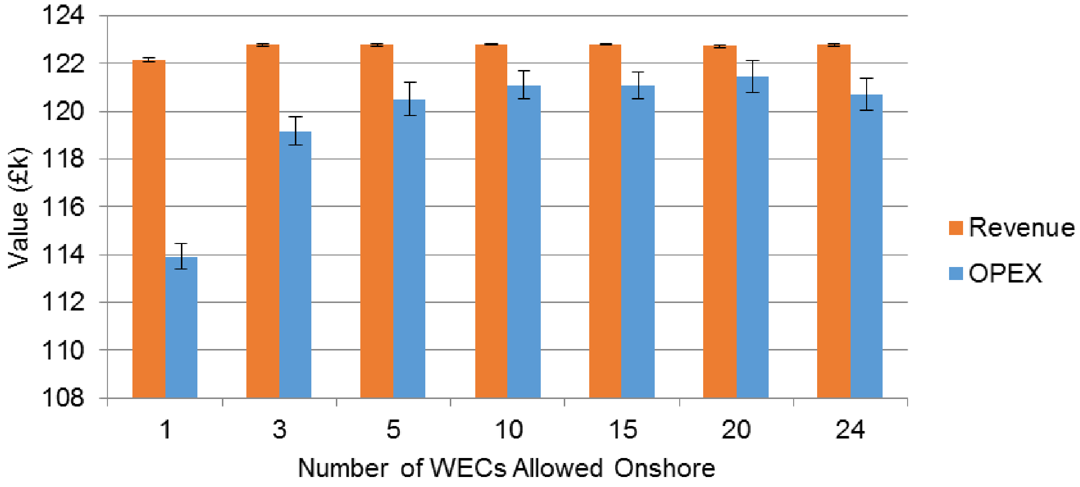


Figure 5.13. Average annual revenue and OPEX for different onshore logistics scenarios, with 95% confidence intervals applied

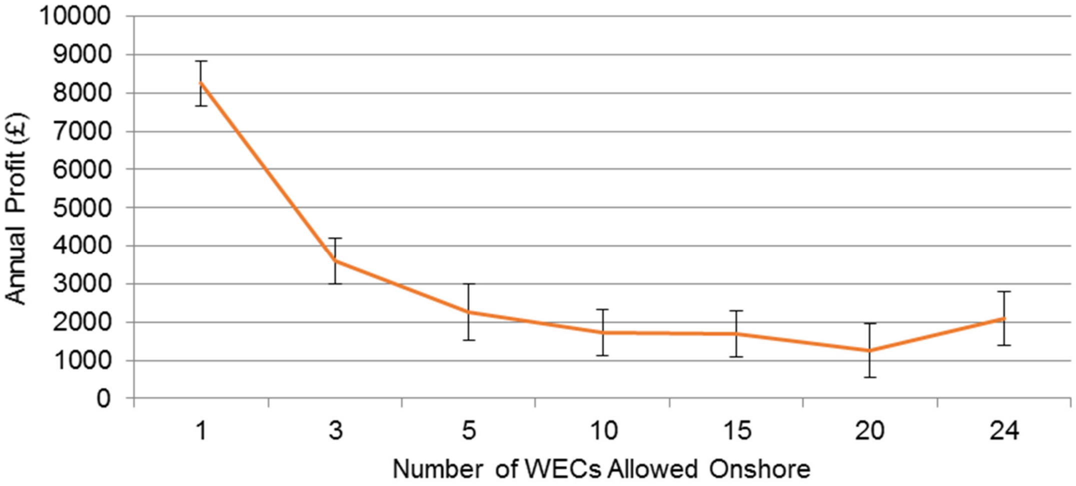


Figure 5.14. Average annual profit of the array for different onshore logistics scenarios, with 95% confidence intervals applied

Figure 5.12 shows that for all cases except scenario 1, the average availability is approximately 97.7%. This drops to 97.0% in scenario 1, implying that the revenue will be lower than in the other cases. This is confirmed by Figure 5.13, where the revenue of the array in scenario 1 is approximately £122.1k per year, compared to around £122.8k for the other cases. However, scenario 1 incurs the least amount of annual OPEX and is therefore shown to be the most profitable case in Figure 5.14. The base case incurs the second lowest amount of annual OPEX and, consequently, achieves the second highest annual net operational income of the scenarios considered. The application of 95% confidence intervals in Figure 5.14 shows that there is no clear difference between the other five scenarios in terms of annual net operational income.

The discrepancy seen between scenario 1 and the rest of the assessed cases can be explained by looking into the breakdown of OPEX. Figure 5.15 shows that the primary reason that total OPEX is lower for scenario 1 is that the contracted labour fees are lower. Contracted labour incurs approximately £20.75k annually, compared to an average of £27.43k for the other cases. This represents almost a 25% decrease. In addition, vessel fuel costs are 2.6% lower in scenario 1 than the average of the other cases. This information shows that there are less marine operations taking place when there is only enough space at the onshore O&M base for one Squid WEC. This anomaly has arisen due to the method of keeping one space available for emergency WEC retrieval in all the other scenarios. During summer months when routine servicing is due, only one WEC can undergo maintenance at any time in scenario 1. This means that other devices may suffer faults whilst waiting to be retrieved for routine servicing. Labour fees and vessel fuel costs are therefore minimised because only one marine operation is required to bring the affected device onshore for both scheduled maintenance and fault repairs. Scenario 1 demonstrates that higher availability of multi-device wave energy arrays does not necessarily lead to higher net operational income.

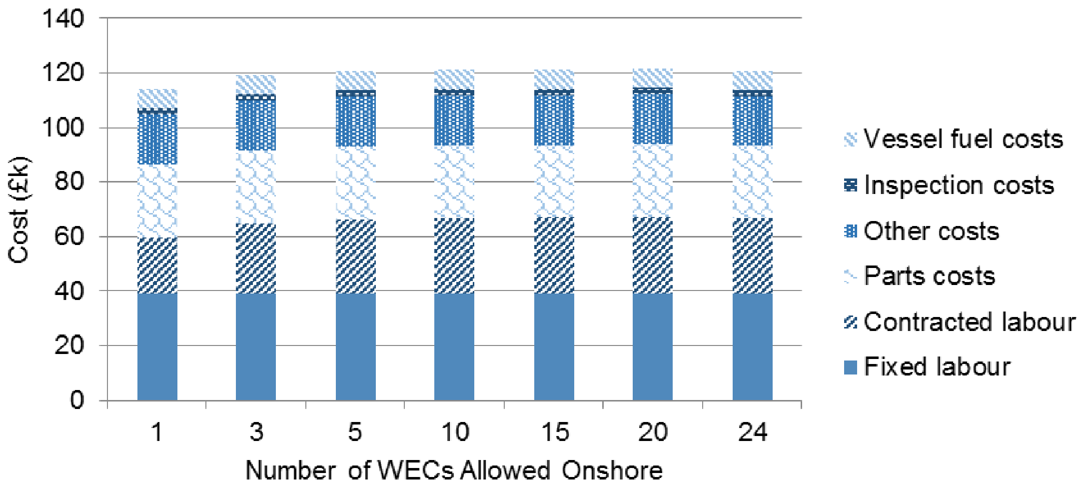


Figure 5.15. Breakdown of annual OPEX for different onshore logistics scenarios

These results have shown that a cost-benefit analysis would be a useful addition to the Albatern-specific O&M model when larger WaveNET arrays are being considered. The net operational income generated by an array is highly sensitive to labour costs. The amount of space available onshore is not a defining factor for the relatively small size of array assessed in this study, although slightly higher profits can be achieved when space at the O&M base is limited to one Squid WEC. When larger arrays are investigated, it will become necessary to include CAPEX into this analysis, as creating more space at an onshore O&M base may incur costs in terms of site development, as well as ongoing land rent charges. This analysis has also not considered that having a lot of WECs onshore at once may increase the preparation time prior to a device installation due to the increased complexity of onshore and near-shore logistics.

The analysis has shown that it is possible to analyse the onshore O&M base facilities for a wave energy array and the impact on operability and profitability of the project. Further analysis could include thorough assessment of staggered maintenance aspects, which becomes more important as the number of WECs in the array increases.

5.7. Vessel Usage

The three vessels used in the base case are representative of the O&M strategy used in the Mingary Bay testing programme. The assumption is that the vessels would be readily available from the WaveNET array customer (i.e. a fish farm or island community), and therefore only fuel costs are incurred. This arrangement requires clear communication and understanding between the array developer and the client. The Albatern-specific O&M model can be used to identify how often a vessel might be required. This information can inform contract negotiations with the customer prior to array deployment. Figure 5.16 shows the average number of days that each vessel is used annually.

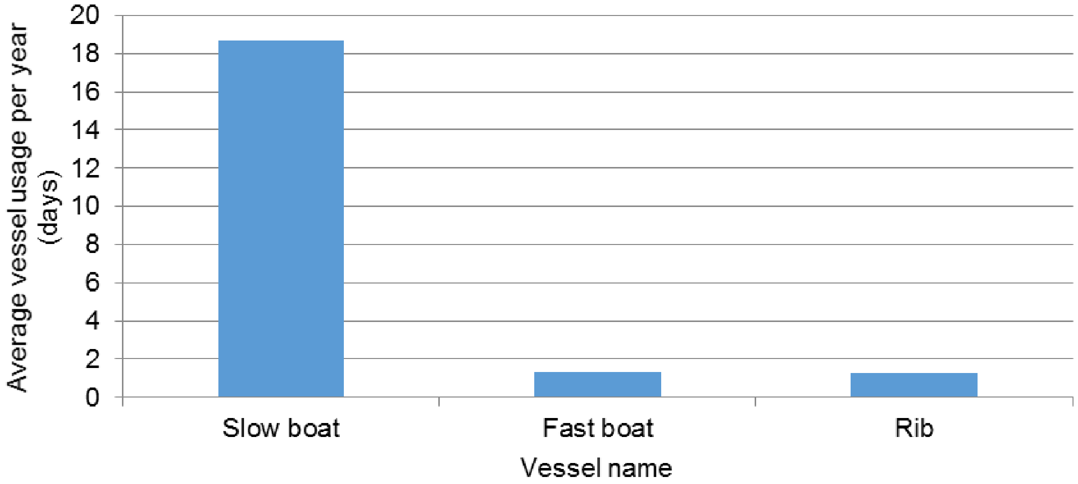


Figure 5.16. Vessel usage for the base case

From Figure 5.16 it can be seen that the slow boat, used for all WEC installation and retrieval operations, is used the most often. The other two vessels are used less than two days per year on average. The O&M model can be used to find how often marine operations are delayed due to a lack of an available vessel suitable for towing a WEC. Table 5.6 shows the results of the O&M model, comparing the base case with the scenario when one extra 'slow boat' is available. The vessel usage chart for this comparison is shown in Figure 5.17.

Table 5.6. Mean results with and without an extra slow boat

	Availability (%)	**Revenue (£k)**	**OPEX (£k)**	**Profit (£k)**
Base Case	97.74	122.78	119.18	3.60
Extra slow boat	97.77	122.83	119.20	3.63

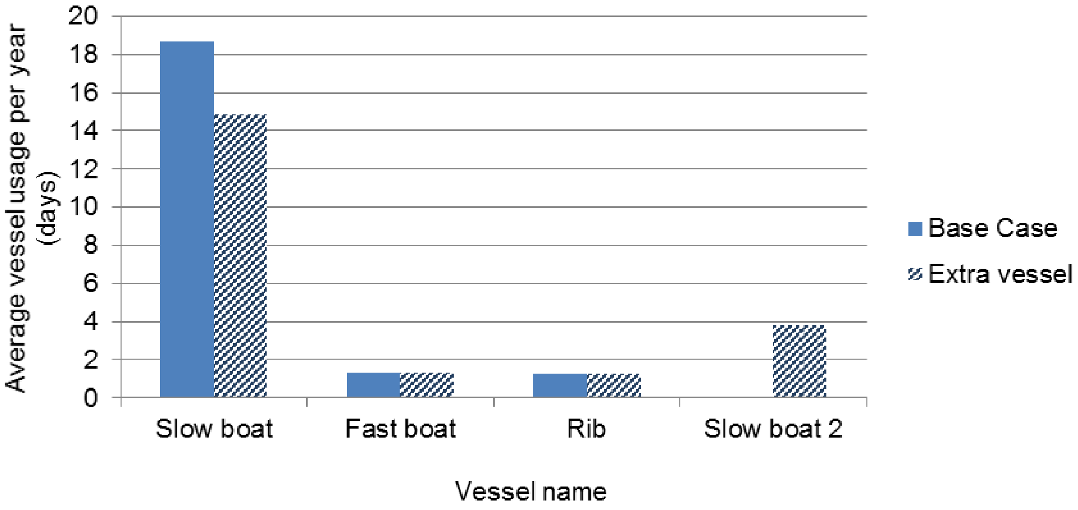


Figure 5.17. Vessel usage comparing the base case with the scenario of an extra slow boat

The results in Table 5.6 show that there is little difference between the base case and the scenario where one extra vessel capable of towing a Squid is available. There are slight increases in availability and revenue, as marine operations are not delayed by the lack of an available vessel as often as in the base case. However, there is also a slight increase in OPEX due to the fact that additional labour costs are incurred when the extra vessel is used. The increase in OPEX would be considerably higher if using a vessel incurred a rental charge. Figure 5.17 shows that marine operations are delayed enough to warrant using the extra vessel for around 4 days per year on average. However, the overall usage of the slow boats does not change from the base case and the effect on annual net operational income is extremely minor.

In larger WaveNET arrays, vessels will be used much more than has been shown for this 24-WEC array. If one or more vessels end up being used above the acceptable limit specified by the customer, then it is likely that a rental fee will be incurred. Table 5.7 details a number of scenarios of rental fees for the base case. The effect that each scenario has on OPEX can be seen in Figure 5.18, with the impact of profitability shown in Figure 5.19.

Table 5.7. Vessel hire fees scenarios

	Vessel day rates (£)		
	Slow boat	**Fast boat**	**Rib**
Base Case	0	0	0
Scenario 1	200	200	100
Scenario 2	400	400	200
Scenario 3	600	600	400
Scenario 4	1000	600	400

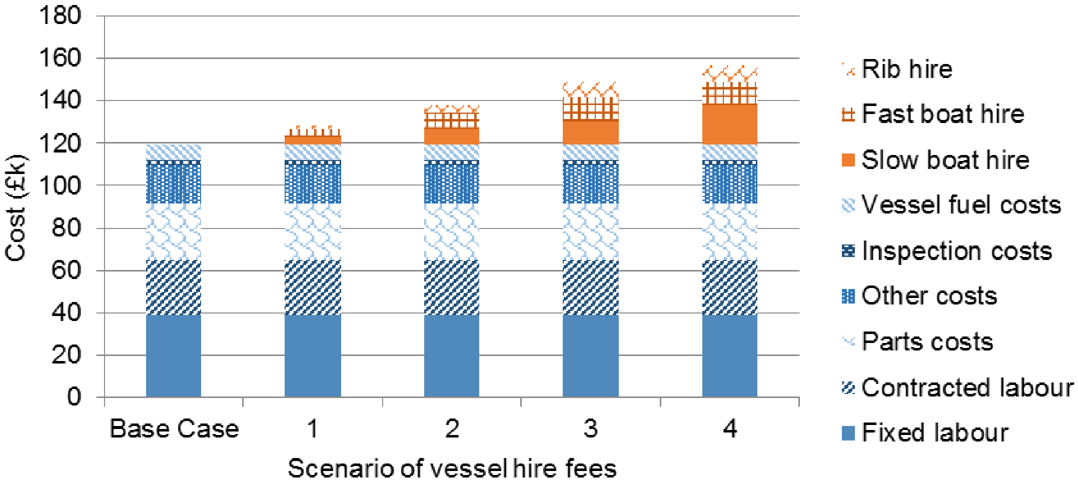


Figure 5.18. Comparison of different vessel hire fees in terms of annual OPEX

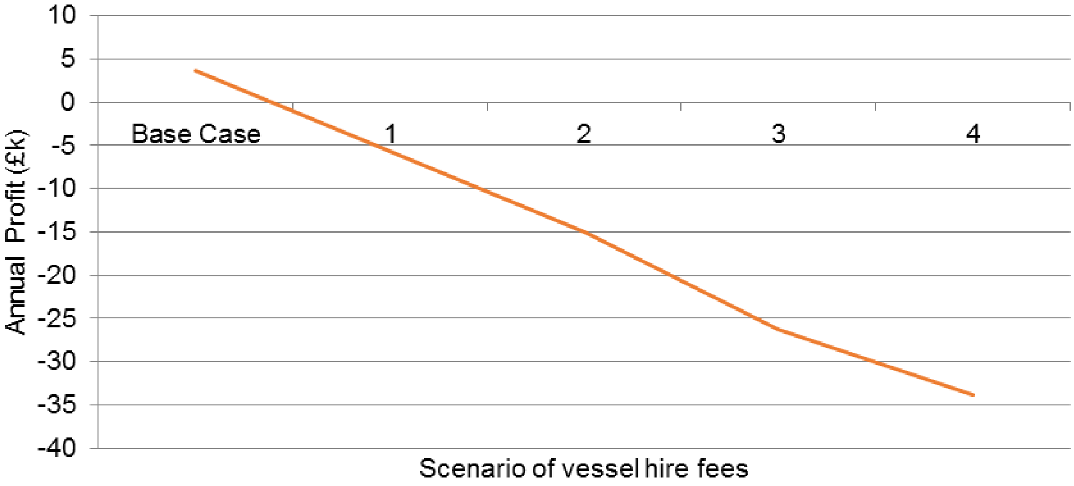


Figure 5.19. Comparison of different vessel hire fees in terms of annual profit

These results show that a 24-Squid WaveNET array is not profitable if rental fees are charged for vessel usage. The analysis in this section has shown that the O&M model is an extremely useful tool when negotiating with customers prior to array deployment. There needs to be clear communication with regards to vessel usage, and it benefits the project if a free-hire arrangement can be reached.

5.8. Offshore Maintenance

Although the Squid WEC has been designed so that some faulty parts can be replaced whilst the device is still offshore, no experience with such tasks has yet been achieved. During the Mingary Bay test phase, it may become apparent that the fast boat is not suitable for offshore repairs. In addition, the assumption that rib vessel can be used for a marine operation to replace the instrumentation box of a Squid has not been validated yet either. This section addresses the uncertainty in these assumptions by running the Albatern-specific O&M model for three different scenarios of offshore logistics, in addition to the base case. The three scenarios are as follows:

- Scenario 1 – the rib vessel is not used at all. Instrumentation boxes can only be replaced with the fast boat.
- Scenario 2 – only one slow boat is used for all marine operations.
- Scenario 3 – no offshore repairs. Every Squid-based failure requires the device to be taken to the O&M base for onshore repair and maintenance.

In scenario 3, it is assumed that any failures that could have been corrected offshore in the base case require a full day to be repaired onshore. The results for each scenario are presented in Table 5.8, with a breakdown of OPEX shown graphically in Figure 5.20. Comparisons of the scenarios with the base case are also given in terms of annual net operational income (Figure 5.21) and vessel usage (Figure 5.22).

Table 5.8. Mean results for different offshore maintenance scenarios

	Availability (%)	**Revenue (£k)**	**OPEX (£k)**	**Profit (£k)**
Base Case	97.74	122.78	119.18	3.60
Scenario 1	97.75	122.78	118.72	4.07
Scenario 2	97.76	122.84	118.96	3.88
Scenario 3	97.44	122.40	121.35	1.05

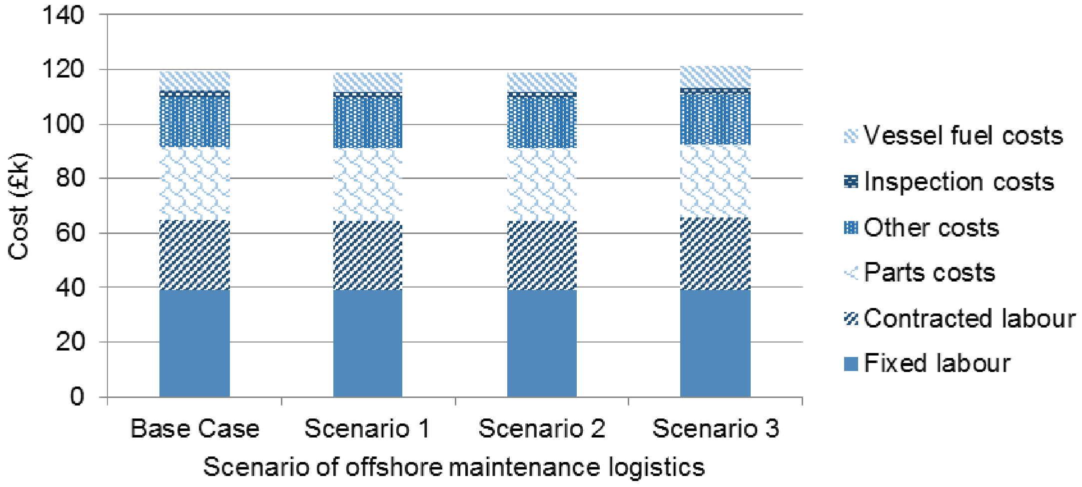


Figure 5.20. Breakdown of annual OPEX for different offshore maintenance scenarios

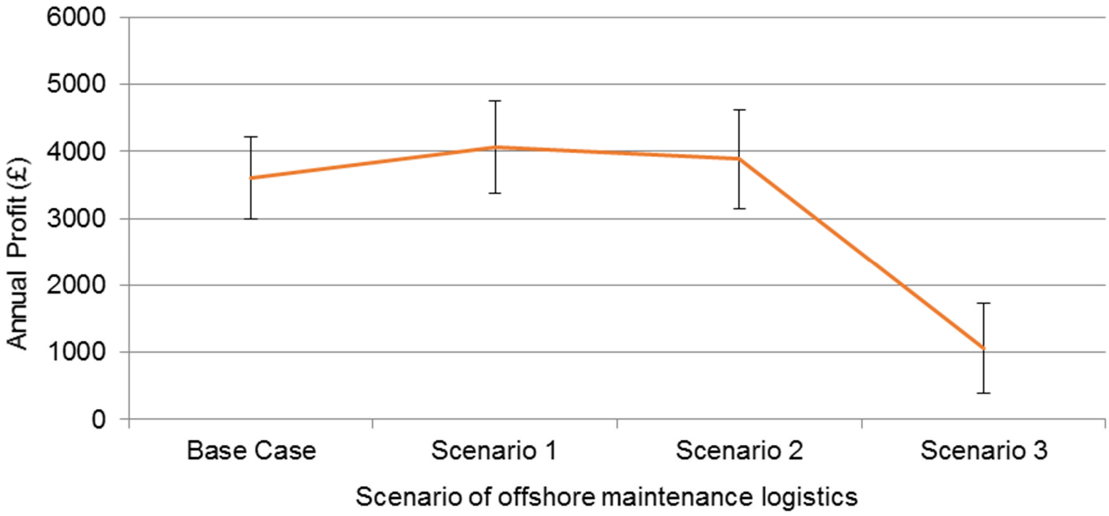


Figure 5.21. Average annual profit of the array for different offshore maintenance scenarios, with 95% confidence intervals applied

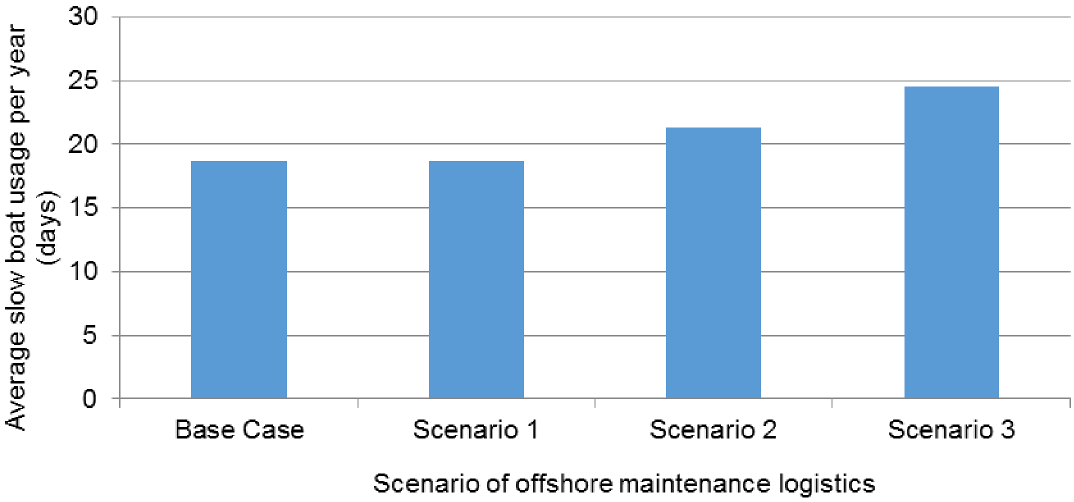


Figure 5.22. Slow boat usage for different offshore maintenance scenarios

Scenario 3 is shown to be the least profitable case in Figure 5.21 due to the increase in operational expenditure. The breakdown of OPEX shown in Figure 5.20 identifies that this increased cost comes from vessel fuel fees. This stems from the greatest number of slow boat marine operations occurring in scenario 3, as shown in Figure 5.22. This information shows that being able to undertake certain repairs and maintenance tasks without having to take the WEC to the O&M base can add profitability to the project. The application of 95% confidence intervals to the values for annual net operational income (Figure 5.21) indicates that there is no clear difference between the base case and the first two scenarios, although the mean values do differ slightly.

5.9. Labour Considerations

The base case results have shown that labour is the dominant component of lifetime operational costs of the assessed WaveNET array. The salaries of the site manager (£30,000pa) and any permanently employed technicians (£18,000pa), as well as the contractor day rate of £120, are in line with typical salaries on the west coast of Scotland. Figure 5.23 shows how much the profitability of the base case WaveNET array changes if labour costs vary from the assumptions made.

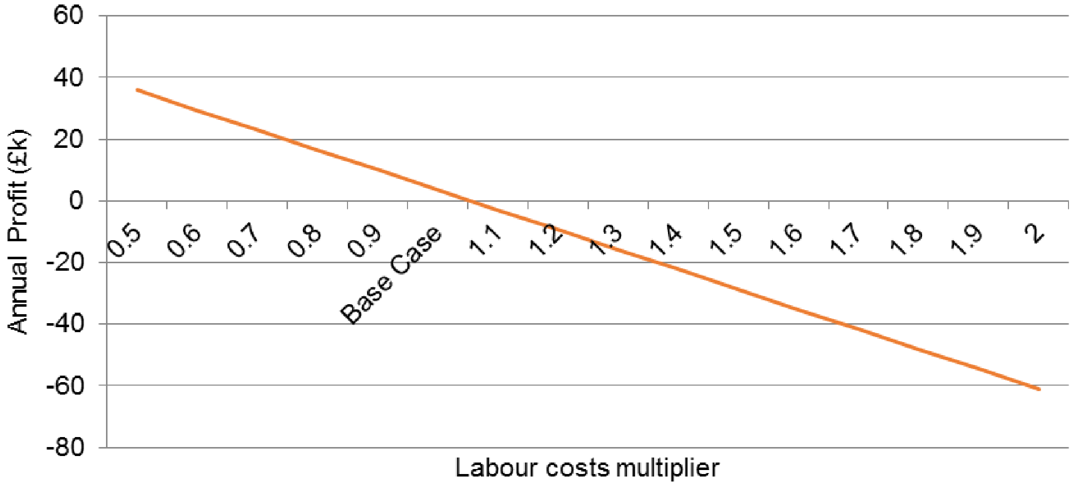


Figure 5.23. Annual profit of the base case array for varying labour costs

It is clear that careful and considered planning of the labour arrangements for an off-grid wave energy array is required for the project to be a success. This section challenges the initial assumptions made with respect to labour costs, by using the Albatern-specific O&M model to analyse different workforce arrangements. Table

5.9 shows the three scenarios to be analysed, along with the base case. In scenario 3, contractors cannot be hired to assist with repairs and maintenance at peak times. Therefore, the minimum amount of permanently employed technicians has been chosen so that even the most personnel-consuming repairs and maintenance tasks can still be undertaken.

Table 5.9. Workforce arrangement scenarios at the O&M base

	Site managers	**Technicians**	**Total salary per year (£k)**	**Contractors enabled?**	**Contractor day rate (£)**
Base Case	1	0	30	Yes	120
Scenario 1	1	1	48	Yes	120
Scenario 2	1	2	66	Yes	120
Scenario 3	1	2	66	No	N/A

Table 5.10 shows the numerical results for each of the three scenarios, as well as the base case. The results are also presented graphically in Figure 5.24 (for revenue and OPEX) and Figure 5.25 (for annual net operational income).

Table 5.10. Mean results for different workforce arrangements

	Availability (%)	**Revenue (£k)**	**OPEX (£k)**	**Profit (£k)**
Base Case	97.74	122.78	119.18	3.60
Scenario 1	97.74	122.82	131.78	-8.96
Scenario 2	97.76	122.82	147.35	-24.52
Scenario 3	96.49	121.30	139.84	-18.55

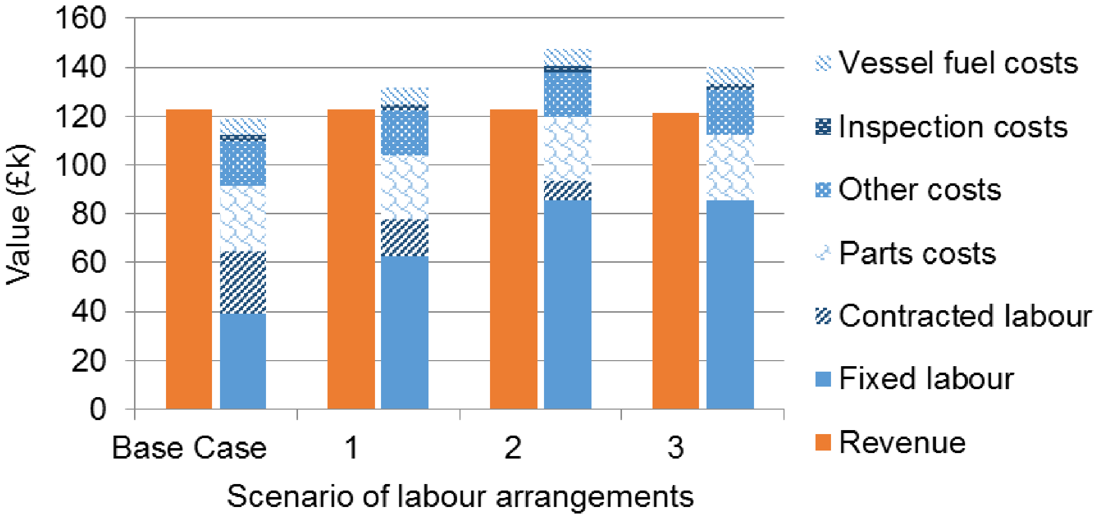


Figure 5.24. Annual revenue and breakdown of annual OPEX for different labour scenarios

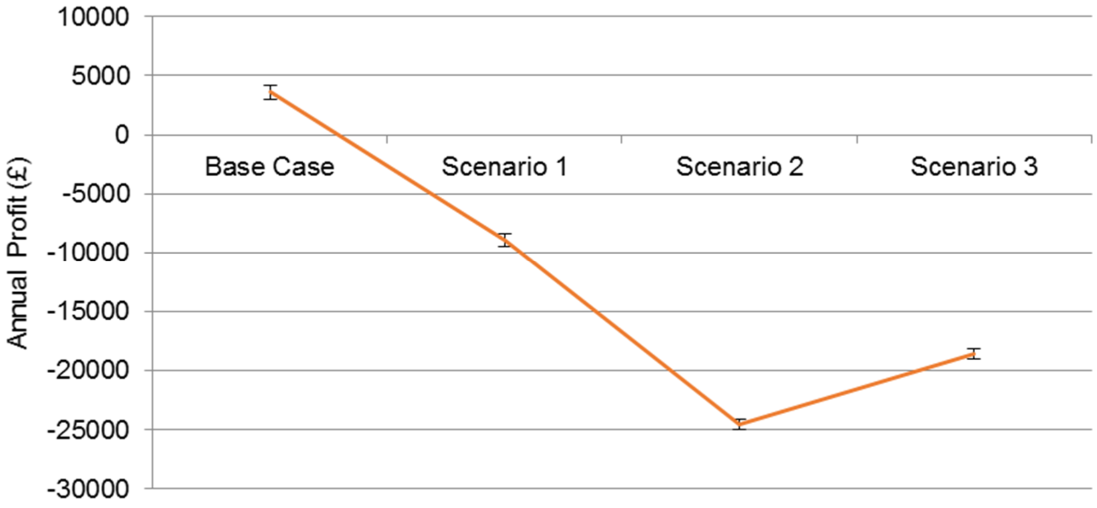


Figure 5.25. Annual profit for different labour scenarios, with 95% confidence intervals applied

The results show that base case is the most profitable labour scenario for the 24-WEC WaveNET array under analysis. In fact, the other three scenarios all incur more OPEX annually than they generate in revenue. Figure 5.24 shows that contractors are required much less frequently in scenario 1 than in the base case. However, this reduced cost does not cancel out the expense of employing a technician with an annual salary of £18k. This same effect can be seen to a greater extent in the results for scenario 2, which consequently incurs the largest annual OPEX. There is no clear difference between the base case, scenario 1 and scenario 2 in terms of availability and revenue because work is never delayed due to a lack of available technicians. In scenario 3 where contractors are not available, however, the availability and revenue both drop by approximately 1.5%

compared to the other cases. However, the negative impact on annual net operational income in scenario 3 is less than in scenario 2. This is because the slight increase in revenue in scenario 2 is negated by the higher OPEX due to contractor fees. For larger WaveNET arrays, an optimal arrangement of the O&M base workforce can be calculated using the Albatern-specific O&M model. The analysis in this section shows that labour arrangements are one of the most important factors to be considered when developing an off-grid wave energy array.

5.10. Site Travel Times

Another aspect of an O&M strategy that will affect the profitability of a wave energy project is the travel time to and from the offshore site. Travel times are a function of vessel speeds, with and without towing a WEC, as well as any preparation time required prior to a marine operation. The WaveNET array site analysed in this chapter is located 7km from the onshore O&M base. Tow speed and average vessel speeds have been inferred from experience gained during the Mingary Bay testing programme. These speeds, together with an assumed preparation time of 30 minutes, provide the site travel times used for the base case simulations, rounded up to the nearest 15 minutes. However, these parameters are not fixed at this early stage of the Albatern O&M strategy development, and may improve as more experience is gained. Therefore, it is useful to analyse the impact that different site travel times have on the profitability of the array. Three scenarios are modelled in this section, along with the base case, as shown in Table 5.11.

Table 5.11. Scenarios of travel times from O&M base to array site

	Preparation time (hrs)	**Tow speed (kts)**	**Vessel average speed (kts)**			**Time site without tow (hrs)**			**Slow boat time to site with tow (hrs)**
			Slow boat	**Fast boat**	**Rib**	**Slow boat**	**Fast boat**	**Rib**	
Base Case	0.5	3	6	10	15	1.25	1	1	2
Scenario 1	1	2	4	7	7	2	1.75	1.75	3
Scenario 2	0.5	4	8	16	20	1	0.75	0.75	1.5
Scenario 3	0.25	4	8	16	20	0.75	0.5	0.5	1.25

The site travel times in scenario 1 are longer than in the base case, whilst scenario 2's travel times are shorter due to the adjusted parameters. Scenario 3 has the shortest travel times, with minimal preparation time required, as well as having increased average vessel speeds. The results for each scenario are presented numerically in Table 5.12 and graphically in Figure 5.26.

Table 5.12. Mean annual results for different site travel time scenarios

	Availability (%)	**Revenue (£k)**	**OPEX (£k)**	**Profit (£k)**
Base Case	97.74	122.78	119.18	3.60
Scenario 1	97.69	122.76	122.23	0.53
Scenario 2	97.81	122.87	116.99	5.87
Scenario 3	97.98	123.12	114.73	8.39

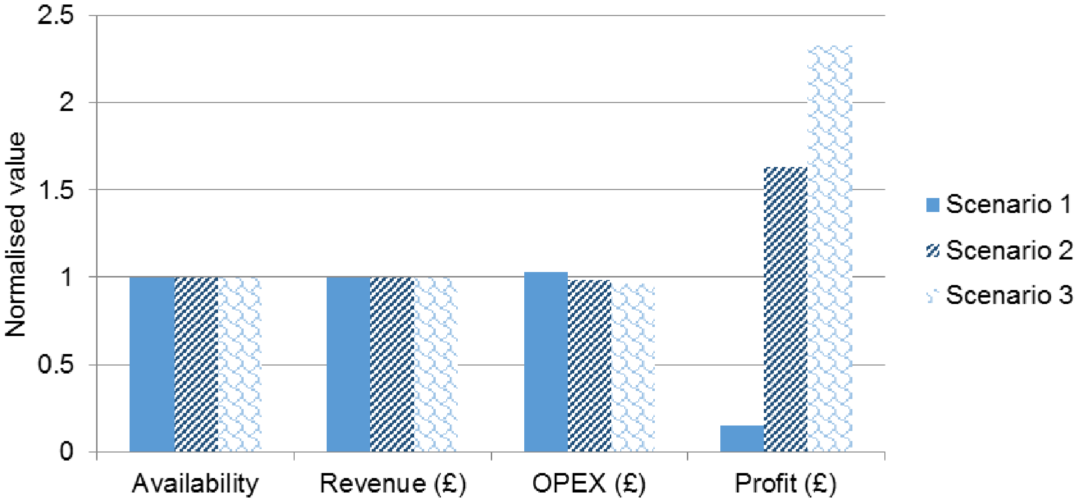


Figure 5.26. Mean results of different site travel time scenarios, normalised against the base case

The results for availability and revenue show very little variation between the scenarios, although the differences, however slight, are in line with the site travel times. The highest availability and revenue is seen for scenario 3, followed by scenario 2 and then the base case. Scenario 1 has the longest travel times and therefore has the lowest availability and revenue. The impact of the different site travel times is much more prominent for operational expenditure. Scenario 1 incurs the most amount of annual OPEX, followed by the base case, scenario 2 and then scenario 3, in that order. Table 5.13 helps explain the differences in OPEX between the scenarios.

Table 5.13. Percentage variation from the base case

Component of OPEX	**Percentage difference from base case (%)**		
	Scenario 1	**Scenario 2**	**Scenario 3**
Fixed labour	0.00	0.00	0.00
Contracted labour	0.36	-2.86	-7.55
Parts costs	-0.44	-0.35	-1.44
Other costs	-0.50	-0.40	-1.46
Inspection costs	0.00	0.00	0.00
Vessel fuel costs	45.73	-18.59	-26.75

From Table 5.13, the biggest deviations from the base case can be seen in vessel fuel costs for all three scenarios. The assumed fuel costs of £20/hr for the slow and fast boats and £10/hr for the rib are fixed and do not account for higher fuel consumption at greater speeds or during tow operations. Therefore, when travel times to and from the site are longer, as in scenario 1, then the vessels are being used for longer periods, thereby incurring greater fuel costs. The opposite is true when site travel times are shorter, as seen in scenarios 2 and 3. The slight increase in revenue and larger decrease in OPEX mean that scenario 3 is more than twice as profitable as the base case for this size of WaveNET array. Further experience will need to be gained with the Squid devices to investigate if pre-operation preparation time can be cut down significantly, and if the vessel speeds used in scenarios 2 and 3 can be achieved safely.

The total length of a weather window required to undertake a marine operation depends on other aspects of offshore logistics, as well as site travel times. The time to undertake marine operations on larger WaveNET arrays may vary between different Squid devices. Although the devices are designed to allow vessels to travel through the array, WECs in the centre of a large array may be harder to access than WECs around the perimeter. This additional complexity needs to be taken into account when much larger arrays are modelled. Further operational experience with the Squid devices will aid the development of offshore logistical procedures, adding confidence to the Albatern-specific O&M model simulations.

5.11. Sale Price of Electricity

The electricity produced by a WaveNET array of Squid devices will replace diesel generated power currently used by fish farms and many off-grid island communities. The sale price of electricity so far in the analysis has been assumed to be 30.5p/kWh, in line with the Contracts for Difference tariff in the UK. However, this subsidy price only applies to grid-connected wave energy devices, and will therefore not be applicable to the array assessed in this chapter. The sale price of electricity for off-grid projects is an area open to negotiation.

Figure 5.27 shows that the profitability of the WaveNET array assessed in this chapter is extremely dependent on the sale price of electricity. Annual net operational income of the 24-device array increases by nearly £60,000 when the sale price is changed from 30.5p/kWh to 45p/kWh.

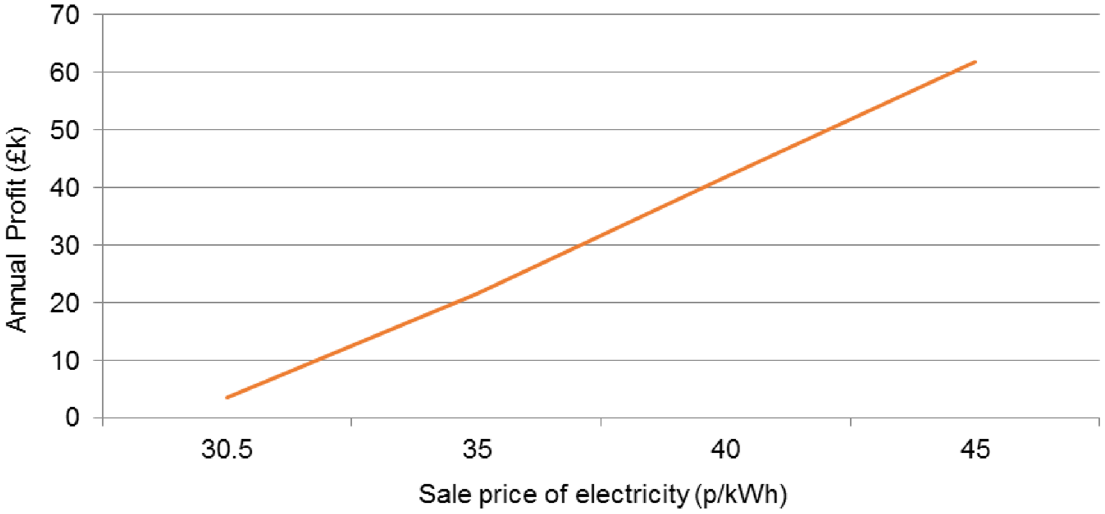


Figure 5.27. Annual profit of the array for different electricity sale prices

The Albatern-specific O&M model can provide an initial economic assessment to inform negotiations with the customer on sale price of electricity. The model also demonstrates the benefit to the local economy, in terms of jobs and vessel usage.

An initial estimate of a revised sale price of electricity can be made by taking these social benefits into account, as well as the cost of diesel. Frost (2015) identified that fish farms in Scotland typically use red-diesel generators with an average efficiency of 30%. The example of a 160kW generator with an average fuel consumption of 45l/hr was used. The study identified that red diesel can typically cost approximately 70p/l. A fish farm is unlikely to operate a diesel generator at full load all the time. The majority of the time, such generators will operate very inefficiently at low load in order to power small components such as underwater lighting. From this information, it has been calculated that the cost of diesel to a fish farm is around 35p/kWh. If the other benefits are made clear during negotiations with the customer, it is reasonable to assume a revised electricity sale price of 40p/kWh.

The O&M model functionality assumes that adequate energy storage is available, thereby ignoring intermittency of the wave energy array. Sufficient storage also means that demand-side issues, such as the fact that fish require more food as they mature, can be ignored in the O&M tool. However, energy storage equipment will incur capital expenditure which needs to be included in future, holistic economic assessments.

5.12. Chapter Discussion

The generic O&M model has been modified to be specific to Albatern's 6-series 'Squid' wave energy converter. The device has a modular design to enable deployment in a much larger 'WaveNET' array. The Albatern-specific O&M model accounts for the expectation that certain component subassemblies, such as the Power Take Off unit, can be replaced whilst the Squid is offshore. This saves time and cost when compared to the usual strategy of taking the device to the O&M base for onshore repair and maintenance. The inputs to the model have mostly come from the expert judgement of the engineers involved in the development of Albatern's wave energy converter. Experience gained at a six-WEC testing programme at Mingary Bay, off the Ardnamurchan coast in Scotland, has also been used to inform the inputs. A preliminary analysis confirmed that Mingary Bay is not suitable for real-sea deployment of the array in terms of generating net operational income. Therefore, a base case was developed consisting of 24 Squid WECs located 7km offshore in the Minch, off the Isle of Skye's west coast in Scotland. The base case assumptions show that the array has annual averages of 97.73% availability, £122.78k revenue and £119.18k operational expenditure.

When a Squid WEC requires retrieval for repair and/or maintenance, it is taken to an onshore O&M base. The Albatern-specific O&M model is representative of real-life onshore logistics by constraining the number of WECs that can be placed onshore at any one time. The base case assumed that three WECs are allowed onshore, with a further constraint of two WECs undergoing routine servicing (thus leaving one space free for emergency WEC retrieval). On further investigation, it was found that limiting the space to one WEC results in greater annual net operational income for the array. This is due to fewer marine operations taking place overall, resulting in lower OPEX negating the slight loss in revenue.

Three vessels are used during the Mingary Bay testing programme, but only one is capable of installing and retrieving a Squid WEC from site. Analysis of the base case results showed that this vessel is used much more than the other two and, furthermore, some marine operations have to be delayed if it is not available. However, it is not necessary to have another vessel available for the analysed 24-WEC array. Experience in replacing certain components whilst the device is still offshore is extremely limited. Yet, the base case assumptions are deemed to be realistic and will be validated during the Squid testing programme.

An analysis into the workforce arrangements at the onshore O&M base was carried out. It was shown that the best scenario for the assessed array is the base case of having one site manager permanently employed, with external contractors hired as technicians whenever marine operations or maintenance activities are required. This is seen as a realistic scenario that provides social benefits to the local area, thereby improving the relationships between the array operator, the customer and the local community. A negative impact on profitability of the array is seen if external contractors cannot be hired.

The limited operational experience gained with the 6-series WEC informs parameters defining travel times to and from the offshore array site, such as average vessel speeds. A preparation time of 30 minutes prior to any marine operation was included in the base case simulations. An analysis into these assumptions showed that overall profitability of the array can be improved when average vessel speeds and tow speeds are increased, and preparation time is halved to 15 minutes. The revised assumptions can be validated with further operational experience of the Squid WECs.

The sale price of electricity was taken to be 30.5p/kWh in the base case simulations, reflecting the UK's Contracts for Difference subsidy for wave energy. However, this tariff is not applicable to off-grid wave energy arrays, making the sale price of electricity a point open to negotiation with the customer (e.g. a fish farm operator). It was found that diesel-generated electricity can cost fish farm operators in the region of 35p/kWh. The revised sale price of 40p/kWh was deemed to be a realistic scenario, given the social and environmental benefits of using power from a renewable source.

The analysis presented in this chapter has shown how an O&M model can be used to assess aspects of lifetime logistics for an off-grid wave energy array. Using the selective analysis undertaken, an 'optimal' case can be defined for the 24-WEC array. Table 5.14 lists the assumptions made for the optimal and base cases. The impact that the optimal case has on operability and profitability of the wave energy array can be seen in Figure 5.28. The results have been normalised to show the percentage differences between the two cases.

Table 5.14. O&M model assumptions for the optimal case compared to the base case

O&M Strategy Consideration	**Base Case**	**Optimal Case**
Onshore space	Three WECs	One WECs
Offshore maintenance	Possible	Possible
Labour arrangements	One permanent employee, contractors allowed	One permanent employee, contractors allowed
Site travel times	See Table 5.11	Scenario 3, see Table 5.11
Sale price of electricity	30.5p/kWh	40p/kWh

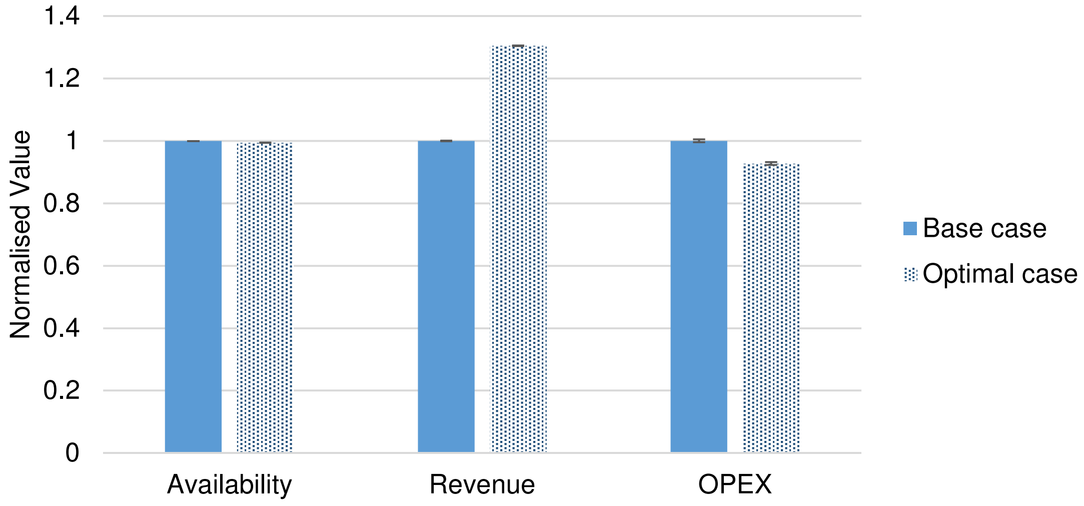


Figure 5.28. Results of the 'optimal' O&M strategy, normalised against the base case, with 95% confidence intervals applied

From Figure 5.28 it can be seen that the optimal case increases revenue by approximately 30% compared to the base case. There is also a reduction in OPEX of 7.3%. The slight reduction is availability is caused by the limitation of one Squid allowed at the O&M base at any one time, though it is negated by the reduction in OPEX. The annual net operational income is greatly improved, with £49.64k in the optimal case compared to £3.60k in the base case. The largest difference between the two cases is seen in the revenue results. This highlights once again the importance of negotiating the best electricity sale price possible with the customer by stressing the social and environmental benefits of replacing diesel-generated power.

The bill of materials used to inform the parts costs for input to the Albatern-specific O&M model estimates that the cost of building of a 6-series Squid device is approximately £70,000. This does not include additional manufacturing costs, such as labour, nor does it include site development costs. It is clear that the annual net operational income generated by a 24-Squid WaveNET array will not be economically viable as this capital expenditure (CAPEX) cannot be cancelled out, even if the optimal case is applied. It could be possible to use the O&M model to investigate the number of 6-series WECs required in a WaveNET array for it to become economically viable. However, an initial analysis into larger arrays (i.e. in the order of 300+ WECs) showed some limitations of the O&M model as it stands.

Firstly, WECs towards the end of list do not undergo routine inspection in the specified year due to work being delayed right through the winter. Delays in work can be caused by a lack of space at the O&M base, lack of technicians (although this isn't an issue if external contractors can be hired), lack of suitable vessels or lack of open weather windows. The space available at the O&M base can already be specified by the user, and weather windows are subject to the weather conditions, although different operational limits can be selected. At present, the model does not allow the user to specify the number of vessels available, although the model algorithm was modified for the simulations presented in section 5.7. However, a far more complicated aspect that causes delays to work is the priorities the model takes when carrying out work. Currently, the functionality of the model assigns the correct number of technicians to a repair or maintenance task when a WEC is taken to harbour. If external contractors are restricted, then this means a new marine operation cannot take place until the previous task has been completed. Allowing the user to select a priority hierarchy of O&M aspects will add a further element of realism to the Albatern-specific O&M model. The complexity in applying this methodology to the already multi-faceted functionality is the primary reason that a cost-benefit analysis has not been included in the Albatern-specific O&M model at this time. Such an addition would be necessary for much larger arrays.

Arrays consisting of hundreds of Squid WECs will also bring additional complexity to the O&M model in terms of offshore logistics, as well as array layout. It is currently unclear what the optimal moorings configuration would be for such arrays. This affects the failure rate inputs to the O&M model. However, this does mean that a fully-functioning Albatern-specific O&M model would be a useful tool in this optimisation process. A large number of Squid WECs also means that some marine operations are likely to take longer than others, adding complexity to offshore logistics which needs to be accounted for in the O&M model.

This chapter has demonstrated how an O&M model tailored to Albatern's 6-series Squid WEC could be used to plan aspects of the O&M strategy and estimate OPEX costs of WaveNET arrays. The model can also be used to help select sites suitable for the offshore array as well as the necessary O&M base onshore. This methodology can be scaled up for new generations of Squid devices, such as the 12-series WEC, rated at 75kW, currently under development by Albatern. Scaling up the device in the O&M model means that inputs, such as failure rates, need to be revised, as well as increasing parts and other costs accordingly. A power matrix for the new device will need to be obtained so that revenue can be calculated by the tool. As more experience is gained with projects such as the Mingary Bay testing programme, the Albatern-specific O&M model can be refined in order to obtain cost estimates with a greater level of confidence.

Chapter 6 – Model Sensitivity

The general rule in the field of numerical modelling is that the outputs are only as good as the inputs. This is an issue in areas where inputs to models contain a large degree of uncertainty. Offshore operations and maintenance of renewable energy projects is one such area, due to the limited amount of real-sea experience gained in the sector, particularly with wave energy devices. It is clear that confidence in the outputs of the O&M models described in the previous chapters can be greatly improved if there is less uncertainty in the inputs. It can also be improved by enhancing the realism of the model in terms of its functionality as more real-sea experience is gained.

Far more real-sea experience has been gained with the Pelamis P2 device than with the Albatern 6s Squid WEC. Figure 6.1 provides a graphical representation of the development steps undertaken by Pelamis Wave Power, including real-sea testing, which have contributed to the relatively high degree of confidence in the O&M model inputs.

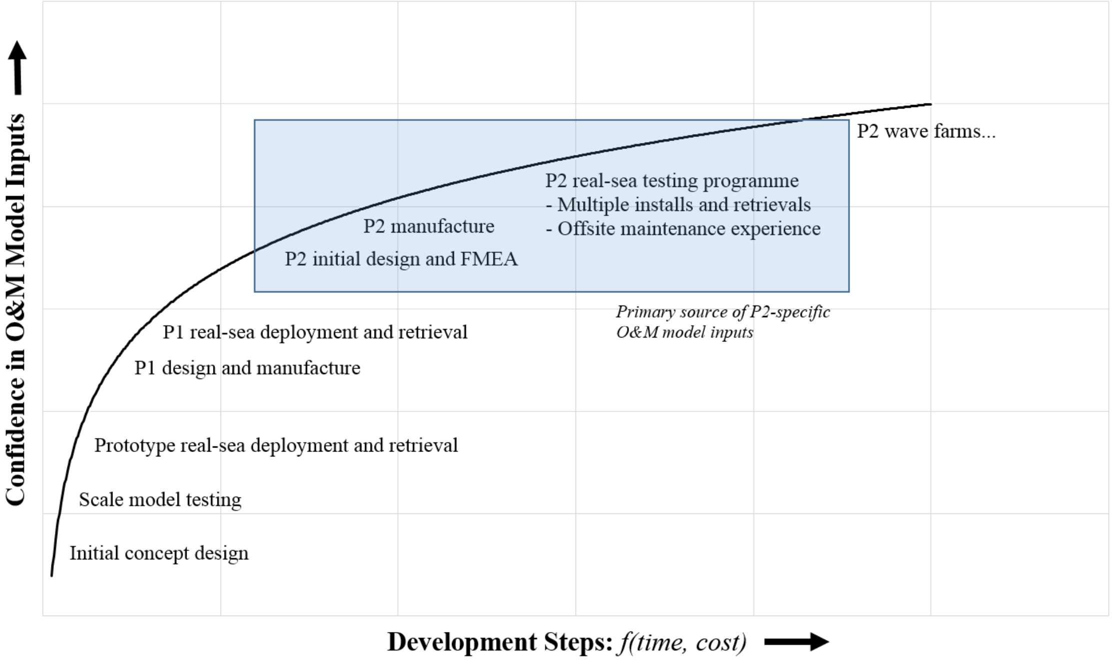


Figure 6.1. Development steps (a function of time and cost) undertaken by Pelamis Wave Power and the associated impact on confidence in O&M model inputs

This chapter sees sensitivity analyses undertaken on key inputs to the Pelamis-specific O&M model in sections 6.1, 6.2 and 6.3, using the base case O&M strategy of the 10-WEC array described in chapter 4. The Albatern-specific tool is then utilised in section 6.4 to investigate how confidence in the model inputs can be improved. Section 6.5 provides discussion of the key outcomes of the analyses.

6.1. Weather Sensitivity

The weather data input to the O&M tool comes from a Markov Chain Model (MCM), as discussed previously. The MCM requires an input of hindcast weather data in order to generate time series' containing significant wave height (Hs), wave energy period (Te) and wind speed (U). Simulated time series' show the same seasonal trends as the hindcast dataset, but offer more variability to the O&M model.

This section uses two different sites in UK waters to demonstrate the sensitivity of the O&M model to weather input data. The Pelamis P2 wave energy converter is used as the case study. The hindcast datasets are analysed first in terms of accessibility and power capture, before the results of simulations with the O&M

model show the differences between the two sites in terms of availability, revenue and operational expenditure of a wave farm.

6.1.1. Site selection

Site A is located off the North coast of Scotland and represents Farr Point; a site previously being developed by Pelamis Wave Power as a potential wave energy array. Site B is found off the North coast of Cornwall and represents Wave Hub; a test facility for offshore renewable energy technologies (Wave Hub Limited, 2015). The locations of the two sites are shown in Figure 6.2.

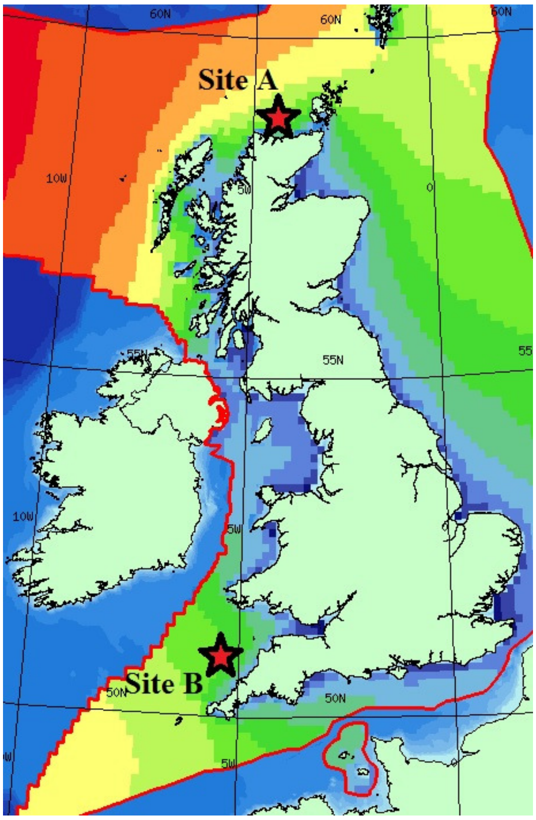


Figure 6.2. Annual UK wave resource map (ABP Marine Environmental Research Ltd., 2016) showing approximate locations of the two sites analysed in this study

Port selection is required for both sites in order to define the number of P2 installations and/or removals that can be carried out in a given weather window; a key input to the Pelamis-specific O&M model. As shown in Figure 6.3, the O&M base for site A would have most likely been located in the natural shelter of Loch Eribol, approximately 30km from the wave energy array. For site B, a study by Walker et al. (2013) investigated ports in Cornwall suitable for mobilisation of a WEC. Figure 6.4 shows the locations of three of the ports considered suitable for access to the Wave Hub site. Hayle port, 25km from the site, has been assumed as the O&M base for a wave farm located at site B for this study.

Figure 6.3. Transit route between the Loch Eribol O&M base and site A (30km)

Figure 6.4. Map of Cornwall showing three ports suitable for access to Wave Hub, 25km from Hayle (Walker et al., 2013)

6.1.2. Tow times and marine operations

Table 6.1 summarises the key timings to consider when defining the length of a weather window required for the installation or removal of a Pelamis P2 WEC. From this information, it is clear that an installation operation at either site would need a weather window of at least 6 hours in length. Therefore, as the resolution of the O&M model used in this study is 6 hours, a weather window of 12 hours has been selected. However, vessel logistics can be applied to the O&M model to account for the fact that a retrieval operation would take significantly less time than an installation. As a result, the O&M model used in this study assumes that at both sites, in a 12 hour window, the vessel can either:

- remove a maximum of two P2 devices and bring them both to the quayside
- install one P2 device at the farm
- install one P2 device at the farm, then remove another one and bring it to the quayside

Table 6.1. Breakdown of timings to calculate weather window length

Description	Notes	Time
Tow time (5kts vessel speed)	30km to site A 25km to site B	3hrs 15mins for site A 2hrs 50mins for site B
Vessel travel time (15kts assumed vessel speed)	30km to site A 25km to site B	1hr 5mins for site A 1hr for site B
Installation time once at site	Conservative estimate from Yemm et al. (2012)	1hr
Pre-ops time required before installation	Yemm et al. (2012)	2hrs
Total time required for installation		***7hrs 20mins for site A*** ***6hrs 50mins for site B***
Retrieval time once at site	Conservative estimate from Yemm et al. (2012)	15mins
Total time required for retrieval		***4hrs 35mins for site A*** ***4hrs 5mins for site B***

6.1.3. Weather conditions

Hindcast data has been used to generate time series’ for these two sites. As stated by Gray, Johanning & Dickens (2015), the hindcast data for Site A (Farr Point) is for an eighteen year period from 1992 to 2010. It contains all three parameters required to define a weather window for the P2 device (Hs, Te and wind speed). Wave Energy Scotland have provided this dataset for the purposes of this thesis.

A 23 year hindcast dataset (1989-2011) for the Cornish coast (Site B) has been provided by the University of Exeter, as part of the PRIMaRE project (PRIMaRE, 2015). This has been validated against buoy measurements by van Nieuwkoop et al. (2013). However, it is only possible to obtain values for significant wave height and wave energy period from this dataset. In order to match wind speeds to the Hs-Te combinations, data from the Channel Coastal Observatory (CCO) at Perranporth was used (see Figure 6.5). This information is readily available from their website (Channel Coastal Observatory, 2015). Real-time data was chosen for the period 12/3/2014 to 10/11/2015 with values obtained for Hs, Te and wind speed in half hourly intervals. The intervals were averaged to align with the three hour resolution of the hindcast dataset. It was then possible to calculate the probabilities of a wind speed matching each combination of Hs and Te. This allowed the completion of 23 year hindcast dataset with the addition of appropriate wind speeds using a Markov-based approach, similar to the method used in the weather simulation model itself (Gray, Johanning & Dickens, 2015). This method is less than ideal, as it assumes that the wind speeds onshore have a direct relationship with the wind speeds 25km offshore. It should also be noted that this method is limited by the fact that extreme waves (i.e. 1 in 100 year storms) will not be accounted for, unless such waves occur in the hindcast dataset. However, the method was deemed suitable for this study as wind speed is a significant part of defining weather constraints on marine operations, as well as the focus in this study being on the comparison of different simulations.

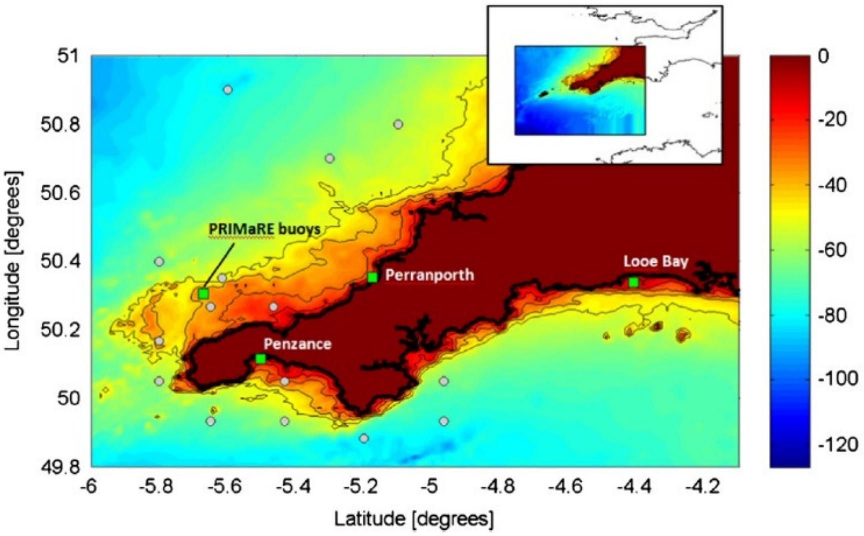


Figure 6.5. Map of Cornwall showing the approximate locations of data buoys and Perranporth (Walker et al., 2013)

A comparison between the binned hindcast datasets for the two sites in terms of the mean seasonal values of each of the three parameters is given in Table 6.2. It can be seen that the mean significant wave heights and wave energy periods are lower at site B than at site A across all seasons. Conversely, the wind speed is lower on average at site A than at site B in every season. The site characteristics are also presented as five-number summaries (i.e. box diagrams) in Figure 6.6, Figure 6.7 and Figure 6.8.

Table 6.2. Mean seasonal weather values of site A and site B with 95% confidence intervals

	Mean values ± 95% confidence intervals					
	Significant Wave Height (m)		**Wave Energy Period (s)**		**Wind Speed (kts)**	
	Site A	**Site B**	**Site A**	**Site B**	**Site A**	**Site B**
Full Dataset	2.18 ± 0.01	1.95 ± 0.01	8.43 ± 0.01	7.32 ± 0.01	17.03 ± 0.07	19.10 ± 0.08
Winter	2.88 ± 0.02	2.65 ± 0.02	9.35 ± 0.03	7.98 ± 0.02	20.73 ± 0.15	24.30 ± 0.19
Spring	2.15 ± 0.02	1.88 ± 0.01	8.44 ± 0.02	7.32 ± 0.02	16.57 ± 0.13	18.55 ± 0.16
Summer	1.42 ± 0.01	1.38 ± 0.01	7.46 ± 0.02	6.81 ± 0.01	13.01 ± 0.10	14.57 ± 0.13
Autumn	2.29 ± 0.02	1.92 ± 0.01	8.52 ± 0.02	7.19 ± 0.02	18.00 ± 0.14	19.18 ± 0.16

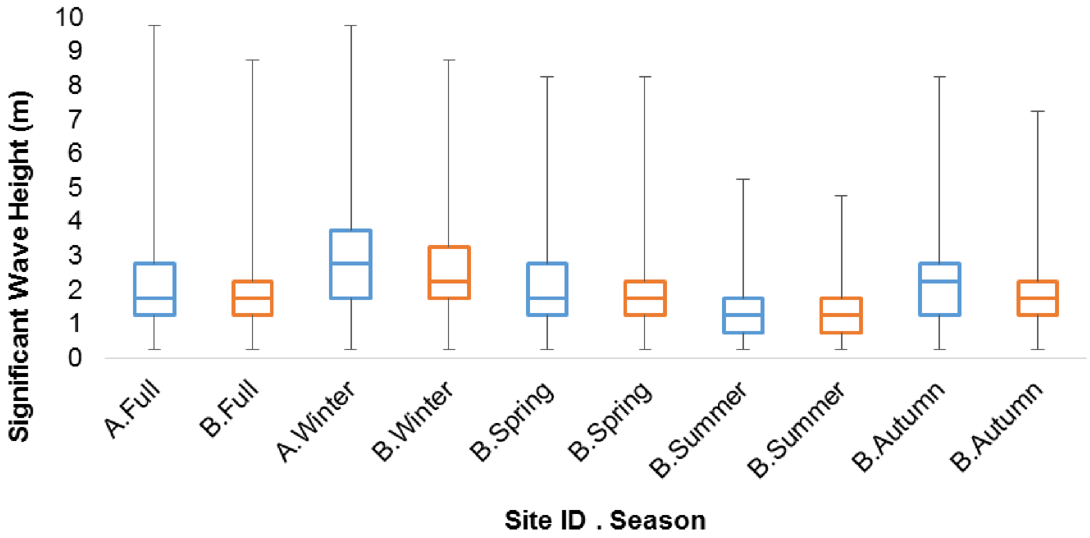


Figure 6.6. Seasonal statistical data of significant wave height, comparing the two sites

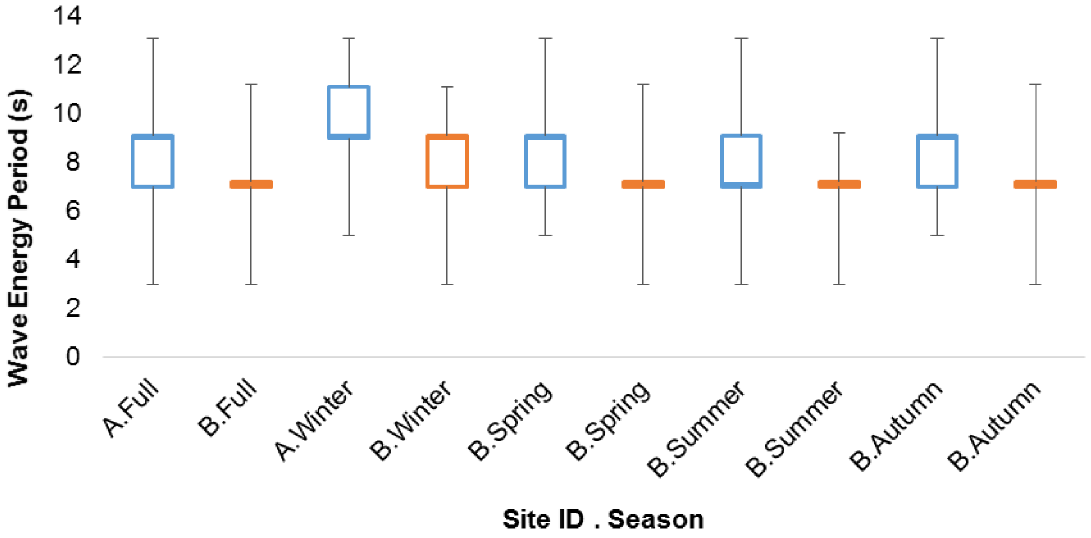


Figure 6.7. Seasonal statistical data of wave energy period, comparing the two sites

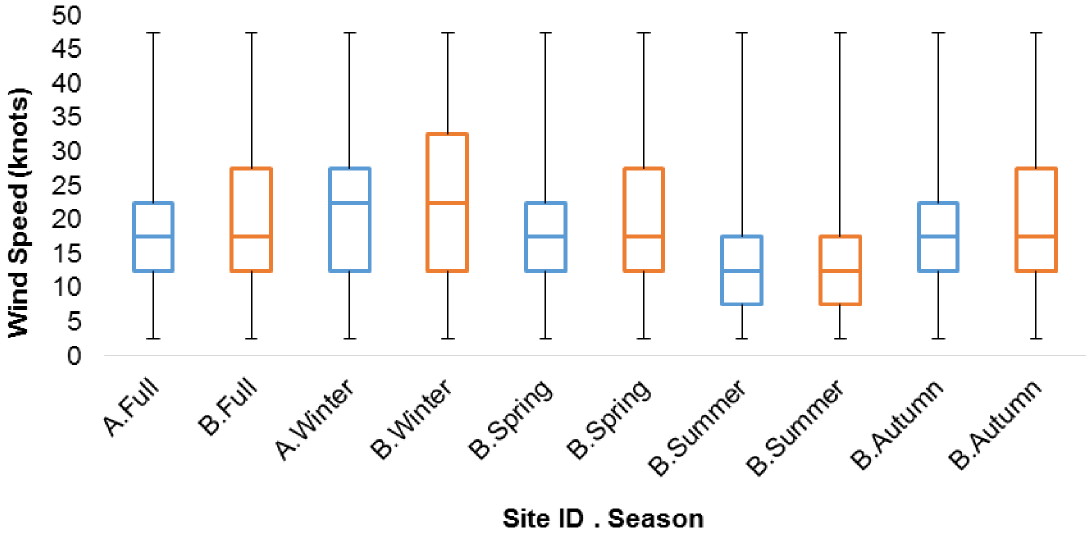
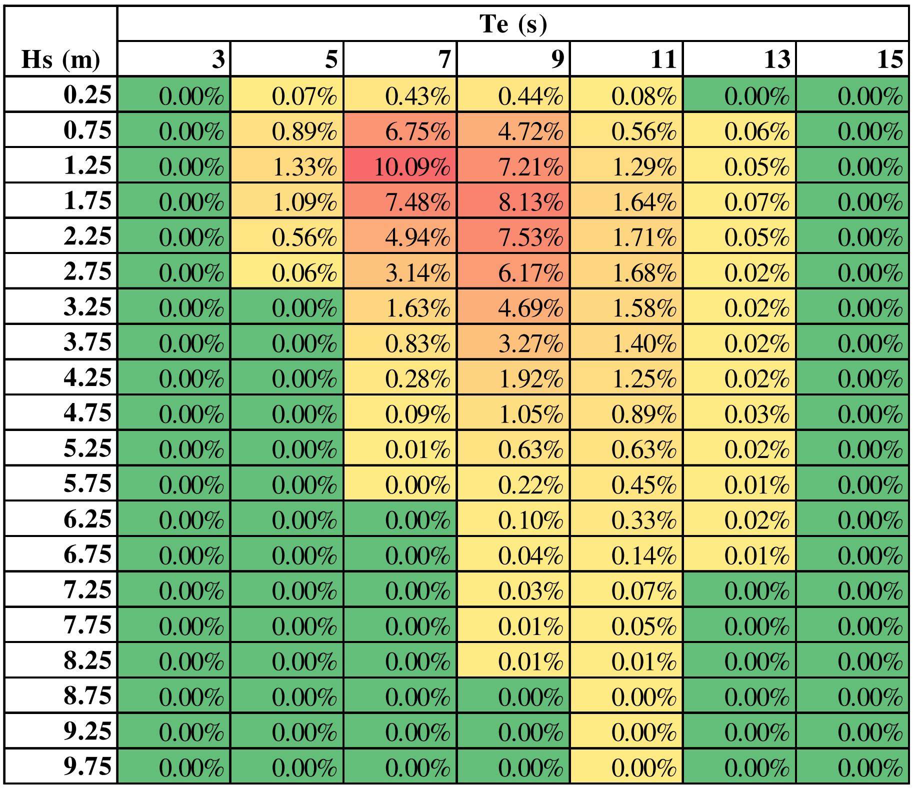


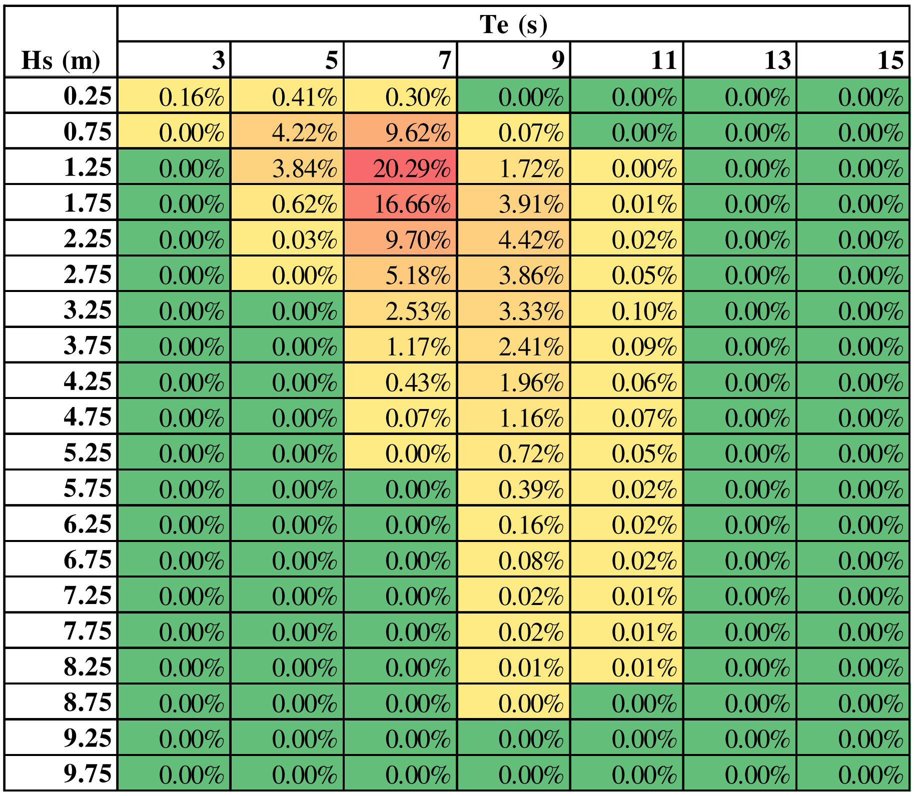
Figure 6.8. Seasonal statistical data of wind speed, comparing the two sites

As part of the MCM process, the hindcast data is placed into bins that match the power matrix for the P2 WEC. The hindcast data can therefore be represented graphically using occurrences tables (see Figure 6.9 and Figure 6.10). It can be seen that site A has a much higher proportion of occurrences in areas of high power capture (when matched to the P2 power matrix), such as in the 9s Te, >1.25m Hs region.



Hs (m)	Te (s)						
	3	5	7	9	11	13	15
0.25	0.00%	0.07%	0.43%	0.44%	0.08%	0.00%	0.00%
0.75	0.00%	0.89%	6.75%	4.72%	0.56%	0.06%	0.00%
1.25	0.00%	1.33%	10.09%	7.21%	1.29%	0.05%	0.00%
1.75	0.00%	1.09%	7.48%	8.13%	1.64%	0.07%	0.00%
2.25	0.00%	0.56%	4.94%	7.53%	1.71%	0.05%	0.00%
2.75	0.00%	0.06%	3.14%	6.17%	1.68%	0.02%	0.00%
3.25	0.00%	0.00%	1.63%	4.69%	1.58%	0.02%	0.00%
3.75	0.00%	0.00%	0.83%	3.27%	1.40%	0.02%	0.00%
4.25	0.00%	0.00%	0.28%	1.92%	1.25%	0.02%	0.00%
4.75	0.00%	0.00%	0.09%	1.05%	0.89%	0.03%	0.00%
5.25	0.00%	0.00%	0.01%	0.63%	0.63%	0.02%	0.00%
5.75	0.00%	0.00%	0.00%	0.22%	0.45%	0.01%	0.00%
6.25	0.00%	0.00%	0.00%	0.10%	0.33%	0.02%	0.00%
6.75	0.00%	0.00%	0.00%	0.04%	0.14%	0.01%	0.00%
7.25	0.00%	0.00%	0.00%	0.03%	0.07%	0.00%	0.00%
7.75	0.00%	0.00%	0.00%	0.01%	0.05%	0.00%	0.00%
8.25	0.00%	0.00%	0.00%	0.01%	0.01%	0.00%	0.00%
8.75	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
9.25	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
9.75	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Figure 6.9. Occurrence table for site A



Hs (m)	Te (s)						
	3	5	7	9	11	13	15
0.25	0.16%	0.41%	0.30%	0.00%	0.00%	0.00%	0.00%
0.75	0.00%	4.22%	9.62%	0.07%	0.00%	0.00%	0.00%
1.25	0.00%	3.84%	20.29%	1.72%	0.00%	0.00%	0.00%
1.75	0.00%	0.62%	16.66%	3.91%	0.01%	0.00%	0.00%
2.25	0.00%	0.03%	9.70%	4.42%	0.02%	0.00%	0.00%
2.75	0.00%	0.00%	5.18%	3.86%	0.05%	0.00%	0.00%
3.25	0.00%	0.00%	2.53%	3.33%	0.10%	0.00%	0.00%
3.75	0.00%	0.00%	1.17%	2.41%	0.09%	0.00%	0.00%
4.25	0.00%	0.00%	0.43%	1.96%	0.06%	0.00%	0.00%
4.75	0.00%	0.00%	0.07%	1.16%	0.07%	0.00%	0.00%
5.25	0.00%	0.00%	0.00%	0.72%	0.05%	0.00%	0.00%
5.75	0.00%	0.00%	0.00%	0.39%	0.02%	0.00%	0.00%
6.25	0.00%	0.00%	0.00%	0.16%	0.02%	0.00%	0.00%
6.75	0.00%	0.00%	0.00%	0.08%	0.02%	0.00%	0.00%
7.25	0.00%	0.00%	0.00%	0.02%	0.01%	0.00%	0.00%
7.75	0.00%	0.00%	0.00%	0.02%	0.01%	0.00%	0.00%
8.25	0.00%	0.00%	0.00%	0.01%	0.01%	0.00%	0.00%
8.75	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
9.25	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
9.75	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Figure 6.10. Occurrence table for site B

The O&M tool has the ability to use different 20 year time series' during the sensitivity analysis. However, this would significantly alter the base case for each simulation, as shown for the Farr Point site in Table 6.3. These results have been produced with the O&M tool randomly selecting one time series from a possible fifty in the dataset store at the start of every simulation. The large variability in the results demonstrates that it is vital to select one time series when a sensitivity analysis on other variables is being undertaken. Therefore, one 20 year dataset has been chosen for each site which best represent the statistics of their respective hindcast datasets. This selection is based on the criteria of the percentage of open weather windows, the average power outputs, and the monthly trends of installation wait times.

Table 6.3. Statistical mean results of the P2-specific O&M model base case for the Farr Point site when weather time series' are selected at random

Statistic	**Availability (per year)**	**Revenue (£k per year)**	**OPEX (£k per year)**
Mean	86.2%	2811.4	1103.5
Minimum	84.8%	2727.9	1014.5
Maximum	87.6%	2919.3	1178.0
Range	2.8%	191.3	163.5
Standard Deviation	0.6%	54.8	37.0

6.1.4. Site accessibility

The site characteristics charts (Figure 6.6, Figure 6.7 and Figure 6.8) show that site A has a greater significant wave height and greater wave energy period on average than site B. The implication from this is that site A will have a higher yield in terms of power output of a wave energy farm. However, this may result in weather conditions suitable for marine operations being more abundant at site B. This effect may be balanced by the wind speed at site A being lower on average than at site B. Figure 6.11, Figure 6.12, Figure 6.13 and Figure 6.14 show the cumulative probability distribution functions of the weather constraints for installation and removal of a P2 device for each season of the year, providing a graphical comparison of wait times for the two sites. This accessibility information can be quantified by calculating the average number of days required to wait for a weather window in each month (see Figure 6.15). A year in the O&M model starts in December, as this makes it easier to assess differences between meteorological seasons.

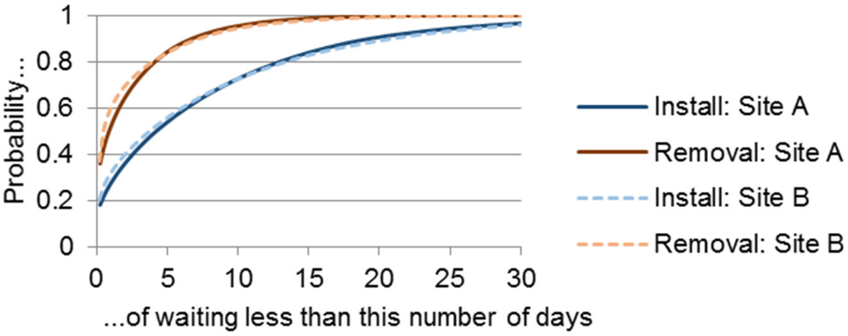


Figure 6.11. Cumulative Distribution Functions of installation and removal accessibility during winter (December, January and February) for the two sites used in this study

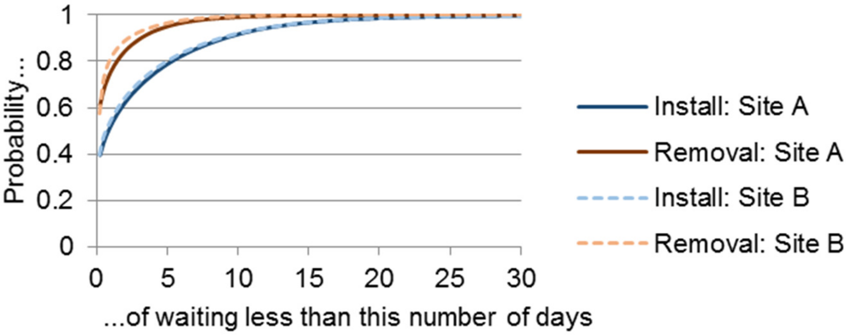


Figure 6.12. Cumulative Distribution Functions of installation and removal accessibility during spring (March, April and May) for the two sites used in this study

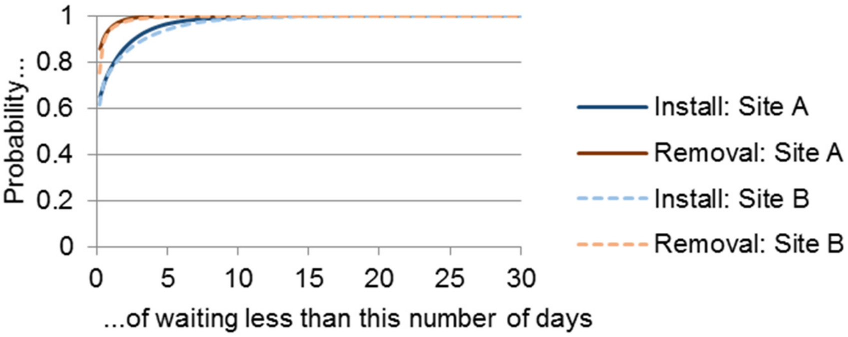


Figure 6.13. Cumulative Distribution Functions of installation and removal accessibility during summer (June, July and August) for the two sites used in this study

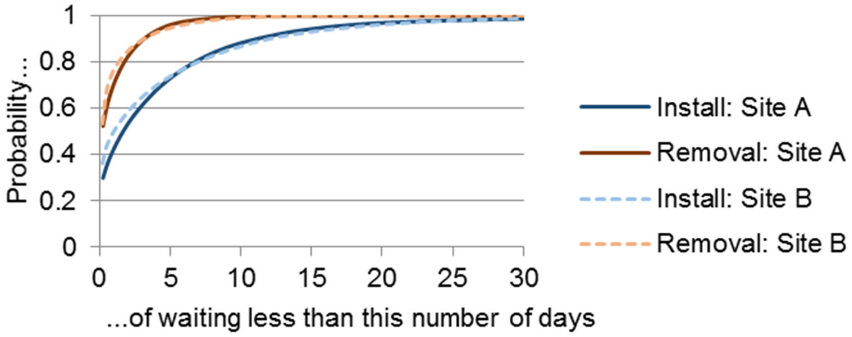


Figure 6.14. Cumulative Distribution Functions of installation and removal accessibility during autumn (September, October and November) for the two sites used in this study

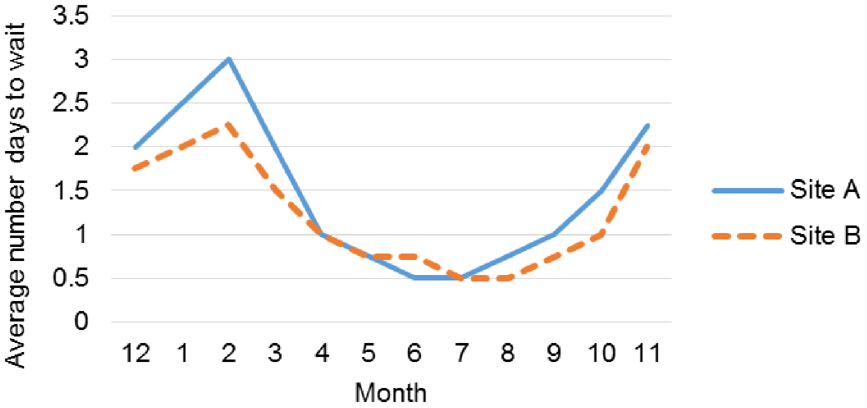


Figure 6.15. Comparison of the two sites in terms of the average number of days to wait for a 12 hour weather window suitable for installation of a P2 device in each month

The cumulative probability distribution functions shown in Figure 6.11, Figure 6.12, Figure 6.13 and Figure 6.14 match up closely for sites A and B. This implies that the time spent waiting for a 12 hour weather window would be approximately equal for the two sites. However, from Figure 6.15 it can be seen that the estimated average number of days to wait for an open weather window is higher for site A in every month of the year except June. On average, a vessel would need to wait 1.48 days for weather conditions suitable for a 12 hour WEC installation in any given month when the wave farm is located at site A, compared to 1.23 days for site B. This information implies that there may be slightly higher operational expenditure at site A due to the vessel being kept on hire for longer periods on average.

6.1.5. Power estimation

The Pelamis P2 power matrix is matched with the occurrence tables for the two sites (Figure 6.9 and Figure 6.10) to provide the O&M model with estimates of power generation, thereby enabling the cost-benefit calculations to take place.

Figure 6.16 represents these inputs graphically by comparing the average estimated power generated across a 6 hour period for the two sites in each season of the year, as well as providing the average values for the full dataset. This estimation assumes wave farm availability to be 100%. Figure 6.16 shows that a wave farm located at site A is estimated to generate more power than at site B in all four seasons of the year.

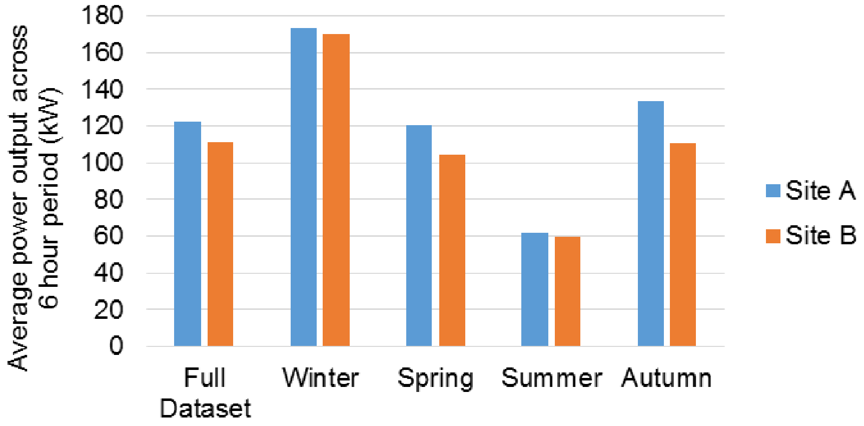


Figure 6.16. Comparison of the two sites in terms of average power output across a 6 hour period

6.1.6. O&M model simulation

The O&M model was set up to simulate a wave farm at each site consisting of 10 P2 WECs over a lifetime of 20 years, using the base case inputs (appendix Tables A.1 and A.2). The results are presented numerically in Table 6.4. The results have also been normalised for graphically representation (Figure 6.17), with 95% confidence intervals applied.

Table 6.4. Mean results for a 10 machine, 20 year Pelamis P2 wave farm located at each site

Site	Availability (per year)	Revenue (£k per year)	OPEX (£K per year)
A	0.865	2836.6	1110.5
B	0.860	2582.3	1087.2

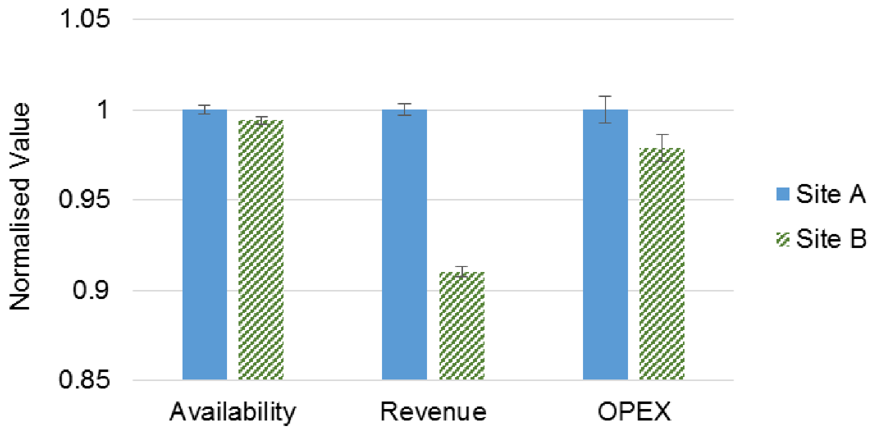


Figure 6.17. Mean results for a 10 machine, 20 year Pelamis P2 wave farm located at each site, normalised against site A, with 95% confidence intervals applied

The slight difference seen in estimated wait times between the two sites suggested that Operational Expenditure (OPEX) would be higher at site A. This is demonstrated by the results of the O&M model, where the average OPEX at site A was calculated to be £1.11m compared to £1.09m for site B, equating to a 2.1% increase. In addition, the implication that a Pelamis P2 wave farm located at site A would generate a higher revenue is confirmed by the results of the O&M tool, where the base case annual revenue at site B is £2.58m compared to £2.84m at site A. This equates to a 9% decrease in revenue if the wave farm was located at site B rather than at site A. The base case results also show that there is a negligible 0.6% difference between the two sites in availability. This is most likely due to the slightly different inputs in terms of estimated wait times and potential revenue, thereby affecting the cost-benefit calculations within the model. The application of 95% confidence intervals shows that there is a clear difference between the results for the two sites.

6.1.7. Further port selection

The O&M model simulations carried out here assume that all maintenance tasks would be undertaken at the ports described previously. However, operators of wave energy arrays would have to consider each maintenance task independently. It is likely that more complex tasks would require specialist equipment, such as a dry dock, meaning that the forward O&M base would need careful planning and significant investment. If such upgrades were unfeasible due to space or logistical restrictions, WECs would need to be taken to larger ports for some maintenance tasks. For site A, this may involve taking the device to Lyness in the Orkney Islands (see Figure 6.3), or Penzance if the farm was at site

B (see Figure 6.4). Transit times to and from Penzance would also suffer from having to travel around the Cornish headland where tidal conditions would play a part in determining weather windows. Both journeys would require a much greater tow time, resulting in longer waits for a suitable weather window and decreased vessel availability for other WECs at the farm. This would have significant knock-on effects on profitability of the wave energy array. The assumed O&M base location for site B has also not taken into account that access to Hayle harbour is tidal dependant. This would mean that a vessel towing a WEC into the O&M base would have to wait outside the harbour until the tide allows entry, thereby extending the time to carry out the marine operation.

A more in-depth analysis of weather window lengths and constraints would be required to assess the true impact of using different ports for the O&M activities of a Pelamis wave farm. However, a preliminary analysis provides an indication of the impact of extending the required length of weather window using the same operational constraints. If a 24 hour weather window is specified with the same permutations of marine operations used previously, then the estimated average number of days to wait for a weather window increases significantly from 1.48 and 1.23 up to 4.77 and 4.60 for sites A and B respectively (see Figure 6.18).

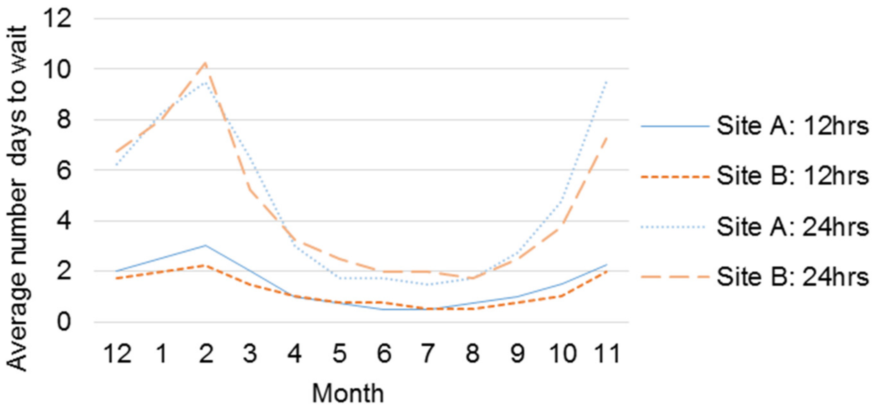


Figure 6.18. Effects of an increased length of weather window in terms of estimated number of days to wait to carry out an installation operation

In addition, the base case results for site B show a significant drop in both availability and revenue (~4% each) when the required length of weather window is specified as 24 hours rather than 12 hours (Figure 6.19). This is matched by an OPEX increase of 6%. Site A shows similar results.

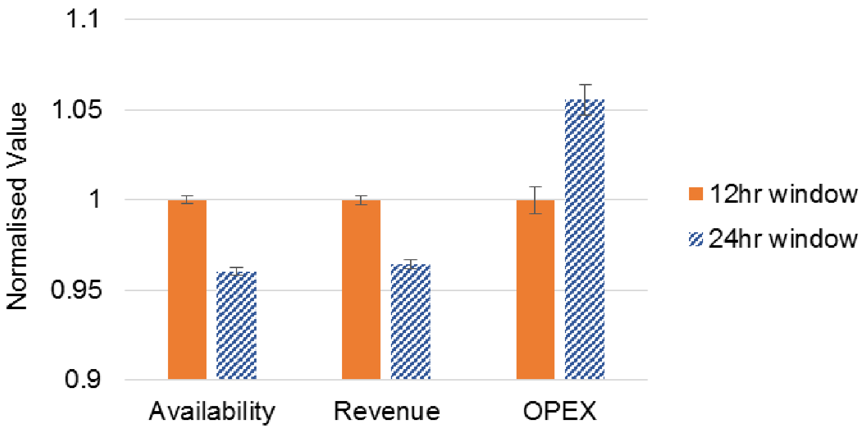


Figure 6.19. Effects of an increased length of weather window for site B, normalised against the 12hr base case, with 95% confidence intervals applied

6.2. Design Sensitivity

The methodology of using fault categories to represent the subsystems and components of a WEC is used so that the O&M model can compare different designs using the same metrics. Prior to the company entering administration in 2014, Pelamis engineers were in the process of designing the next generation WEC; named the P3. From the initial design, it has been possible to obtain failure rate inputs for the P3 device using the same FMEA methodology used for the P2 inputs. This section sees the Pelamis-specific O&M tool used to compare the P2 and P3 devices in order to demonstrate the model's sensitivity to new WEC designs.

6.2.1. P3 inputs

Pelamis engineers carried out a Failure Modes and Effects Analysis (FMEA) when designing the P3 WEC. The design changes from the P2 (shown in Table 6.5) aimed to improve the reliability of the device and increase profitability, resulting in a commercially competitive WEC. An extra power take off unit was to be added, increasing the power rating of the device from 750kW (for the P2) to 1MW.

Table 6.5. Key design changes from Pelamis P2 to P3

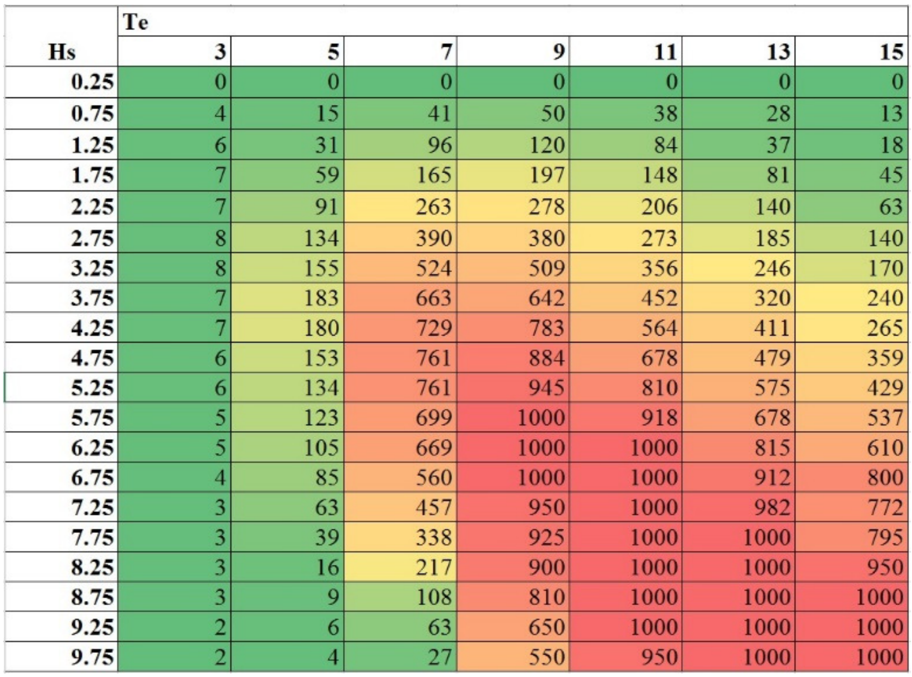
System	**Number in P2**	**Number in P3**
Accumulator pack	8	6
Reservoir	8	6
Heat exchanger	8	6
Ram	16	30
Ram manifold	16	30
MG set	4	3
Hoses (and layout)	4	3
Bellow seals & inflation	8	6
Cables (and transits)	8	9
Tether Latch Assembly	1	1
Module & Nose DC supply	5	4
Control & Comms Hardware	1	1
Transformer & Switchgear	1	1
Structural		
Active Yaw	1	1
Endcap	8	6
Main Bearing Assembly	8	6
Module	4	3
Moorings	1	1
Tube	5	4

The FMEA process involved assigning failure rates to all potential failure modes and then allocating each to one or more fault categories. As with the P2 device, the failure modes for the P3 WEC were informed by reliability handbooks, component testing, expert judgement, as well as the experience gained during the P2 testing programme. The failure rate inputs for the P3-specific O&M model can be seen in Table 6.6.

Table 6.6. Changes to failure rate inputs for O&M model from P2 device to P3

ID	Failure Category	P2 Probability of Failure (per year)	P3 Probability of Failure (per year)
1	Major mooring	0.0159	0.0085
2	Major structure (no warning)	0.0624	0.0099
3	Major structural failure (monitored)	0.0302	0.1390
4	Major primary hydraulic	0.0100	0.0130
5	Loss of GPS comms & main comms	0.0040	0.0020
6	Major sealing	0.0317	0.0770
7	Half circuit failure	0.3600	0.2788
8	Minor mooring	0.0337	0.0291
9	Data communications	0.0140	0.0070
10	Electrical unions/ tieback	0.0396	0.0208
11	Control system	0.2604	0.3336
12	Minor structural	0.0262	0.4407
13	Minor primary hydraulic	0.9375	0.9252
14	Minor sealing	0.1900	0.0862
15	Secondary hydraulic	0.2256	0.1395
16	Generator or switchgear	0.0396	0.0149

The only other change required for the P3-specific O&M model was the power matrix input (Figure 6.20). The power matrix for the P3 WEC has been inferred from hydrodynamic computational modelling carried out by Pelamis Wave Power. No changes were made to other inputs such as maintenance parameters (e.g. repair times) or vessel tow times, although it could be expected that the length of these tasks would reduce as more experience was gained. This is speculation and therefore does not feature in this study.



	Te						
Hs	**3**	**5**	**7**	**9**	**11**	**13**	**15**
0.25	0	0	0	0	0	0	0
0.75	4	15	41	50	38	28	13
1.25	6	31	96	120	84	37	18
1.75	7	59	165	197	148	81	45
2.25	7	91	263	278	206	140	63
2.75	8	134	390	380	273	185	140
3.25	8	155	524	509	356	246	170
3.75	7	183	663	642	452	320	240
4.25	7	180	729	783	564	411	265
4.75	6	153	761	884	678	479	359
5.25	6	134	761	945	810	575	429
5.75	5	123	699	1000	918	678	537
6.25	5	105	669	1000	1000	815	610
6.75	4	85	560	1000	1000	912	800
7.25	3	63	457	950	1000	982	772
7.75	3	39	338	925	1000	1000	795
8.25	3	16	217	900	1000	1000	950
8.75	3	9	108	810	1000	1000	1000
9.25	2	6	63	650	1000	1000	1000
9.75	2	4	27	550	950	1000	1000

Figure 6.20. P3 power matrix

6.2.2. Design comparison

Using the same boat permutations for a 12 hour weather window as described in section 6.1, the O&M model has been run 50 times for each of the P2 and P3 devices. The Farr Point dataset has been used for the weather input data. The mean results for each year are presented in terms of farm availability, revenue generated and OPEX incurred in Figure 6.21, Figure 6.22 and Figure 6.23 respectively.

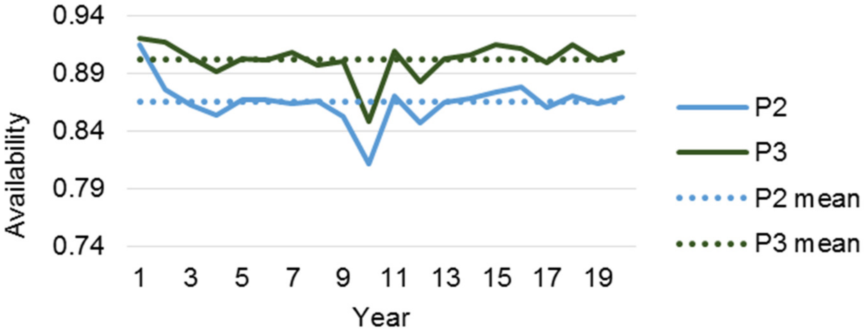


Figure 6.21. Mean results in terms of availability comparing the P2 and P3 WECs

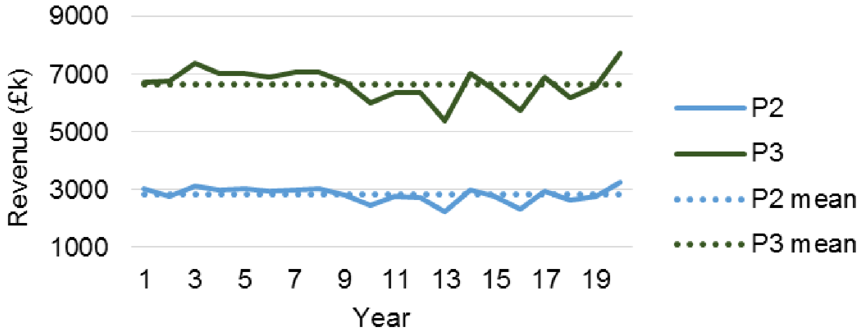


Figure 6.22. Mean results in terms of revenue comparing the P2 and P3 WECs

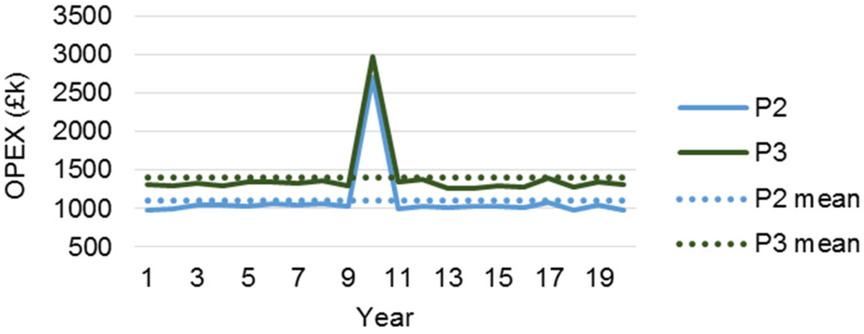


Figure 6.23. Mean results in terms of OPEX comparing the P2 and P3 WECs

The results of the O&M model simulations show that a wave farm consisting of 10 P3 devices, given the inputs stated previously, would yield a much greater revenue (over 230% more) and have a higher availability (~3.5%) than a P2 wave farm. The higher revenue is simply an effect of having a different power matrix with much higher yield. The OPEX results (Figure 6.23) show that a P3 wave farm incurs a higher operational cost than a P2 array due to the increased number of failures that occur. This is caused by the differences in failure rates laid out in Table 6.6. However, the simulations do not take into account further learning rates in terms of undertaking maintenance tasks, which would have an impact on total OPEX. Although the P3 farm incurs greater OPEX costs, the availability is higher due to the increased revenue, leading the cost-benefit analysis part of the tool to instigate the immediate repair of faults in order to avoid lost revenue.

The O&M tool can also be used to identify the faults that have the biggest impact on farm operability. Figure 6.24 and Figure 6.25 show the top five fault categories for the P2 and the P3 devices respectively.

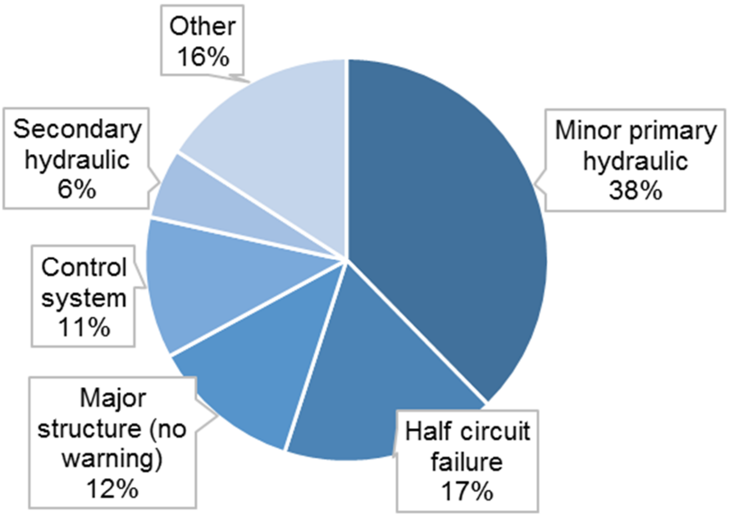


Figure 6.24. Top five failures in terms of percentage of total annual OPEX incurred for a P2 wave farm

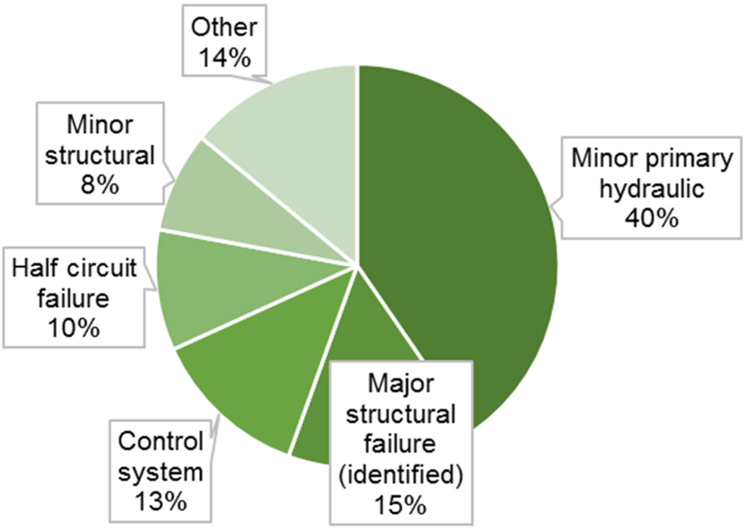


Figure 6.25. Top five failures in terms of percentage of total annual OPEX incurred for a P3 wave farm

The fault category which has the biggest impact on OPEX of wave farms of both devices is minor primary hydraulic faults. This category has by far the highest failure rate for both devices. Significantly increasing the failure rates of the ‘major structural (identified through monitoring system)’ and ‘minor structural’ faults has seen them enter the top five most costly failures for the P3 WEC. Such significant increases have led to the increase in overall OPEX incurred by a P3 wave farm compared to a P2 array. If the P3 design had been developed further, the information obtained from the O&M tool would be used to identify target areas for design development. As demonstrated in this section, the O&M model could be used to compare different iterations of WEC design in order to help find the optimal solution in terms of operability when deployed in a wave energy array.

6.3. Failure Rate Sensitivity

A more detailed analysis on the sensitivity of failure rates in the O&M model can be undertaken by changing each fault category at a time. For each new input scenario presented in this study, the O&M model was run ten times to obtain the mean values. As demonstrated in Appendix A, mean outputs from ten simulations still contain an acceptably low level of variance. A base case was first simulated by running the Pelamis P2-specific O&M model with the original failure rates (see appendix Table A.1). Martin et al. (2016) undertook a sensitivity analysis on offshore wind farms using the O&M model developed by Douard, Domecq & Lair (2012) and state that an uncertainty envelope of at least 20% should be applied. For the sensitivity study presented in this section, a factor of 10 was chosen in order to provide clear differences between the results. It would be possible to estimate uncertainty envelopes with better confidence, given that the components represented by the fault categories are known and that the reliabilities of some components (e.g. subsea cables) are better understood than others. This was not deemed suitable for this study as a consistent factor of uncertainty is required to compare the results directly. Therefore, for subsequent runs following the base case, the failure rates of fault categories were decreased, then increased, by a factor of 10. The failure rate information in the model is provided as a probability of failure per year. Therefore, increasing the rate by a factor of 10 requires the use of equation 6.1.

$$P_{\text{fail: increased}} = 1 - (P_{\text{not fail: original}})^{0.1} \qquad (6.1)$$

Table A.6 in the appendices contains the numerical results of this sensitivity analysis and Table A.7 provides the percentage changes from the base case. Although the sensitivity analysis has been undertaken for both sites assessed in section 6.1 (Gray et al., 2017), only the results for Farr Point are presented in this section. 95% confidence intervals have been applied to the results. The analysis identifies hydraulic valves as the component most sensitive to changes in estimated failure rate in the Pelamis P2 device, and highlights the importance of obtaining realistic failure rate estimates.

6.3.1. Minor primary hydraulic faults

From the results of the sensitivity analysis, it can be seen that the biggest drop in profitability of the P2 wave farm occurs when the failure rate for fault category 13 (‘minor primary hydraulic’) is increased by a factor of 10. The percentage changes from the base case are represented graphically in Figure 6.26.

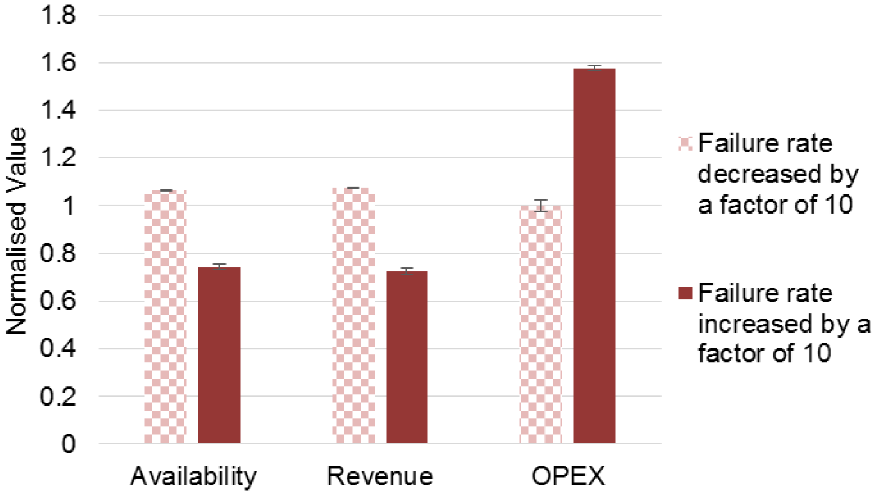


Figure 6.26. Sensitivity analysis results for ‘Minor primary hydraulic’ faults, normalised against the base case

Availability decreases from the base case by approximately 22.2%, whilst revenue decreases by 27.4%. Operational expenditure also increases significantly in this case by 57.7%. As shown in appendix Table A.1, the base failure rate for category 13 is a probability of failure per year (P_{fail}) of 0.9375. Increasing this rate by a factor of 10 leads to a probability of failure of 0.9938 per year. Therefore, a minor primary hydraulic failure is almost guaranteed to occur at least once per year on each machine in this scenario. On the other hand, the values for associated parameters such as power loss, time off site and repair costs are minimal when compared to other fault categories. However, the results from the sensitivity analysis show that the increased failure rate of minor primary hydraulic faults has a significant impact on profitability of the wave farm. This indicates that an increase in the number of minor primary hydraulic faults leads the cost-benefit analysis (CBA) part of the O&M tool to set affected devices for retrieval more often than in the base case, regardless of the low-impact associated parameters.

Conversely, when the failure rate for category 13 is decreased by a factor of 10, the results show the largest increases in availability and revenue. This increase stems from the fact that there are fewer minor primary hydraulic faults occurring in the farm, and thus the cumulative impact of power loss is reduced compared to the base case. However, this scenario does not lead to an equally significant decrease in OPEX. An explanation for this is that the reduced number of minor primary hydraulic faults does not have enough of an impact on the cost-benefit calculations to lead to a decrease in either the average number of marine operations or the time a machine spends off site over the lifetime of the farm.

It is possible to look into the fault category at a component level by investigating the P2 FMEA spreadsheet. From this, it can be seen that the component with the biggest influence on the minor primary hydraulic fault category is the hydraulic valves within the ram manifolds. There were 8 such valves within a single ram manifold, with a total of 16 manifolds in a Pelamis P2 device. Each of these 128 hydraulic valves has a manufacturer's target Mean Time Between Failure (MTBF) of 100 years. This equates to a probability of failure of 0.7313 per year, making up the majority of the 0.9375 base failure rate for the minor primary hydraulic fault category. As with many components within a WEC, these hydraulic valves are being used in a different environment from the one they were designed for. As a consequence, it is not unfeasible that the manufacturer's specified MTBF could be an underestimate of the true failure rate when deployed in a WEC. The results from this sensitivity analysis show that an increase in the number of failures in the minor primary hydraulic fault category could have a significant impact on profitability of a wave farm. Therefore, developers of WECs should work closely with manufacturers to design components specifically for the marine environment, and carry out testing accordingly for more realistic failure rate estimates.

6.3.2. Half circuit failure

The biggest increase in OPEX occurs when the failure rate of category 7 ('half circuit failure') is increased by a factor of 10. This is a 64.5% increase, as shown in Figure 6.27. There are also decreases in availability and revenue in the region of 5% and 7.5% respectively. There are also minor increases in availability and revenue, and a slight decrease in OPEX, when the failure rate for the half circuit failure category is decreased by a factor of 10.

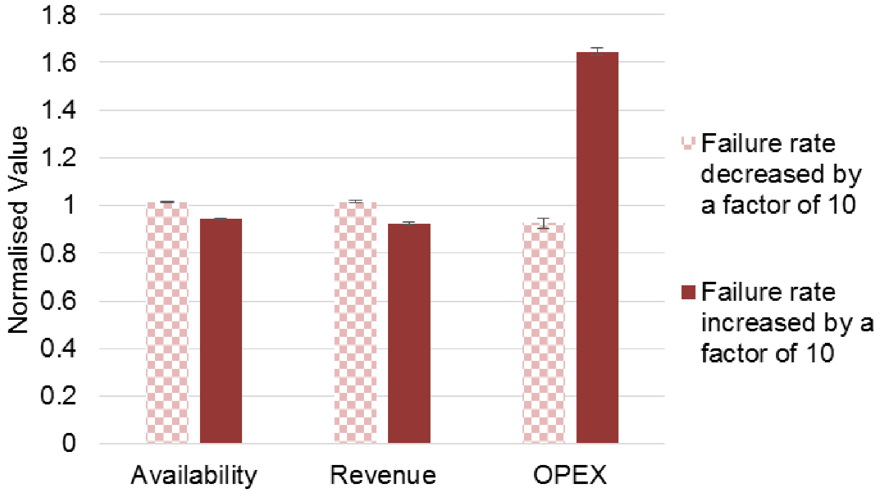


Figure 6.27. Sensitivity analysis results for 'Half circuit failure', normalised against the base case

A Pelamis P2 device was made up of four articulating joints called modules, each housing a hydraulic power take off unit. A half circuit failure is defined as any mechanical or hydraulic fault, such as an oil leak or ram manifold crack, which leads to one half of a module becoming incapable of power generation. This category has the second highest base failure rate (P_{fail} = 0.36) due to the sheer number of potential faults that could contribute to a half circuit failure. In the O&M model, this is classed as an intermediate failure where the associated power loss, time off site and repair costs are not particularly large when compared to the major faults. Therefore, it can be assumed that the results of the sensitivity analysis for this category come from the high probability of failure in the base case.

This assumption can be confirmed when the results are compared to the results for category 9 ('data communications'). Here, the power loss and repair parameters are similar to the half circuit failure but with a much lower base failure rate (P_{fail} = 0.0139). The sensitivity analysis for data communications faults shows virtually no impact on profitability of the wave farm. This information highlights that in subsystems where many individual faults lead to the same overall failure, those components must be over engineered and thoroughly tested to ensure minimal impact over the lifetime of the wave farm.

6.3.3. Control system faults

The results of the sensitivity analysis are also quite significant for fault category 11 ('control system'), as shown in Figure 6.28. When the control system base failure rate (P_{fail} = 0.2604) is increased by a factor of 10, availability and revenue drop by approximately 7% and 9.5% respectively. A control system failure is classed as a minor fault and therefore most likely requires other faults to have occurred before the CBA deems it beneficial to repair the affected P2 machine. Only minor impacts are seen when the base failure rate is decreased by a factor of 10.

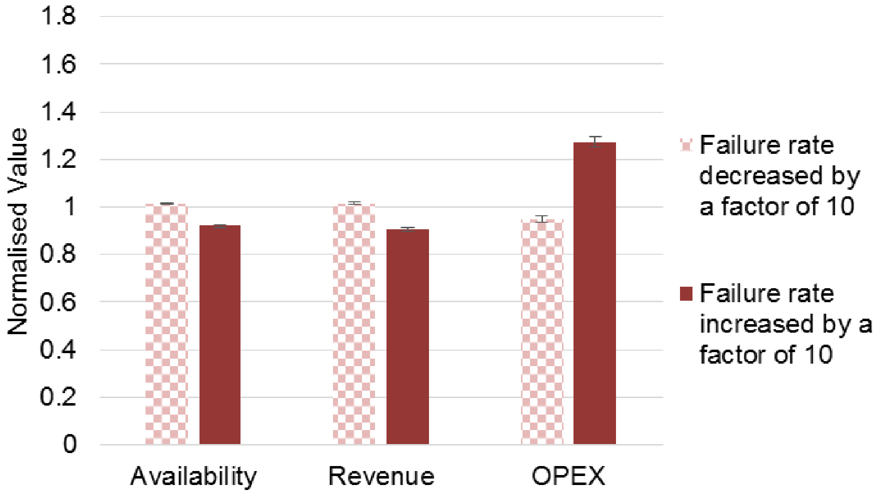


Figure 6.28. Sensitivity analysis results for ‘Control system faults’, normalised against the base case

Similar to category 7, a control systems failure can arise from several sources, such as the pressure sensors in a ram manifold. This cumulative effect leads to the control systems failure having the third largest base failure rate of all 16 fault categories. Obtaining the failure rate for this category is made difficult due to different specifications of pressure sensor having very different failure rates, and also because pressure sensor failure rates are highly dependent on the operating environment. When comparing categories 7 (half circuit failure) and 11 (control systems), it can be seen that they have the exact same values for power loss (0.2), time to fix (2 days) and repair costs (£3,000 in total). The three differences that contribute to the variation in the sensitivity analysis results are the base failure rate (P_{fail} = 0.36 for half circuit failure versus P_{fail} = 0.2604 for control systems failure), classification (intermediate versus minor) and labour requirements (two technicians versus one). The much larger increase in OPEX when the base failure rate for category 7 is increased by a factor of 10 compared to the same scenario for category 11 (64.5% versus 27.4%) must be attributed to the greater base failure rate. However, this does not explain the variation in availability and revenue. With the half circuit failure having the greater base failure rate, it was expected that the scenario of increasing it by a factor of 10 would lead to a greater decrease in availability and revenue than for the control systems category. The reverse has been shown in the results which could perhaps be explained by the different classifications of the two faults. The P2-specific O&M model operates in a way that if a device suffers either one major fault or two intermediate ones, it is retrieved for repair as soon as weather permits. Therefore, the fact that a half circuit failure is classed as an intermediate fault could mean that the O&M model sets devices for immediate retrieval more when the base failure rate is increased, thus avoiding the complexities of the cost-benefit analysis.

Another fault category with similar parameters to the control systems one is category 15; secondary hydraulic failure (see appendix Table A.1). It has the fourth highest base failure rate at $P_{fail} = 0.2256$, has total repair costs of £3,500, takes one technician two days to carry out the repair and is also classed as a minor fault. The biggest difference between the two categories is the associated power loss; 0.2 for control systems and 0.06 for secondary hydraulic. The results from the sensitivity analysis show that changing the base failure rate of category 15 has less of an impact than category 11 (Figure 6.29). This indicates that the power loss associated with a control systems failure is a significant factor. Therefore, redundancy needs to be built into WEC subsystems in order to minimise the power loss and improve the profitability of the wave farm.

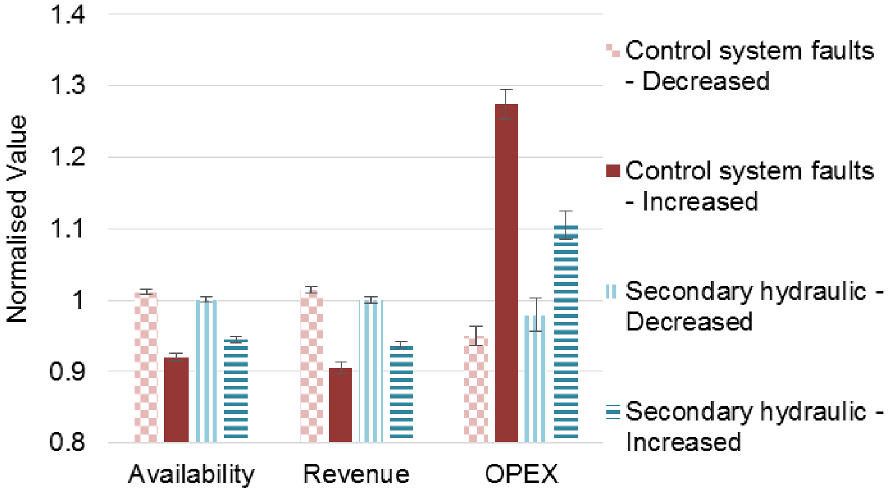


Figure 6.29. Comparison of sensitivity analysis results for 'control system faults' and 'secondary hydraulic' failures, normalised against the base case

6.3.4. Faults leading to immediate recovery

Category 2 (‘major structural – no warning’) shows the third largest increase in OPEX when the base failure rate is increased by a factor of 10 (see appendix Table A.1); at 54 %. However, the decreases in availability (~1%) and revenue (~1.5%) are negligible in comparison. This difference is due to the classification of category 2 as a major failure. The O&M tool does not enter the cost-benefit analysis when a major failure occurs, instead it sets the affected machine for removal and repair as soon as a weather window is open. This effect can also be seen to a lesser extent in the results for categories 1 (‘major mooring’) and 3 (‘major structural – identified’). Category 2 sees the largest impacts because it has the highest failure rate of the three and requires the longest time off site for repair. This decision making process also occurs when power output on a machine drops to zero, which is why similar results are produced for category 10 (‘electrical unions & tieback’), even though it is classed as intermediate. The base failure rates for these four categories are already so minimal that similar impacts do not occur when the failure rate is decreased by a factor of 10.

6.4. Increasing Confidence

The failure rates and maintenance parameters for the fault categories in the Pelamis-specific model have been obtained with a reasonable degree of confidence, due to the operational experience gained during the P2 testing programme. Albatern’s 6s Squid WEC has only very limited experience in sheltered-sea conditions and the Albatern-specific O&M model therefore contains a larger degree of uncertainty. This section first highlights how such uncertainty in the inputs of the Albatern-specific O&M model can affect the outputs, before suggesting how this uncertainty could be reduced in the future.

6.4.1. Modelling uncertainty

Three input scenarios are modelled using the Albatern-specific O&M tool in order to analyse the impact of uncertainty. The base case scenario of having 24 Squid WECs in the WaveNET array, described in chapter 5, is used for the analysis in this section. The ‘realistic’ scenario is where the inputs to the O&M tool are provided primarily by expert judgement, as shown in the appendices (Tables A.3 and A.4). The array-based failure categories are adjusted for the 24-WEC array by using the parameters shown in appendix Table A.5. The ‘optimistic’ scenario is where particular inputs, defined as 'adjusted parameters', are decreased from the 'realistic' case by approximately 20% (or as close to 20% as possible). The adjusted parameters include all parts costs, other costs, inspection costs and repair & replacement times. Failure rates are reduced by a factor of 2. Other inputs contain far less uncertainty, such as power loss, technicians' salaries, site travel times and vessel fuel costs, and are therefore not adjusted. For the third and final scenario, the adjusted parameters are increased from the 'realistic' case by ~20%, and the failure rates are increased by a factor of 2. This is labelled the 'pessimistic' scenario. Tables listing these inputs for the fault categories and the scheduled maintenance events can be seen in the appendices (Tables A.8 and A.9 respectively). The dataset of weather conditions for the Minch site, described in chapter 5, has been used to run the Albatern-specific O&M model for each of the three scenarios. The mean results of 50 simulations in terms of availability, revenue and OPEX, normalised against the 'realistic' case, are shown in Figure 6.30.

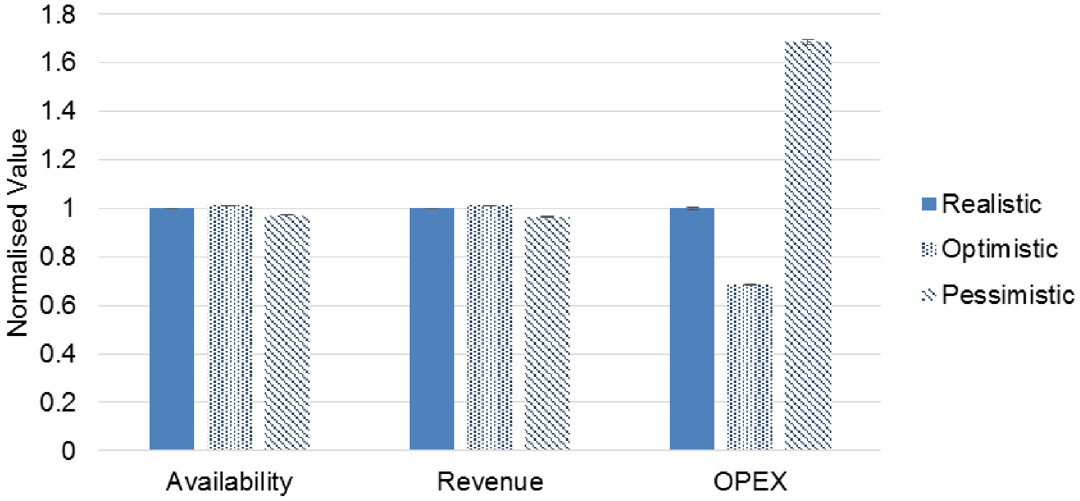


Figure 6.30. Annual availability, revenue and OPEX of the base case WaveNET array for the three input scenarios, normalised against the 'realistic' case, with 95% confidence intervals applied

The method of applying 95% confidence intervals shows that the results for all three scenarios are sufficiently different. The 'optimistic' scenario yields slight greater annual availability and revenue than the 'realistic' case, with increases of around 1% in both parameters. The 'pessimistic' case results are lower than the 'realistic' scenario, with 2.8% and 3.5% reductions in availability and revenue respectively. The results for OPEX are more extreme. The 'optimistic' case shows a 32% decrease in OPEX from the 'realistic' scenario, whilst the 'pessimistic' case

OPEX increases by 69%. These results has a significant impact on the profitability of the array. The annual net operational income (i.e. ‘profit’) increases from £3.6k in the ‘realistic’ scenario to £42.6k in the ‘optimistic’ case; a 12-fold increase. The impact on profitability is even greater for the ‘pessimistic’ scenario with an annual loss of £82.5k, representing a 22-fold decrease from the ‘realistic’ case. These significant effects on profitability of the array demonstrate the importance of obtaining realistic inputs with a large degree of confidence.

6.4.2. Development steps

Improving the confidence in the inputs to the Albatern-specific O&M model is vital in order to gain more realistic results. As shown in Figure 6.31, the inputs used in this thesis have been obtained early in Albatern’s development plan and, therefore, there are many milestones that need to be achieved before outputs of the Albatern-specific O&M model can be produced with a similar level of confidence to the Pelamis P2 results.

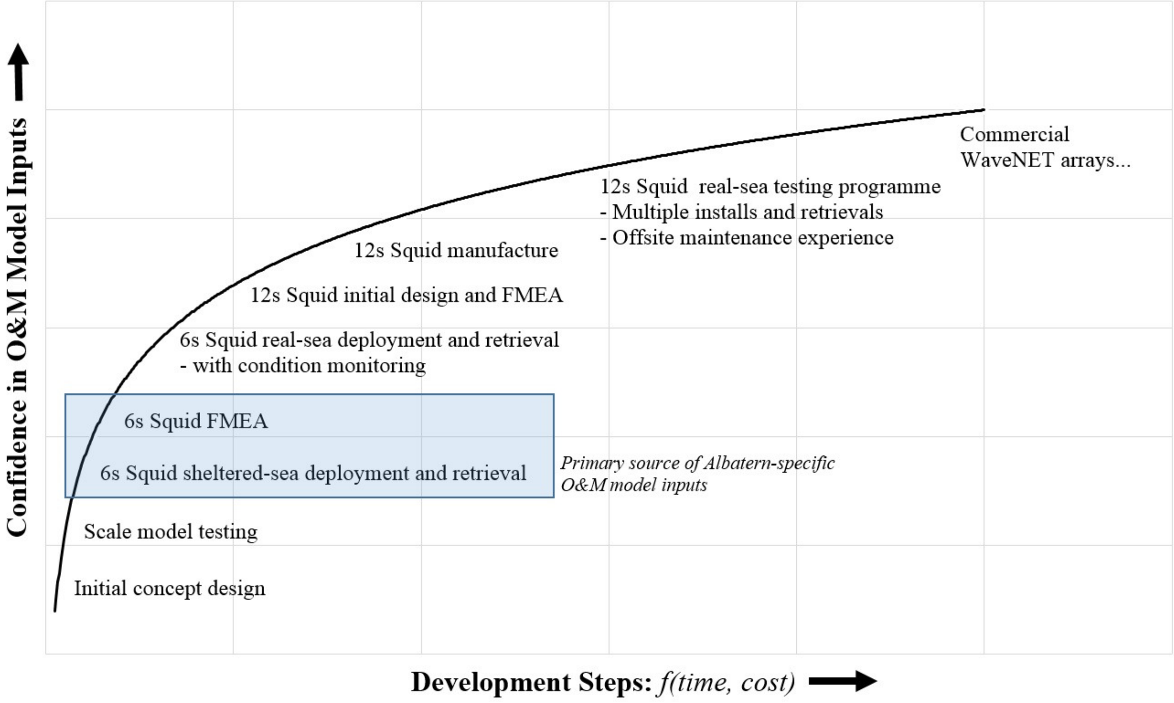


Figure 6.31. Development steps (a function of time and cost) undertaken and planned by Albatern and the associated impact on confidence in O&M model inputs

The key step that will improve confidence with the 6s Squid WEC is testing the device in more energetic seas than has previously been undertaken. This will mean that engineers will gain much more experience in all aspects of operations and maintenance, and the implementation of a condition monitoring system (outlined by Kenny et al., 2016) will help improve estimates of component failure rates. The information gained from testing the 6s device will provide the basis for inputs to an O&M model for the next generation Squid WEC, under development as the 12s. Although the 12s will be a significantly larger device, with a proposed rating of 75kW rather than 7.5kW, Albatern are applying similar principles to the design. Lessons learnt from the 6s design and testing processes need to be taken forward, such as carrying out a FMEA early in the design process to mitigate risks. Failure rate estimates will be improved significantly by undergoing the FMEA process, as well as working closely with component manufacturers during WEC fabrication. Real-sea testing of the 12s will then allow further refinement of all the inputs to the Albatern-specific O&M model, such as repair times and offshore maintenance procedures, and provide greater confidence in estimating the profitability of commercial wave energy array.

6.5. Chapter Discussion

The usefulness of a numerical model depends primarily on the level of confidence in the inputs. The inputs to the Pelamis P2-specific O&M tool have been obtained using the expert judgement of the engineers involved in the device development and subsequent real-sea testing programmes. This testing is limited, especially when compared to the offshore wind industry, meaning the P2 inputs still contain a degree of uncertainty. This chapter has seen a series of sensitivity analyses carried out on the P2-specific O&M tool in order to assess the impact of uncertainty on the model results and draw relevant conclusions.

An analysis into the sensitivity of the weather data input to the P2-specific model was undertaken by assessing two different sites at opposite ends of the UK. The wave period values in the hindcast datasets for the two sites were given in terms of wave peak period (Tp). In order to match the weather conditions up to the Pelamis power matrix, these values were converted to wave energy period (Te) using an empirical equation calculated based on weather conditions at the European Marine Energy Centre (EMEC) in Orkney. One potential issue with this method is the assumption that the wave characteristics in the north of Scotland are similar to in the south west of England. In addition, the method of completing the Wave Hub dataset by matching wind speeds from the onshore MET mast at Perranporth assumes a direct relationship between wind speeds at the coast and wind speeds 25km offshore. Clearly, this is unlikely to be the case and, as such, a hindcast dataset complete with onsite wind speed data would be more applicable. The Markov Chain method is also limited by only replicating extreme waves and winds if they have occurred in the original hindcast dataset. However, even with these limitations, the methods were deemed suitable for the analysis presented due to the focus on site comparison, rather than claiming true accuracy in the input data. Characteristic analysis of the two sites initially showed that there was very little difference in terms of accessibility. However, some variation in power performance was identified when the occurrence tables for the two sites were matched to the power matrix for the Pelamis P2 device. The outputs of the O&M tool confirmed the expected variation in power performance, where a 10% difference in revenue was identified between the two sites. These results suggest that a wave energy converter (WEC) should be designed for the weather conditions at a specific site in order to maximise revenue.

A demonstration of how an O&M model can be used to compare different generations of WEC design was provided. The third generation Pelamis WEC was used as a case study and compared to the P2 device. Input changes for the P3-specific O&M model were obtained from the expert judgement of the Pelamis engineers involved in the design process. The results showed that the increase in OPEX of the P3 array, incurred due to a larger number of hydraulic components, was negated by the far greater power output. Information such as this could prove vital in optimising the design of a profitable wave energy device.

The sensitivity analysis on the failure rate inputs to the O&M tool identified hydraulic valves as the component most sensitive to changes in estimated failure rate in the Pelamis P2 device. To minimise the uncertainty surrounding failure rates of these valves, as well as other components, WEC developers should collaborate with manufacturers to design and test components for the marine environment. In cases where several individual faults can cause the same overall failure within a WEC, the associated components must be over engineered and tested to reduce the impact on operability of a wave farm. In addition, redundancy of components must be built in to WEC subsystems to minimise the power loss associated with faults. It is vital that major failures, such as a structural breach, are planned for in order to deal with such occurrences in a rapid and efficient manner. One limitation of using constant failure rates in WEC system effectiveness models, such as the O&M tool presented in this thesis, is that component degradation is not taken into account. Another drawback of the failure rate methodology used in the O&M tool is that the modelled failure rates are not affected by changes in the weather. In reality, it is likely that storm weather conditions will result in a greater number of failures than in calm seas, unless the survival mechanism of the WEC can negate any such effects.

The 6-series Squid WEC, designed by Albatern, has undergone far less testing than was achieved with the Pelamis P2 device. Therefore, there is inherently a larger degree of uncertainty in the inputs to the Albatern-specific O&M tool. A sensitivity analysis was carried out on the model by simulating three different scenarios of inputs, using the expert judgement of the Albatern engineers as the 'realistic' base case. The 'optimistic' scenario led to a slight increase in revenue and a 32% drop in OPEX, leading to an almost 12-fold increase in annual net operational income. Conversely, the revenue decreased in the 'pessimistic' scenario and OPEX increased by 69%, resulting in a 22-fold drop in annual net operational income. Such large variations in the O&M model results highlight the importance of improving confidence in the inputs. Development steps to achieve this are both time consuming and financially costly, as indicated by the logarithmic nature of the confidence-development steps graphs. It is vital that WECs undergo real-sea testing in order to obtain realistic O&M tool inputs, in terms of failure rates, maintenance parameters, and model functionality, so that the best estimates of device performance and economic viability can be made.

Chapter 7 – Conclusions & Discussion

7.1. Summary of work

The work presented in this thesis was aimed at achieving the three primary contributions to knowledge listed in chapter 1; provide a blueprint for modelling lifetime logistics for wave energy arrays, assess aspects of their O&M strategies, and identify the development steps required to gain more confidence in cost estimates. This section summarises the work undertaken in the context of achieving these aims.

7.1.1. Creating an O&M model

A generic O&M tool, providing a bottom-up approach for estimating lifetime costs of a wave energy array, is described in detail in chapter 3. It is clear that better cost estimates can be obtained when an O&M model is tailored to the specific wave energy converter (WEC) under analysis. Such detailed descriptions of the inputs and functionality of the O&M model used in this thesis have been given to provide a reference for developers of wave energy technology, thereby avoiding unnecessary repetition in the sector. The approach used involves taking information learned from the design and deployment of a small number of WECs and using it to inform logistical decisions about a full array. The O&M model inputs and functionality, sourced primarily from expert judgement at present, can be reviewed as more experience with the small number of WECs is gained. In this regard, it is a 'living and breathing' piece of software.

Both case studies presented in this thesis use devices with hydraulic-based power take-off principles. As discussed in chapter 2, several concepts of wave energy converter are being considered at the present time, such as oscillating wave columns (OWCs) and linear generators. The type of power take-off unit is not a factor in modelling operations and maintenance strategies for wave energy converters, given that the device will either be repaired offshore or taken to the safety of a sheltered quayside or onshore O&M base. As demonstrated throughout this thesis, the generic O&M model described in chapter 3 can be tailored to simulate either of these strategies. The same methodology can therefore be used to model any type of wave energy converter, whether it be floating, seabed-fixed or contained within a breakwater, provided that appropriate input information is obtained.

7.1.2. Obtaining realistic OPEX estimations

Wave energy arrays have not yet been developed in the real world. Therefore, assessing whether or not the performance estimations made are realistic comes down to the level of confidence in the model inputs and functionality. Table 7.1 presents the key operational expenditure (OPEX) results from chapters 4 and 5 in terms of cost per machine. The table also presents the operational cost of each machine calculated relative to the amount of electricity produced.

Table 7.1. Results per machine using base cases and optimal scenarios for the two WECs analysed in this thesis

	Pelamis P2		**Albatern Squid 6-series**	
	Base Case	**Optimal Case**	**Base Case**	**Optimal Case**
Average annual OPEX per machine (£k)	108.92	102.67	4.96	4.61
Average AEP per machine (MWh)	931.58	932.28	16.77	16.69
Machine OPEX per unit of electricity produced (£/MWh)	116.92	110.12	296.05	276.03

From Table 7.1, it can be seen that OPEX per unit of electricity produced is one metric by which different types of WEC could be directly compared. However, such comparisons should also consider Levelised Cost of Energy (LCOE), as low unit OPEX could be negated by high capital costs. From the analysis of different O&M strategies in this thesis, it is clear that an increase in availability does not necessarily lead to an increase in annual net operational income, as an increase in OPEX may be incurred to achieve this level of performance. On the other hand, progress in marine operation techniques should not be constrained by the effects on one particular wave farm because increased OPEX may reduce as more experience is gained.

7.1.3. Assessing O&M strategies

Chapters 4 and 5 have seen the assessment of different O&M strategy aspects of the Pelamis P2 and the Albatern 6-series wave energy converters respectively. The two chapters both have discussion sections at the end highlighting the key points from the analysis. It is also useful to draw conclusions that are common for both devices and for wave energy arrays in general. The studies have shown that the use of low-cost vessels is paramount to the financial success of a wave energy array, as is having a carefully considered workforce arrangement. The analysis has also shown that the terms of finance for a wave energy array affect the decisions in determining the best O&M strategy. For example, buying a vessel outright specifically for use at the wave energy array could be a financially viable option, depending on the discount rate used for investment. Such O&M strategy decisions are also affected by the design lifetime of the wave energy array.

7.1.4. Identifying critical components

A sensitivity analysis presented in chapter 6 assessed the impact on wave farm profitability given changes to the estimated failure rates of the Pelamis P2 WEC. This study identified hydraulic valves as one of the most critical components in the device. This information is extremely useful to the wave energy sector, as many WECs under development are taking the approach of having hydraulic-based power take-off systems. It will therefore be beneficial to the sector if such components are thoroughly tested under the same conditions they would experience in the marine environment. This would reduce the uncertainty in the failure rate estimates, meaning that cost estimates of a wave energy array could be obtained with more confidence.

7.1.5. Addressing uncertainty

The series of sensitivity analyses carried out in chapter 6 have shown how the results of the O&M model can differ depending on the input data used. It has become clear over the course of the research presented in this thesis that the inputs to the O&M model can be reviewed and updated as additional experience is gained with testing WECs. Uncertainty in the O&M model can be reduced further if the functionality is made to be as realistic as possible. An example of this evolution of the coding methodology can be seen between the two device-specific models, with vessel fuel costs calculated for each marine operation in the

Albatern-specific tool, compared to just taking a flat rate for vessel fuel costs in the Pelamis version.

7.2. Limitations of the methods

A number of limitations of the methods used throughout this thesis have been identified. A general limitation is that the method of creating an O&M model for a specific WEC requires close collaboration with the device developer. In addition, the best way of obtaining inputs with a high degree of confidence is by working closely with component manufacturers. Such cross-sector collaboration is difficult to achieve in commercial industries, but it is vital in order to obtain realistic cost estimates for wave energy arrays. This section critically assesses other limitations of the methods used in this thesis.

7.2.1. Fault categories

The method of grouping all the components within a WEC into fault categories has been used in the O&M tool so that different generations of devices can be compared directly without major changes to the model code. This method, however, means that categories with a large range of different components contain a larger degree of variance than others, in terms of the input parameters (e.g. failure rate, time to repair, parts cost etc.). This variance would be removed if each of the WEC components have their own input parameters, meaning the Monte Carlo analysis runs for each one at every time step. On the other hand, this method would greatly increase the computational run time of the model, as shown in Figure 7.1.

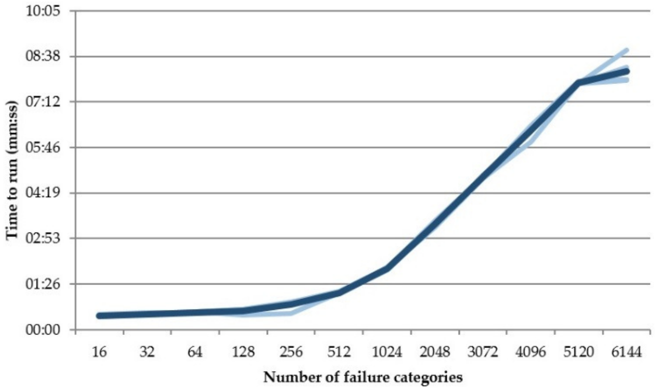


Figure 7.1. Time to run a 10 Pelamis P2 farm for 20 years for an increasing number of fault categories

The Pelamis-specific O&M model was used to produce Figure 7.1 with the fault categories doubled for each new run. The failure probabilities are adjusted according to the product probability law, with an example shown in equation 7.1.

$$F(\,when\ \mathbf{64}\ categories) = 1 - R(\,when\ \mathbf{16}\ categories)^{\mathbf{1}/\mathbf{4}} \qquad (7.1)$$

Where: R = Reliability (Probability of no failure per year)

F = Unreliability (Probability of failure per year)

There is clearly a balance to be achieved between having a reduced amount of variance in the fault category inputs and limiting the amount of time it takes to run the model. An O&M simulation tool would benefit from an increased number of fault categories, each with a small range of components than the model used in this thesis. Results could then be gained with more confidence because maintenance parameters, such as parts costs, would contain less uncertainty.

Another limitation of the fault category method in the Pelamis-specific O&M model is that array-based failures, such as issues with the main electrical cable, are not considered. This omission was due to the fact that subsea components were not the responsibility of Pelamis Wave Power during the P2 testing programme at the European Marine Energy Centre (EMEC). In a commercial wave farm, however, it is very likely that the array operator would be responsible for subsea components. The methodology of the Albatern-specific O&M model shows that the inclusion of array-based failures in the Monte Carlo analysis is possible and should be implemented into future tools.

7.2.2. Weather simulation

The weather conditions limiting marine operations in the Pelamis-specific O&M model have been informed through experience gained during the P2 testing programme, and have therefore been deemed realistic enough for use in the tool. Only significant wave height, wind speed and wave period are considered. This means that the effects of tidal velocity and elevation are not taken into account, even though these may be limiting factors, particularly in terms of port access.

There have been several other limitations of the weather simulation method identified throughout this thesis. The Markov Chain method of generating time series' from a hindcast dataset means that extreme events are only included in the O&M model if such events occurred in the hindcast dataset. This method also has an anomaly where an unnatural ‘jump’ between two months can occur if a suitable sea state cannot be found in the next month’s dataset. Although this anomaly rarely occurs (~1% of the monthly transitions), an alternative method could be to find the next ‘closest’ sea state, ideally in terms of significant wave height due to its importance in defining weather windows.

In general, suitable hindcast datasets of weather conditions are obtained with resolutions of 3 or 6 hours. This means that the O&M model is limited to this resolution, meaning the estimates for power generation are averaged across these periods. Better estimations of power, as well as more realistic representations of weather windows, could be achieved if the model resolution was increased. One factor limiting this development at present is the quality of office computer processors. This constraint will become less of an issue as the technology advances.

7.2.3. Functionality

A major limitation of the Albatern-specific O&M model at it stands is that the functionality is not equipped to deal with very large arrays (i.e. of over 300 WECs). The primary issue is that some of the WECs in the array do not get retrieved for the bi-annual routine servicing at any stage due to restrictions on the amount of space available onshore, as well as issues with the assumed priorities in undertaking marine operations and maintenance. These issues need addressing before larger wave energy arrays can be analysed.

A limitation identified in the functionality of the Pelamis-specific O&M model is with the approach of keeping one or more WECs at the quayside ready to be installed. In reality, this approach would incur costs (i.e. due to personnel training and ongoing maintenance) that have not been included in the model. As the model does not recognise that the spare machine has been undergoing maintenance, the device could be returned to the quayside soon after being installed to undergo its annual routine service. These aspects need to be taken into account if the spare machine approach is going to be considered for wave energy arrays in the future.

The generic O&M model could be further modified to incorporate all possibilities of an O&M strategy. For example, some seabed-fixed wave energy devices could be accessed by helicopter, as discussed by Ambühl et al. (2015). This strategy is not included in the O&M model used for this thesis at present. Other WECs may require diving operations to be spread over several different time periods to repair one fault or undertake one maintenance task, due to logistical constraints (e.g. amount of gas in a single diving canister). In addition, certain tasks within the same operation (e.g. vessel transit) may have different weather constraints compared to other tasks (e.g. WEC installation). This level of detailed operations is not included in the O&M model at present.

Logistical delays could also be added to the O&M model. At present, the tool doesn't account for delays to tasks such as repairs, installation, device retrieval, obtaining additional labour, or delivery of new parts. The only way of incorporating possible delays into the current method is to add extra time onto the number of days required to repair a fault, for example. In reality, logistical delays could either occur randomly, or be influenced by other factors such as the time of year, turnover of staff, other projects/events in the area, or current workload. Further research is required on this topic before such aspects can be modelled realistic in O&M simulation tools.

7.2.4. Obtaining base case results

For the results presented in chapter 4, the Pelamis-specific O&M model was run with the base case assumptions for each strategy assessment undertaken. As shown in Table 7.2, the application of 95% confidence intervals demonstrates that the majority of these base case results are not sufficiently different. Therefore, it was unnecessary to simulate the base case for each analysis. This lesson was carried over into the analysis with the Albatern-specific O&M model presented in chapter 5. However, Table 7.2 does show that the one base case simulation that is different is from the 'daylight hours' assessment. For that analysis, a version of the Pelamis-specific O&M model with a three hour resolution was used, rather than the six hour version used for all other analyses. This discrepancy highlights the importance of using the same resolution model when comparing results.

Table 7.2. Summary of chapter 4 sensitivity analyses, in terms of 95% confidence intervals overlapping with the base case

Section ID	Section Notes	Availability (%)			Revenue (£k)			OPEX (£k)		
		Mean	**95% conf.**	**Overlap**	**Mean**	**95% conf.**	**Overlap**	**Mean**	**95% conf.**	**Overlap**
4.3	*Base case*	*86.61*	*0.15*	-	*2841.30*	*6.20*	-	*1089.20*	*8.70*	-
4.4	Vessels	86.61	0.15	YES	2841.32	6.17	YES	1089.23	8.72	YES
4.5	Daylight	86.22	0.18	NO	2777.62	15.11	NO	1110.86	9.51	NO
4.6	Offshore logistics	86.63	0.17	YES	2840.80	7.22	YES	1099.45	7.59	YES
4.7	Operational limits	86.62	0.18	YES	2840.24	7.37	YES	1098.95	9.52	YES
4.8	Spare machine	86.62	0.19	YES	2840.91	7.74	YES	1096.87	9.89	YES
4.9	Labour	86.52	0.17	YES	2836.69	7.28	YES	1103.27	8.45	YES

7.3. Further work

7.3.1. Model Validation

It is difficult to validate the results obtained from the O&M models used in this thesis, due to the fact that no operational wave farms currently exist with which to compare the outputs.

The offshore wind industry is far more advanced than the wave energy sector. It is possible to apply the same methodology of the generic O&M tool described in chapter 3 to an offshore wind farm, provided that the appropriate inputs are obtained. The methodology of undertaking onsite repairs would need to be expanded for this to be achieved. A comparison with O&M simulation tools for offshore wind farms, such as EDF's ECUME tool (Douard, Domecq & Lair, 2012), could then be made. This method of validation could also be used as the tidal stream sector advances.

Another validation step could be to compare the results against other O&M models developed for the wave energy sector. For example, the inputs could be matched to a simulation of the DTOcean open-source tool to cross-compare the outputs. However, this method does not validate whether the results of both models are realistic.

7.3.2. Industrial research and development

The inputs to the two device-specific O&M models presented in this thesis have come primarily from expert judgement of the engineers involved in their design. This is the best source of information at this early stage of the wave energy sector. However, future estimates for failure rates can be improved by undertaking accelerated destructive testing. Based on the results of this thesis, a useful example could be the mass testing of hydraulic valves placed on a test rig in a marine environment, such as a WEC test facility. In addition, real-sea testing by wave energy developers should involve condition monitoring systems so that failure rate data can be obtained. An example of how this could be used to improve initial failure rates, obtained by expert judgement or manufacturers' specifications, is with Bayesian updating, as discussed by Thies, Smith and Johanning (2012).

Real-sea experience at operating and maintaining WECs will also improve the functionality of O&M models. With limited testing, many aspects of the model functionality come down to expert 'feel' about their device. An example of this is the condition used in the Pelamis-specific O&M model where a WEC is retrieved for repair if either one major fault or two intermediate faults have occurred, therefore by-passing the decision making process (i.e. cost-benefit analysis). Such conditions can be reviewed as more experience is gained. This experience will also feed into the design of the cost-benefit analysis in order to provide the framework for real-world decision making and optimise the O&M strategy for wave energy arrays.

The O&M model methodology described in this thesis can be utilised for other wave energy devices if the fundamental inputs are obtained. The key process is a Failure Modes and Effects Analysis (FMEA) to list all the components within the WEC and identify initial severity and consequence of all possible failures. Not only is this a vital part of obtaining failure rate estimates and maintenance parameters, it is also an extremely useful process for wave energy developers in terms of identifying weaknesses within their design that require mitigation, and should therefore be carried out early in the design process. This thesis has shown how significant the O&M strategy can be in terms of reducing Levelised Cost of Energy (LCOE) of WECs. Modelling the strategy with a bottom-up approach also means that WEC developers have to consider O&M aspects early in the design, thereby avoiding unnecessary and time-consuming design changes further down the line. The methodology could also be applied to seabed-fixed wave energy converters, as well as the floating devices presented in this thesis.

Capital Expenditure (CAPEX) has not been a significant aspect of the calculations presented in this thesis. The focus has been on improving estimates of Operational Expenditure (OPEX) as a means of reducing the uncertainty involved in calculating LCOE. It is clear that further work also needs to be undertaken on improving estimates of CAPEX in order to add confidence to LCOE calculations.

Different types of wave energy converter can be directly compared based on LCOE, as well as power performance and survivability. At this early stage of the wave energy sector's development, there are a number of ways of estimating the LCOE of devices, making direct comparisons difficult to validate. It is possible that WECs could also be compared based on their operability. This could involve aspects such as ease of access and the level of specialist technicians required. As shown in this thesis, higher wave farm availability does not necessarily lead to lower LCOE. It could be useful if an industry-wide benchmarking system based on operability of wave energy devices is developed, rather than comparing devices based on uncertain LCOE estimates.

7.3.3. Academic research

The O&M model presented in this thesis assumes that the failure rates are constant throughout the array lifetime. This would not be the case in reality, as some components are likely to degrade over time, thereby gradually increasing the failure rates. Further academic research into understanding component degradation will enable Weibull curves, as described by Thies, Smith and Johanning (2012), to be built into the failure rates of O&M models, thereby enhancing their realism and enabling cost estimates to be obtained with more confidence. Such research will also enable wave energy developers to consider predictive maintenance strategies; replacing certain components before they fail, thereby increasing overall reliability of the WEC system.

Another area of academic research that could improve the cost estimates obtained from O&M models is weather forecasting. The inputs to the cost-benefit analysis (i.e. decision making about WEC retrieval) could be made more realistic if a degree of uncertainty in the weather conditions over the coming days could be modelled prior to every marine operation simulation. This would better reflect how decisions will be made in real-world wave energy arrays.

References

Abdulla, K., Skelton, J., Doherty, K., O'Kane, P., Doherty, R. & Bryans, G. (2011) Statistical Availability Analysis of Wave Energy Converters. Aquamarine Power Ltd. IN: Proc. 21st International Offshore & Polar Engineering. Maui, Hawaii. 1, 572-577.

ABP Marine Environmental Research Ltd. (2016) Atlas of UK Marine Renewable Energy Resources. Retrieved from www.renewables-atlas.info/. Accessed 15/3/16.

Ambühl, S., Marquis, L., Kofoed, J. & Sørensen, J. (2015) Operation and maintenance strategies for wave energy converters. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, 1-25.

Apland-Hitz, J. (2010) LIMPET: Land Installed Marine Powered Energy Transformer. Retrieved from blogs.ei.columbia.edu/2010/05/19/limpet-land-installed-marine-powered-energy-transformer/. State of the Planet, Columbia University. Accessed 30/1/17.

Aquatera. (2011) The Farr Point Wave Farm Development: Request for Scoping Opinion. Prepared OBO Pelamis Wave Power, April 2011. Retrieved from www.gov.scot/Topics/marine/Licensing/marine/scoping/FarrPoint/scoping-report. Accessed 31/8/16.

Astariz, S. & Iglesias, G. (2015) The economics of wave energy: A review. Renewable and Sustainable Energy Reviews. 45, pp. 397-408.

Atlantis Resources Ltd. (2016) Meygen: Project Update Spring 2016. Retrieved from www.meygen.com/wp-content/uploads. Accessed 5/2/17.

AWS. (2017) Archimedes Waveswing Submerged Wave Power Buoy. Retrieved from www.awsocean.com/archimedes-waveswing.html. Accessed 30/1/17.

Bahaj, A.S. (2011) Generating electricity from the oceans. Renewable and Sustainable Energy Reviews. 15 (7), pp. 3399-3416.

Baldwin, N. & Power, R. (1988) World oil market simulation. Energy Economics. 10 (3), pp 185-198.

BEIS. (2013) An explanation of the energy-producing potential of wave and tidal stream energy in the UK. HM Government, Department for Business, Energy & Industrial Strategy.

Bertling-Tjernberg, L. & Wennerhag, P. (2012) Wind Turbine Operation and Maintenance – Survey of the Development and Research Needs. Elforsk report 12:41.

Borthwick, A.G.L. (2016) Marine Renewable Energy Seascape. Engineering. 2, pp. 69-78.

Boud, R. (2012) UK wave energy resource. AMEC Environment & Infrastructure UK Limited, OBO Carbon Trust.

Budal, K. (1977) Theory for absorption of wave power by a system of interacting bodies. J. Ship Res. 21 (4), pp. 248–253.

BVG Associates. (2013) Offshore wind: Industry's journey to £100/MWh.

Carroll, J., McDonald, A., & McMillan, D. (2015) Reliability Comparison of Wind Turbines With DFIG and PMG Drive Trains. IEEE Transactions on Energy Conversion. 30, pp. 663-670.

Channel Coastal Observatory. (2015) Regional Coastal Monitoring Programmes: Perranporth. Retrieved from www.channelcoast.org/data_management/real_time_data/charts/?chart=76. Accessed 19/1/16.

Dalgic, Y., Lazakis, I. & Turan, O. (2015) Investigation of Optimum Crew Transfer Vessel Fleet for Offshore Wind Farm. Wind Engineering. 39 (1), pp. 31–52.

Dalgic, Y., Lazakis, I., Turan, O. & Judah, S. (2015) Investigation of optimum jack-up vessel chartering strategy for offshore wind farm O&M activities. Ocean Engineering. 95, pp. 106-115.

Dalton, G.J., Alcorn, R. & Lewis, T. (2010) Case study feasibility analysis of the Pelamis wave energy convertor in Ireland, Portugal and North America. Renewable Energy. 35 (2), pp. 443-455.

Davidson, N. (2012) Wave energy – the challenge, the opportunity. Energy Technology Partnership. Retrieved from www.etp-scotland.ac.uk/Portals/57/document%20library/Aquamarine%20Power%20-%20Neil%20Davidson.pdf. Accessed 8/3/17.

Dawid, R., McMillan, D. & Revie, M. (2015) Review of Markov Models for Maintenance Optimization in the Context of Offshore Wind. IN: Annual Conference of the Prognostics and Health Management Society 2015. 18-24 October 2015. Coronado, California, USA.

De Andres, A., Maillet, J., Todalshaug, J.H., Moller, P., Bould, D. & Jeffrey, H. (2016) Techno-Economic Related Metrics for a Wave Energy Converters Feasibility Assessment. Sustainability. 8 (11), pp. 1109-1127.

DECC. (2010) Marine Energy Action Plan 2010 – Executive Summary & Recommendations. HM Government, Department of Energy and Climate Change.

DECC. (2013a) Electricity Generation Costs 2013. HM Government, Department of Energy and Climate Change.

DECC. (2013b) Electricity Market Reform Delivery Plan. HM Government, Department of Energy and Climate Change.

Dinwoodie, I., Endrerud, O., Hofmann, M., Martin, R. & Sperstad, I. (2015) Reference Cases for Verification of Operation and Maintenance Simulation Models for Offshore Wind Farms. Wind Engineering. 39, pp. 1–14.

Dinwoodie, I., McMillan, D., Revie, M., Lazakis, I. & Dalgic, Y. (2013) Development of a Combined Operational and Strategic Decision Support Model for Offshore Wind. Energy Procedia. 35, pp. 157–166.

Douard, F., Domecq, C. & Lair, W. (2012) A Probabilistic Approach to Introduce Risk Measurement Indicators to an Offshore Wind Project Evaluation – Improvement to an Existing Tool ECUME. Électricité de France (EDF). IN: DeepWind. 19-20 January 2012. Trondheim, Norway. Energy Procedia. 24, pp. 255–262.

DTOcean. (2014) Methodology report and logistic model flow charts. Deliverable 5.1. European Commission; Grant agreement number 608597.

DTOcean. (2016) DTOcean Project. Retrieved from www.dtocean.eu/. Accessed 10/2/16.

Eco Green Globe. (2016) Aguçadoura Wave Park. Retrieved from www.ecogreenglobe.com/2011/09/20/agucadoura-wave-park/. Accessed 5/4/16.

Ederer, N. (2014) The right size matters: Investigating the offshore wind turbine market equilibrium. Energy. 68, pp. 910-921.

Eecen, P.J., Braam, H., Rademakers, L.W.M.M. & Obdam, T.S. (2007) Estimating costs of operations and maintenance of offshore wind farms. IN: EWEC 2007 Conference. 7-10 May 2007. Milan, Italy.

EERE. (2017) Wave Energy Prize. U.S. Department of Energy. Retrieved from waveenergyprize.org/. Accessed 5/2/17.

EMEC. (2015) Guest blog: Ian Bryden – Reflections on 35 years in marine energy. Retrieved from www.emec.org.uk/blog-ian-bryden-reflections-on-35-years-in-marine-energy/. European Marine Energy Centre. Accessed 30/1/17.

EMEC. (2016a) Wave Devices. Retrieved from www.emec.org.uk/marine-energy/wave-devices/. European Marine Energy Centre. Accessed 5/4/16.

EMEC. (2016b) Our History. Retrieved from www.emec.org.uk/about-us/emec-history/. European Marine Energy Centre. Accessed 5/4/16.

EMEC. (2017) Alstom (Formerly TGL). European Marine Energy Centre. Retrieved from www.emec.org.uk/about-us/our-tidal-clients/alstom/. Accessed 6/3/17.

Ente Vasco de la Energía. (2017) Marine Energy. Retrieved from www.eve.eus/Proyectos-energeticos/Proyectos/Energia-Marina. Accessed 30/1/17.

EQUIMAR. (2011) Protocols for the Equitable Assessment of Marine Energy Converters. The Institute of Energy Systems, The University of Edinburgh. Edited by: Ingram, D., Smith., G., Bittencourt-Ferreira, C. & Smith, H.

Evans, D.V. (1976) A theory for wave-power absorption by oscillating bodies. J. Fluid Mech. 77 (1), pp. 1–25.

Falcão, A.F.O. (2010) Wave energy utilization: a review of the technologies. Renew Sust Energy Rev 2010; 14 (3), pp. 899-918.

Feuchtwang, J. & Infield, D. (2013) Offshore Wind Turbine Maintenance Access: A Closed-Form Probabilistic Method for Calculating Delays Caused by Sea-State. Wind Energy. 16, pp. 1049–1066.

Folley, M., Whittaker, T.W.T. & van't Hoff, J. (2007) The design of small seabed-mounted bottom-hinged wave energy converters. IN: Proceedings of the 7th European Wave and Tidal Energy Conference. 11-13 September 2007. Porto, Portugal.

Frost, C. (2015) Feasibility of Hybridising a Fish Farm Electrical Feeding System. Internal Document: Albatern Ltd.

Guanche, R., Martini, M., Jurado, A. & Losada, I.J. (2016) Walk-to-work accessibility assessment for floating offshore wind turbines. Ocean Engineering. 116, pp. 216-225.

GL Garrad Hassan (2013) A Guide to UK Offshore Wind Operations and Maintenance. OBO The Crown Estate & Scottish Enterprise.

Gray, A. (2014) Investigating the Number of Fault Categories in the O&M Model. Internal Document: Pelamis Wave Power.

Gray, A., Dickens, B., Bruce, T., Ashton, I. & Johanning, L. (2017) Reliability and O&M sensitivity analysis as a consequence of site specific characteristics for wave energy converters. Ocean Engineering. (Under Review).

Gray, A. & Johanning, L. (2016) Identifying key O&M strategy considerations for a wave energy array – a case study on Pelamis. ICOE: International Conference on Ocean Energy. 23-25 February 2016. Edinburgh, UK.

Gray, A., Johanning, L. & Dickens, B. (2014) The Modelling of Pelamis Wave Power's Operations and Maintenance Strategy. ASRANet International Conference on Offshore Renewable Energy. 15-17 September 2014. Glasgow, UK.

Gray, A., Johanning, L. & Dickens, B. (2015) A Markov Chain Model to Enhance the Weather Simulation Capabilities of an Operations and Maintenance Tool for a Wave Energy Array. 11th European Wave and Tidal Energy Conference. 6-11 September 2015. Nantes, France.

Gunn, K., & Stock-Williams, C. (2012) Quantifying the global wave power resource. Renewable Energy, 44, pp. 296-304.

GWEC. (2017) Global Wind 2016 Report: Offshore Wind. Retrieved from www.gwec.net/wp-content/uploads/2017/05. Accessed 3/3/17.

Hagen, B., Simonsen, I., Hofmann, M. & Muskulus, M. (2013) A Multivariate Markov Weather Model for O&M Simulation of Offshore Wind Parks. Energy Procedia. 35, pp. 137-147.

Hameed, Z., Vatn, J. & Heggset, J. (2011) Challenges in the reliability and maintainability data collection for offshore wind turbines. Renewable Energy. 36, pp. 2154–2165.

Henderson, R. (2006) Design, simulation, and testing of a novel hydraulic power take-off system for the Pelamis wave energy converter. Renewable Energy. 31, pp. 271-283.

Highlands and Islands Enterprise. (2016) Wave Energy Scotland: Progress Report 2016. Retrieved from www.waveenergyscotland.co.uk/media. Accessed 5/2/17.

Hofmann, M. (2011) A Review of Decision Support Models for Offshore Wind Farms with an Emphasis on Operation and Maintenance Strategies. SINTEF Energi AS. Wind Engineering. 35, pp. 1–16.

Hofmann, M. & Sperstad, I. (2013) NOWIcob – A tool for reducing the maintenance costs of offshore wind farms. SINTEF Energy Research. IN: DeepWind. 24-25 January 2013. Trondheim, Norway. Energy Procedia. 35, pp. 177-186.

Hofmann, M., Heggset, J. & Nonås, L.M. & Halvorsen-Weare, E.E. (2011) A Concept for Cost and Benefit Analysis of Offshore Wind Farms with Focus on Operation and Maintenance. IN: 24th International Congress on Condition Monitoring and Diagnostics Engineering Management (COMADEM 2011). 30 May – 1 June 2011. Stavanger, Norway.

Huckerby, J., Jeffrey, H., Moran, B. & Sedgwick, J. (2012) An International Vision for Ocean Energy, Version II. Ocean Energy Systems Implementing Agreement.

IDCORE. (2016) About IDCORE. Retrieved from www.idcore.ac.uk/public/about-idcore. Industrial Doctoral Centre for Offshore Renewable Energy. Accessed 5/4/16.

JBA Consulting. (2015) ForeCoast Marine. Retrieved from JBA Consulting: www.jbaconsulting.com/blog/forecoast-marine. Accessed 10/2/16.

Kenny, CJ., Findlay, D., Lazakis, I., Shek, J. & Thies, PR. (2016) Proposed Control and Instru-mentation Topologies for an Integrated Wave Energy. RENEW Progress in Renewable Energies Offshore. 24-26 October 2016. Lisbon, Portugal.

Koutoulakos, E. (2008) Wind Turbine Reliability Characteristics and Offshore Availability Assessment. MSc Project. TU Delft.

Lewis, A., Estefen, S., Huckerby, J., Lee, K.S., Musial, W., Pontes, T., et al. (2012) Ocean energy. IN: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., et al., editors, Renewable energy sources and climate change mitigation: Special report of the intergovernmental panel on climate change. Cambridge: Cambridge University Press; 2012. pp. 497–534.

Lavidas, G., Venugopal, V. & Friedrich, D. (2017) Wave energy extraction in Scotland through an improved nearshore wave atlas. International Journal of Marine Energy. 17, pp. 64-83.

Magagna, D., Monfardini, R. & Uihlein, A. (2016) JRC Ocean Energy Status Report. European Commission. Retrieved from publications.jrc.ec.europa .eu/repository. Accessed 5/2/17.

Maples, B., Saur, G., Hand, M., van de Pietermen, R. & Obdam, T. (2013) Installation, Operation and Maintenance Strategies to Reduce the Cost of Offshore Wind Energy. National Renewable Energy Laboratory - NREL/TP-5000e57403.

Martin, R., Lazakis, I., Barbouchi, S. & Johanning, L. (2015) Identification and Quantification of Important Offshore Wind Operations and Maintenance Factors.

IN: Proceedings of the European Wind Energy Association (EWEA) Expo. 17-20 November 2015. Paris, France.

Martin, R., Lazakis, I., Barbouchi, S. & Johanning, L. (2016) Sensitivity analysis of offshore wind farm operation and maintenance cost and availability. Renewable Energy. 85, pp. 1226-1236.

Martins, D., Muraleedharan, G. & Guedes Soares, C. (2015) Analysis on weather windows defined by significant wave height and wind speed. Proceedings of Progress in Renewable Energies Offshore – Guedes Soares, pp. 91-98. Taylor & Francis Group, London.

MCT. (2017a) About Marine Current Turbines: Company History. Retrieved from www.marineturbines.com/About-Marine-Current-Turbines. Accessed 6/3/17.

MCT. (2017b) O&M. Retrieved from www.marineturbines.com/Seagen-Technology/O-M. Accessed 6/3/17.

Mei, C.C. (1976) Power extracted from water waves. J. Ship Res. 20, pp. 63–66.

Mérigaud, A. & Ringwood, J.V. (2016) Condition-based maintenance methods for marine renewable energy. Renewable and Sustainable Energy Reviews. 66, pp. 53-78.

Mojo Maritime. (2016). Mermaid. Retrieved from mojomermaid.com/. Accessed 10/2/16.

Morandeau, M., Walker, R., Argall, R. & Nicholls-Lee, R. (2013) Optimisation of marine energy installation operations. International Journal of Marine Energy. 3-4, pp. 14-26.

Musial, W. & Ram, B. (2010) Large-scale Offshore Wind Power in the United States: Assessment of Opportunities and Barriers. National Renewable Energy Laboratory - NREL/TP-500-40745.

Mustapa, M.A., Yaakob, O.B., Ahmed. Y.M., Rheem, C., Koh, K.K. & Adnan, F.A. (2017) Wave energy device and breakwater integration: A review. Renewable and Sustainable Energy Reviews. 77, pp. 43-58.

O'Connor, M., Lewis, T. & Dalton, G. (2013a) Operational expenditure costs for wave energy projects and impacts on financial returns. Renewable Energy. 50, pp. 1109-1131.

O'Connor, M., Lewis, T., & Dalton, G. (2013b) Weather window analysis of Irish west coast wave data with relevance to operations & maintenance of marine renewables. Renewable Energy. 52, pp. 57-66.

OpenHydro. (2017) History. Retrieved from www.openhydro.com. Accessed 6/3/17.

ORE Catapult. (2016) Our Projects: SPARTA. Retrieved from ore.catapult.org.uk/ourprojects//asset_publisher/fXyYgbhgACxk/content/sparta. Accessed 10/2/16.

OREDA. (2015) Offshore & Onshore Reliability Data: About. Retrieved from www.oreda.com/about-us/. Accessed 10/2/16.

Oreskes, N. (2004) Beyond the Ivory Tower: The Scientific Consensus on Climate Change. Science. 5702 (306), pp. 1686.

Pelamis Wave Power. (2013) Qualification & Development Testing D-RD-0006.

Phillips, J., Morgan, C. & Jacquemin, J. (2006) Evaluating O&M strategies for offshore wind farms through simulation – the impact of wave climatology. IN: OWEMES. 20-22 April 2006. Civitavecchia, Italy.

Polinder, H., Damen, M.E.C. & Gardner, F. (2004) Linear PM generator system for wave energy conversion in the AWS. IEEE transaction on Energy Conversion 2004. 19 (3), pp. 583-589.

Poore, R. & Walford, C. (2008) Development of an Operations and Maintenance Cost Model to Identify Cost of Energy Savings for Low Wind Speed Turbines. Global Energy Concepts, LLC. NREL, National Renewable Energy Laboratory. Seattle, Washington. NREL/SR-500-40581.

PRIMaRE. (2015) Partnership for Research In Marine Renewable Energy: World-class research and technology transfer in marine energy. Retrieved from www.primare.org/. Accessed 10/2/16.

Rademakers, L.W.M.M., Braam, H., Zaaijer, M.B. & van Bussel, G.J.W. (2003) Assessment and Optimisation of Operation and Maintenance of Offshore Wind Turbines. IN: European Wind Energy Conference. 16-19 June 2003. Madrid, Spain.

Ramboll. (2010) Aquamarine Power Oyster. Retrieved from www.ramboll.co.uk/projects/re/aquamarine_oyster2. Accessed 30/1/17.

Redfern, R. & Phillips, J.L. (2009) Assessing the Impact of Serial Defects on the Performance of Offshore Wind Projects. IN: EWEA Offshore. 14-16 September 2009. Stockholm, Sweden.

Renews. (2016) Wavestar future on knife edge. Retrieved from renews.biz/102918/wavestar-future-on-knife-edge/. Accessed 12/12/16.

Rinaldi, G., Thies, P.R., Walker, R. & Johanning, L. (2016) On the Analysis of a Wave Energy Farm with Focus on Maintenance Operations. Journal of Marine Science and Engineering. 4, pp. 51-61.

RovMarine Technologies. (2017) The history of ROVs. Retrieved from www.rovmarine.it/en/home-eng/14-not-categorized/16-the-history-of-rovs. Accessed 6/3/17.

Rühlicke, I. & Haag, M. (2013) Oyster - Wave Energy Power Plants: A new Challenge for hydraulic Cylinders. Hydraulics & Pneumatics.

Salter, S. (1974) Wave power. Nature. 249, pp. 720–724.

Salter, S.H., Jeffrey, D.C. & Taylor, J.R.M. (1976) The architecture of nodding duck wave power generators. Naval Archit. January 1976, 30, pp. 63.

Scheu, M., Matha, D., Hofmann, M. & Muskulus, M. (2012) Maintenance strategies for large offshore wind farms. IN: DeepWind. 19-20 January 2012. Trondheim, Norway. Energy Procedia. 24, pp. 281–288.

Scot Kobus, L.C. & Fogal, R.W. (1989) Jack-up conversion for production. Marine Structures. 2 (3-5), pp. 193-211.

ScotRenewables Tidal Power Ltd. (2017) The Concept. Retrieved from www.scotrenewables.com/technology-development/the-concept. Accessed 6/3/17.

Scottish Government. (2014) Wave Energy Scotland – Fact sheet. Retrieved from www.gov.scot/Resource/0046/00464410.pdf. Accessed 5/4/16.

Segura, E., Morales, R., Somolinos, J.A. & López, A. (2017) Techno-economic challenges of tidal energy conversion systems: Current status and trends. Renewable and Sustainable Energy Reviews. 77, pp. 536-550.

SEM (2017) Tidal Energy Turbine Platform Technology. Sustainable Marine Energy Ltd. Retrieved from sustainablemarine.com/technology. Accessed 6/3/17.

Silva, N.S.H., Martins, V.J.F.F. & Bahiense, L. (2014) Logistics network planning for offshore air transport of oil of crews. Computers & Industrial Engineering. 75, pp. 41-54.

Smith, S., Thomson, M. & Whelan, J. (2010) Planning and optimising the construction and O&M strategy of tidal stream turbine arrays. Garrad Hassan. IN: 3rd International Conference on Ocean Energy. 6 October 2010. Bilbao, Spain.

SPICe – Scottish Parliament Information Centre. (2015) Financial Scrutiny Unit Briefing – Earning in Scotland 2015. Published by The Scottish Parliament, 10 December 2015.

Taylor, J. (2009) Edinburgh Wave Power Group. Retrieved from www.homepages.ed.ac.uk/v1ewaveg/. The University of Edinburgh. Accessed 30/1/17.

Taylor, L. (2014) Compact Work Class ROVs and related solutions for Offshore Wind Support. DOER Marine. Retrieved from www.doermarine.com/wp-content/uploads/2014/10/TOWS.pdf. Accessed 6/3/17.

Tedd, J. (2007) Testing, Analysis and Control of Wave Dragon, Wave Energy Converter. PhD Thesis. Aalborg University.

Teillant, B., Costello, R., Weber, J. & Ringwood, J. (2012) Productivity and economic assessment of wave energy projects through operational simulations. Renewable Energy. 48, pp. 220-230.

Teillant, B., Chainho, P., Raventós, A. & Sarmento, A. (2015) Characterization of the logistic requirements for the marine renewable energy sector. Proceedings of Progress in Renewable Energies Offshore – Guedes Soares, pp. 983-991. Taylor & Francis Group, London.

Teillant, B., Chainho, P., Raventós, A., Nava, V. & Jeffrey, H. (2014) A decision supporting tool for the lifecycle logistics of ocean energy arrays. IN: International Conference on Ocean Energy. 4-6 November 2014. Halifax, Canada.

TEL (2017) The DeltaStream Technology. Tidal Energy Ltd. Retrieved from www.tidalenergyltd.com/?page_id=1373. Accessed 6/3/17.

Telford, S., Ilyas Mazhar, M. & Howard, I. (2011) Condition Based Maintenance (CBM) in the Oil and Gas Industry: An Overview of Methods and Techniques. IN: Proceedings of the International Conference on Industrial Engineering and Operations Management. 22-24 January 2011. Kuala Lumpur, Malaysia.

Thies, P.R., Flinn, J. & Smith, G.H. (2009) Is it a showstopper? Reliability assessment and criticality analysis for wave energy converters. IN: Proc. Of 8th European Wave and Tidal Energy Conference EWTEC. 7-10 September 2009. Uppsala, Sweden.

Thies, P.R., Johanning, L. & Smith, G.H. (2011) Towards component reliability testing for marine energy converters. Ocean Engineering. 38, pp. 360-370.

Thies, P.R., Smith, G.H., & Johanning, L. (2012). Addressing failure rate uncertainties of marine energy converters. Renewable Energy, 44, pp. 359-367.

Thorpe, T. (2004) Survey of Energy Resources (Twentieth Edition). Chapter 15 - Wave Energy. pp 401-417.

US Department of Defense. (1991) Military Handbook: Reliability Prediction of Electronic Equipment. Washington DC.

Van Bussel, G. (1999) The Development of an Expert System for the determination of Availability and O&M costs for Offshore Wind Farms. Proceedings from the European Wind Energy Conference, pp. 402-405.

Van Bussel, G.J.W. & Bierbooms, W. (2003) Analysis of Different Means of Transport in the Operation and Maintenance Strategy for the Reference DOWEC Offshore Wind Farm. IN: Offshore Wind and Other Marine Renewable Energies in Mediterranean and European Seas. October 1993. Naples, Italy.

Van Bussel, G.J.W. & Schöntag, C. (1997) Operation and Maintenance Aspects of Large Offshore Windfarms. IN: European Wind Energy Conference, European Wind Energy Association. October 1997. Dublin, Ireland.

Van Bussel, G.J.W. & Zaaijer, M. (2001) Reliability, availability and maintenance aspects of large-scale offshore wind farms, a concepts study. MAREC Conference Proceedings, pp. 119-126.

Van de Pieterman, R., Braam, H., Obdam, T., Rademakers, L., Van der Zee, T. (2011) Optimisation of maintenance strategies for offshore wind farms. Energy Research Centre of the Netherlands. IN: The Offshore 2011 Conference. 29 November-1 December 2011. Amsterdam, The Netherlands. ECN-M—11-103.

Van Endrerud, O.E., Liyanage, J. & Keseric, N. (2014) Marine Logistics Decision Support for Operation and Maintenance of Offshore Wind Parks with a Multi Method Simulation Model. IN: Winter Simulation Conference. 7-10 December 2014. Savannah, Georgia.

Van Nieuwkoop, J., Smith, H., Smith, G., & Johanning, L. (2013). Wave resource assessment along the Cornish coast (UK) from a 23-year hindcast dataset validated against buoy measurements. Renewable Energy, 58, pp. -14.

Voith. (2016). WSR Way Valve. Retrieved from www.voith.com/en/products-services/powertransmission/actuators-and-control-systems/wsr-way-valve-proportional-directional-control-39739.html. Accessed 4/3/16.

Walker, R.T., Johanning, L. & Parkinson, R.J. (2011) Weather Windows for Device Deployment at UK Test Sites: Availability and Cost Implications. IN: 9th European Wave and Tidal Energy Conference. 5-9 September 2011. Southampton, UK.

Walker, R.T., van Nieuwkoop-McCall, J., Johanning, L., & Parkinson, R. (2013) Calculating weather windows: Application to transit, installation and the implications on deployment success. Ocean Engineering, 68, pp. 88-101.

Wave Hub Limited. (2015) Wave Hub: Advancing Offshore Renewable Energy. Retrieved from www.wavehub.co.uk/. Accessed 10/2/16.

Webb, G.D. (1981) Inspection and repair of oil and gas production installations in deep water. Ocean Management. 7 (1-4), pp. 313-326.

Weller, S., Thies, P., Gordelier, T., Harnois, V., Parish, D., & Johanning, L. (2014) Navigating the Valley of Death: Reducing Reliability Uncertainties for Marine Renewable Energy. ASRANet International Conference on Ocean Energy. 15-17 September, Glasgow, UK.

Whittaker, T.J.T., Beattie, W., Raghunathan, S., Thompson, A., Stewart, T. & Curran, R. (1997) The Islay wave power project: an engineering prospective. Proceedings of the Institution of Civil Engineers - Water and Maritime Engineering. 124 (3), pp. 189-201.

Wolfram, J. (2006) On Assessing the Reliability and Availability of Marine Energy Converters: The Problems of a New Technology. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability. 220, pp. 55-68.

Wu, M. (2014) Numerical analysis of docking operation between service vessels and offshore wind turbines. Ocean Engineering. 91, pp. 379-388.

Yemm, R., Pizer, D., Retzler, C., & Henderson, R. (2012) Pelamis: experience from concept to connection. Philosophical Transactions of the Royal Society A, 370, pp. 365-380.

Appendices

Appendix A – Convergence Study

The Monte Carlo nature of the operations and maintenance simulation tool used in this thesis means that no two runs will produce the exact same outputs. Therefore, useful results are only obtained by running the tool multiple times and taking the statistical parameters (i.e. mean, minimum, maximum, range). A convergence study has been used to indicate how many simulations should be undertaken to obtain mean results with an acceptable level of 95% confidence boundaries (as described in section 1.7.4, page 33). An 'acceptable' level of error has been deemed to be below 1% of the mean output values. The Pelamis P2-specific O&M model described in Chapter 4 is used for this convergence study, with the base case inputs applied (see section 4.3, page 74).

The model was run for 100 lifetimes of the wave energy array, with the 95% confidence intervals of average availability, revenue and OPEX calculated each time. Figure A.1 presents this information with the confidence intervals (i.e. error) as a percentage of the mean output values.

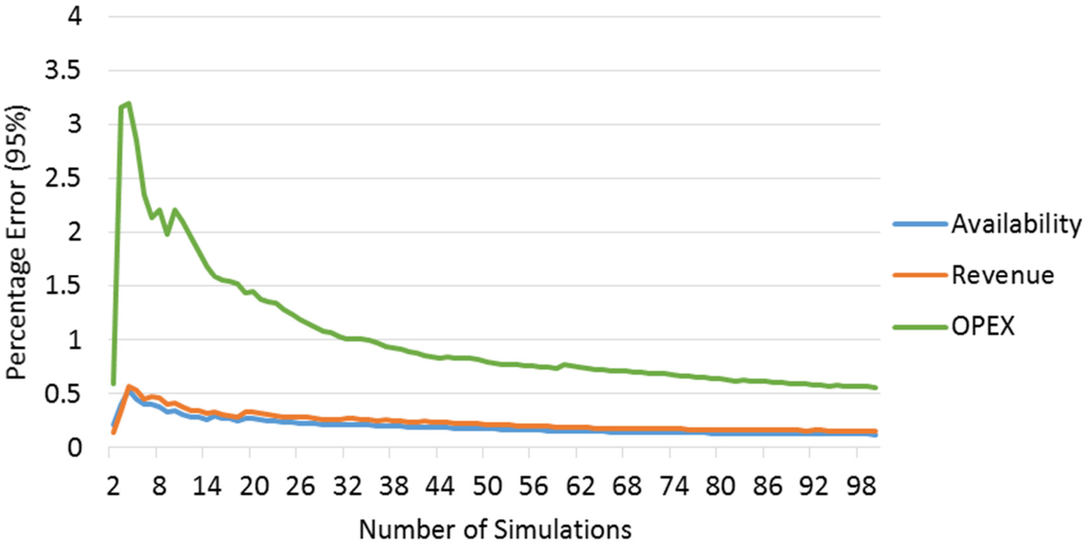


Figure A.1. Convergence of 95% confidence boundaries of key output parameters, as a percentage of the mean

Figure A.1 shows that OPEX outputs contain the largest errors compared to availability and revenue. Percentage errors for both availability and revenue remain below the acceptable 1% limit throughout the increasing number of simulations. OPEX estimates, however, reach a peak error of 3.2% after 4 simulations have been completed. The error drops below the 1% acceptable limit after 35 simulations and looks to converge on approximately 0.5% after 100 simulations. Therefore, at least 35 lifetimes of the wave energy array should be simulated to obtain results with an acceptable level of confidence.

The O&M model exhibits the stochastic behaviour seen in the real world by generating a truly random number whenever the Monte Carlo method is used to simulate the occurrence of faults. The seed value of these random numbers can be fixed from one simulated lifetime to the next in an attempt to repeat results. Figure A.2 presents the average OPEX in terms of 95% confidence intervals as a percentage of the mean, comparing the stochastic model against the 'fixed seeds' version.

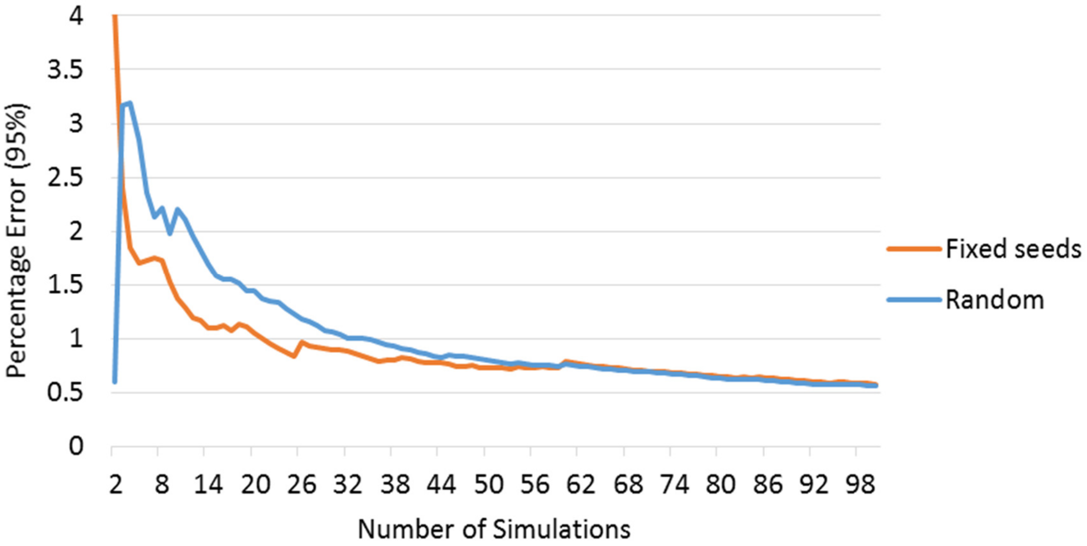


Figure A.2. Convergence of 95% confidence boundaries of average OPEX, as a percentage of the mean, for fixed seed numbers compared to stochastic behaviour

As expected, the percentage error is reduced when the seed values are fixed. The 1% acceptable limit is reached after 21 simulations, whilst it drops below 1.5% after only 10 simulations. However, the results of the two models begin to converge after approximately 60 simulations.

Appendix B - Appendix Tables

Table A.1, part i. Pelamis P2-specific O&M tool fault categories and associated parameters

ID	Full name	Classification	Probability of failure per year	Power loss	Parts cost (£k)	Other costs (£k)	Days off-site
1	Major mooring	Major	0.01594	1	20	30	5
2	Major structure (no warning)	Major	0.0624	0.5	15	30	15
3	Major structural failure (identified through monitoring system)	Major	0.03017	0.5	15	20	10
4	Major primary hydraulic	Major	0.00997	1	10	5	5
5	Loss of GPS comms & main comms	Major	0.004	1	2	2.5	2
6	Major sealing	Intermediate	0.03174	0.33	1	2	5
7	Half circuit failure	Intermediate	0.36	0.2	1	2	2
8	Minor mooring	Intermediate	0.03371	0	2.5	5	3
9	Data communications	Intermediate	0.01395	0.33	1	2	2
10	Electrical unions/ tieback	Intermediate	0.0396	1	25	5	2
11	Control system	Minor	0.2604	0.2	1	2	2
12	Minor structural	Minor	0.02621	0	2	2	2
13	Minor primary hydraulic	Minor	0.9375	0.05	0.15	1	1
14	Minor sealing	Minor	0.19	0	0.25	2	2
15	Secondary hydraulic	Minor	0.2256	0.06	1.5	2	2
16	Generator or switchgear	Minor	0.0396	0.06	1	2	2

Table A.1, part ii. Pelamis P2-specific O&M tool fault categories and associated parameters

ID	Full name	Moorings specialists required	Hydraulic specialists required	Structural specialists required	Electrical specialists required	Other technicians required
1	Major mooring	2	0	0	0	1
2	Major structure (no warning)	0	0	3	0	1
3	Major structural failure (identified through monitoring system)	0	0	2	0	1
4	Major primary hydraulic	0	1	0	0	1
5	Loss of GPS comms & main comms	0	0	0	1	1
6	Major sealing	0	0	3	0	1
7	Half circuit failure	0	0	0	1	1
8	Minor mooring	2	0	0	0	1
9	Data communications	0	0	0	1	1
10	Electrical unions/ tieback	0	0	0	1	1
11	Control system	0	0	0	1	0
12	Minor structural	0	0	1	0	1
13	Minor primary hydraulic	0	1	0	0	0
14	Minor sealing	0	0	1	0	0
15	Secondary hydraulic	0	1	0	0	0
16	Generator or switchgear	0	0	0	1	0

Table A.2. Pelamis P2-specific O&M tool scheduled maintenance categories and associated parameters

Full name	Interval if machine in for another repair	Interval if vessel is on hire	Maximum allowable time	Parts cost (£k)	Other costs (£k)	Inspection costs (£k)	Days off-site	Moorings specialists required	Hydraulic specialists required	Structural specialists required	Electrical specialists required	Other technicians required
Routine service	May - every year	July - every year	September - every year	2	1	3.25	7	0	1	1	1	1
Half-life refit	May - year 10	July - year 10	September - year 10	100	3	47.25	30	0	2	2	2	1

Table A.3. Albatern-specific O&M tool fault categories and parameters for a six Squid array

ID	Full name	Action required	Probability of failure per year	Power loss *(relevance)*	Parts cost (£)	Other costs (£)	Hours required offshore	Days required onshore	Vessel required	Hs limit (m)	Techs required
1	Major mooring	Moorings/ subsea work	0.0066	1 *(Array)*	1000	3000	12	N/A	Fast boat	1	2
2	Major structure	Retrieve Squid	0.1204	1 *(Squid)*	1500	1000	1	7	Slow boat	1.5	3
3	Major hydraulic	Retrieve Squid	0.1234	1 *(Squid)*	1500	1000	1	7	Slow boat	1.5	3
4	Major electrical	Moorings/ subsea work	0.0100	1 *(Array)*	2000	1000	24	N/A	Fast boat	1	2
5	Major comms	Moorings/ subsea work	0.0083	0 *(Array)*	500	500	12	N/A	Fast boat	1	2
6	Intermediate mooring	Moorings/ subsea work	0.0567	1 *(Array)*	500	1500	6	N/A	Fast boat	1	2
7	Intermediate structure	Retrieve Squid	0.3012	1 *(Squid)*	500	500	1	2	Slow boat	1.5	2
8	Intermediate hydraulic	Replace PTO	0.1364	1 *(Squid)*	400	500	1	N/A	Fast boat	1	2
9	Intermediate instrumentation	Replace box	0.0182	0 *(Squid)*	300	500	2	N/A	Rib	1	2
10	Intermediate comms	Replace comms	0.0050	0 *(Squid)*	300	500	2	N/A	Rib	1	2
11	Minor mooring	Retrieve Squid	0.0198	0 *(Squid)*	100	100	1	1	Slow boat	1.5	1
12	Minor structural	Retrieve Squid	0.3750	0.25 *(Squid)*	100	100	1	1	Slow boat	1.5	1
13	Minor hydraulic	Replace PTO	0.0328	0.25 *(Squid)*	100	100	1	N/A	Fast boat	1	1
14	Minor electrical	Replace PTO	0.0676	0.25 *(Squid)*	100	100	2	N/A	Fast boat	1	1
15	Minor instrumentation	Replace box	0.1758	0 *(Squid)*	100	100	2	N/A	Rib	1	1

Table A.4. Albatern-specific O&M tool scheduled maintenance categories and associated parameters for a six Squid WaveNET array

Full name	**Frequency (years)**	**Time of year**	**Action required**	**Max no Squids off site**	**Vessel required**	**Hs limit (m)**	**Hours required offshore**	**Days require onshore**	**Parts cost (£)**	**Other costs (£)**	**Inspection costs (£)**	**Technicians required**
Routine service	2	Summer	Retrieve Squid units	1	Slow boat	1.5	1	4	800	300	200	2
Moorings inspection	1	Summer	Moorings work	N/A	Fast boat	1	3	N/A	0	0	1500	1

Table A.5. Parameters used to modify the probabilities of failure for array-based fault categories in the Albatern-specific O&M model

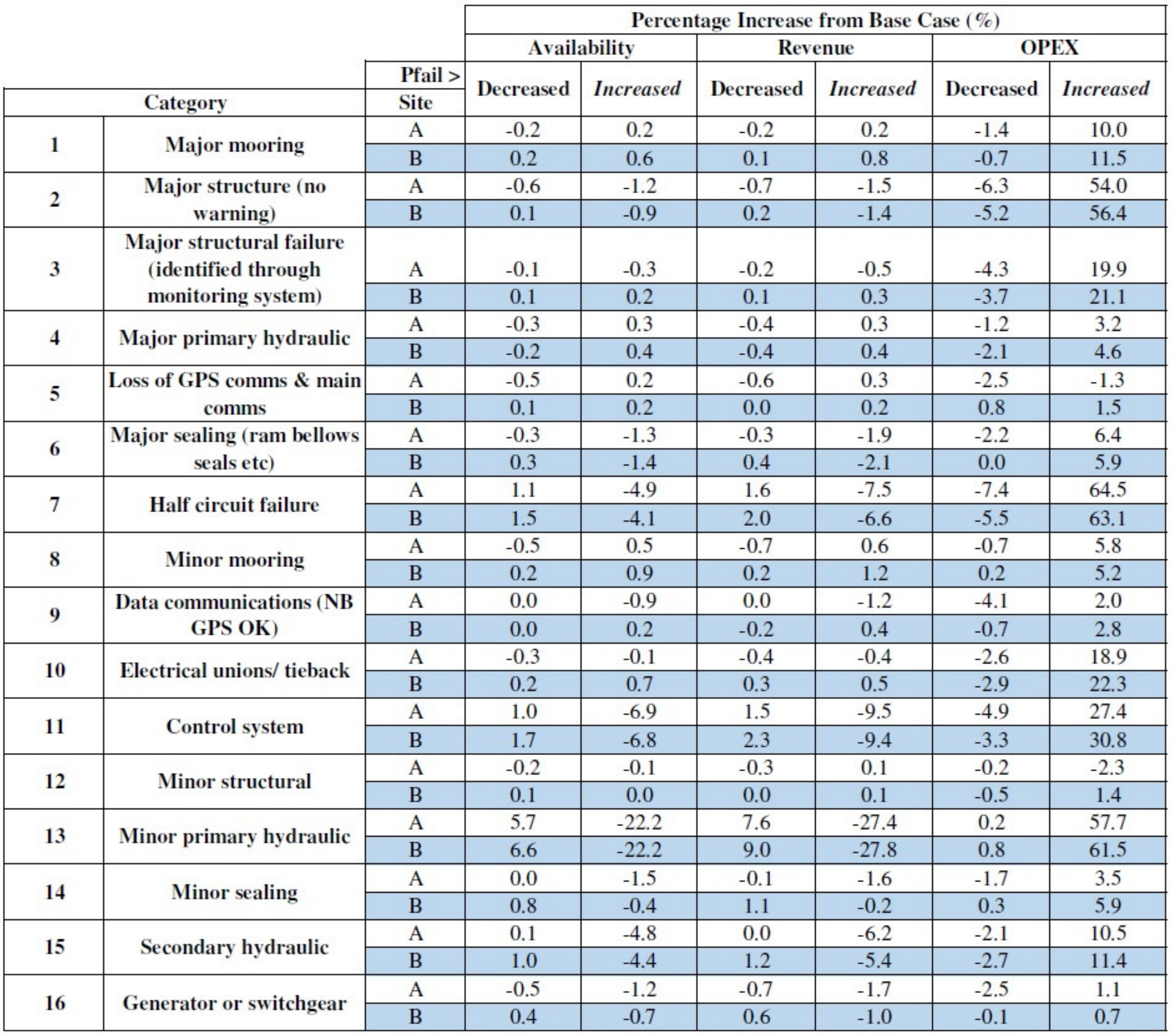
Array-based fault category	**Number of components in fault category (n)**	**Component (i)**	**Annual probability of no failure (R_i)**	**Number of component (i) in mooring system (N_i)**
Major mooring	2	Mooring leg	0.0017	3
		Mooring grid	0.0017	1
Major electrical	5	Housing	0.0017	1
		Diodes	0.0017	2
		DC/DC converter	0.0017	1
		Offshore Connection	0.0017	1
		750m Subsea Cable	0.0017	1
Major communications	1	FO Media Converter & Switch	0.0083	1
Intermediate mooring	4	Drag Embedment Anchor	0.0083	3
		Corner float assembly	0.0017	3
		Navigation buoy	0.0083	1
		Mooring Connector	0.0017	12

Table A.6. Numerical results of the Pelamis-specific O&M model sensitivity analysis

	Site	Availability (per year)	Revenue (£k per year)	OPEX (£k per year)
Base Case	A	0.868	2848.9	1116.3
	B	0.857	2570.0	1087.7

			Availability (per year)		**Revenue (£k per year)**		**OPEX (£k per year)**	
		Pfail >	**Decreased**	***Increased***	**Decreased**	***Increased***	**Decreased**	***Increased***
Category		**Site**						
1	**Major mooring**	A	0.867	*0.870*	2842.1	*2854.6*	1101.1	*1227.7*
		B	0.859	*0.863*	2573.3	*2591.0*	1080.5	*1212.9*
2	**Major structure (no warning)**	A	0.863	*0.857*	2829.2	*2807.0*	1046.0	*1718.5*
		B	0.858	*0.848*	2574.3	*2534.0*	1030.9	*1701.2*
3	**Major structural failure (identified through monitoring system)**	A	0.867	*0.865*	2843.1	*2834.1*	1068.2	*1338.3*
		B	0.857	*0.859*	2571.4	*2577.9*	1047.8	*1317.6*
4	**Major primary hydraulic**	A	0.866	*0.871*	2838.9	*2857.7*	1103.0	*1152.4*
		B	0.855	*0.860*	2559.6	*2581.3*	1065.0	*1137.8*
5	**Loss of GPS comms & main comms**	A	0.863	*0.870*	2830.7	*2856.7*	1088.2	*1101.3*
		B	0.858	*0.859*	2570.4	*2574.6*	1096.9	*1103.8*
6	**Major sealing (ram bellows seals etc)**	A	0.866	*0.855*	2841.4	*2795.8*	1092.0	*1187.9*
		B	0.860	*0.843*	2581.1	*2515.6*	1088.0	*1151.6*
7	**Half circuit failure**	A	0.880	*0.820*	2895.8	*2635.9*	1033.4	*1836.7*
		B	0.871	*0.816*	2622.4	*2400.6*	1028.0	*1774.2*
8	**Minor mooring**	A	0.864	*0.873*	2829.2	*2866.4*	1108.3	*1181.4*
		B	0.859	*0.866*	2576.0	*2600.1*	1090.0	*1144.0*
9	**Data communications (NB GPS OK)**	A	0.868	*0.859*	2849.3	*2813.5*	1071.0	*1138.8*
		B	0.856	*0.859*	2565.6	*2579.1*	1080.2	*1117.8*
10	**Electrical unions/ tieback**	A	0.865	*0.868*	2838.6	*2836.5*	1086.8	*1327.1*
		B	0.859	*0.864*	2578.1	*2583.4*	1056.1	*1330.4*
11	**Control system**	A	0.878	*0.799*	2890.5	*2577.6*	1061.1	*1421.7*
		B	0.874	*0.789*	2629.2	*2328.8*	1051.5	*1423.1*
12	**Minor structural**	A	0.866	*0.868*	2840.7	*2850.4*	1113.7	*1090.3*
		B	0.858	*0.857*	2571.2	*2571.3*	1082.3	*1103.4*
13	**Minor primary hydraulic**	A	0.925	*0.646*	3065.0	*2067.9*	1118.2	*1760.0*
		B	0.923	*0.634*	2801.3	*1855.1*	1096.1	*1756.5*
14	**Minor sealing**	A	0.868	*0.853*	2845.4	*2804.6*	1097.5	*1155.0*
		B	0.865	*0.853*	2597.6	*2564.1*	1090.7	*1151.7*
15	**Secondary hydraulic**	A	0.869	*0.820*	2847.6	*2671.6*	1092.9	*1233.1*
		B	0.866	*0.813*	2601.8	*2431.1*	1058.5	*1211.8*
16	**Generator or switchgear**	A	0.864	*0.856*	2829.2	*2801.5*	1087.9	*1128.3*
		B	0.861	*0.850*	2584.4	*2545.3*	1087.1	*1095.8*

Table A.7. Results of the Pelamis-specific O&M model sensitivity analysis in terms of percentage change from the base case



Category		Pfail > Site	Percentage Increase from Base Case (%)					
			Availability		Revenue		OPEX	
			Decreased	*Increased*	Decreased	*Increased*	Decreased	*Increased*
1	Major mooring	A	-0.2	0.2	-0.2	0.2	-1.4	10.0
		B	0.2	0.6	0.1	0.8	-0.7	11.5
2	Major structure (no warning)	A	-0.6	-1.2	-0.7	-1.5	-6.3	54.0
		B	0.1	-0.9	0.2	-1.4	-5.2	56.4
3	Major structural failure (identified through monitoring system)	A	-0.1	-0.3	-0.2	-0.5	-4.3	19.9
		B	0.1	0.2	0.1	0.3	-3.7	21.1
4	Major primary hydraulic	A	-0.3	0.3	-0.4	0.3	-1.2	3.2
		B	-0.2	0.4	-0.4	0.4	-2.1	4.6
5	Loss of GPS comms & main comms	A	-0.5	0.2	-0.6	0.3	-2.5	-1.3
		B	0.1	0.2	0.0	0.2	0.8	1.5
6	Major sealing (ram bellows seals etc)	A	-0.3	-1.3	-0.3	-1.9	-2.2	6.4
		B	0.3	-1.4	0.4	-2.1	0.0	5.9
7	Half circuit failure	A	1.1	-4.9	1.6	-7.5	-7.4	64.5
		B	1.5	-4.1	2.0	-6.6	-5.5	63.1
8	Minor mooring	A	-0.5	0.5	-0.7	0.6	-0.7	5.8
		B	0.2	0.9	0.2	1.2	0.2	5.2
9	Data communications (NB GPS OK)	A	0.0	-0.9	0.0	-1.2	-4.1	2.0
		B	0.0	0.2	-0.2	0.4	-0.7	2.8
10	Electrical unions/ tieback	A	-0.3	-0.1	-0.4	-0.4	-2.6	18.9
		B	0.2	0.7	0.3	0.5	-2.9	22.3
11	Control system	A	1.0	-6.9	1.5	-9.5	-4.9	27.4
		B	1.7	-6.8	2.3	-9.4	-3.3	30.8
12	Minor structural	A	-0.2	-0.1	-0.3	0.1	-0.2	-2.3
		B	0.1	0.0	0.0	0.1	-0.5	1.4
13	Minor primary hydraulic	A	5.7	-22.2	7.6	-27.4	0.2	57.7
		B	6.6	-22.2	9.0	-27.8	0.8	61.5
14	Minor sealing	A	0.0	-1.5	-0.1	-1.6	-1.7	3.5
		B	0.8	-0.4	1.1	-0.2	0.3	5.9
15	Secondary hydraulic	A	0.1	-4.8	0.0	-6.2	-2.1	10.5
		B	1.0	-4.4	1.2	-5.4	-2.7	11.4
16	Generator or switchgear	A	-0.5	-1.2	-0.7	-1.7	-2.5	1.1
		B	0.4	-0.7	0.6	-1.0	-0.1	0.7

Table A.8. Albatern-specific O&M tool fault categories and associated parameters for the ‘optimistic’ and ‘pessimistic’ scenarios for a 24-WEC array

ID	Full name	Action required	Probability of failure per year	Power loss *(relevance)*	Parts cost (£)	Other costs (£)	Hours required offshore	Days required onshore
1	Major mooring	Moorings/ subsea work	Optimistic - 0.0132 Pessimistic - 0.0519	1 *(Array)*	800 1200	2400 3600	9.6 14.4	N/A N/A
2	Major structure	Retrieve Squid	Optimistic - 0.0621 Pessimistic - 0.2263	1 *(Squid)*	1200 1800	800 1200	0.8 1.2	5 9
3	Major hydraulic	Retrieve Squid	Optimistic - 0.0637 Pessimistic - 0.2316	1 *(Squid)*	1200 1800	800 1200	0.8 1.2	5 9
4	Major electrical	Moorings/ subsea work	Optimistic - 0.0198 Pessimistic - 0.0769	1 *(Array)*	1600 2400	800 1200	19.2 28.8	N/A N/A
5	Major communications	Moorings/ subsea work	Optimistic - 0.0083 Pessimistic - 0.0328	0 *(Array)*	400 600	400 600	9.6 14.4	N/A N/A
6	Intermediate mooring	Moorings/ subsea work	Optimistic - 0.1101 Pessimistic - 0.3729	1 *(Squid)*	400 600	1200 1800	4.8 7.2	N/A N/A
7	Intermediate structure	Retrieve Squid	Optimistic - 0.1641 Pessimistic - 0.5117	1 *(Squid)*	400 600	400 600	0.8 1.2	1 3
8	Intermediate hydraulic	Replace PTO	Optimistic - 0.0707 Pessimistic - 0.2542	1 *(Squid)*	320 480	400 600	0.8 1.2	N/A N/A
9	Intermediate instrumentation	Replace box	Optimistic - 0.0091 Pessimistic - 0.0361	0 *(Squid)*	240 360	400 600	1.6 2.4	N/A N/A
10	Intermediate communications	Moorings/ subsea work	Optimistic - 0.0025 Pessimistic - 0.0100	1 *(Array)*	240 360	400 600	1.6 2.4	N/A N/A
11	Minor mooring	Retrieve Squid	Optimistic - 0.0099 Pessimistic - 0.0392	0 *(Squid)*	80 120	80 120	0.8 1.2	1 2
12	Minor structural	Retrieve Squid	Optimistic - 0.2094 Pessimistic - 0.6094	0.25 *(Squid)*	80 120	80 120	0.8 1.2	1 2
13	Minor hydraulic	Replace PTO	Optimistic - 0.0165 Pessimistic - 0.0645	0.25 *(Squid)*	80 120	80 120	0.8 1.2	N/A N/A
14	Minor electrical	Replace PTO	Optimistic - 0.0344 Pessimistic - 0.1306	0.25 *(Squid)*	80 120	80 120	1.6 2.4	N/A N/A
15	Minor instrumentation	Replace box	Optimistic - 0.0921 Pessimistic - 0.3207	1 *(Squid)*	80 120	80 120	1.6 2.4	N/A N/A

Table A.9. Albatern-specific O&M tool scheduled maintenance categories and associated parameters for the ‘optimistic’ and ‘pessimistic’ scenarios for a 24-WEC array

Full name	**Frequency (years)**	**Time of year**	**Action required**	**Hours required offshore**	**Days require onshore**	**Parts cost (£)**	**Other costs (£)**	**Inspection costs (£)**
Routine service	2	Summer	Retrieve Squid units	Optimistic – 0.8 Pessimistic – 1.2	3 5	640 960	240 360	160 240
Moorings inspection	1	Summer	Moorings work	Optimistic – 2.4 Pessimistic – 3.6	N/A N/A	0 0	0 0	1200 1800

Appendix C – Appendix Figures

The following figures present the results of each analysis undertaken in chapters 4 and 5 in terms of availability, revenue, OPEX and net operational income (i.e. 'profit' over the lifetime of the assessed wave energy array. A graph of the cumulative net operational income generated over the lifetime of the array is also generated for each analysis. The appropriate section from the main text is highlighted. In each graph, individual simulation runs are represented by thin, faint lines, with the average values shown by thicker, bolder lines.

Chapter 4 Appendix Figures

Section 4.4

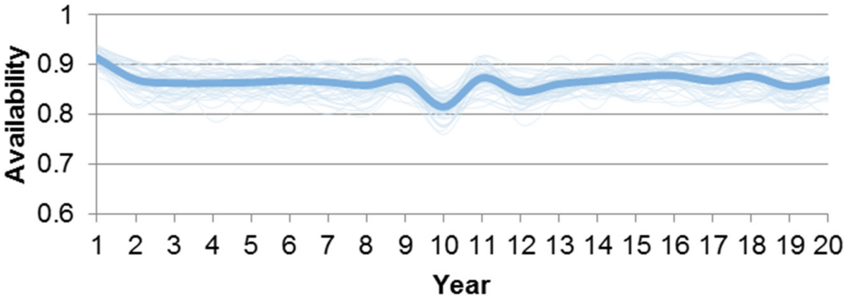


Figure A.4.4.1. Annual results of the 'Hire when required' vessel arrangement, for a lifetime of 20 years, in terms of availability

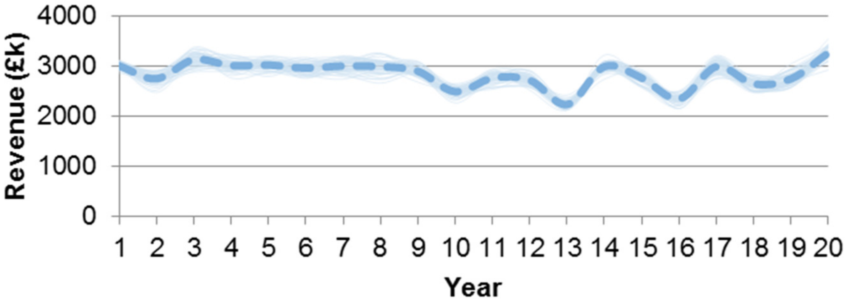


Figure A.4.4.2. Annual results of the 'Hire when required' vessel arrangement, for a lifetime of 20 years, in terms of revenue

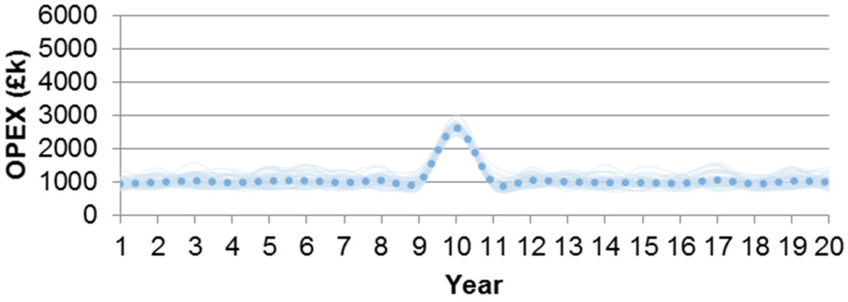


Figure A.4.4.3. Annual results of the 'Hire when required' vessel arrangement, for a lifetime of 20 years, in terms of OPEX

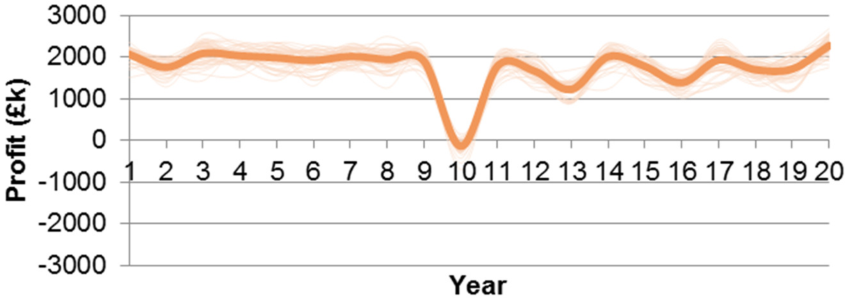


Figure A.4.4.4. Annual results of the 'Hire when required' vessel arrangement, for a lifetime of 20 years, in terms of profit

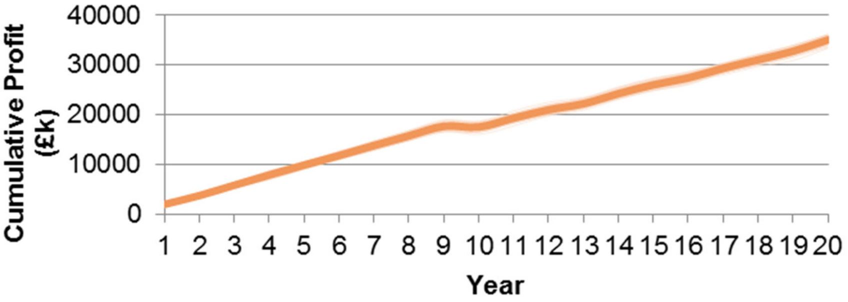


Figure A.4.4.5. Cumulative profit of the 'Hire when required' vessel arrangement, for a lifetime of 20 years

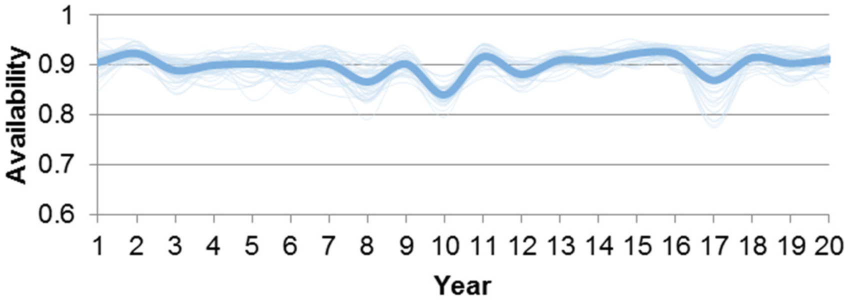


Figure A.4.4.6. Annual results of the 'Long term lease' vessel arrangement, for a lifetime of 20 years, in terms of availability

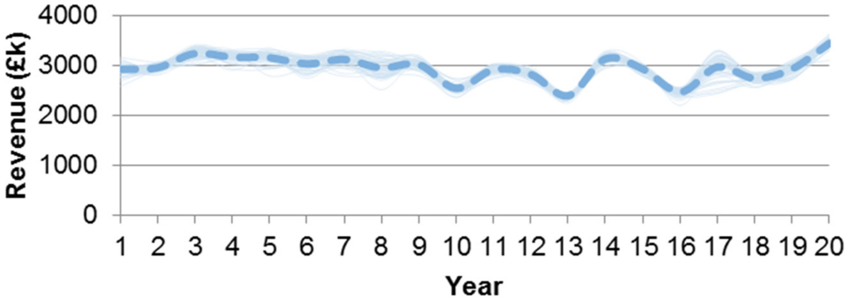


Figure A.4.4.7. Annual results of the 'Long term lease' vessel arrangement, for a lifetime of 20 years, in terms of revenue

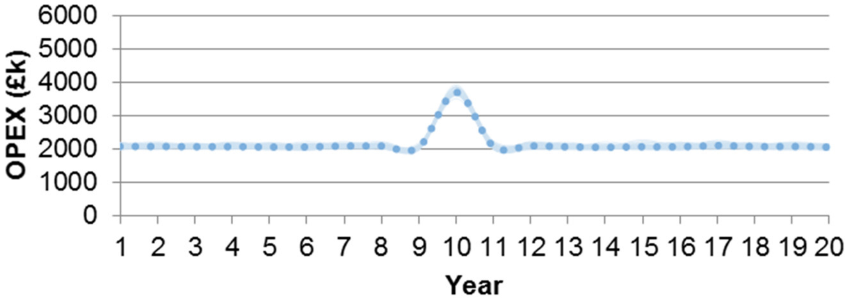


Figure A.4.4.8. Annual results of the 'Long term lease' vessel arrangement, for a lifetime of 20 years, in terms of OPEX

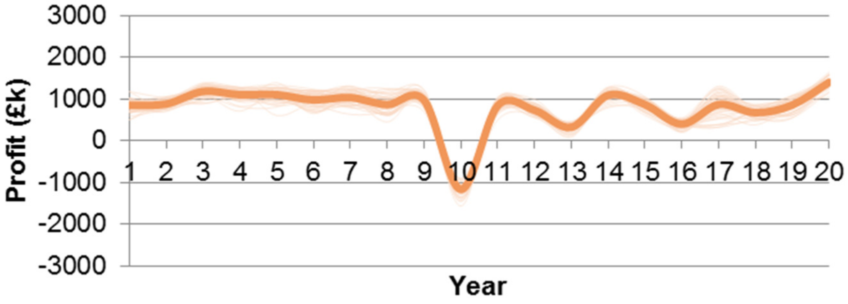


Figure A.4.4.9. Annual results of the 'Long term lease' vessel arrangement, for a lifetime of 20 years, in terms of profit

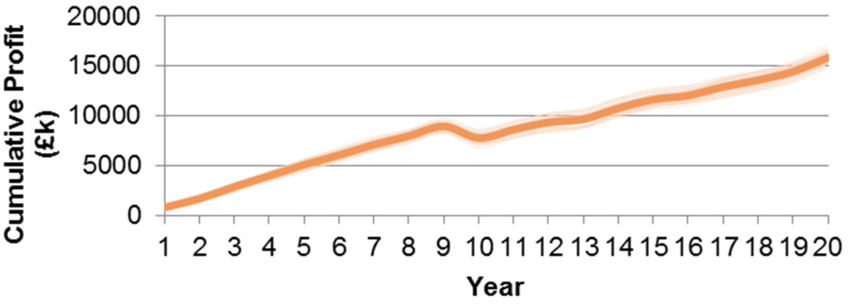


Figure A.4.4.10. Cumulative profit of the 'Long term lease' vessel arrangement, for a lifetime of 20 years

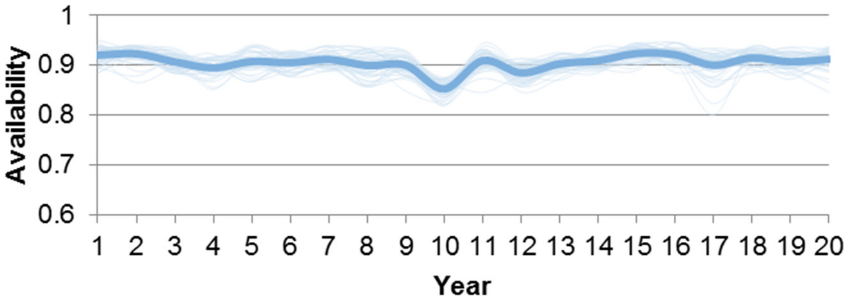


Figure A.4.4.11. Annual results of the 'Long term standby rate' vessel arrangement, for a lifetime of 20 years, in terms of availability

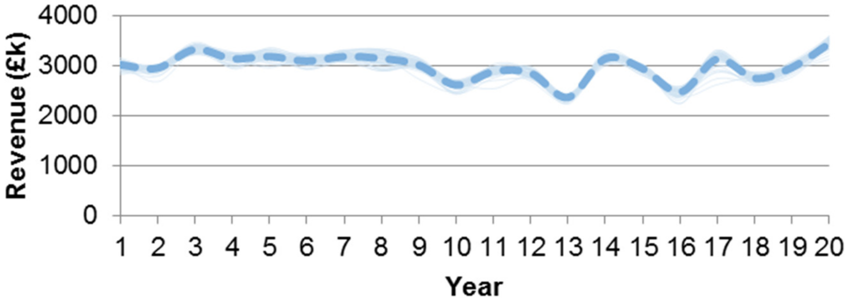


Figure A.4.4.12. Annual results of the 'Long term standby rate' vessel arrangement, for a lifetime of 20 years, in terms of revenue

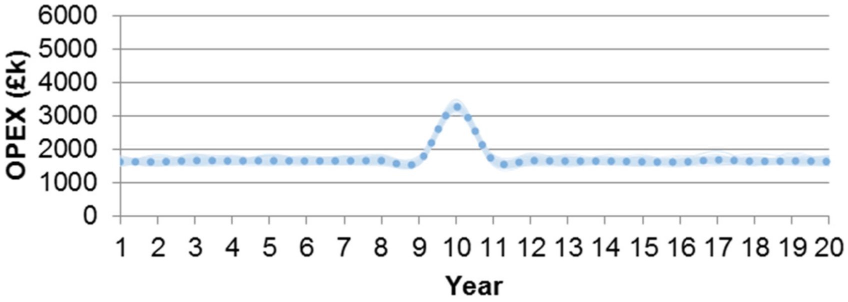


Figure A.4.4.13. Annual results of the 'Long term standby rate' vessel arrangement, for a lifetime of 20 years, in terms of OPEX

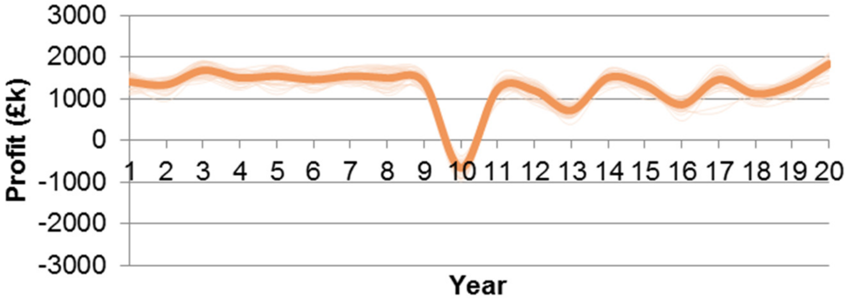


Figure A.4.4.14. Annual results of the 'Long term standby rate' vessel arrangement, for a lifetime of 20 years, in terms of profit

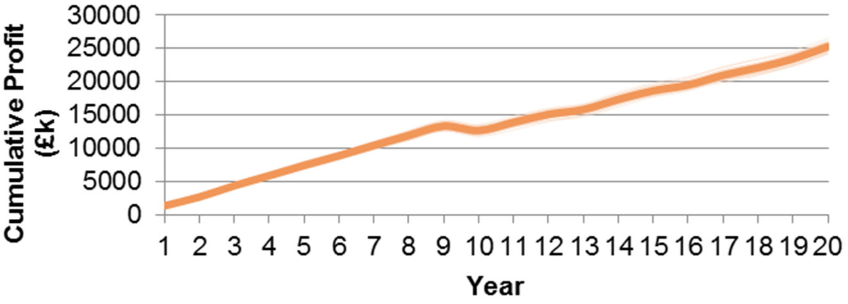


Figure A.4.4.15. Cumulative profit of the ‘Long term standby rate’ vessel arrangement, for a lifetime of 20 years

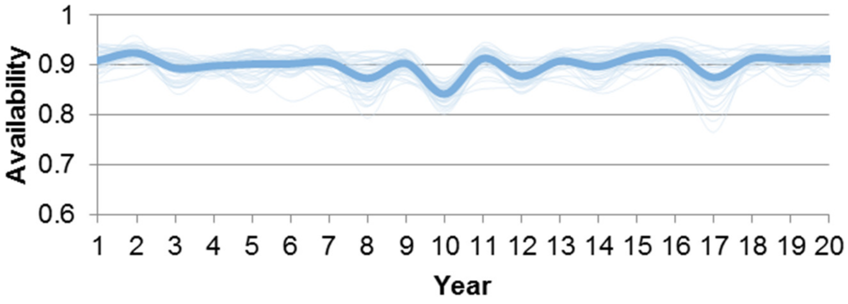


Figure A.4.4.16. Annual results of the ‘Hire to purchase’ vessel arrangement, for a lifetime of 20 years, in terms of availability

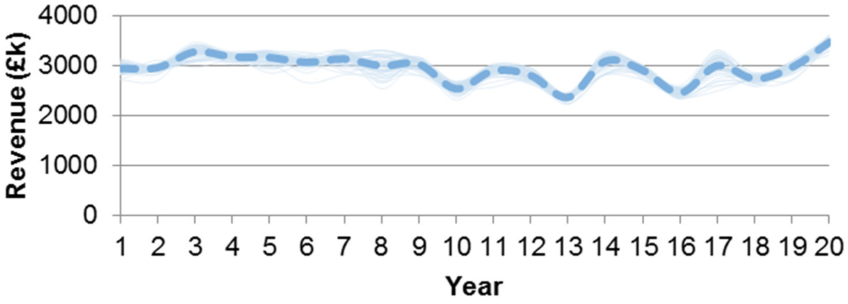


Figure A.4.4.17. Annual results of the ‘Hire to purchase’ vessel arrangement, for a lifetime of 20 years, in terms of revenue

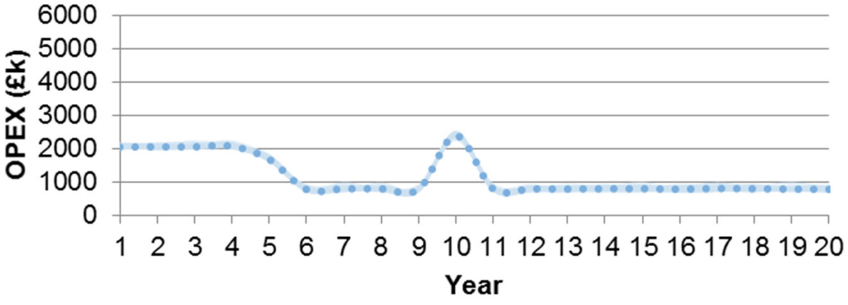


Figure A.4.4.18. Annual results of the ‘Hire to purchase’ vessel arrangement, for a lifetime of 20 years, in terms of OPEX

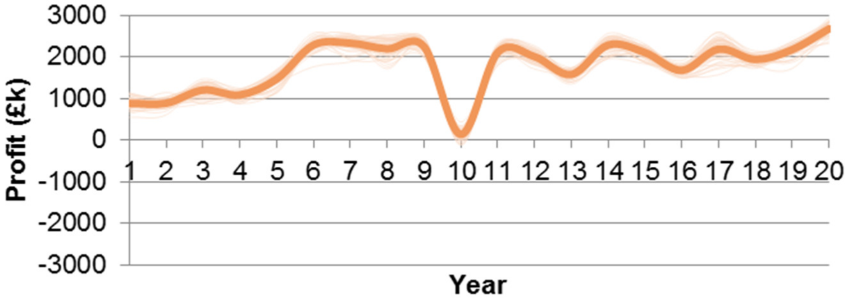


Figure A.4.4.19. Annual results of the ‘Hire to purchase’ vessel arrangement, for a lifetime of 20 years, in terms of profit

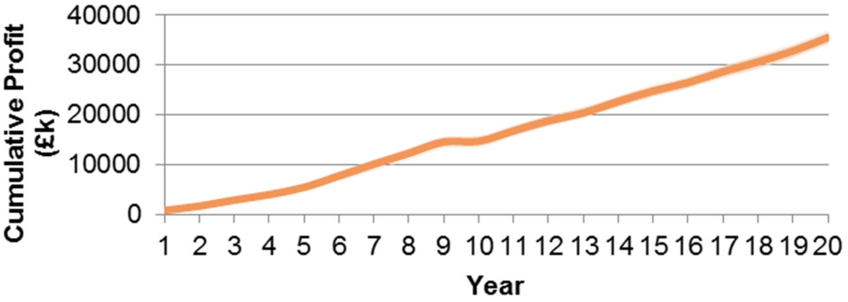


Figure A.4.4.20. Cumulative profit of the ‘Hire to purchase’ vessel arrangement, for a lifetime of 20 years

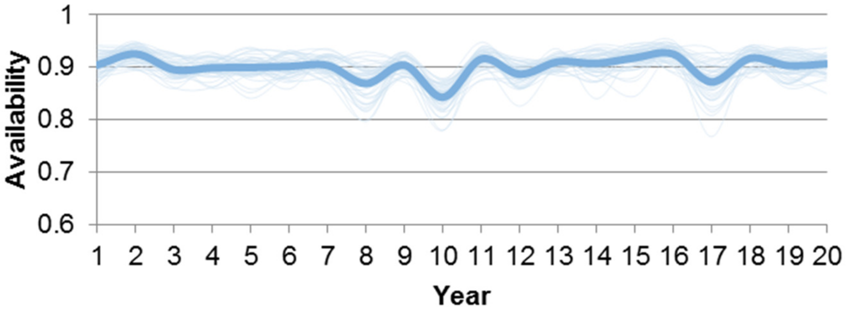


Figure A.4.4.21. Annual results of the ‘Outright purchase’ vessel arrangement, for a lifetime of 20 years, in terms of availability

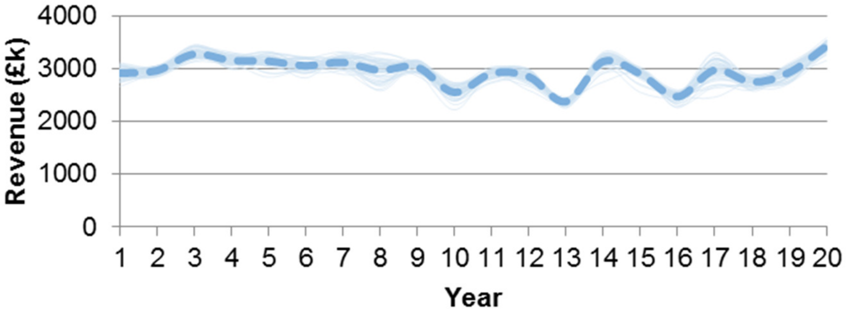


Figure A.4.4.22. Annual results of the ‘Outright purchase’ vessel arrangement, for a lifetime of 20 years, in terms of revenue

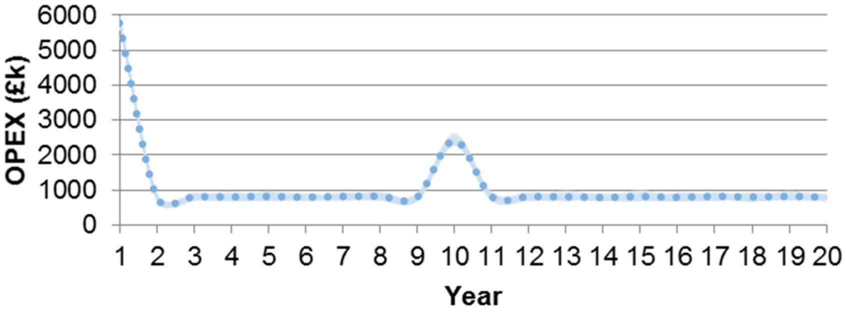


Figure A.4.4.23. Annual results of the 'Outright purchase' vessel arrangement, for a lifetime of 20 years, in terms of OPEX

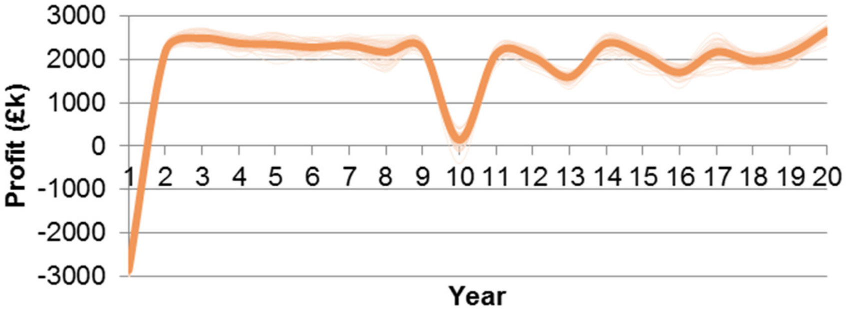


Figure A.4.4.24. Annual results of the 'Outright purchase' vessel arrangement, for a lifetime of 20 years, in terms of profit

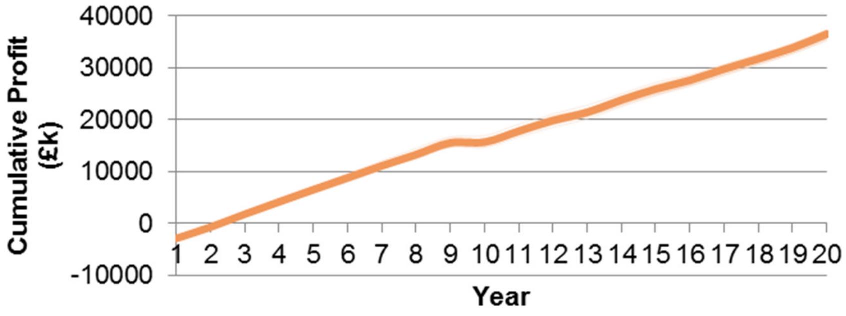


Figure A.4.4.25. Cumulative profit of the 'Outright purchase' vessel arrangement, for a lifetime of 20 years

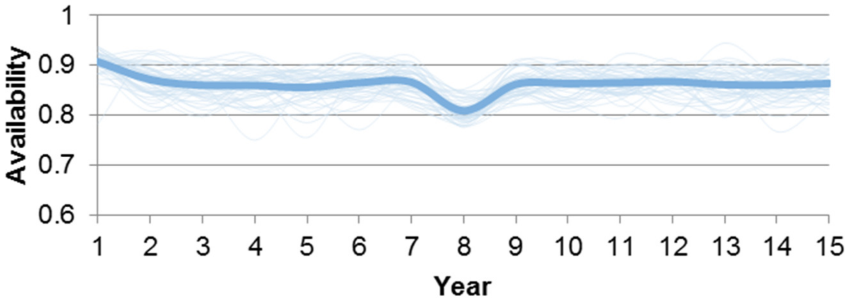


Figure A.4.4.26. Annual results of the 'Hire when required' vessel arrangement, for a lifetime of 15 years, in terms of availability

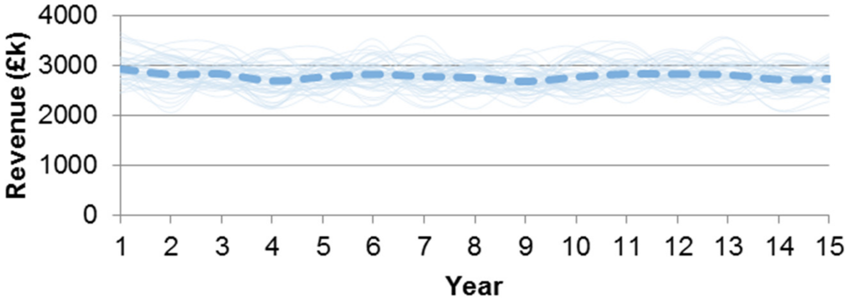


Figure A.4.4.27. Annual results of the 'Hire when required' vessel arrangement, for a lifetime of 15 years, in terms of revenue

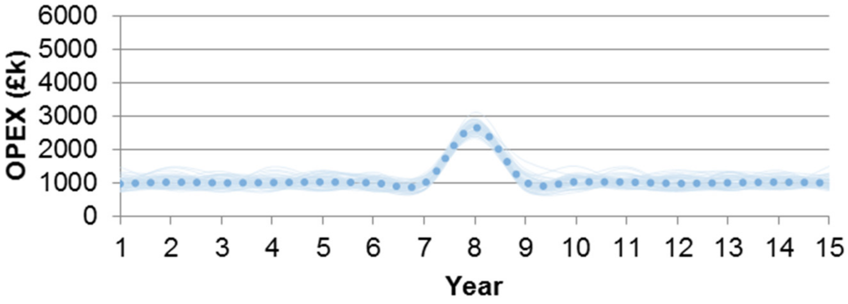


Figure A.4.4.28. Annual results of the 'Hire when required' vessel arrangement, for a lifetime of 15 years, in terms of OPEX

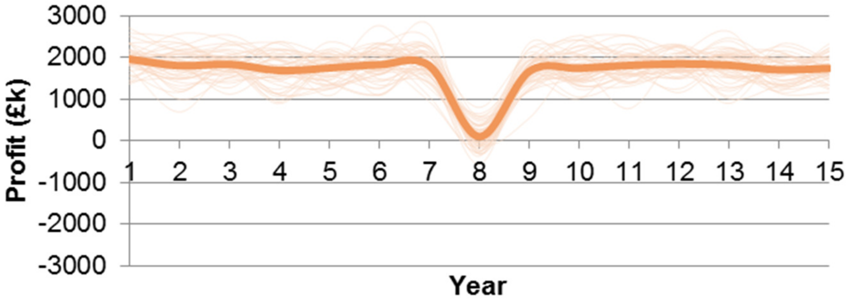


Figure A.4.4.29. Annual results of the 'Hire when required' vessel arrangement, for a lifetime of 15 years, in terms of profit

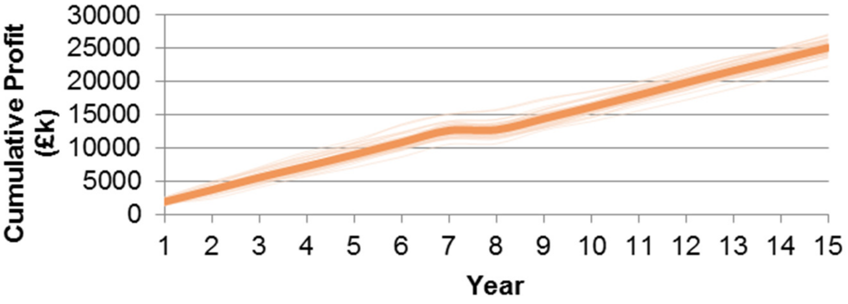


Figure A.4.4.30. Cumulative profit of the 'Hire when required' vessel arrangement, for a lifetime of 15 years

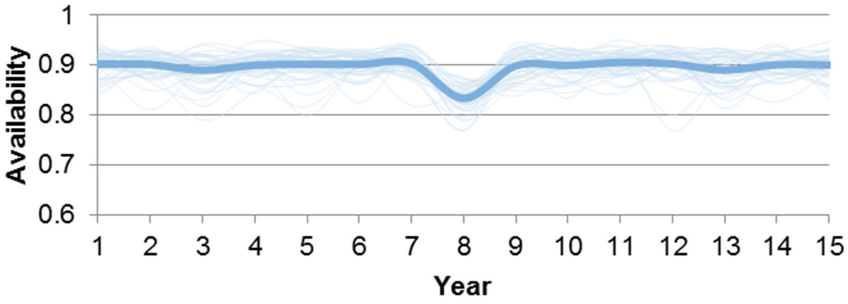


Figure A.4.4.31. Annual results of the 'Outright purchase' vessel arrangement, for a lifetime of 15 years, in terms of availability

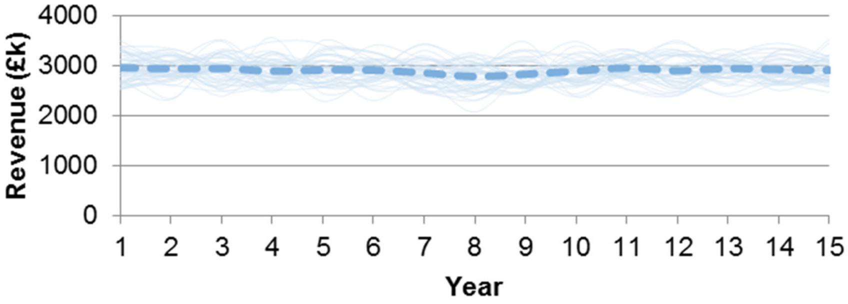


Figure A.4.4.32. Annual results of the 'Outright purchase' vessel arrangement, for a lifetime of 15 years, in terms of revenue

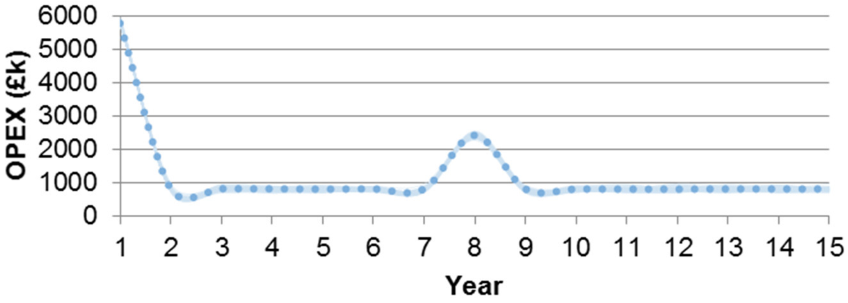


Figure A.4.4.33. Annual results of the 'Outright purchase' vessel arrangement, for a lifetime of 15 years, in terms of OPEX

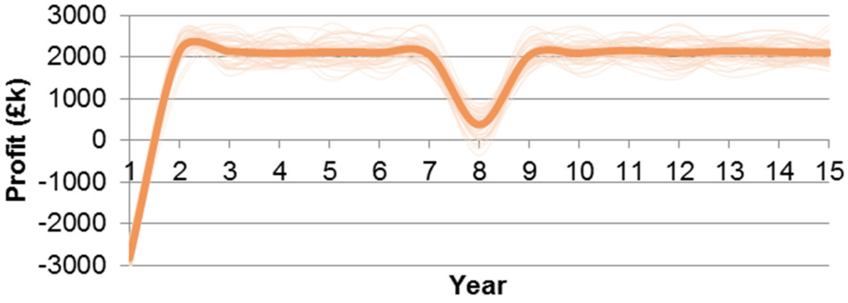


Figure A.4.4.34. Annual results of the 'Outright purchase' vessel arrangement, for a lifetime of 15 years, in terms of profit

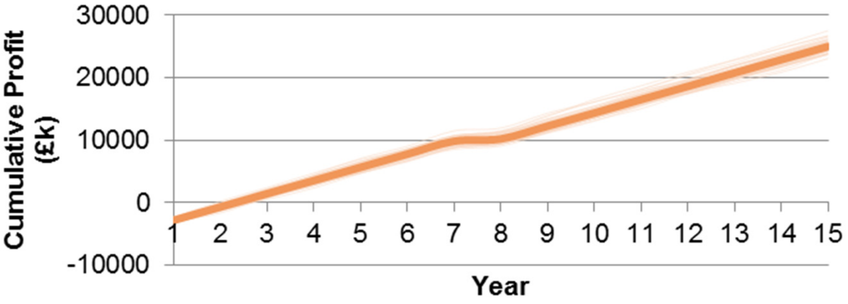


Figure A.4.4.35. Cumulative profit of the 'Outright purchase' vessel arrangement, for a lifetime of 15 years

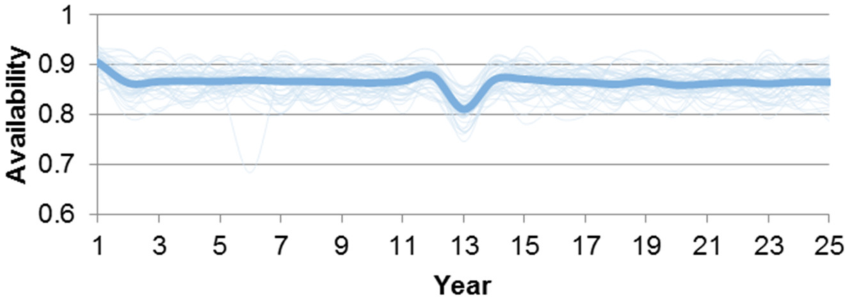


Figure A.4.4.36. Annual results of the 'Hire when required' vessel arrangement, for a lifetime of 25 years, in terms of availability

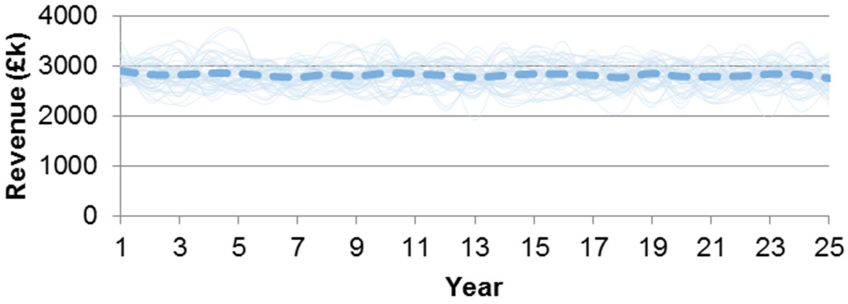


Figure A.4.4.37. Annual results of the 'Hire when required' vessel arrangement, for a lifetime of 25 years, in terms of revenue

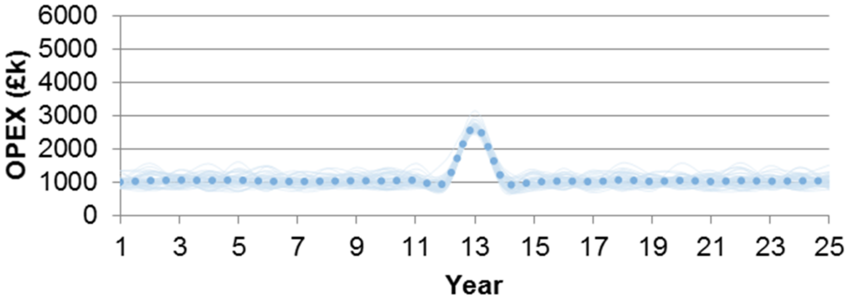


Figure A.4.4.38. Annual results of the 'Hire when required' vessel arrangement, for a lifetime of 25 years, in terms of OPEX

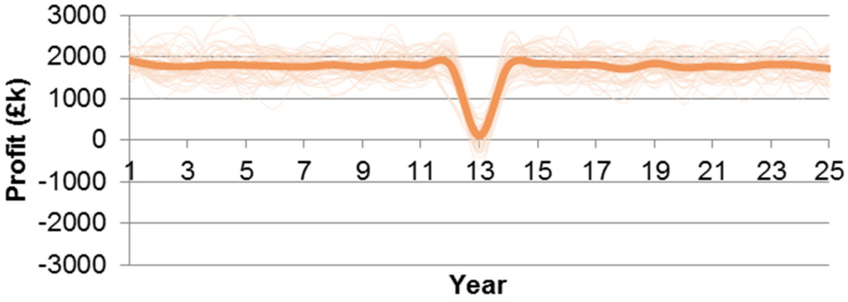


Figure A.4.4.39. Annual results of the 'Hire when required' vessel arrangement, for a lifetime of 25 years, in terms of profit

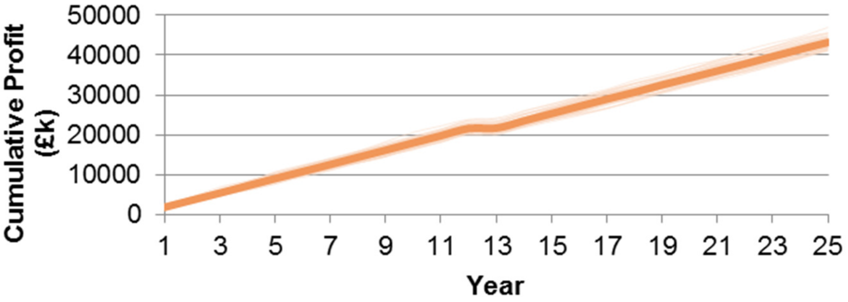


Figure A.4.4.40. Cumulative profit of the 'Hire when required' vessel arrangement, for a lifetime of 25 years

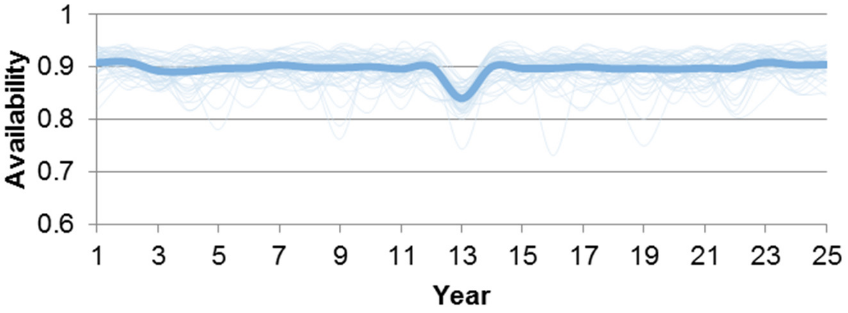


Figure A.4.4.41. Annual results of the 'Outright purchase' vessel arrangement, for a lifetime of 25 years, in terms of availability

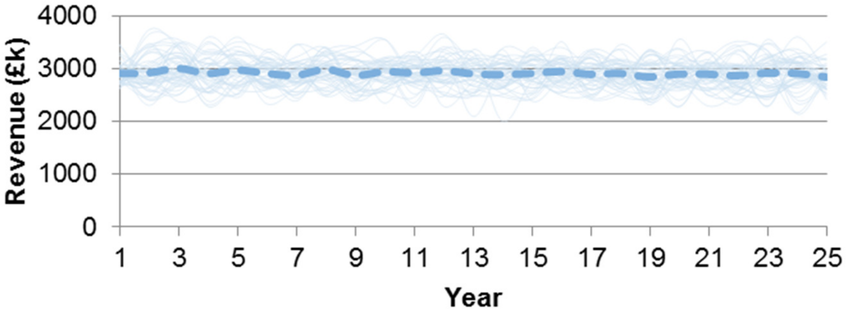


Figure A.4.4.42. Annual results of the 'Outright purchase' vessel arrangement, for a lifetime of 25 years, in terms of revenue

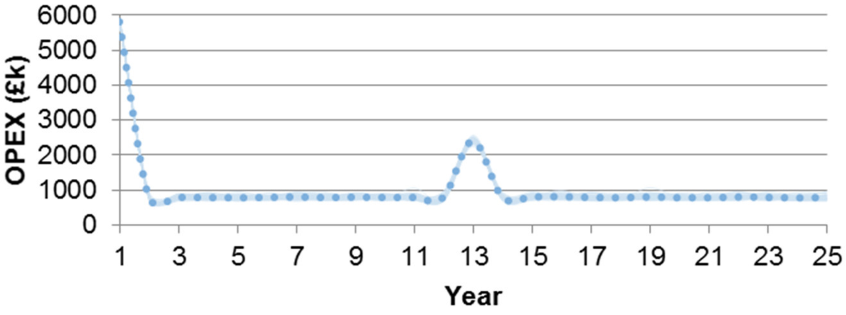


Figure A.4.4.43. Annual results of the 'Outright purchase' vessel arrangement, for a lifetime of 25 years, in terms of OPEX

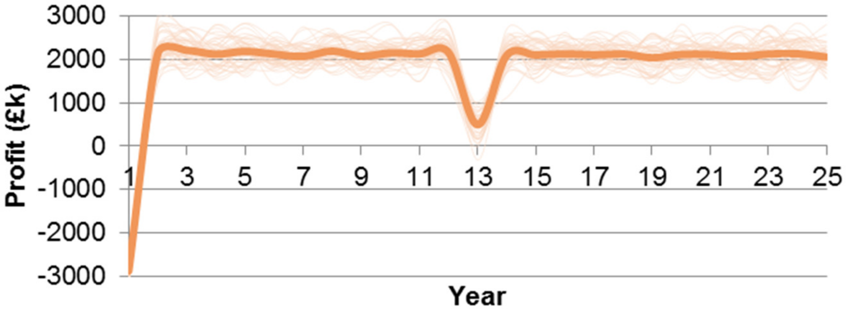


Figure A.4.4.44. Annual results of the 'Outright purchase' vessel arrangement, for a lifetime of 25 years, in terms of profit

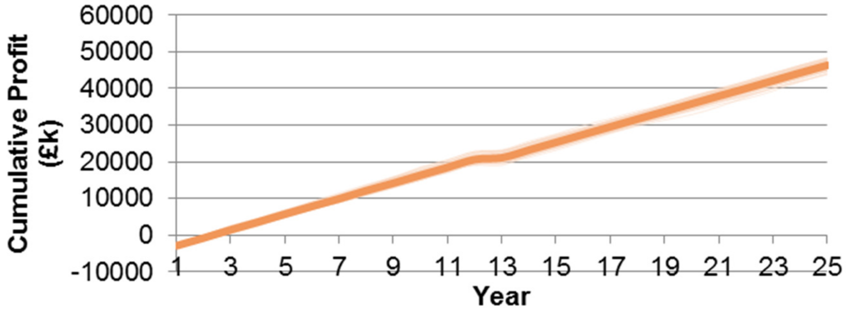


Figure A.4.4.45. Cumulative profit of the 'Outright purchase' vessel arrangement, for a lifetime of 25 years

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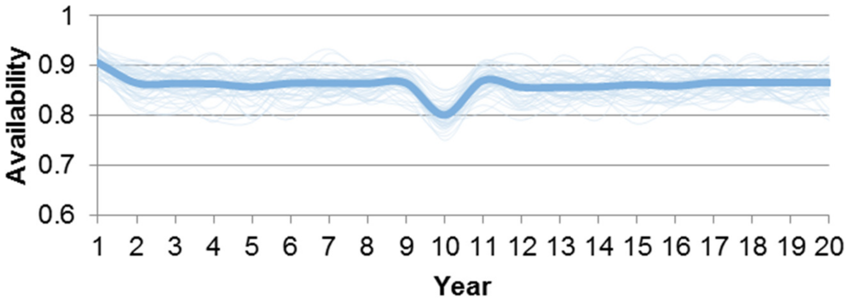

Figure A.4.5.1. Annual results of the 'Night ops on' scenario, for a lifetime of 20 years, in terms of availability

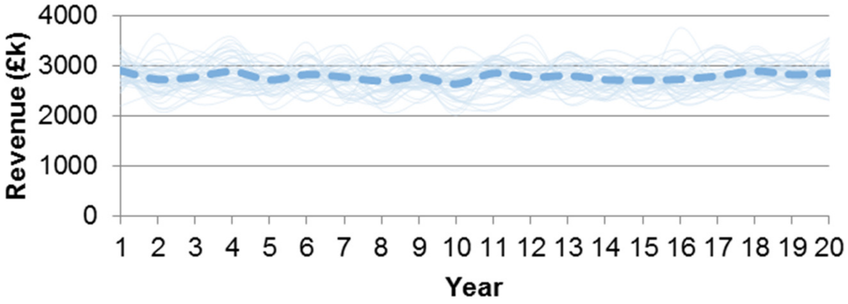

Figure A.4.5.2. Annual results of the 'Night ops on' scenario, for a lifetime of 20 years, in terms of revenue

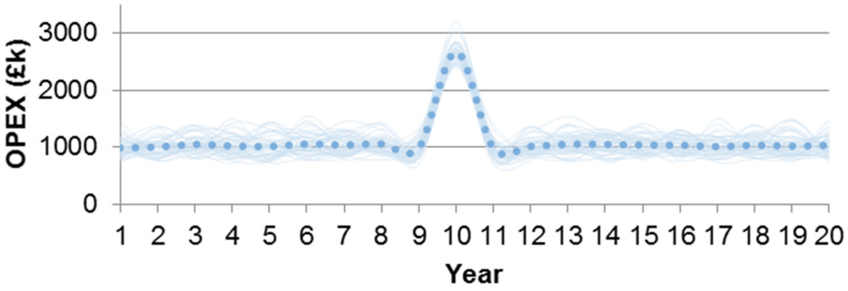

Figure A.4.5.3. Annual results of the 'Night ops on' scenario, for a lifetime of 20 years, in terms of OPEX

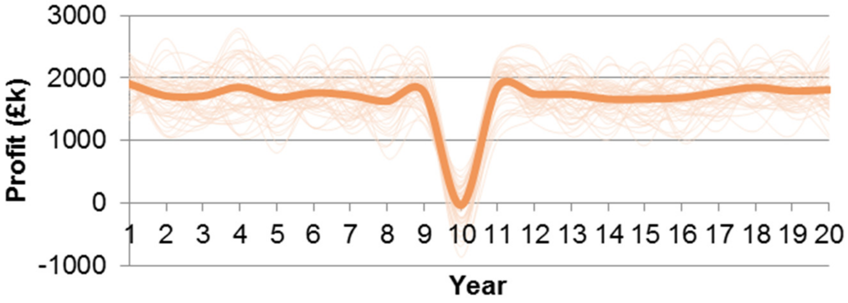

Figure A.4.5.4. Annual results of the 'Night ops on' scenario, for a lifetime of 20 years, in terms of profit

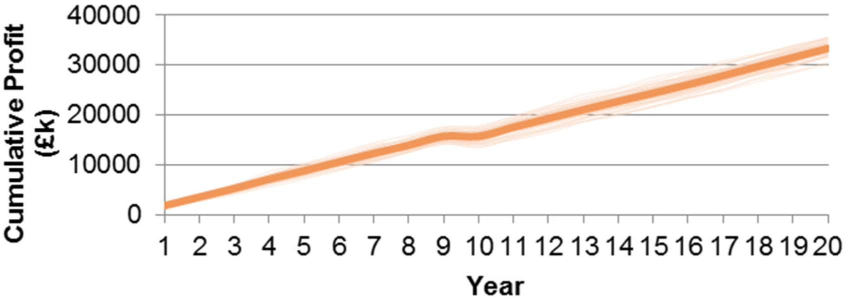

Figure A.4.5.5. Cumulative profit of the 'Night ops on' scenario, for a lifetime of 20 years

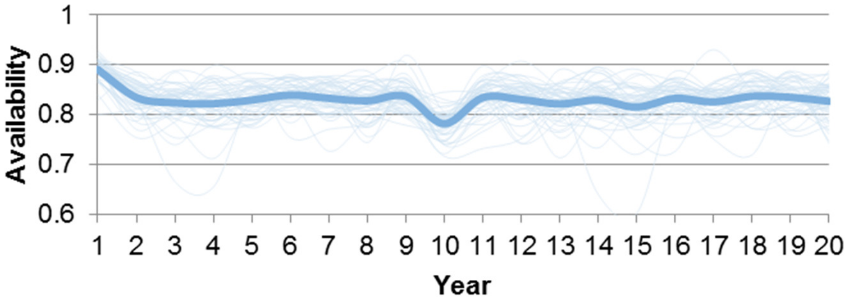

Figure A.4.5.6. Annual results of the 'Night ops off' scenario, for a lifetime of 20 years, in terms of availability

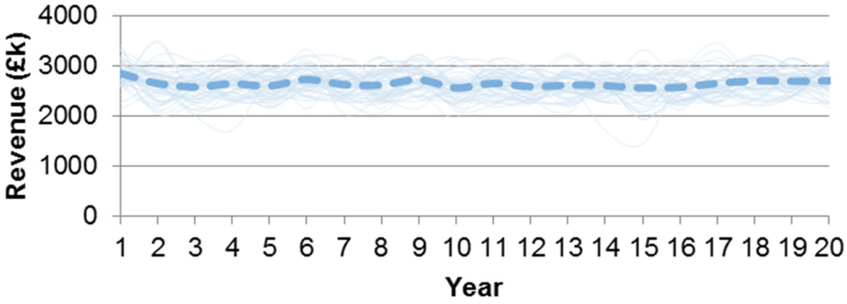

Figure A.4.5.7. Annual results of the 'Night ops off' scenario, for a lifetime of 20 years, in terms of revenue

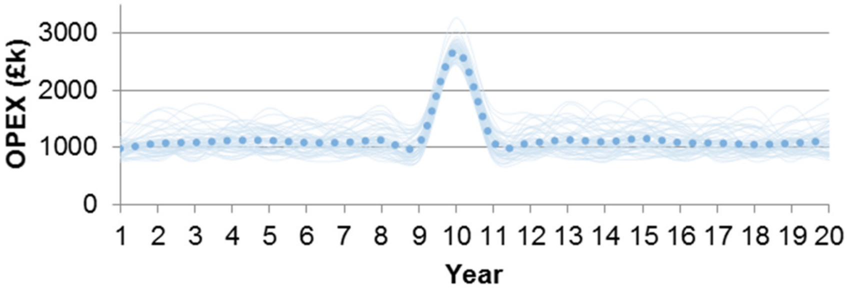

Figure A.4.5.8. Annual results of the 'Night ops off' scenario, for a lifetime of 20 years, in terms of OPEX

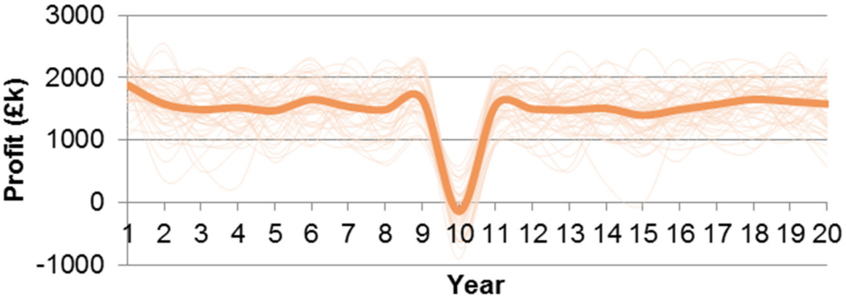

Figure A.4.5.9. Annual results of the 'Night ops off' scenario, for a lifetime of 20 years, in terms of profit

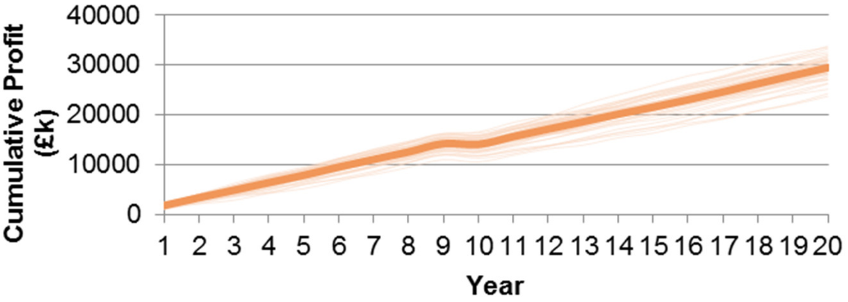

Figure A.4.5.10. Cumulative profit of the 'Night ops off' scenario, for a lifetime of 20 years

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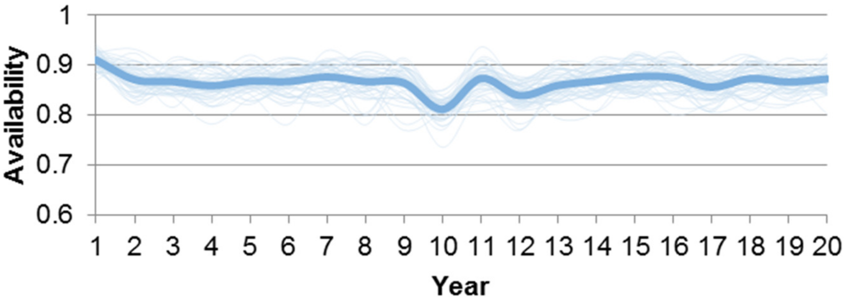

Figure A.4.6.1. Annual results of the 'Offshore logistics base case' scenario, for a lifetime of 20 years, in terms of availability

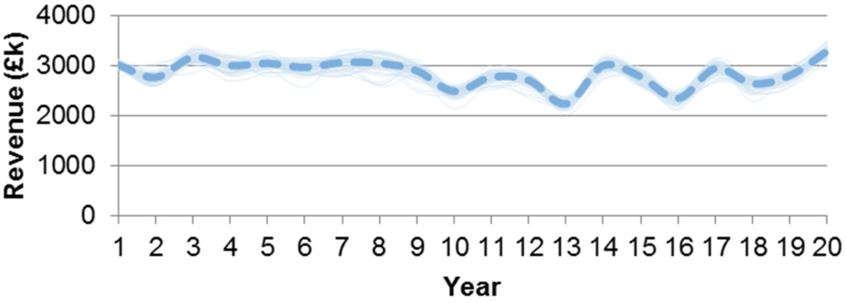

Figure A.4.6.2. Annual results of the 'Offshore logistics base case' scenario, for a lifetime of 20 years, in terms of revenue

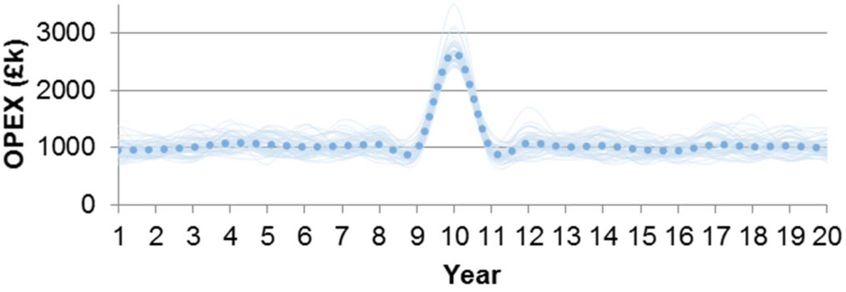

Figure A.4.6.3. Annual results of the 'Offshore logistics base case' scenario, for a lifetime of 20 years, in terms of OPEX

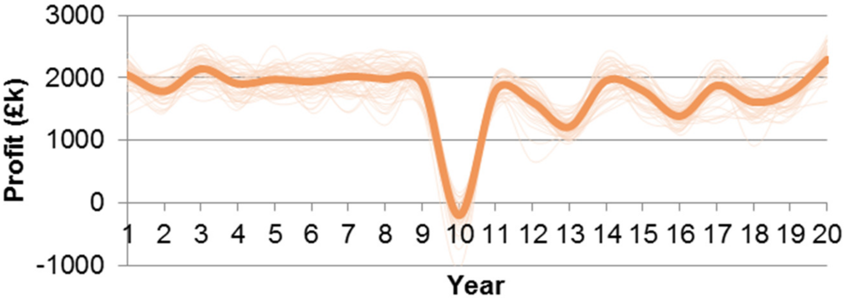

Figure A.4.6.4. Annual results of the 'Offshore logistics base case' scenario, for a lifetime of 20 years, in terms of profit

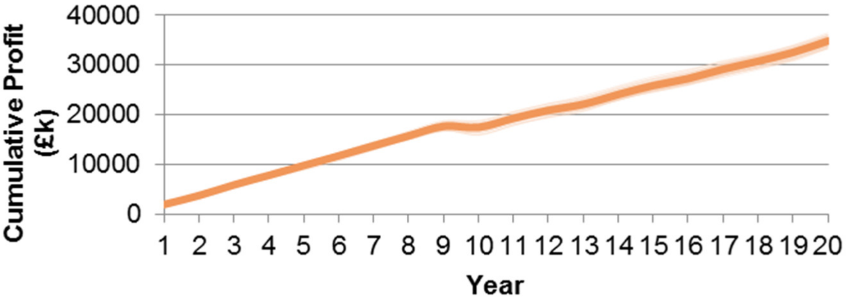

Figure A.4.6.5. Cumulative profit of the 'Offshore logistics base case' scenario, for a lifetime of 20 years

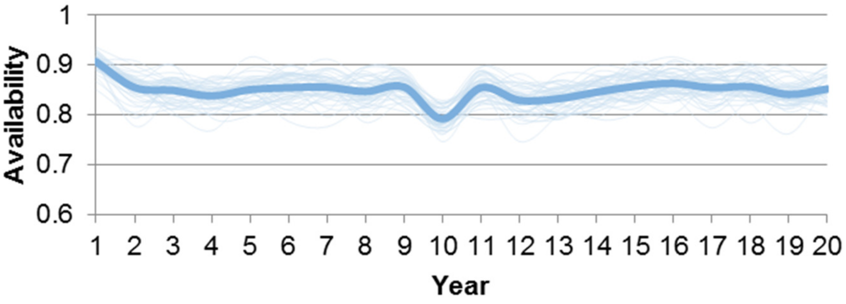

Figure A.4.6.6. Annual results of 'Offshore logistics scenario 1', for a lifetime of 20 years, in terms of availability

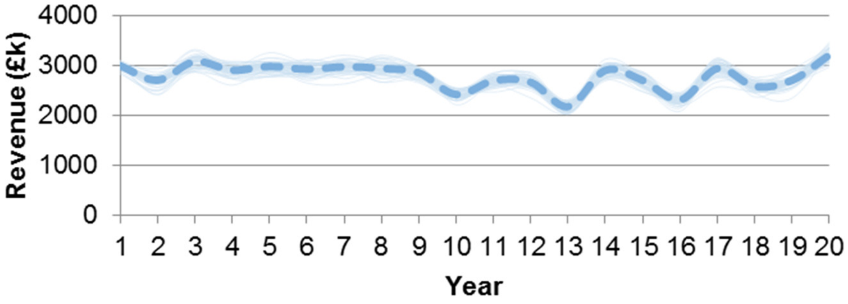

Figure A.4.6.7. Annual results of 'Offshore logistics scenario 1', for a lifetime of 20 years, in terms of revenue

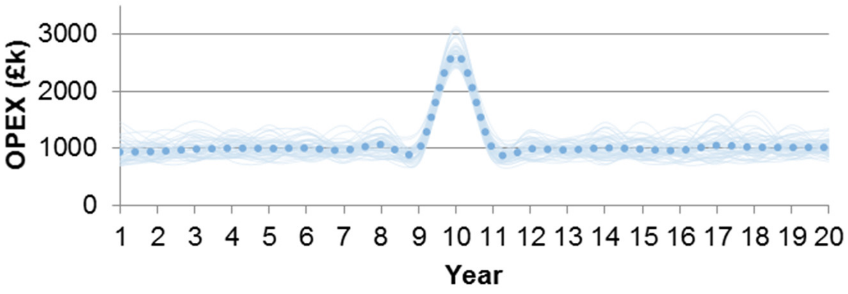

Figure A.4.6.8. Annual results of 'Offshore logistics scenario 1', for a lifetime of 20 years, in terms of OPEX

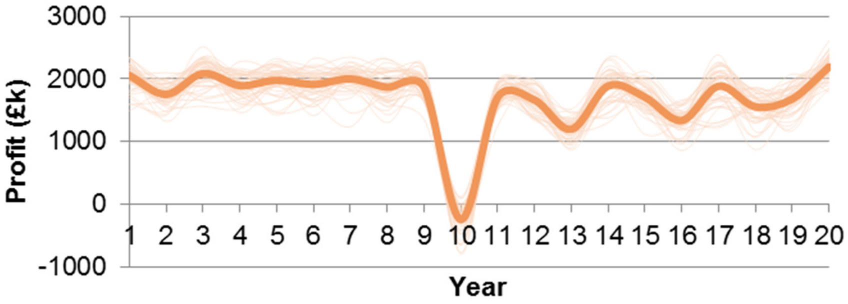

Figure A.4.6.9. Annual results of 'Offshore logistics scenario 1', for a lifetime of 20 years, in terms of profit

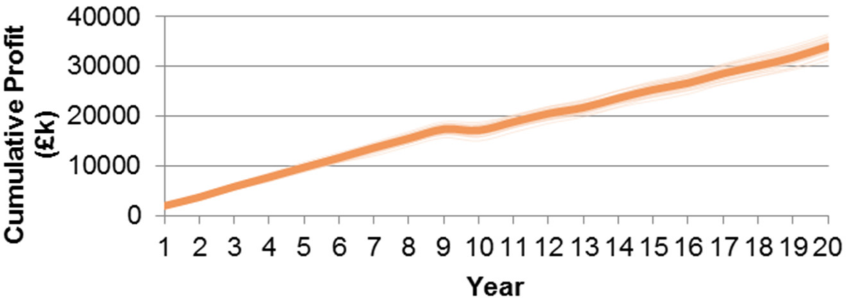

Figure A.4.6.10. Cumulative profit of 'Offshore logistics scenario 1', for a lifetime of 20 years

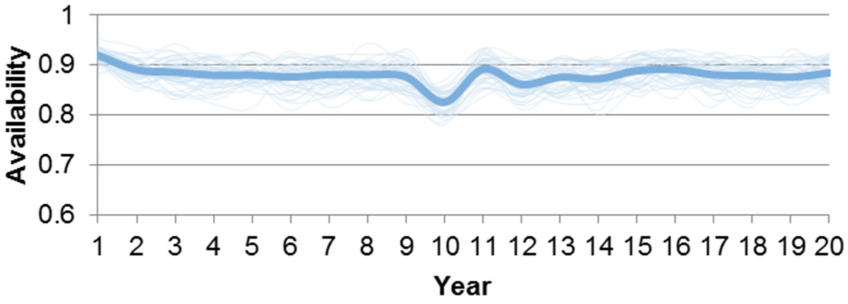

Figure A.4.6.11. Annual results of 'Offshore logistics scenario 2', for a lifetime of 20 years, in terms of availability

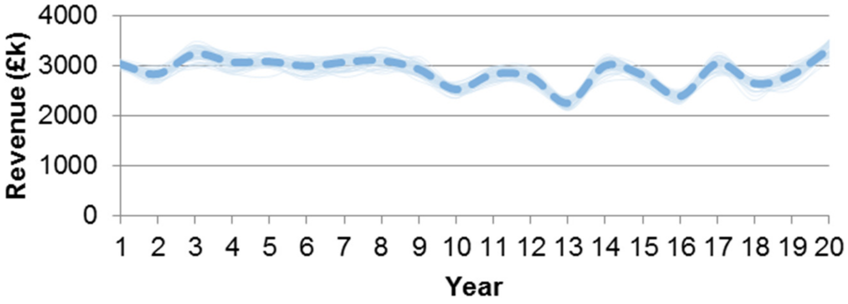

Figure A.4.6.12. Annual results of 'Offshore logistics scenario 2', for a lifetime of 20 years, in terms of revenue

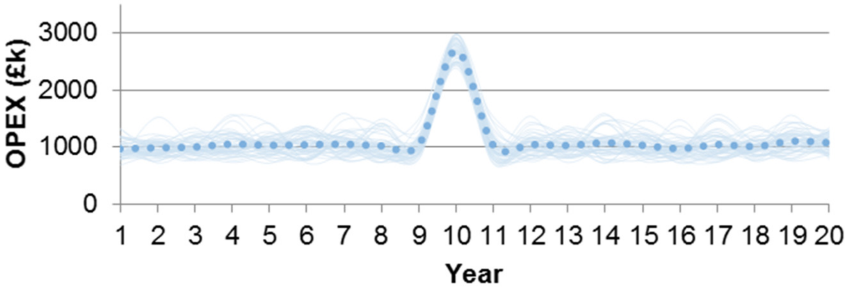

Figure A.4.6.13. Annual results of 'Offshore logistics scenario 2', for a lifetime of 20 years, in terms of OPEX

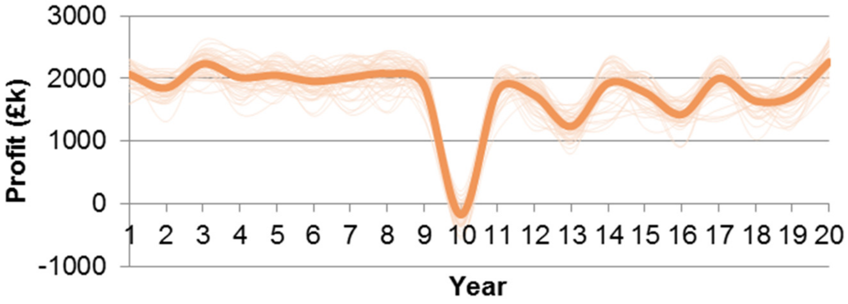

Figure A.4.6.14. Annual results of 'Offshore logistics scenario 2', for a lifetime of 20 years, in terms of profit

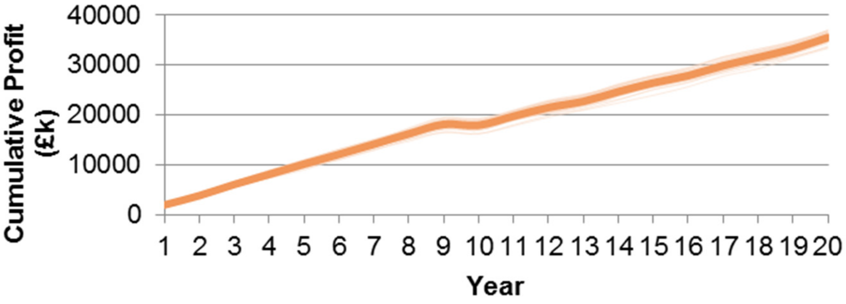

Figure A.4.6.15. Cumulative profit of 'Offshore logistics scenario 2', for a lifetime of 20 years

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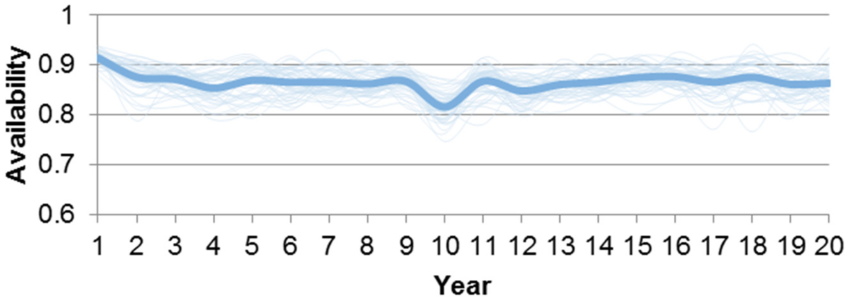

Figure A.4.7.1. Annual results of the 'Operational limits base case' scenario, for a lifetime of 20 years, in terms of availability

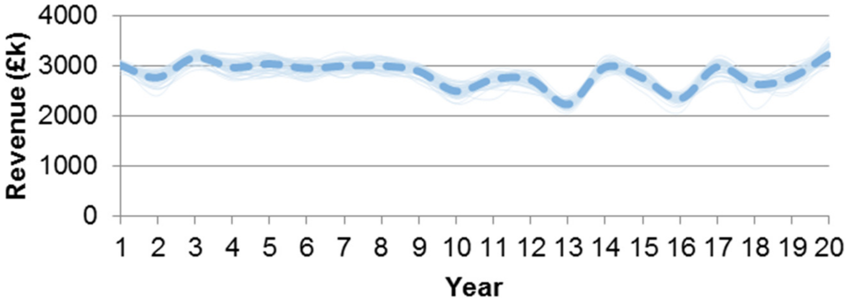

Figure A.4.7.2. Annual results of the 'Operational limits base case' scenario, for a lifetime of 20 years, in terms of revenue

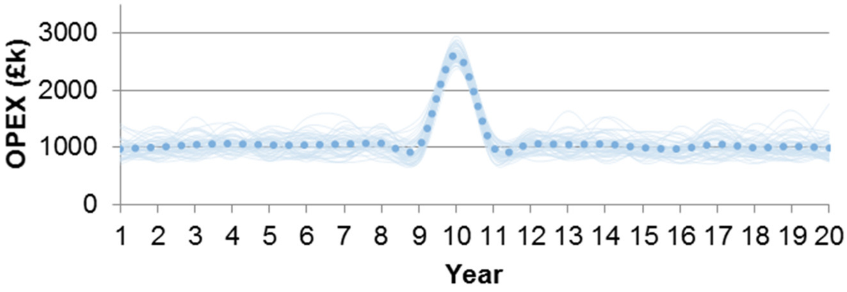

Figure A.4.7.3. Annual results of the 'Operational limits base case' scenario, for a lifetime of 20 years, in terms of OPEX

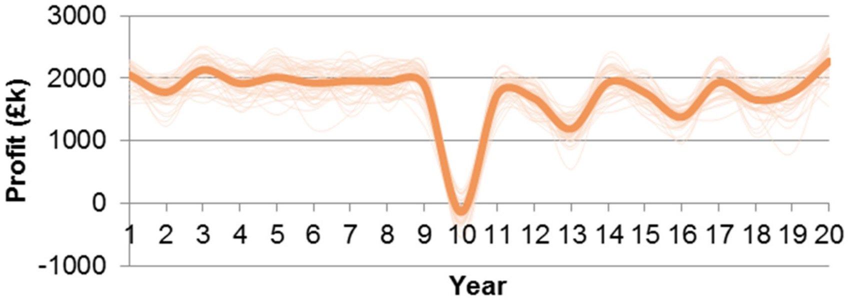

Figure A.4.7.4. Annual results of the ‘Operational limits base case’ scenario, for a lifetime of 20 years, in terms of profit

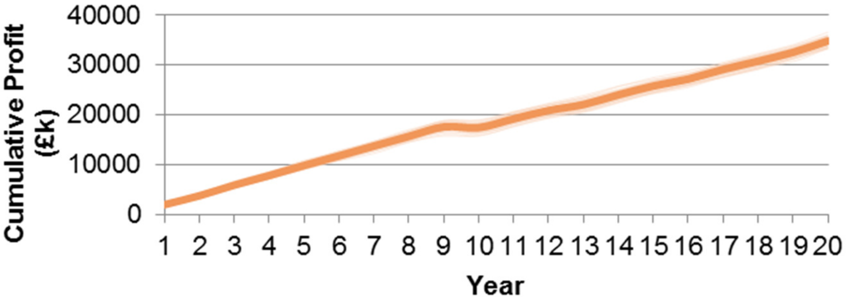

Figure A.4.7.5. Cumulative profit of the ‘Operational limits base case’ scenario, for a lifetime of 20 years

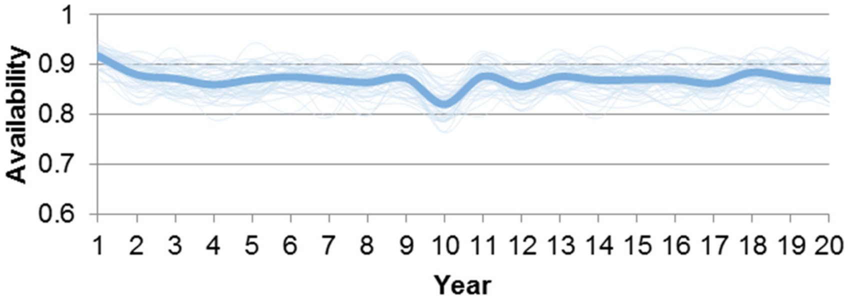

Figure A.4.7.6. Annual results of ‘Operational limits scenario 1’, for a lifetime of 20 years, in terms of availability

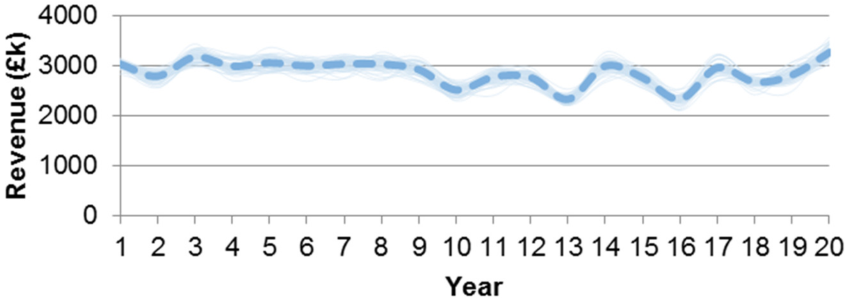

Figure A.4.7.7. Annual results of ‘Operational limits scenario 1’, for a lifetime of 20 years, in terms of revenue

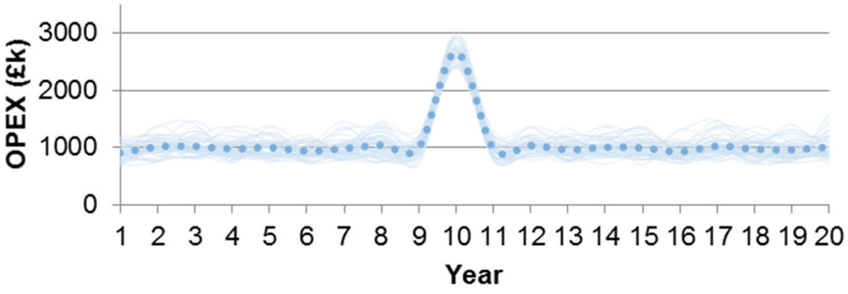

Figure A.4.7.8. Annual results of 'Operational limits scenario 1', for a lifetime of 20 years, in terms of OPEX

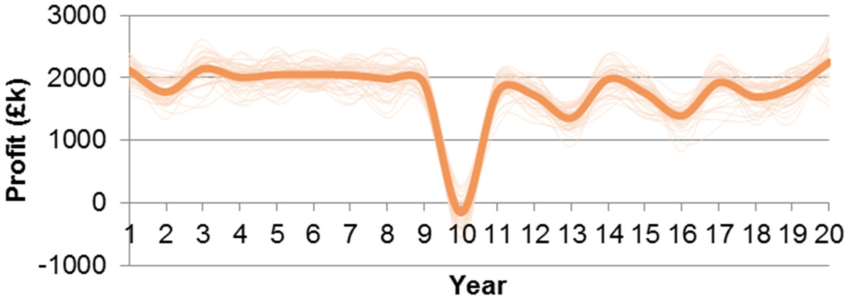

Figure A.4.7.9. Annual results of 'Operational limits scenario 1', for a lifetime of 20 years, in terms of profit

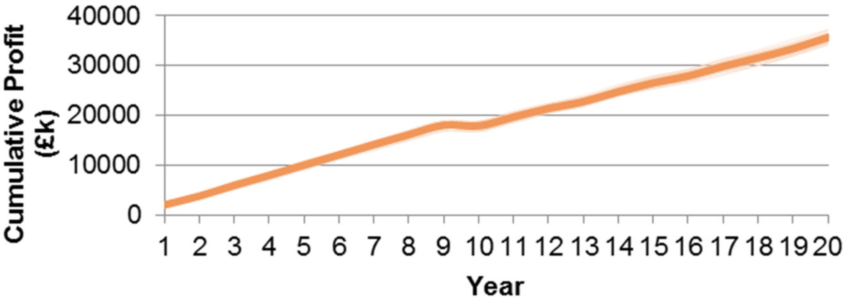

Figure A.4.7.10. Cumulative profit of 'Operational limits scenario 1', for a lifetime of 20 years

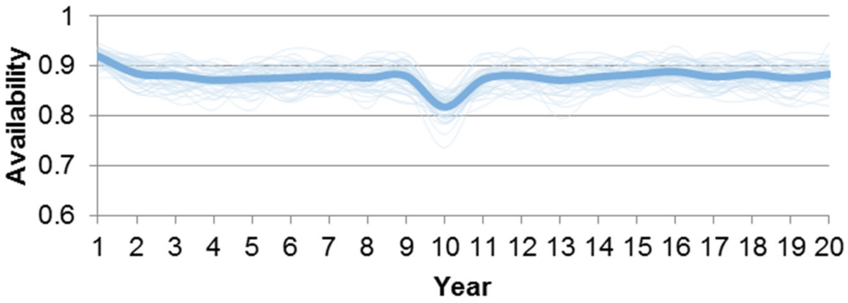

Figure A.4.7.11. Annual results of 'Operational limits scenario 2', for a lifetime of 20 years, in terms of availability

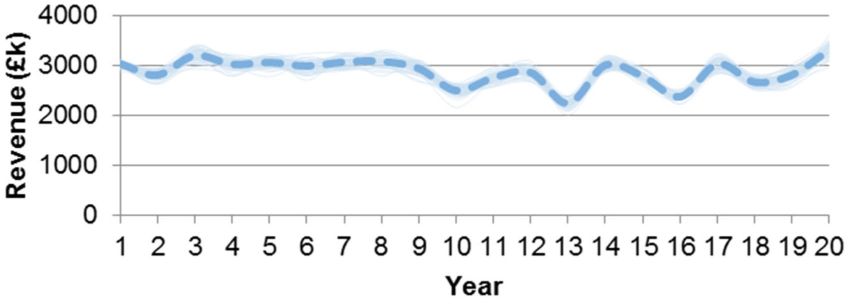

Figure A.4.7.12. Annual results of 'Operational limits scenario 2', for a lifetime of 20 years, in terms of revenue

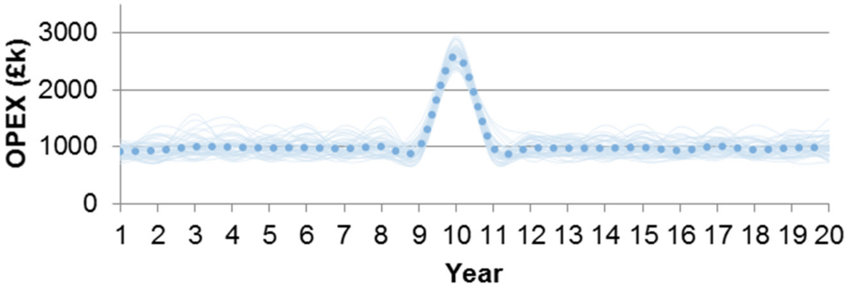

Figure A.4.7.13. Annual results of 'Operational limits scenario 2', for a lifetime of 20 years, in terms of OPEX

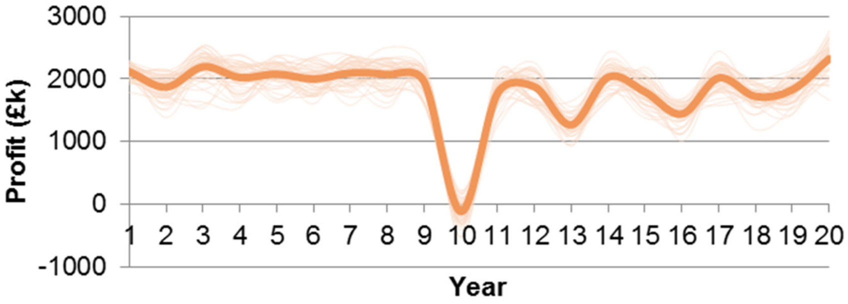

Figure A.4.7.14. Annual results of 'Operational limits scenario 2', for a lifetime of 20 years, in terms of profit

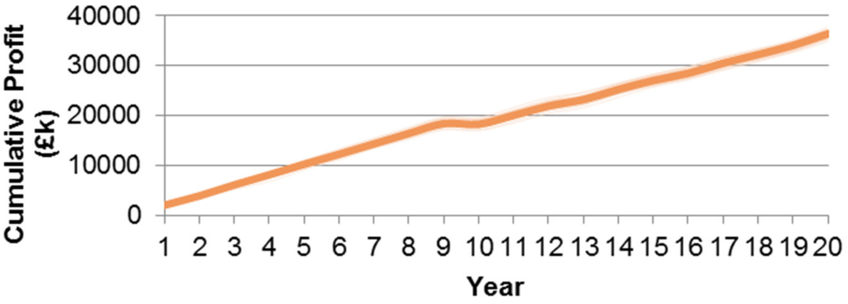

Figure A.4.7.15. Cumulative profit of 'Operational limits scenario 2', for a lifetime of 20 years

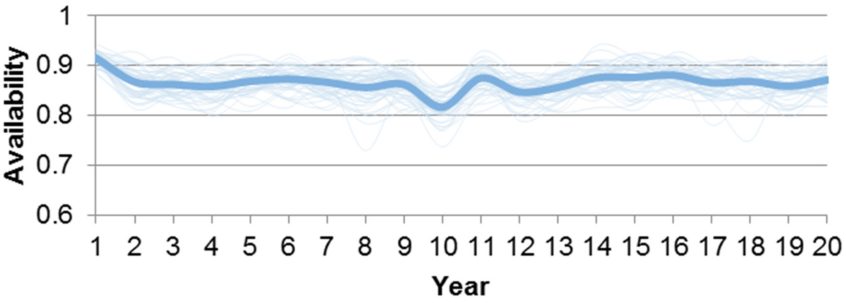

Figure A.4.8.1. Annual results of the 'no spare machines' scenario, for a 10 berth farm over a lifetime of 20 years, in terms of availability

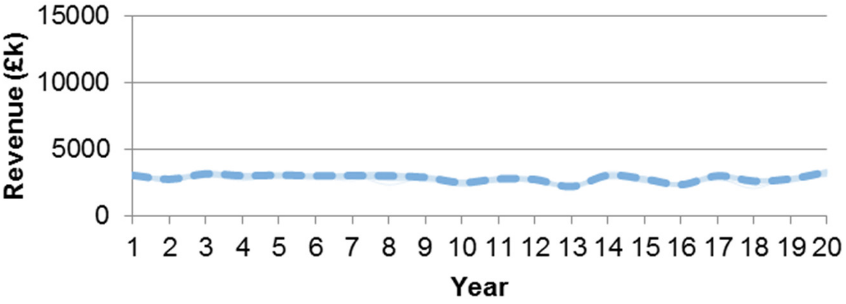

Figure A.4.8.2. Annual results of the 'no spare machines' scenario, for a 10 berth farm over a lifetime of 20 years, in terms of revenue

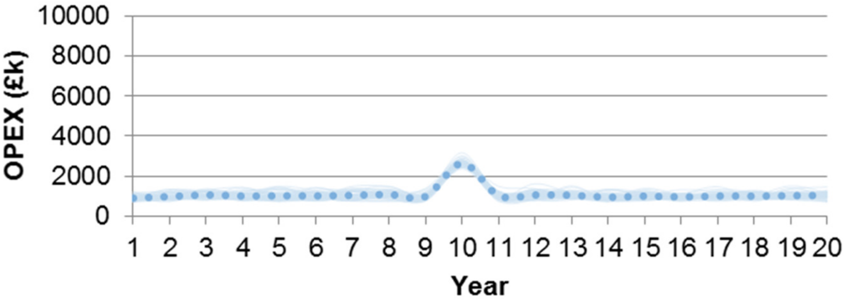

Figure A.4.8.3. Annual results of the 'no spare machines' scenario, for a 10 berth farm over a lifetime of 20 years, in terms of OPEX

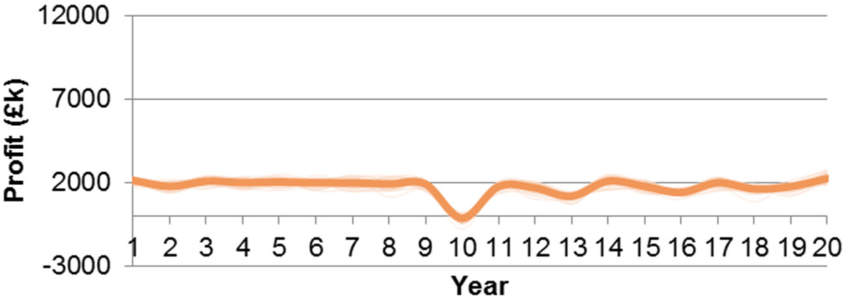

Figure A.4.8.4. Annual results of the 'no spare machines' scenario, for a 10 berth farm over a lifetime of 20 years, in terms of profit

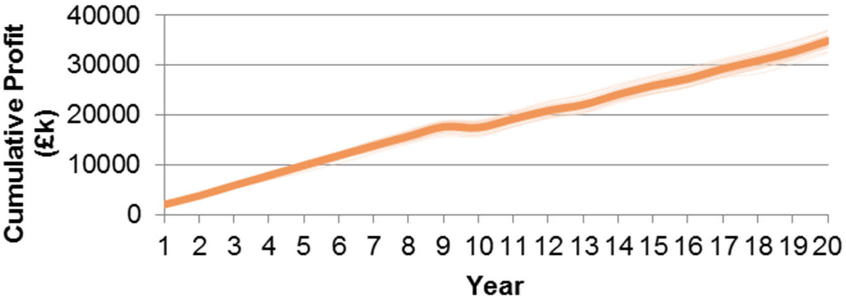

Figure A.4.8.5. Cumulative profit of the 'no spare machines' scenario, for a 10 berth farm over a lifetime of 20 years

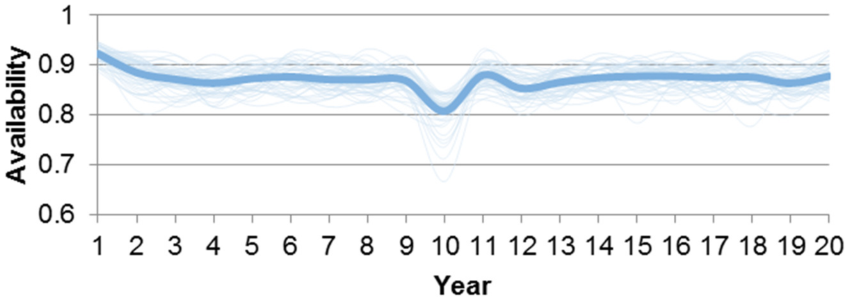

Figure A.4.8.6. Annual results of the 'one spare machine' scenario, for a 10 berth farm over a lifetime of 20 years, in terms of availability

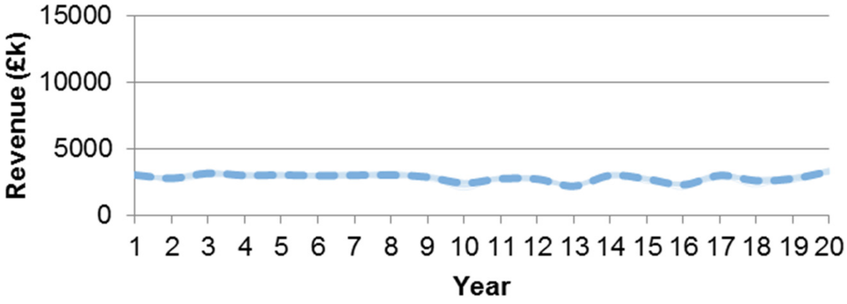

Figure A.4.8.7. Annual results of the 'one spare machine' scenario, for a 10 berth farm over a lifetime of 20 years, in terms of revenue

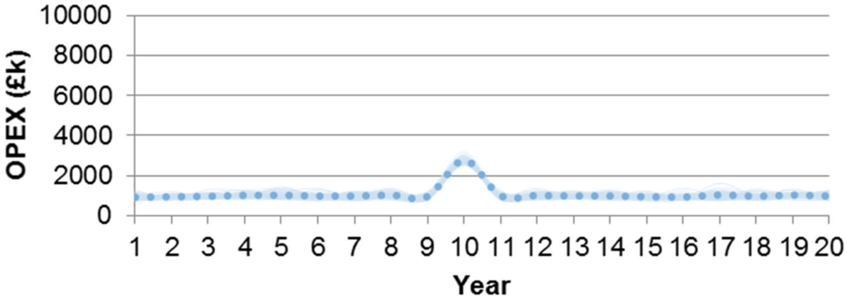

Figure A.4.8.8. Annual results of the 'one spare machine' scenario, for a 10 berth farm over a lifetime of 20 years, in terms of OPEX

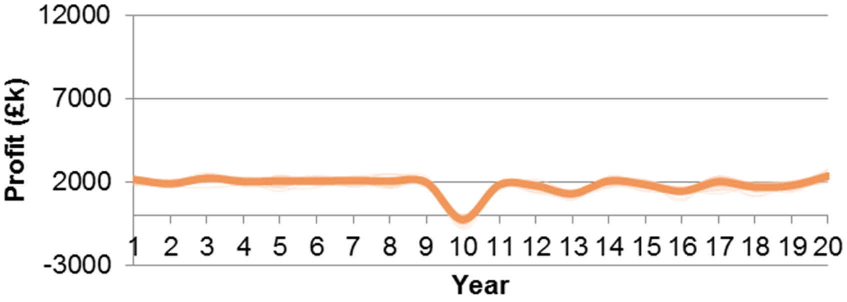

Figure A.4.8.9. Annual results of the 'one spare machine' scenario, for a 10 berth farm over a lifetime of 20 years, in terms of profit

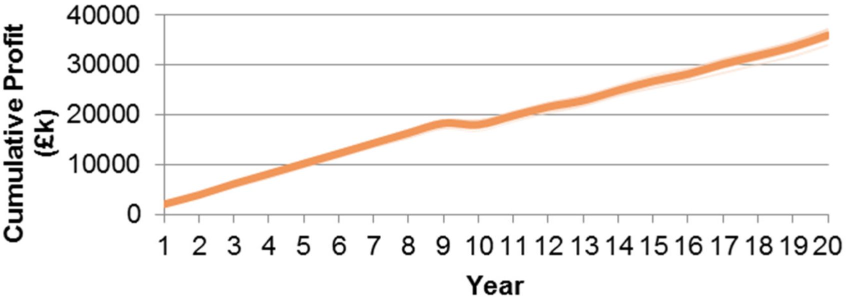

Figure A.4.8.10. Cumulative profit of the 'one spare machine' scenario, for a 10 berth farm over a lifetime of 20 years

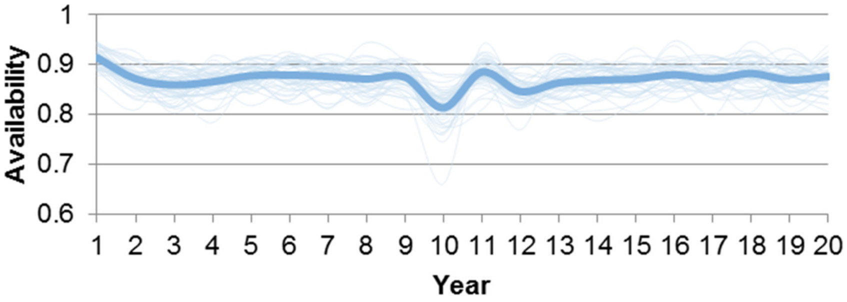

Figure A.4.8.11. Annual results of the 'two spare machines' scenario, for a 10 berth farm over a lifetime of 20 years, in terms of availability

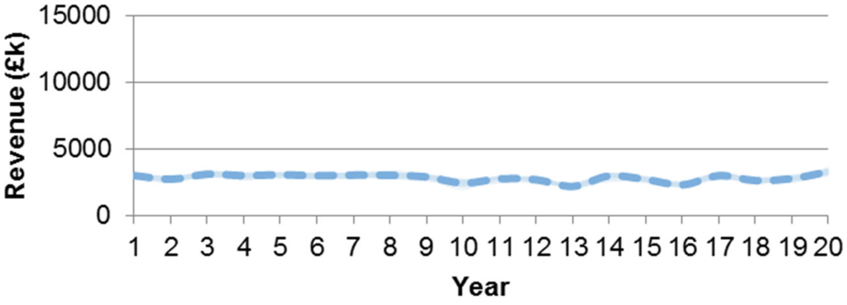

Figure A.4.8.12. Annual results of the 'two spare machines' scenario, for a 10 berth farm over a lifetime of 20 years, in terms of revenue

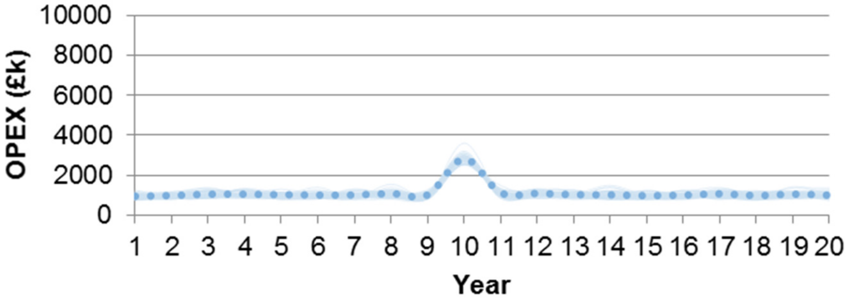

Figure A.4.8.13. Annual results of the 'two spare machines' scenario, for a 10 berth farm over a lifetime of 20 years, in terms of OPEX

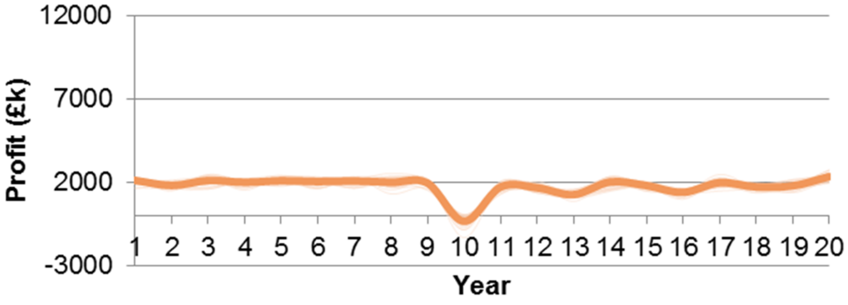

Figure A.4.8.14. Annual results of the 'two spare machines' scenario, for a 10 berth farm over a lifetime of 20 years, in terms of profit

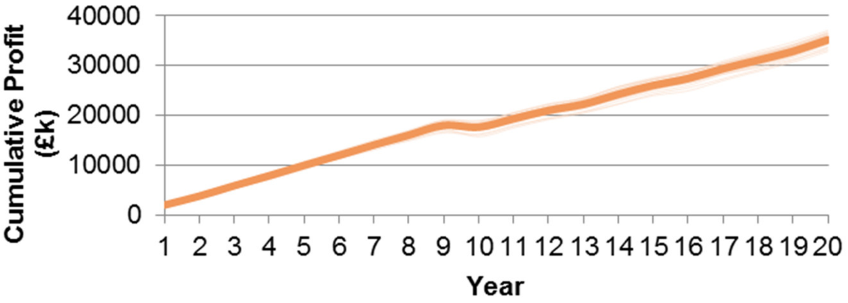

Figure A.4.8.15. Cumulative profit of the 'two spare machines' scenario, for a 10 berth farm over a lifetime of 20 years

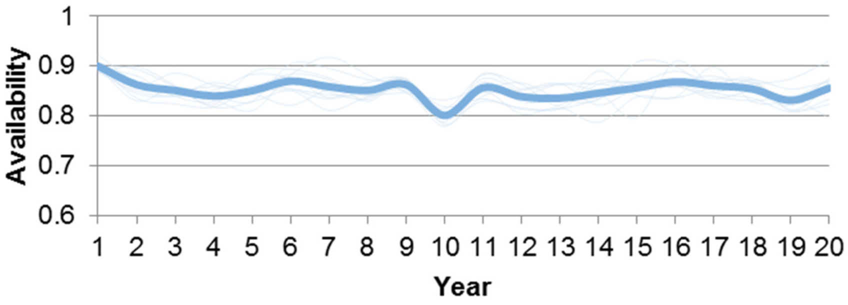

Figure A.4.8.16. Annual results of the 'no spare machines' scenario, for a 15 berth farm over a lifetime of 20 years, in terms of availability

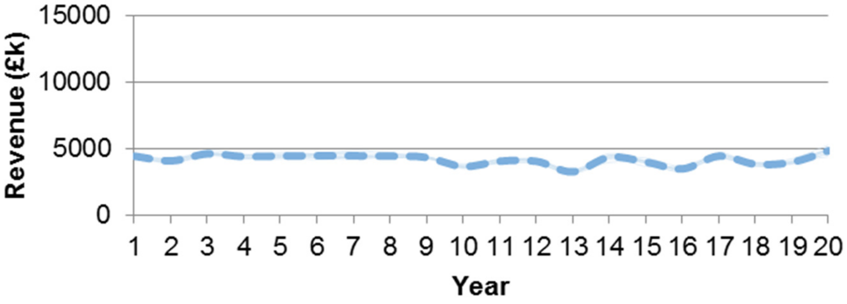

Figure A.4.8.17. Annual results of the 'no spare machines' scenario, for a 15 berth farm over a lifetime of 20 years, in terms of revenue

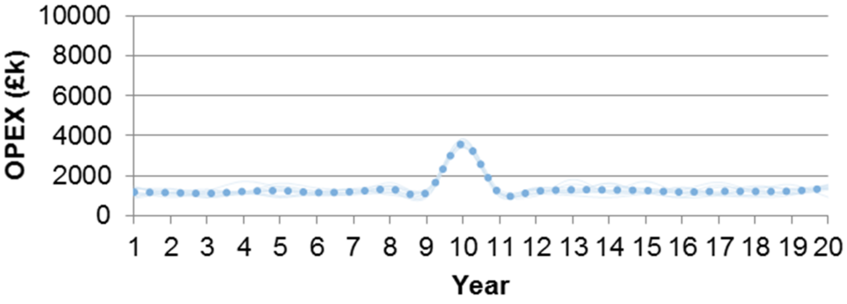

Figure A.4.8.18. Annual results of the 'no spare machines' scenario, for a 15 berth farm over a lifetime of 20 years, in terms of OPEX

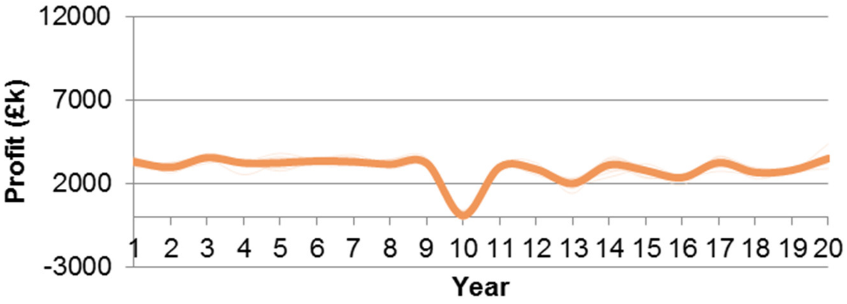

Figure A.4.8.19. Annual results of the 'no spare machines' scenario, for a 15 berth farm over a lifetime of 20 years, in terms of profit

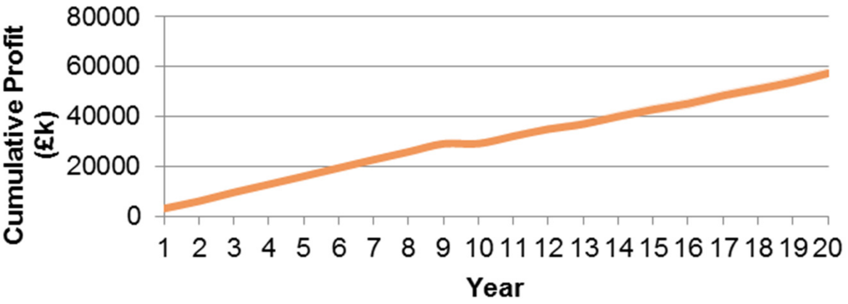

Figure A.4.8.20. Cumulative profit of the 'no spare machines' scenario, for a 15 berth farm over a lifetime of 20 years

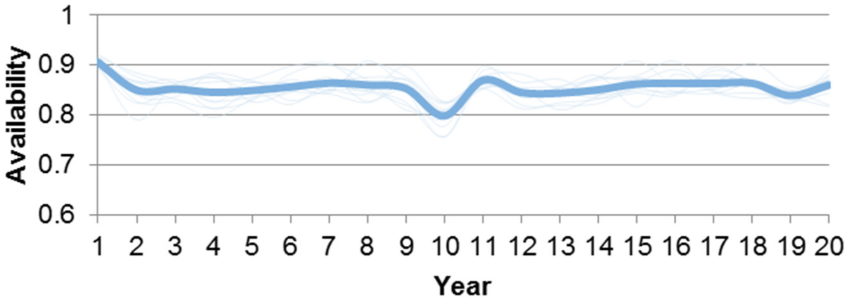

Figure A.4.8.21. Annual results of the 'one spare machine' scenario, for a 15 berth farm over a lifetime of 20 years, in terms of availability

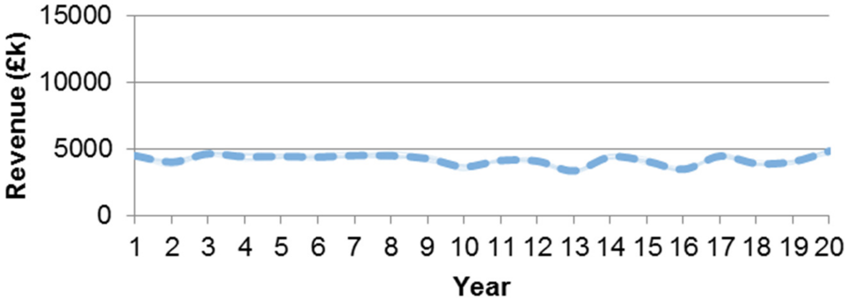

Figure A.4.8.22. Annual results of the 'one spare machine' scenario, for a 15 berth farm over a lifetime of 20 years, in terms of revenue

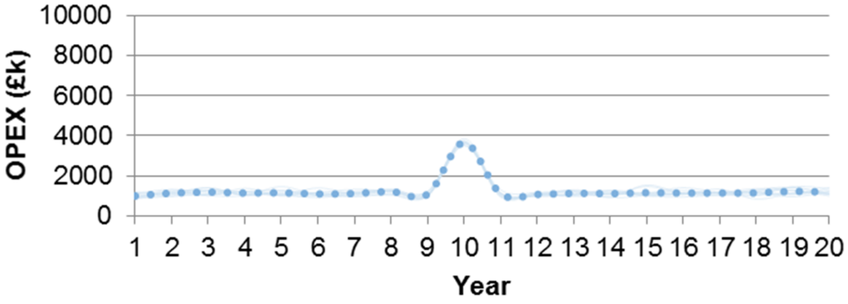

Figure A.4.8.23. Annual results of the 'one spare machine' scenario, for a 15 berth farm over a lifetime of 20 years, in terms of OPEX

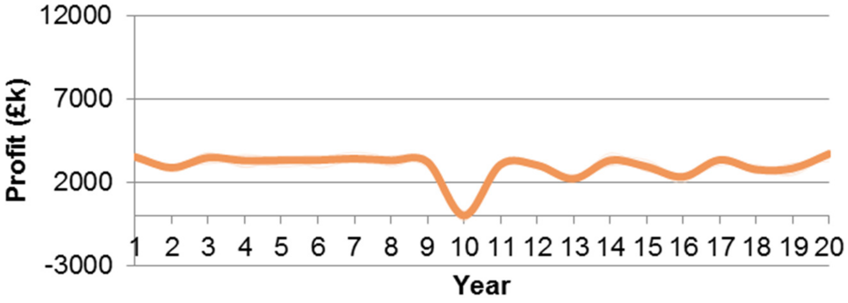

Figure A.4.8.24. Annual results of the 'one spare machine' scenario, for a 15 berth farm over a lifetime of 20 years, in terms of profit

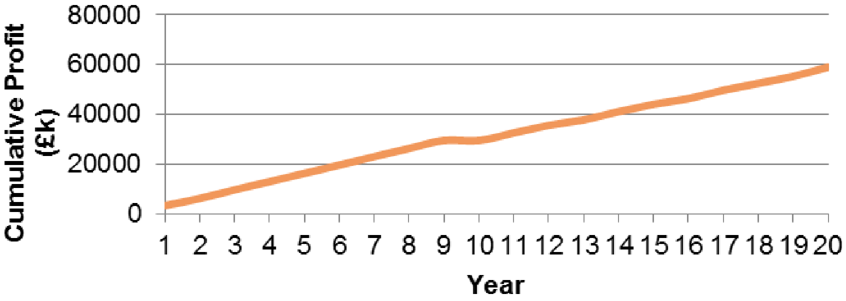

Figure A.4.8.25. Cumulative profit of the 'one spare machine' scenario, for a 15 berth farm over a lifetime of 20 years

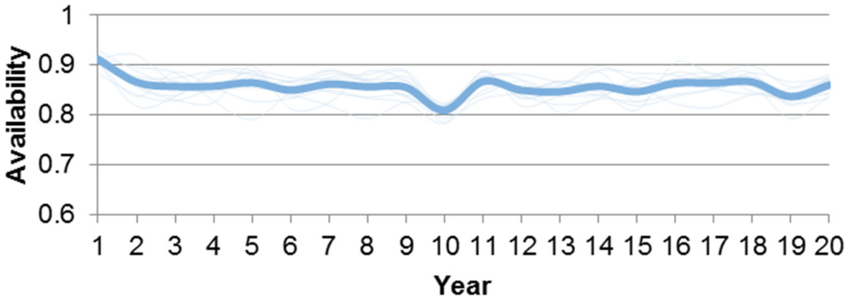

Figure A.4.8.26. Annual results of the 'two spare machines' scenario, for a 15 berth farm over a lifetime of 20 years, in terms of availability

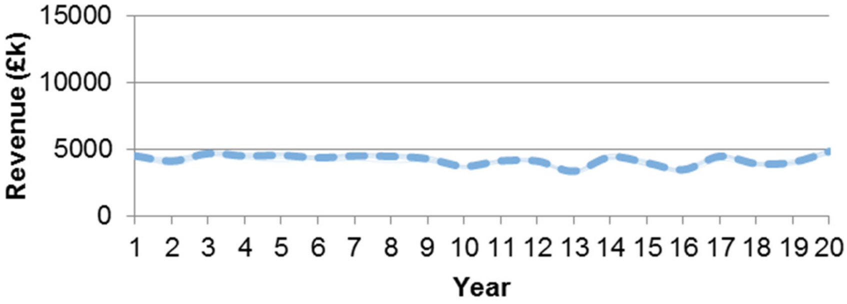

Figure A.4.8.27. Annual results of the 'two spare machines' scenario, for a 15 berth farm over a lifetime of 20 years, in terms of revenue

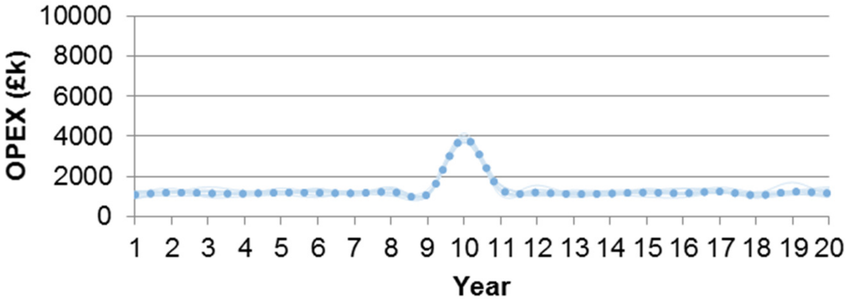

Figure A.4.8.28. Annual results of the 'two spare machines' scenario, for a 15 berth farm over a lifetime of 20 years, in terms of OPEX

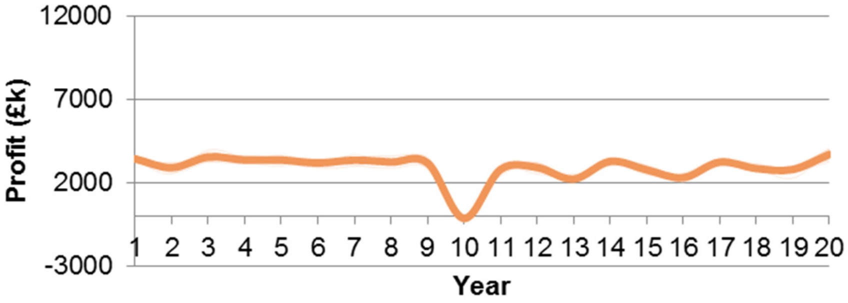

Figure A.4.8.29. Annual results of the 'two spare machines' scenario, for a 15 berth farm over a lifetime of 20 years, in terms of profit

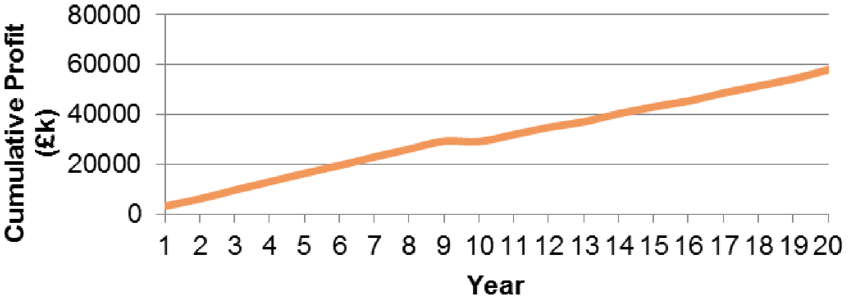

Figure A.4.8.30. Cumulative profit of the 'two spare machines' scenario, for a 15 berth farm over a lifetime of 20 years

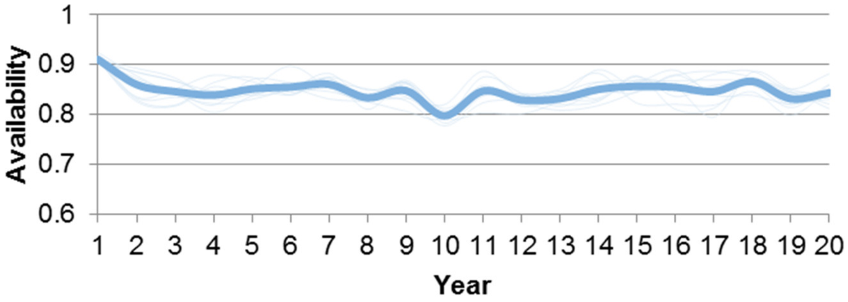

Figure A.4.8.31. Annual results of the 'no spare machines' scenario, for a 20 berth farm over a lifetime of 20 years, in terms of availability

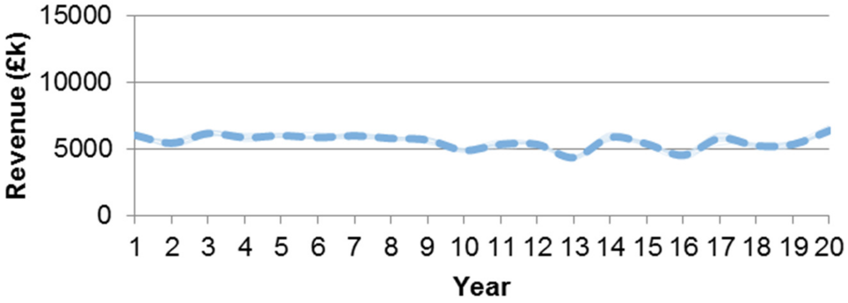

Figure A.4.8.32. Annual results of the 'no spare machines' scenario, for a 20 berth farm over a lifetime of 20 years, in terms of revenue

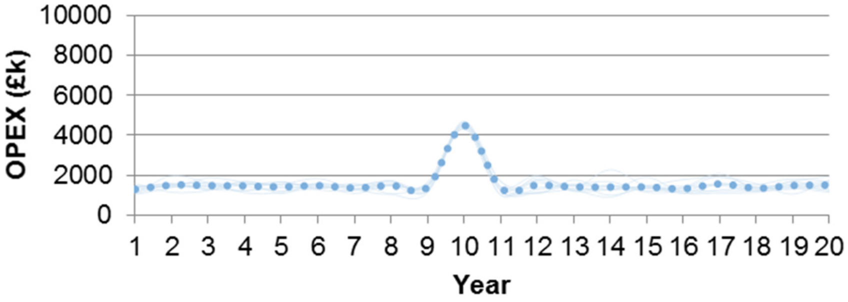

Figure A.4.8.33. Annual results of the 'no spare machines' scenario, for a 20 berth farm over a lifetime of 20 years, in terms of OPEX

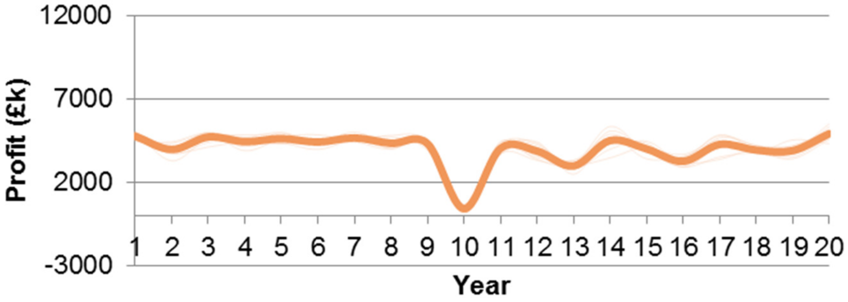

Figure A.4.8.34. Annual results of the 'no spare machines' scenario, for a 20 berth farm over a lifetime of 20 years, in terms of profit

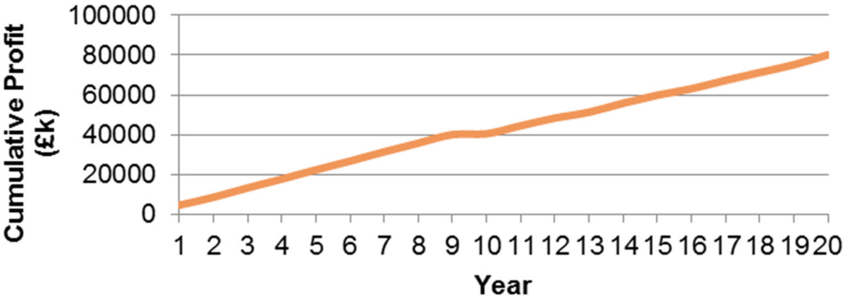

Figure A.4.8.35. Cumulative profit of the 'no spare machines' scenario, for a 20 berth farm over a lifetime of 20 years

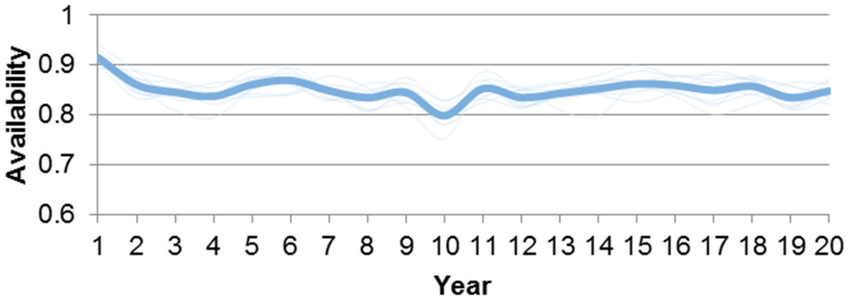

Figure A.4.8.36. Annual results of the 'one spare machine' scenario, for a 20 berth farm over a lifetime of 20 years, in terms of availability

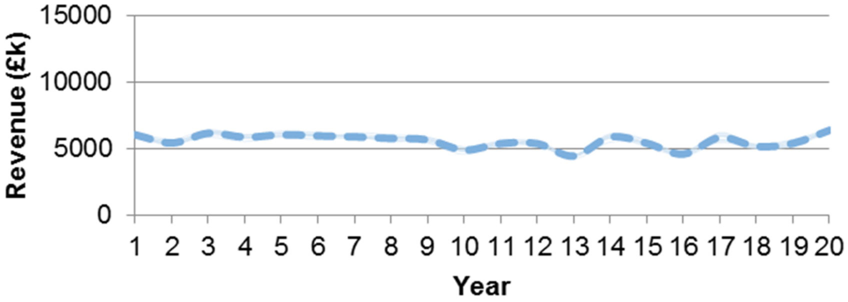

Figure A.4.8.37. Annual results of the 'one spare machine' scenario, for a 20 berth farm over a lifetime of 20 years, in terms of revenue

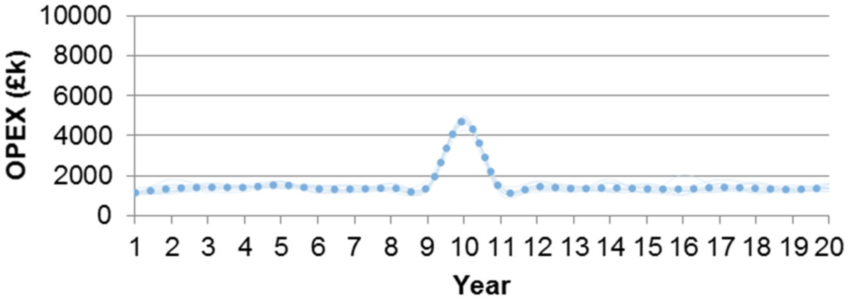

Figure A.4.8.38. Annual results of the 'one spare machine' scenario, for a 20 berth farm over a lifetime of 20 years, in terms of OPEX

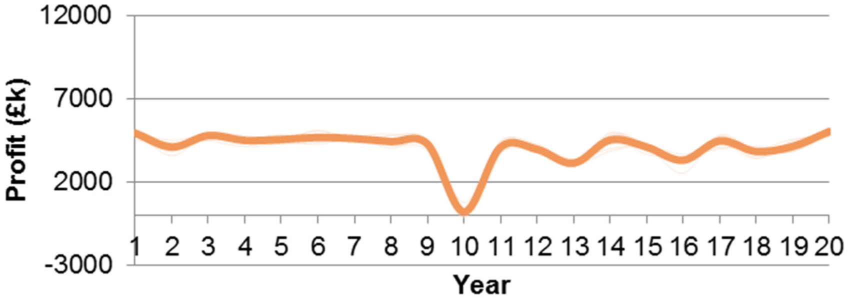

Figure A.4.8.39. Annual results of the 'one spare machine' scenario, for a 20 berth farm over a lifetime of 20 years, in terms of profit

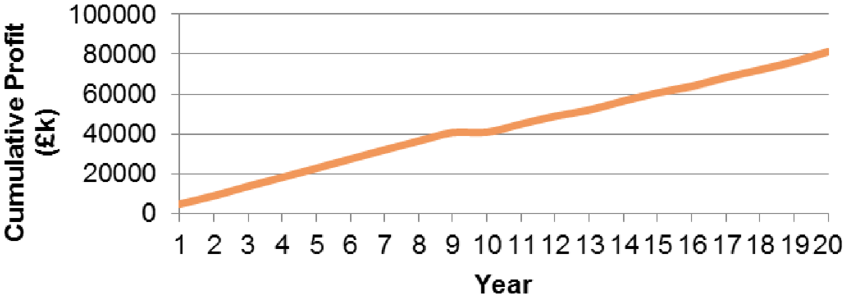

Figure A.4.8.40. Cumulative profit of the 'one spare machine' scenario, for a 20 berth farm over a lifetime of 20 years

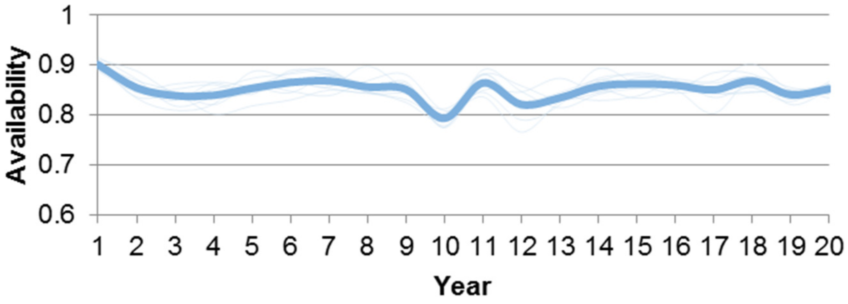

Figure A.4.8.41. Annual results of the 'two spare machines' scenario, for a 20 berth farm over a lifetime of 20 years, in terms of availability

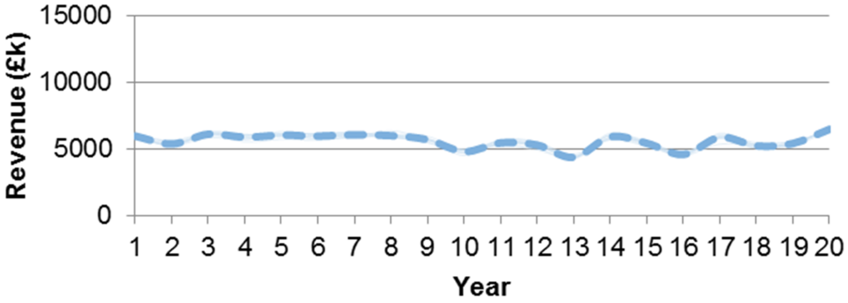

Figure A.4.8.42. Annual results of the 'two spare machines' scenario, for a 20 berth farm over a lifetime of 20 years, in terms of revenue

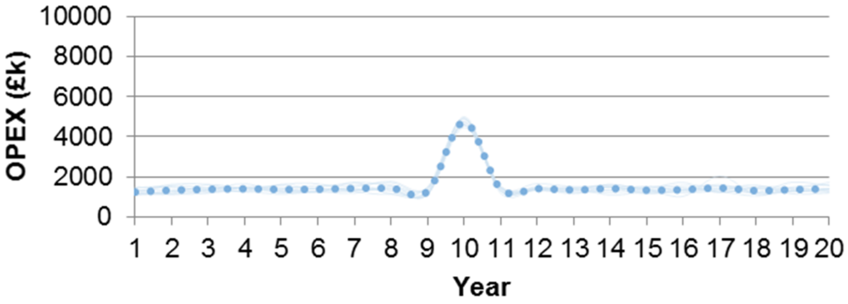

Figure A.4.8.43. Annual results of the 'two spare machines' scenario, for a 20 berth farm over a lifetime of 20 years, in terms of OPEX

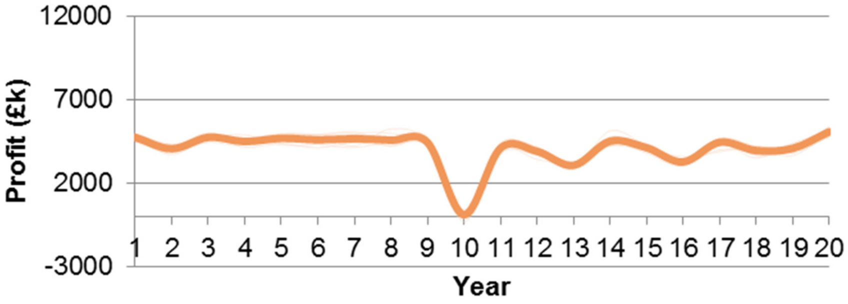

Figure A.4.8.44. Annual results of the 'two spare machines' scenario, for a 20 berth farm over a lifetime of 20 years, in terms of profit

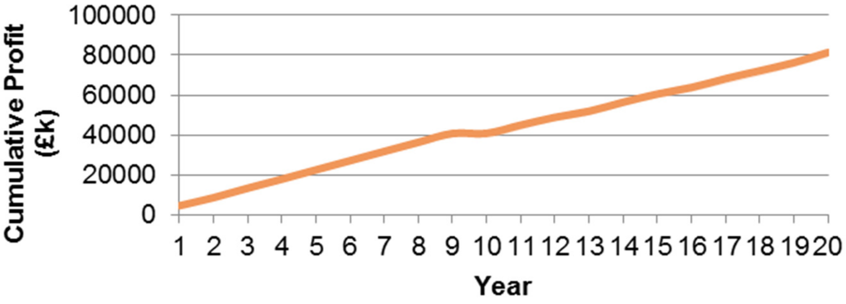

Figure A.4.8.45. Cumulative profit of the 'two spare machines' scenario, for a 20 berth farm over a lifetime of 20 years

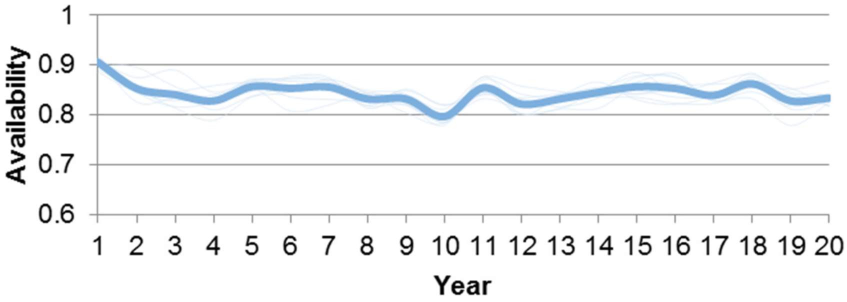

Figure A.4.8.46. Annual results of the 'no spare machines' scenario, for a 25 berth farm over a lifetime of 20 years, in terms of availability

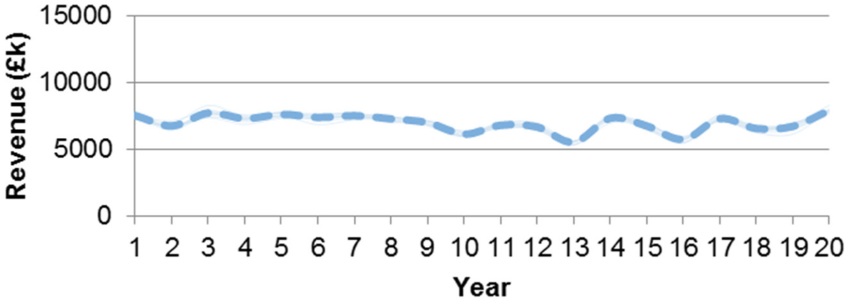

Figure A.4.8.47. Annual results of the 'no spare machines' scenario, for a 25 berth farm over a lifetime of 20 years, in terms of revenue

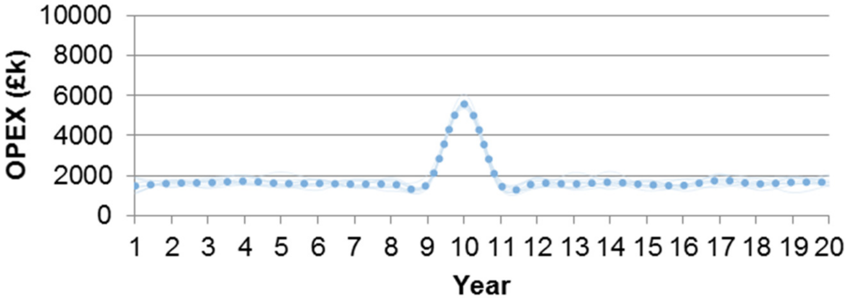

Figure A.4.8.48. Annual results of the 'no spare machines' scenario, for a 25 berth farm over a lifetime of 20 years, in terms of OPEX

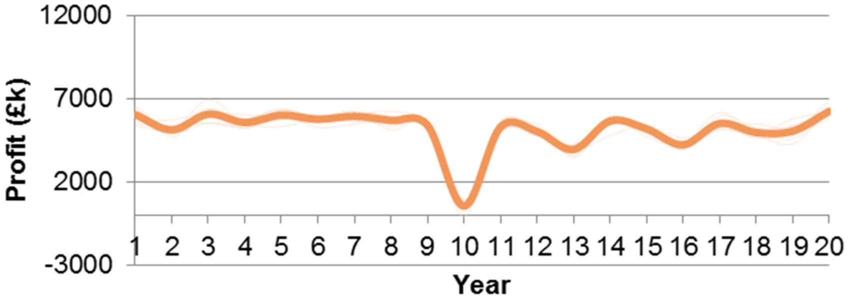

Figure A.4.8.49. Annual results of the 'no spare machines' scenario, for a 25 berth farm over a lifetime of 20 years, in terms of profit

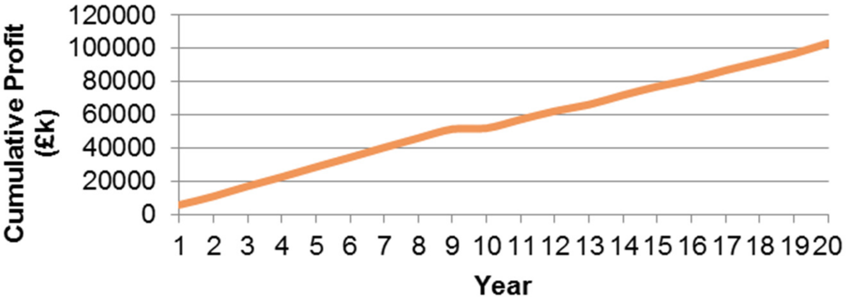

Figure A.4.8.50. Cumulative profit of the 'no spare machines' scenario, for a 25 berth farm over a lifetime of 20 years

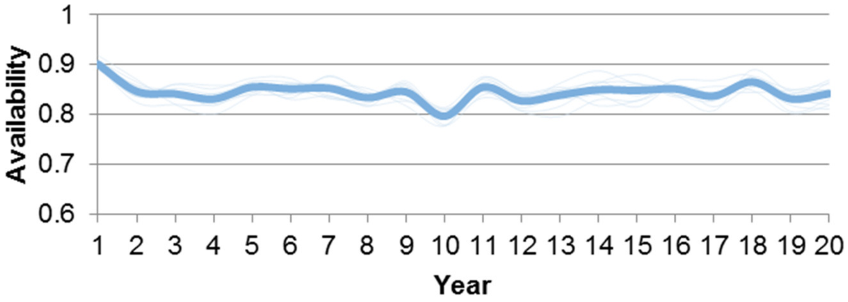

Figure A.4.8.51. Annual results of the 'one spare machine' scenario, for a 25 berth farm over a lifetime of 20 years, in terms of availability

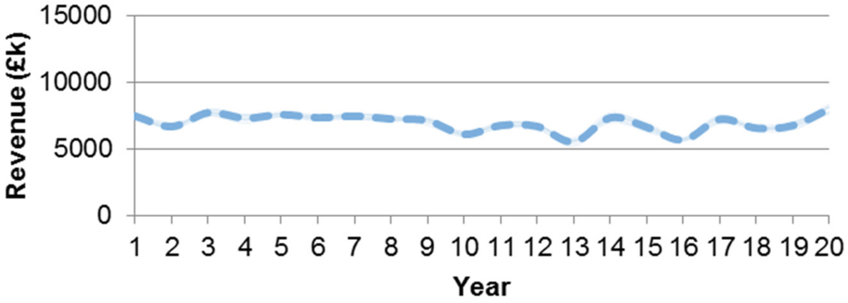

Figure A.4.8.52. Annual results of the 'one spare machine' scenario, for a 25 berth farm over a lifetime of 20 years, in terms of revenue

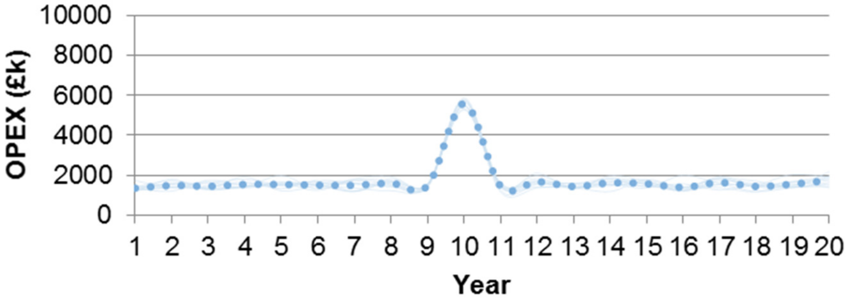

Figure A.4.8.53. Annual results of the 'one spare machine' scenario, for a 25 berth farm over a lifetime of 20 years, in terms of OPEX

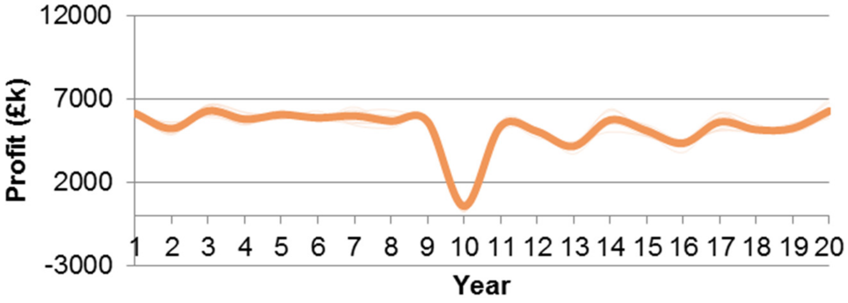

Figure A.4.8.54. Annual results of the 'one spare machine' scenario, for a 25 berth farm over a lifetime of 20 years, in terms of profit

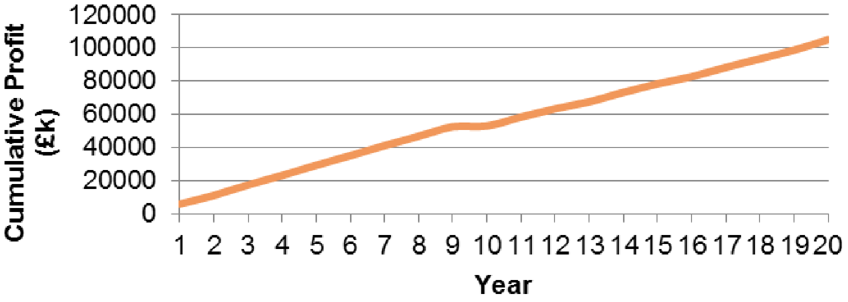

Figure A.4.8.55. Cumulative profit of the 'one spare machine' scenario, for a 25 berth farm over a lifetime of 20 years

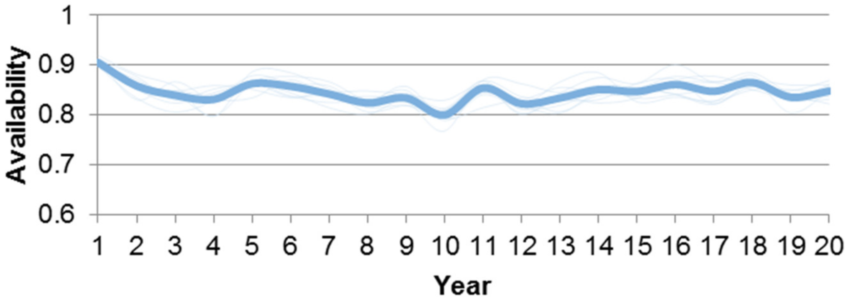

Figure A.4.8.56. Annual results of the 'two spare machines' scenario, for a 25 berth farm over a lifetime of 20 years, in terms of availability

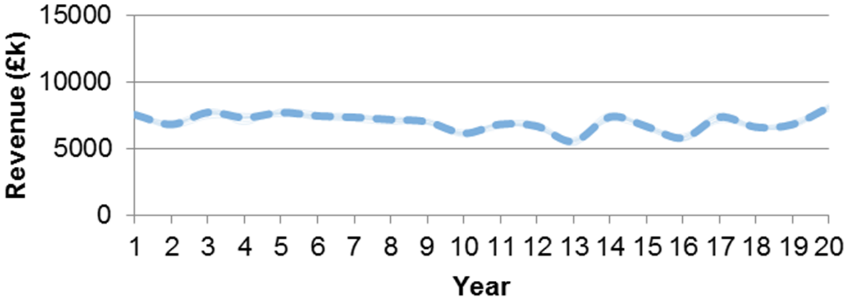

Figure A.4.8.57. Annual results of the 'two spare machines' scenario, for a 25 berth farm over a lifetime of 20 years, in terms of revenue

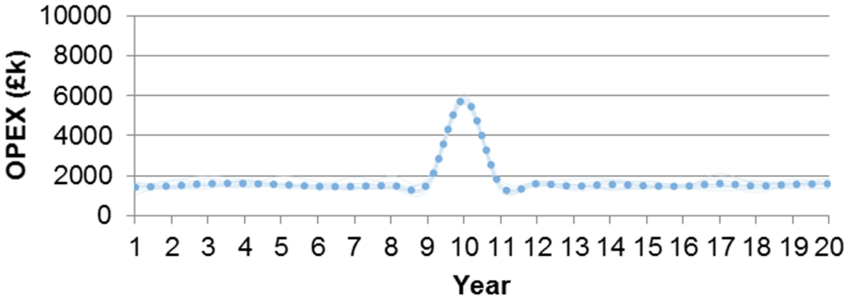

Figure A.4.8.58. Annual results of the 'two spare machines' scenario, for a 25 berth farm over a lifetime of 20 years, in terms of OPEX

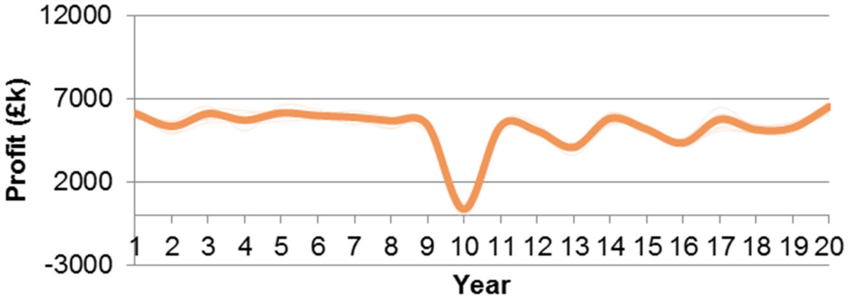

Figure A.4.8.59. Annual results of the 'two spare machines' scenario, for a 25 berth farm over a lifetime of 20 years, in terms of profit

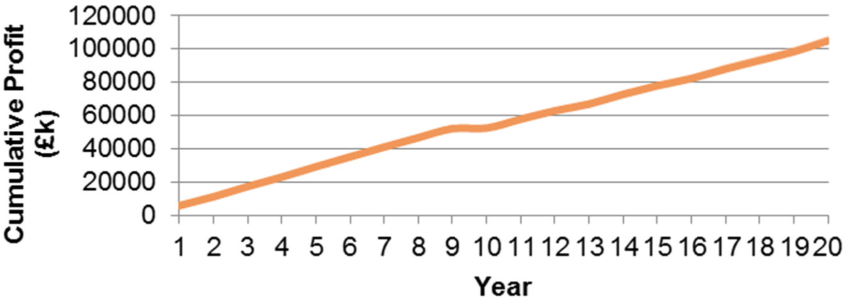

Figure A.4.8.60. Cumulative profit of the 'two spare machines' scenario, for a 25 berth farm over a lifetime of 20 years

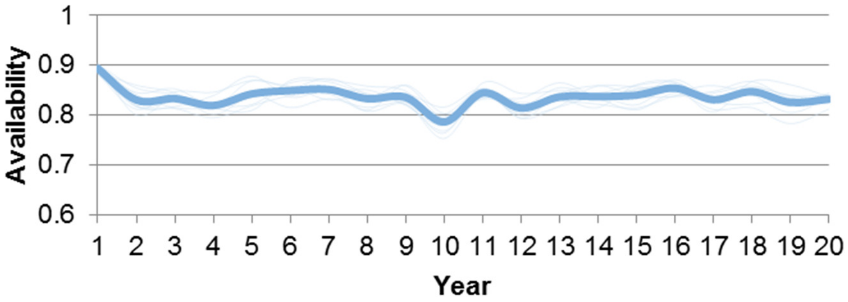

Figure A.4.8.61. Annual results of the 'no spare machines' scenario, for a 30 berth farm over a lifetime of 20 years, in terms of availability

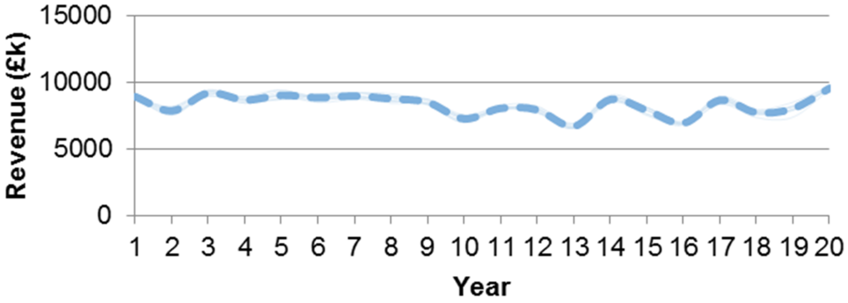

Figure A.4.8.62. Annual results of the 'no spare machines' scenario, for a 30 berth farm over a lifetime of 20 years, in terms of revenue

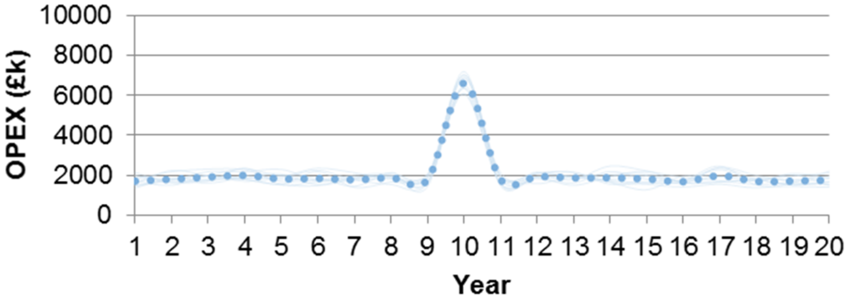

Figure A.4.8.63. Annual results of the 'no spare machines' scenario, for a 30 berth farm over a lifetime of 20 years, in terms of OPEX

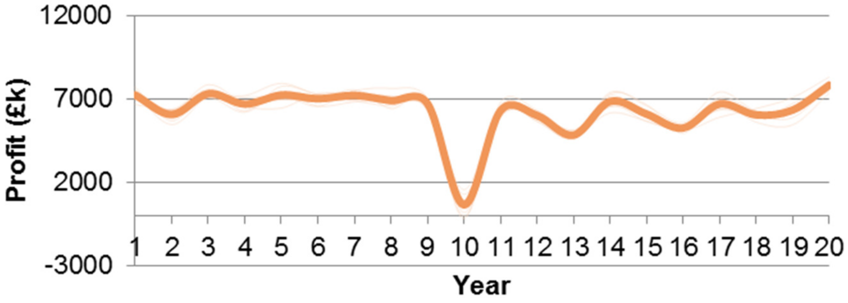

Figure A.4.8.64. Annual results of the 'no spare machines' scenario, for a 30 berth farm over a lifetime of 20 years, in terms of profit

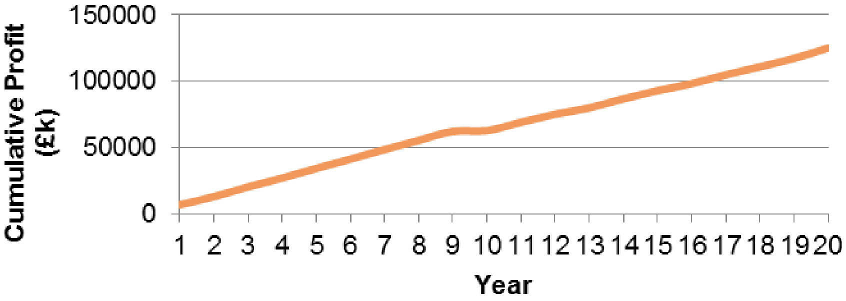

Figure A.4.8.65. Cumulative profit of the 'no spare machines' scenario, for a 30 berth farm over a lifetime of 20 years

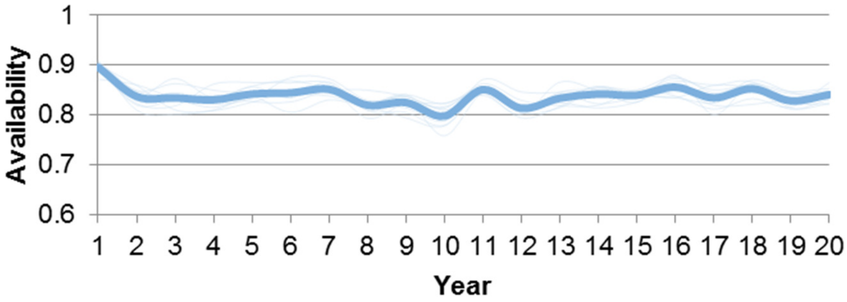

Figure A.4.8.66. Annual results of the 'one spare machine' scenario, for a 30 berth farm over a lifetime of 20 years, in terms of availability

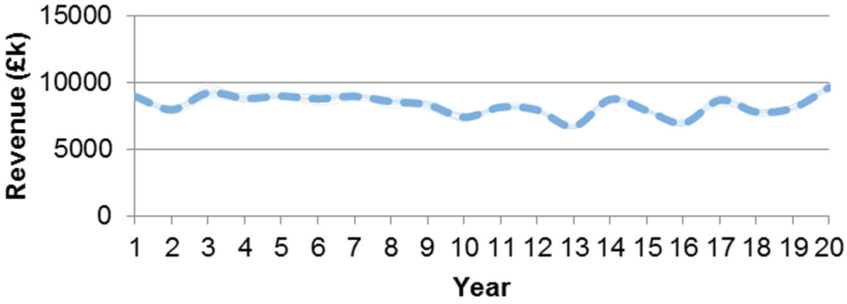

Figure A.4.8.67. Annual results of the 'one spare machine' scenario, for a 30 berth farm over a lifetime of 20 years, in terms of revenue

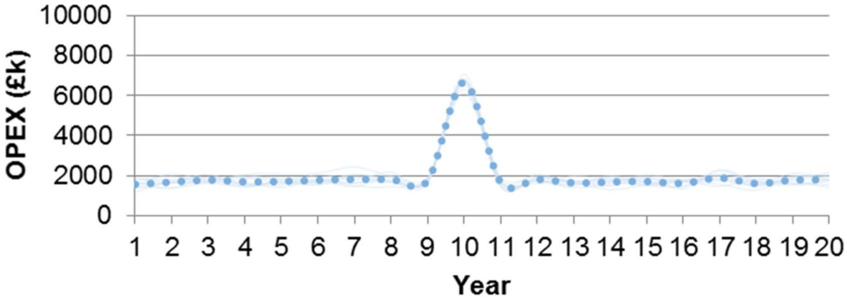

Figure A.4.8.68. Annual results of the 'one spare machine' scenario, for a 30 berth farm over a lifetime of 20 years, in terms of OPEX

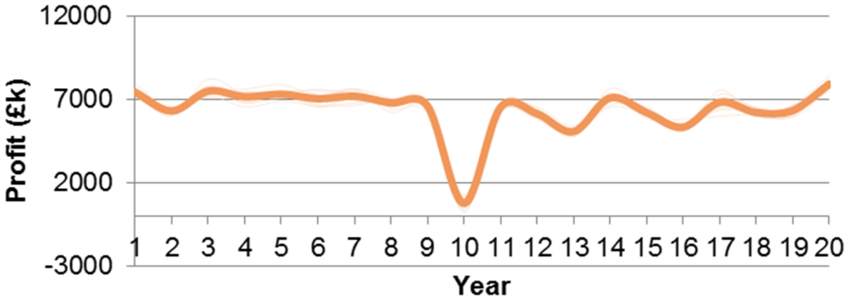

Figure A.4.8.69. Annual results of the 'one spare machine' scenario, for a 30 berth farm over a lifetime of 20 years, in terms of profit

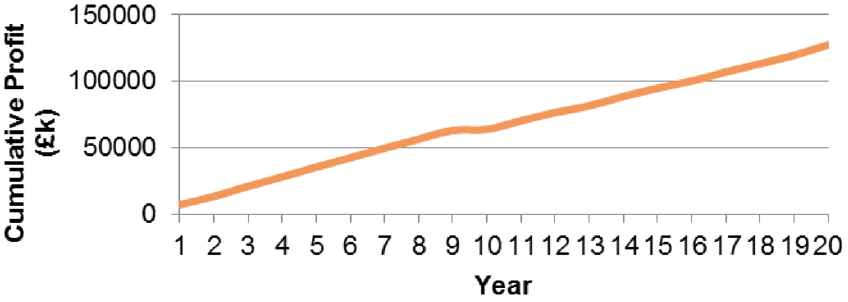

Figure A.4.8.70. Cumulative profit of the 'one spare machine' scenario, for a 30 berth farm over a lifetime of 20 years

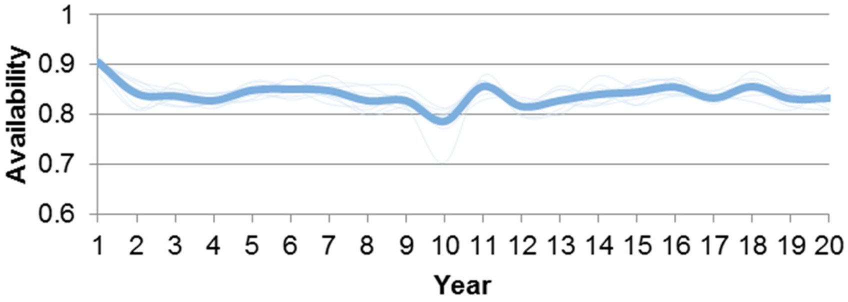

Figure A.4.8.71. Annual results of the 'two spare machines' scenario, for a 30 berth farm over a lifetime of 20 years, in terms of availability

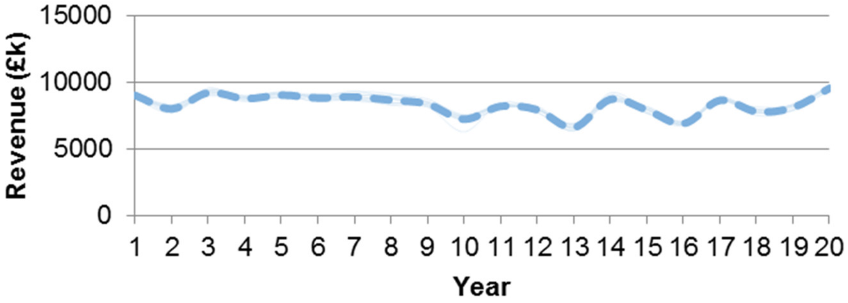

Figure A.4.8.72. Annual results of the 'two spare machines' scenario, for a 30 berth farm over a lifetime of 20 years, in terms of revenue

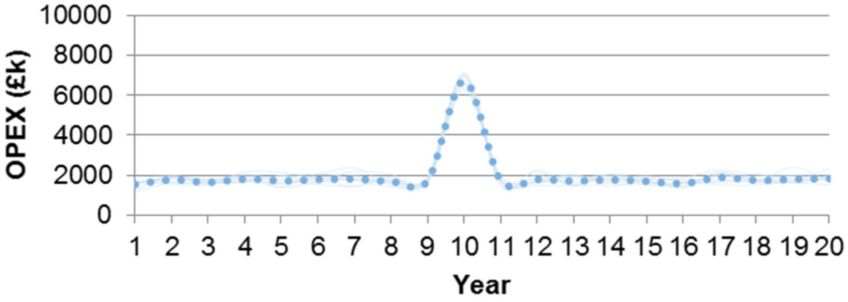

Figure A.4.8.73. Annual results of the 'two spare machines' scenario, for a 30 berth farm over a lifetime of 20 years, in terms of OPEX

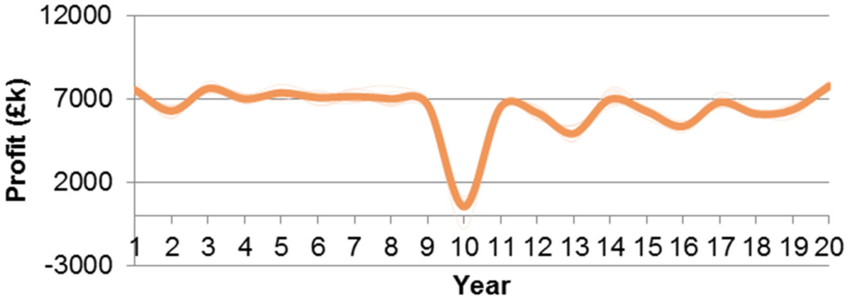

Figure A.4.8.74. Annual results of the 'two spare machines' scenario, for a 30 berth farm over a lifetime of 20 years, in terms of profit

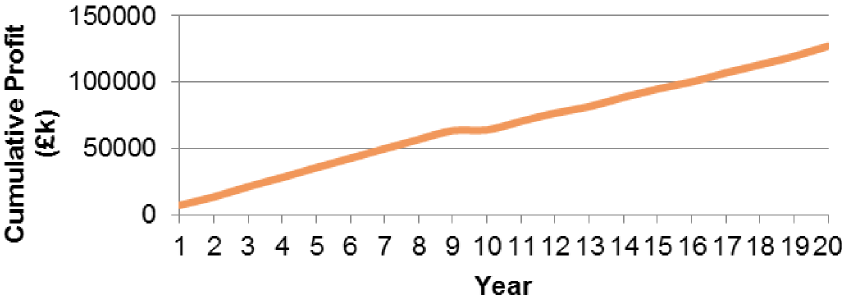

Figure A.4.8.75. Cumulative profit of the 'two spare machines' scenario, for a 30 berth farm over a lifetime of 20 years

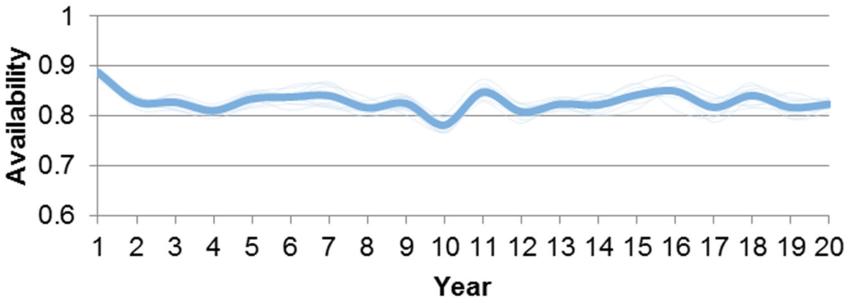

Figure A.4.8.76. Annual results of the 'no spare machines' scenario, for a 35 berth farm over a lifetime of 20 years, in terms of availability

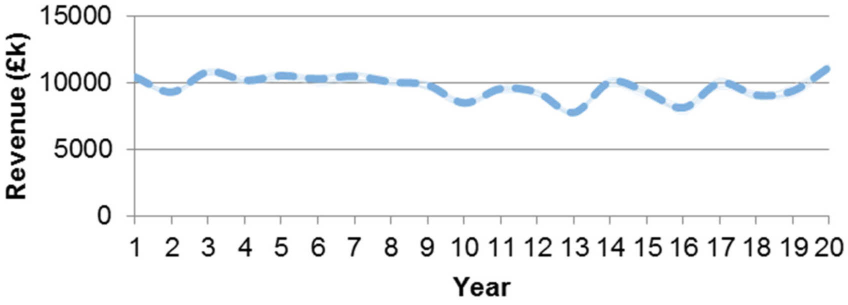

Figure A.4.8.77. Annual results of the 'no spare machines' scenario, for a 35 berth farm over a lifetime of 20 years, in terms of revenue

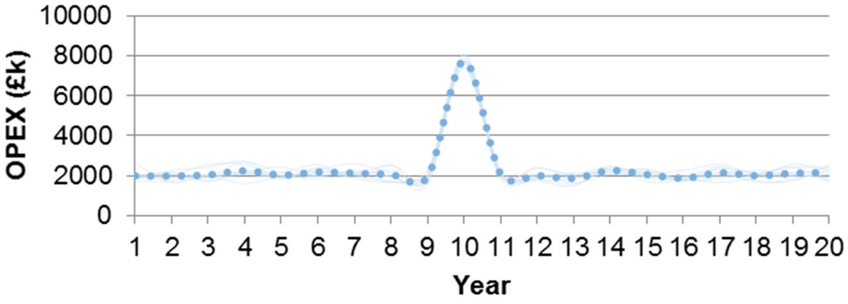

Figure A.4.8.78. Annual results of the 'no spare machines' scenario, for a 35 berth farm over a lifetime of 20 years, in terms of OPEX

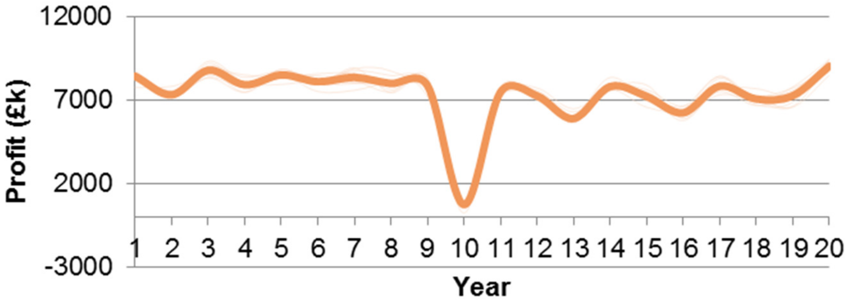

Figure A.4.8.79. Annual results of the 'no spare machines' scenario, for a 35 berth farm over a lifetime of 20 years, in terms of profit

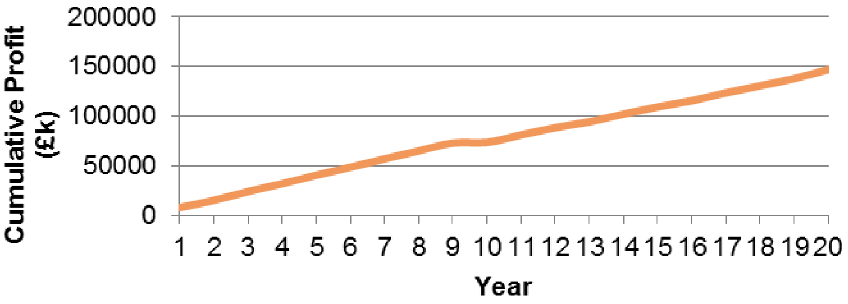

Figure A.4.8.80. Cumulative profit of the 'no spare machines' scenario, for a 35 berth farm over a lifetime of 20 years

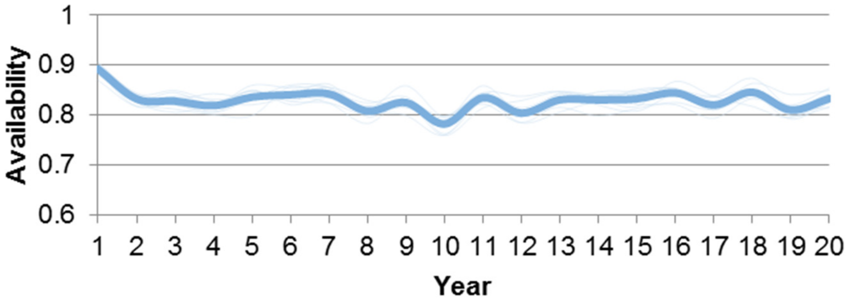

Figure A.4.8.81. Annual results of the 'one spare machine' scenario, for a 35 berth farm over a lifetime of 20 years, in terms of availability

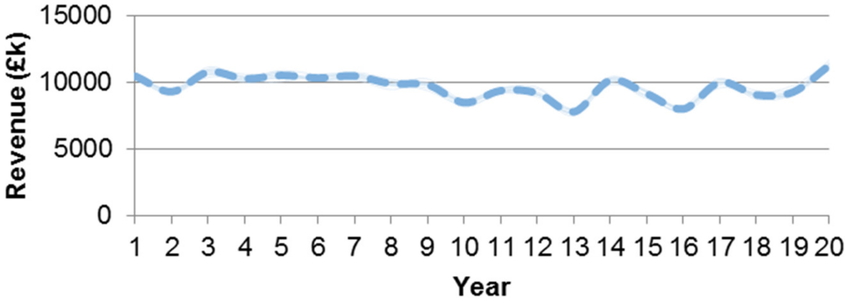

Figure A.4.8.82. Annual results of the 'one spare machine' scenario, for a 35 berth farm over a lifetime of 20 years, in terms of revenue

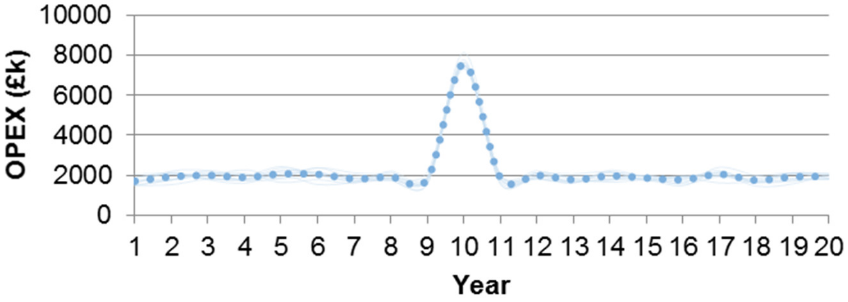

Figure A.4.8.83. Annual results of the 'one spare machine' scenario, for a 35 berth farm over a lifetime of 20 years, in terms of OPEX

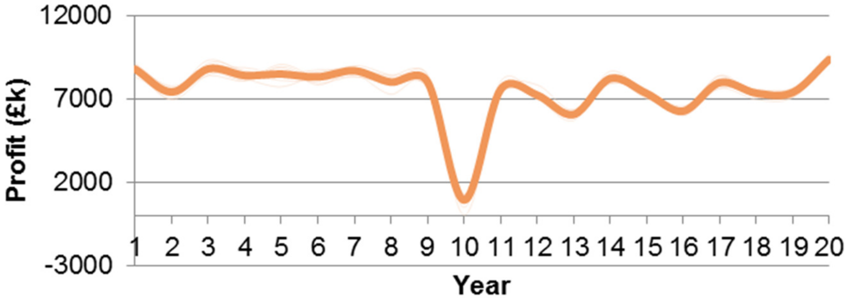

Figure A.4.8.84. Annual results of the 'one spare machine' scenario, for a 35 berth farm over a lifetime of 20 years, in terms of profit

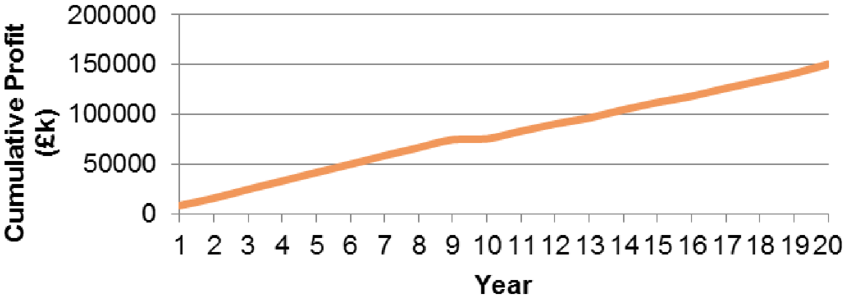

Figure A.4.8.85. Cumulative profit of the 'one spare machine' scenario, for a 35 berth farm over a lifetime of 20 years

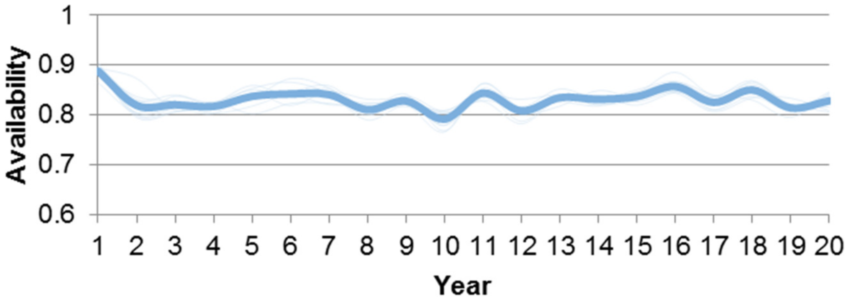

Figure A.4.8.86. Annual results of the 'two spare machines' scenario, for a 35 berth farm over a lifetime of 20 years, in terms of availability

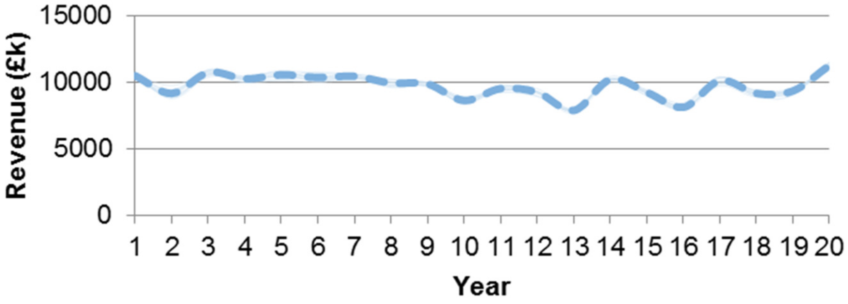

Figure A.4.8.87. Annual results of the 'two spare machines' scenario, for a 35 berth farm over a lifetime of 20 years, in terms of revenue

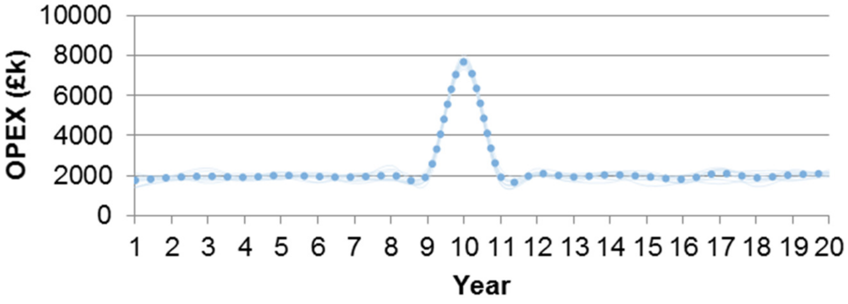

Figure A.4.8.88. Annual results of the 'two spare machines' scenario, for a 35 berth farm over a lifetime of 20 years, in terms of OPEX

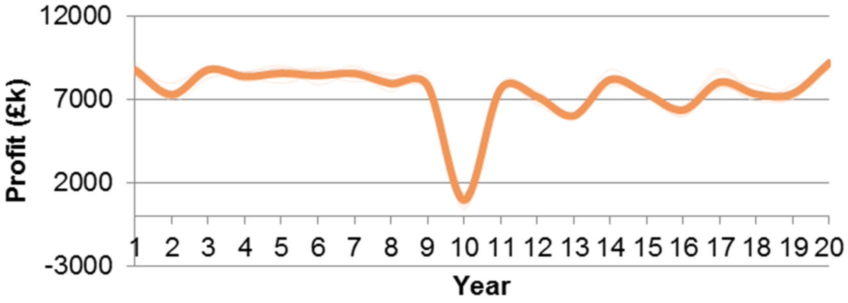

Figure A.4.8.89. Annual results of the 'two spare machines' scenario, for a 35 berth farm over a lifetime of 20 years, in terms of profit

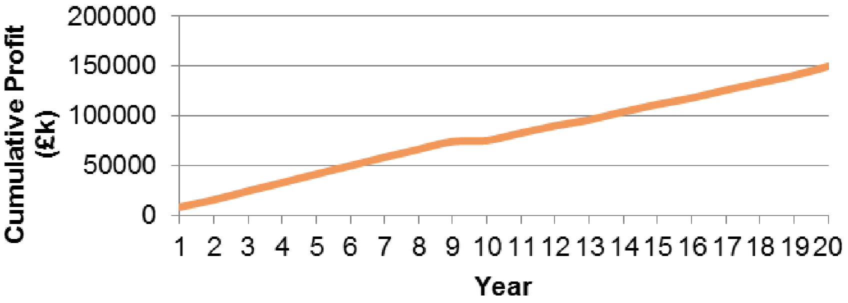

Figure A.4.8.90. Cumulative profit of the 'two spare machines' scenario, for a 35 berth farm over a lifetime of 20 years

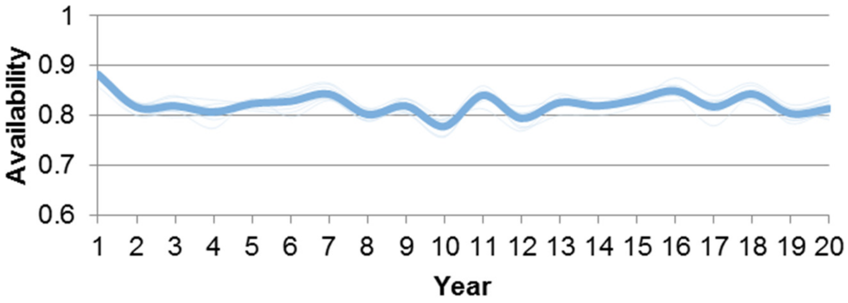

Figure A.4.8.91. Annual results of the 'no spare machines' scenario, for a 40 berth farm over a lifetime of 20 years, in terms of availability

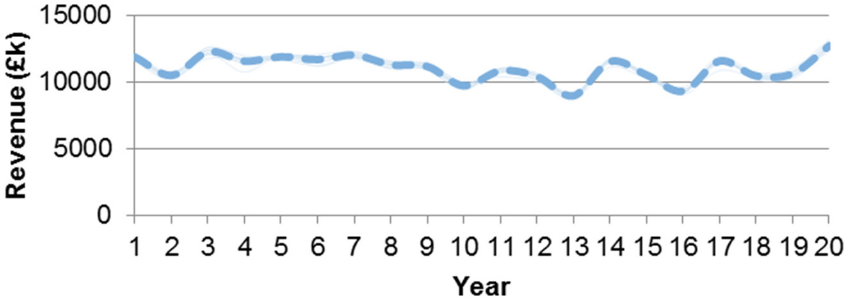

Figure A.4.8.92. Annual results of the 'no spare machines' scenario, for a 40 berth farm over a lifetime of 20 years, in terms of revenue

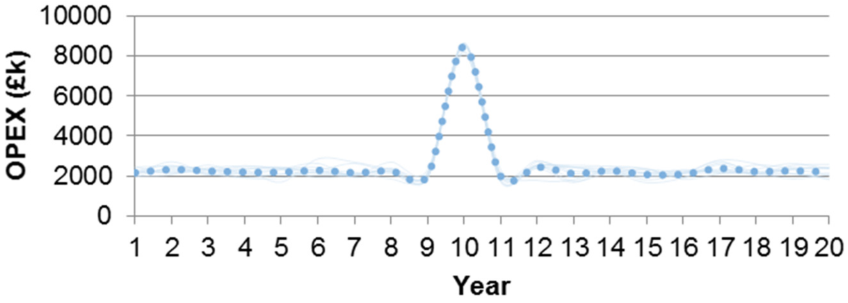

Figure A.4.8.93. Annual results of the 'no spare machines' scenario, for a 40 berth farm over a lifetime of 20 years, in terms of OPEX

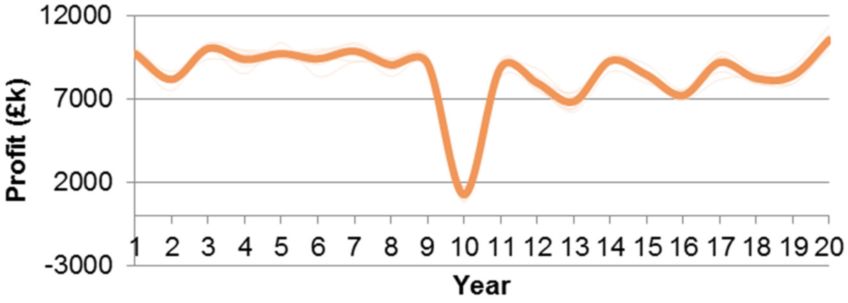

Figure A.4.8.94. Annual results of the 'no spare machines' scenario, for a 40 berth farm over a lifetime of 20 years, in terms of profit

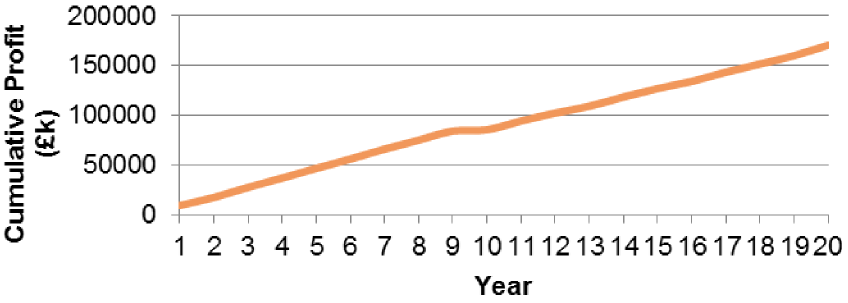

Figure A.4.8.95. Cumulative profit of the 'no spare machines' scenario, for a 40 berth farm over a lifetime of 20 years

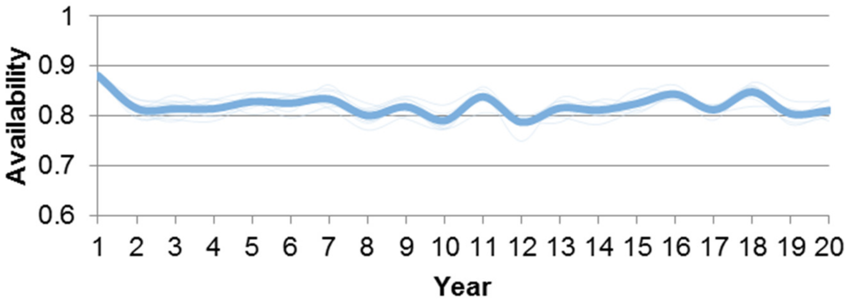

Figure A.4.8.96. Annual results of the 'one spare machine' scenario, for a 40 berth farm over a lifetime of 20 years, in terms of availability

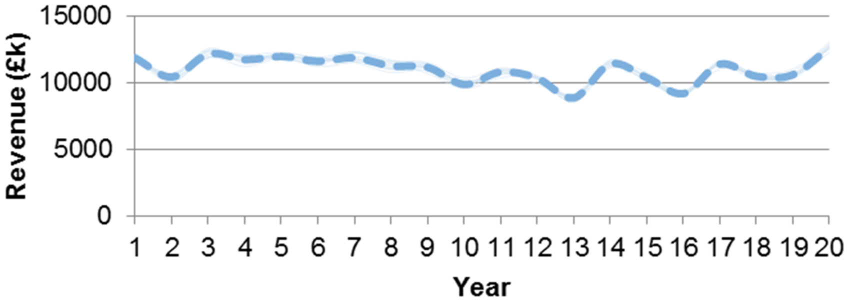

Figure A.4.8.97. Annual results of the 'one spare machine' scenario, for a 40 berth farm over a lifetime of 20 years, in terms of revenue

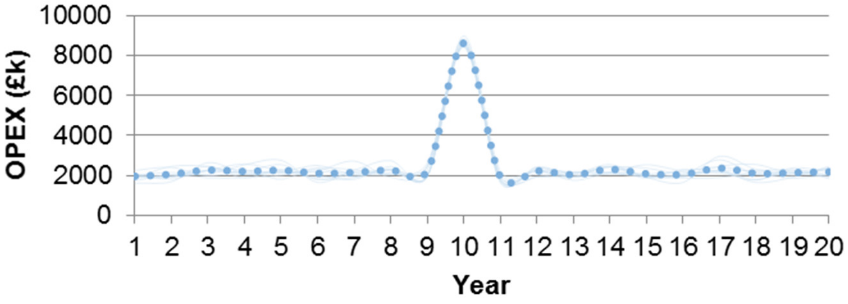

Figure A.4.8.98. Annual results of the 'one spare machine' scenario, for a 40 berth farm over a lifetime of 20 years, in terms of OPEX

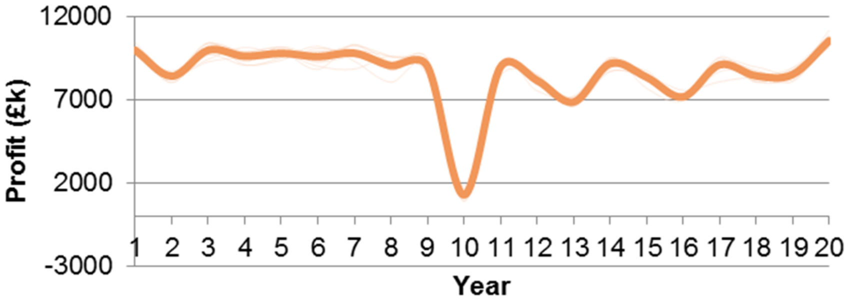

Figure A.4.8.99. Annual results of the 'one spare machine' scenario, for a 40 berth farm over a lifetime of 20 years, in terms of profit

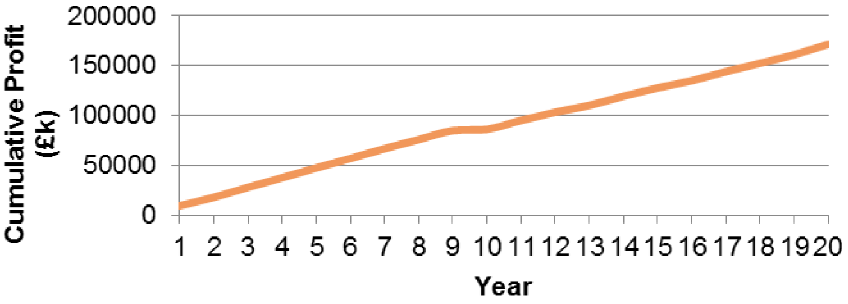

Figure A.4.8.100. Cumulative profit of the 'one spare machine' scenario, for a 40 berth farm over a lifetime of 20 years

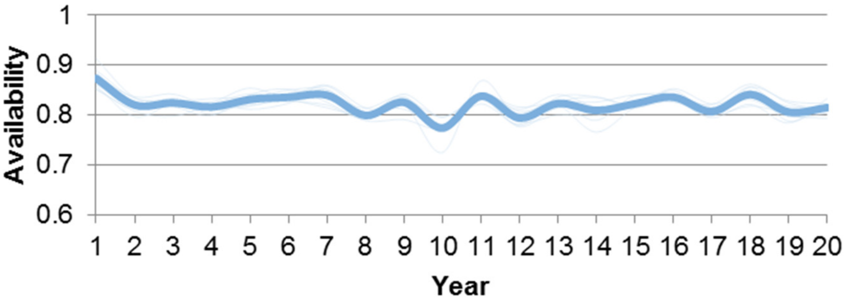

Figure A.4.8.101. Annual results of the 'two spare machines' scenario, for a 40 berth farm over a lifetime of 20 years, in terms of availability

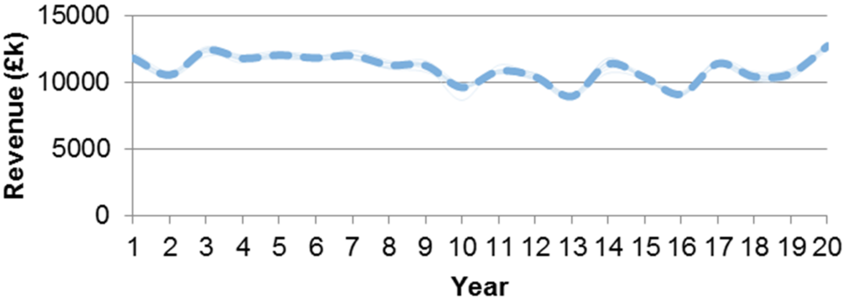

Figure A.4.8.102. Annual results of the 'two spare machines' scenario, for a 40 berth farm over a lifetime of 20 years, in terms of revenue

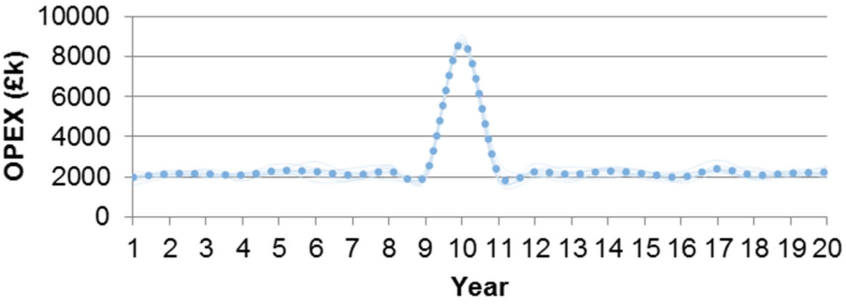

Figure A.4.8.103. Annual results of the 'two spare machines' scenario, for a 40 berth farm over a lifetime of 20 years, in terms of OPEX

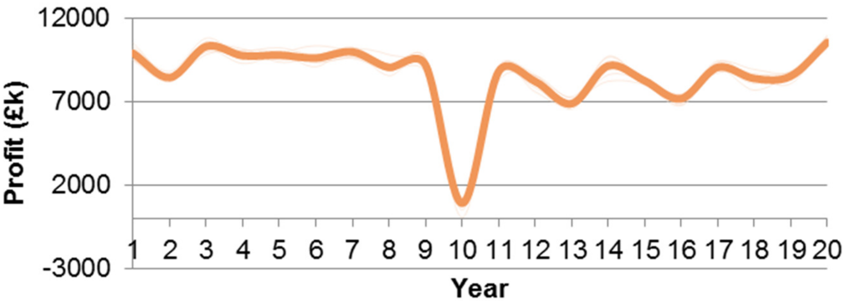

Figure A.4.8.104. Annual results of the 'two spare machines' scenario, for a 40 berth farm over a lifetime of 20 years, in terms of profit

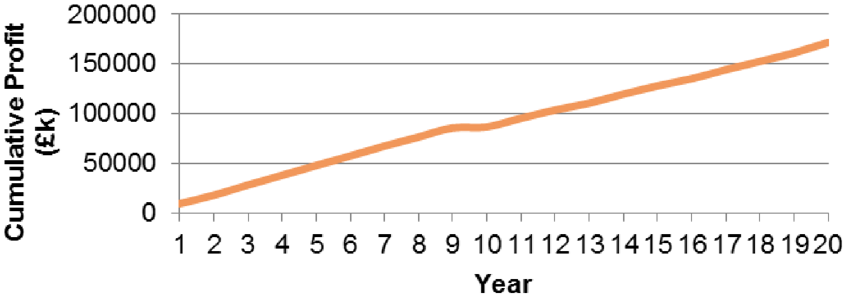

Figure A.4.8.105. Cumulative profit of the 'two spare machines' scenario, for a 40 berth farm over a lifetime of 20 years

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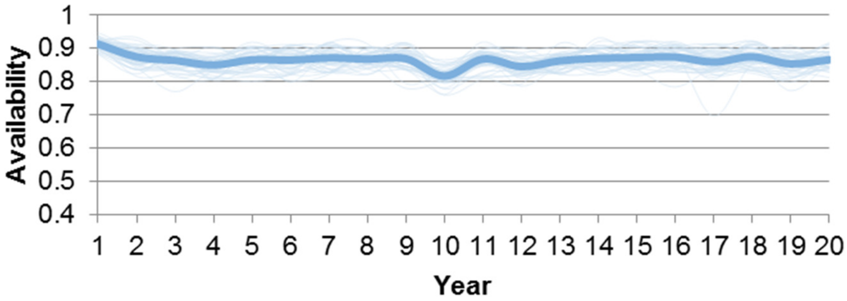

Figure A.4.9.1. Annual results of the labour 'contractors' scenario, for a lifetime of 20 years, in terms of availability

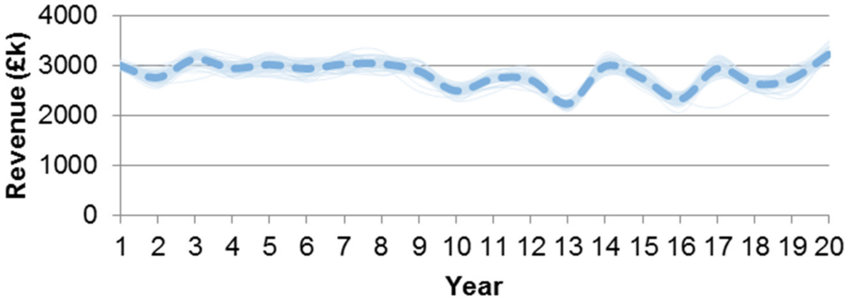

Figure A.4.9.2. Annual results of the labour 'contractors' scenario, for a lifetime of 20 years, in terms of revenue

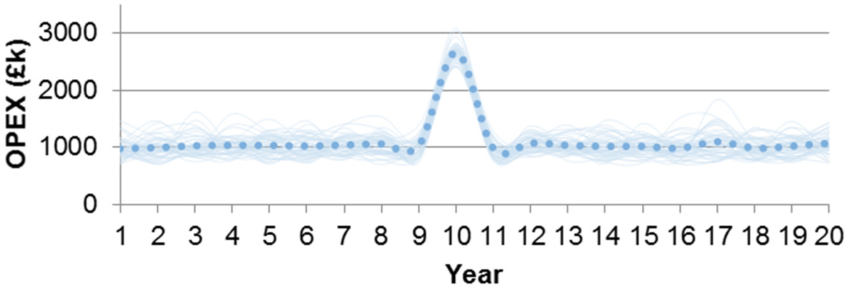

Figure A.4.9.3. Annual results of the labour 'contractors' scenario, for a lifetime of 20 years, in terms of OPEX

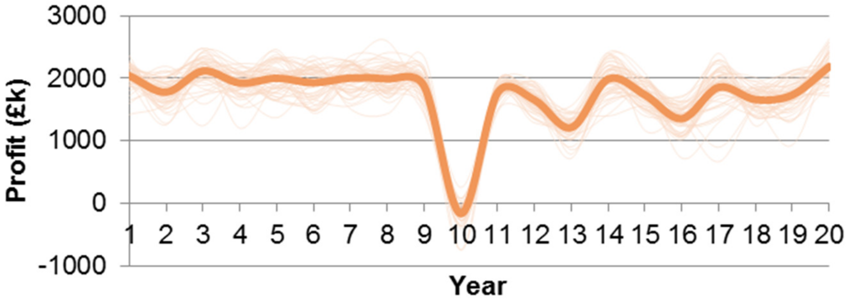

Figure A.4.9.4. Annual results of the labour 'contractors' scenario, for a lifetime of 20 years, in terms of profit

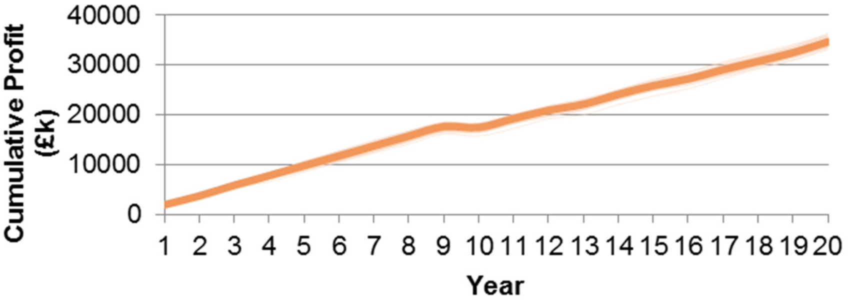

Figure A.4.9.5. Cumulative profit of the labour 'contractors' scenario, for a lifetime of 20 years

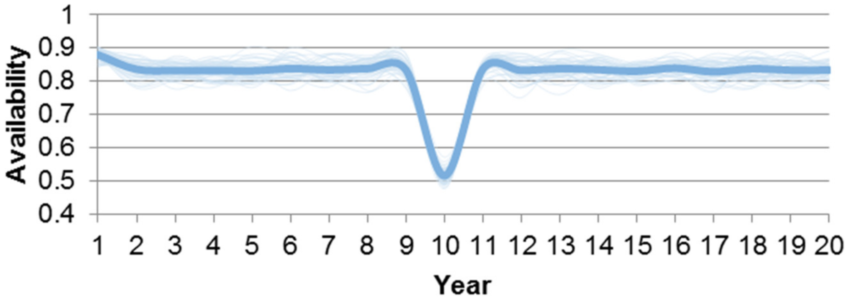

Figure A.4.9.6. Annual results of the labour 'no contractors' scenario, for a lifetime of 20 years, in terms of availability

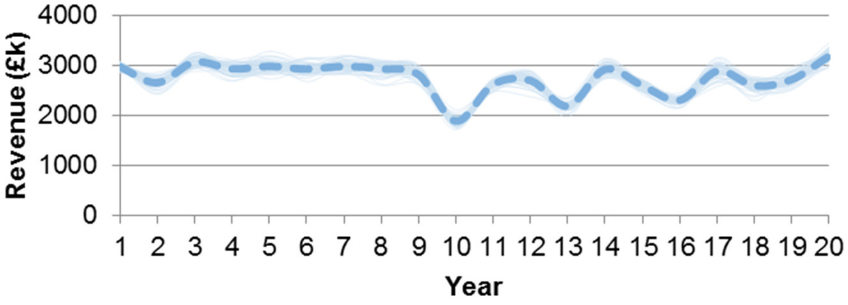

Figure A.4.9.7. Annual results of the labour 'no contractors' scenario, for a lifetime of 20 years, in terms of revenue

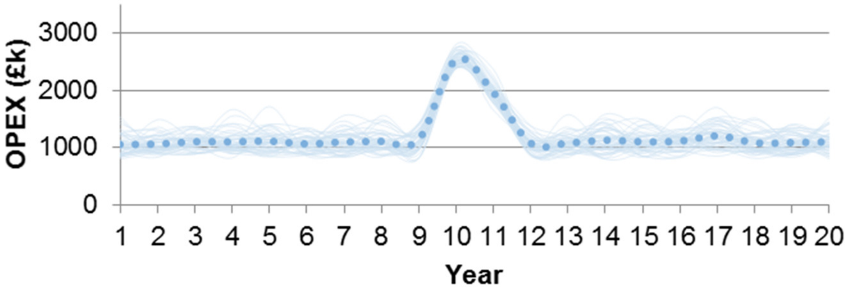

Figure A.4.9.8. Annual results of the labour 'no contractors' scenario, for a lifetime of 20 years, in terms of OPEX

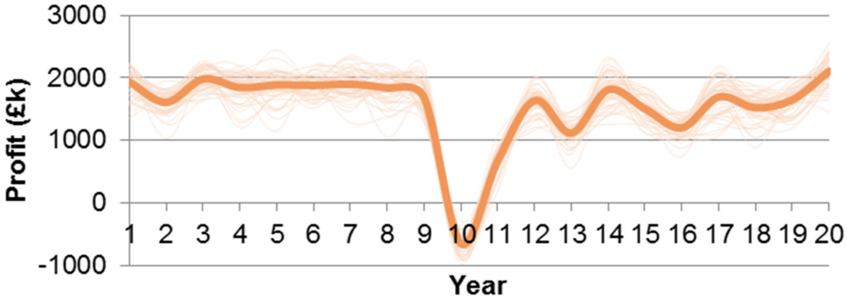

Figure A.4.9.9. Annual results of the labour 'no contractors' scenario, for a lifetime of 20 years, in terms of profit

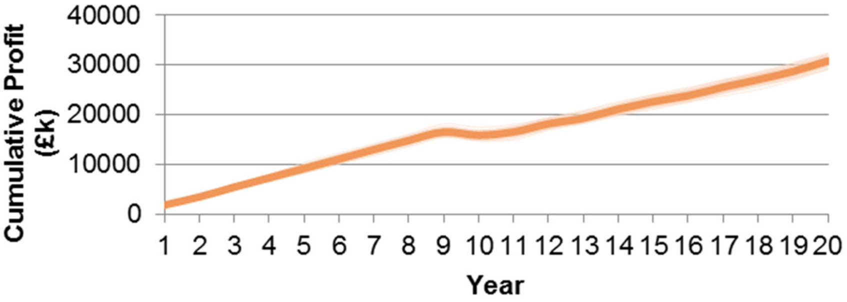

Figure A.4.9.10. Cumulative profit of the labour 'no contractors' scenario, for a lifetime of 20 years

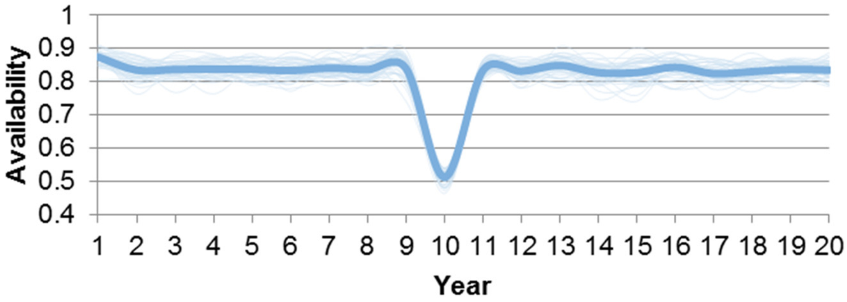

Figure A.4.9.11. Annual results of the labour 'no contractors, base case 2' scenario, for a lifetime of 20 years, in terms of availability

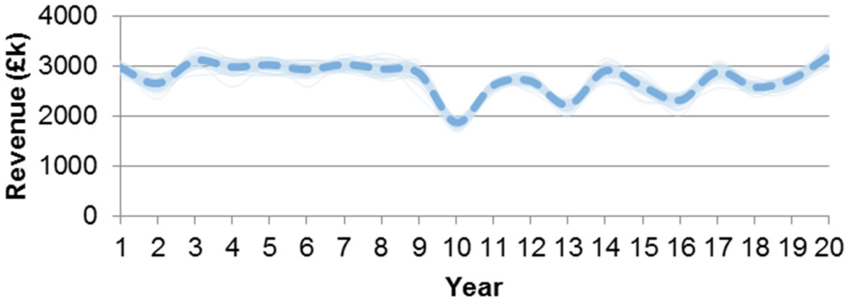

Figure A.4.9.12. Annual results of the labour 'no contractors, base case 2' scenario, for a lifetime of 20 years, in terms of revenue

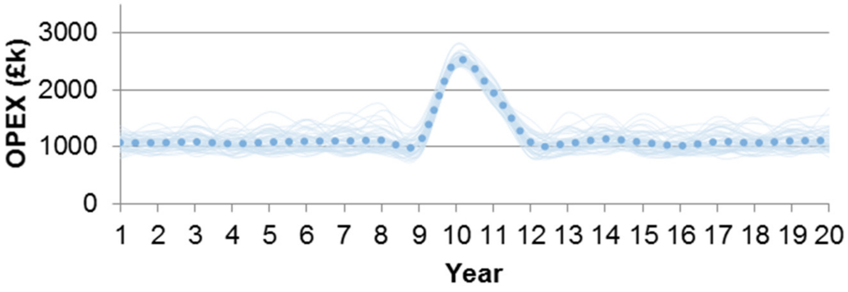

Figure A.4.9.13. Annual results of the labour 'no contractors, base case 2' scenario, for a lifetime of 20 years, in terms of OPEX

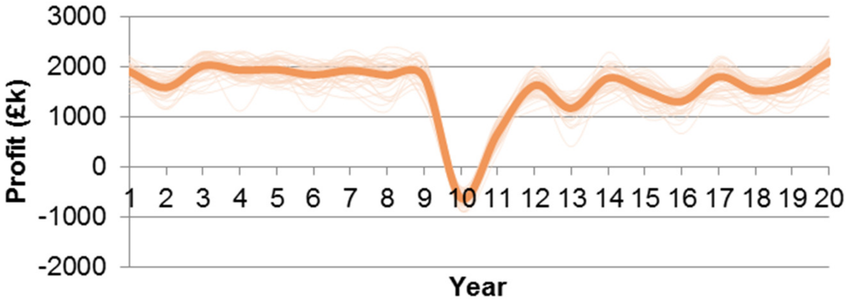

Figure A.4.9.14. Annual results of the labour 'no contractors, base case 2' scenario, for a lifetime of 20 years, in terms of profit

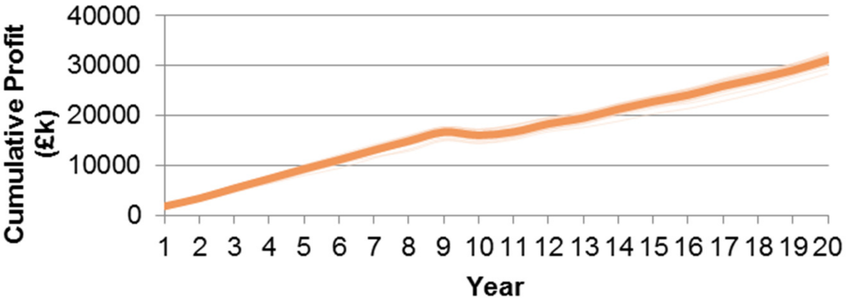

Figure A.4.9.15. Cumulative profit of the labour 'no contractors, base case 2' scenario, for a lifetime of 20 years

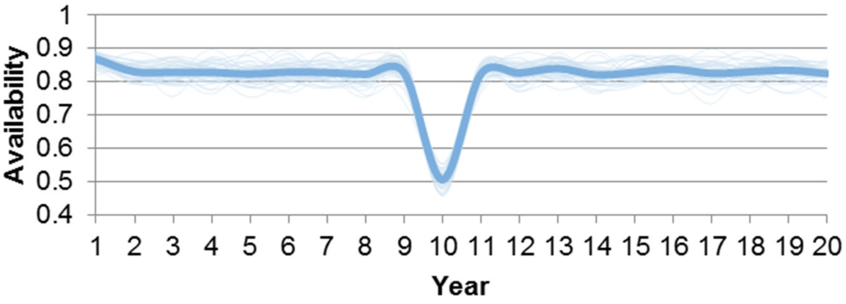

Figure A.4.9.16. Annual results of labour 'no contractors, scenario 1', for a lifetime of 20 years, in terms of availability

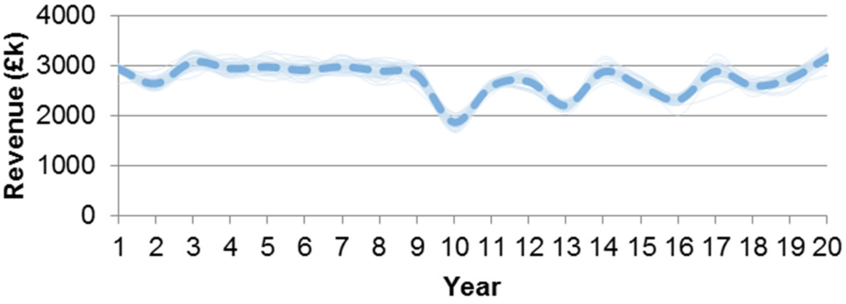

Figure A.4.9.17. Annual results of labour 'no contractors, scenario 1', for a lifetime of 20 years, in terms of revenue

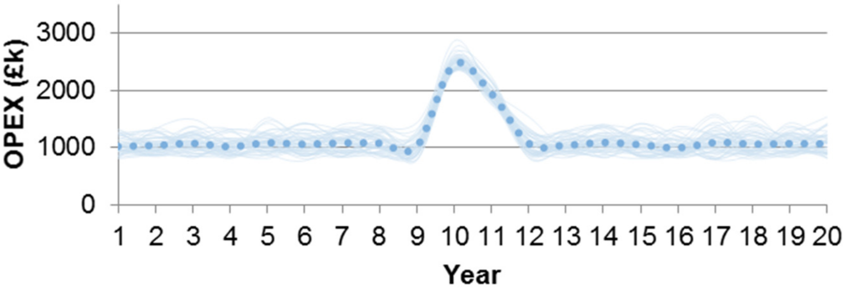

Figure A.4.9.18. Annual results of labour 'no contractors, scenario 1', for a lifetime of 20 years, in terms of OPEX

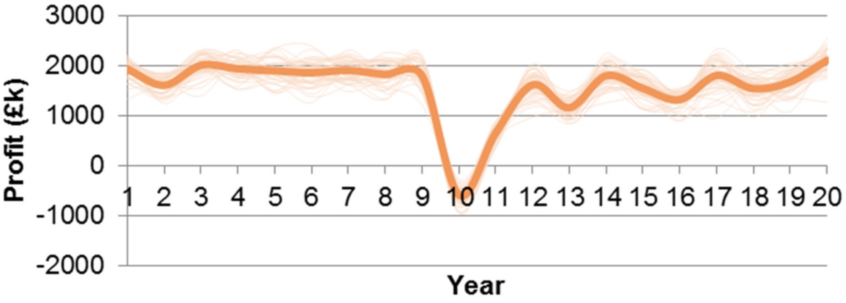

Figure A.4.9.19. Annual results of labour 'no contractors, scenario 1', for a lifetime of 20 years, in terms of profit

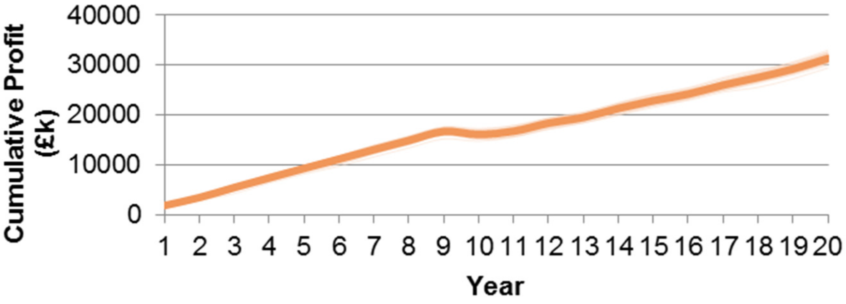

Figure A.4.9.20. Cumulative profit of labour 'no contractors, scenario 1', for a lifetime of 20 years

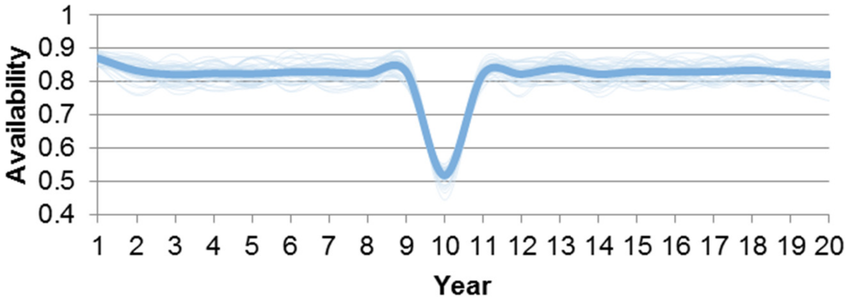

Figure A.4.9.21. Annual results of labour 'no contractors, scenario 2', for a lifetime of 20 years, in terms of availability

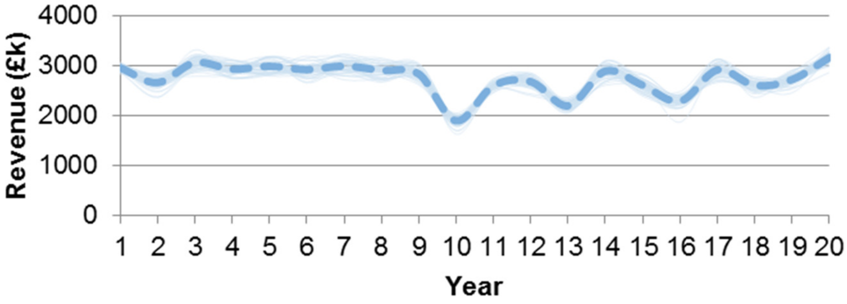

Figure A.4.9.22. Annual results of labour 'no contractors, scenario 2', for a lifetime of 20 years, in terms of revenue

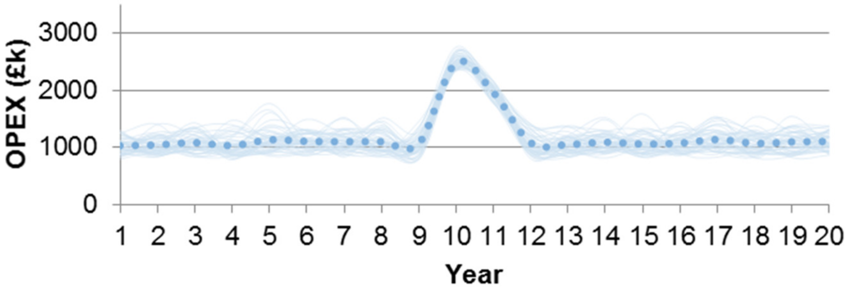

Figure A.4.9.23. Annual results of labour 'no contractors, scenario 2', for a lifetime of 20 years, in terms of OPEX

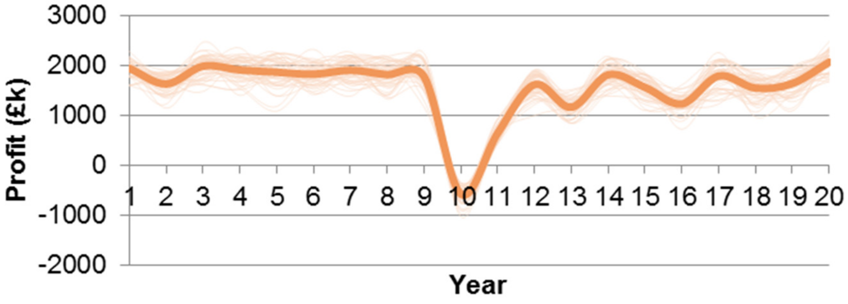

Figure A.4.9.24. Annual results of labour 'no contractors, scenario 2', for a lifetime of 20 years, in terms of profit

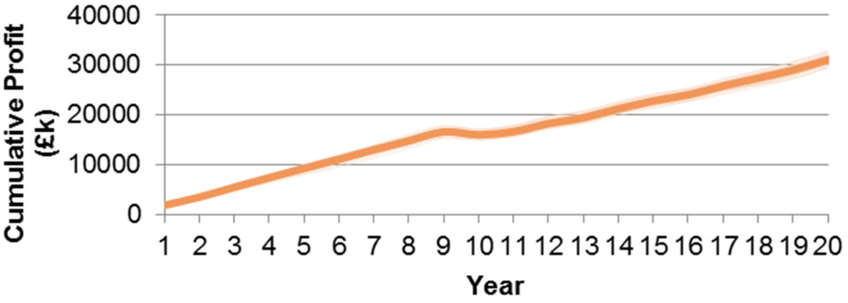

Figure A.4.9.25. Cumulative profit of labour 'no contractors, scenario 2', for a lifetime of 20 years

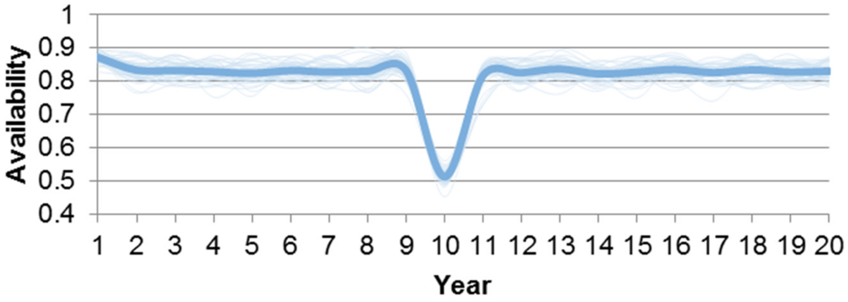

Figure A.4.9.26. Annual results of labour 'no contractors, scenario 3', for a lifetime of 20 years, in terms of availability

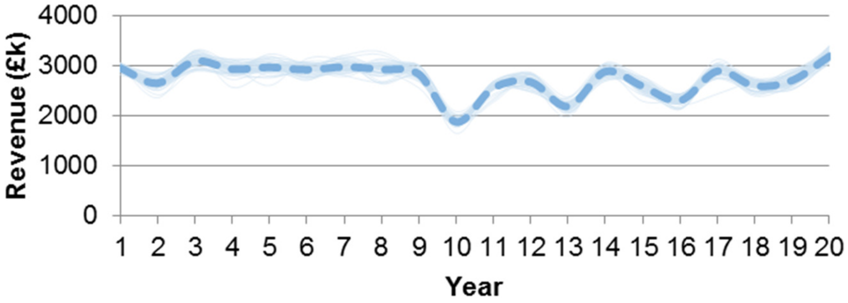

Figure A.4.9.27. Annual results of labour 'no contractors, scenario 3', for a lifetime of 20 years, in terms of revenue

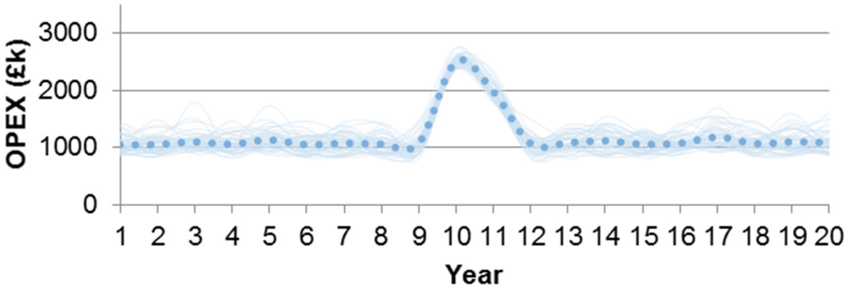

Figure A.4.9.28. Annual results of labour 'no contractors, scenario 3', for a lifetime of 20 years, in terms of OPEX

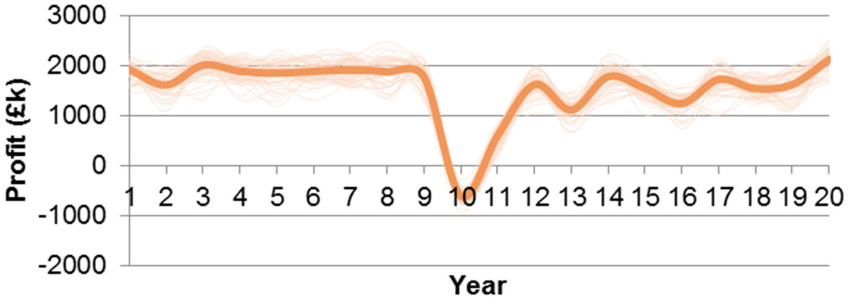

Figure A.4.9.29. Annual results of labour 'no contractors, scenario 3', for a lifetime of 20 years, in terms of profit

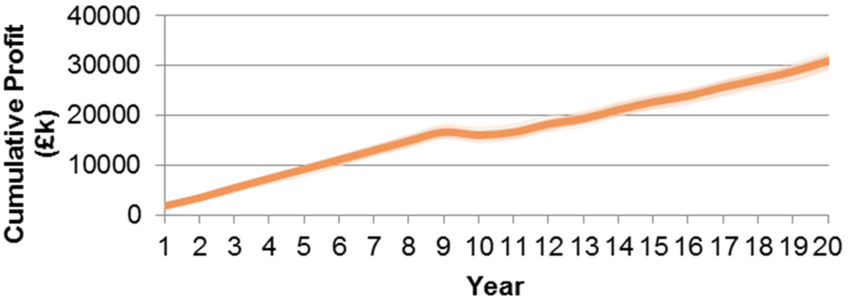

Figure A.4.9.30. Cumulative profit of labour 'no contractors, scenario 3', for a lifetime of 20 years

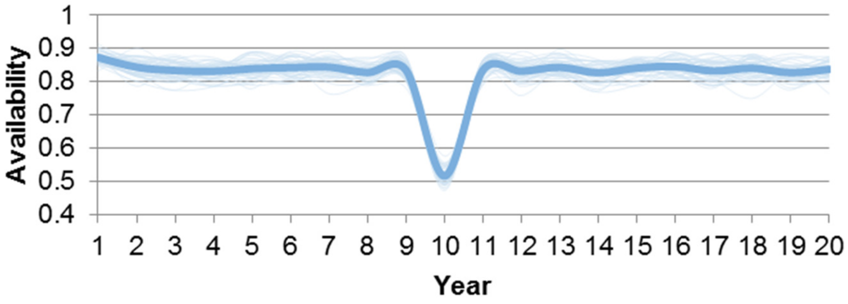

Figure A.4.9.31. Annual results of labour 'no contractors, scenario 4', for a lifetime of 20 years, in terms of availability

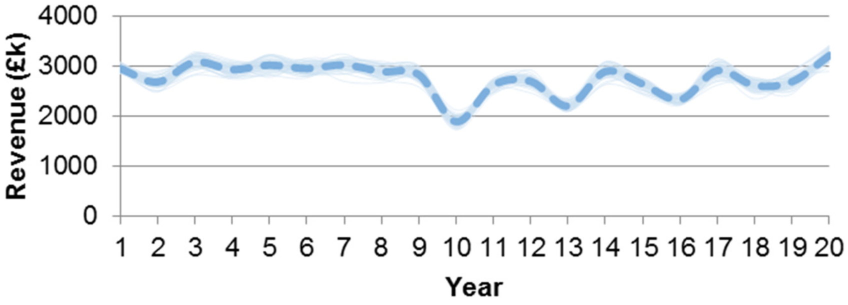

Figure A.4.9.32. Annual results of labour 'no contractors, scenario 4', for a lifetime of 20 years, in terms of revenue

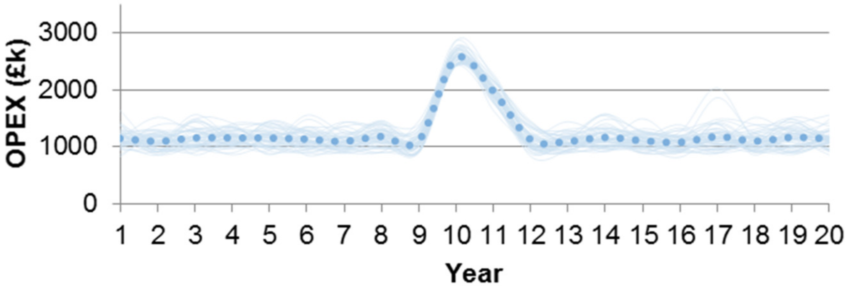

Figure A.4.9.33. Annual results of labour 'no contractors, scenario 4', for a lifetime of 20 years, in terms of OPEX

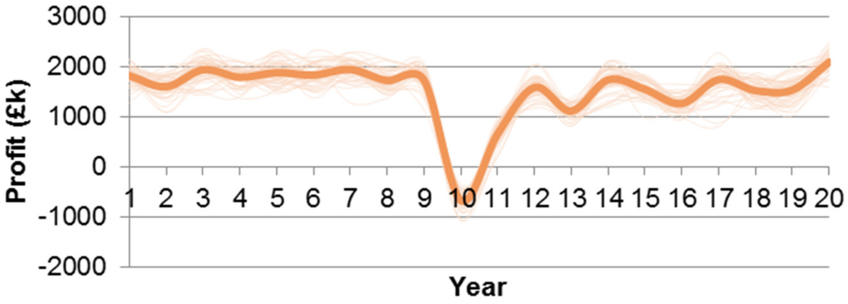

Figure A.4.9.34. Annual results of labour 'no contractors, scenario 4', for a lifetime of 20 years, in terms of profit

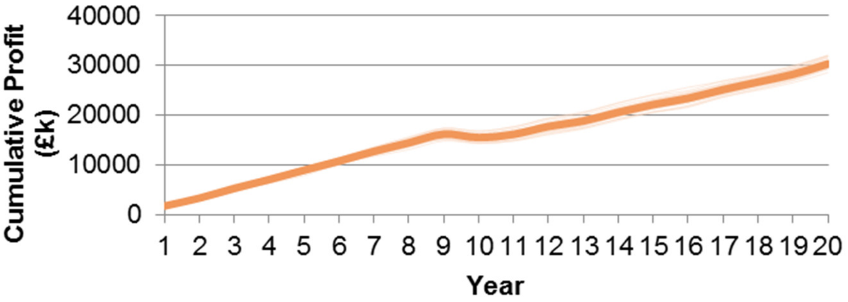

Figure A.4.9.35. Cumulative profit of labour 'no contractors, scenario 4', for a lifetime of 20 years

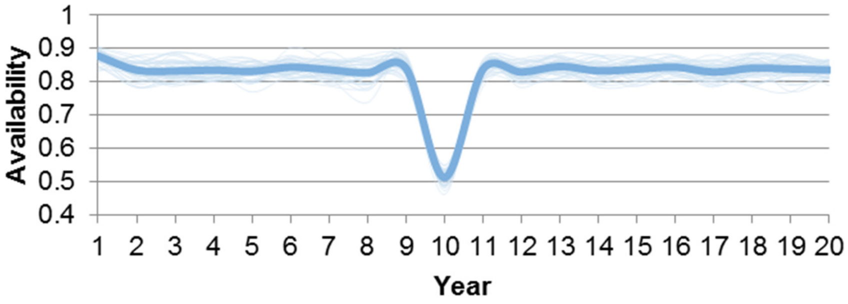

Figure A.4.9.36. Annual results of labour 'no contractors, scenario 5', for a lifetime of 20 years, in terms of availability

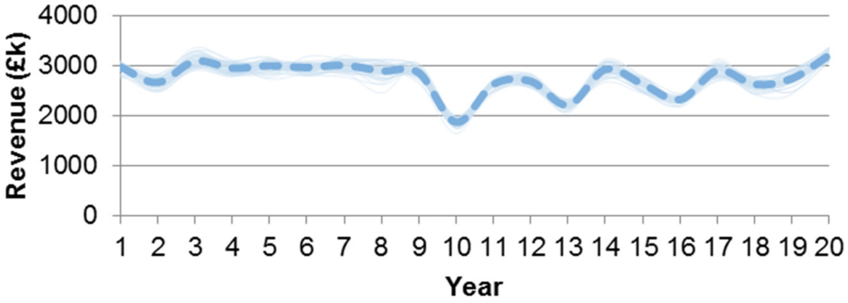

Figure A.4.9.37. Annual results of labour 'no contractors, scenario 5', for a lifetime of 20 years, in terms of revenue

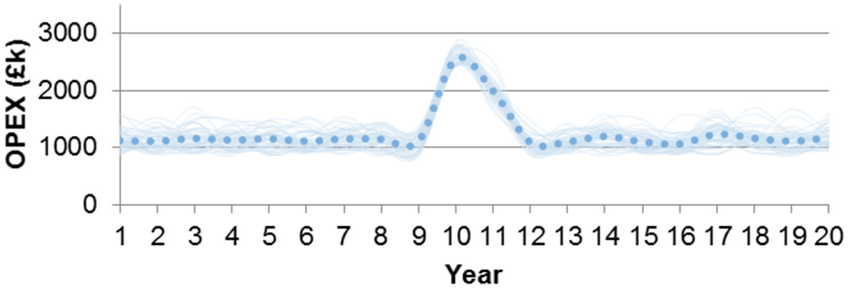

Figure A.4.9.38. Annual results of labour 'no contractors, scenario 5', for a lifetime of 20 years, in terms of OPEX

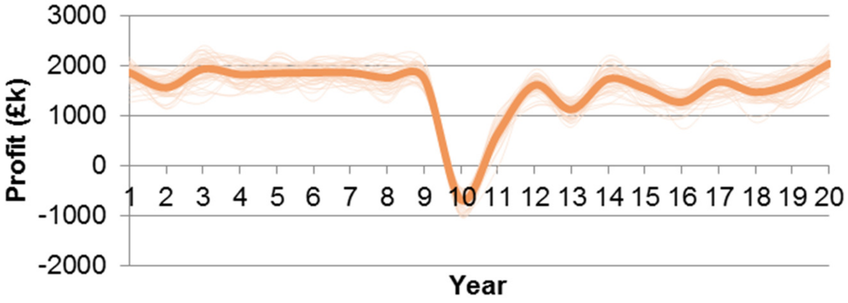

Figure A.4.9.39. Annual results of labour 'no contractors, scenario 5', for a lifetime of 20 years, in terms of profit

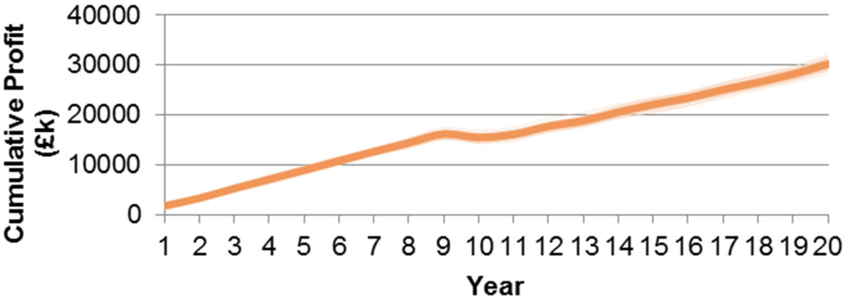

Figure A.4.9.40. Cumulative profit of labour ‘no contractors, scenario 5', for a lifetime of 20 years

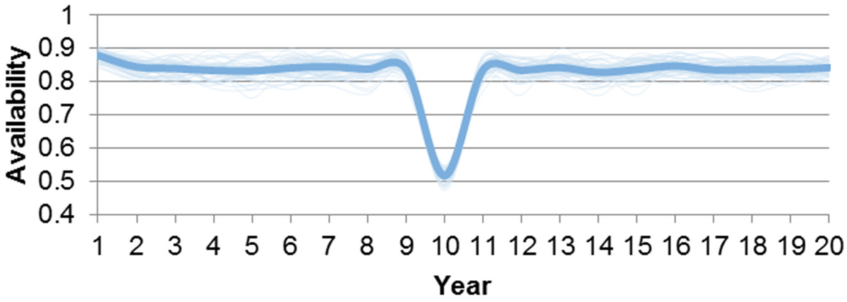

Figure A.4.9.41. Annual results of labour ‘no contractors, scenario 6’, for a lifetime of 20 years, in terms of availability

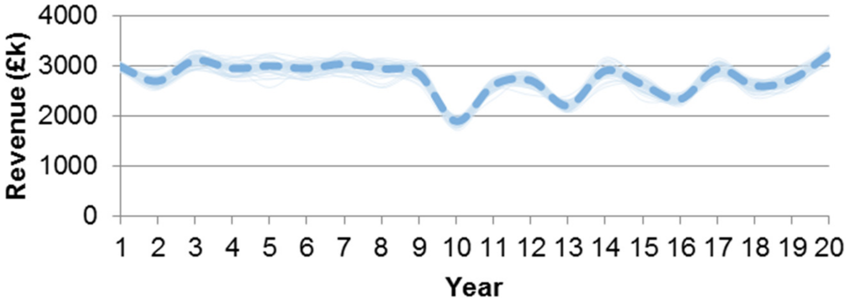

Figure A.4.9.42. Annual results of labour ‘no contractors, scenario 6’, for a lifetime of 20 years, in terms of revenue

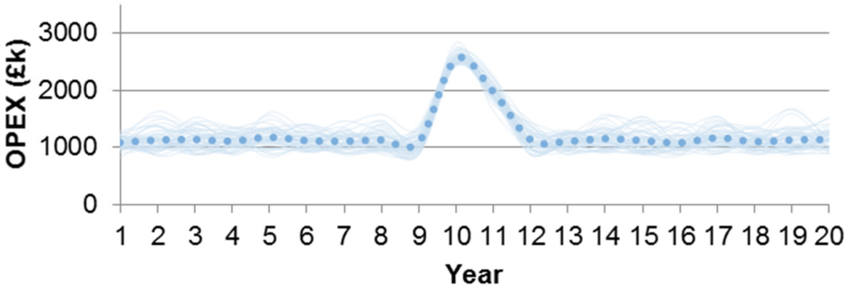

Figure A.4.9.43. Annual results of labour ‘no contractors, scenario 6’, for a lifetime of 20 years, in terms of OPEX

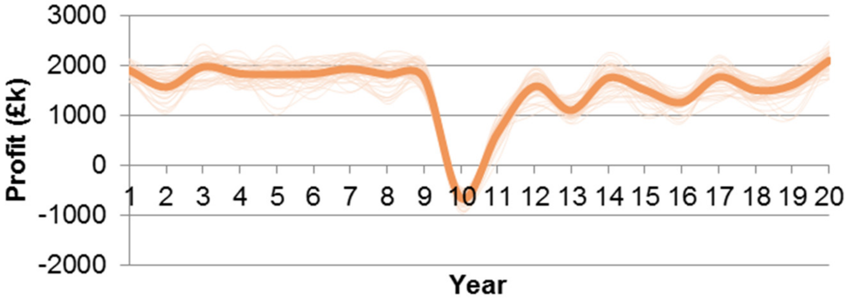

Figure A.4.9.44. Annual results of labour 'no contractors, scenario 6', for a lifetime of 20 years, in terms of profit

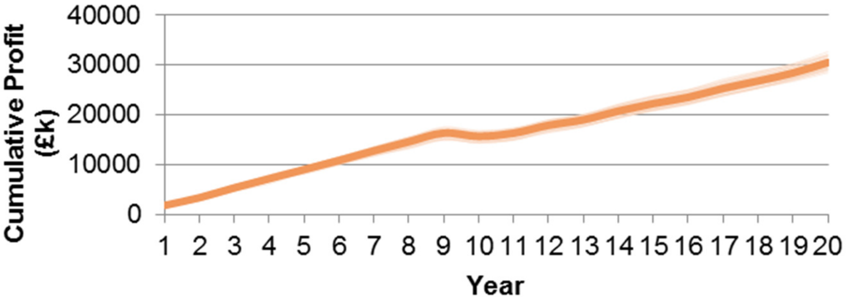

Figure A.4.9.45. Cumulative profit of labour 'no contractors, scenario 6', for a lifetime of 20 years

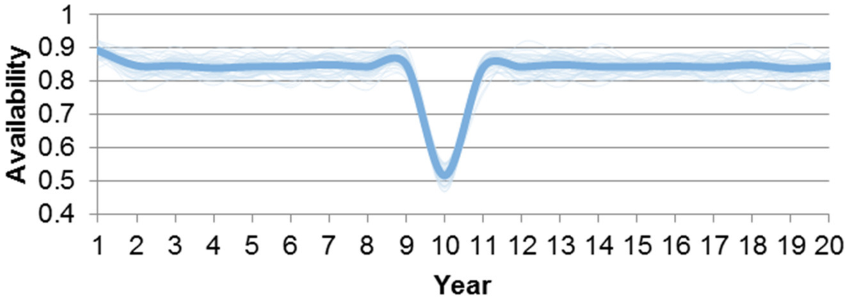

Figure A.4.9.46. Annual results of labour 'no contractors, scenario 7', for a lifetime of 20 years, in terms of availability

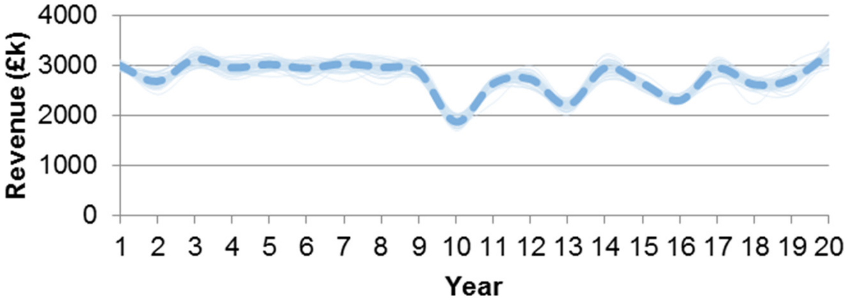

Figure A.4.9.47. Annual results of labour 'no contractors, scenario 7', for a lifetime of 20 years, in terms of revenue

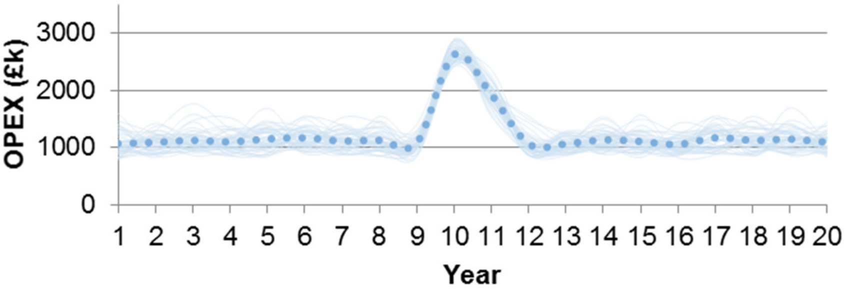

Figure A.4.9.48. Annual results of labour 'no contractors, scenario 7', for a lifetime of 20 years, in terms of OPEX

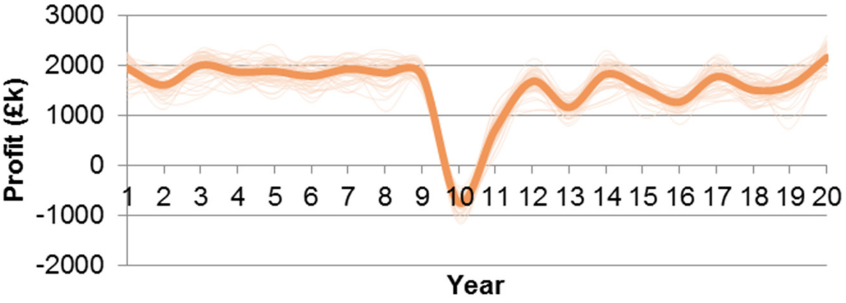

Figure A.4.9.49. Annual results of labour 'no contractors, scenario 7', for a lifetime of 20 years, in terms of profit

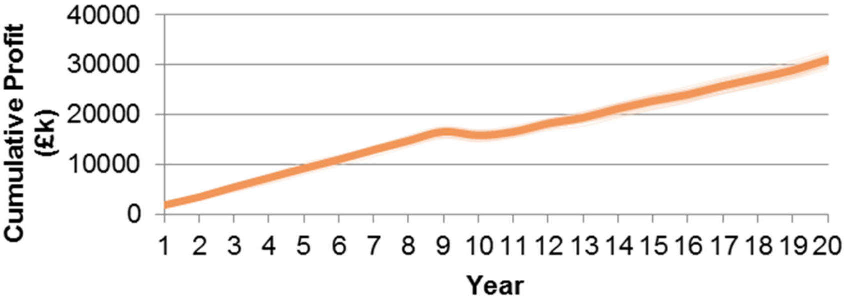

Figure A.4.9.50. Cumulative profit of labour 'no contractors, scenario 7', for a lifetime of 20 years

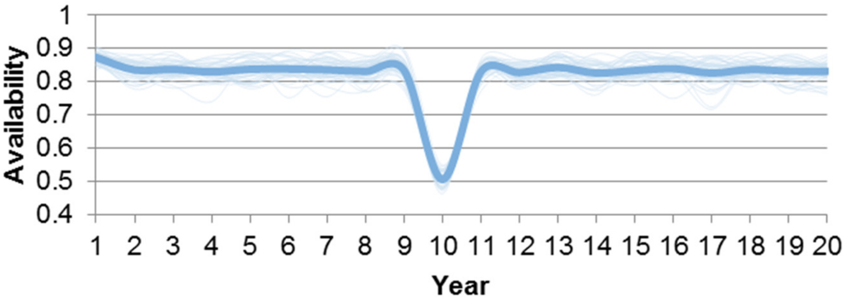

Figure A.4.9.51. Annual results of labour 'no contractors, scenario 8', for a lifetime of 20 years, in terms of availability

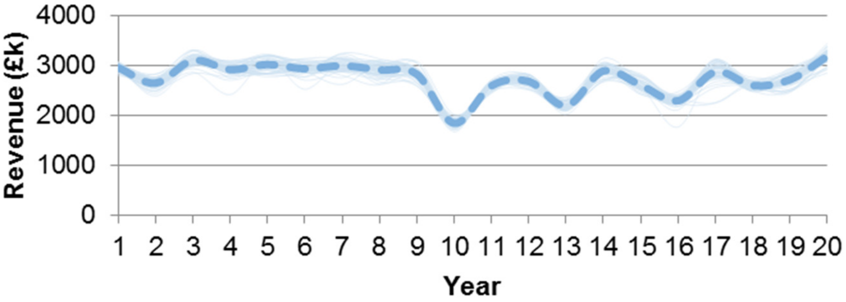

Figure A.4.9.52. Annual results of labour 'no contractors, scenario 8', for a lifetime of 20 years, in terms of revenue

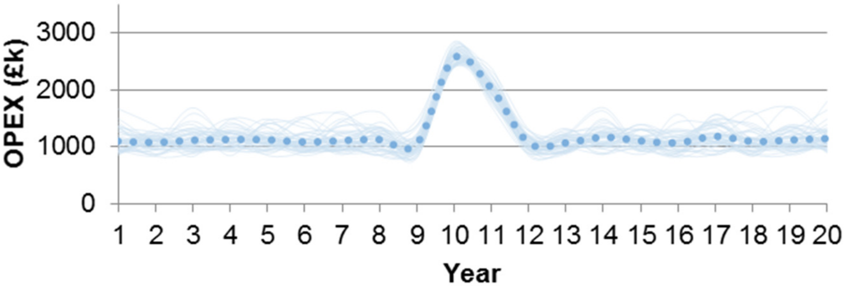

Figure A.4.9.53. Annual results of labour 'no contractors, scenario 8', for a lifetime of 20 years, in terms of OPEX

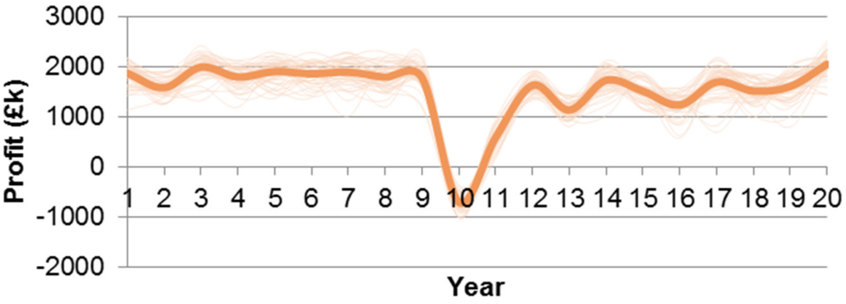

Figure A.4.9.54. Annual results of labour 'no contractors, scenario 8', for a lifetime of 20 years, in terms of profit

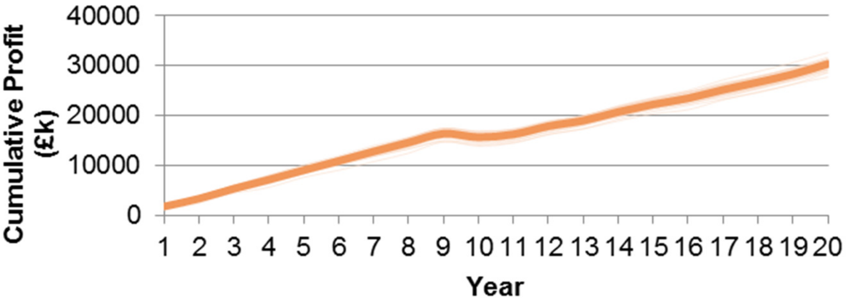

Figure A.4.9.55. Cumulative profit of labour 'no contractors, scenario 8', for a lifetime of 20 years

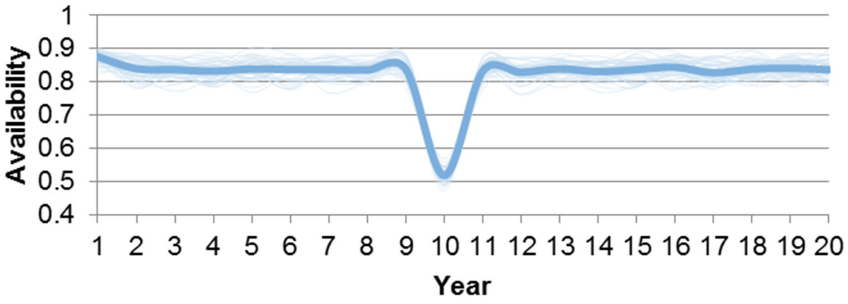

Figure A.4.9.56. Annual results of labour ‘no contractors, scenario 9’, for a lifetime of 20 years, in terms of availability

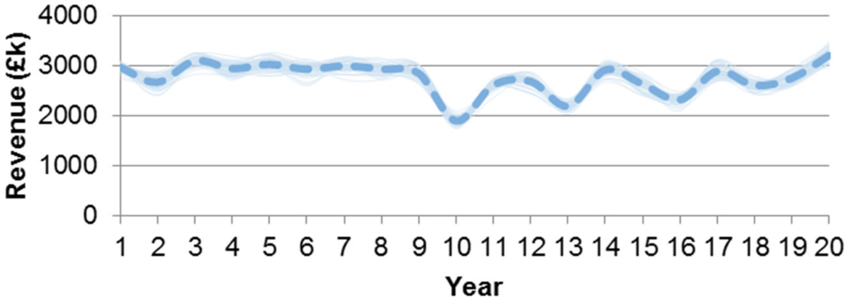

Figure A.4.9.57. Annual results of labour ‘no contractors, scenario 9’, for a lifetime of 20 years, in terms of revenue

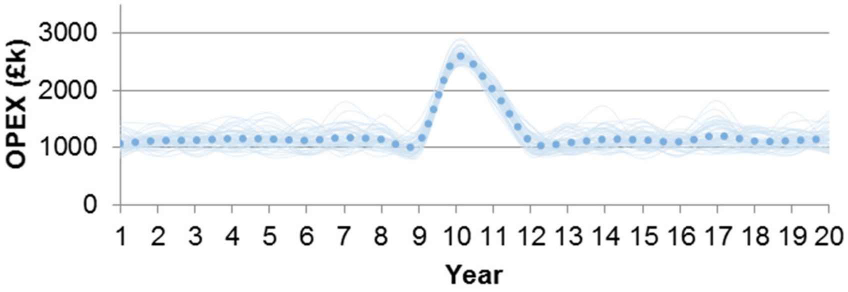

Figure A.4.9.58. Annual results of labour ‘no contractors, scenario 9’, for a lifetime of 20 years, in terms of OPEX

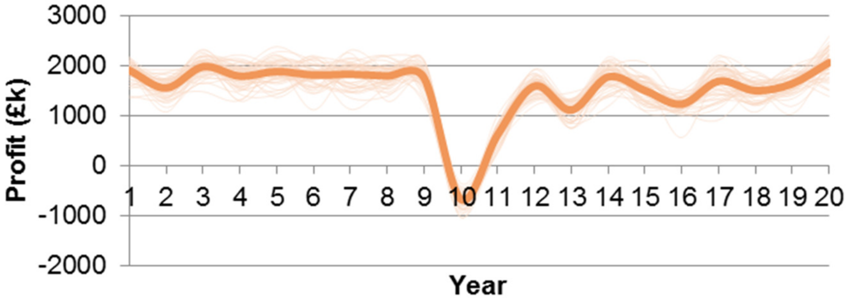

Figure A.4.9.59. Annual results of labour ‘no contractors, scenario 9’, for a lifetime of 20 years, in terms of profit

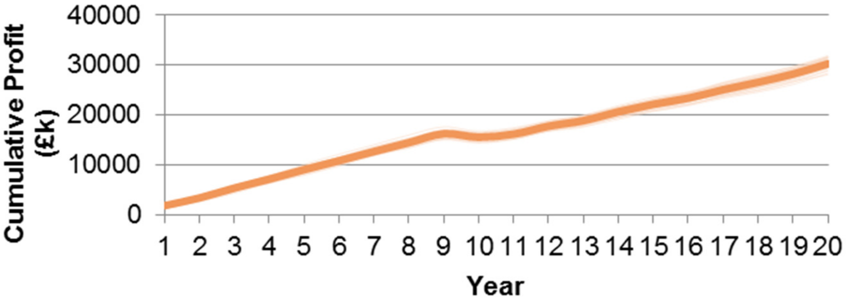

Figure A.4.9.60. Cumulative profit of labour 'no contractors, scenario 9', for a lifetime of 20 years

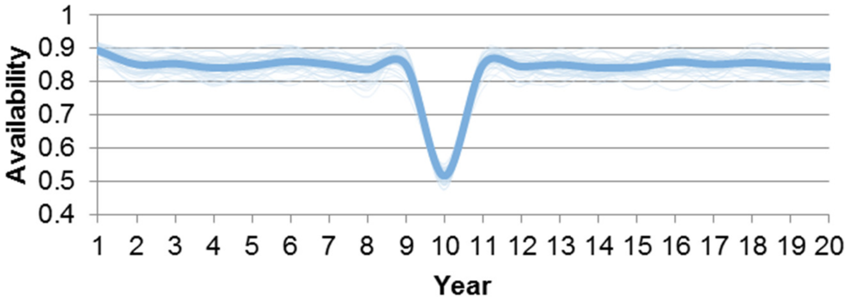

Figure A.4.9.61. Annual results of labour 'no contractors, scenario 10', for a lifetime of 20 years, in terms of availability

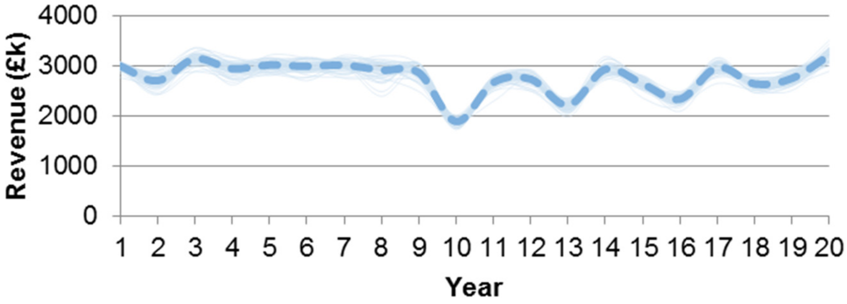

Figure A.4.9.62. Annual results of labour 'no contractors, scenario 10', for a lifetime of 20 years, in terms of revenue

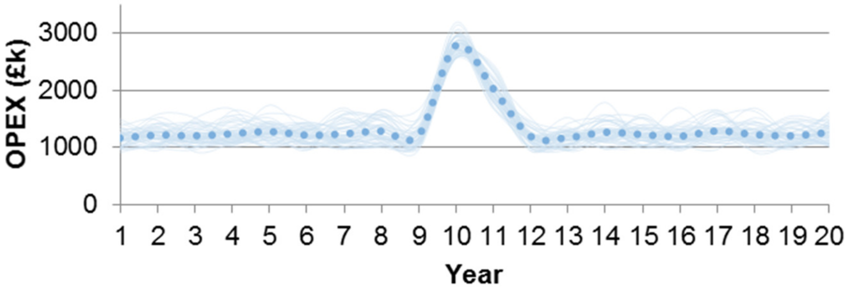

Figure A.4.9.63. Annual results of labour 'no contractors, scenario 10', for a lifetime of 20 years, in terms of OPEX

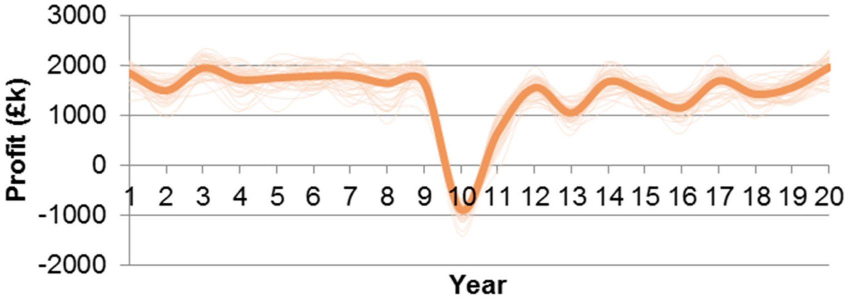

Figure A.4.9.64. Annual results of labour 'no contractors, scenario 10', for a lifetime of 20 years, in terms of profit

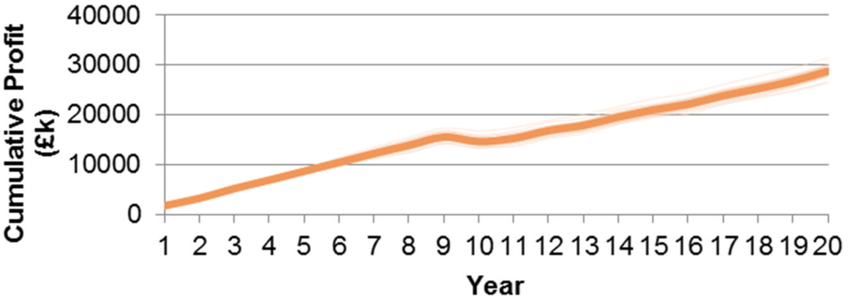

Figure A.4.9.65. Cumulative profit of labour 'no contractors, scenario 10', for a lifetime of 20 years

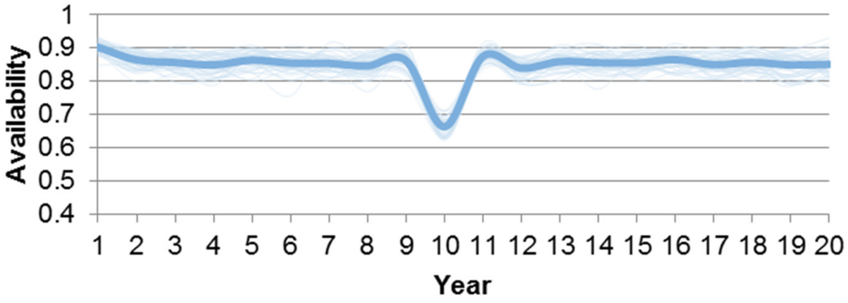

Figure A.4.9.66. Annual results of labour 'no contractors, scenario 11', for a lifetime of 20 years, in terms of availability

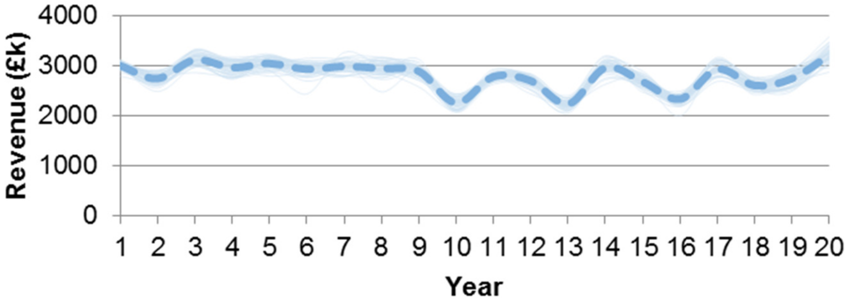

Figure A.4.9.67. Annual results of labour 'no contractors, scenario 11', for a lifetime of 20 years, in terms of revenue

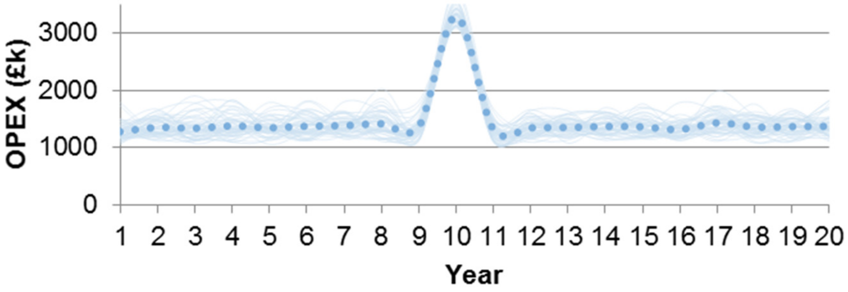

Figure A.4.9.68. Annual results of labour 'no contractors, scenario 11', for a lifetime of 20 years, in terms of OPEX

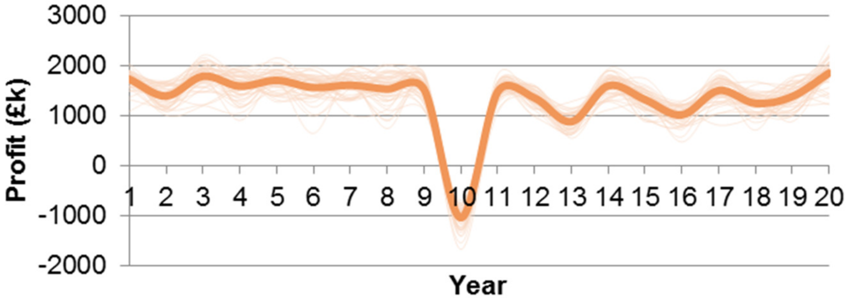

Figure A.4.9.69. Annual results of labour 'no contractors, scenario 11', for a lifetime of 20 years, in terms of profit

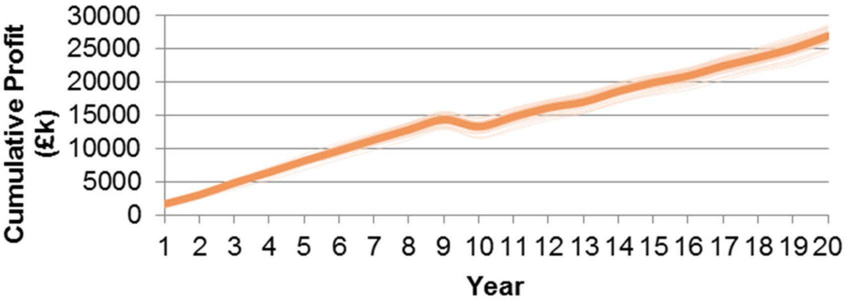

Figure A.4.9.70. Cumulative profit of labour 'no contractors, scenario 11', for a lifetime of 20 years

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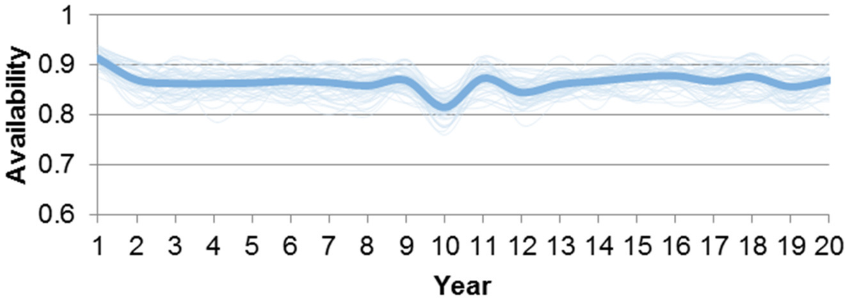

Figure A.4.10.1. Annual results of the 'base case' scenario, for a lifetime of 20 years, in terms of availability

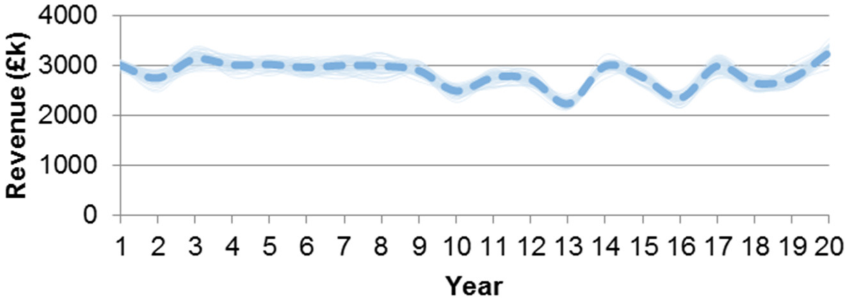

Figure A.4.10.2. Annual results of the 'base case' scenario, for a lifetime of 20 years, in terms of revenue

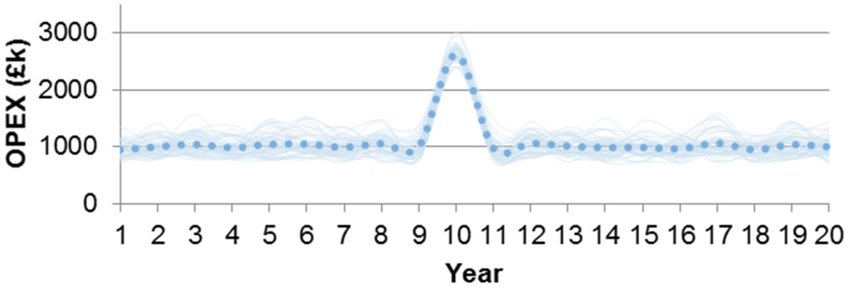

Figure A.4.10.3. Annual results of the 'base case' scenario, for a lifetime of 20 years, in terms of OPEX

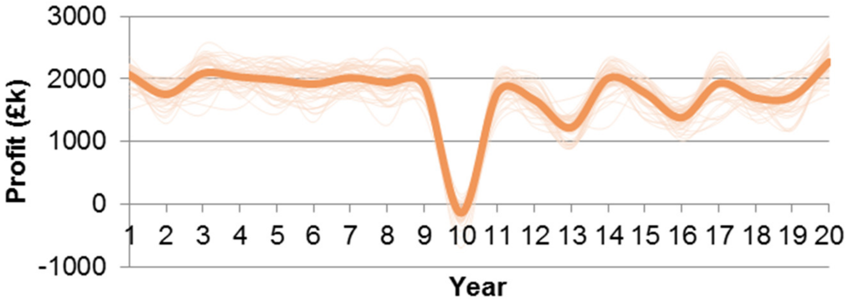

Figure A.4.10.4. Annual results of the 'base case' scenario, for a lifetime of 20 years, in terms of profit

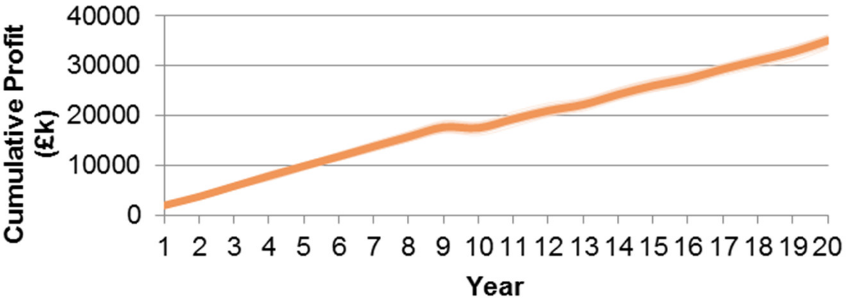

Figure A.4.10.5. Cumulative profit of the 'base case' scenario, for a lifetime of 20 years

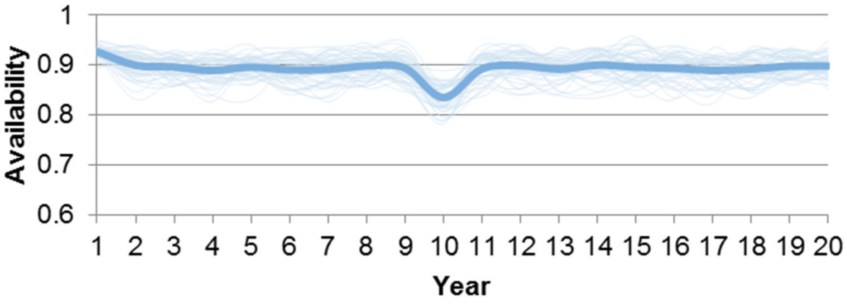

Figure A.4.10.6. Annual results of the 'optimal case' scenario, for a lifetime of 20 years, in terms of availability

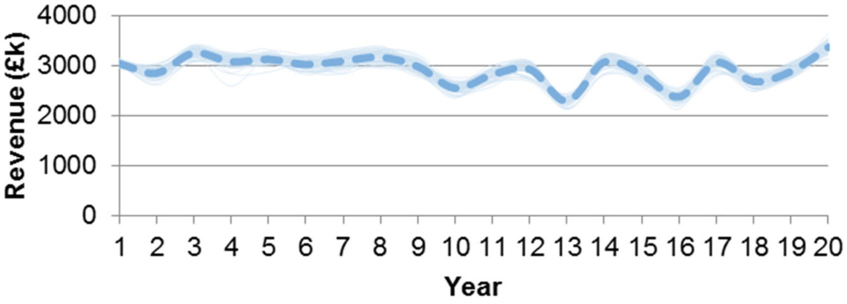

Figure A.4.10.7. Annual results of the 'optimal case' scenario, for a lifetime of 20 years, in terms of revenue

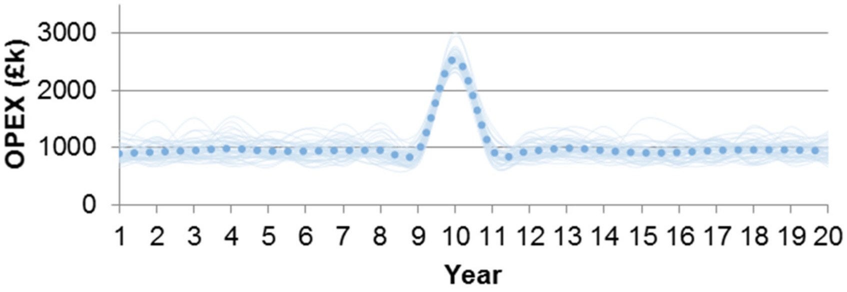

Figure A.4.10.8. Annual results of the 'optimal case' scenario, for a lifetime of 20 years, in terms of OPEX

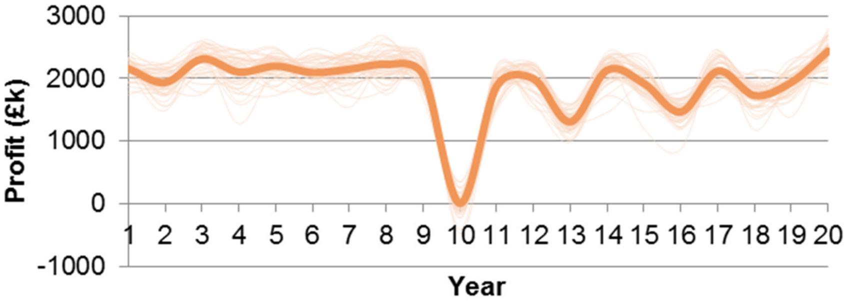

Figure A.4.10.9. Annual results of the 'optimal case' scenario, for a lifetime of 20 years, in terms of profit

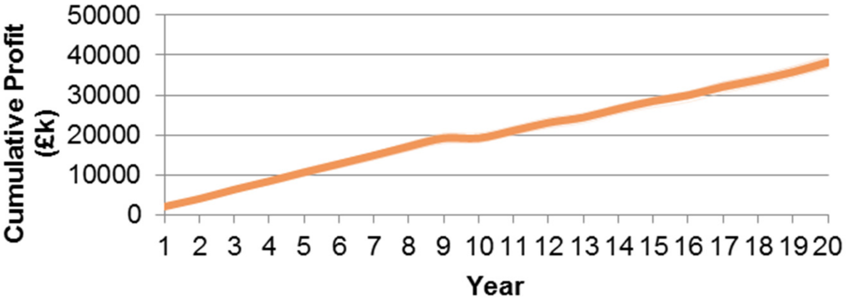

Figure A.4.10.10. Cumulative profit of the 'optimal case' scenario, for a lifetime of 20 years

Chapter 5 Appendix Figures

Section 5.3

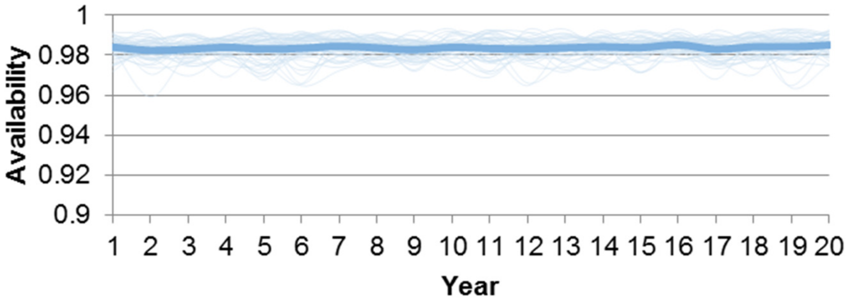

Figure A.5.3.1. Annual results of a six device WaveNET array at Mingary Bay, for a lifetime of 20 years, in terms of availability

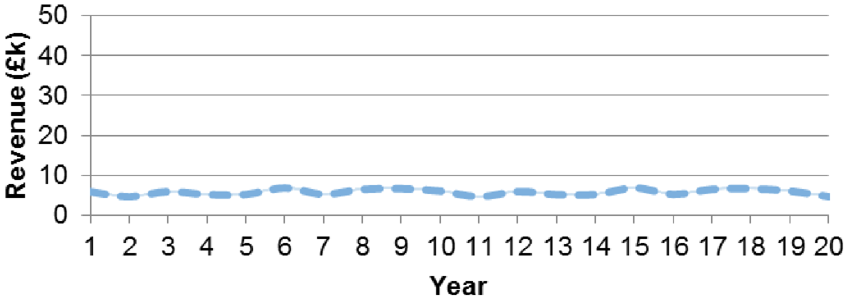

Figure A.5.3.2. Annual results of a six device WaveNET array at Mingary Bay, for a lifetime of 20 years, in terms of revenue

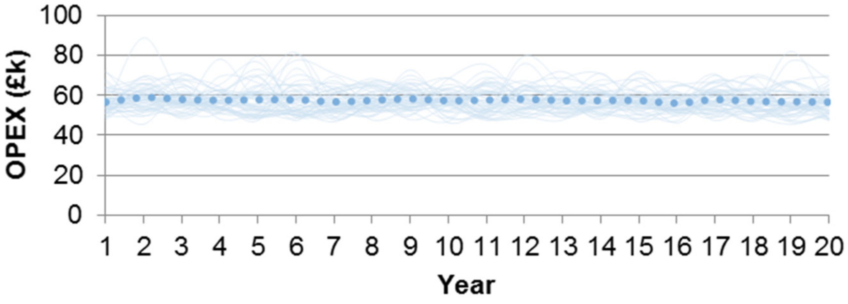

Figure A.5.3.3. Annual results of a six device WaveNET array at Mingary Bay, for a lifetime of 20 years, in terms of OPEX

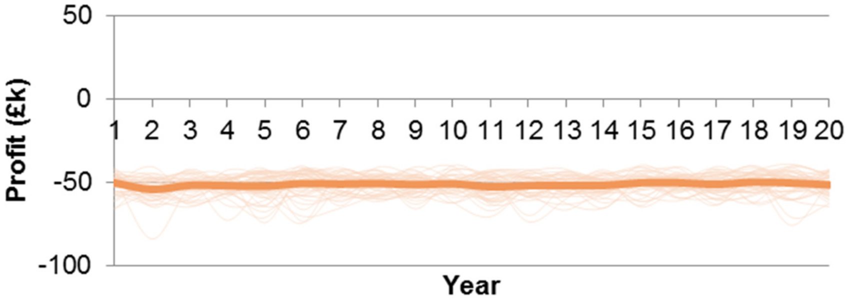

Figure A.5.3.4. Annual results of a six device WaveNET array at Mingary Bay, for a lifetime of 20 years, in terms of profit

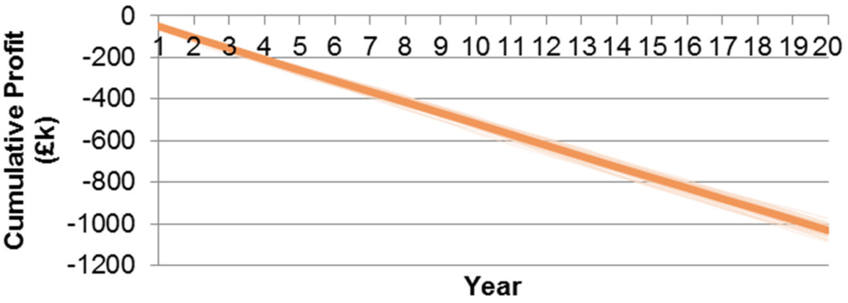

Figure A.5.3.5. Cumulative profit of a six device WaveNET array at Mingary Bay, for a lifetime of 20 years

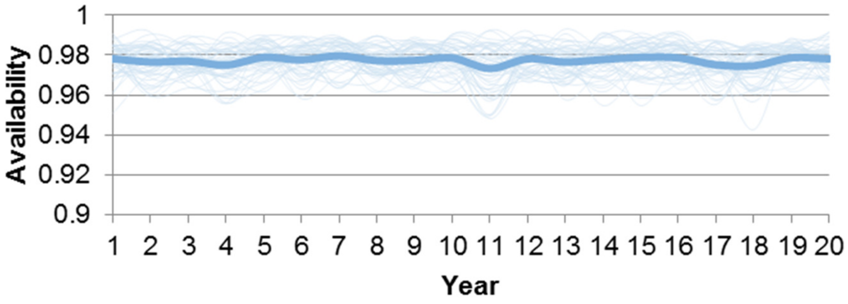

Figure A.5.3.6. Annual results of a six device WaveNET array at the Minch site, for a lifetime of 20 years, in terms of availability

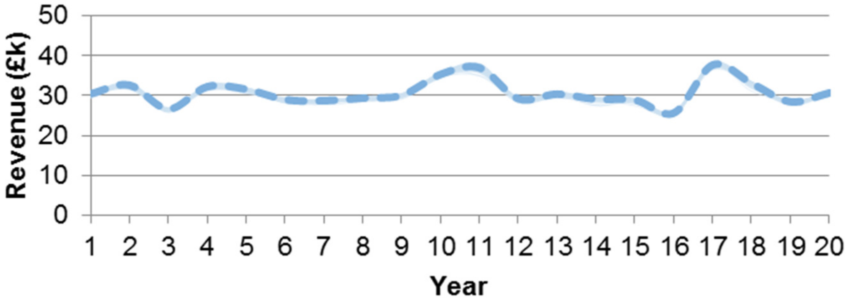

Figure A.5.3.7. Annual results of a six device WaveNET array at the Minch site, for a lifetime of 20 years, in terms of revenue

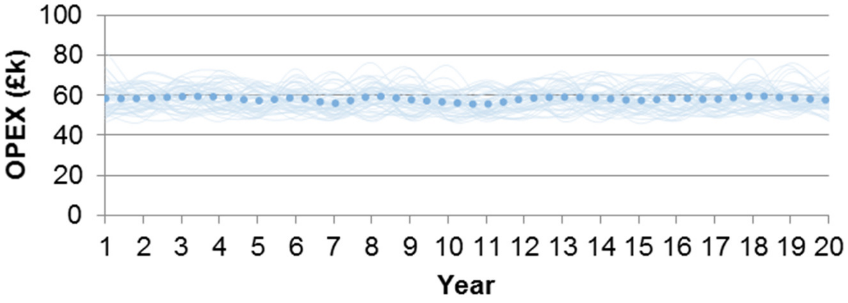

Figure A.5.3.8. Annual results of a six device WaveNET array at the Minch site, for a lifetime of 20 years, in terms of OPEX

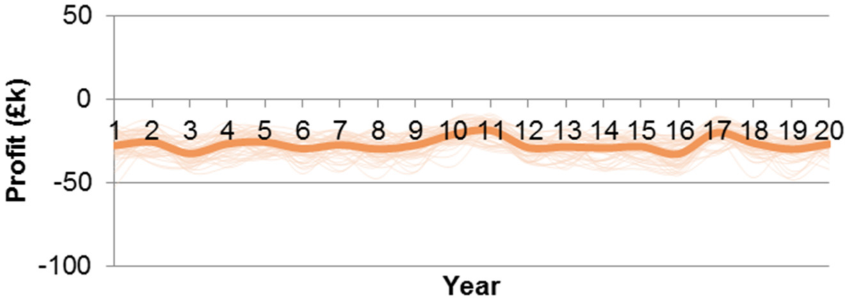

Figure A.5.3.9. Annual results of a six device WaveNET array at the Minch site, for a lifetime of 20 years, in terms of profit

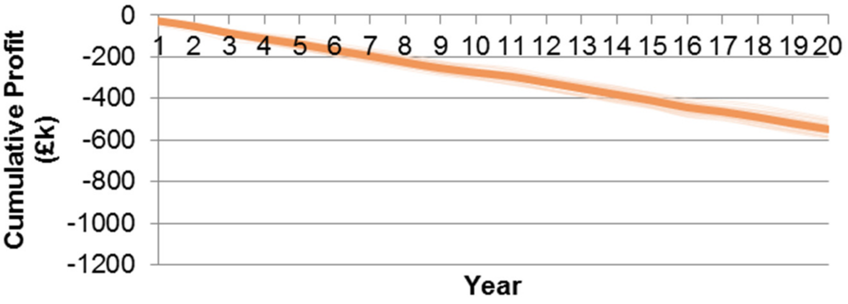

Figure A.5.3.10. Cumulative profit of a six device WaveNET array at the Minch site, for a lifetime of 20 years

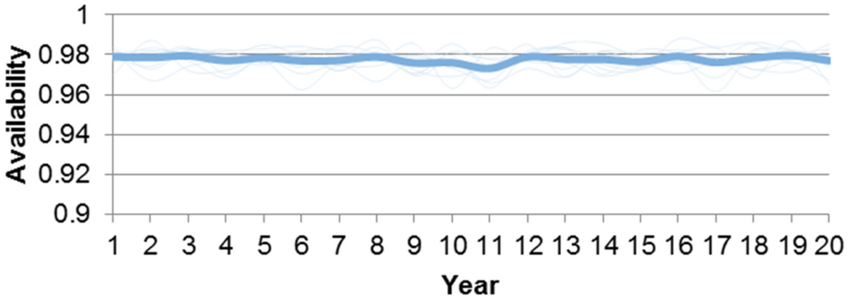

Figure A.5.4.1. Annual results of a 12 device WaveNET array, for a lifetime of 20 years, in terms of availability

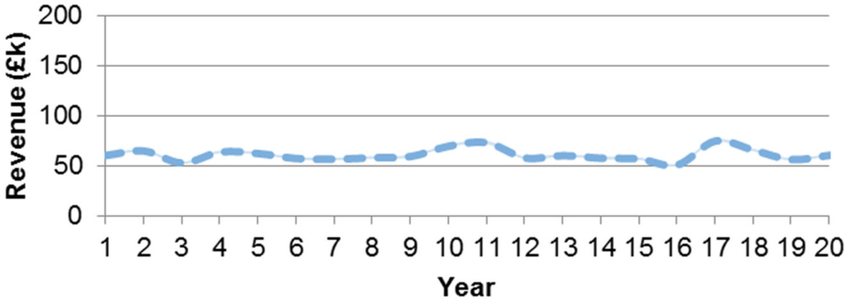

Figure A.5.4.2. Annual results of a 12 device WaveNET array, for a lifetime of 20 years, in terms of revenue

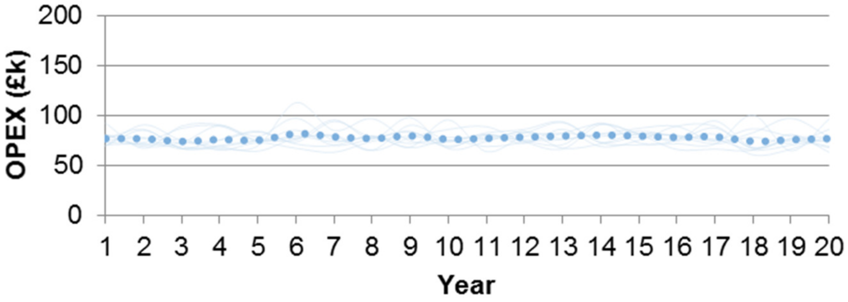

Figure A.5.4.3. Annual results of a 12 device WaveNET array, for a lifetime of 20 years, in terms of OPEX

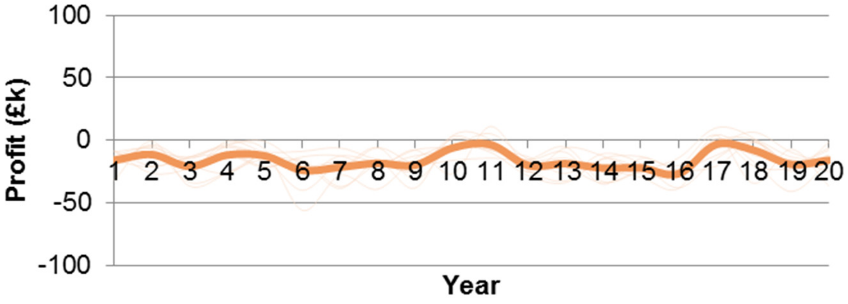

Figure A.5.4.4. Annual results of a 12 device WaveNET array, for a lifetime of 20 years, in terms of profit

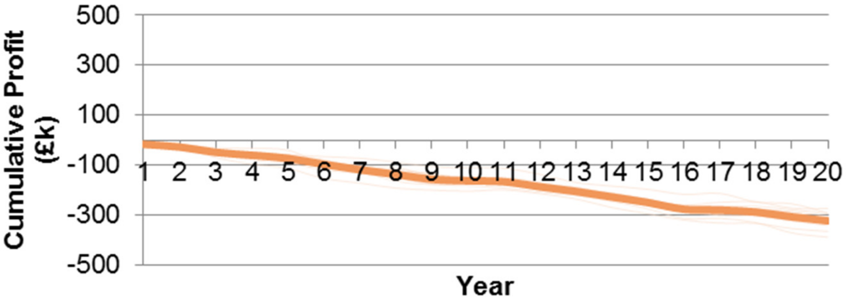

Figure A.5.4.5. Cumulative profit of a 12 device WaveNET array, for a lifetime of 20 years

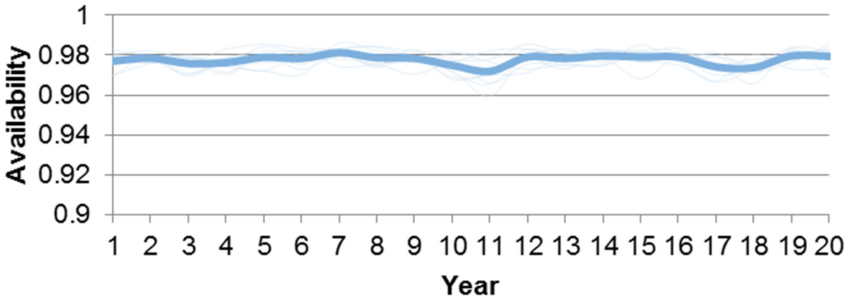

Figure A.5.4.6. Annual results of an 18 device WaveNET array, for a lifetime of 20 years, in terms of availability

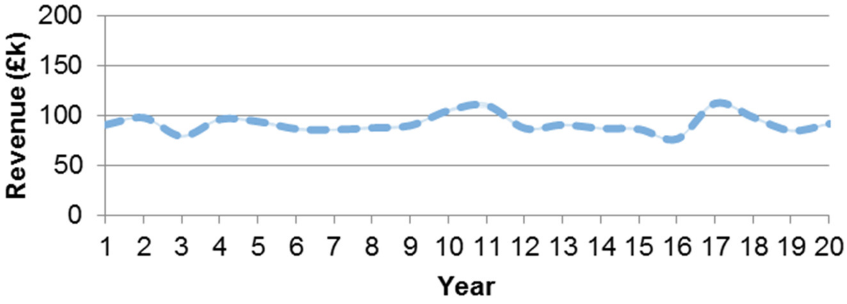

Figure A.5.4.7. Annual results of an 18 device WaveNET array, for a lifetime of 20 years, in terms of revenue

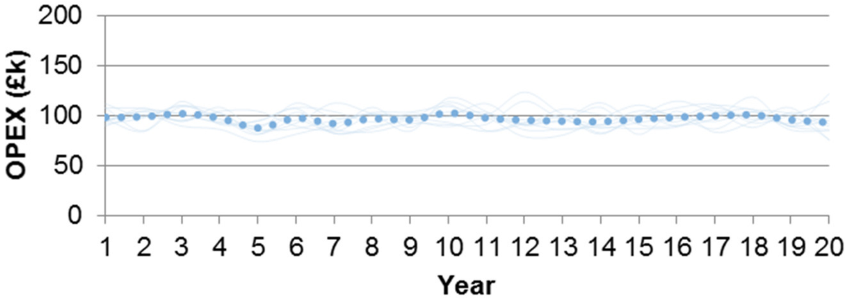

Figure A.5.4.8. Annual results of an 18 device WaveNET array, for a lifetime of 20 years, in terms of OPEX

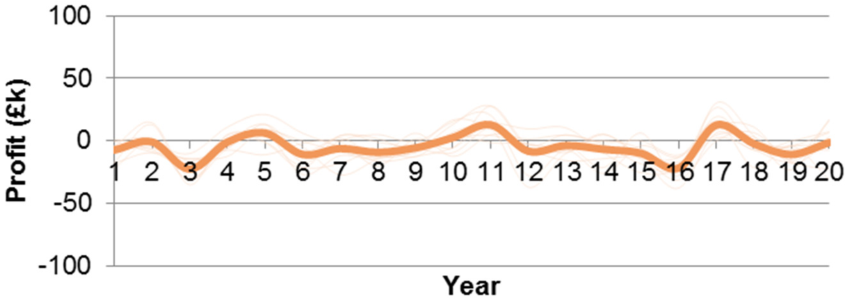

Figure A.5.4.9. Annual results of an 18 device WaveNET array, for a lifetime of 20 years, in terms of profit

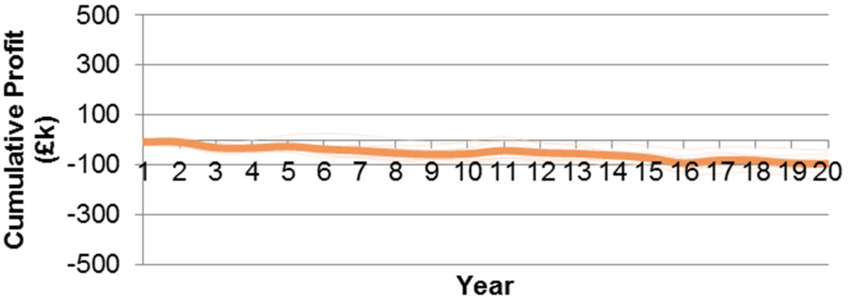

Figure A.5.4.10. Cumulative profit of an 18 device WaveNET array, for a lifetime of 20 years

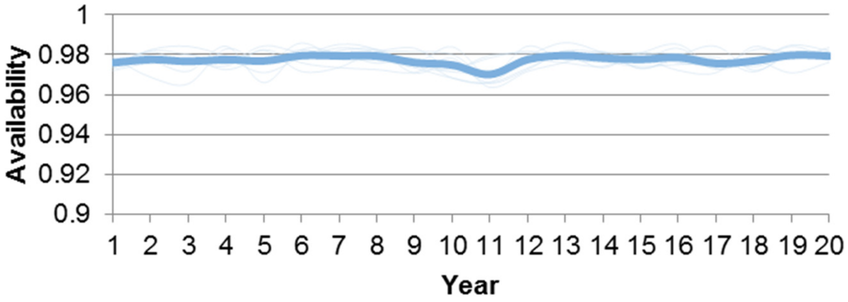

Figure A.5.4.11. Annual results of a 24 device WaveNET array, for a lifetime of 20 years, in terms of availability

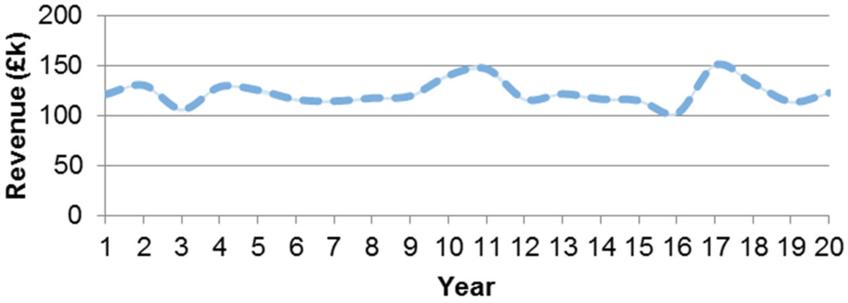

Figure A.5.4.12. Annual results of a 24 device WaveNET array, for a lifetime of 20 years, in terms of revenue

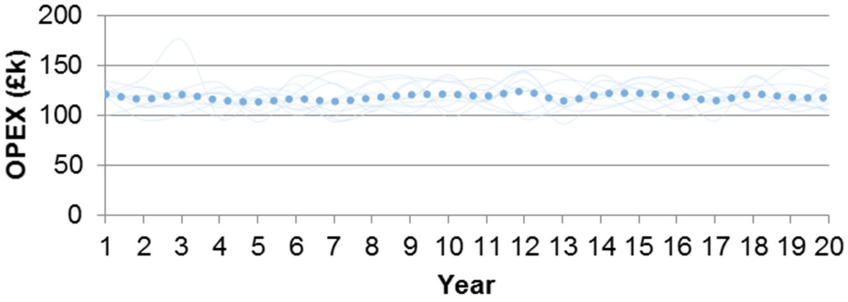

Figure A.5.4.13. Annual results of a 24 device WaveNET array, for a lifetime of 20 years, in terms of OPEX

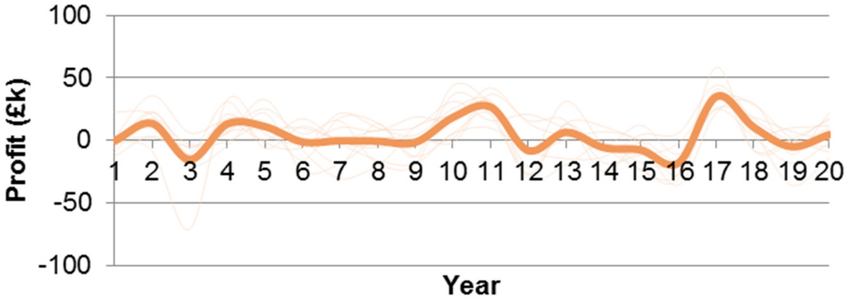

Figure A.5.4.14. Annual results of a 24 device WaveNET array, for a lifetime of 20 years, in terms of profit

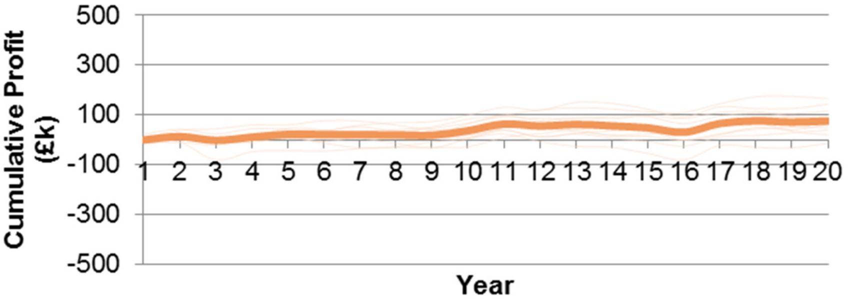

Figure A.5.4.15. Cumulative profit of a 24 device WaveNET array, for a lifetime of 20 years

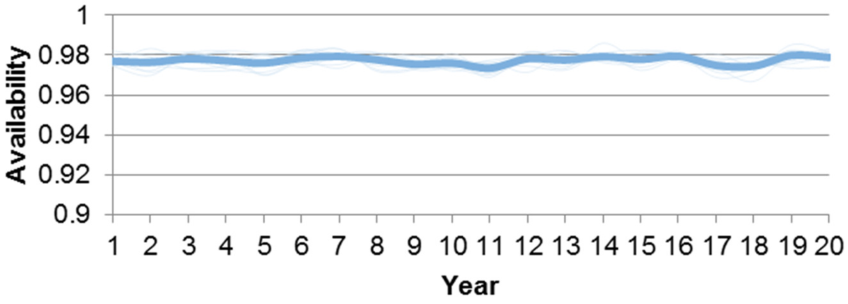

Figure A.5.4.16. Annual results of a 30 device WaveNET array, for a lifetime of 20 years, in terms of availability

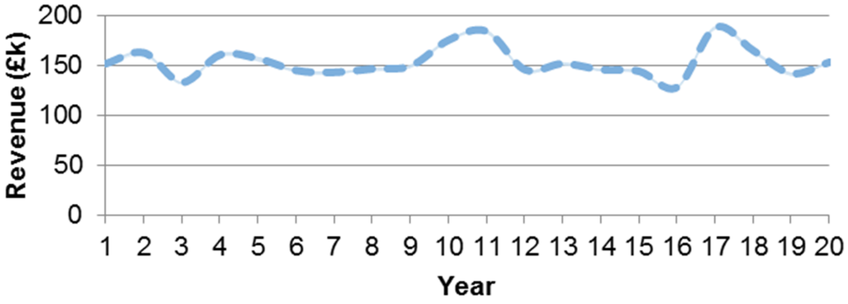

Figure A.5.4.17. Annual results of a 30 device WaveNET array, for a lifetime of 20 years, in terms of revenue

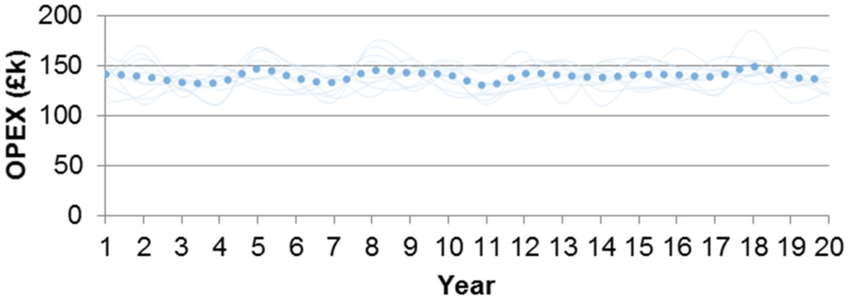

Figure A.5.4.18. Annual results of a 30 device WaveNET array, for a lifetime of 20 years, in terms of OPEX

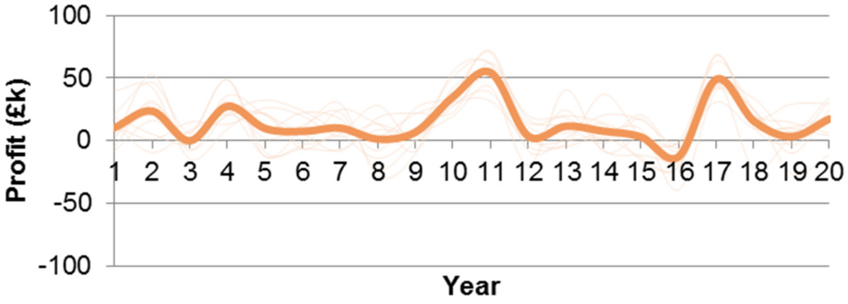

Figure A.5.4.19. Annual results of a 30 device WaveNET array, for a lifetime of 20 years, in terms of profit

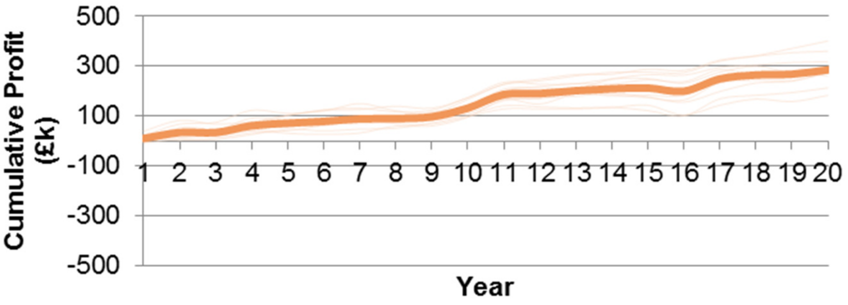

Figure A.5.4.20. Cumulative profit of a 30 device WaveNET array, for a lifetime of 20 years

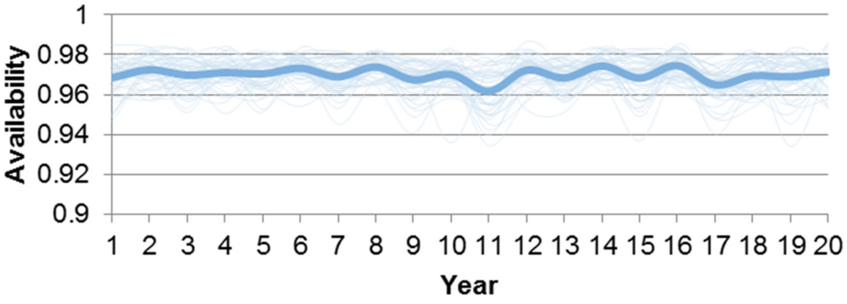

Figure A.5.6.1. Annual results of the 'onshore logistics scenario 1', for a lifetime of 20 years, in terms of availability

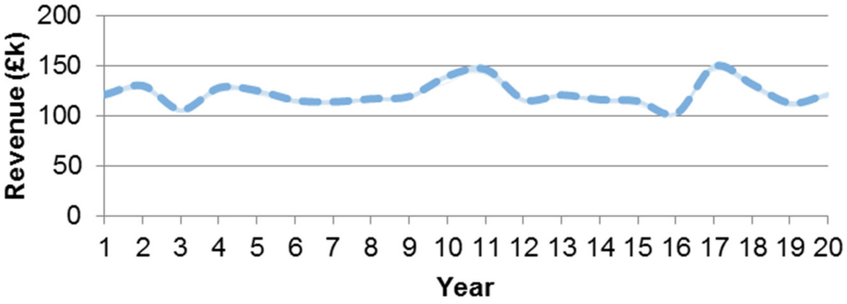

Figure A.5.6.2. Annual results of the 'onshore logistics scenario 1', for a lifetime of 20 years, in terms of revenue

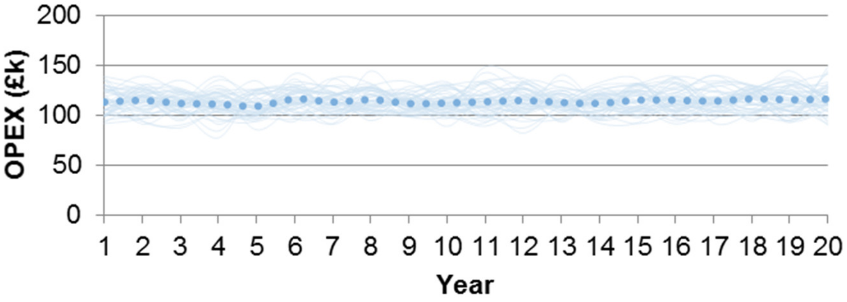

Figure A.5.6.3. Annual results of the 'onshore logistics scenario 1', for a lifetime of 20 years, in terms of OPEX

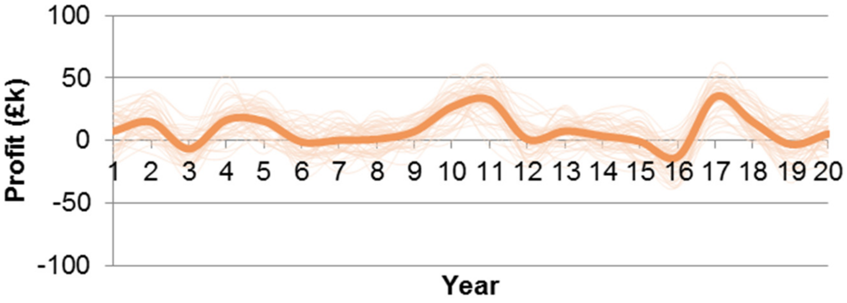

Figure A.5.6.4. Annual results of the 'onshore logistics scenario 1', for a lifetime of 20 years, in terms of profit

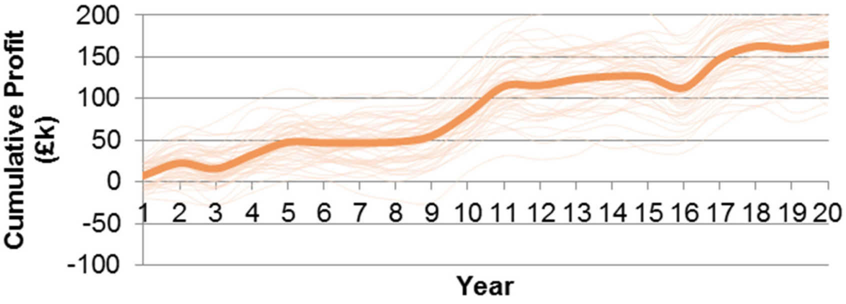

Figure A.5.6.5. Cumulative profit of the 'onshore logistics scenario 1', for a lifetime of 20 years

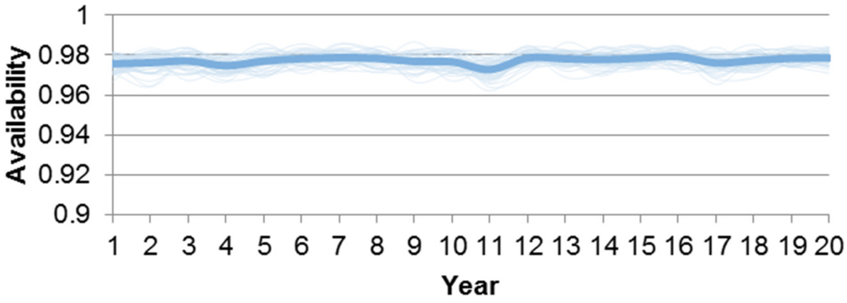

Figure A.5.6.6. Annual results of the 'onshore logistics scenario 2', for a lifetime of 20 years, in terms of availability

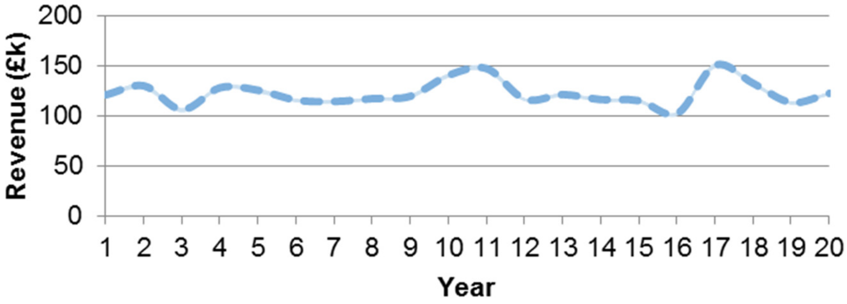

Figure A.5.6.7. Annual results of the 'onshore logistics scenario 2', for a lifetime of 20 years, in terms of revenue

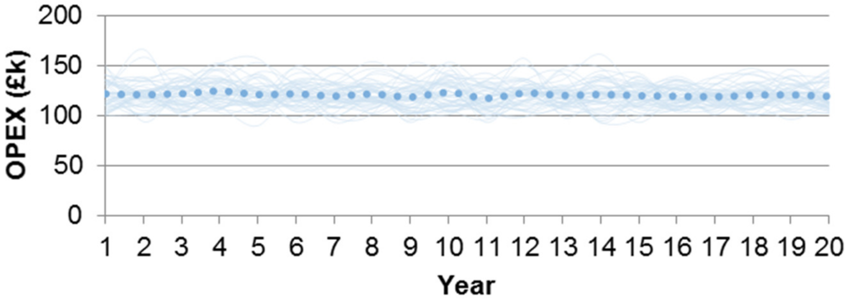

Figure A.5.6.8. Annual results of the 'onshore logistics scenario 2', for a lifetime of 20 years, in terms of OPEX

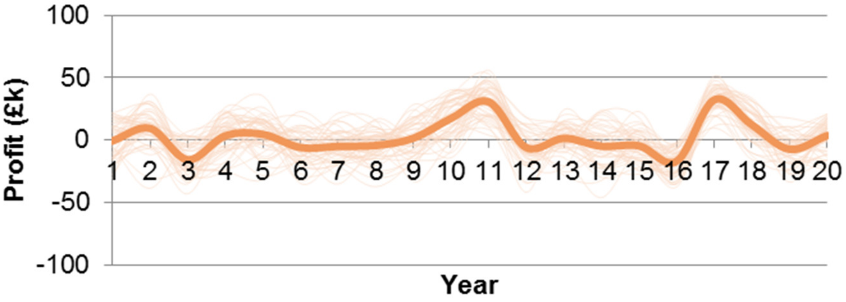

Figure A.5.6.9. Annual results of the 'onshore logistics scenario 2', for a lifetime of 20 years, in terms of profit

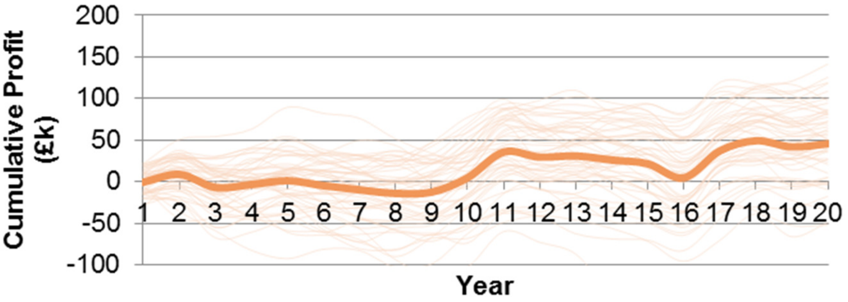

Figure A.5.6.10. Cumulative profit of the 'onshore logistics scenario 2', for a lifetime of 20 years

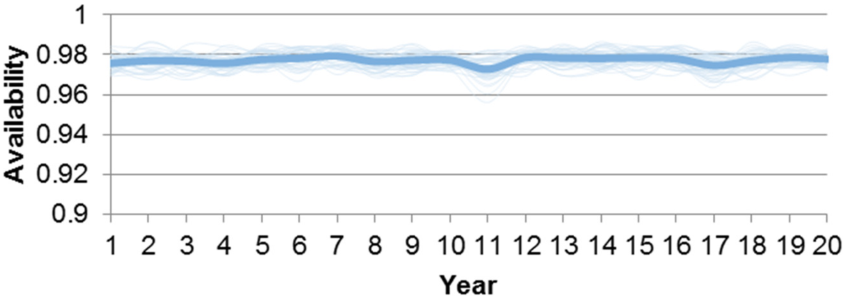

Figure A.5.6.11. Annual results of the 'onshore logistics scenario 3', for a lifetime of 20 years, in terms of availability

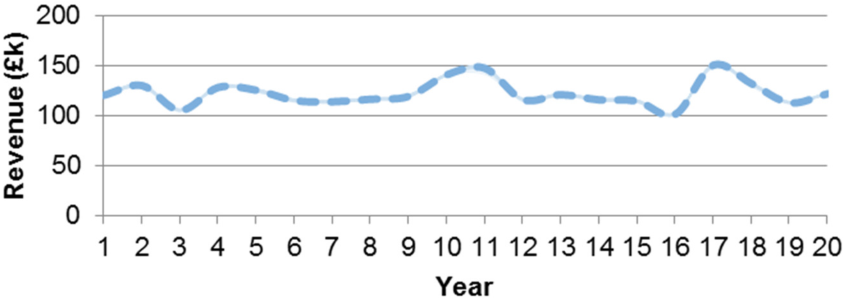

Figure A.5.6.12. Annual results of the 'onshore logistics scenario 3', for a lifetime of 20 years, in terms of revenue

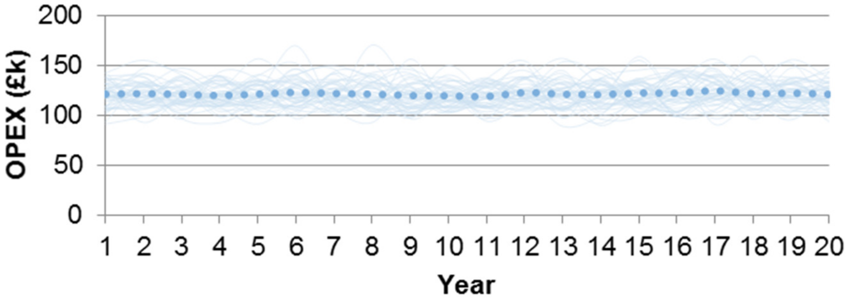

Figure A.5.6.13. Annual results of the 'onshore logistics scenario 3', for a lifetime of 20 years, in terms of OPEX

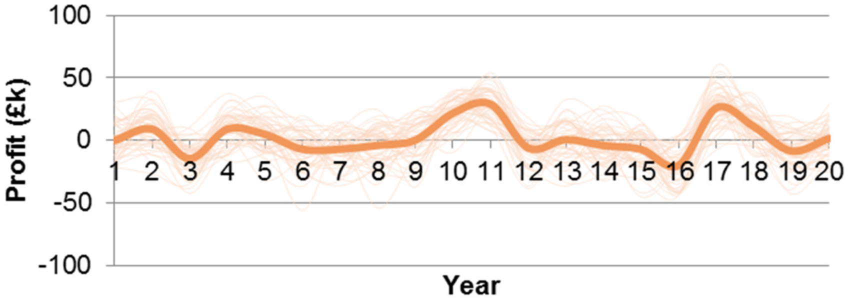

Figure A.5.6.14. Annual results of the 'onshore logistics scenario 3', for a lifetime of 20 years, in terms of profit

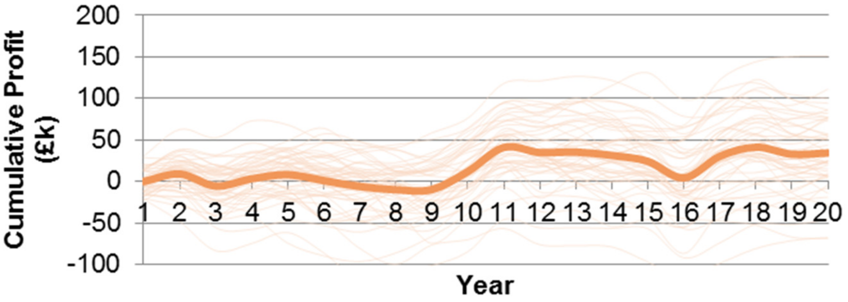

Figure A.5.6.15. Cumulative profit of the 'onshore logistics scenario 3', for a lifetime of 20 years

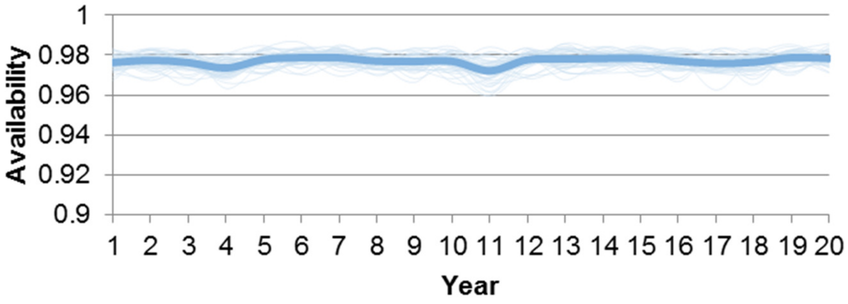

Figure A.5.6.16. Annual results of the 'onshore logistics scenario 4', for a lifetime of 20 years, in terms of availability

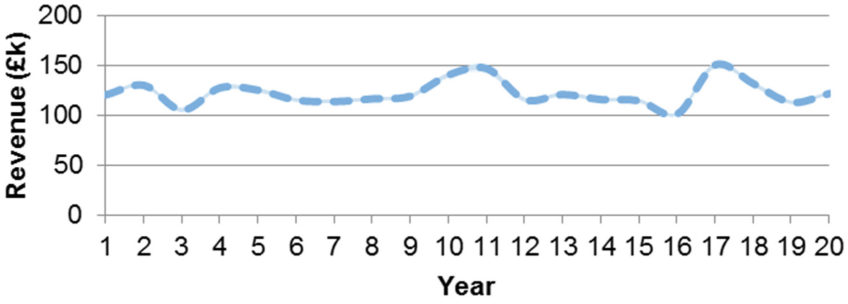

Figure A.5.6.17. Annual results of the ‘onshore logistics scenario 4’, for a lifetime of 20 years, in terms of revenue

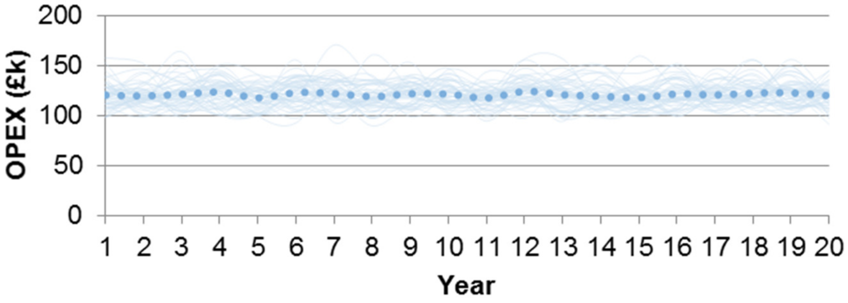

Figure A.5.6.18. Annual results of the ‘onshore logistics scenario 4’, for a lifetime of 20 years, in terms of OPEX

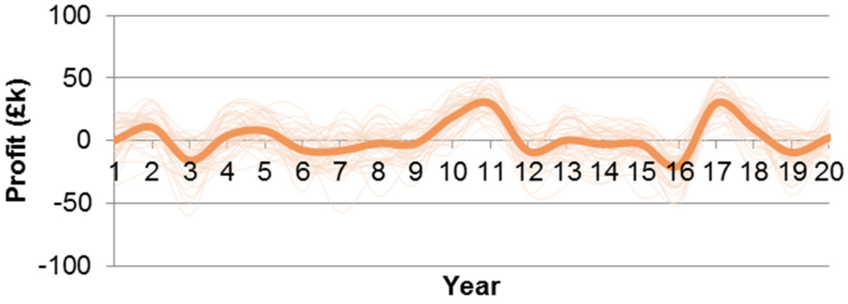

Figure A.5.6.19. Annual results of the ‘onshore logistics scenario 4’, for a lifetime of 20 years, in terms of profit

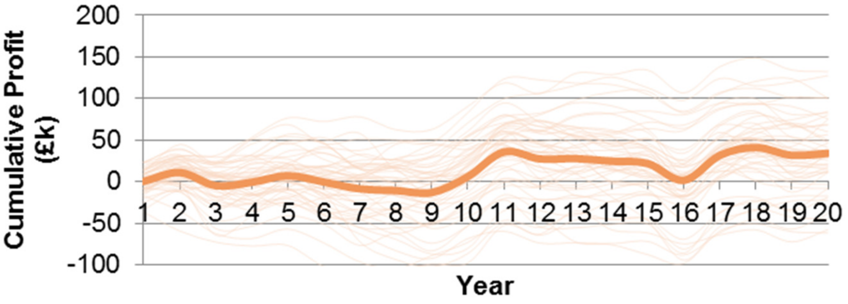

Figure A.5.6.20. Cumulative profit of the ‘onshore logistics scenario 4’, for a lifetime of 20 years

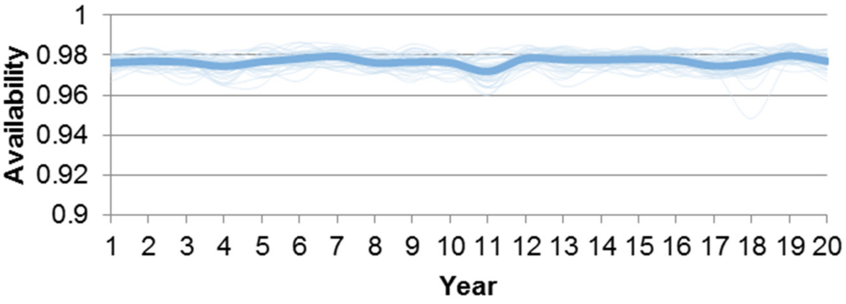

Figure A.5.6.21. Annual results of the 'onshore logistics scenario 5', for a lifetime of 20 years, in terms of availability

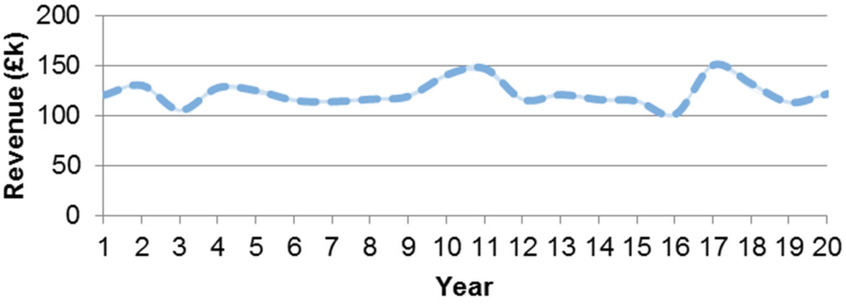

Figure A.5.6.22. Annual results of the 'onshore logistics scenario 5', for a lifetime of 20 years, in terms of revenue

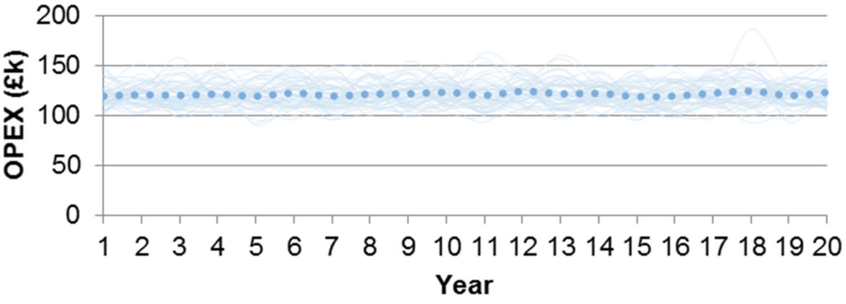

Figure A.5.6.23. Annual results of the 'onshore logistics scenario 5', for a lifetime of 20 years, in terms of OPEX

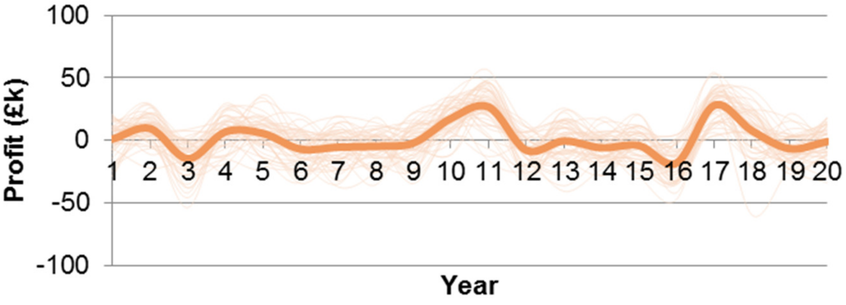

Figure A.5.6.24. Annual results of the 'onshore logistics scenario 5', for a lifetime of 20 years, in terms of profit

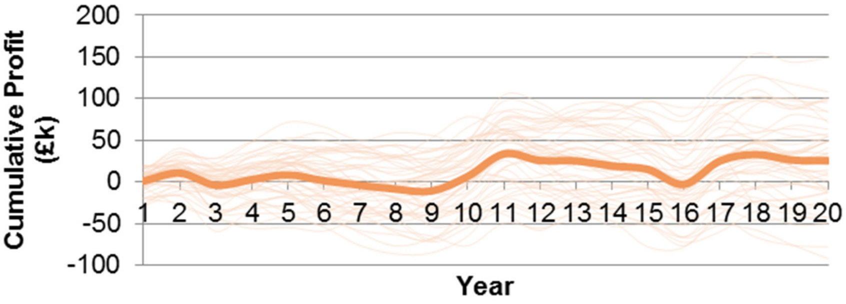

Figure A.5.6.25. Cumulative profit of the 'onshore logistics scenario 5', for a lifetime of 20 years

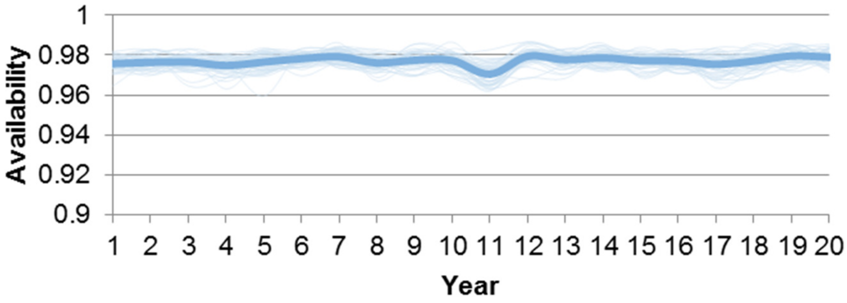

Figure A.5.6.26. Annual results of the 'onshore logistics scenario 6', for a lifetime of 20 years, in terms of availability

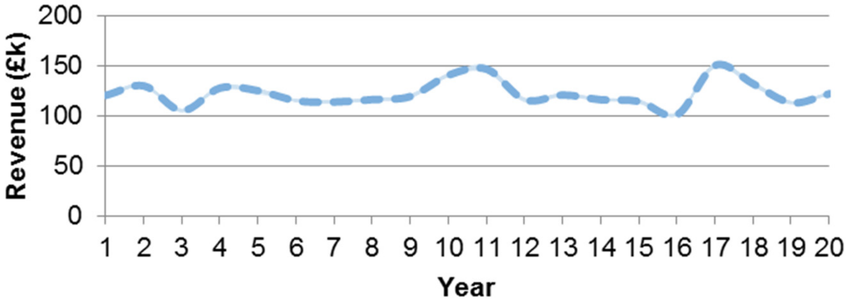

Figure A.5.6.27. Annual results of the 'onshore logistics scenario 6', for a lifetime of 20 years, in terms of revenue

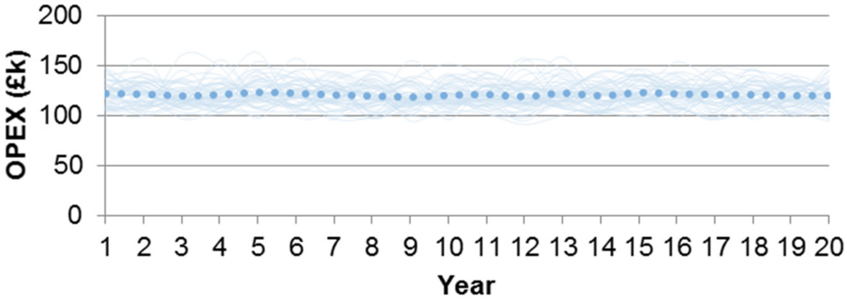

Figure A.5.6.28. Annual results of the 'onshore logistics scenario 6', for a lifetime of 20 years, in terms of OPEX

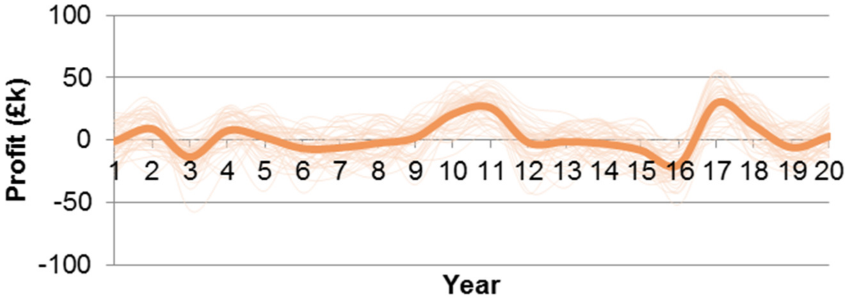

Figure A.5.6.29. Annual results of the 'onshore logistics scenario 6', for a lifetime of 20 years, in terms of profit

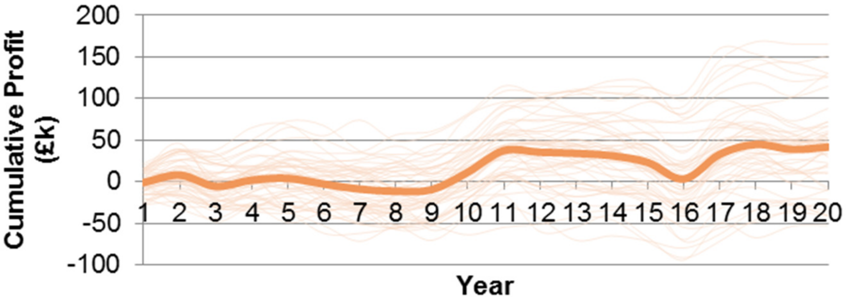

Figure A.5.6.30. Cumulative profit of the 'onshore logistics scenario 6', for a lifetime of 20 years

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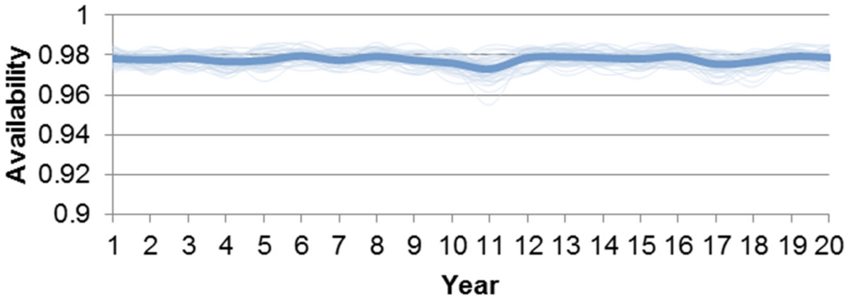

Figure A.5.7.1. Annual results with an extra 'slow boat', for a lifetime of 20 years, in terms of availability

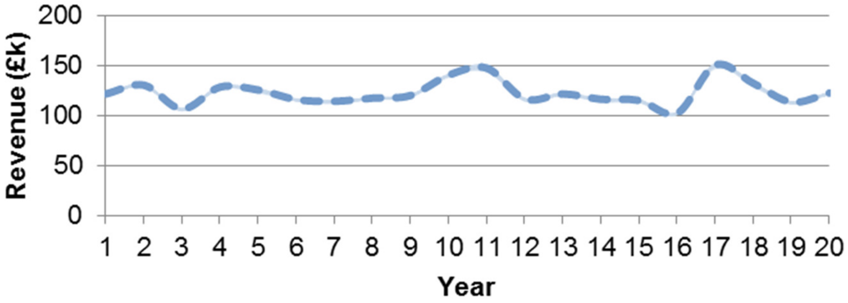

Figure A.5.7.2. Annual results with an extra 'slow boat', for a lifetime of 20 years, in terms of revenue

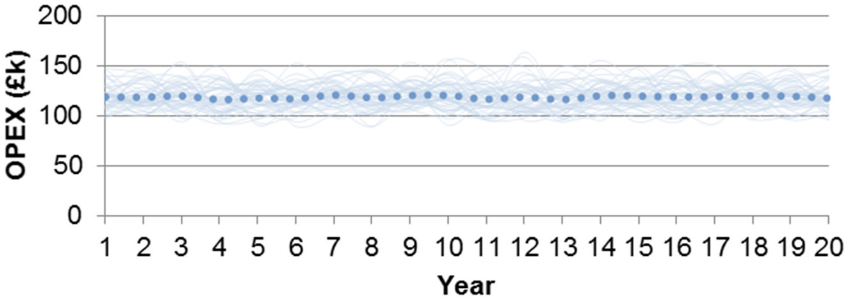

Figure A.5.7.3. Annual results with an extra 'slow boat', for a lifetime of 20 years, in terms of OPEX

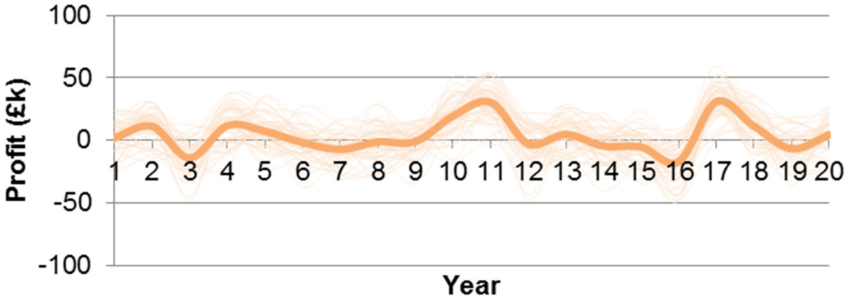

Figure A.5.7.4. Annual results with an extra 'slow boat', for a lifetime of 20 years, in terms of profit

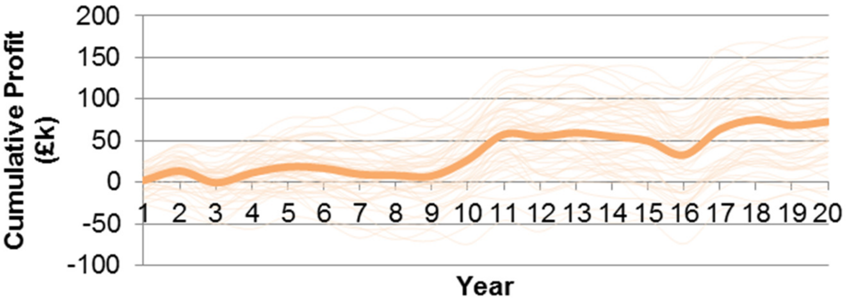

Figure A.5.7.5. Cumulative profit with an extra 'slow boat', for a lifetime of 20 years

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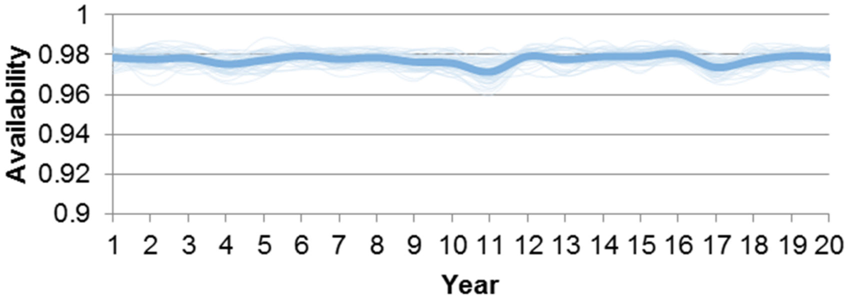

Figure A.5.8.1. Annual results of 'offshore maintenance scenario 1', for a lifetime of 20 years, in terms of availability

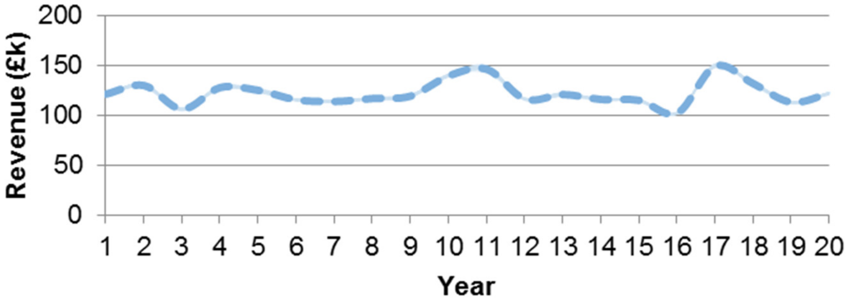

Figure A.5.8.2. Annual results of 'offshore maintenance scenario 1', for a lifetime of 20 years, in terms of revenue

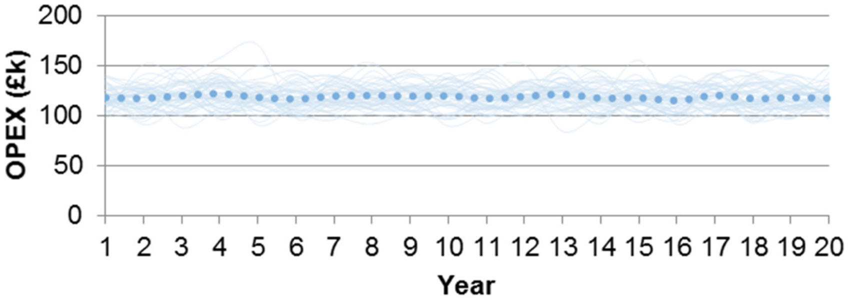

Figure A.5.8.3. Annual results of 'offshore maintenance scenario 1', for a lifetime of 20 years, in terms of OPEX

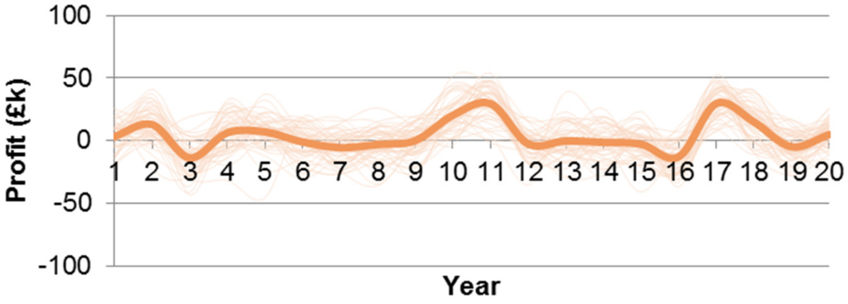

Figure A.5.8.4. Annual results of 'offshore maintenance scenario 1', for a lifetime of 20 years, in terms of profit

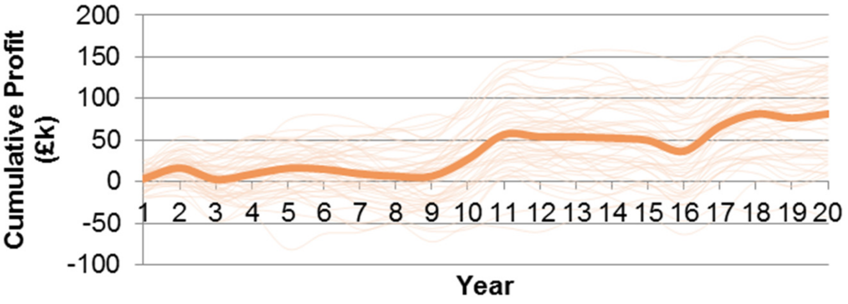

Figure A.5.8.5. Cumulative profit of 'offshore maintenance scenario 1', for a lifetime of 20 years

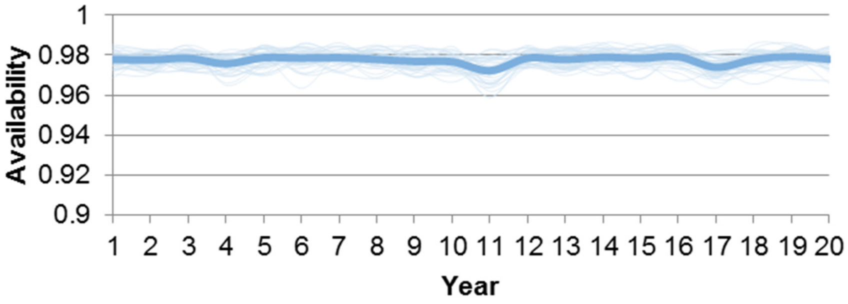

Figure A.5.8.6. Annual results of 'offshore maintenance scenario 2', for a lifetime of 20 years, in terms of availability

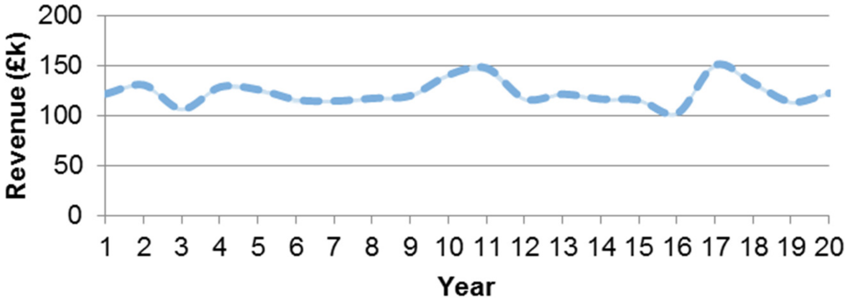

Figure A.5.8.7. Annual results of 'offshore maintenance scenario 2', for a lifetime of 20 years, in terms of revenue

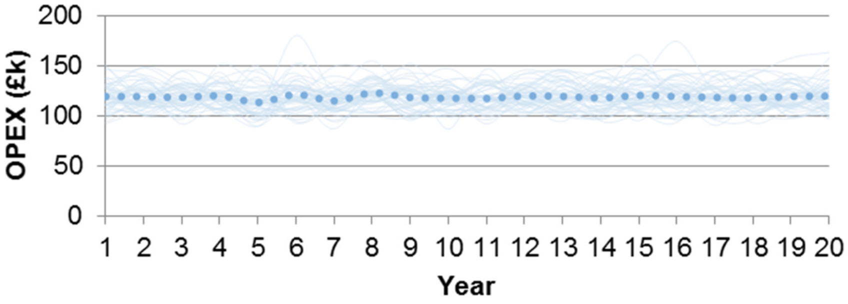

Figure A.5.8.8. Annual results of 'offshore maintenance scenario 2', for a lifetime of 20 years, in terms of OPEX

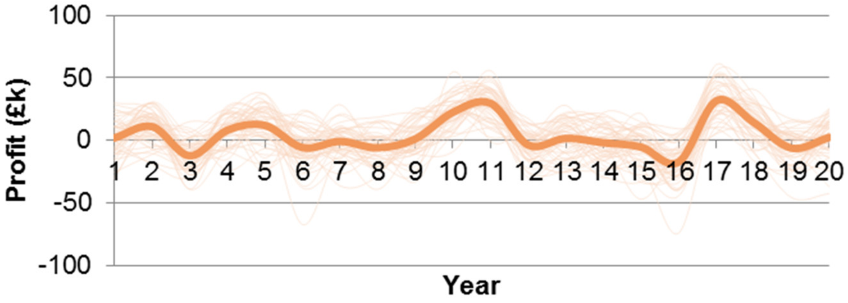

Figure A.5.8.9. Annual results of 'offshore maintenance scenario 2', for a lifetime of 20 years, in terms of profit

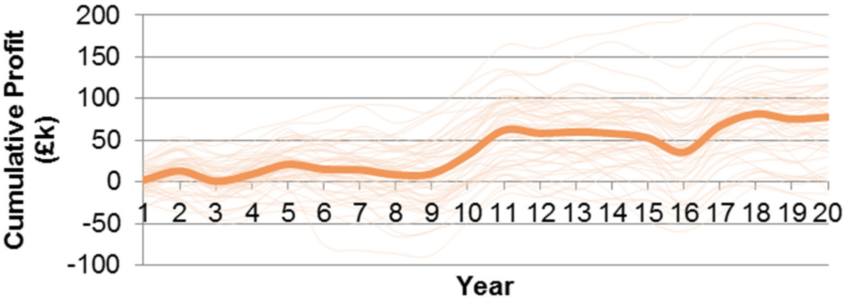

Figure A.5.8.10. Cumulative profit of 'offshore maintenance scenario 2', for a lifetime of 20 years

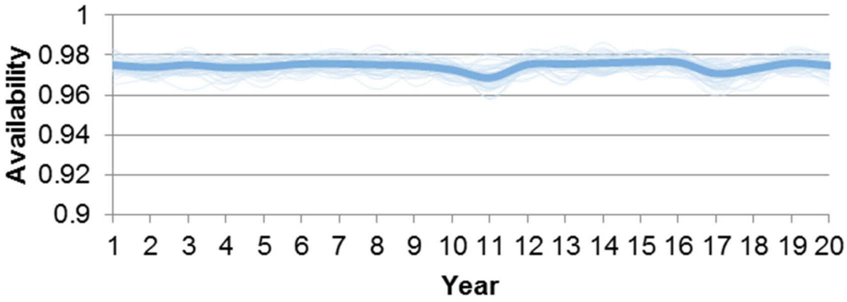

Figure A.5.8.11. Annual results of 'offshore maintenance scenario 3', for a lifetime of 20 years, in terms of availability

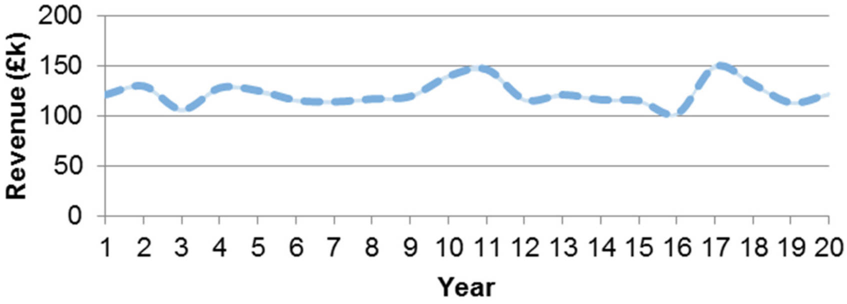

Figure A.5.8.12. Annual results of 'offshore maintenance scenario 3', for a lifetime of 20 years, in terms of revenue

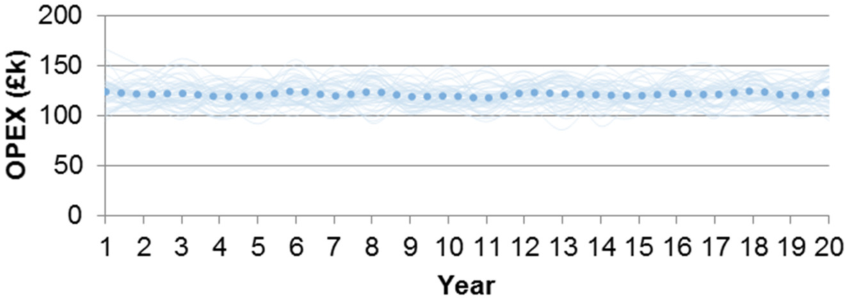

Figure A.5.8.13. Annual results of 'offshore maintenance scenario 3', for a lifetime of 20 years, in terms of OPEX

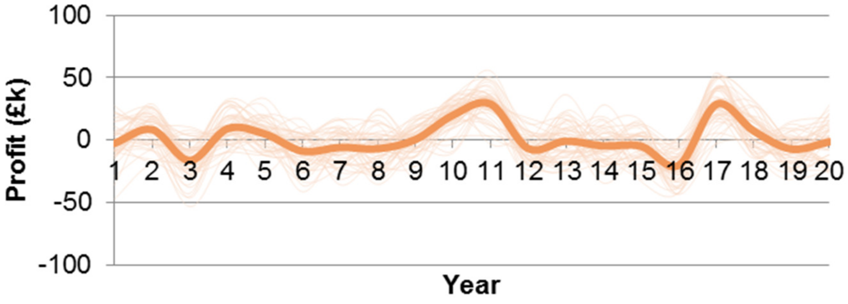

Figure A.5.8.14. Annual results of 'offshore maintenance scenario 3', for a lifetime of 20 years, in terms of profit

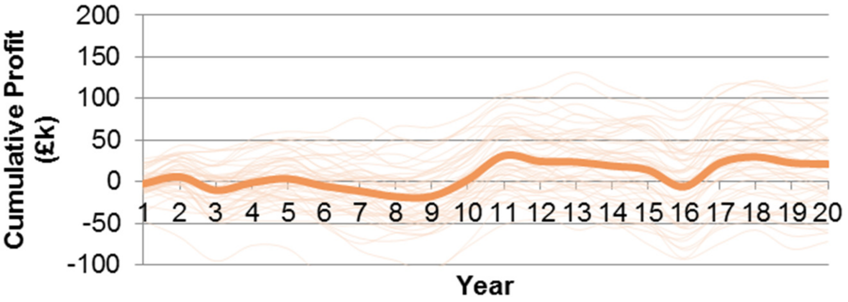

Figure A.5.8.15. Cumulative profit of 'offshore maintenance scenario 3', for a lifetime of 20 years

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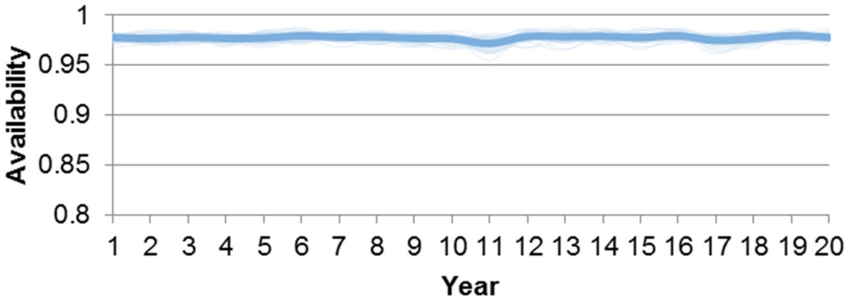

Figure A.5.9.1. Annual results of 'workforce arrangement scenario 1', for a lifetime of 20 years, in terms of availability

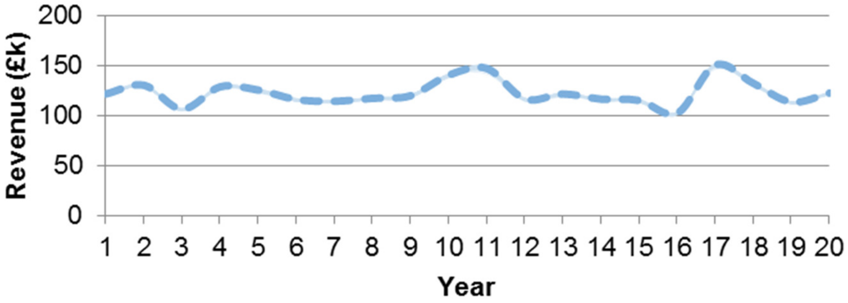

Figure A.5.9.2. Annual results of 'workforce arrangement scenario 1', for a lifetime of 20 years, in terms of revenue

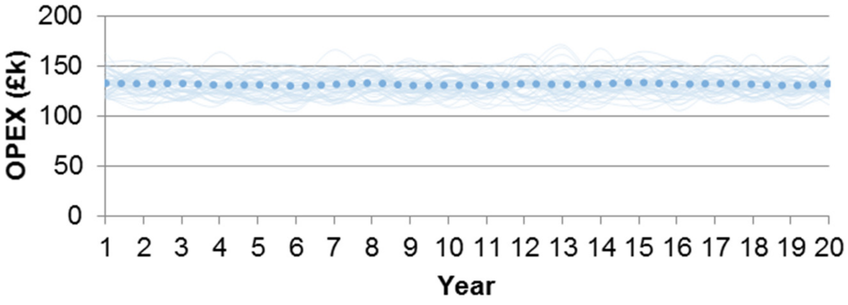

Figure A.5.9.3. Annual results of 'workforce arrangement scenario 1', for a lifetime of 20 years, in terms of OPEX

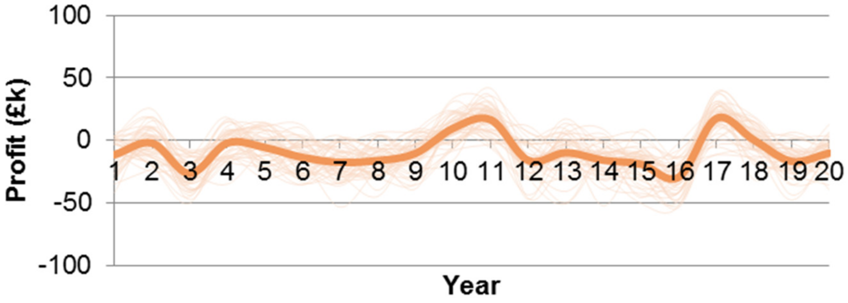

Figure A.5.9.4. Annual results of 'workforce arrangement scenario 1', for a lifetime of 20 years, in terms of profit

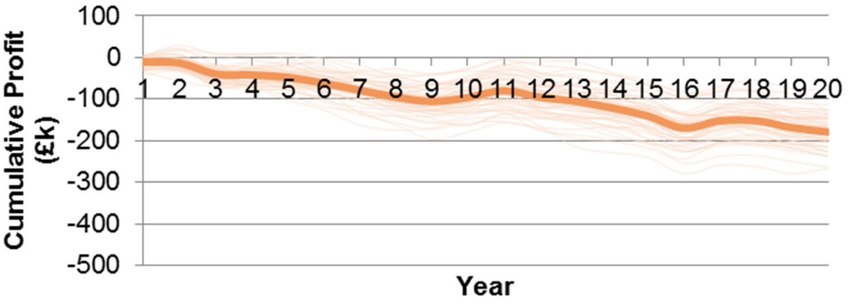

Figure A.5.9.5. Cumulative profit of 'workforce arrangement scenario 1', for a lifetime of 20 years

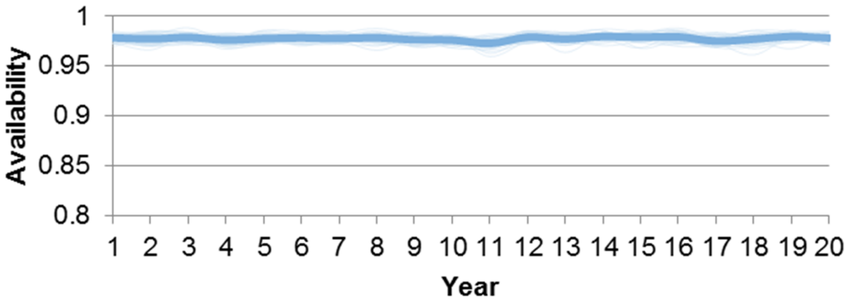

Figure A.5.9.6. Annual results of 'workforce arrangement scenario 2', for a lifetime of 20 years, in terms of availability

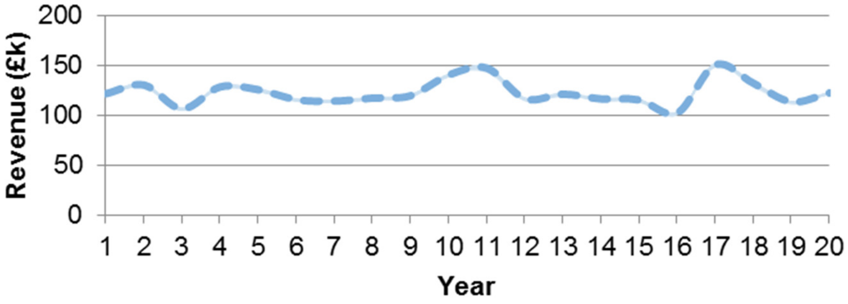

Figure A.5.9.7. Annual results of 'workforce arrangement scenario 2', for a lifetime of 20 years, in terms of revenue

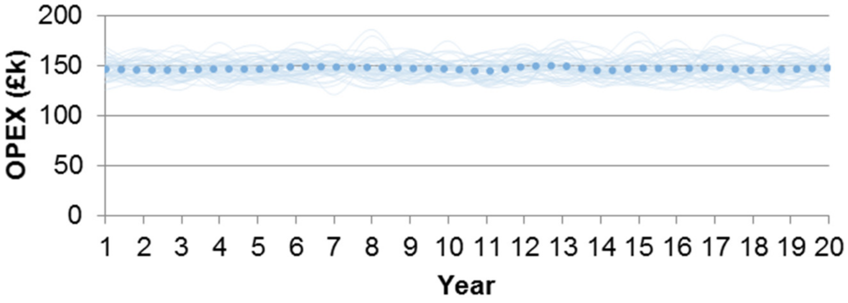

Figure A.5.9.8. Annual results of 'workforce arrangement scenario 2', for a lifetime of 20 years, in terms of OPEX

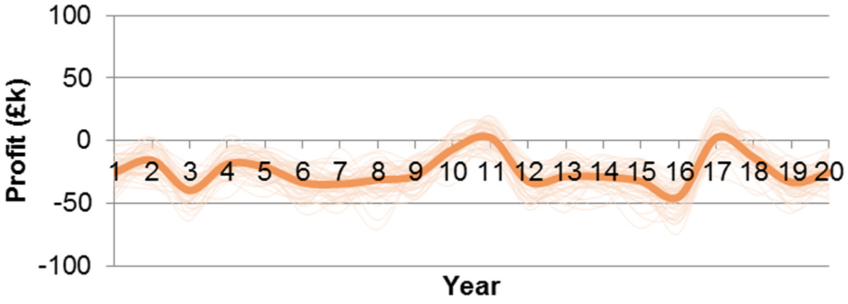

Figure A.5.9.9. Annual results of 'workforce arrangement scenario 2', for a lifetime of 20 years, in terms of profit

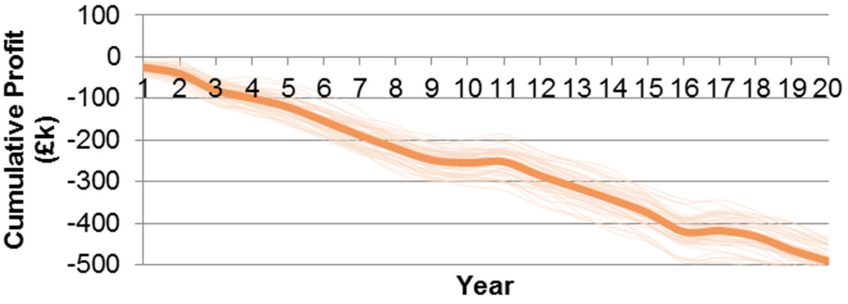

Figure A.5.9.10. Cumulative profit of 'workforce arrangement scenario 2', for a lifetime of 20 years

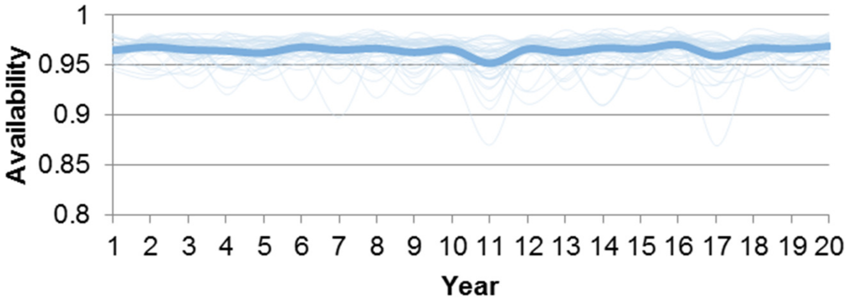

Figure A.5.9.11. Annual results of 'workforce arrangement scenario 3', for a lifetime of 20 years, in terms of availability

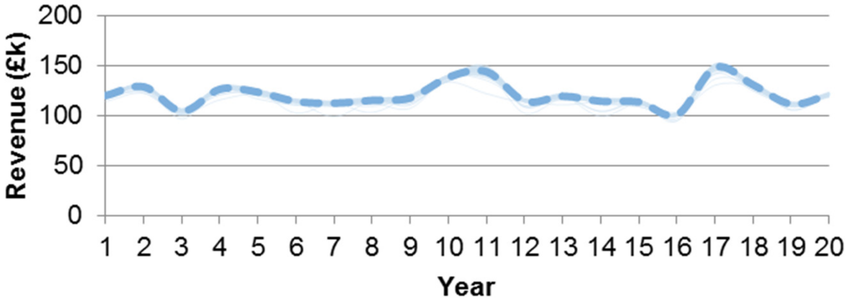

Figure A.5.9.12. Annual results of 'workforce arrangement scenario 3', for a lifetime of 20 years, in terms of revenue

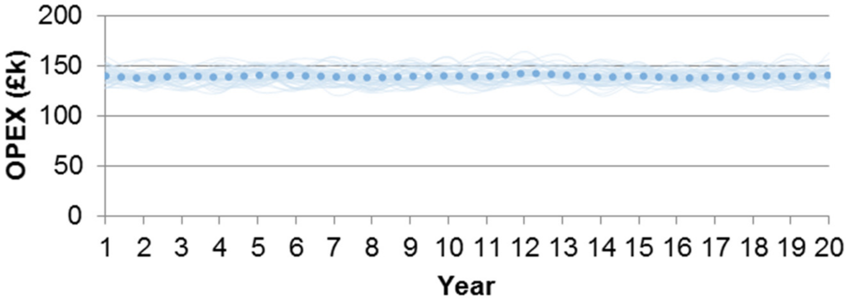

Figure A.5.9.13. Annual results of 'workforce arrangement scenario 3', for a lifetime of 20 years, in terms of OPEX

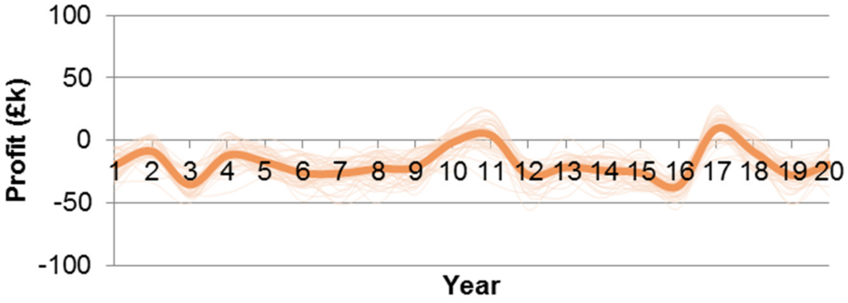

Figure A.5.9.14. Annual results of 'workforce arrangement scenario 3', for a lifetime of 20 years, in terms of profit

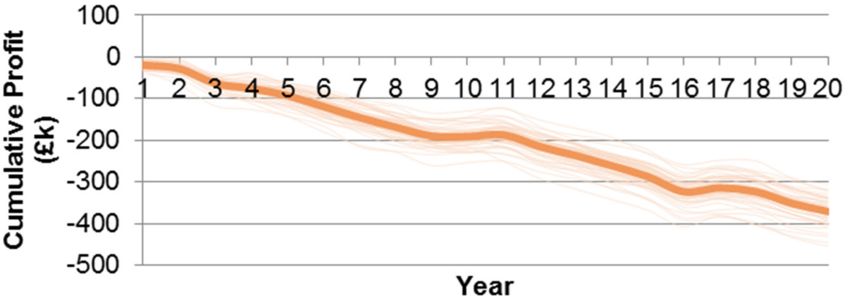

Figure A.5.9.15. Cumulative profit of 'workforce arrangement scenario 3', for a lifetime of 20 years

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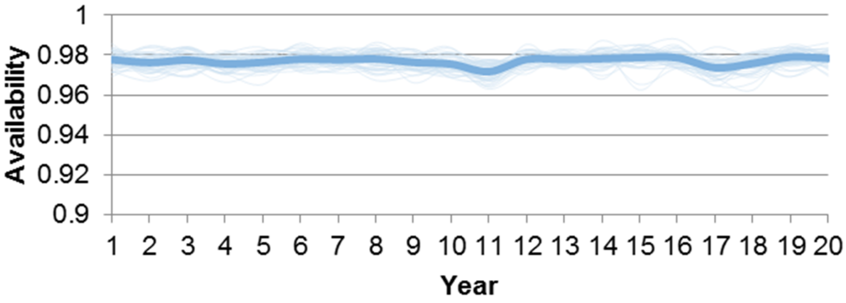

Figure A.5.10.1. Annual results of 'travel times scenario 1', for a lifetime of 20 years, in terms of availability

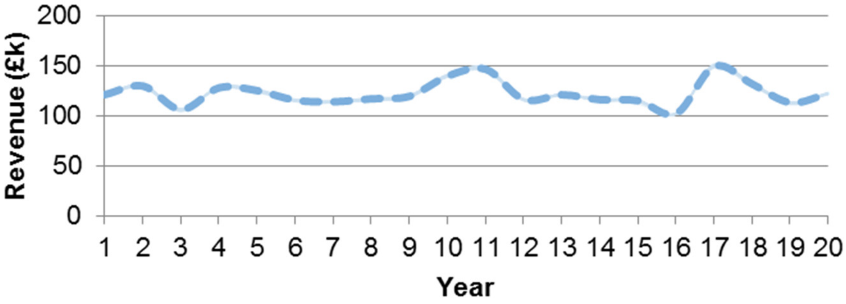

Figure A.5.10.2. Annual results of 'travel times scenario 1', for a lifetime of 20 years, in terms of revenue

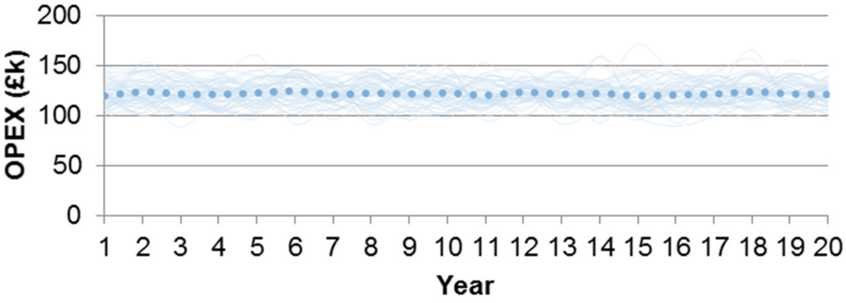

Figure A.5.10.3. Annual results of 'travel times scenario 1', for a lifetime of 20 years, in terms of OPEX

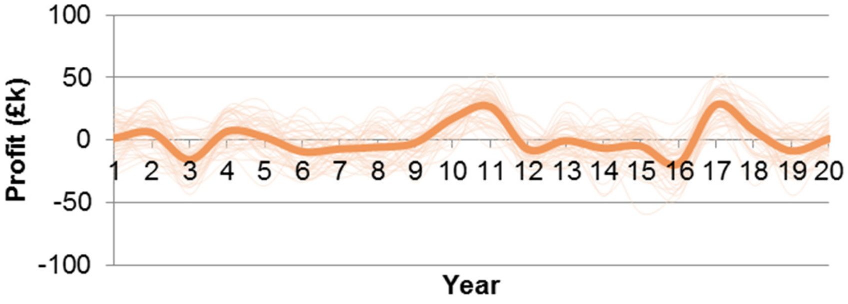

Figure A.5.10.4. Annual results of 'travel times scenario 1', for a lifetime of 20 years, in terms of profit

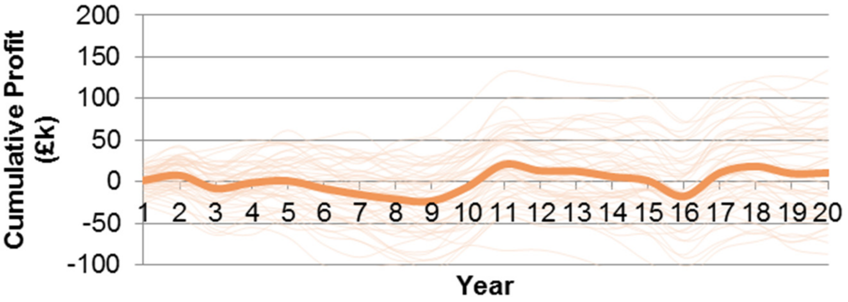

Figure A.5.10.5. Cumulative profit of 'travel times scenario 1', for a lifetime of 20 years

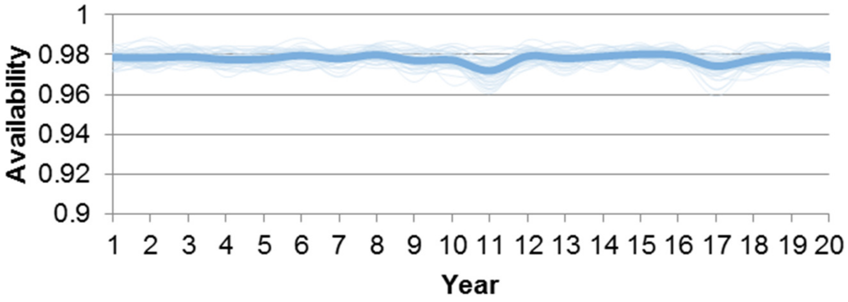

Figure A.5.10.6. Annual results of 'travel times scenario 2', for a lifetime of 20 years, in terms of availability

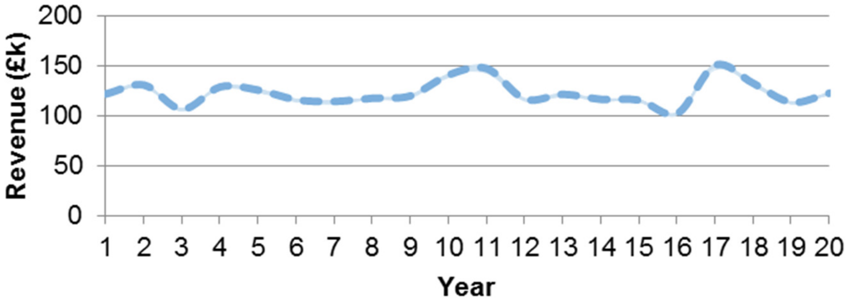

Figure A.5.10.7. Annual results of 'travel times scenario 2', for a lifetime of 20 years, in terms of revenue

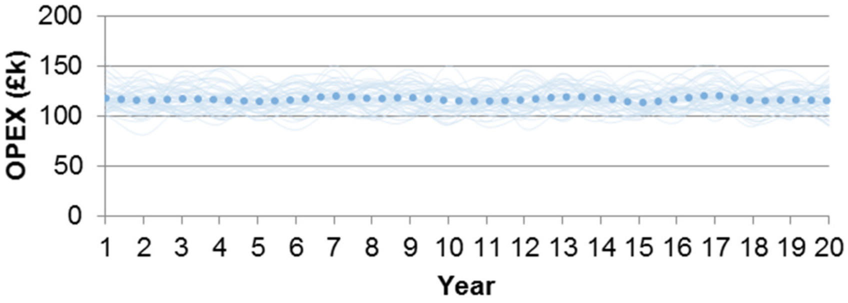

Figure A.5.10.8. Annual results of 'travel times scenario 2', for a lifetime of 20 years, in terms of OPEX

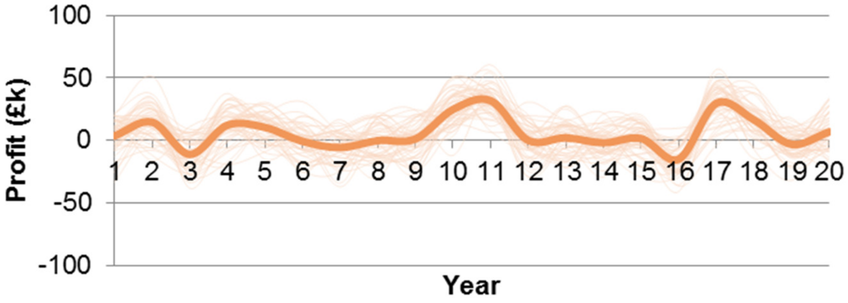

Figure A.5.10.9. Annual results of 'travel times scenario 2', for a lifetime of 20 years, in terms of profit

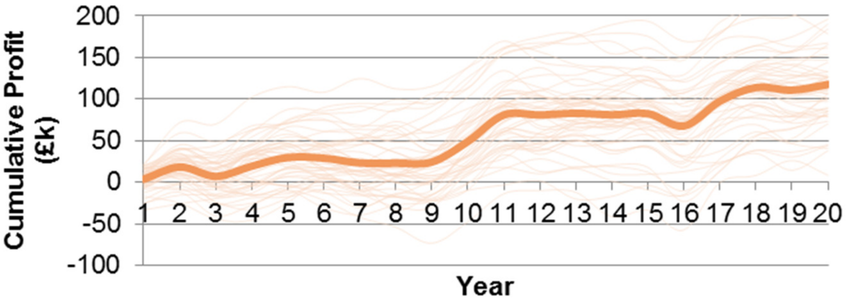

Figure A.5.10.10. Cumulative profit of 'travel times scenario 2', for a lifetime of 20 years

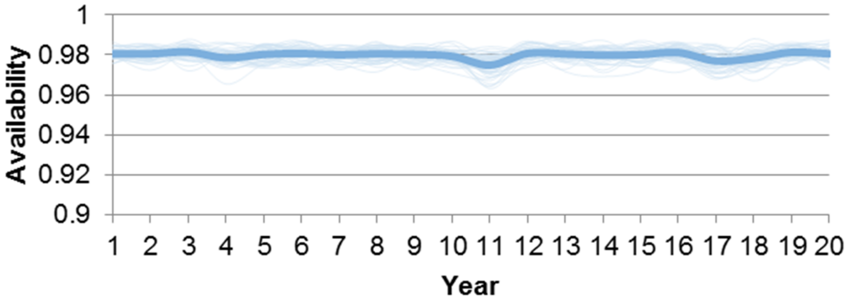

Figure A.5.10.11. Annual results of 'travel times scenario 3', for a lifetime of 20 years, in terms of availability

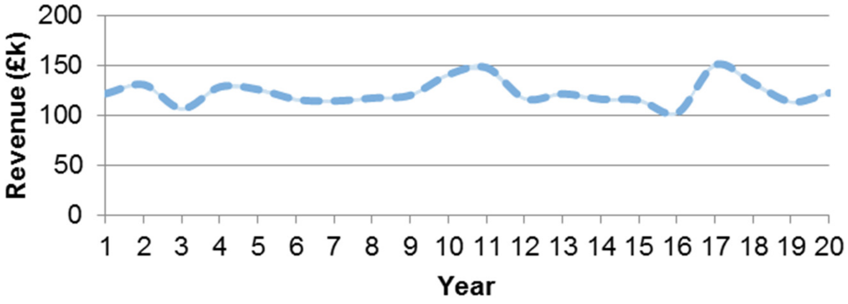

Figure A.5.10.12. Annual results of 'travel times scenario 3', for a lifetime of 20 years, in terms of revenue

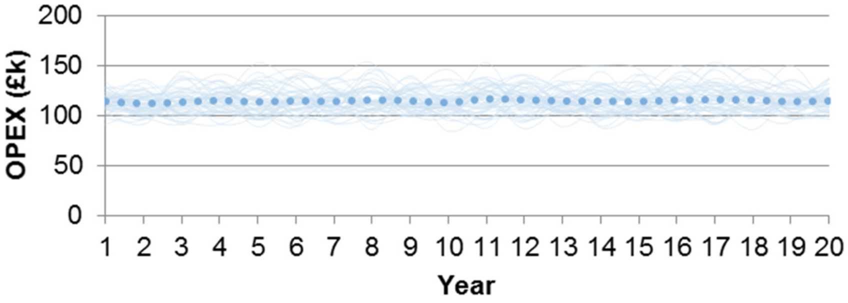

Figure A.5.10.13. Annual results of 'travel times scenario 3', for a lifetime of 20 years, in terms of OPEX

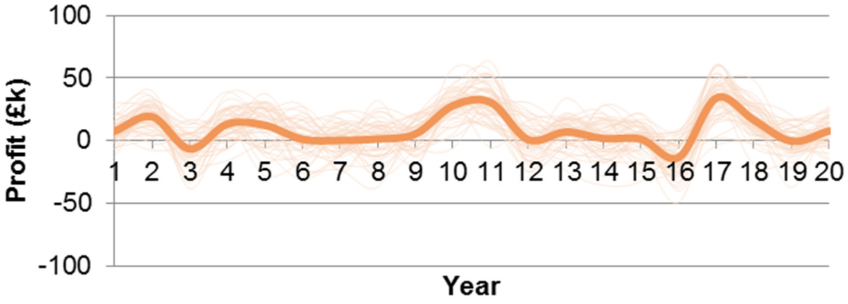

Figure A.5.10.14. Annual results of 'travel times scenario 3', for a lifetime of 20 years, in terms of profit

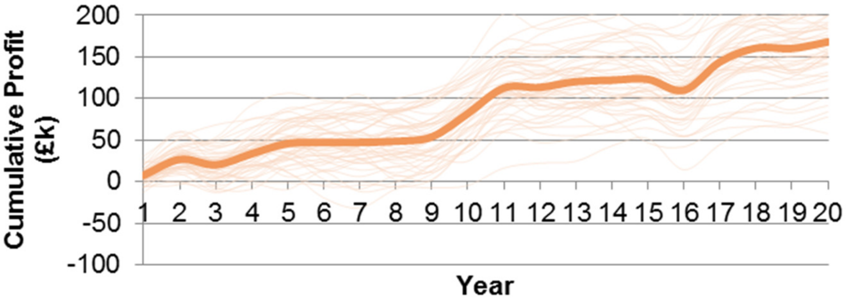

Figure A.5.10.15. Cumulative profit of 'travel times scenario 3', for a lifetime of 20 years

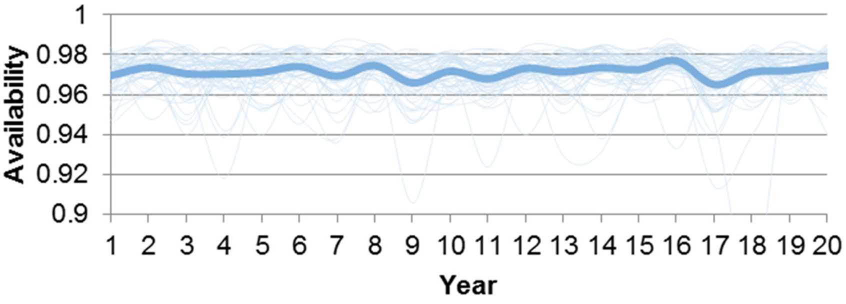

Figure A.5.12.1. Annual results of the 'optimal case' scenario, for a lifetime of 20 years, in terms of availability

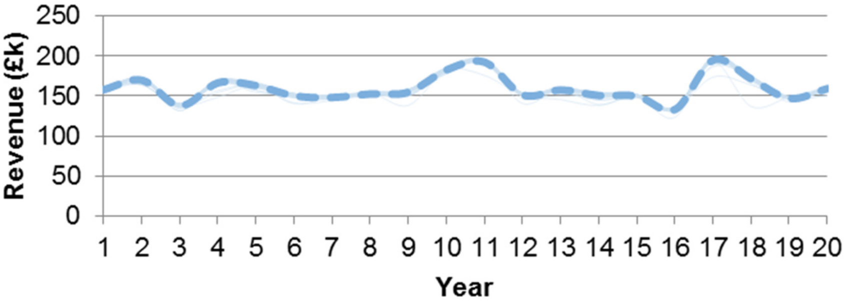

Figure A.5.12.2. Annual results of the 'optimal case' scenario, for a lifetime of 20 years, in terms of revenue

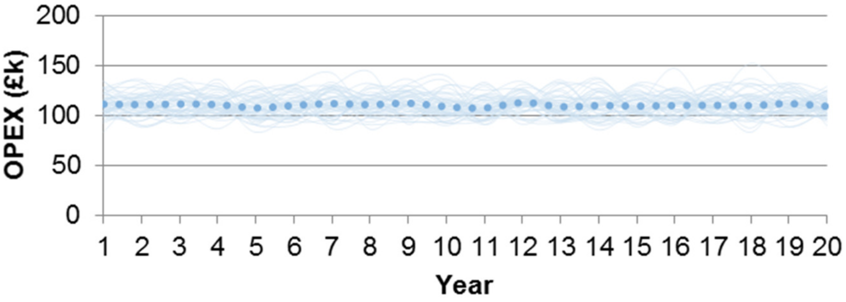

Figure A.5.12.3. Annual results of the 'optimal case' scenario, for a lifetime of 20 years, in terms of OPEX

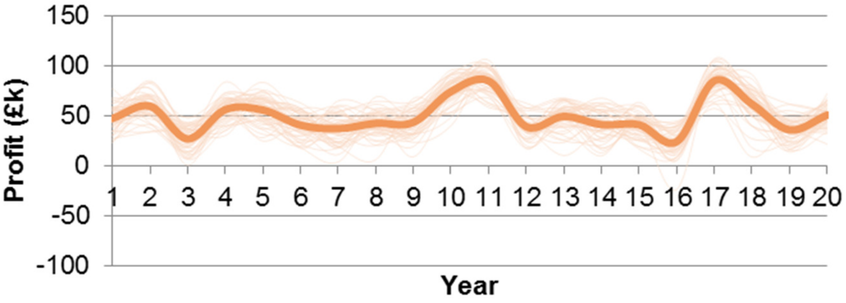

Figure A.5.12.4. Annual results of the 'optimal case' scenario, for a lifetime of 20 years, in terms of profit

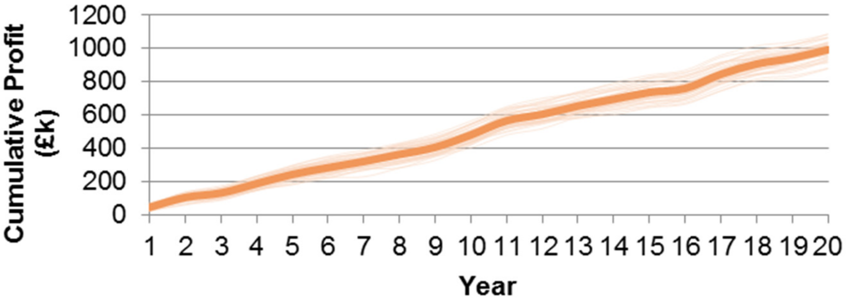

Figure A.5.12.5. Cumulative profit of the 'optimal case' scenario, for a lifetime of 20 years