Installation optimisation for marine energy converters to inform the designation process: Technical solutions to maximise economic benefits

Submitted by Richard Thomas Walker,

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

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Abstract

Whilst a number of methods exist for the analysis of site availability and weather downtime via metocean exceedance, there is little available for the detailed analysis of holistic marine energy installation projects. Given the magnitude of expenditure relating to the installation phase of marine energy extraction it is essential that significant cost reduction is achieved in this area.

This thesis presents methods for the analysis of marine operations, considering not just the at site work but the project as a whole. The methods developed consider multiple facets of installation in a geo-spatially diverse environment and utilize multiple resources, for example vessels. Consideration of not only the efficiency of work at site, but also the accessibility of the site due to vessel station keeping, mooring and transit limits is included.

By considering the project in its entirety work may be scheduled in a realistic manner; including simultaneous operations and at site transit to any of multiple working locations. These methods, packaged as a whole, represent a valuable new tool for utilisation in this area.

Novel application of the methods developed is demonstrated and highlights the value, importance and power of this type of analysis. Two marine energy installations are considered as case studies; the Wave Hub in south west England, and a tidal installation at the European Marine Energy Centre in Orkney. These applications demonstrate the knowledge which may be gained and, explicitly in the latter case, the significant cost reductions which may be achieved through the essential optimisation of the installation operations using this newly developed analysis tool.

Outputs

Walker, R.T., Johanning, L. and Parkinson, R.J. (2011) “Weather Windows for Device Deployment at UK Test Sites: Availability and Cost Implications”, In the *9th European Wave and Tidal Energy Conference (EWTEC 2011)*, Southampton, 5^{th} to 9^{th} September, 2011.

Walker, R.T., van Nieuwkoop-McCall, J., Johanning L., and Parkinson, R.J. (2013) “Calculating Weather Windows: Application to transit, installation and the implications on deployment success”, *Ocean Engineering*, vol. 68, pp. 88-101.

Morandeau, M., Walker, R.T., Argall, R. and Nicholls-Lee, R.F. (2013) “Optimisation of Marine Energy Installation Operations”, In the *10^{th} European Wave and Tidal Energy Conference (EWTEC 2013)*, Aalborg, 2^{nd} to 5^{th} September, 2013.

Mermaid (Marine Economic Risk Management Aid), a software package based on the described methods which is utilized by Mojo Maritime in the analysis of offshore operations.

Acknowledgements

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Special thanks to my wife Heather and daughter Catherine for being by my side throughout this undertaking. Catherine, Daddy will try to be home before bedtime more often now that the end is in sight.

Finally, any errors, omissions or oversights are entirely my own.

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Nomenclature

Weibull Method

b	-	Weibull slope parameter
k	-	Weibull shape parameter
A	-	Site specific parameter relating to calculation of window length
C_{ac}	-	Site specific parameter relating to probability of persistence for a normalised window
D	days	Duration of interval under study
H	m	Wave height
$\overline{H}$	-	Site specific parameter relating to calculation of window length
H_{ac}	m	Access wave height, upper threshold for access
N_{ac}	days	Access days, for site access
N_{wa}	days	Waiting days, for site access
Pw	-	Weibull probability of exceedance
X_0	-	Weibull location parameter
X_{ac}	-	Site specific parameter relating to probability of persistence for a normalised window
X_i	-	Normalised duration of persistence
β	-	Site specific parameter relating to calculation of window length
γ	-	Site specific parameter relating to calculation of window length
τ_{ac}	hours	Average window length

Mermaid Method

$d_{(n)}$	km	Cumulative transit distance at time step n
d_{sp}	km	Total distance between site and port
hu	-	Array of hook up time steps
m	-	Transit waypoint index
m_{sp}	-	Total number of transit way points between site and port
n	-	Time step index
r_j	-	Task working efficiency, of individual metocean types
r_{j0}	-	Task working efficiency, considering all metocean types
r_{jh}	-	Vessel hook up/unhook efficiency
r_{jv}	-	Vessel station keeping efficiency
$r_{j\tau}$	-	Transit efficiency
s	-	Suspendable (1) or non-suspendable (0) task
s_n	time steps	Total score of work performed on a task
s_{nh}	time steps	Total score of work during hook up/unhook window
$s_{n\text{-}temp}$	time steps	Total score of work performed at each time step
st	hours or time steps	Array of storm time steps
t	time steps	Time, as input, in time steps
$t_{(dp)}$	time steps	Time step for departure from port
$t_{(ds)}$	time steps	Time step for departure from site

$t_{(n)}$	time steps	Time step
t_{as}	time steps	Time steps spend at site waiting for hook up
t_{down}	time steps	Time spent in downtime
$u(r_{j\tau(n)})$	m/s	Transit velocity at given time step and efficiency
uh	-	Array of unhook time steps
w	-	Column index of metocean types array
R	km	Radius of Earth
T	hours	Time, as input, in hours
α	hours or time steps	Task start up time, α_0 or α_s depending on context
α_0	hours or time steps	Task start up time
α_s	hours or time steps	Task re-start time
α_{vp}	hours or time steps	Hook up time required in port
α_{vs}	hours or time steps	Hook up time required at site
β_{vp}	hours or time steps	Unhook time required in port
β_{vs}	hours or time steps	Unhook time required at site
γ	-	Number of time task has been suspended after work has started
Δt	hours or time steps	Time step size, or difference in time steps
η_0	-	0% efficiency threshold
$\eta_{0.5}$	-	50% efficiency threshold

θ	°	Transit bearing
λ_0	hours or time steps	Task minimum working time
λ_{0s}	hours or time steps	Task maximum pause time
λ_{calm}	hours or time steps	Vessel calm threshold
λ_{st}	hours or time steps	Vessel storm threshold
μ	° or radians	Latitude
σ_0	hours or time steps	Task required working time, at 100% efficiency
σ_h	hours or time steps	Hook up/unhook required working time, σ_{hu} or σ_{uh} depending on context
σ_{hu}	hours or time steps	Hook up required working time
σ_{uh}	hours or time steps	Unhook required working time
τ_1	time steps	Fastest transit between port and site
τ_{sp}	time steps	Slowest transit between port and site
φ	° or radians	Longitude
ω	-	Metocean types

1 Literature review

1.1 Marine renewable energy in the UK

The UK Renewable Energy Strategy outlines the method by which the United Kingdom intends to meet its legally binding targets of 15% of all energy needs being produced from renewable resources by 2020. This target represents almost a seven fold increase in renewable energy generation in ‘scarcely more than a decade’ (Department of Energy and Climate Change (DECC), 2009, p.8). The document discusses both how and why Her Majesties Government (HM Government) intends to increase renewable usage in the United Kingdom and proposes methods for achieving these ambitious targets. HM Government believe that *more than* 30% of the UK’s electricity can be generated from renewable sources; this is an increase from 5.5% (in 2009). It is stated that much of this will be from wind power, both on- and offshore, but also that technologies such as wave and tidal generation will have an important part to play in the new energy mix (DECC, 2009).

The UK is an island nation with approximately 11,000 miles of coast line (Darkes, 2008); consequently it has a number of marine energy test sites (e.g. Wave Hub, EMEC, FabTest) and a number of large scale array deployments and marine energy parks proposed in the future (BBC, 2010, and DECC, 2012). Furthermore, the Carbon Trust has estimated that the UK has a practically exploitable wave resource of 50TWh/yr and a practically exploitable tidal stream resource of 18TWh/yr (Callaghan, 2006). The significance of this resource should not be underestimated with marine renewable energy sources having an integral role in both diversifying and supplementing the UK energy mix.

HM Government has therefore made a series of commitments, including the provision of funds for research and development, and enhancing support for marine renewable through the Renewables Obligation rebranding (ENVIROS, 2009 and Cheeseman, 2012). The provision of research and development funds has been undertaken through the establishment of the Marine Renewables Deployment Fund, the Marine Renewables Proving Fund, Technology Strategy Board (TSB) grants and the Saltire Prize. These Grants (TSB, 2010a; 2010b; 2012) are focused on reducing the cost of marine renewables by improving performance and addressing some of the key issues relating to the underpinning deployment. Alongside these financial commitments HM Government intend to contribute to the growth of the industry by identifying suitable deployment sites in the UK via Strategic Environmental Assessments.

The Strategy clearly outlines the framework which supports, and indeed makes vital, research in this field.

In response to the UK Renewable Energy Strategy further documents have been produced, including the Marine Energy Action Plan (DECC, 2010), the RenewableUK Manifesto 2010 (RenewableUK, 2010) and the RenewableUK State of the Industry report (RenewableUK, 2011). The Marine Energy Action Plan outlines the actions required by the private and public sector to 'facilitate the development and deployment of marine energy' (DECC, 2010, p.6). RenewableUK is the trade and professional body for the UK wind and marine energy industry. In response to the UK Renewable Energy Strategy RenewableUK, urge early, focussed, long term support for marine renewable energy. This is in keeping with the aims of the Strategy and the vision of the Marine Energy Action Plan.

Two important points are identified in the manifesto, firstly, the potential skills shortage; both skilled labour in the long term and quality post-doctoral specialists in the short term are required, to be achieved through the provision of research funding to higher education institutions. Secondly there is concern regarding the cost burden to be overcome. It is stated that 'projects are already facing high development costs because the technology is in its early stages' (RenewableUK, 2010, p.25). The Marine Energy Action Plan also supports cost reduction via research and development. It states that 'cost reduction is likely to be found through fundamental changes in the engineering design of devices; anchoring; more efficient use of materials; *new and innovative ways of conducting installation, operation and maintenance*; and increased efficiency of components' (DECC, 2010, p.9, [emphasis added]). This statement defines the current state of the industry, and to some extent defines the challenge ahead.

The Royal Academy of Engineering (2004) estimated the cost of generating electricity via marine renewable energy at almost 7 pence/kilowatt hour. By comparison onshore wind costs just over 5p/kWh and gas fired power stations just over 2p/kWh. The Carbon Trust (2006) placed the cost of marine renewable energy significantly higher, between 9 and 25 p/kWh depending on the type of technology. For the uptake of renewable energy to increase the cost associated with generation must be minimised.

The Carbon Trust and Dudziak *et al.* (2009) have discussed the cost breakdown of marine renewable energy projects, specifically wave energy converters. Both documents identify the major cost points in a project; these being the device itself and the installation process. They report that for a single device the cost of installation can be 30% of the total project cost. The cost of the device itself is estimated to be between 24% and 34%.

The Marine Energy Action Plan suggests cost reduction could be achieved by optimisation of moorings and the installation process. Figure 1-1, produced from the data contained within the Carbon Trust and Dudziak's reports, supports these conclusions. Installation, at almost one-third of the total cost, is an area in which cost reductions can and should be achieved. The term "installation", however, is broad given the diversity seen in the marine energy sector is not one which easily directs a research effort. For example, "installation" with respect to a floating, offshore oscillating water column has different implications than when applied to a horizontal axis tidal turbine project. It is therefore essential to qualify the industry under assessment.

Figure 1-1: Installation and device costs as a proportion of the total project cost for a single wave energy converter

Utilising data from the European Marine Energy Centre website (EMEC, 2010a; EMEC 2010b) a study was conducted in which 66 wave energy and 44 tidal energy device developers were identified. It was seen that 50% of devices across both generation types were seabed fixed, whilst 40% were moored (Figure 1-2).

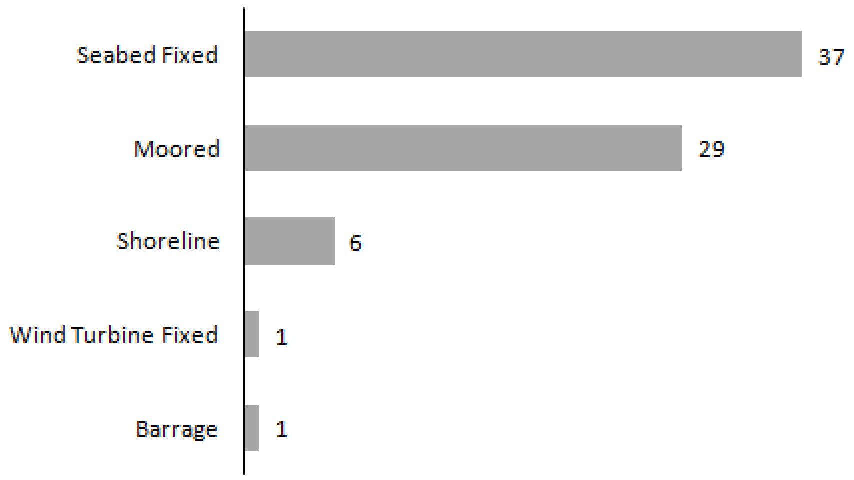


Figure 1-2: Types of station keeping technology as employed in the marine renewable energy sector

Figure 1-3 shows the potential cumulative installed capacity of marine renewable energy projects in the UK from 2009 to 2020. This chart was produced by the British Wind Energy Association (BWEA, now known as RenewableUK), and they state 'The graph is for illustrative purposes only to demonstrate the potential growth of the industry to reach the estimated targets of [between] 1 GW […] and 2 GW installed capacity by 2020. The actual level of capacity installed by 2020 will be very dependent on enabling actions and policies that support the development of the marine industry' (BWEA, 2009, p.8).

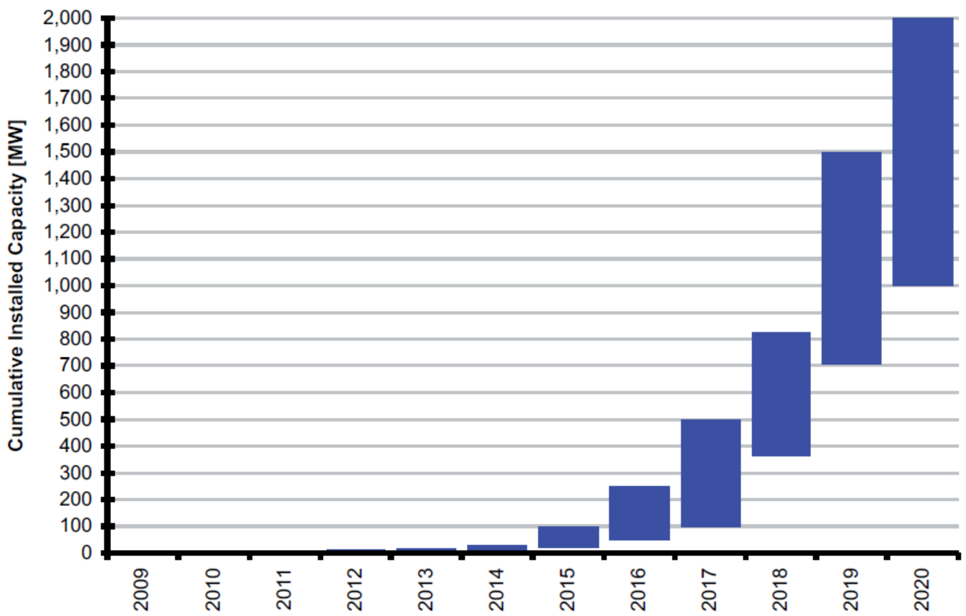


Figure 1-3: Potential UK cumulative installed capacity of marine energy projects to 2020 (BWEA, 2009, pp. 8)

As previously stated, installation is a generic term in the marine energy industry and work must be performed to identify the type, challenges and areas in which progress can be made regarding the cost of deployment. In addition a further reduction in the cost of operating and maintaining devices, and in decommissioning, is desirable.

1.2 Installation

It may be reasonable to hypothesise that through economies of scale array installations may allow for a reduction in overall project cost. Furthermore, innovative mooring arrangements and installation methods offer an opportunity to reduce the capital expenditure related to these areas. The following sections of this thesis consider the current state of the industry, utilising some specific examples, and the direction in which these aspects of marine energy are moving.

1.2.1 Mooring arrangement

One method of mooring a point absorber wave energy device is comprised of three mooring lines, three Auxiliary Surface Buoys (ASBs) and three anchors. This system was devised by OPT who previously used gravity based anchors, although it is stated that any anchor ‘designed for the particular seabed geology’ can be used (Ocean Power Technologies, Inc., 2007, p.2). It was noted that ‘if a plurality of WECs is used, for increasing the amount of generated power, a mooring arrangement using three anchors and three ASBs for each WEC is both expensive and space consuming’ (Ocean Power Technologies, Inc., 2007, p.1). The proposed array mooring system is such that it keeps six PowerBuoys on station with six ASBs and six anchors. The buoys are arranged in a hexagon formation with the anchors to the outside of this ring. Therefore each PowerBuoy still has three moorings, one to an anchor and two to its neighbouring buoys.

Whilst the approach proposed by OPT does reduce the required mooring hardware (from 18 anchors and ASBs to 6) and reduces the space required (stated as being from 90,000m^2 to 2,500m^2) there are some issues. Firstly, the system is dependent on all six buoys being in place to maintain the required tension and whilst Draper indicates that a “dummy” buoy can be used if a device is extracted, full details appear to be lacking. Also, any unplanned, i.e. damage case, removal of buoys will be without opportunity to position a dummy.

Secondly, any cost saving achieved here may be minimal. The Carbon Trust and Dudziak (2009) place the cost of mooring apparatus between 2 and 9% of the total project cost, with installation vessels at 12%. Less apparatus is required, however, the apparatus that is used will need to be more substantial (i.e. a heavier grade of mooring chain). OPT state that the cost associated with this is 'still significantly reduced' although it is unknown if vessel cost is included in this consideration as larger components may require a larger vessel to perform lifts (OPT Inc., 2007, p.4).

An improvement to the previous invention was suggested which mitigated the buoy to buoy connections (Ocean Power Technologies, Inc., 2009). This is still a very complex system, however, and O&M access might be hampered by the close proximity of so many PowerBuoys, ASBs and mooring lines thus reducing the cost benefits. Also the anchors would need to be significantly larger than those used for a single buoy mooring as they are now intended to be connected to up to six mooring lines. If gravity based anchors were used the increased lift mass during deployment could lead to significant cost increases as larger vessel are required.

There is no impact on early stage development costs, however, which may be critical (RenewableUK, 2010) as any cost reduction in this approach only occurs when a technology has reached commercial maturity. Therefore, perhaps a consideration of installation methods may be more applicable than such array designs especially if tidal power devices are considered.

'Wave device installation is likely to rely on weather windows of days, whereas tidal installation is likely to depend on slack water windows of under an hour' (Institute of Mechanical Engineers). Given these small weather windows, the speed with which installation can occur becomes critical and this implies that, as previously suggested, the installation methods themselves present the best cost reduction opportunity.

1.2.2 Installation methods

OpenHydro discuss 'a method for installing and connecting a hydroelectric turbine generator that provides certainty and safety, and reduces the operations required in potentially hazardous conditions' (OpenHydro IP Ltd, 2010a, p.2). The document describes the method for locking the turbine during deployment, and completing the electrical hook-up. Information regarding the submerging operation or the vessels used (the custom built OpenHydro Installer) is considered in a further publication (OpenHydro Group Ltd, 2009).

OpenHydro define the problem facing the installation of tidal turbines as being two fold. Firstly, tidal turbines must be deployed at sites with relatively fast currents which is problematic for installation. Secondly, the process of installing and removing these turbines often requires the use of multiple vessels and associated large, heavy lift machinery. It is also stated that often experienced divers are required and that 'the availability of such equipment and divers is relatively scarce, and thus it is extremely desirable to reduce the time and equipment necessary to perform the installation and removal of tidal turbines.' (OpenHydro Group Ltd, 2009, p.2).

As described the installation process involves no heavy lifts and no excessively expensive vessels; however the use of a specific installation vessel can be problematic. If such a vessel is owned by the developer it is always available, though it sits idle between jobs and whilst this constant availability may reduce the cost associated with weather downtime risk it also increases the time for the capital outlay to be recouped. Also in the future multiple vessels may be required and this only becomes commercially viable when arrays are suitably large. The OpenHydro Installer cost £4 million to design and build (New Energy Focus, 2008).

The possibility of using existing dynamic positioning vessels is raised by OpenHydro (2009) and is a method commonly employed in this field, albeit with runoff caution. Such vessels, however, are costly and therefore if the intention is to drive down cost and increase vessel availability it may not be prudent to employ these.

Open Hydro IP Ltd (2010b) considered an all in one method which, whilst reducing the number of marine operations, and thus costs, results in concerns if the size of the device increases over time. In addition operations and maintenance interventions may be very costly essentially requiring a decommissioning and installation process to occur. This is a concern for all seabed mounted devices.

In order to try and minimise costs associated with O&M Marine Current Turbines developed a system to raise the rotors up the monopile such that they are above the water level and easily accessed for O&M (Wright, 2008; Fraenkel, 2009).

Originally SeaGen, the MCT device, was to be installed using a monopile arrangement. Issues with the availability of a suitable jack-up barge vessel, however, lead to a re-design and the pin pile method being adopted. In this configuration a temporary drilling platform was positioned on top of the foundation from which the drilling and grouting was carried out (Frankel, 2009).

A gravity based solution was considered to reduce costs associated with specialist equipment and seabed preparation. This approach was not used, however, as the seabed preparation via grout bags, and the use of floating gravity based structures had not been fully realised (MCT Ltd, 2007).

As with SeaGen, the Aquamarine Oyster wave device is kept on station with pin piles and therefore it is possible to compare and contrast these two technologies and their intended development direction (Collier, Whittaker and Crowley, 2008). Aquamarine Power had also considered a gravity based solution for simplicity (Collier, Whittaker and Crowley, 2008, p.3). However concerns were apparent regarding the size of the base that would be required (Collier, Whittaker and Crowley, 2008, p.7).

A number of devices have been installed using gravity based structures in the offshore wind sector, e.g. for the Thornton Bank wind farm. (Peire, Nonneman and Bosschem, 2009). Peire *et al.* describe the processes involved in seabed preparation, anchor fabrication and installation. Whilst this project has, to date, been successful it is on a much larger scale than any marine renewable energy deployment (six turbines were installed) and in a less aggressive environment (less excessive waves and current). The authors propose scour protection methods and use seabed preparation to ensure the turbines are installed in a level manner. However this can be a time consuming and, depending on the vessel requirements, costly operation. The cost of fabricating such a structure has been shown to be very expensive before the consideration of any heavy lift vessel day rates and therefore, despite this success, it still appears that there are a number of issues to overcome.

Fraenkel (2009) proposes levelling solutions which remove the requirement for seabed preparation. However, they do not appear to be fully optimised and there is perhaps further work to be pursued in this area.

Thomson is also somewhat critical of piling, the approach selected by Aquamarine for their Oyster demonstration device at EMEC; indicating they are expensive and difficult to install. He states that, 'Jack up rigs or vessel using dynamic positioning systems are very expensive to operate and can only be positioned and used in favourable weather conditions […] therefore foundation installation costs can be prohibitive and subject to long delays' (Aquamarine Power Ltd, 2009, p.1-2).

Drilling, particularly in a tidal race, can be a challenging operation with problems associated with large vortex induced vibrations apparent. This would need to be overcome should this method be utilized in the future (Maritime Journal, 2010). Such issues are less prevalent in wave energy sites and thus Aquamarine Power successfully used this approach for their Oyster installation. Both a jack up and a crane barge were used, and a sum of around £2 million spent on the operation (aquamarinepowerltd, 2010; Wave and Tidal Energy, 2009).

Given the difficulties currently associated with both gravity based and piled solutions it is clear that there is potential for cost reductions to be achieved by focusing research in this area. Whilst improvements may be attained by refining the technologies themselves, it is also possible that developments in the associated vessel types might also yield positive results; therefore it is prudent to consider anchor technology and subsequently installation vessels.

1.2.3 Anchoring

Thus far only large gravity based systems (GBAs), and drilled pile systems have been discussed as anchoring methods. A number of alternative technologies are also in use or are being considered for use in the industry, among these are:

- Drag Embedment Anchors (DEA), such as the Stevpris Anchor (Vryhof Anchors, 2010a)
- Vertical Lift Anchors (VLA) such as the Stevmanta VLA (Vryhof Anchors, 2010b)
- Suction Embedment Anchors (SEA) (suction caissons)
- Driven Piles
- Torpedo Anchors
- SPT Offshore's Suction Embedded Anchor (SPT Offshore)

DEA and VLA anchors are installed in a similar manner and operate almost identically. Figure 1-4 shows the installation steps for a Stevmanta VLA being installed by a single anchor handling tug (AHT). Whilst other methods of installing this type of anchor exist this is the simplest, and thus the most cost effective if it proves suitable.

The anchor is lowered to the seabed (1) and once positioned correctly the AHT pays out the mooring line whilst slowly sailing away from the anchor (2). The line tension is then increased and the anchor will begin to embed (3 & 4). Once a predetermined installation tension has been achieve a shear pin in the angle adjuster fails and the anchor enters its normal vertical loading mode (5).

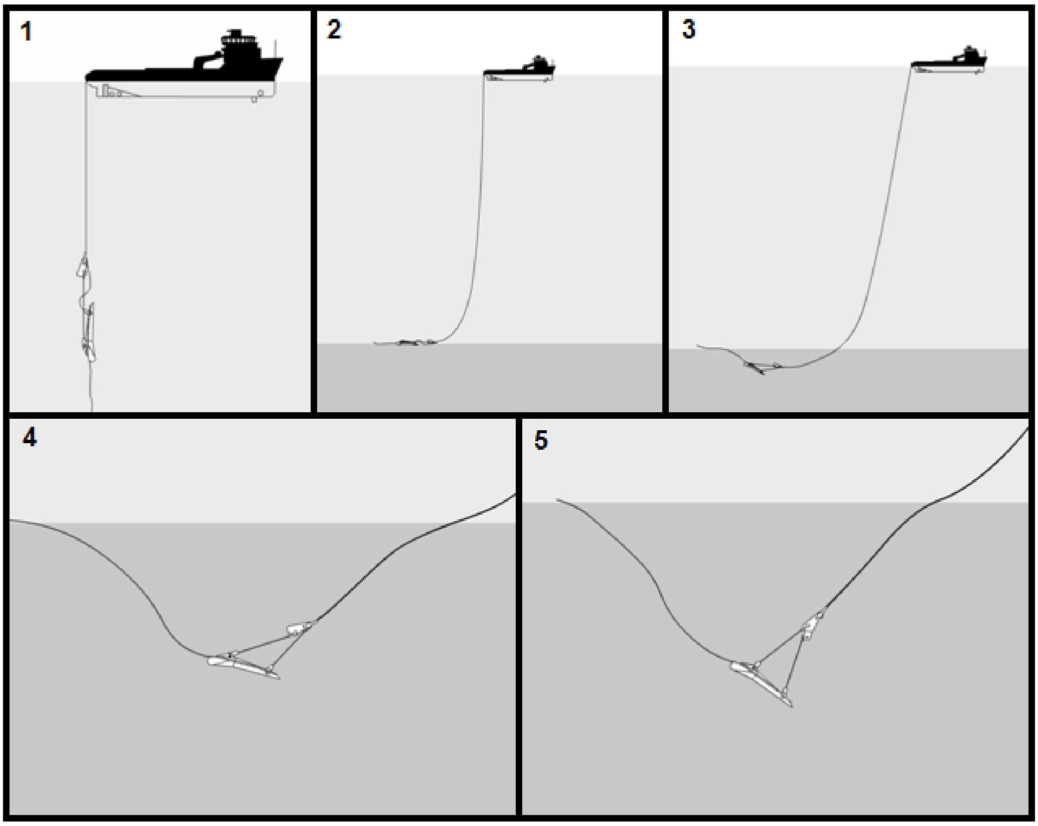


Figure 1-4: Installation storyboard of Stevmanta VLA showing lowering, positioning, drag embedment and deployment following shear pin failure (adapted from Vryhof Anchors, 2010c)

SEAs are effectively ‘huge upturned steel buckets’ (Houlsby and Byrne, 2000, p.3). These are placed on the seabed where the rim of the SEA penetrates slightly. At this point a pump is used to evacuate the sea water trapped inside the caisson, creating a pressure differential and sucking the anchor into the seabed, Figure 1-5. This process typically takes two to three hours although this is dependent on the seabed geology and penetration depth required.

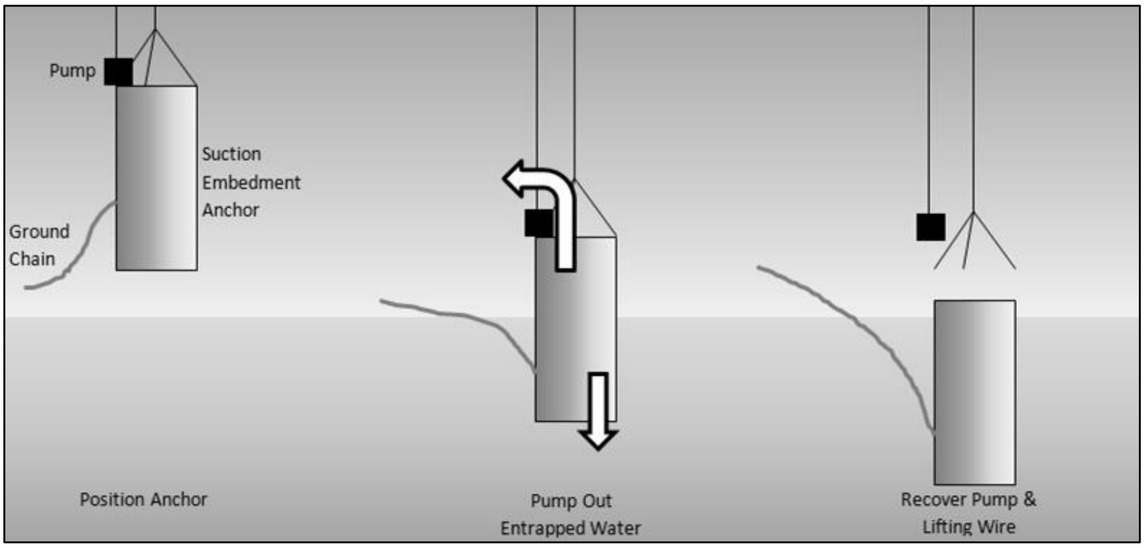


Figure 1-5: Installation steps for a suction embedment anchor showing lowering, embedment and recover of rigging (adapted from NGI [Online])

Other derivatives akin to SEAs exist. SPT Offshore's Suction Embedded Anchor is installed using a suction follower which is removed after the operation is complete, therefore reducing the cost. The installation process, shown in Figure 1-6, is similar to that for SEAs. Once the anchor is positioned and embedded (1) reverse suction is applied (2). This causes the anchor to open as the follower is retrieved (3), and once the anchor is fully open the mooring lines can be connected (4).

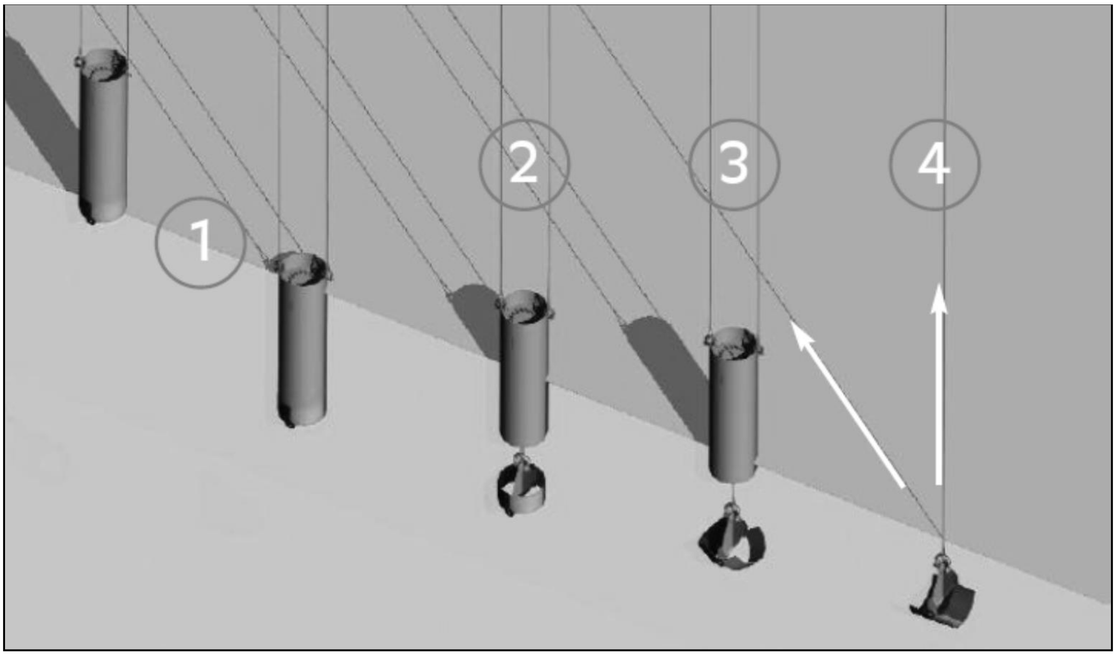


Figure 1-6: Installation of SPT Offshore's Suction Embedded Anchor showing lowering, embedment, application of reverse suction to recover the follower and opening of anchor unit (SPT Offshore)

Driven piles resemble drilled and grouted piles, with the difference being that the pile is installed using a piling hammer which drives the pile, often a steel cylinder, into the seabed.

Figure 1-7: Driven monopile (brown cylinder, centre) and piling hammer (yellow unit, top centre)

Similar to driven piles are torpedo anchors, Figure 1-8. These are comprised of pile tube with stabilizing fins, a conical tip and ballast and penetrate the soil dynamically by the “free-fall velocity attained by the effects of gravity”. They are dropped from a height above the seabed which allows terminal velocity to be reached and penetration to occur. (Wilde, 2009)

Figure 1-8: Torpedo Anchor in vertical configuration (NGI, 2010)

Consideration of not only the anchor but the additional associated costs is important. Vryhof Anchors (2010a) state that whilst the cost of the pile may be up to 40% cheaper the installation costs are much higher due to the required vessels and equipment. Here, once again, it is seen that when attempts are made to reduce the cost of a marine renewable energy project it is not only the mooring technology and the device which need to be considered, but the entire marine spread.

Table 1-1 briefly summarises the cost benefits of the anchors and piles previously discussed in this work.

Table 1-1: Indicative comparison of the cost of piles, suction piles and drag embedment anchors (adapted from Vryhof Anchors, 2010a)

Description	Pile	Suction Pile	Anchor
Soil Survey	£££	£££	£
Procurement	£	£££	£££
Installation Spread	£££	£££	£
Installation Time	£££	£££	£
Pile Hammer	£££	£	£
Follower	£££	£	£
Pump Unit	£	£££	£
Pretensioning	£	£££	£££
Extra Chain	£	£	£££
Rest Value Pile/Anchor	£££	£	£
Removal of Anchor Point	£££	£	£
ROV	£	£££	£

£ = Less Expensive
£££ = More Expensive

The majority of anchors rely on penetration or embedment with the exception of GBAs. It is imperative to choose the correct anchor for each installation for optimal performance. Most noteworthy are tidal races where the flow scours the bottom clear of sediment. In this type of environment embedment type anchors, without drilling, are unlikely to succeed and this is, to a large extent, the challenge facing the development of this technology.

1.3 Vessels

Previously the size, cost and availability of installation and O&M vessels has been alluded to and concern has been raised. Elliot (2010, p.26) states that ‘a major stumbling block [to the deployment of marine renewable energy is] the shortage of suitable deployment vessels […] particularly in adverse weather conditions.'

Sourcing suitable vessels, given the requirements which they are expected to perform to (i.e. heavy lifts in extreme environments) and the shortage of vessels capable of the tasks, is problematic enough without cost constraint.

The offshore oil and gas industry has a direct effect on the cost of suitable installation vessels, as this is the field the majority of vessels have been designed for, and this leads to high levels of fluctuation in the day rates charged (Junginger, Faaij and Turkenburg, 2004, p.107). It was noted that these price fluctuations were directly linked to the price of oil and that development of specific installation vessels would de-couple this relationship, potentially bringing some stability to the market.

Figure 1-9 illustrates this fluctuation in recent years. The prices of vessels, particularly heavy lift vessels (HLVs), seem to follow the increase in oil price, whilst the Anchor Handler Tug (AHT) price fluctuates both on monthly average (with peaks in the summer when larger weather windows exist) and on daily average. It can be determined from this variation that the timing of an operation may be critical to the cost, and therefore its success.

Given the cost of heavy lift vessels (~£270,000/day) and of jack up barges (~£150,000/day), both of which are often used in tidal device deployment, it is evident that development of fit for purpose vessels would decrease the overall operational cost.

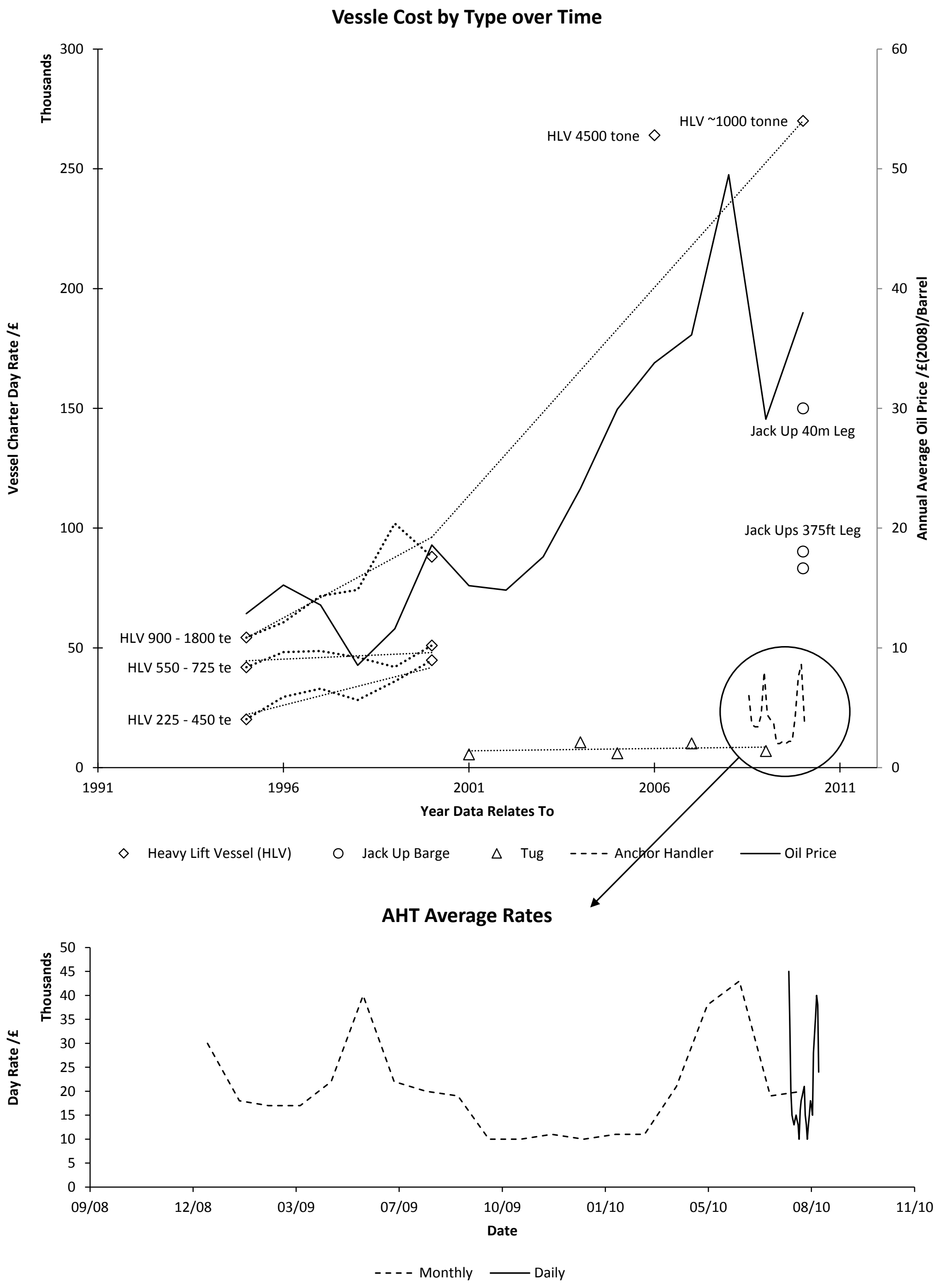


Figure 1-9: Vessel day rates and average oil process between 1995 and 2010 for a number of vessel types featuring detailed consideration of Anchor Handling Tug day rates between December 2008 and August 2010

Sources:

BP (2000); Steenbuch (2008); Orme & Masters; Nixon (2004); Seadrill (2010); The Crown Estate; Pride International (2010); Beegle (2007); Mojo Maritime (2010a; 2010b); McMahon (2010); Offshore Shipbrokers (2010)

There are two approaches to the specific vessel installation approach. Firstly a self-installing device, such as the method used for installation of the piles for

SeaGen or the method considered by Aquamarine for self-installation of Oyster onto the pin piles via floating and ballasting. Neither, however, were successful with SeaGen requiring a HLV for positioning before drilling, and Oyster responding too vigorously to the incoming wave field (Collier, Whittaker and Crowley, 2008).

Secondly, a specific installation barge or vessel can be designed and fabricated, e.g. the OpenHydro installer (£4 million), the proposed MCT Installer (Mojo Maritime, 2010c), or the yet to be commissioned HF4 (Nicholls-Lee *et al.*, 2013). The short term issues of this approach have already been considered (idle time, initial capital outlay, profitability); however, the long term benefits may still be significant enough to mitigate these (such as de-coupling installation cost from the oil industry).

Figure 1-3 demonstrated that the predicted growth of the marine energy industry is likely to be rapid. Previous discussion indicates that growth in the marine renewable energy industry is heavily dependent upon a long term view (BWEA, 2009, p.8,). This includes resolving installation issues with multiple devices in mind, i.e. the development of specific installation vessels. Any development of specific installation vessels should be relevant and must address the issues previously presented with regard to the deployment of marine renewable energy; particularly those relating to lifting, drilling and the use of gravity based solutions.

1.4 Physical constraints

As support for marine renewable energy systems increases the provision of appropriate sites for installation becomes increasingly important. Whilst a number of developers will endeavour to obtain these locations independently, (e.g. OPT's Santoña buoy and Pelamis Wave Power's Aguçadoura array) many will not have the facility to do so. For those in this group marine energy test facilities will be of great importance.

Figure 1-10 shows the location of seven wave and tidal stream energy test sites across Europe. Four are located in the UK (with three of these in Scotland), one in France and two on the Iberian Peninsula. In addition the FORCE test site at the Bay of Fundy in Canada is also considered. Not all of these facilities are in place although all are a reasonable way along the path to construction and therefore can be considered indicative of the type of environment which deployment will shortly be occurring in. Considering this a study of the geology and water depth and of the weather windows available at site was carried out.

Figure 1-10: Wave and tidal stream energy test sites in Europe, note that EMEC includes separate wave and tidal test berths

1.4.1 Seabed geology

A discussion of the types of station keeping, or anchoring, technology was presented in Section 1.2.3 and from this work it was determined that the seabed composition is a key element regarding correct anchor choice.

Figure 1-11 and Figure 1-12 illustrate the seabed geology types at the test facilities previously identified. In Figure 1-1 these are presented by type, with any penetrable seabed being considered sand/gravel (i.e. mud is included here). In Figure 1-12 the data is presented by the type of site, i.e. wave or tidal stream test facility.

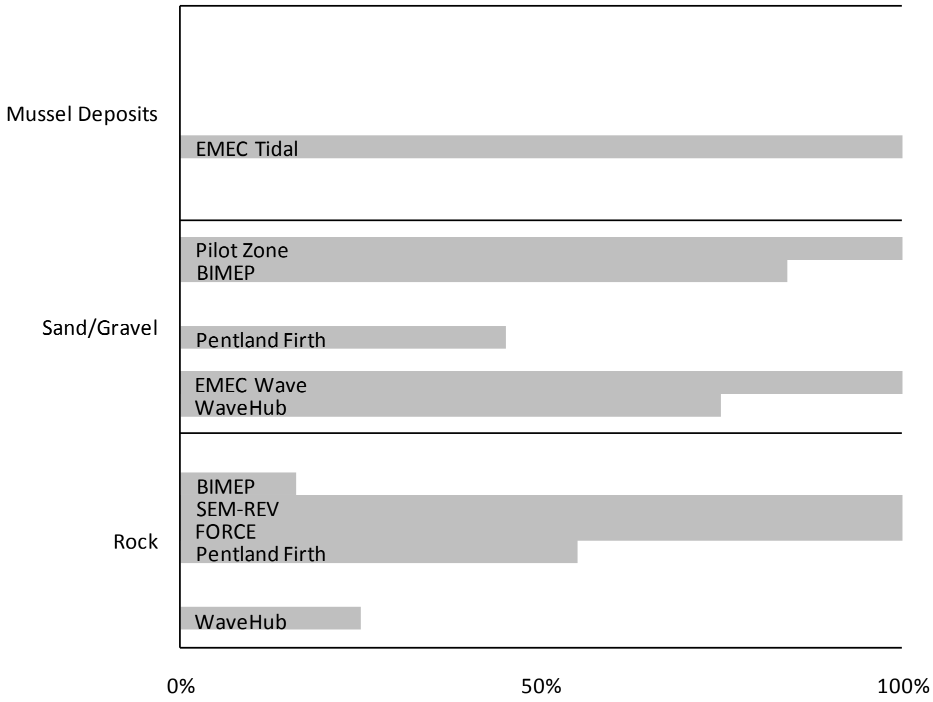


Figure 1-11: Site seabed geology by type for global marine energy test sites

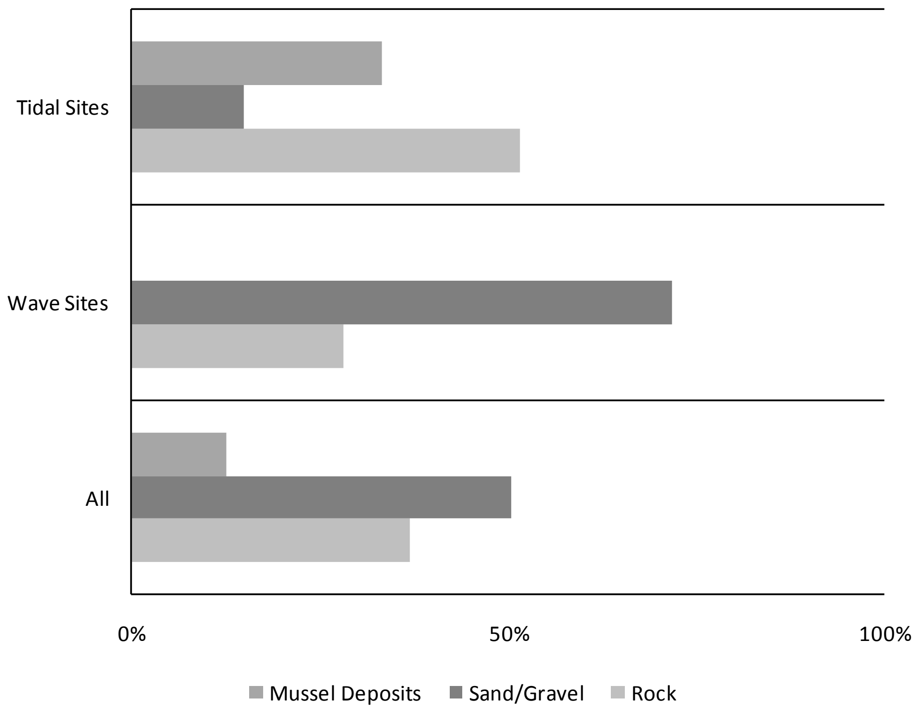


Figure 1-12: Site seabed geology by test site type

Figure 1-13 shows the seabed geology for these site types classified by penetration and limited penetration. It should be noted here that the depth of sediment has not been considered since this information was not always available. This may lead to an exaggeration in the percentage of site seabed for which penetration can be achieved, however, it is not important in this context.

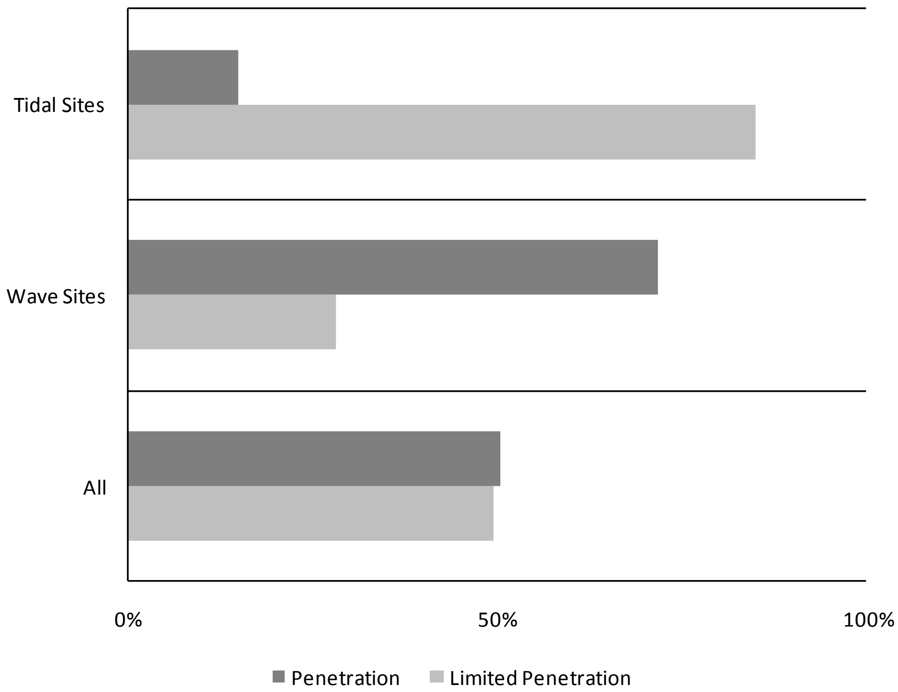


Figure 1-13: Site seabed geology by test site type considering availability of anchor penetration

Sources:
Marine Scotland et al.; EMEC; Halcrow (2006); Scott, Smeed and McLaren (2009); EMEC; Hagerman *et al.* (2006); AECOM (2009); Mouslim (2007); EVE and CIC energiGUNE, Wave Energy Centre; Olstad *et al.* (2009); Jaurlaritza and Vasco (2009); EMEC (2010c); South West Regional Development Agency (2010); Force (2013)

It can be seen that the balance of seabed types which allow penetration to those that do not is approximately 50:50 if both wave and tidal stream test sites are considered. This balance quickly changes, however, if the data is sorted by site type. Tidal sites are primarily (85%) non-penetrative, i.e. rock, whilst wave energy test are primarily (72%) penetrative, i.e. sand, gravel or mud.

These test sites present geology types which are very different hence the repercussions for general research in this area are large. An innovative solution may exist, however, which is applicable to both types of seabed.

1.4.2 Water depth

Only the EMEC tidal site and the SEM-REV test site have berths with a water depth of less than 45 metres; this is problematic for device installation. A common method of installing devices, particularly tidal stream turbines, is from a jack-up barge. This presents a relatively stable platform to work on, however in strong tidal currents they are not feasible (Nicholls-Lee *et al.*, 2013) and will soon be redundant with new bespoke vessels being developed.

Figure 1-14 shows the number of jack-up barges owned by some leading vessel charter companies. Two data sets are presented: firstly the number of barges at a specified depth rating; and secondly, the cumulative number of barges able to work at a given depth.

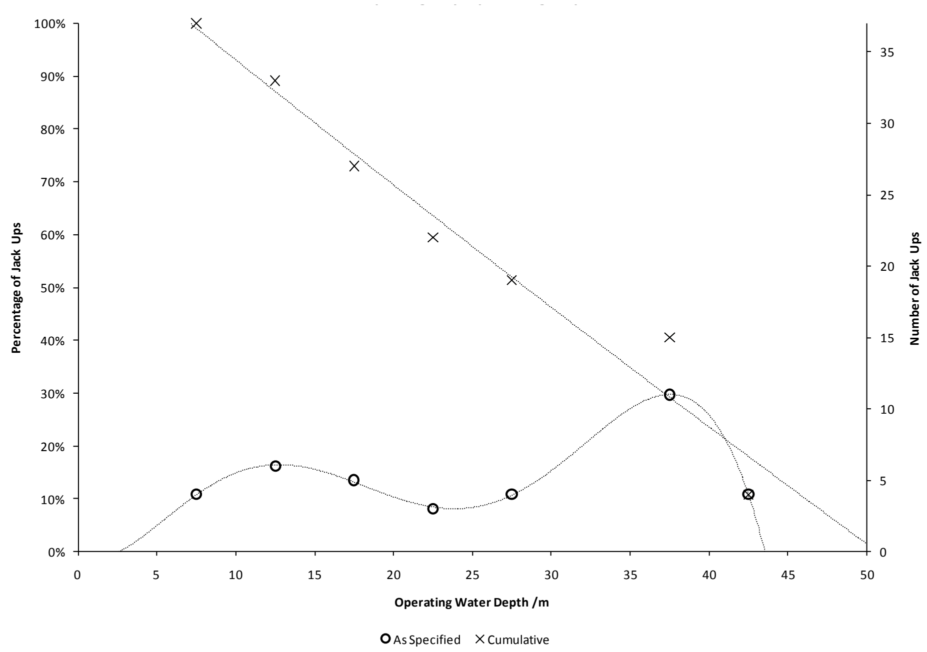


Figure 1-14: Jack up barges available considering operating water depth

Sources:

GustoMSC (2013); Fugro Seacore (2013); MPI Offshore (2013); Red7 Marine (2013): Fastnet Shipping Ltd. (2013)

In the former a double peak can be seen, demonstrating that there are more barges available to work in 12m and 40m of water. The cumulative data set has a large downward trend, indicating that vessels able to work at greater depths are limited in numbers. This indicates few vessels are capable of operating at the global test sites considered, since the water depth at the majority of these is in excess of 45 metres (Table 1-2).

Table 1-2: Summary data for the global marine renewable energy test sites considered, detailing key parameters for stationkeeping technology selection

Site	Type	Country	Depth	Primary Seabed
BIMEP	Wave	Spain	60m	Penetration
EMEC Tidal	Tide	Scotland	12 – 45m	Limited Penetration
EMEC Wave	Wave	Scotland	50m	Penetration
FORCE	Tide	Canada	46 – 70m	Limited Penetration
Pentland Firth	Tide	Scotland	60m	Limited Penetration
Pilot Zone	Wave	Portugal	50 – 80m	Penetration
SEM-REV	Wave	France	35m	Limited Penetration
Wave Hub	Wave	England	50m	Penetration

Sources:
Marine Scotland et al.; EMEC; Halcrow (2006); Scott, Smeed and McLaren (2009); EMEC; EPRI (2006); AECOM (2009); Mouslim (2007); EVE and CIC energiGUNE, Wave Energy Centre; Olstad *et al.* (2009); Jaurlaritza and Vasco (2009); EMEC (2010c); South West Regional Development Agency (2010); Force (2013)

This depth obstacle is not limited only to jack up barges; all operations are more challenging in deeper water. Vessels capable of working in significantly deeper water do exist, primarily in the offshore oil and gas sector, however this does not necessarily overcome the issue of depth. Such vessels, for example jack-up drilling rigs, may not be appropriate for construction work and also if the vessels do prove appropriate, the specialised deep water nature of these vessels is likely to increase the price demanded for their services significantly.

1.4.3 Metocean conditions

Metocean conditions relating to waves, currents and wind conditions may have limiting effects on offshore operations and structures. These conditions may be described by a number of parameters, many of these have unique relevance to offshore operations.

1.4.3.1 Wave height

A number of measures for wave height exist, for example H, H_s, H_{50}, H_{s50} (respectively the general height of an individual wave system; the significant wave height; the height of the 50-year individual design wave, the value of significant wave height with a 50-year return period). With regard to offshore operations H_s is often considered as a limiting sea state, although on occasion H_{max} (the maximum wave height in a given sea state) may be utilized. Hs represents the average of the highest third of waves. Provided that consistency exists between the metocean parameter being considered and the metocean limiting factors flexibility between the parameters is possible (see Sections 1.4.4 and 1.5 for further discussion of metocean limiting factors).

1.4.3.2 Wave period and steepness

Waves may also be defined by their period, and as with wave height a number of parameters are available for this classification. Again, the selected parameter for consideration of an offshore operation is not of great consequence provided consistency exists across all uses of the parameter.

Wave period can limit workability in two ways, firstly, if a resonant frequency occurs excitation of umbilicals, for example, may become unacceptable leading to the suspending of operations. Generally, it is more likely that such excitation will occur as a result of wind driven or tidal current velocities.

Secondly, when coupled with wave height it is possible to determine the wave steepness. In a number of cases this parameter has an impact on the stationkeeping capability of a vessel, for example a multicat or an FPSO (Floating Production, Storage and Offloading vessel). For such vessels the height of the wave is of little concern at large wave periods, however, as the wave period shortens and the steepness of the wave increases issues with stationkeeping may arise.

1.4.3.3 Current and wave speed

Both tidal and wind driven current and wave speed result in the flow of water past an object placed in the water column during an installation operation. At higher velocities the force, particularly through drag, exerted on such an object is increased, potentially to dangerous levels and often to levels where controlling an object becomes problematic.

At deployment sites of the nature seen in the marine renewable energy field the velocity of currents is greatest at the surface where seabed friction is lesser. A number of metrics for the definition of current velocity exist, the main being depth-average current. This reduces the current velocity to a single value which describes the current through the water column; this value will be less than the peak current at the surface and greater than the minimum velocity at the seabed. The alternative parameter is depth varying flows, where the velocity is known at all heights through the water column. The selection of one of these parameters will be dictated by the type of analysis being performed.

1.4.3.4 Wind speed

As with operations which lower items through the water column the velocity of the surrounding fluid is important when lifting above deck. Wind speed can exert unsafe forces on object and can increase the difficulty and complexity of operations.

Wind speed can be described as a mean or maximum value (gust) and as with current velocity the appropriate parameter is often dictated by the type of analysis being performed. The specification of wind speed tends not to be depth (or height in this case) averaged and is often, but not always, specified at 10 metres above sea level (ASL). A number of established equations may be applied to wind speed to increase or decrease this reference height however this may introduce error if the parameters to such wind shear equations are not well understood. Often it is more appropriate to consider the wind at the provided height ASL.

1.4.3.5 Direction

All of the parameters discussed may be defined relative to their direction of propagation and in some instances this may be significant. The direction of a wave height, tidal current, or wind speed may impact on an operation due to the orientation of installed objects and vessels (for example, when lowering a tidal turbine nacelle to a monopile the orientation of the nacelle, blades and monopile can be critical to lift success).

1.4.3.6 Temperature

Ambient temperature can impact on the success of offshore operations, for example, if the water of air temperature is below a given grout cure threshold delays or failures in the curing process may occur.

1.4.4 Weather windows

Deployment weather windows may be categorized into three distinct types; wave, tidal and wind. As noted previously, these can be critical to the success of deployment operations. For example, when performing a lift operation wind speeds in excess of a threshold may result in high forces being exerted on the raised item, potentially damaging the crane structure; tidal current velocities may restrict the times at which equipment can be lowered/lifted through the water column; wave heights may limit the times at which a vessel can maintain station suitably to allow an operation to be performed. These three parameters, wave height, tidal current velocity and wind speed are most commonly the limiting factor for a marine operation and whilst the other metocean conditions discussed in Section 1.4.2 can impact upon success it is appropriate to consider these three only at this point.

In order to fully understand the environment at a deployment location detailed metocean data is required and whilst recording this data is often preferable it is not always possible (DNV, 2011). A number of modelling methods exist which can be used as an alternative, with reasonable accuracy.

Almost any marine operation will have a limiting sea state. Therefore, the conditions in which an installation is possible are a major consideration in this work. If the weather window in which an operation may occur is increased (e.g. by allowing the operation to take place in larger wave heights) the cost of the operation is likely to be reduced, due to considerations such as less weather down time and greater vessel availability.

As with wave energy sites, which are selected primarily for their wave climates, tidal stream energy sites are selected primarily for their higher current velocities. This leads to difficulties where the deployment of devices is concerned.

Figure 1-15 illustrates the tidal velocity for the tide station at EMEC. As stated previously tidal currents can affect various operations, and in order for a number of critical tasks in a deployment to be completed successfully these procedures are often carried out at “slack water”; the time at which the tidal flow is at a virtual standstill. The exact level of this threshold will vary from operation to operation but it is often very low, for example 0.5m/s. Figure 1-15 highlights a threshold of 2.5m/s, significantly larger than these low limits, and it can be seen that the periods of time for which the current is below this limit are relatively short. Considering that vessel station keeping may also require a neap tide it is easy to comprehend how the working windows are particularly short.

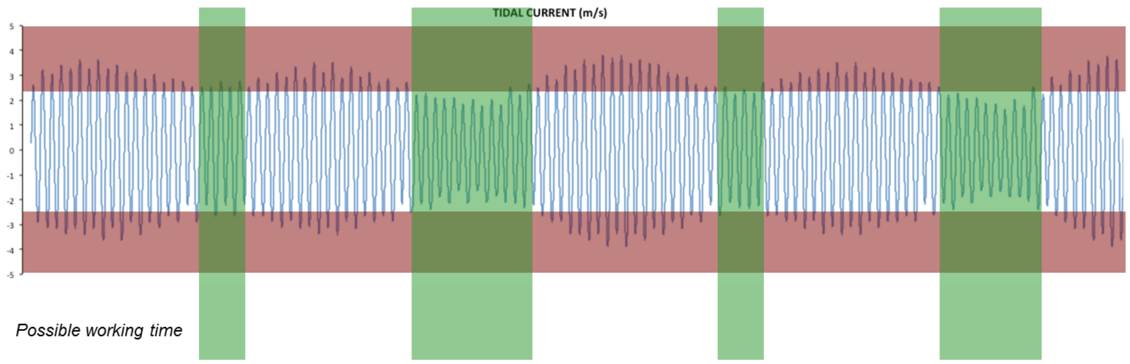


Figure 1-15: Tidal current velocity at the EMEC tidal station, neap tides and slack water periods are identifiable from the excluded tidal current velocities (red) giving accessible times (green). The x-axis details the passage of time across five spring tides (inaccessible) and four neap tides (two short and two long accessible periods) (Mojo Maritime, 2012)

In addition, tidal current is a limiting factor to the type of vessel that may be used. MPI Offshore state that jacking operations can only occur in currents of less than 1.86m/s whilst the survival condition limits are for currents of up to 2.21m/s (MPI Offshore, 2013). Given a peak velocity at the EMEC test site of 3.5m/s it is clear that these vessels will struggle to work throughout the ideal cycle. Such issues relating to the hostile environment are not limited to jack-ups alone.
These limitations can have a large effect on the likely success of marine operations performed in a tidal site. To achieve success the following alternatives are available:

- Design a simple operation which can be executed in the short, slack water windows;
- Design a robust operation which can be executed in greater tidal currents (e.g. OpenHydro (2009)),
- Design an operation which can be performed without topside intervention, reducing the effect of currents in the water column.

To simplify weather windows to the point where only waves are considered for wave energy test sites, and tidal current are only considered at tidal stream energy test sites, is both naive and irresponsible. Therefore the effect of both must be considered for all marine operations. This greatly increases the complexity of work in this environment and outlines the difficulties facing offshore engineers (Maritime Journal, 2010).

1.5 Numerical Methods

It is apparent that the effect of vessel downtime rates on project cost and the effect of the weather in causing this downtime are key variables. .

It is often true that ‘the ideal conditions for windfarms, including constant high winds, are almost exactly the opposite of the ideal conditions for cable laying, which requires almost millpond-like still water’ (Deign, 2012). This is often true for wave and tidal energy deployments; the source of greatest resource often being the source of greatest problems for installation operations.

Accurate forecasts alone are not sufficient, providing short term information as to whether a job is “go” or “no-go” but failing to consider longer term data, thus not allowing for efficient planning and task specification. Prediction of proper weather windows becomes extremely important when the travelling distance from port to site increases (Glover, 2012). These transits result in additional complexity to consider and also present another possible area of optimisation and cost reduction.

Methods exist for reduction of weather risk to a project; e.g. starting early and therefore ensuring time for delays is included or hiring heavy duty equipment capable of operation in extremes. Such methods, however, increase costs (Bowers and Mould, 1994]).

By performing a detailed analysis it is possible to remove a number of assumptions, simplifications and oversights from the scheduling of an installation project. Utilising published methods allows a detailed analysis to be performed for a variety of different project types. In reviewing the available methods and software packages, however, it is apparent that the methods available in this field are focused in different areas of marine installation work; for example, loading logistics (Bush, 2012), project tracking (SeaRoc, 2013), or are metocean related (Open Ocean, 2013), or are too simple or too complex.

Packages which more closely relate to the analysis of installations (for example Fugro GEOS Weather Windows, or Garrad Hassan’s O2C and O2M packages) also have a number of shortcomings (Fugro GEOS 2005; 2011, Garrad Hassan 2013a; 2013b). They are geographically unaware, limited only by task thresholds and do not consider vessels, ports, transits, storms, station keeping and mooring. It is possible to utilize only limited metocean data and the time steps are dictated by metocean spacing (Fugro) or limited to one hour (Garrad Hassan) meaning that analysing slack water operations, in the order of 10 minutes, may be difficult or, in the latter case, impossible. In O2C and O2M packages the vessel is essentially in one location at the start, remains there, works or doesn't work, and finishes at this location. In Weather Windows, transit can be simulated as a task which prevents a response to storm conditions being to leave the site.

Marine operations have been performed across the globe for a number of years, and many nations have been seafaring for much longer. It may be expected that a number of successful methods to analyse the installability of marine energy already exist. A number of methods to analyse site accessibility and weather windows are in existence and whilst many of these methods experience some shortcoming, it would be frivolous not to consider them here. Of interest are:

- Experience
- Probability of exceedance
- Weibull persistence
- Markov chains

All of these methods have either been documented in published material or utilized in industry on projects.

1.5.1 Experience

"Experience" is based on project managers scheduling work against some known limiting factor, such as tidal elevation forecasts which identify spring and neap tide events, and then providing some degree of contingency. This may be a doubling or tripling of the scheduled on hire time, and the value of this constant is essentially unknown. It may be qualified by the extensive experience of the project manager to some degree but as new installation methods, vessels and harsher sites are implemented this experience will become less relevant.

This method is quick and simple; both of which are benefits, particularly in a rapidly developing industry. Furthermore, this method utilizes prior experience which is, despite the concerns relating to new technology, highly beneficial. There are, however, some key limitations; as indicated the accuracy of this method cannot be defined and whilst a conservative estimate of on hire time is likely to allow sufficient opportunity for the required work to be completed there is a concern as to what is "conservative". If an estimate is insufficiently long the vessels may be off hire before completion of the work, potentially causing greater cost to be incurred as charters are re-negotiated.

1.5.2 Probability of exceedance

This method seeks to address the shortcomings of the prior estimation approach by quantifying the amount (percentage) of time for which a given metocean condition, or conditions, is exceeded. The process can be performed for a given duration, i.e. on a month by month basis, to give an overview of the conditions by season.

This method is quick and simple to perform; requiring metocean data and a small number of basic equations. Having defined an acceptable threshold, or thresholds, which may not be exceeded the application of the method may be undertaken in standard spreadsheet or data analysis software.

The method provides a quantifiable site to site, and season to season comparison. The key limitation, however, is the lack of consideration of the persistence of calms. The probability of exceedance approach may inform a project manager that the wave height threshold is exceeded for 50% of the time in the summer months, however, information is lacking regarding how this 50% occurs. It may be in a series of short windows or, conversely, as one long window. These two examples are at the extremes of the likely weather window occurrence; however, they serve to illustrate how a lack of knowledge of persistence may impact on the scheduling of work and the associated cost.

1.5.3 Weibull persistence

In order to develop an understanding of the conditions at, and on route to, a site modelled and recorded wave data may be applied in a Weibull model to identify significant wave height exceedance, and to calculate the accessible periods for marine operations. The method uses site specific parameters and empirical expressions to calculate accessible periods via cumulative distributions of the mean duration of persistence of exceedance.

There are two key parameters to consider when seeking a weather window for marine operations. Foremost amongst this is the environmental threshold, which for a number of operations is often considered to be predominantly wave height, although wave period, wind speed, tidal current velocity and tidal elevation can all impact an operation and may also require consideration. For the purposes of explaining the Weibull persistence method used it shall be considered that the limiting factor is the wave height.

This environmental threshold, i.e. the height beneath which the waves at the site must remain, can be an informative measure and the Weibull approach is used to produce simple probability of exceedance data. This data details the likelihood of wave heights (H), or access wave heights (H_{ac}), being exceeded and can assist in the identification of the times of the year for which the lower wave heights desired are experienced. The shortcoming of this data is that it neglects the second key parameter, the length of the window.

Marine operations take time and it is crucial to identify if a particular weather window is sufficiently long to allow an operation to be successfully executed. If only probability of exceedance data is used those performing the operation would not be informed of the length of the available window. Consequently there is a possibility that operations may need to be aborted if the length is not sufficient, incurring additional cost.

The Weibull approach presented herein allows for a consideration of the length of the window at a specified threshold to be made, thus defining a window by length and H_{ac}, or similar accessible condition. The outputs obtained from this method are the access days (N_{ac}) and the waiting days (N_{wa}) for a window. N_{ac} details the number of days in a time period, typically a month or season, for which it will be possible to move to site, i.e. the length of time for which a window can be accessed for installation, maintenance or recovery. N_{wa} detail the number of days of downtime likely to be experienced when attempting to access a window, again, this is detailed for a specified time period.

To assess N_{ac} and N_{wa} a Weibull model is used. This model has been validated for a range of cases (Stallard *et al.*, 2010).

Initially the input metocean data set requires partitioning into appropriate subsets, such as monthly, or by wave period. It is possible to apply this method to the entire data set; however, whilst this may provide a useful broad comparison of the conditions at different sites, it is of little benefit for an assessment of operations which will be completed in specific months.

By calculating the probability of exceedance from the partitioned input wave height data it is possible to apply a Weibull fit using Equation 1-1 and Equation 1-2 and to plot this as shown in Figure 1-16. In this analysis the Weibull location parameter, X_0, should be adjusted until the best possible fit, based on the R^2

value, is obtained. Following this the remaining site specific parameters can be obtained, these being:

1. The Weibull shape parameter, *k*.
2. The Weibull slope parameter, *b*.

$$X = ln(H - X_0)$$ **Equation 1-1**

$$Y = ln\left(ln\frac{1}{P(H>H_{ac})}\right)$$ **Equation 1-2**

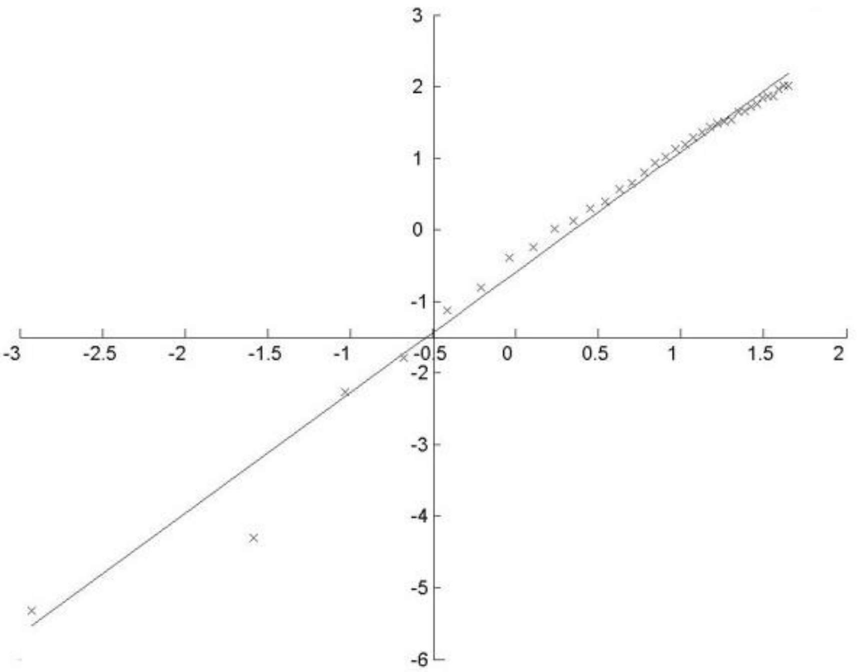


Figure 1-16: Example of Weibull fit to probability of exceedance data. X-axis as defined in Equation 1-1 and y-axis as defined in Equation 1-2

Having obtained *k* and *b* from the Weibull fit it is possible to determine and plot the Weibull probability of exceedance (Figure 1-17) by applying Equation 1-3.

$$P_w(H > H_{ac}) = e^{\left(-\left(\frac{H_{ac}-X_0}{b}\right)^k\right)}$$ **Equation 1-3**

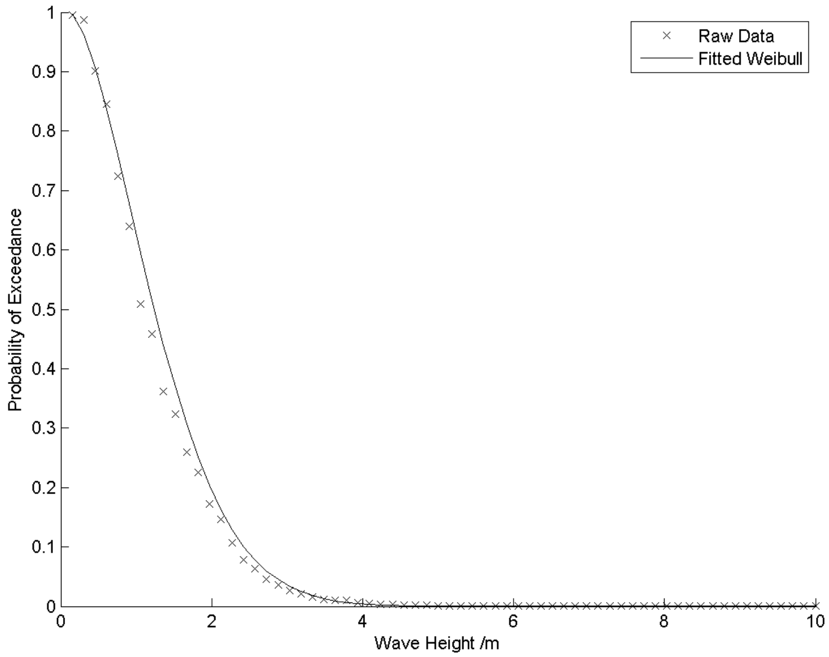


Figure 1-17: Example of Weibull probability of exceedance ($P_w(H > H_{ac})$) compared with the original probability of exceedance

In turn the average window length, τ_{ac}, Figure 1-18, can be calculated using Equation 1-4 to Equation 1-8, where Equation 1-7 and Equation 1-8 are used in the calculation of the variables A and β (Equation 1-5 and Equation 1-6). These are fundamental to the calculation of τ_{ac}. Here, Γ represents the Gamma function.

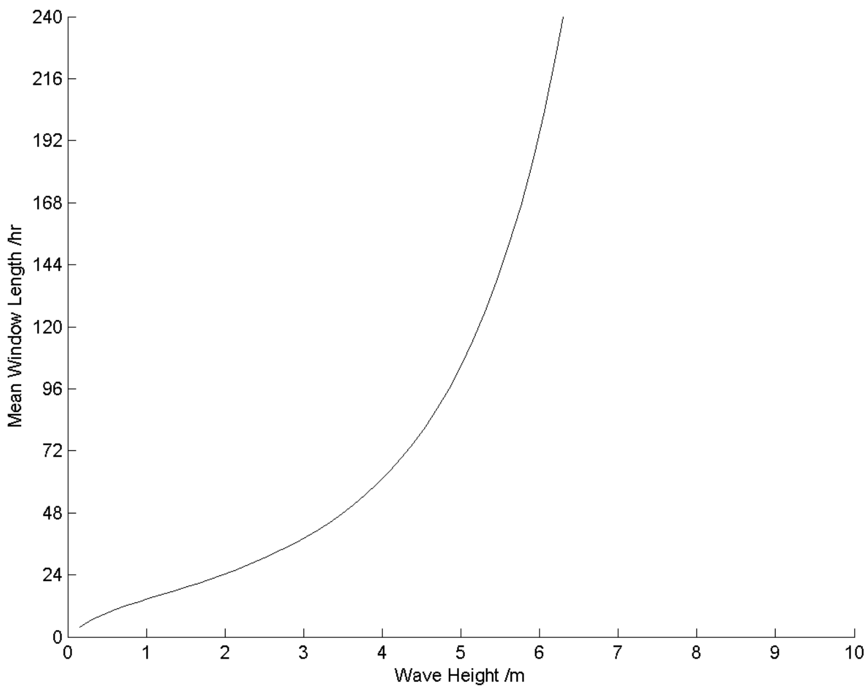


Figure 1-18: Example of the mean window length (τ_{ac})

$$\tau_{ac} = \frac{1 - P_w(H>H_{ac})}{P_w(H>H_{ac})} \cdot \frac{A}{\left[-\ln\left(P_w(H>H_{ac})\right)\right]^{\beta}}$$ **Equation 1-4**

$$A = \frac{35}{\sqrt{\gamma}}$$ **Equation 1-5**

$$\beta = 0.6\gamma^{0.287}$$ **Equation 1-6**

$$\gamma = k + \frac{1.8X_0}{\bar{H} - X_0}$$ **Equation 1-7**

$$\bar{H} = b\Gamma\left(1 + \frac{1}{k}\right) + X_0$$ **Equation 1-8**

If the Weibull parameters are inaccurate or incorrect, for any reason, the method will fail to produce accurate results. This, in turn, will have an effect on the cost implication, i.e. the downtime, which this method seeks to mitigate, as the error is propagated throughout. Key to obtaining accurate site specific parameters is the quantity and quality of the input data

Before determining N_{ac} and N_{wa} it is necessary to calculate the probability that the accessible wave conditions persist for a normalised duration ($P(X_i > X_{ac})$ where X_i is the normalised duration). To calculate this probability Equation 1-9 to Equation 1-11 are applied.

$$P(X_i > X_{ac}) = e^{-C_{ac}(X_i)^{\alpha_{ac}}}$$ **Equation 1-9**

$$C_{ac} = \left[\Gamma\left(1 + \frac{1}{\alpha_{ac}}\right)\right]^{\alpha_{ac}}$$ **Equation 1-10**

$$\alpha_{ac} = 0.267\gamma\left(\frac{H_{ac}}{\bar{H}}\right)^{-0.4}$$ **Equation 1-11**

Then, using Equation 1-12, it is possible to calculate the probability of occurrence of a weather window with a specified environmental threshold and duration. This probability ($P(T > \tau_{ac}$) is an indicator of the windows available at a site, Figure 1-19.

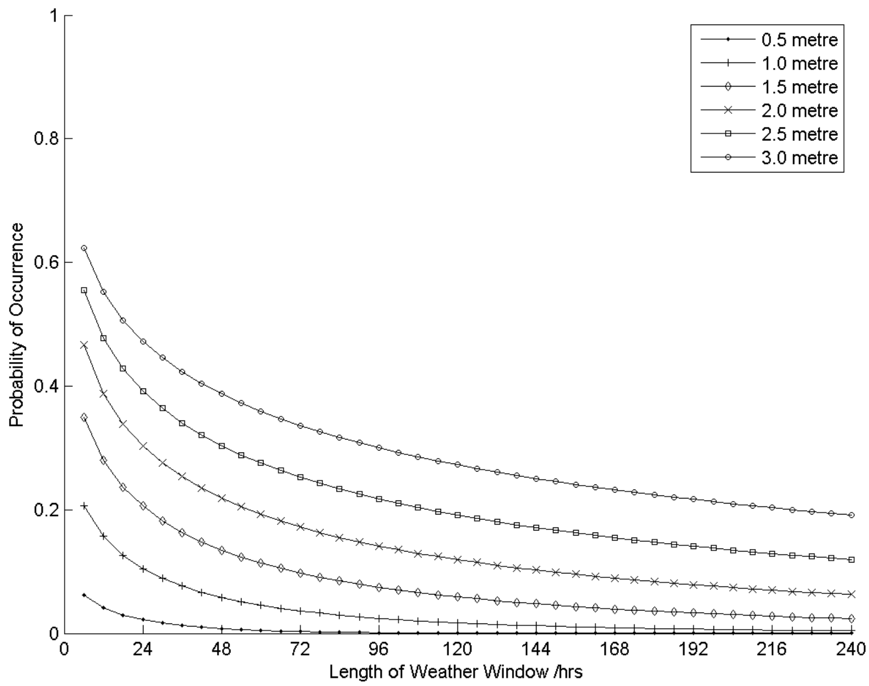


Figure 1-19: Example of probability of occurrence of a specified weather window at wave heights between 0.5 metres and 3 metres (*P(T* > *τac*))**

By calculating N_{ac} and N_{wa} a "real" value can be applied to the likelihood of a marine operation being executed; N_{ac} and N_{wa} can also be used to obtain more detailed operational costs.

N_{ac} and N_{wa} are calculated from Equation 1-13 and Equation 1-14; where *D* is the duration of the interval under study, i.e. the period of time available for the completion of a marine operation (for example, when partitioning the data into individual months *D* is the number of days in the month).

$$P(T > \tau_{ac}) = P(X_i > X_{ac}) \cdot P_w(H > H_{ac})$$ **Equation 1-12**

$$N_{ac} = D \cdot P(T > \tau_{ac})$$ **Equation 1-13**

$$N_{wa} = \begin{cases} \frac{(D - N_{ac} \cdot \tau_{ac})}{N_{ac}} & N_{wa} \leq D \\ N_{wa} = D & N_{wa} > D \end{cases}$$ **Equation 1-14**

This method again provides a useful site to site, and season to season, comparison and, due to the handling of the persistence of calms, mitigates issues relating to the length of the available window. At face value, it appears that this is a highly statistical method which may lead to frustrations on the part of those applying the method and considering its outputs. Also there is no consideration of projects, linked tasks and consecutive or partial windows. Furthermore, cost considerations are not natively considered in the method.

1.5.4 Markov chains

Anastasiou and Tsekos (1996a; 1996b; Tsekos and Anastasiou, 1996) have published a number of papers relating to the analysis of marine projects utilising Markov theory. They utilize methods to analyse these weather related circumstances, these being:

1. Probabilities for activities which do not require a weather window, i.e. operations which can be suspended,
2. Probabilities for activities which require a window, i.e. operations which, once started must be completed.
3. Probabilities of combined activities (1 + 2), i.e. the analysis of a whole project.

This method has the capability to handle simple marine energy installation projects and considers the persistence of calms. It outputs the probability of completing a given package of work (task) in a given time. It is slow and a computationally intense, complex, statistical method and whilst it is possible to house this method in a user-friendly package it may be limited in application due to the nature of the background calculations.

Considering the method and the analysis of activities which do not require a weather window, i.e. suspendable tasks, it can be seen that over 40 separate equations are required; this is the simpler of the two analysis methods utilized.

Firstly the user must specify a number of parameters relating to the task:

α = the number of intervals to restart a suspended operation;

β = the number of intervals required to suspend an active operation;

λ = the number of intervals between two non-operable points (N) to justify a restart, i.e. the length of time for which working is reasonable. Note that: $\lambda > \alpha + \beta$ and $\lambda \geq 1$.

It is also necessary to specify the differing working efficiency factors (r_j); these are dependent on metocean conditions. The efficiency factor of the state *N* must be 0, i.e. this state must be the point at which the task becomes inoperable. The equations (Anastasiou and Tsekos, 1996a) may then be applied to produce the required probabilities (Figure 1-20).

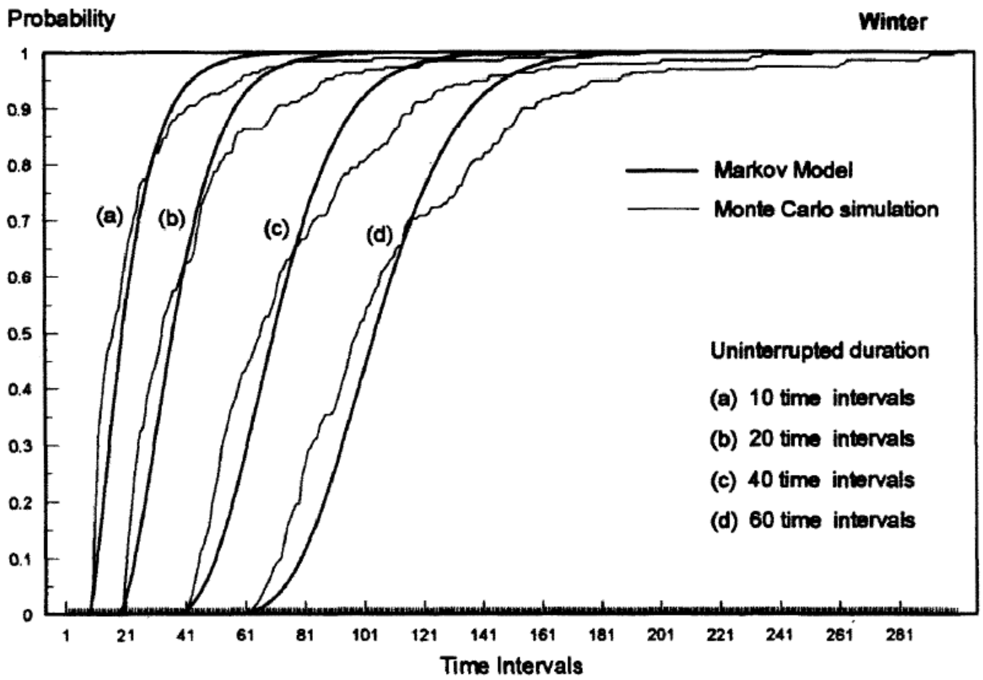


Figure 1-20: Cumulative probability density function as an output of the Markov method (Anastasiou and Tsekos, 1996a)

This is a computationally intensive and complex method and including additional task types in the analysis, i.e. suspendable and non-suspendable, further increases the complexity. Whilst the method has benefits, for example determining a probability of success, there are sufficient limitations to exclude this from further consideration. This method, however, does provide a degree of inspiration for future new methods; in so far as a consideration of not just working, but working efficiency, a consideration of the start up time to work, the sub-classification of tasks into suspendable and non-suspendable, and the concept of total score.

1.5.5 Time series analysis

In addition to the discussed Weibull persistence method Stallard *et al.* (2010) describe the application of a time series analysis approach. This methods is employed by O'Connor *et al.* (2013) in a case study analysis for operations and maintenance access in the Irish Sea.

The method outlined by Stallard *et al.* allows the coupling of metocean types (i.e. wave with tidal current) and acknowledges that the main limiting factor to an operation is likely to be the metocean condition which provides greatest resource to the power generation device. Stallard *et al.* note that, as a time series process, the quality and, particularly, quantity of data is of importance. It is stated that the longer the interval of available date, i.e. the number of years available) the more reliable the results.

This method allows some coupling of tasks to produce simple projects for analysis and it is possible to consider a period of accessible time required before the access of the window. This is of use given that transit and the process of site access may be weather limited; however this method stops short of a full transit and access analysis.

O'Connor *et al.* note in their work that the access to a device has not been considered, simplifying the analysis slightly but potentially introducing some error. This is an acknowledged limitation of their study rather than of the methods. The authors also acknowledge the importance of considering the persistence of an accessible window (as discussed previously, section 1.5.2) and this is considered by the method described.

This time series method is clear, easy to understand and provides useful information regarding the ease, and success, of a given offshore operation. There exists a possible issue with the simplicity of some elements of the analysis and the methods could include more detail and take a significantly more holistic nature, which is worth exploration in this work.

2 Research opportunity

Consultation with the marine renewable energy industry has indicated the often haphazard manner in which offshore installation projects are planned. Whilst this is frequently dependant on a wealth of knowledge and experience it is regularly performed without any detailed analysis, quantification of risks, or quantifiable understanding of cost implications. One method of project analysis was highlighted which indicated that the time required to access enough slack water periods was determined, and then doubled to allow for sufficient vessel charter to be undertaken to ensure project completion. With vessels costing £10,000 - £200,000 per day this is potentially a very expensive assumption to be making.

These considerations indicate that research is required regarding the full, effective planning, budgeting, optimisation and execution of marine installation projects. In practice this means the development of methods for analysing the planning of an operation and fully detailing the associated cost and risk.

2.1 Aims and objectives

This research aims to establish methods to enable the:

- (i) assessment of downtime incurred by marine operations;
- (ii) identification of the factors that influence downtime;
- (iii) development of installation strategies that are robust and, hence, improve installability of marine energy projects.

This is achieved by addressing three key objectives:

1. To optimise installation methodologies and arrangements according to variations in device characteristics and installation conditions;
2. To ensure that the designs whilst being reliable and safe will also minimise costs;
3. To establish design decision criteria based on numerical and experimental investigations;

An intended outcome of achieving these objectives is the improvement of the capabilities of Mojo Maritime. This work should allow an enhanced service portfolio to be developed in support of marine renewable energy clients and should promote Mojo Maritime’s entry into the marine renewable energy service industry, The research performed has a number of key focuses to achieve this main objective. The results of the research are presented, including the application and assessment of existing methods to analyse accessible windows, the development of new methods to accurately analyse installation project accessibility and to manage the associated downtime and the consideration of logistics, vessels and ports for site access and the implication of these elements on total cost. In addition, cost, risk and effective planning, prioritisation of cost and completion time and methods to optimise a project are considered.

Finally case study installations are presented, utilising the methods developed in this work and demonstrating the importance of this type of analysis in the planning of marine energy installation projects.

2.2 Analytical methodology overview

It is intended to establish methods to analyse the downtime incurred during marine operations. These methods consider:

- Vessel availability;
- Weather windows (tidal, wind, wave, daylight, etc.);
- Crew and equipment availability;
- Critical operations;
- Cost;

Furthermore these methods should:

- allow users to optimise their operation plan and quickly understand the consequences;
- allow users to consider contingencies and quickly understand the consequences.

The methods developed should, where possible, conform to the requirements laid out by classification societies such as Det Norske Veritas (DNV).

It is intended for these requirements to be met via methods for long term planning using multi-period hindcast, or recorded, data and this represents the bulk of the work performed here. A “Live Mode” allowing informed decisions to be made as weather windows approach, progress is made and, more than likely, downtime is incurred will be implemented. Whilst this development is not considered in detail here it is important to keep this in mind whilst considering the long term planning as this may be a key aspect of the tool for a project manager.

An outline project execution flowchart is included in Figure 2-1. This illustrates the working method used here; this being the identification and collection of suitable input data, including but not limited to metocean data (wind, wave and tide hindcast datasets). Utilising this data, and the objectives laid out herein, a model suitable for the assessment of marine energy installation projects is described and developed; including, but not limited to, a consideration of the metocean conditions, transit and vessel capabilities and costs. Methods, or applications, to optimise the model will also be included and a series of outputs relating to the reduction of cost should be produced.

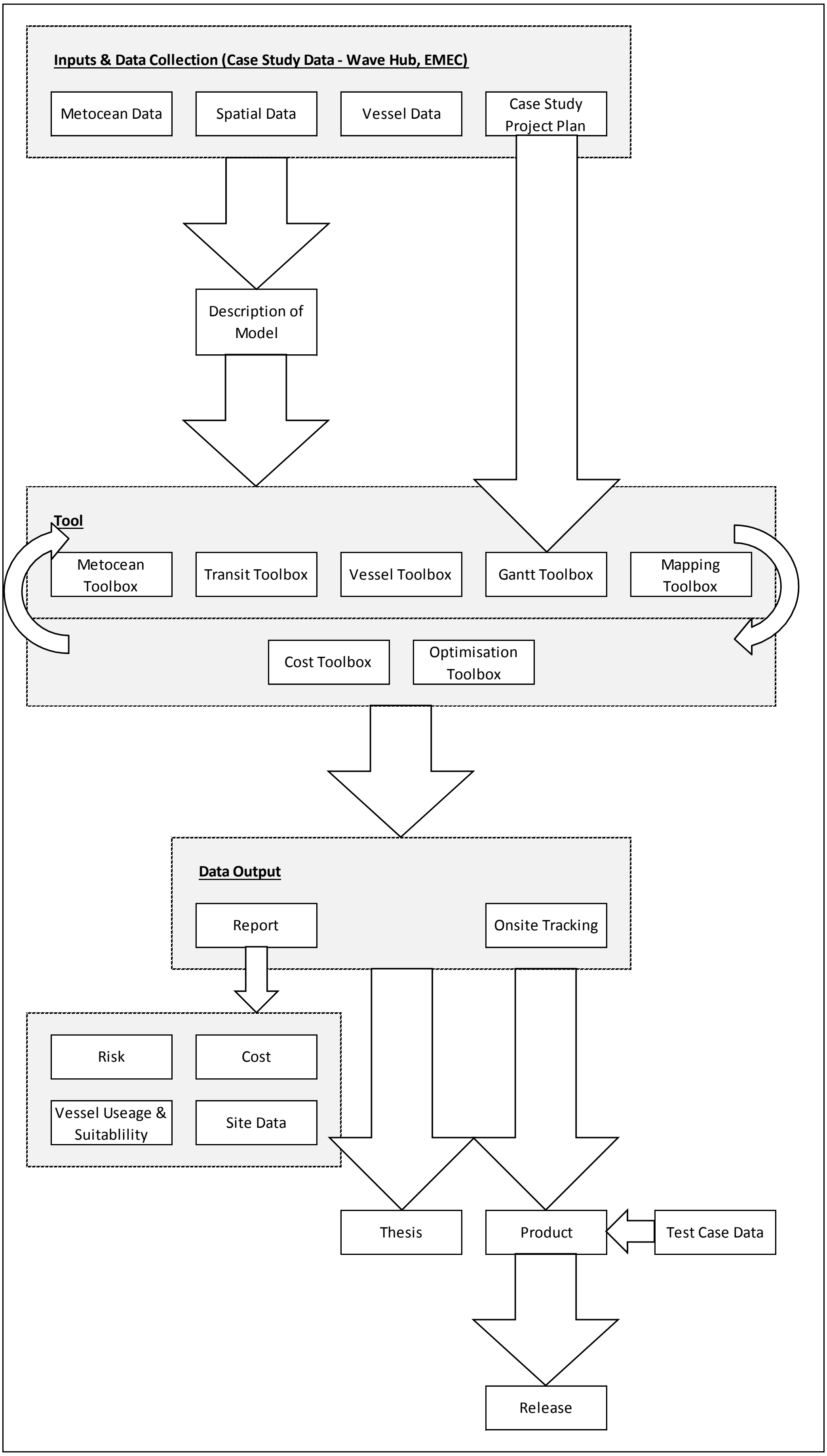


Figure 2-1: Project overview and development structure

All of the methods outlined previously share a common flaw; they only consider defining a weather window at site. Whilst this is of use, and whilst it is possible to manipulate a number of these methods to consider multiple locations, linked tasks and transit, a preferable method is the consideration of a project as a complete, geo-spatially diverse, multi-vessel analysis.

For achievable cost reduction to be identified, and achieved, at any stage of marine renewable energy installation an efficient, effective and reliable tool must be created. With this aim methods are presented in the following section which allow for the full analysis of an installation project of any complexity, with any number of linked tasks and multiple vessel resources. Furthermore, these methods aim to be simple, repeatable and of use to the marine energy industry and its diverse technologies, installation methods and vessel types.

The analysis method is motivated by the objective of performing an installation, or installations, in the model as opposed to at sea. This allows device developers, installation contractors and vessel owners to consider in detail the options available to them and to optimise their design, method or resource before incurring any high costs. By allowing such a process to take place it swiftly becomes apparent that lessons may be learnt from the safety of an onshore work station, rather than offshore where costs and risks are significantly higher.

These methods, however, are not centred on health and safety or project risk and should installation processes be incorrectly defined in the inputs errors are likely to propagate through the analysis. There is no scope here to prevent a user of said methods defining a wholly unrealistic project, leading fallacious conclusions. This, however, presents little concern since these methods should be utilized by experienced personnel with sufficient experience to scope work accurately. It is not possible to develop a software tool which is omniscient and it is unreasonable, given the diversity seen in the marine energy, and indeed the entire offshore industry, to expect to be able to develop a database of installation tasks which may be simple “dragged and dropped” into an analysis.

What is expected from these methods is an analysis of the economic risk a project faces; specifically from weather downtime, but also from inefficient scheduling of tasks and poor utilisation of resources, many of which are highly expensive. In order to achieve this a number of analysis methods exist within the hierarchy demonstrated in Figure 2-2.

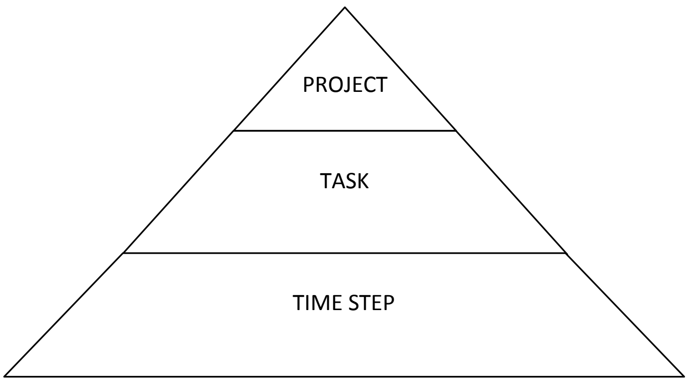


Figure 2-2: Analysis hierarchy for the development methods which are analysed top-down as shown.

To demonstrate the application of this hierarchy, for example; a project wide analysis of the periods of time (calms) for which a vessel is capable of keeping station must be first identified. Following this the vessel working efficiency can be identified for the individual task and, in turn, the transit requirements (it is a prerequisite of task analysis that the vessel is in the correct location) and work progress can be analysed for the individual task at a time step resolution.

It is then possible to work back up this hierarchy considering the scheduling of the tasks at an individual task level, and the cost of the work at both a task and project level. With all of these factors becoming more complex when multiple vessels or simultaneous tasks are utilized.

As indicated, a number of prerequisites exist for work, transit, or task suspension to occur. The overwhelming majority of these prerequisites are as they occur in the real world and a number of attempts have been made to limit the number of unrealistic assumptions required. These prerequisites and assumptions will be discussed as required throughout these descriptions.

Any analysis is dependent on the quality of the inputs provided and these methods are no different. The quality of input metocean data is a concern in all work of this type, especially when spatial variability becomes a factor (Walker *et al*., 2013, and Saulnier *et al.*, 2012). Furthermore, the specification of the project itself may be a concern should working limits be incorrectly defined. If values are genuinely unknown it is possible to perform a sensitivity analysis, something which may be useful even when values are known. This allows knowledge of how small changes in scope, specification etc. affect the outcome of the analysis, this ultimately being the cost.

In many cases it is possible to produce a task list (the main data input method to this analysis method) which is suitably accurate; however, where any uncertainty or debate occurs regarding inputs the conservative approach may be the better option.

Finally, having defined the project inputs and utilized the methods outlined, an array of outputs may be produced. In many cases these outputs will be a representation of a single installation procedure, costs, vessel utilisation and yearly variability. In the most powerful applications of these methods, however, these outputs will also be related to comparisons between different installation procedures allowing an informed decision to be made relating to how, when, where from and with what a marine energy device should be deployed.

3 Analytical methodology

3.1 Analysis requirements

A number of data sources are required to allow the complete analysis of an installation operation. These can be broadly categorised as:

- Metocean inputs;
- Vessel inputs;
- Spatial inputs;
- Task inputs;
- Project inputs.

A project is a series of linked tasks which must be completed to achieve an installation. A task is a package of work which can be considered independent of the other tasks to which it is linked, therefore tasks may have different limits, resource requirements and scheduling details.
The described methods are parameterised from three tabular inputs, these being:

- Vessels;
- Map;
- Task List.

These tables, and particularly the task list, will be discussed throughout the following sections and provide useful context and visualisation of the input requirements. Firstly, however, the required inputs are summarised below in Figure 3-1 and Figure 3-2.

Input	Relative To	Required	Type	Comment
Metocean				
Wave Height		Required	Time Series	Preferably multiple years for multiple locations at the finest possible time resolution. May be a zero time series.
Tidal Current		Required	Time Series	Preferably multiple years for multiple locations at the finest possible time resolution. May be a zero time series.
Wind Speed		Required	Time Series	Preferably multiple years for multiple locations at the finest possible time resolution. May be a zero time series.
Location (s)		Required	Coordinates	A location must be specified for each optional metocean data set supplied.
Vessels				
Name		Required	Text	A unique vessel name.
Additional Crew		Optional	Integer	On-board crew in excess of those covered by the vessel charter agreement.
Day Rate		Optional	Currency	Fee incurred per working day.
Standby Rate		Optional	Currency	Fee incurred per non-working day.
Accommodation Fee		Optional	Currency	Fee incurred per person per night for additional crew.
Port Fee		Optional	Currency	Fee incurred per port departure.
Station Keeping Limits	Wave Height	Required	Upper Threshold	Limit above which station keeping is not possible. May be ∞.
	Tidal Current	Required	Upper Threshold	Limit above which station keeping is not possible. May be ∞.
	Wind Speed	Required	Upper Threshold	Limit above which station keeping is not possible. May be ∞.
At Site Hookup Duration		Required	Time	Time required to complete at site mooring operations. May be 0.
At Site Hookup Limit	Wave Height	Required	Upper Threshold	Limit above which station keeping is not possible. May be ∞.
	Tidal Current	Required	Upper Threshold	Limit above which station keeping is not possible. May be ∞.
	Wind Speed	Required	Upper Threshold	Limit above which station keeping is not possible. May be ∞.
At Site Unhook Duration		Required	Time	Time required to complete site departure operations. May be 0.
At Site Unhook Limit	Wave Height	Required	Upper Threshold	Limit above which station keeping is not possible. May be ∞.
	Tidal Current	Required	Upper Threshold	Limit above which station keeping is not possible. May be ∞.
	Wind Speed	Required	Upper Threshold	Limit above which station keeping is not possible. May be ∞.
In Port Hook Up Duration		Required	Time	Time required to complete in port mooring operations. May be 0.
In Port Unhook Duration		Required	Time	Time required to complete port departure operations. May be 0.
Cruising Speed	Wave Height	Required	Height/Speed	The transit speed achievable at different wave heights. Wave heights may be ∞.

Figure 3-1: Required inputs - metocean and vessels

Input	Relative To	Required	Type	Comment
Ports and Safe Havens				
Locations		Required	Coordinates	The position of the port and lay up. One of each is required, although they can be the same location.
Route	Port	Required	Waypoints	The coordinates of the way points on the transit route between site and port.
Route	Layup	Required	Waypoints	The coordinates of the way points on the transit route between layup and port.
Tasks				
Task ID		Required	Integer	A numeric identifier for the task.
Task Description		Optional	Text	A text description of the task.
Start Date(s)		Required	Date and Time	Indicates the start of a task, required for the first task.
Dependencies		Optional	Task ID	Indicates which tasks the current tasks follow. Defaults to the previously defined task.
Suspendability		Required	Boolean	Indicates if a task may be suspended during execution
Location		Required	Coordinates	Position of the working location.
Working Vessel(s)		Required	Vessel ID	The vessel(s) which are required to work on the task.
Start Up Duration	100% Efficiency	Required	Time	The time, at 100% efficiency, required to start work.
Restart Duration	100% Efficiency	If Suspendable	Time	The time, at 100% efficiency, required to restart work after suspension.
Minimum Working Time	100% Efficiency	If Suspendable	Time	The time, at 100% efficiency, required to justify starting work on a suspendable task.
Maximum Pause Time		If Suspendable	Time	The downtime duration at which work is suspended and the restart time penalty is incurred.
Task Length	100% Efficiency	Required	Time	The time, at 100% efficiency, required to complete a task.
Daylight Requirement		Required	Boolean	Indicates if daylight is required for work to be performed.
50% Efficiency Threshold	Wave Height	Required	Upper Threshold	The threshold at which working efficiency is reduced to 50%. Must be less than or equal to the 0% threshold.
	Tidal Current	Required	Upper Threshold	The threshold at which working efficiency is reduced to 50%. Must be less than or equal to the 0% threshold.
	Wind Speed	Required	Upper Threshold	The threshold at which working efficiency is reduced to 50%. Must be less than or equal to the 0% threshold.
0% Efficiency Threshold	Wave Height	Required	Upper Threshold	The threshold at which working efficiency is reduced to 0%. May be ∞.
	Tidal Current	Required	Upper Threshold	The threshold at which working efficiency is reduced to 0%. May be ∞.
	Wind Speed	Required	Upper Threshold	The threshold at which working efficiency is reduced to 0%. May be ∞.
Project				
Storm Duration Threshold	Return to Port	Required	Time	The time for which storm conditions must persist for a return to port to occur. May be ∞.
	Go to Layup	Required	Time	The time for which storm conditions must persist for a move to lay up to occur. May be ∞.
Vessel ID	Vessel Name	Required	Integer	A numeric identifier for the vessel.

Figure 3-2: Required inputs - ports and safe havens, tasks and project

3.2 Data inputs

3.2.1 Metocean

To perform an analysis metocean data is required correlating to all required limiting factors, e.g. wind, wave, tide at sufficient geographic locations to satisfy the needs of the transit route and port and site locations. This metocean data should be at the highest possible time resolution, and should be at least three hourly. This data can then be interpolated to a finer resolution, these being the individual time steps upon which the analysis structure is based (DNV, 2011, p.71).

If multiple years of data are available it is possible to run an analysis a repeated number of times, therefore quantifying the sensitivity, and the range of cost and lengths for execution expected as a result of varying metocean conditions.

3.2.2 Vessels

An analysis must contain at least one vessel. For each vessel used in the analysis an array of information is required, these elements being:

- The vessel name;
- The fiscal costs associated with the vessel;
  - Day rate;
  - Standby rate;
  - Accommodation fee per person per night (excluding permanent crew);
  - Port departure fees;
- The vessel station keeping limits and mooring requirements;
  - Station keeping limits for any/all metocean conditions when the vessel is moored/jacked up/on DP (Dynamic Positioning system is engaged) etc.;
  - The required time to hook up (moor/jack up/engage DP) or unhook (reverse said processes);
    - When arriving at site, (α_{vs});
    - When leaving site (β_{vs});
    - When arriving in port (α_{vp});
    - When leaving port (β_{vp});

    - The metocean limits relating to hook up/unhook tasks when arriving at site;
- The cruising speed achievable at different wave heights during transit;
- The number of personnel on board, excluding permanent crew, for whom accommodation/living fees are payable. The fees associated with permanent crew are included in the vessel day rate.

In practice it is possible to assemble this information into a database housed in the Vessel table of the input file (Figure 3-3). Identification of a vessel by her name facilitates extraction of the relevant information into an analysis. Multiple iterations of an installation with different vessels in use for comparative purposes can also be achieved.

Vessel Name	Barge				DP OCV			
Crew team	0				12			
Day Rate	£1,000				£110,000			
Standby Rate	£1,000				£85,000			
Overnight fees /person	£0				£150			
Port Fees /trip	£5,000				£5,000			
Station Keeping Limits	Tide /m/s	H_s /m	Wind /m/s		Tide /m/s	H_s /m	Wind /m/s	
	5	1.5	20		3	3	18	
Hook Up	Duration	Threshold			Duration	Threshold		
		Tide /m/s	H_s /m	Wind /m/s		Tide /m/s	H_s /m	Wind /m/s
αvs	2	2	1	15	1	2	1.5	10
βvs	1	2	1.5	15	0.5	3	3	18
αvp	1				1			
βvs	0.5				1			
Transiting	H_s /m	Speed /m/s			H_s /m	Speed /m/s		
	1	7			1	15		
	3	6.5			2	13		
	5	6.5			3	12		
	7	4			6	11		
					8	7		

Figure 3-3: Example vessel input sheet

Whilst day rates vary and the number of personnel on board may not be fixed the largest area of uncertainty in these inputs are the limits applied to vessel station keeping and transit. It is possible for much debate to occur over these limits, especially in situations where a number of different parties have an interest in the outcome of an analysis. In specifying these limits, if too conservative an approach is taken, the time to complete working, due to the accessing of the site, will increase and, therefore, so will the cost. If too cavalier an approach is taken the time to complete working, due to the ease of accessing the site, will be reduced, artificially reducing the expenditure and providing unrealistic expectations.

Whilst it is possible to advise a conservative approach so that costs are over, rather than under, estimated there is as much danger to the future approval, and success, of a project in either of these methods. As noted previously, if it is not possible to be certain regarding a parameter it is advisable to perform a sensitivity analysis to attempt to quantify the potential risk of misrepresenting a value.

3.2.3 Spatial data

There are essentially three main types of location which exist in the analysis of an operation; these being ports, layup locations and the site.

For this analysis it is only possible to specify one port and whilst some operations will deploy from multiple ports (for example a number of forward staging ports) it is thought that more often than not a single base of operation will be acceptable. Furthermore, multiple ports raises a series of logistical considerations and at this point in development this complexity is beyond the means of the methods.

The port has two main occupations; firstly it functions as a base of operation for the vessel(s) working on the installation project. In practice this means that it provides a centre for project management, and a location for the re-fuelling, re-stocking etc. of the vessels. Secondly the port acts as a location in which the vessel can seek refuge if storm conditions prevail across the working area. In these methods vessels seek refuge in port if:

- They cannot keep station at site, i.e. a storm is occurring, and;
    - They are already in port;
    - They are at site and the storm length exceeds a pre-defined threshold.

In the event of a short storm it may not be preferential to transit back to port to seek safety. In this case a layup location may be of use. As with ports it is only possible to define a single safe haven and this should be, although it is not imperative, close to the site and in a sheltered location. No assessment is made as to which locations are sheltered or otherwise and therefore accurate input of this information is essential. As with ports, if storm conditions prevail across the working area the vessels will seek refuge at layup if:

- They cannot keep station at site, i.e. a storm is occurring, and;
    - They are at site and the storm length exceeds a pre-defined threshold relating to layup and does not exceed the related threshold for returning to port.

These thresholds mean that when a period identified as being storm conditions occurs one of three outcomes can take place:

1. The vessel does not leave site and attempts to hold station;
2. The vessel leaves site and moves to layup;
3. The vessel leaves site and returns to port.

Multiple site locations can be specified via the input task list and during analysis the coordinates of the working location will be updated as applicable and especially for transit application. In practice when defining the input locations the first at site location is often suitable, although an alternative location may be presented if required for any reason. Site locations will often be defined by some external source, for example an analysis of site bathymetry or resource distribution. These locations, and those of the port and layup, should be specified in decimal degrees of latitude and longitude in the mapping input table.

In addition to the location of port, layup and site, the coordinates of the available metocean data points should also be provided. These data points will ideally be close to the site, port (where work may also occur) and the transit track (Figure 3-4).

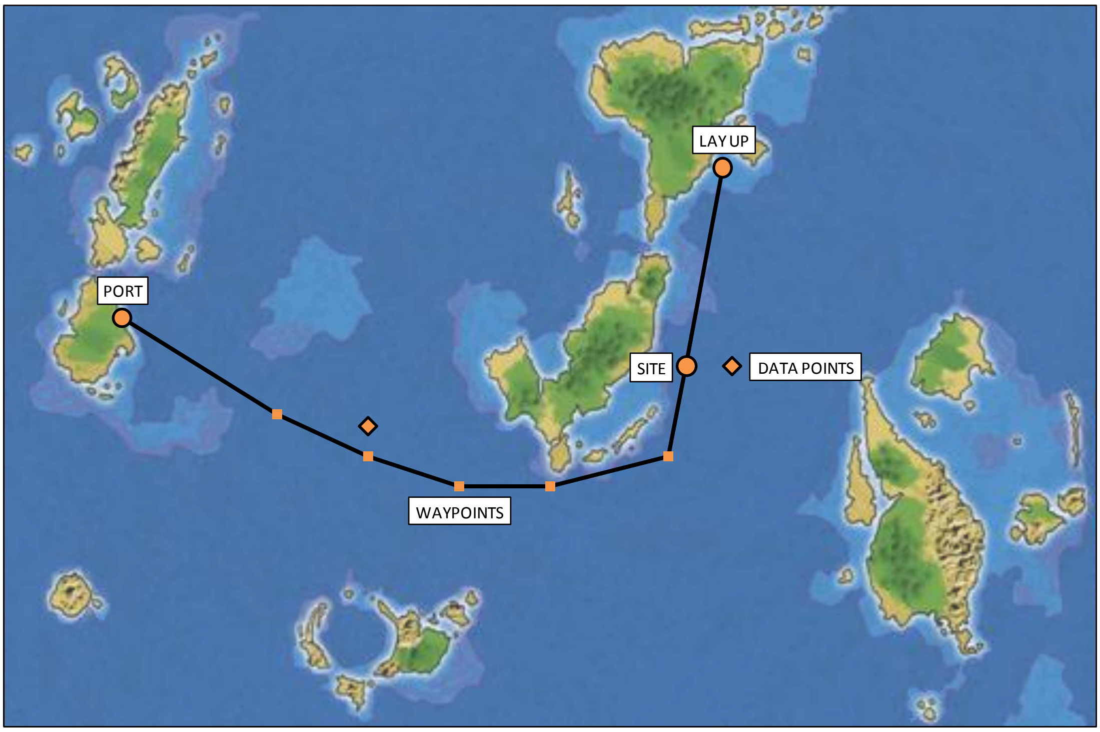


Figure 3-4: Spatial inputs including vessel transit way points and tracks, key locations and metocean data points (Map: Tipex, 2011)

The work presented here is not a vessel route optimisation software package or method. Firstly, this is because of number of such software packages exist (e.g. Aalbers *et al.*; Jeppesen. 2013) and a wealth of material has been published in this area (e.g. Aalbers and van Dongen, 2008; Catalani, 2009). Secondly, many such analysis methods consider shipping, or similar vessel usage, over a large area, for example the North Atlantic. The spatial range considered here is unlimited (within sensible restrictions of the spatial range of the planet); however, often marine energy deployment will be happening in a substantially smaller area, the Inner Sound of the Pentland Firth or the North Sea for example. Even at the larger end of this scale this spatial range may only be some 200km^2, and it is highly likely that sufficient metocean data will not exist to allow for transit route optimisation to take place accurately.

Furthermore, the view of the working area is that of a flat, unobstructed domain defined by longitude and latitude. There is no method allowing for the inclusion of bathymetry or topography and therefore it is impossible to be aware if an area is sea or, crucially, land or interaction with other vessels.

Given these factors it is necessary for the user to define transit track between port and site, and site and layup. To do this any number of waypoints may be input, via their longitude and latitude, which the vessel must pass through en-route. It is not necessary to define waypoints should a straight line transit between two locations be desired and/or possible. The analysis process uses an "as the crow flies" approach to considering the transit between these waypoints and as such it is essential that:

1. No waypoints lie in an area of land;
2. No waypoints lie either side of land, resulting in vessels attempting (and succeeding) to transit through islands.

Studying Figure 3-4 the waypoints defining the transit track, and the track itself, between port and site can be seen. Here it was essential that these waypoints defined a track which caused transit to occur to the south of the central island. Were these waypoints not sufficiently defined, or not defined at all, the track would pass through the central island from west to east. In addition, this figure demonstrates a transit where no waypoints were defined, this being between port and the sheltered layup location to the north.

3.2.4 Project and task data

The bulk of the inputs required to parameterise the model are provided via the "Task List" tabular input. Alongside the map and vessel inputs, this sheet provides all of the data required for a complete analysis to take place. An example sheet is shown in Figure 3-5.

For the largest projects it becomes somewhat time consuming, and potentially error inducing to input all of the tasks manually; therefore looping of certain steps is required. For example, multiple installations of turbines in an array.

Taking the columns in turn; a task ID and text description of the work may be supplied. Following these, details on the scheduling of the tasks is required, which may be achieved as follows:

1. Supply a start date and time;
2. Supply information regarding which task, or tasks, the current operation follows by using the task ID'
3. Provide a start date and time and tasks to follow, the software then determines which start to use based on the execution of the prior tasks'
4. Leave both the start date and tasks to follow blank. In this case the task follows the one immediately above it in the task list.

Two types of tasks may be considered in the analysis. The first of these, "non-suspendable", requires that the available weather window is sufficient to achieve the completion of the task in one complete attempt. The second, "suspendable", allows for work to be paused, or suspended entirely, if the working efficiency becomes zero. This means that the task may be completed over a number of weather windows, providing parameters relating to window length and achievable work are satisfied. During input it is necessary to specify if a task is non-suspendable, $s = 0$, or suspendable, $s = 1$. Having specified the nature of the task it is then possible to define the durations relating to said task, noting that suspendable tasks require significantly more information.

	Task	Start Date	Follows	Suspend?	Location (East)	Location (North)	Vessel	Start Up	Durations /hours: Restart	Durations /hours: Minimum Working Time	Durations /hours: Maximum Pause	Task Length	Daylight?	Tide Limit /m/s: 50%	Tide Limit /m/s: 0%	H_s Limit /m: 50%	H_s Limit /m: 0%	Wind Limit /m/s: 50%	Wind Limit /m/s: 0%
1	Vessel Arrives - On Hire	03/05/2013 09:03		0	-3.5444	58.6114	HLV	0.01				0.1	0	100	100	100	100	100	100
2	Vessel inductions			0	-3.5444	58.6114	HLV	0.4				4	0	100	100	100	100	100	100
3	Arrange Permits		1	0	-3.5444	58.6114	HLV	0.3				3	1	100	100	100	100	100	100
4	Seafasten Substructure Grillage		2	0	-3.5444	58.6114	HLV	3				30	0	100	100	100	100	15	20
5	Load 3x Substructure (including weights)			0	-3.5444	58.6114	HLV	2.4				24	0	100	100	100	100	15	20
6	Deck Inspection			1	-3.5444	58.6114	HLV	0.2	0.1	1	0.5	2	0	100	100	100	100	15	20
7	DP Trials			0	-3.1317	58.6590	HLV	0.6				6	0	2	4	3	4	15	20
8	MMO Clearance			0	-3.1317	58.6590	HLV	0.2				2	0	100	100	100	100	15	20
9	Surveyor Verification: Set Up Site			0	-3.1317	58.6590	HLV	0.3				3	0	100	100	100	100	15	20
10	Prepare Installation			1	-3.1317	58.6590	HLV	0.7	0.3	1.5	0.25	7	0	2	4	1	1.5	15	20
11	Install Substructure and Level			0	-3.1317	58.6590	HLV	0.1				1	0	1	2	1.5	2	15	20
12	ROV Survey			0	-3.1317	58.6590	HLV	0.6				1	0	1	2	2	2.5	15	20
13	Surveyor Verification: Set Up Site			0	-3.1309	58.6584	HLV	0.3				3	0	100	100	100	100	15	20
14	Prepare Installation			1	-3.1309	58.6584	HLV	0.7	0.3	1.5	0.25	7	0	2	4	1	1.5	15	20
15	Install Substructure and Level			0	-3.1309	58.6584	HLV	0.1				1	0	1	2	1.5	2	15	20
16	ROV Survey			0	-3.1309	58.6584	HLV	0.6				1	0	1	2	2	2.5	15	20
17	Surveyor Verification: Set Up Site			0	-3.1304	58.6595	HLV	0.3				3	0	100	100	100	100	15	20

Figure 3-5: Example task list for tidal energy installation

There are five durations that must be defined which should be specified in hours. Durations required for both task types are:

- Start up duration (α_0)
- Task duration (σ_0)

In addition suspendable tasks require:

- Restart duration (α_s)
- Minimum working duration (λ_0)
- Maximum pause duration (λ_{0s})

Here α_0, σ_0, α_s and λ_0 are dependent on efficiency and should be defined assuming 100% working efficiency at all points. α_0 relates to the work required to initiate a task the first time it is performed (the only time work is performed if $s = 0$) and α_s relates to the time required to restart a task following suspension due to downtime. Often this value will be less than α_0 as more work will take place starting than restarting; however, there is no limitation on the length of either, with the exception that both must be greater than zero.

The minimum working time (λ_0) specifies the length of the weather window needed to perform work on a suspendable task. As stated this should be defined assuming 100% efficiency and equates to the quantity of work performed in a window. This means that a window of length exactly equal to $\lambda_0 + \alpha$ will only allow work to be performed if the efficiency at each time step is 100%. If the efficiency at each, and every, time step is 50% the window will need to be $2(\lambda_0 + \alpha)$ to permit work. These two points, with a consideration of λ_{0s}, represent the limits of those windows which will be acceptable; as it is not possible to work faster than 100%, thus shortening the window. Equally, any time step which has zero efficiency results in the window being declared unworkable and the work rejected (once λ_{0s} is exceeded). λ_0 may be set to any positive number; however, if it is specified at a low value work will repeatedly start and stop as short windows are accessed, and if it is specified at too high a value significant downtime may be incurred.

λ_{0s} is the only one of these parameters which is specified in time, as opposed to at 100% efficiency, and represents the longest period of downtime for which it is acceptable to pause (instead of suspend) a task. This, in essence, permits some flexibility to the working limits by allowing exceedance of the limits to incur a lesser penalty than if the limits were strict. Should a single time step, which has an order of magnitude of less than 5 minutes, exceed the working limit during a period of otherwise calm conditions it may not be considered necessary to suspend work, but merely to pause. This means that the progress made in these time steps is zero, owing to the working efficiency being zero, but that α_S is not incurred and progress towards completing the job may resume immediately once the working efficiency increased. A point may arise at which suspending, and incurring α_S is the preferable, safer, option. This occurs once the period of downtime is in excess of this minimum pause time threshold. λ_{0S} may take any positive value as desired, although it is likely that this will be in the magnitude of minutes rather than hours, and it is highly unlikely to be of the magnitude of days.

The task duration represents the total working time required for completion (working time is assigned at the working efficiency of the time step). This results in tasks undertaken entirely at 100% efficiency completing in a time equal to σ_0, tasks entirely at 50% efficiency completing in a time equal to $2\sigma_0$, those with variable efficiency completing at a point in between these values, and those incurring downtime taking significantly longer. A detailed discussion relating to the assigning of working units is presented in Section 3.3.1 where these parameters, which are among the most important to define accurately, are utilized extensively.

Completing work requires knowledge of the efficiency at which the task may be executed. The limiting factors to working at maximum efficiency are primarily related to metocean conditions. As such weather windows are a main focus in this work; however, it is possible to limit the efficiency based on any parameter provided that sufficient time series data and thresholds can be supplied. Here, as in most cases, the conditions considered are:

- Water particle velocity (primarily, but not limited to, tidal current velocity) (m/s);
- Significant wave height (m);
- Mean wind speed (m/s);
- Daylight hours.

Significant wave height and mean wind speed may be defined in other terms (maximum, gust, etc.) provided that the thresholds and the supplied time series data correspond. Here thresholds are defined at 50% and 0% efficiency; this being the wave height, or similar, at which when exceeded the efficiency reduces to the specified value. These efficiencies may be adjusted, and may take any value less than 100%, although a negative value results in work being “un-done” and the task failing to complete. Should no limitation exist for a task it is possible to set a parameter to a null value of 100 (or a similarly large number which does not occur in the time series) thereby causing a working efficiency of 100% to be applied at all times.

Defining these limits correctly is one of the most vital inputs to the model given that not only is the task go/no-go decision based upon them but also the time required to complete the task. Setting these thresholds inaccurately may result in tasks failing to complete as working windows are unavailable, or the speed of work is excessively slow.

In addition to metocean parameters it is also possible to consider the requirement for daylight conditions. Safety, complexity or other water users (or in the case of nearshore applications the general public etc.) may dictate that work can only be performed during hours of daylight. In this case daylight hours are sought for a task if the input is equal to one, and whilst it is likely that an input of zero will be default this ability to consider both cases is considered vital. Daylight is not supplied in a time series manner but instead calculated. Established formulae exist from which the times of sunrise and sunset can be determined, if the coordinates of the location of interest are known (Sunrise/Sunset Algorithm [Online], 2013). Given the data supplied relating to the geo-spatial frame of reference of the project, namely the location of the port, layup and a central site coordinate, it is possible to determine the durations of daylight and thus consider the effect on operability.

As mentioned previously, multiple working locations may exist. These can be specified for each task in terms of their latitude and longitude as seen in Figure 3-5. Here the location specified in green text represents an in port task, with the black and blue locations representing six at sea locations (the colours alternating for ease of identification of transit prerequisites).

The final requirement is the identification of which vessels, or vessel are required for work to be performed on a task. There must be at least one vessel assigned and no maximum limit exists, although all vessels used must be specified in the vessel input list.

3.3 Analytical method

The methods outlined below have been realised through a number of modular functions. This means that the methods are not applied strictly in the order defined below but as required by the hierarchy and prerequisites of the analysis process. The objective of each method is to contribute to the progression of the project, allowing work to occur, providing some aid to facilitate a working opportunity or providing steps to safe downtime. For work to occur the following must be satisfied:

1. The working location must be accessible, i.e. the vessel station keeping limits must not be exceeded for all of the vessels required for work;
2. The vessel(s) required for work must be at the working location and hooked up, i.e. prepared for work;
3. The task limits must not be exceeded, i.e. a working weather window must exist;
4. The length of the window must be sufficient to perform the task, if it is not suspendable, or be sufficient to perform the minimum required amount of work, if it is suspendable.

Having satisfied these requirements progress made on the task is dependant on the working efficiency at each time step, until sufficient work has been achieved for the task to be declared complete. The analysis progresses through the tasks until all are completed, and the project itself is finished.

At all phases in the analysis a time-step orientated method is used. The progress and completion of work on a task is determined in time steps, which are accredited depending on the efficiency of the individual time step. For the approach to be successful all time based inputs (for example α_0, λ_0, σ_0 etc.) must be converted from their native units (hours) to non-dimensional time steps (t); this is achieved by applying Equation 3-1.

$$t = \frac{T}{24\Delta t}$$ **Equation 3-1**

Where T is the input time (hours) and Δt is the time step length (hours).

The first time step ($n = 1$) must be identified from the given start date for the first task, as subsequent tasks obtain their start point from those which have been completed previously. This is done by identifying which time step in the metocean data is closest to the specified start date. For the purposes of working with multiple years of data all dates are converted to be in the year of the metocean data (i.e. when analysing data from 1998 with a start date of 3rd May 2013 this becomes 3rd May 1998). With this information determined the methods below may be applied.

3.3.1 Progress efficiency

Limits exist for four components of an analysis:

- Task limits;
- Vessel station keeping limits;
- Vessel hook up (mooring) limits;
- Vessel transit limits.

The latter two relate to moving to the working location and preparing to be able to work, whereas the former two relate to the ability to work. If the vessel is at site and moored the station keeping limits, hook up limits and transit efficiencies have, at some prior series of time steps been acceptable and remain so in the current time step. This places particular importance on the task limits. Circumstances can arise where the remaining three limits have not prevented progress; it then transpires that a go/no go decision depends on the efficiency at which the task can be performed, this being zero when the limits are exceeded. Accurate specification is therefore important otherwise expensive at site down time may occur, this being downtime that incurs day rate charges, accommodation fees and fuel burn.

A requirement for future analysis steps is a vector relating to the available working efficiency at each time step in the metocean record. This vector (r_{j0}) considers all specified metocean types (ω) by applying Equation 3-2, which in turn utilizes Equation 3-3. Equation 3-3 creates an array with the working efficiency of each metocean type across the columns (w) at each time step (the rows, n). These are determined by looking at the metocean data value at each time step and applying an efficiency of 1 if the metocean data is less than the 50% efficient threshold, 0.5 if the data is between the 50% and 0% thresholds and 0 if the 0% threshold is reached or exceeded. The minimum efficiency, for each time step, is taken from this array giving the vector r_{j0}.

$$r_{j0(n)} = \min_{w}(r_{j(n,w)}) \qquad \textbf{Equation 3-2}$$

$$r_{j(n,w)} = \begin{cases} 1, & \omega_{(n,w)} < \eta_{0.5} \\ 0.5, & \omega_{(n,w)} \geq \eta_{0.5} \ \& \ \omega_{(n,w)} < \eta_0 \\ 0, & \omega_{(n,w)} \geq \eta_0 \end{cases}$$ **Equation 3-3**

This process is illustrated in Figure 3-6. Tidal current velocity, wave height and wind speed are presented with red, orange and green lines representing the various thresholds. The efficiency of each metocean trace can be seen beneath the plot. Efficiencies are the columns of the array, r_j, with the x-axis representing the passage of time seen in the rows of the array. The axes presented at the base of the figure detail the minimum working efficiency, r_{j0}. It can be seen that, in this case, it is the tidal current velocity which dominates the workability, as is the case at many tidal energy sites where only short slack water periods occur. However, it can also be seen that towards the end of the period under study it is the wave height which at times effects the working efficiency, capping this value at 50%.

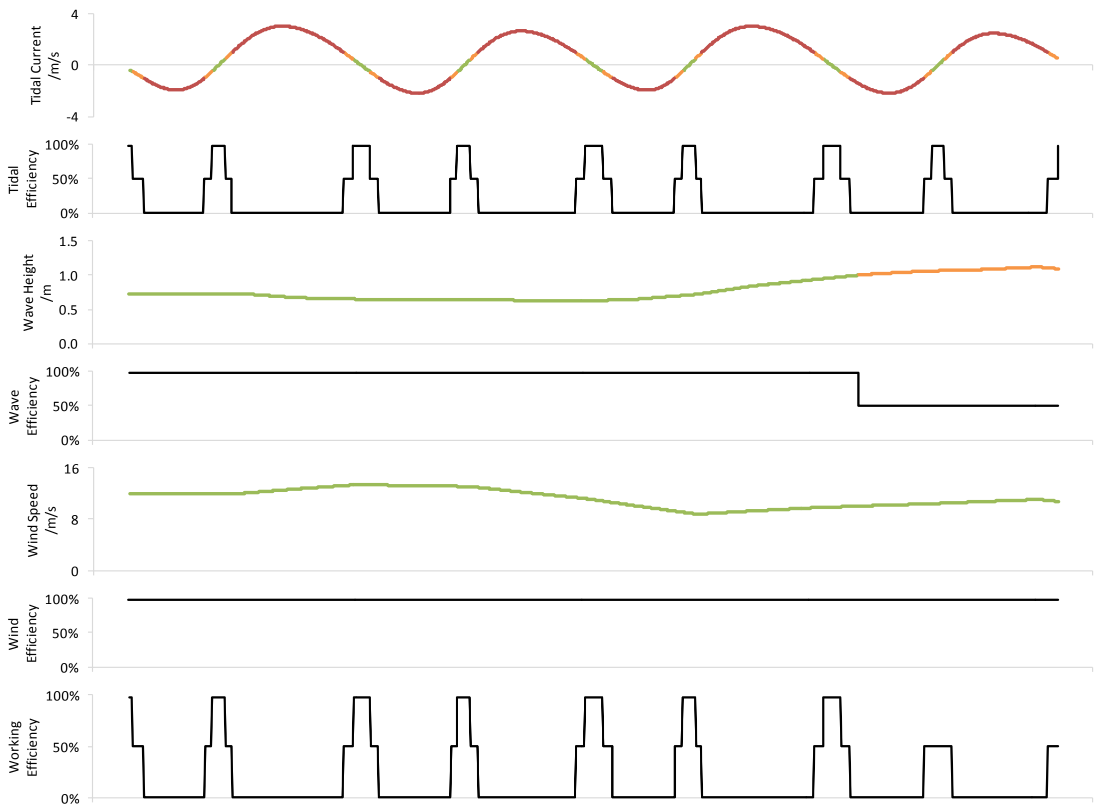


Figure 3-6: Efficiency factors of a task for tidal velocity (top charts), wave height (upper middle charts) and wind speed (lower middle charts) relative to metocean parameters, and the resultant task efficiency (bottom chart). Metocean conditions are colour coded red, orange and green and relate to 0%, 50% and 100% efficiency respectively.

It is of interest to determine which metocean condition is the limiting factor for performing work and whether this limitation is an efficiency reduction or a task suspension. By using r_j output plots may be produced (Figure 3-7).

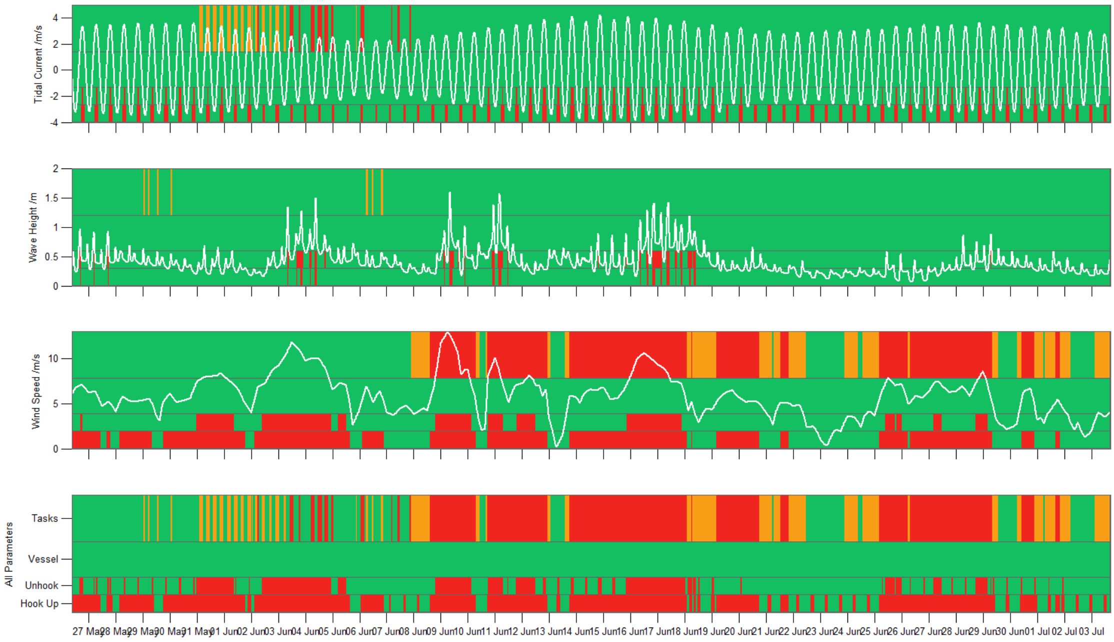


Figure 3-7: Example limiting factor output considering efficiency/accessibility (0%/inaccessible - red; 50% - orange; 100%/accessible green) for operational elements (task efficiency, vessel stationkeeping, vessel hook up and unhook) for all metocean conditions and the total project

These limiting factor plots allow resource to be focused in the correct area when optimising an installation process. For example, considering the limitations identified in Figure 3-6, enhancing the crane capabilities of a vessel may be of little benefit when the limiting factor is the tidal current. Conversely, if wind speed were limiting the ability to work there would be little point in devising new subsea drilling technologies which are not as sensitive to tidal velocity when a new crane would suffice.

3.3.2 Station keeping

Vessel station keeping is a factor of any downtime likely to be endured. In short, if a vessel cannot hold station it cannot perform work and costly downtime, either returning from site and therefore paying day rates, burning fuel etc., or in port, may be incurred. Any time for which it is unfeasible to hold station must be identified early in the analysis process to allow for the correct vessel location to be determined.

Given the inputs available to the user it is possible to simulate a range of downtime scenarios, and storm events, such that a variety of installation operations may be performed.

Firstly, a simple operation with task limits and some basic binary station keeping limits may be specified. This being a situation where the vessel is either able to be on site or is forced into port (or layup) as a results of metocean conditions exceeding given limits. When at site this vessel is able to work if all pre-requisites to work are satisfied, including the task limits.

In some scenarios the station keeping limits may not be binary. Particularly in the case of a tidal energy converter installation it is possible for the vessel to be in three states:

1. Incurring station keeping downtime due to an in ability to be at site;
2. Being at site and holding a general station, but unable to hold station over a specific location and therefore unable to perform some of the tasks;
3. Being at site and holding a specific location, therefore being able to work if all pre-requisites are satisfied.

In these three cases the first is defined via the input of the previously discussed task and vessel limits. The second case is defined via a careful balancing of these two limits:

- Specify the vessel station keeping limits, noting that when these are exceeded the vessel will return to port;
- For each task specify the limits such that the lowest applicable limit of the following is used:
    - The limit at which the vessel ceases work when at a general location;
    - The limit at which the vessel ceases work when at a specific location, i.e. the point at which the vessel moves from a specific location to a general location;
    - The limit at which the task cannot be performed.

The appropriate application of these task limits and their effect on the efficiency factors has previously been discussed in Section 3.3.1. Here the method for identifying periods of time for which the vessel fails to keep station are discussed.

For each metocean parameter the threshold is specified. In addition there is a requirement to specify the length of time for which conditions must persist to be considered a storm (λ_{st}). This is important as a brief gust of wind, for example, may lead to the wind limit being exceeded for one or two time steps, this is unlikely to be considered a storm for which site must be left but merely a momentary period of uncomfortable conditions. Conversely, were the wind speed limit to be exceeded for a number of days, some hundreds or even thousands of time steps, this would be a case where remaining on station was both unsafe and ill advised. Obtaining this value may be somewhat subjective and defining it accurately is of importance to the correct modelling of the station keeping capabilities

It is necessary, at the same juncture, to define the length of time for which a calm period should be considered accessible. As before it is not sensible to consider short windows to be accessible. Here "short" is likely to vary from project to project and thus requires definition of this parameter λ_{calm}.

Figure 3-8 shows the identification of a storm period. Here the vessel station keeping limit is exceeded for a number of time steps ($r_{jv} = 0$). The times for which this occurs are bounded by $t_{(1)}$ and $t_{(2)}$ where $t_{(1)}$ is the first time step at which $r_{jv} = 0$ given that $r_{jv} = 1$ at the previous time step (Equation 3-6). The inverse is true for $t_{(2)}$ (Equation 3-7). This period of time, $t_{(1)}$:$t_{(2)}$ is considered to be a storm, and therefore a member of the storm array (*st*) if its length exceeds the previously defined limit (Equation 3-4).

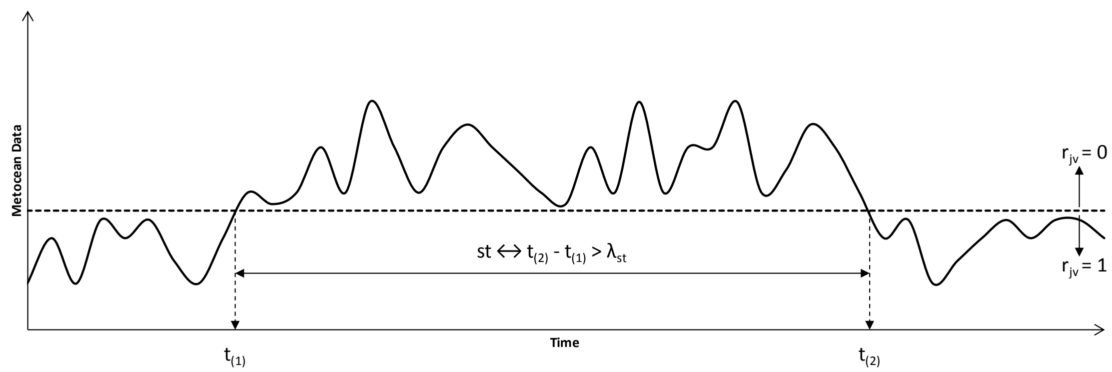


Figure 3-8: Storm (metocean conditions exceed presented threshold) with no intermediate calm

$$t_{(t_1:t_2)} \in st \Leftrightarrow t_{(2)} - t_{(1)} > \lambda_{st} \qquad \textbf{Equation 3-4}$$

Figure 3-9 represents a scenario in which two storms occur within close proximity to each other. Here the first storm is bounded by $t_{(1)}$ and $t_{(2)}$ as in the previous case, with the second storm being described by $t_{(3)}$ and $t_{(4)}$. These time steps being determined from the changing of the r_{jv} efficiency from time step to time step. To determine if these two potential storm events should be considered as one then $(t_{(3)} - t_{(2)})$, the length of the intermediate calm, must be less than the calm limit. If this is true, as in this example, the period $t_{(1)}:t_{(4)}$ should be considered a storm if $t_{(4)} - t_{(1)}$ exceeds the storm limit. This is as described in Equation 3-5. If $t_{(4)} - t_{(1)}$ does not satisfy these requirements this period is not considered to be a storm event.

Where the intermediate calm is of sufficient length to allow site accessibility the periods $t_{(1)}:t_{(2)}$ and $t_{(3)}:t_{(4)}$ may still be considered storm events provided that their individual lengths satisfy Equation 3-4.

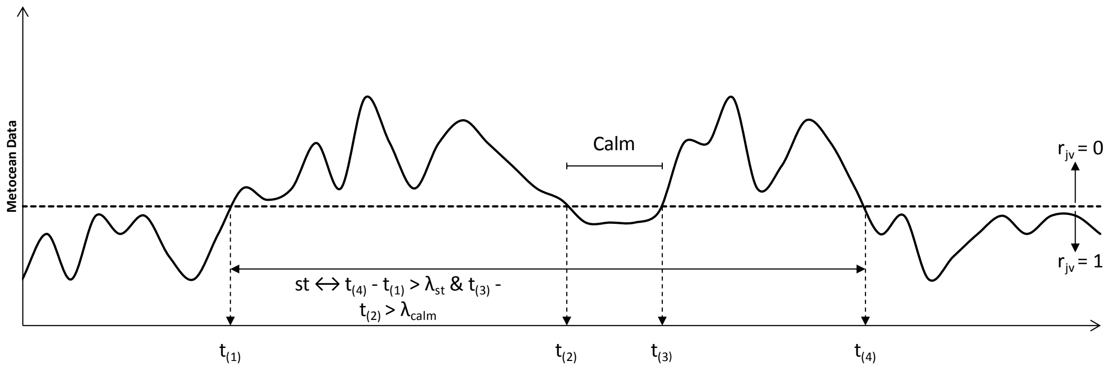


Figure 3-9: Storm (metocean conditions exceed presented threshold) with intermediate calm (metocean conditions become workable below presented threshold)

$$t_{(t_1:t_4)} \in st \leftrightarrow t_{(4)} - t_{(1)} > \lambda_{st} \;\&\; t_{(3)} - t_{(2)} < \lambda_{calm}$$ **Equation 3-5**

Where:

$$t_{(1)} = t_{(n)} \leftrightarrow r_{jv(n)} = 0 \;\&\; r_{jv(n-1)} = 1$$ **Equation 3-6**

$$t_{(2)} = t_{(n)} \leftrightarrow r_{jv(n-1)} = 0 \;\&\; r_{jv(n)} = 1$$ **Equation 3-7**

$$t_{(3)} = t_{(n)} \leftrightarrow r_{jv(n)} = 0 \;\&\; r_{jv(n-1)} = 1$$ **Equation 3-8**

$$t_{(4)} = t_{(n)} \leftrightarrow r_{jv(n-1)} = 0 \;\&\; r_{jv(n)} = 1$$ **Equation 3-9**

Having performed this process for the entire project (for the whole year for all working vessels) an array that identifies whether a time step is part of a storm, or part of an accessible period, exists. The process of accessing a site, however, is not as simple as just identifying the periods for which metocean conditions allow availability. There is a requirement when the vessel arrives on site for it to begin station keeping, be this via hooking up to a mooring, jacking up, engaging the dynamic positioning system or similar.

3.3.3 Vessel hook up

Upon arriving at site a vessel must firstly perform a hook up operation; the mooring, making safe and preparation to work of the vessel. Equally when leaving site a vessel must reverse this process, disconnecting its station keeping apparatus and preparing for transit. For many vessels these processes are metocean dependant. For example, a jack-up barge will have very sensitive metocean limits during its jacking up process but once fully jacked will be reasonably non-responsive to changes in metocean condition providing, as it is designed to, a stable working platform.

For simplicity it would be possible to assign tasks such as jacking up/down it the task list at the points at which the location changes. If this approach were used, however, two issues arise. Firstly, were the vessel to leave station due to a storm event the unhook process would be neglected. Equally when it returned to site the hook up process would not occur since it would not be specified in the task list. Secondly, in this case, when hooking up is a specified task, the vessel would transit to site based on the vessel station keeping limits and then wait until an available window to perform the hooking up task occurred. This has the potential to lead to an extended period of time during which a vessel is at site and not moored, this being both unrealistic and dangerous.

The solution to this problem is to define vessel hook up limits and durations. These being the metocean conditions not to be exceeded during the hook up operation and the length of time required to complete such a process. Hook up operations are considered to be non-suspendable, i.e. it is not possible to pause the hook up and return later to complete the operations, therefore a complete window must exist during which hook up may occur.

A method to identify the time steps at which a vessel cannot keep station has been presented and, as indicated in Figure 3-10, an array of accessible/non-accessible time steps may be determined. In addition to this an array of time steps for which hook up is possible must be determined. This method is initially presented in Figure 3-11 and the following equations. The metocean arrays are assessed from $t_{(max)}$ to $t_{(min)}$, i.e. n, the time step number is monotonically decreasing. At each time step Equation 3-10 is applied. This states that the value s_{nh}, the total score of hook up work performed in a window, is increased by the hook up efficiency of the time step (in practice a value of 1 or 0). This total score is multiplied by said efficiency which results in the value of s_{nh} being reset to zero on any occasion for which the r_{jh} is zero. This can be seen in the central chart of Figure 3-11.

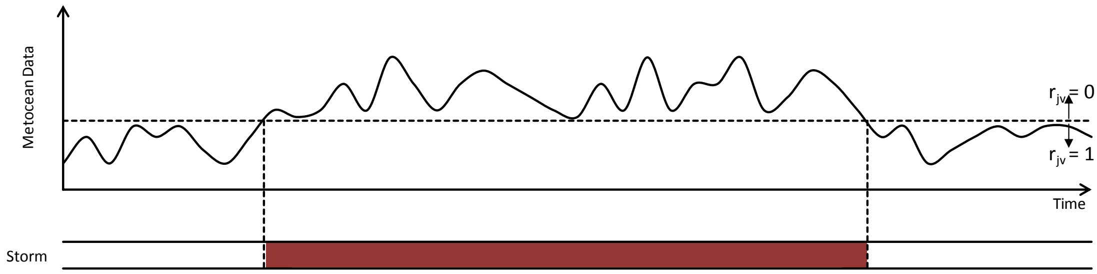


Figure 3-10: Identifying storm events where metocean conditions exceed specified threshold (red)

Once the total score at each time step has been obtained feasible hook up windows can be identified. Sufficient time is available for hook up from any time step for which s_{nh} is greater than or equal to the required amount of work for hook up to succeed (σ_h, where σ_h is either σ_{hu} or σ_{uh} depending on the type of operation occurring, Equation 3-11 and Equation 3-12). These time steps are indicated in Figure 3-11 in green, with the period of time for which hook up will be occurring from the latest possible hook up time step indicated in pale green. For unhook operations the process is identical albeit with the option to use different limits.

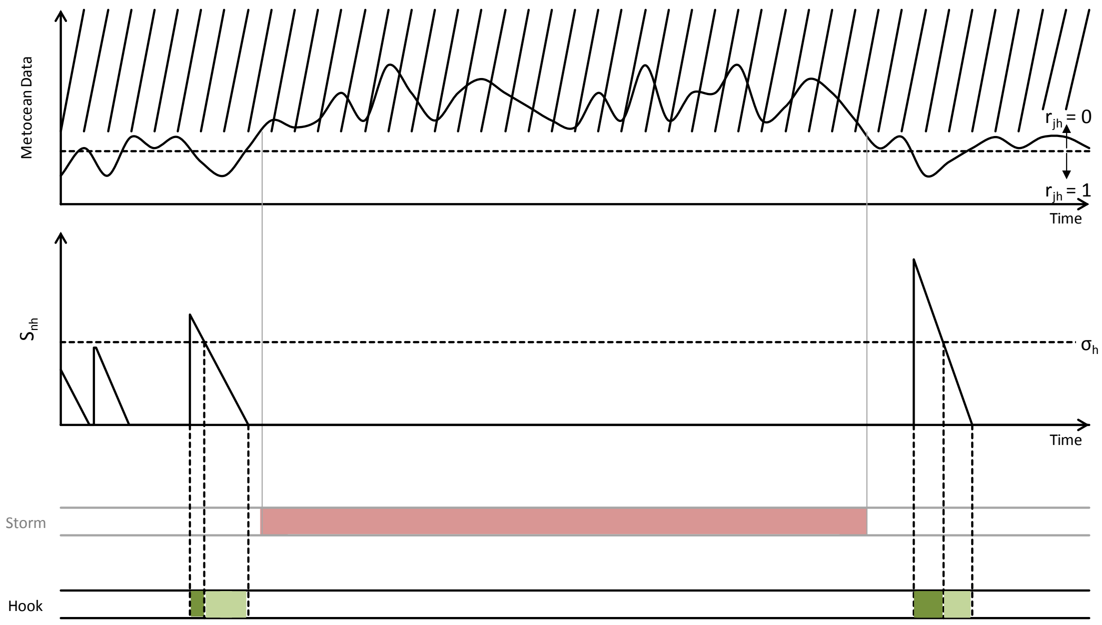


Figure 3-11: Identifying hook up opportunities relative to storm conditions. Dark green represents time steps during which hook up may be started; Light green time steps where hook up may be performed.

$$s_{nh(n)} = r_{jh(n)}\left(s_{nh(n-1)} + r_{jh(n)}\right) \quad \textbf{Equation 3-10}$$

$$t_{(n)} \in hu \leftrightarrow s_{nh(n)} \geq \sigma_{hu} \quad \textbf{Equation 3-11}$$

$$t_{(n)} \in uh \leftrightarrow s_{nh(n)} \geq \sigma_{uh} \quad \textbf{Equation 3-12}$$

At this point in the procedure two arrays exist, *hu* and *uh*, detailing the time steps from which it is possible to start these processes. Transits to and from site may occur for a number of reasons; however, the primary cause of transits may be reduced to scheduled transit and storm transit.

For all transit types it is necessary to determine the time step $t_{(ds)}$, the time at which site is departed, or $t_{(dp)}$, the time at which port is. In storm transits these time steps are dependent on two key parameters; the time at which the storm starts/ends, and the periods for which hook up/unhook may occur. In both cases the transit at the slowest defined speed, τ_{sp}, is used, this being the least efficient transit and therefore one which may not be exceeded.

Considering hook up first; when a storm ends the primary goal of the vessel, assuming a task is at site, is to return to site and resume working. As an initial proposition the time, $t_{(dp)}$, is taken as the time step for which the storm concludes, thus meaning that the vessel will not be at sea during storm conditions. If this time step is defined as $t_{(4)}$, the time step $t_{(4)} + \tau_{sp}$ is of interest. In the example shown in Figure 3-12 this time step is a member of *hu* and therefore it is appropriate for transit to occur with $t_{(dp)} = t_{(4)}$ as specified in the first condition of Equation 3-13. When the time step $t_{(4)} + \tau_{sp}$ is not a member of *hu*, i.e. not indicated in dark green and as shown in Figure 3-13, it is not possible for the transit to occur. Here the time step proposed as $t_{(ds)}$ initially should be advanced until a time step $t_{(4+n)}$ (which is a member of *hu*) is identified. The departure time step is now this time step as indicated in Equation 3-13. The effect of increasing the departure time step is that the time steps from $t_{(4)}$ to the now identified $t_{(ds)}$ become part of the storm, despite the site conditions being accessible. As a result the storm is extended, as indicated in Figure 3-14 and Equation 3-14 and unsafe waiting at site is avoided.

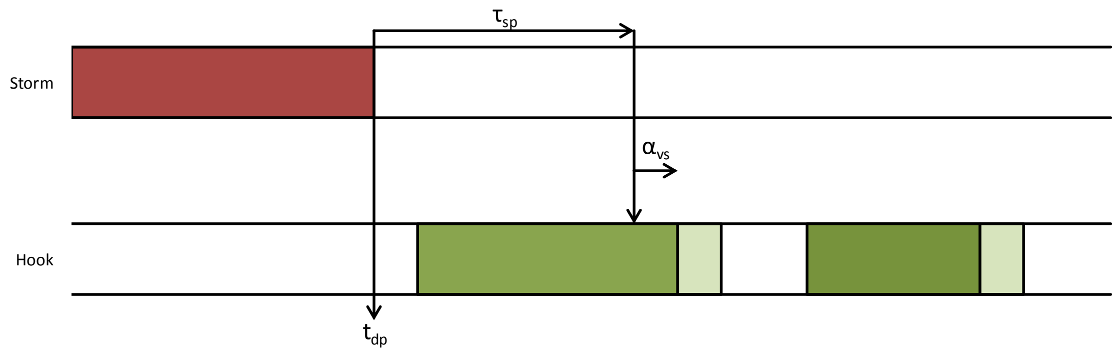


Figure 3-12: Hook up - available after storm with no complications; following transit (τ_{sp}) the vessel is immediately able to access a start hook up time step (dark green)

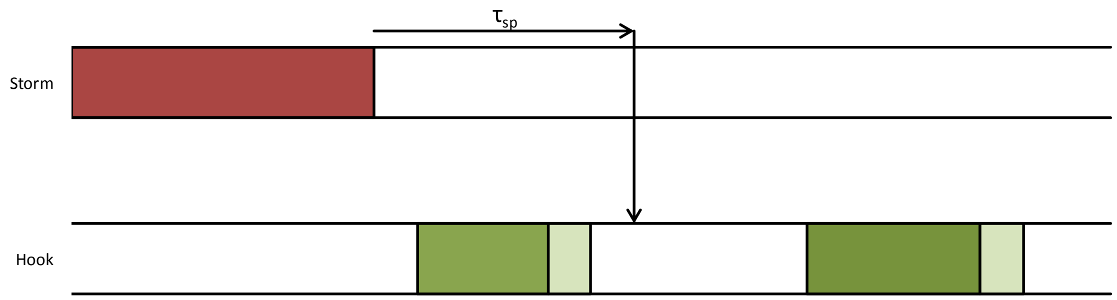


Figure 3-13: Hook up – unavailable after storm; following transit (τ_{sp}) the vessel is not immediately able to access a start hook up time step (dark green)

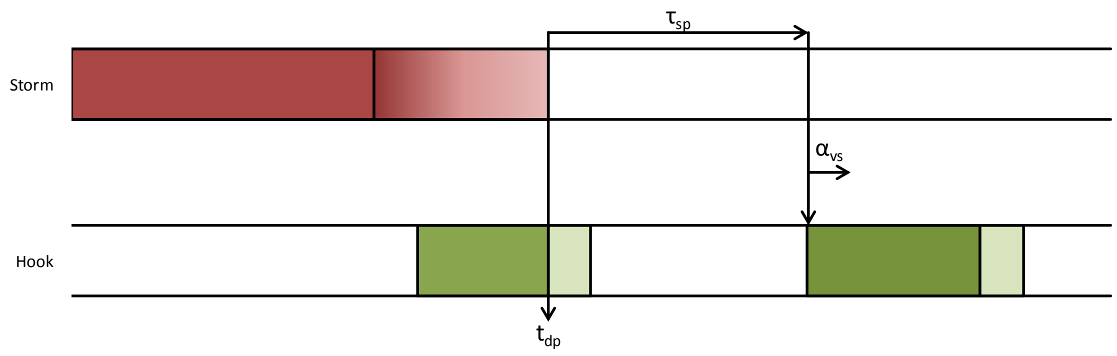


Figure 3-14: Extending storm - hook up available when the port departure time step (t_{dp}) is delayed to allow arrival at site during hook up available conditions

$$t_{(dp)} = \begin{cases} t_{(4)}, & t_{(4)} + \tau_{sp} \in hu \\ t_{(4+1)}, & t_{(4+1)} + \tau_{sp} \in hu \\ t_{(4+2)}, & t_{(4+2)} + \tau_{sp} \in hu \\ \vdots & \\ t_{(4+n)}, & t_{(4+n)} + \tau_{sp} \in hu \end{cases}$$ **Equation 3-13**

$$t_{(4:dp)} \in st \leftrightarrow t_{(ds)} > t_{(4)}$$ **Equation 3-14**

The process of identifying the departure from port time step follows a similar process and is described in Figure 3-15 to Figure 3-17, Equation 3-15 and Equation 3-16. Instead of looking forwards to identify if hook up is available it is necessary to look backward an amount of time equal to τ_{sp} + β_{vs} to determine if unhook is available. As before if unhook window is unavailable the storm must be extended.

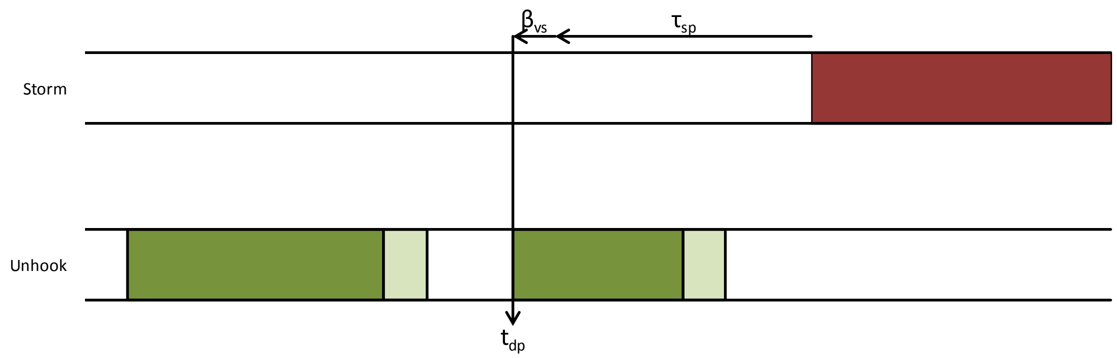


Figure 3-15: Unhook - available before storm with no complications, the vessel is able to complete unhook and return to port before the start of the storm

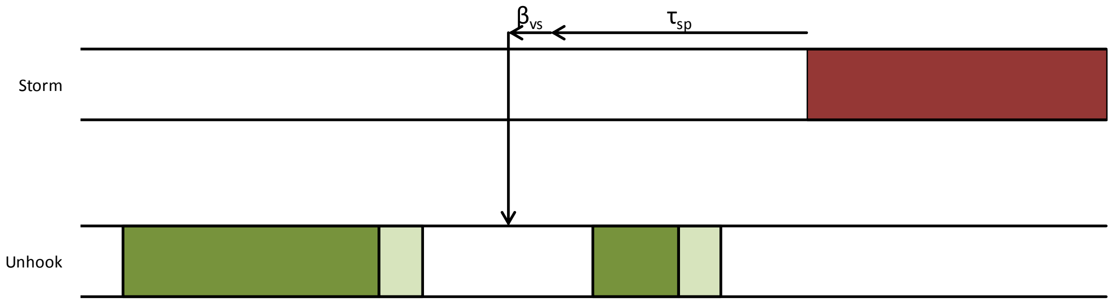


Figure 3-16: Unhook – unavailable, the vessel is unable to unhook and return to port before the start of a storm

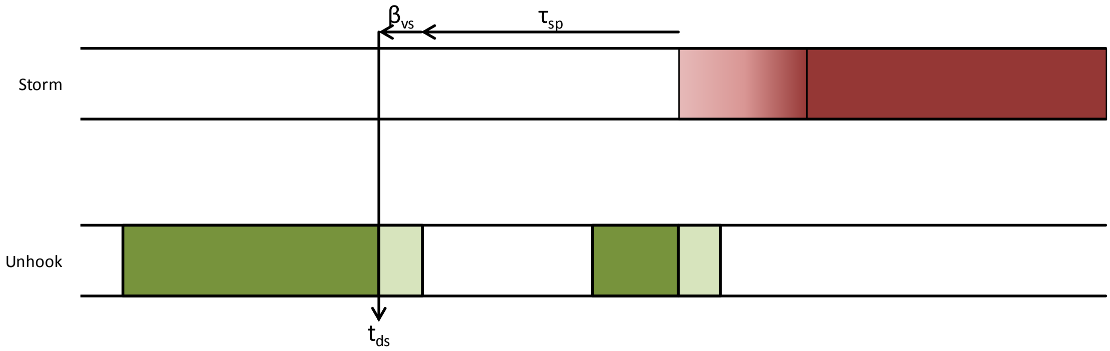


Figure 3-17: Extending storm - unhook available when the site departure time step (t_{ds}) is placed earlier, allowing the vessel to return to port before the storm

$$t_{(ds)} = \begin{cases} t_{(1)}, & t_{(1)} + \tau_{sp} + \beta_{vs} \in uh \\ t_{(1+1)}, & t_{(1+1)} + \tau_{sp} + \beta_{vs} \in uh \\ t_{(1+2)}, & t_{(1+2)} + \tau_{sp} + \beta_{vs} \in uh \\ \vdots & \\ t_{(1+n)}, & t_{(1+n)} + \tau_{sp} + \beta_{vs} \in uh \end{cases}$$ **Equation 3-15**

$$t_{(ds:1)} \in st \leftrightarrow t_{(dp)} < t_{(1)}$$ **Equation 3-16**

Due to the reversing of time during this process it must occur at a project level in the analysis hierarchy (Figure 2-2). If, when analysing tasks, the time step index can increase or decrease it is possible that work can occur *before* the specified start of the task. This is unacceptable; if the user has specified a start date it is reasonable to assume that this is the earliest point at which work may occur (for example, due to a vessel being taken on hire). When analysing tasks the start time is considered in relation to either; i) an absolute time (as in the case of the project start date), or ii) other completed tasks. Were a task to have a decreasing time step index and go past its own start date overlapping with a predecessor it is now no longer obeying the project scheduling.

When calculating the transit time for use in determining the departure time step vessel transit considers the worst possible performance. Until the transit is triggered, however, the metocean conditions are not known and therefore the transit could occur in a faster time than τ_{sp}. Figure 3-18 demonstrates the effect of a more efficient transit. Here the storm has been extended to access the first available hook up time step; however, the transit may occur in a time between τ_1 and τ_{sp}. As shown this may result in a number of time steps, t_{as}, for which the vessel is at site and waiting. Whilst this is a situation which the method has sought to avoid it is, in some cases inevitable. Given that the longest time for which the vessel will be waiting at site is the difference between the longest and the shortest transit it is not problematic to allow this to occur. This variable waiting time, indicated in orange, is at site downtime.

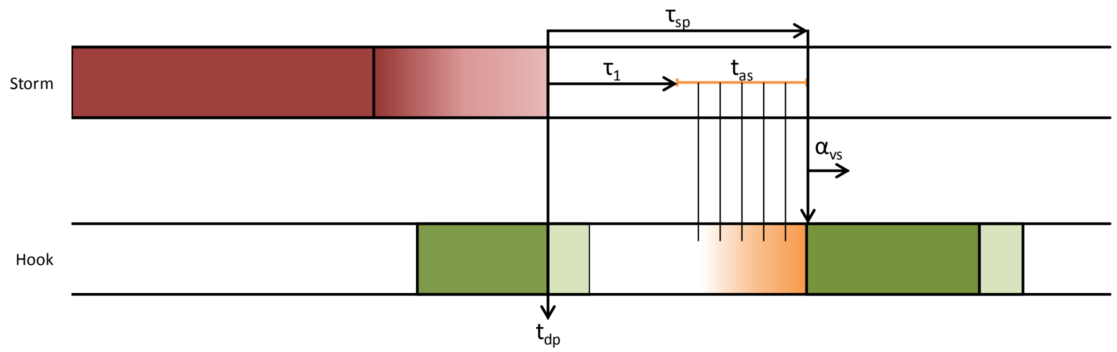


Figure 3-18: Waiting for hook up due to fast transit speed, orange time steps represent the period of time for which the vessel is at site but unable to hook up to station

3.3.4 Transit

Transit will occur when:

- The vessel's task is located at site, the vessel is in port, a storm is not occurring and a departure time which accesses a hook up opportunity exists;
- The vessel's next task is located in port, or this is the vessel's last task, the vessel is at site and a departure time which accesses an unhook opportunity exists;
- The vessel is at site and a storm departure time step occurs;

- The vessel is in port, a storm ending time step occurs and the task is at site;
- The vessel is at layup, a storm ending time step occurs and the task is at site.

Figure 3-19 details a number of parameters relating to the transit calculation. Here the previously specified track is visible between port and site (and site and layup) with the individual way points, $m = 1$ to $m = 7 = m_{sp}$ shown. $d_{(n)}$ is the cumulative distance which the vessel has moved from the start of the transit to the current time step n. The bearing (θ), taken from due north for each waypoint line is shown for the point $m = 3$.

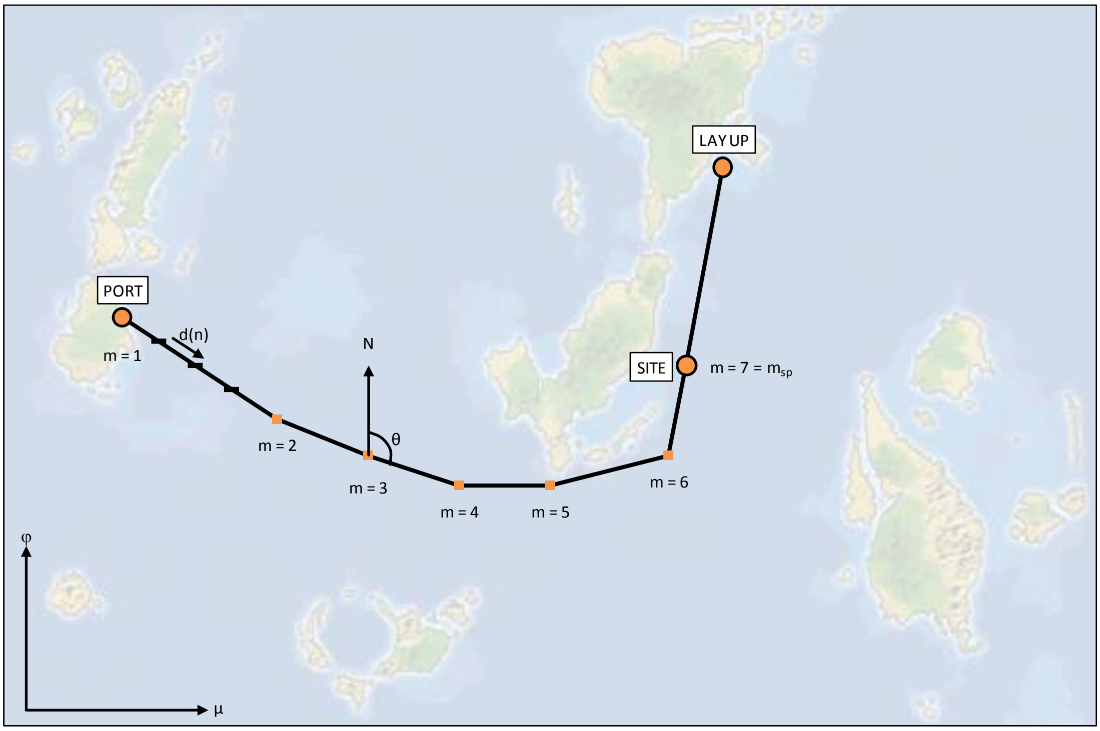


Figure 3-19: Transit parameters and their application, including $d_{(n)}$, the cumulative distance travelled and θ the bearing of transit

For a transit to be complete the value of $d_{(n)}$ must be greater than or equal to the total distance, d_{sp}, as specified in Equation 3-17. This equation states that a transit of length (hours) of $n\Delta t$, is complete at the time step n for which the cumulative magnitude of $d_{(n)}$ has satisfied the requirements of d_{sp}. To determine the elements of the vector $d_{(n)}$ Equation 3-18 is applied. At each time step the distance travelled is dependent on the speed of the vessel given the metocean conditions [$u(r_{j\tau(n)})$]. If information relating transit performance to metocean conditions exists the transit efficiency at the current time step ($r_{j\tau(n)}$) can be determined in much the same manner as the calculation of the task efficiency array (r_{j0}). Briefly, the process at each time step is thus:

1. Identify the magnitude metocean parameter under consideration;
2. If this value is greater than the lowest efficiency threshold and less then the next efficiency threshold assign this efficiency to $r_{j\tau(n)}$;
3. If point 2 is not satisfied proceed to the next efficiency band until $r_{j\tau(n)}$ is assigned.

If multiple metocean types are to be considered this process can be repeated and the lowest efficiency taken.

$$\tau = n\Delta t \leftrightarrow d_{(n)} \geq d_{sp} \qquad \textbf{Equation 3-17}$$

Where:

$$d_{(n)} = u(r_{j\tau(n)}) \cdot \Delta t + d_{(n-1)} \qquad \textbf{Equation 3-18}$$

As discussed in Section 3.1 it is desirable to have metocean data specified at a number of points along, or near to, the vessel transit track. This allows a more detailed analysis of the efficiency of transit to occur. The nearest metocean data point to the last known location, i.e. the location at the last time step, is utilized in determining $r_{j\tau(n)}$. It is assumed that the weather incumbent on the vessel is more like the nearest metocean dataset than any other. This is regardless of whether the vessel has transited beyond this data point or not; Figure 3-20 illustrates this. In order to determine which data point is nearest a variant of Equation 3-19 is used for all data points and the minima identified.

Equation 3-19, structured as shown is used for the calculation of d_{sp} specifically and the distance between two known points generally. This equation utilizes the radius of the Earth (R) and the latitude (μ) and longitude (φ) of the known points. If these known points are the waypoints and the distances between them are summed the total transit track distance is determined. If these two known points are the vessel and the data point locations the most appropriate data set can be determined.

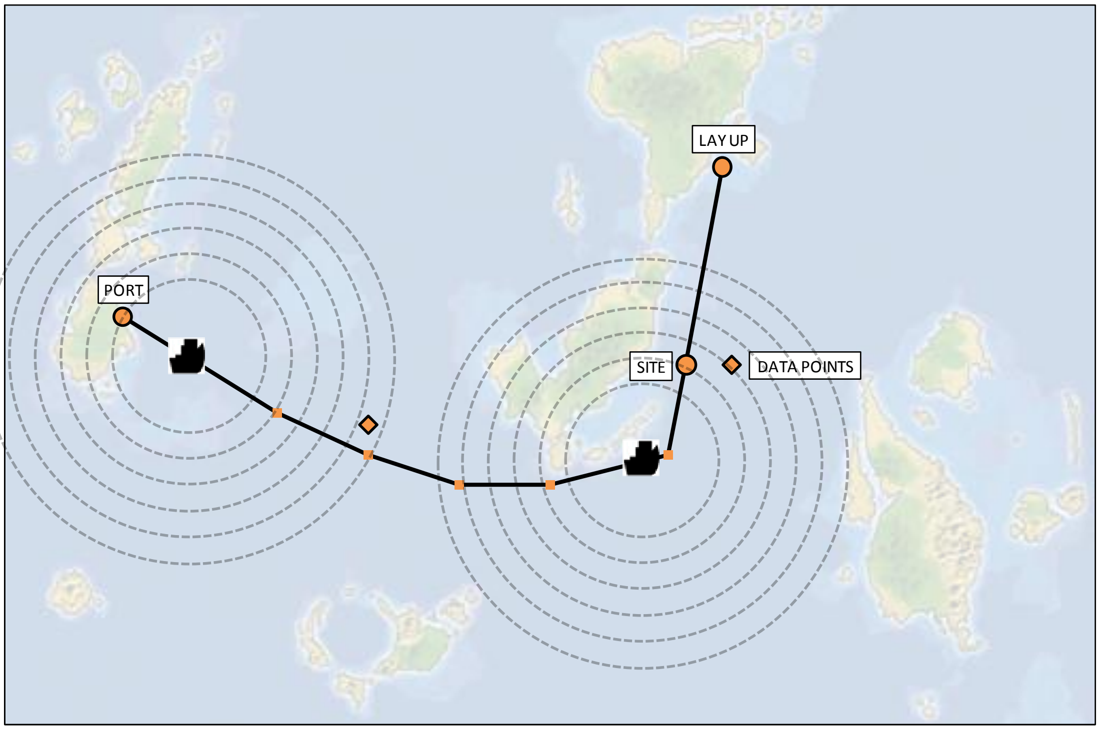


Figure 3-20: Determining appropriate metocean points for use in transit analysis based on distance from the vessels current location. Two vessels are shown which utilize different metocean points

$$d_{sp} = \sum_{m=2}^{m_{sp}} R \cos^{-1}(\sin \mu_{(m-1)} \cdot \sin \mu_{(m)} + \cos \mu_{(m-1)} \cdot \cos \mu_{(m)} \cdot \cos(\varphi_{(m)} - \varphi_{(m-1)})) \quad \textbf{Equation 3-19}$$

Two additional considerations require observing in relation to Equation 3-19. Firstly, the "site" location is subject to variation across large array installations; the site location becomes that of the device currently being installed. In this case the coordinates of the point m_{sp} may be updated to match those of the current working location, with the point m_{sp-1} remaining as specified.

Secondly, only transits between site and port and site and layup have pre-defined tracks. This is appropriate when downtime causes a retreat to a known location, or a vessel resupply, crew change or other given, known transit occurs. Assuming a suitably supplied vessel is at site, has completed installing a device and weather conditions permit moving directly to a second at site location for a second installation to occur no transit track is defined. It is assumed that sites are sufficiently offshore for islands, bars or other barriers to present no obstacle to an as the crow flies transit, see Figure 3-21. In many cases the most likely barrier to a straight line transit is the presence of other at site features, such as installation vessels, turbines, substations etc. Such features are transparent to the transiting vessel, i.e. they can be passed through.

It is possible to apply the defined transit analysis process with $m_{sp} = 2$ and the start and end coordinates (μ, φ) as the site locations under consideration. The slight reduction in transit time obtained via transiting through these obstacles will be minimal and that this approach is acceptable.

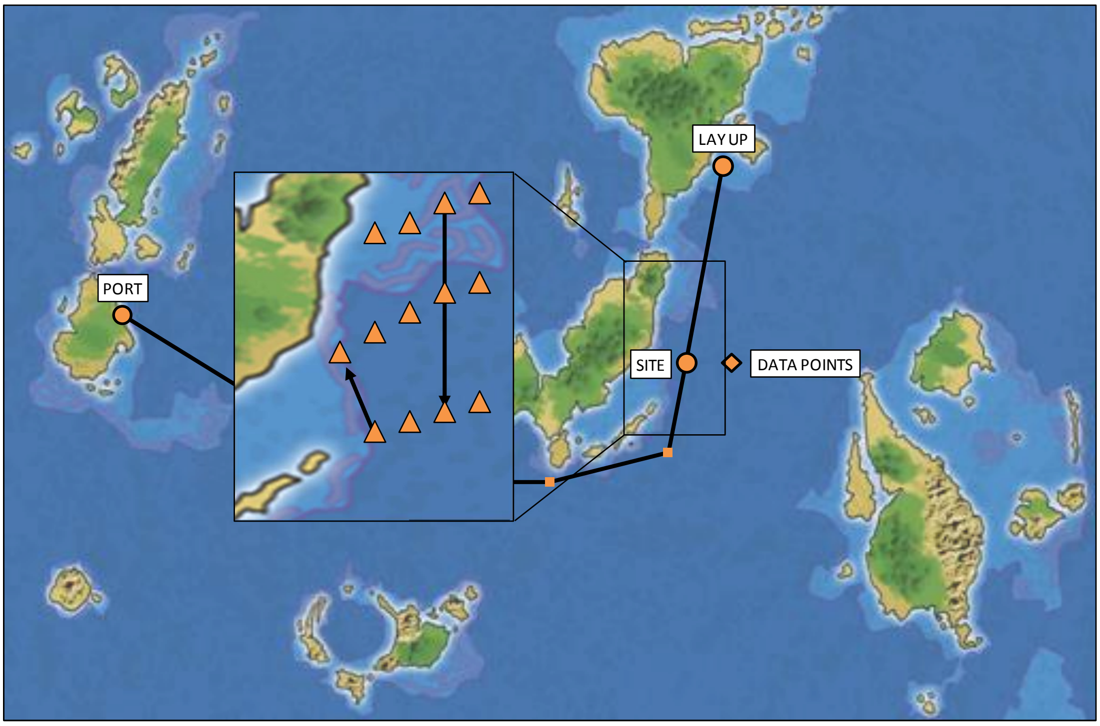


Figure 3-21: At site transit, "as the crow flies"; zoomed area shows transit between working locations and the issue of transparent installations

In addition to determining how long is required for a given transit, it is also beneficial to be able to track the location of the vessel(s) throughout a project. This information is useful in support of any vessel state vector information (i.e. what the vessel is doing at each time step), for additional post processing calculations, such as fuel burn usage, and for visualising complex operations via animations.

To determine the vessel location at the time step Equation 3-20, for the new longitude, and Equation 3-21, for the new latitude are utilized. The radius of the Earth (R), the cumulative distance travelled at the current time step ($d(n)$) and at the last time step ($d(n-1)$) and the original location of the vessel are all known. It is, therefore, a simple process to determine the new location once the parameters θ (the bearing the vessel is travelling on) and $\Delta\mu$ (the change in latitude) are known (Equation 3-22 and Equation 3-23 respectively). ATAN2 is a common programming function which returns the four-quadrant inverse tangent (Veness, 2012).

$$\varphi_{(n)} = \sin^{-1}(\sin\varphi_{(n-1)} \cdot \cos\left(\frac{d_{(n)}-d_{(n-1)}}{R}\right) + \cos\varphi_{(n-1)} \cdot \sin\left(\frac{d_{(n)}-d_{(n-1)}}{R}\right) \cdot \cos\theta) \qquad \text{Equation 3-20}$$

$$\mu_{(n)} = \mu_{(n-1)} + ATAN2(\sin\theta \cdot \sin\left(\frac{d_{(n)}-d_{(n-1)}}{R}\right) \cdot \cos\varphi_{(n-1)}, \cos\left(\frac{d_{(n)}-d_{(n-1)}}{R}\right) - \sin\varphi_{(n-1)} \cdot \sin\varphi_{(n)}) \qquad \text{Equation 3-21}$$

Where:

$$\theta = ATAN2(\sin\Delta\mu \cdot \cos\varphi_{(m)}, \cos\varphi_{(m-1)} \cdot \sin\varphi_{(m)} - \sin\varphi_{(m-1)} \cdot \cos\varphi_{(m)} \cdot \cos\Delta\mu) \qquad \text{Equation 3-22}$$

$$\Delta\mu = \mu_{(m)} - \mu_{(m-1)} \qquad \text{Equation 3-23}$$

3.3.5 Working

Two basic types of task can be analysed, these being “suspendable” and “non-suspendable”. Work can occur at one of two sites, an offshore location or in port, and can involve a single or a multitude of vessels. Even with these numerous task specification possibilities the core analysis objective is constant and the process similar; this is that sufficient work must be performed to declare the task complete. This is specified in Equation 3-24 which states that for a task to be complete s_n (the total score) must be greater than or equal to σ_0 (the required working duration). This duration is specified in hours and converted to times steps, therefore s_n is accumulated in units of time steps.

$$s_n \geq \sigma_0 \qquad \text{Equation 3-24}$$

For work to occur a sufficient length calm period, where r_{j0} does not equal zero, must occur. s_n is used to track the progress achieved (i.e. work which counts towards achieving σ_0). This excludes any start up work (as defined by the appropriate α value) and any work which would be performed during a calm of insufficient duration. To track the work achieved at each time step the variable $s_{n\text{-}temp}$, a time step dependent vector, is utilized.

As specified in Equation 3-25, a period of work has occurred during a calm if the value of $s_{n\text{-}temp}$ reaches or exceeds zero (it is possible for $s_{n\text{-}temp}$ to exceed zero and for this to be the first time step for which the calm period is satisfied if $r_{j0(n)} > |0 - s_{n\text{-}temp(n-1)}|$).

$$Calm \leftrightarrow s_{n-temp(n)} \geq 0 \qquad \textbf{Equation 3-25}$$

$s_{n\text{-}temp}$ is calculated at each time step using Equation 3-26. Here it is stated that $s_{n\text{-}temp}$ is "reset" if the working efficiency is zero, or if this is the first time step of the task. This resetting is dependent upon whether the task is suspendable or not with the variation between the two being the use of λ_0 (which ensures sufficient work is performed on a suspendable task before downtime is incurred) or σ_0 (which ensures the total amount of work is performed before downtime is incurred). Also included is a period of start-up, i.e. the preparation to work. This is always α_0 if the task is non-suspendable and is as specified in Equation 3-27 when suspension may occur, this is discussed further below.

$$s_{n-temp(n)} = \begin{cases} -(\alpha + \lambda_0), & \left(r_{j0(n)} = 0 \parallel n = 1\right) \& \, s = 1 \\ -(\alpha_0 + \sigma_0), & \left(r_{j0(n)} = 0 \parallel n = 1\right) \& \, s = 0 \\ s_{n-temp(n)} + r_{j0(n),} & r_{j0(n)} > 0 \, \& \, n > 1 \end{cases} \qquad \textbf{Equation 3-26}$$

The use of this $s_{n\text{-}temp}$ set/reset and the requirements of the previous equations ensure that the conditions for successful work are satisfied. In order to establish when Equation 3-24 and Equation 3-25 are satisfied it is necessary to track the amount of work performed at each time step. This occurs as shown in the final row of Equation 3-26. Here the value of $s_{n\text{-}temp}$ is increased by the working efficiency of the time step if the working efficiency is greater than. This once again demonstrates the utilisation of time step as a currency of work rather than judging progress by real time.

When assigning an α value to $s_{n\text{-}temp}$ for suspendable tasks a couple of considerations become important. If this is the first time work has been performed, that is the task is yet to have been suspended after real progress ($\gamma = 0$) the start-up time is α_0, i.e. the initial lead in time. This start-up value remains α_0 until real progress occurs ($s_{n\text{-}temp}$ reaches zero). At this point work can continue to completion without any change to α, however, if downtime occurs ($r_{j0(n)} = 0$) before Equation 3-24 is satisfied γ increases by one and the number of time steps of downtime (t_{down}) is determined. At subsequent inoperable time steps Equation 3-26 is invoked to reset $s_{n\text{-}temp}$ where the values of γ and t_{down} are used to determine if the task has been paused or suspended based on the input threshold λ_{0s}. If the task is suspended (i.e. steps have been taken to formally cease work) a start-up period equal to α_s is required, allowing steps to be taken to restart the task. If the downtime period is short the task is considered to be paused and it is possible to restart work without incurring additional requirements (therefore $\alpha = 0$, see Equation 3-27).

$$\alpha = \begin{cases} \alpha_0, & \gamma = 0 \\ \alpha_{s,} & \gamma > 0 \,\&\, t_{down} > \lambda_{0s} \\ 0, & \gamma > 0 \,\&\, t_{down} < \lambda_{0s} \end{cases}$$ **Equation 3-27**

s_n is a numeric value as opposed to a vector or array and can be changed as described in Equation 3-28. Firstly, if $s_{n\text{-}temp(n)}$ is less than zero it is not possible to say with certainty if the work performed in the current time step will become progress, therefore the value of s_n is preserved. s_n will be equal to zero at this point if no progress has occurred on a suspendable task, greater than zero if work has been achieved previously on a suspendable task (it will be equal to the last know value of work), or zero if the task is non-suspendable. This latter case is due to the fact that given the nature of the specification of $s_{n\text{-}temp}$ work occurring satisfies Equation 3-24 at the same time step, thus completing the task.

It is only possible to be certain that the work performed represents work in a viable calm when $s_{n\text{-}temp}$ becomes positive. At this point s_n may be updated to reflect this work and if the task is suspendable the work performed as $s_{n\text{-}temp}$ becomes positive is equal to λ_0, thus $s_n = s_n + \lambda_0$, as specified below. By summing λ_0 and the existing value of s_n all previous work is preserved. If the task is non-suspendable this time step represents the completion of the task therefore $s_n = \sigma_0$ with no requirement to preserve any previous s_n value.

Finally, in suspendable tasks it is possible that progress is being made beyond the minimum requirements without the job being complete. In this case s_n is updated at each time step in the same manner as $s_{n\text{-}temp}$, i.e. the working efficiency of the current time step is added to the work already performed, moving ever closer to completing the task.

$$s_n = \begin{cases} s_n, & s_{n-temp(n)} < 0 \\ s_n + \lambda_0, & s_{n-temp(n-1)} < 0 \,\&\, s_{n-temp(n)} \geq 0 \,\&\, s = 1 \\ \sigma_0, & s_{n-temp(n-1)} < 0 \,\&\, s_{n-temp(n)} \geq 0 \,\&\, s = 0 \\ s_n + r_{j0(n)}, & s_{n-temp(n-1)} \geq 0 \,\&\, s_{n-temp(n)} \geq 0 \end{cases}$$ **Equation 3-28**

Considering both a non-suspendable and suspendable task which incur no downtime (Figure 3-22 and Figure 3-23 respectively) it can be seen that once the working efficiency exceeds 0% a number of time steps of start-up work are completed; following this the main task work is executed. In the suspendable task the work assigned the λ-phase is also indicated, demonstrating the time during which the minimum desired working progress is achieved. In an ideal project all tasks would be executed at 100% efficiency incurring no downtime, delays or additional costs.

Figure 3-22: Steps to task completion when non-suspendable with no downtime, working phases (i.e. start up and progress) are shown relative to the task efficiency

Figure 3-23: Steps to task completion when suspendable with no downtime, working phases (i.e. start up and progress, included the minimum required work) are shown relative to the task efficiency

When downtime is incurred, as shown in Figure 3-24 to Figure 3-26, the handling of this delay is dependent on the type of task being under taken. It is necessary for a non-suspendable task to operate in a window of sufficient length for completion. Comparing Figure 3-24 to Figure 3-22 it can be seen that both the initial period of time for which the working efficiency is greater than zero and the brief period for which the working efficiency is 50% are not off sufficient length to complete the task. In this case work is performed after the second storm period when a sufficient window exists. This task incurs downtime that more than doubles the length of time required to complete the operation.

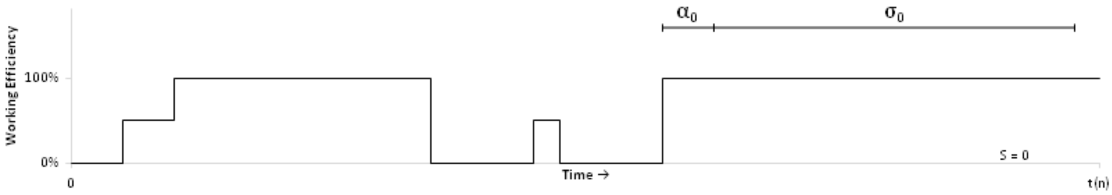


Figure 3-24: Steps to task completion when non-suspendable with downtime, working phases (i.e. start up and progress) are shown relative to the task efficiency, downtime is incurred when the efficiency reduces to 0%

When analysing a suspendable task it has been seen that additional start-up periods may be required should downtime greater than λ_{0S} be incurred. This is seen in Figure 3-25 where the central period of downtime (including the period of time at 50% working efficiency which is not of sufficient length for work to be performed) exceeds this value. This results in α_S being applied and this task now incurs an additional length over ideal equal to the downtime and the required restart time. Note that here the two periods of work identified as $\Delta\sigma_0$ total to σ_0, indicating that work is complete.

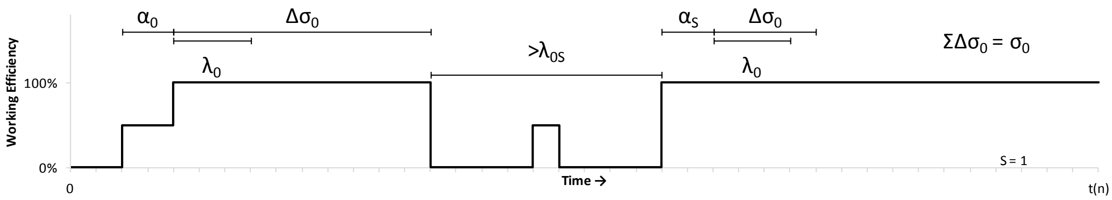


Figure 3-25: Steps to task completion when suspendable with downtime suspension, working phases (i.e. start up and progress, included the minimum required work) are shown relative to the task efficiency, restart (α_S) is incurred as the downtime is longer than the acceptable pause duration (λ_{0s})

The task in Figure 3-26 incurs downtime. This period of zero working efficiency, however, is less than the pause/suspend threshold and thus the task is only paused. The effect of this is the lack of requirement to apply α_S, and the effect on task duration is reduced compared to a suspended task but is still in excess of the ideal.

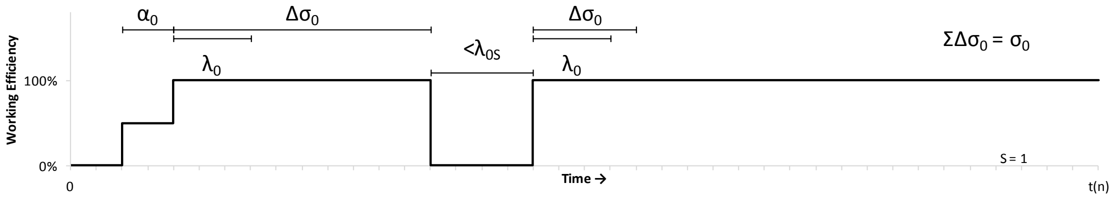


Figure 3-26: Steps to task completion when suspendable with downtime pause, working phases (i.e. start up and progress, included the minimum required work) are shown relative to the task efficiency, restart (α_s) is not incurred as the downtime is shorter than the pause/suspend threshold duration (λ_{0s})

Considering Figure 3-27, the previous non-suspendable task with downtime; the dashed horizontal line represents $s_{n\text{-}temp} = 0$, the point at which it is known that work has successfully been performed (and as this is a non-suspendable task the point at which the requirements for completion are satisfied). The axis at $y = 0$ represents both $r_{j0} = 0$ and $s_{n\text{-}temp} = -(\alpha_0 + \sigma_0)$ as calculated from Equation 3-26. It can be seen that during the periods where r_{j0} exceeds zero the value of $s_{n\text{-}temp}$ increases at a rate consistent with the value of r_{j0}, approaching but not reaching $s_{n\text{-}temp} = 0$. Only in the latter working window where the task is completed does $s_{n\text{-}temp}$ reach zero. s_n is set to σ_0 and the task finished.

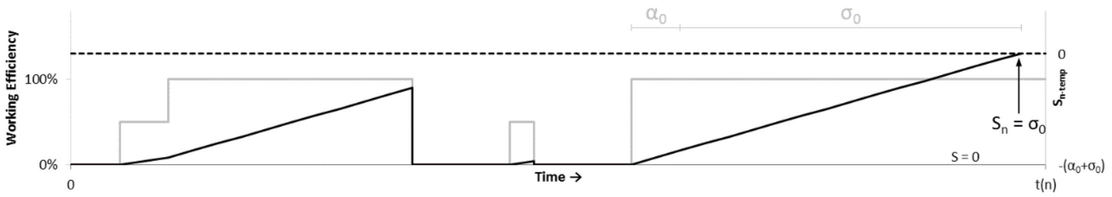


Figure 3-27: S_n and $S_{n\text{-}temp}$ during non-suspendable tasks, including the rejection of incomplete work. $y = 0$ represents both $r_{j0} = 0$ and $s_{n\text{-}temp} = -(\alpha + \sigma_0)$; $s_{n\text{-}temp} = 0$ is shown as a dashed line

In Figure 3-28 and Figure 3-29 both the suspended and paused cases of the suspendable task and the modification of $s_{n\text{-}temp}$ via Equation 3-26 and Equation 3-27 can be seen. The axis at $y = 0$ represents both $r_{j0} = 0$ and $s_{n\text{-}temp} = -(\alpha + \lambda_0)$, however, this time α varies and this change can be seen whenever $s_{n\text{-}temp}$ is reset. Initially $s_{n\text{-}temp} = -(\alpha_0 + \lambda_0)$, increasing as work is performed. This increase continues with $r_{j0(n)}$ being added to $s_{n\text{-}temp(n)}$ and s_n until the first downtime time step occurs. At this point $\gamma = 1$ and $t_{down} < \lambda_{0S}$, with this value increasing by one at each downtime time step, and therefore $s_{n\text{-}temp} = -\lambda_0$. A brief period of workable time steps occur and $s_{n\text{-}temp}$ briefly increases, however, $s_{n\text{-}temp}$ does not reach zero, further downtime is incurred and $s_{n\text{-}temp}$ is reset to $s_{n\text{-}temp} = -\lambda_0$. Eventually t_{down}, which does not reset to zero until real work is performed, is greater than λ_{0S}

and a period of restart time is required now that the task has been suspended; $s_{n\text{-}temp} = -(\alpha_S + \lambda_0)$. Finally, a sufficiently long window occurs to finish the task and $s_{n\text{-}temp}$ and s_n increase as previously seen in the suspendable work until s_n equals or exceeds σ_0. A similar pattern exists in Figure 3-29, however the threshold λ_{0S} is not exceeded here and as a result $s_{n\text{-}temp}$ does not need to consider α_S.

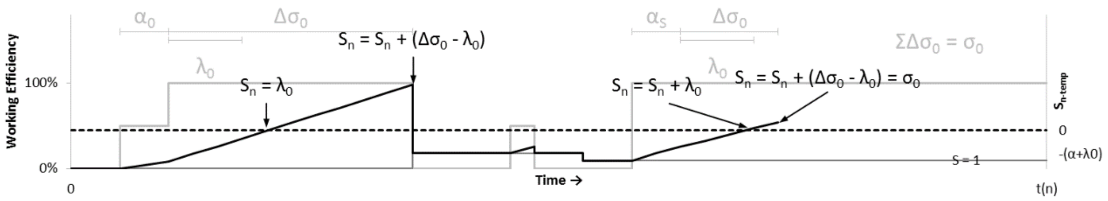


Figure 3-28: S_n and $S_{n\text{-}temp}$ during suspendable tasks with downtime suspension, including the acceptance of partial work and the rejection of incomplete work. $y = 0$ represents both $r_{j0} = 0$ and $s_{n\text{-}temp} = -(\alpha + \lambda_0)$; $s_{n\text{-}temp} = 0$ is shown as a dashed line

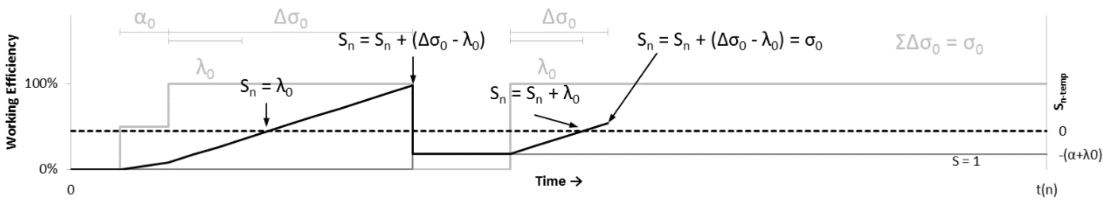


Figure 3-29: S_n and $S_{n\text{-}temp}$ during suspendable tasks with downtime pause, including the acceptance and pausing of partial work. $y = 0$ represents both $r_{j0} = 0$ and $s_{n\text{-}temp} = -(\alpha + \lambda_0)$; $s_{n\text{-}temp} = 0$ is shown as a dashed line

3.3.6 Scheduling

The main feature of these methods is the analysis of weather related downtime, however the methods are not intended for this purpose alone. In a number of cases, and particularly as large arrays which require multiple installation vessel are installed, a limiting factor will be inefficient scheduling of marine operations. In fact changes to scheduling can have significant impacts on the performance of an operation.

Thus far the focus has been on a single vessel in each analysis and whilst these methods are applied in exactly the same manner for multiple vessels (generally, with each calculation performed for each vessel) additional complexities arise via the addition of more vessels.

Complexity is introduced when the order of task execution is non-linear. This occurs when some tasks may be performed simultaneously or a task follows one other than that immediately before it, or follows multiple tasks. This scheduling complexity more effectively matches the reality of marine operations.

The simplest of projects require one vessel working in a strictly linear order, this being where task 2 follows task 1, task 3 follows task 2 and so on through the project. This type of project is specified in the reduced task list shown in Figure 3-30. Here the first task is given a specified start date (as required by the method), each task follows entry is blank (meaning that the task follows its immediate predecessor) and the vessel *V1* works on all tasks. The first two tasks occur in port with the remaining tasks occurring at site. The project concludes after these five brief tasks.

Base Case	Task	Start Date	Follows	Vessel	Location
	1	03/05/2013 09:03		V1	Port
	2			V1	Port
	3			V1	Site
	4			V1	Site
	5			V1	Site

Figure 3-30: Scheduling base case – Task List

For each task in a project it is necessary to determine the start date of the work, the start date being the time step index at which work may attempt to begin. In Figure 3-31 the execution of this project is indicated and here grey time steps represent the start date. Determining the time step index of the first task is a simple process of identifying the time step nearest, but after, the specified start time, in this case 09:03 am on 3rd May. The first time step after the start time is considered so that work may not occur before the specified early limit of the project. Were this start date to represent the earliest possible point for which the vessel is taken on hire it would not be possible to work before 09:03 am and whilst time steps are of the order of magnitude of minutes (often 3 or 4 minutes) it is preferable to handle start times in this manner.

This first task is in port and as this is the beginning of the the vessel *V1* is also in port. Work may proceed immediately given that an appropriate window exists. Work proceeds as described previously until the quantity of work performed (s_n) reaches the required quantity of work (σ_0) with downtime incurred when conditions dictate.

Having completed task 1 it is necessary to determine the start time of task 2. Given that this task, task 2, follows task 1 and only one vessel is included the start date of task 2 is the end date of task 1. Again this task is in port and it is known that *V1* is in port having completed work on the prior task, therefore work may once again proceed as soon as a window exists. Task 3 follows this procedure as do the remaining tasks.

Having determined the start date of task 3 it is noted that this operation is at site and that *V1* is currently in port, therefore a transit is required following the procedures outlined in the prior sections.

Work continues in this manner until the end of task 5, here, upon completion of work, it is identified that this is the final task and that the vessel should return home. This transit is performed and once the vessel is back in port successfully the project is considered complete.

Figure 3-31 also shows the on hire time of the vessel which is taken as its first working time step through to its final working time step (the successful return home). When only one vessel works on a project this on hire time is the entire project length, however, with more than one vessel this is not the case and successful project scheduling may reduce the time for which a vessel is on hire and in turn reduce the cost associated with the vessel.

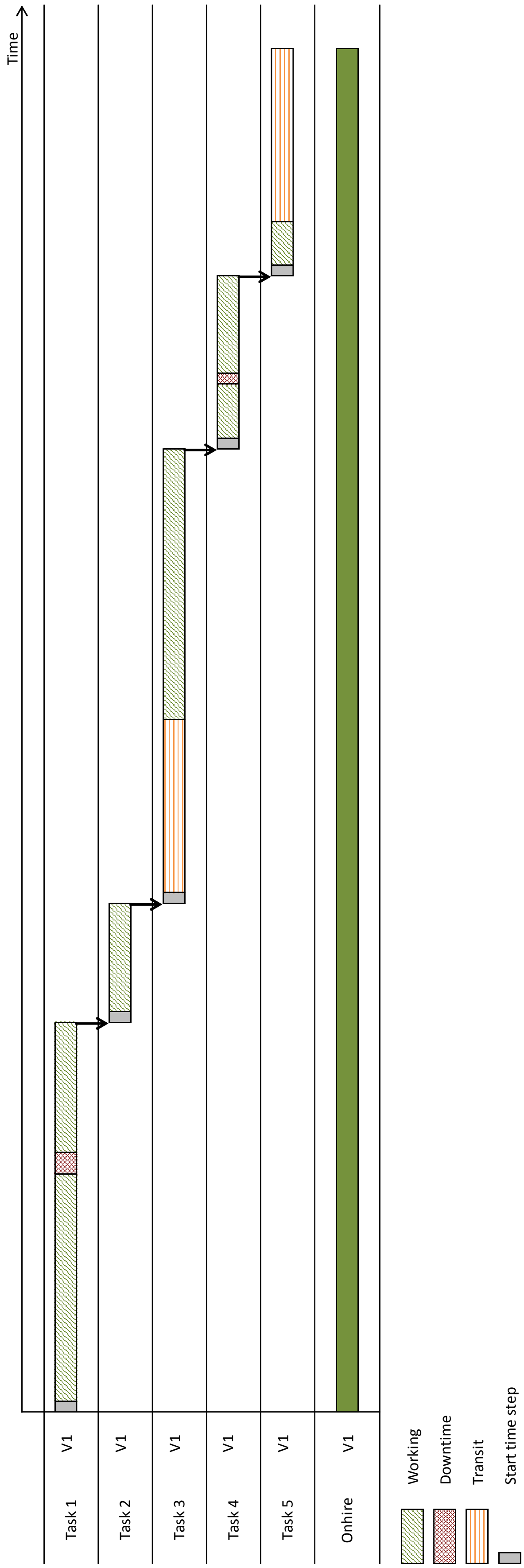


Figure 3-31: Scheduling base case, showing the status of tasks relative to time, the interconnectivity of tasks and start dates and the vessel on hire time

Not all projects may be defined in a simple linear progression with a single vessel. Presented in Figure 3-32 are three reduced task lists of varying complexity and presented in Figure 3-34, Figure 3-35 and Figure 3-36 are the project execution diagrams. In each case five tasks are performed and as before the first two are in port with the latter three being performed at site. Also in each case two vessels work with vessel *V1* working independently on tasks 1, 3 and 5 and vessel *V2* working independently on task 2. Both vessels work on task 4.

In each example the scheduling of the tasks has been varied via the introduction of additional specified start dates or through amendments to the task follows data.

Case 1	Task	Start Date	Follows	Vessel	Location
	1	03/05/2013 09:03		V1	Port
	2			V2	Port
	3			V1	Site
	4			V1,V2	Site
	5			V1	Site

Case 2	Task	Start Date	Follows	Vessel	Location
	1	03/05/2013 09:03		V1	Port
	2			V2	Port
	3		1	V1	Site
	4			V1,V2	Site
	5			V1	Site

Case 3	Task	Start Date	Follows	Vessel	Location
	1	03/05/2013 09:03		V1	Port
	2	03/05/2013 09:03		V2	Port
	3		1,2	V1	Site
	4			V1,V2	Site
	5			V1	Site

Figure 3-32: The effect of task list changes on scheduling - Task lists for alternate cases

In case 1 the only change to scheduling from the base case is the addition of the second vessel, no changes have been made to the start date and no task follows data has been entered meaning that each task follows its immediate predecessor regardless of which vessel has worked on that task.

As before the first step is to determine the start date of the first task. This determining of the start time step of task 1 for all vessels, *V1* and *V2*, can be seen in Figure 3-34, and once this time step has been determined the first task can be executed as before.

Upon completion of task 1 the start time step of task 2 must be determined. The last known time step of *V2* is the start time step of the first task, however this task on which *V2* works follows task 1 on which *V1* works. Here both start time steps are considered, both being the end time of task 1 and the last know time step of *V2*. Since the end of task 1 is the latter time step this is taken as the start time of this second task and the time step of *V2* is "accelerated" to accommodate this. Work is then performed on task 2.

An identical process then occurs for task 3, on which *V1* works. Having identified the final time step of the previous task as being the most appropriate start point the vessel can perform the transit and required work (this task being at site).

Task 4 features one of the more complex methods required in task scheduling and whilst its input is simple for the user of the software multiple time accelerations and the pausing of time are required. At the start of task 4 *V1* is at site with *V2* in port. Both vessels are required for this task and, given the location of the work both are required at site. At the end of task 3 *V1*'s task 4 start time step is known, furthermore it is possible to obtain the last known time step of *V2*, this being the time step at the end of task 2. The previously discussed method would accelerate the second vessel's start time to match that of *V1* and work, initially *V2*'s transit, would occur from this point. This method would, however, result in *V1* waiting at site for the arrival of *V2*, incurring schedule related downtime. This is an unrealistic proposition as *V2* has been in port and idle since the conclusion of the second task, it is reasonable that *V2* will have started its transit some time before it is required at site.

In order to arrive at site and perform work *V2* must perform a transit and a hook up operation. Here for simplicity it is assumed that the start time step for *V1* on this task (and a number of preceding time steps) is also, coincidentally, a member of *hu*, i.e. hook up is available at this point. Now it is possible to consider two starting time steps for this second vessel, these being; i) the previously determined start time (from the end of task 2), and ii) a time τ_{sp} before *V1*'s start time. The latter of these two time steps should be taken, thus avoiding a situation where *V2* attempts to leave port before the conclusion of its prior work.

The transit to site of this vessel may now be considered. At this point the time step index of *V2* is increasing as it performs work to facilitate the execution of the task. *V1* at this time is working on the prior task, however this is not known to the time line of this later task and therefore *V1* is actually at site waiting for the arrival of *V2*. Furthermore, *V1* is waiting at some (known) point in the future (its own start time). This results in its own time line being paused until *V2* arrives and catches up to *V1*'s "present day". This pausing of time is indicated in Figure 3-33. If the two vessels are at the same time step, at site and hooked up (i.e. the pre-requisites to work are all satisfied) the passage of time may be "turned on" for both vessels. Both vessels will perform work at the same rate due to the task specific limits affecting the progress rather than the vessel specific limits (assuming that a storm event does not affect the station keeping of either vessel). Once the time step of the two vessels are equal the passage of time should be on for both, meaning that any storm events which occur during the analysis, or during waiting, are correctly handled.

Considering Figure 3-34 once more, upon completion of work on task 4 *V1* is required to stay at site to perform work on task 5, however for *V2* this is the final task in the project. This results in *V2* performing a transit back to port and completing its participation in the project, and in *V1* and *V2* having both different start and finish times for this task. This is important when considering task 5, which clearly follows task 4, as the vessel specific start time must be considered. This is as indicated and upon completion of this final task *V1* also transits home. Considering the on hire time of both vessels it can be seen that *V2* is on hire for considerably less time than *V1*, working as it does, on only tasks 2 and 4.

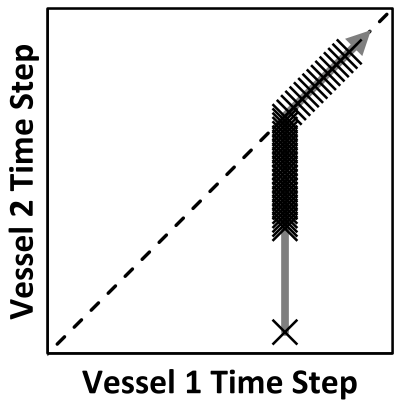


Figure 3-33: Relative time steps for vessels working simultaneously on a task showing the jump which occurs during the acceleration of simulation time

Case 2 introduces the execution of simultaneous tasks. The project is as previously defined but now has the introduction of task 3 following task 1. Since task 2 has no task follows information and therefore defaults to task 1 as its immediate predecessor, both task 2 and task 3 start simultaneously, albeit with different resources, after task 1. With the exception of this introduction this case is performed identically to case 1, with vessels waiting at site as previously discussed.

Case 3 further amends the scheduling of the project, with task 1 and task 2 being given explicit start dates, these being determined at the outset of the analysis as all vessels are assigned an initial point in time. In addition, this case considers a task having more than one predecessor; in this case task 3 follows both task 1 and task 2. When task 3 commences it is necessary to consider the end time step of both of the first tasks and to take the latter point. This scheduling has a knock on effect of increasing the time for which *V2* is on hire, being taken on charter at the start of task 2 (which is also the project start) and ending its on hire period following a period of considerable waiting to perform task 4. The handling of task 4, and this waiting, is as described previously, however in this case the required acceleration of time, and therefore the incurred downtime, is significantly greater. Indeed it quickly becomes apparent that simple changes to the scheduling of a project and the use of its resource can affect the length of time required for completion and in turn the cost of installation.

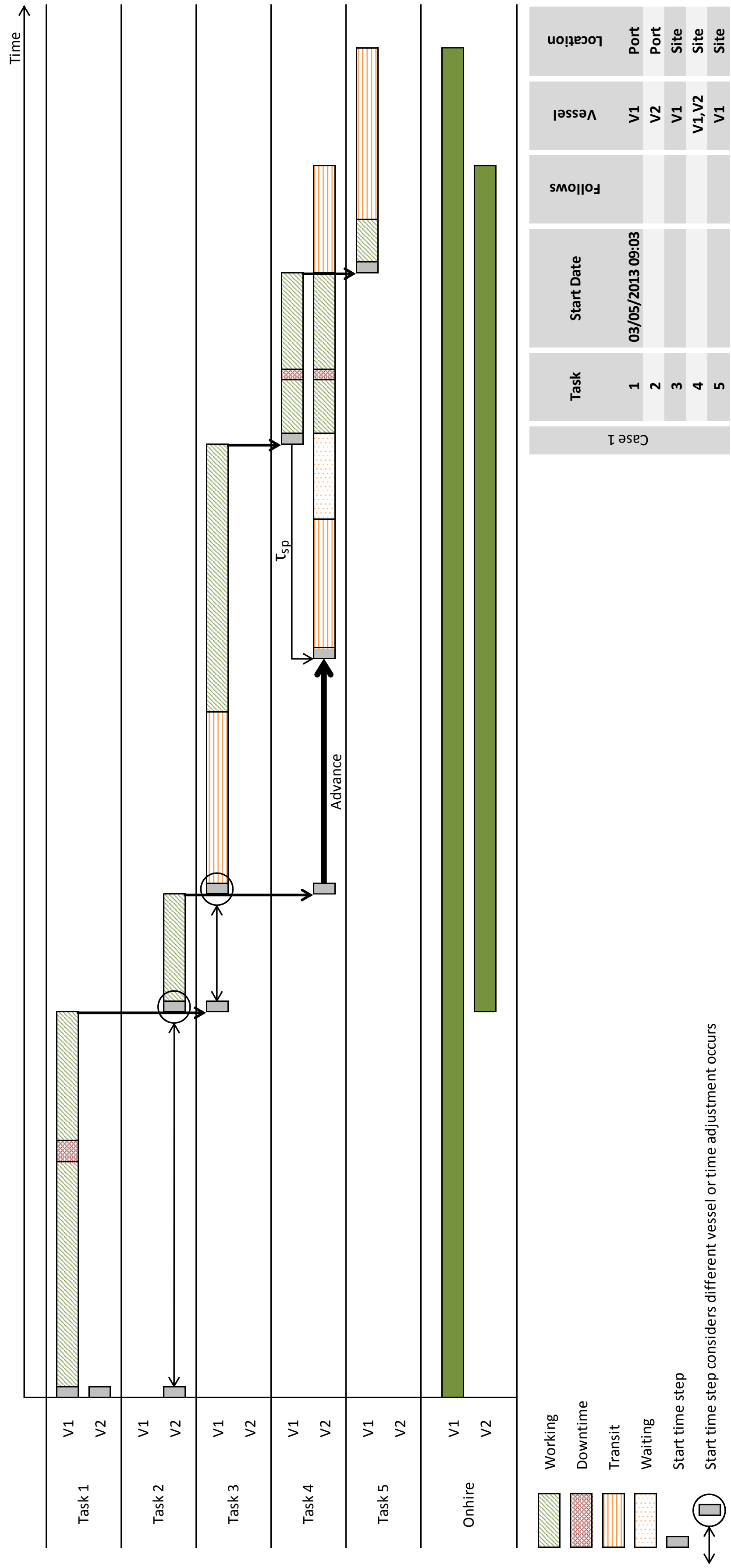


Figure 3-34: The effect of task list changes on scheduling - Case 1, showing the status of tasks relative to time, the interconnectivity of tasks and start dates and the vessel on hire time

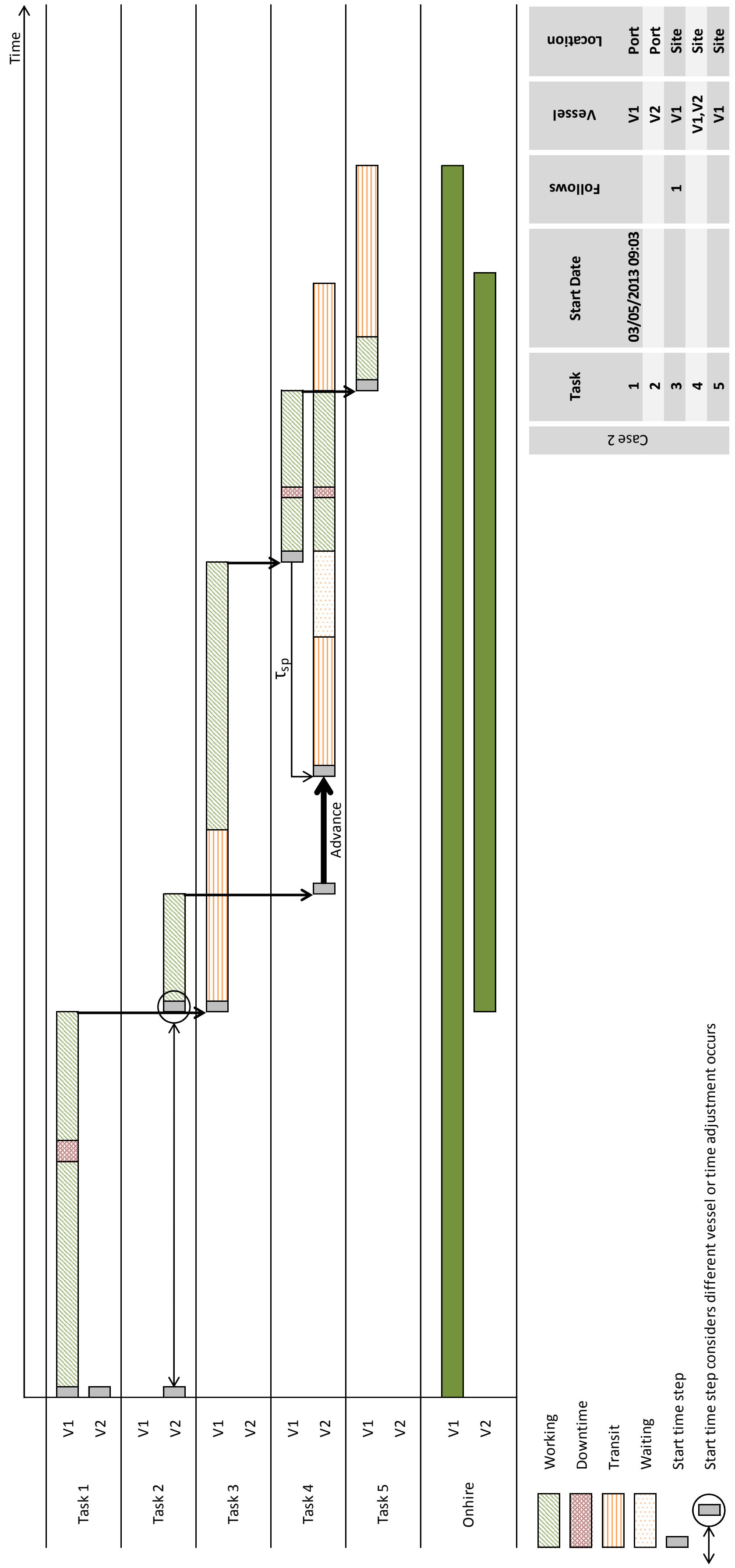
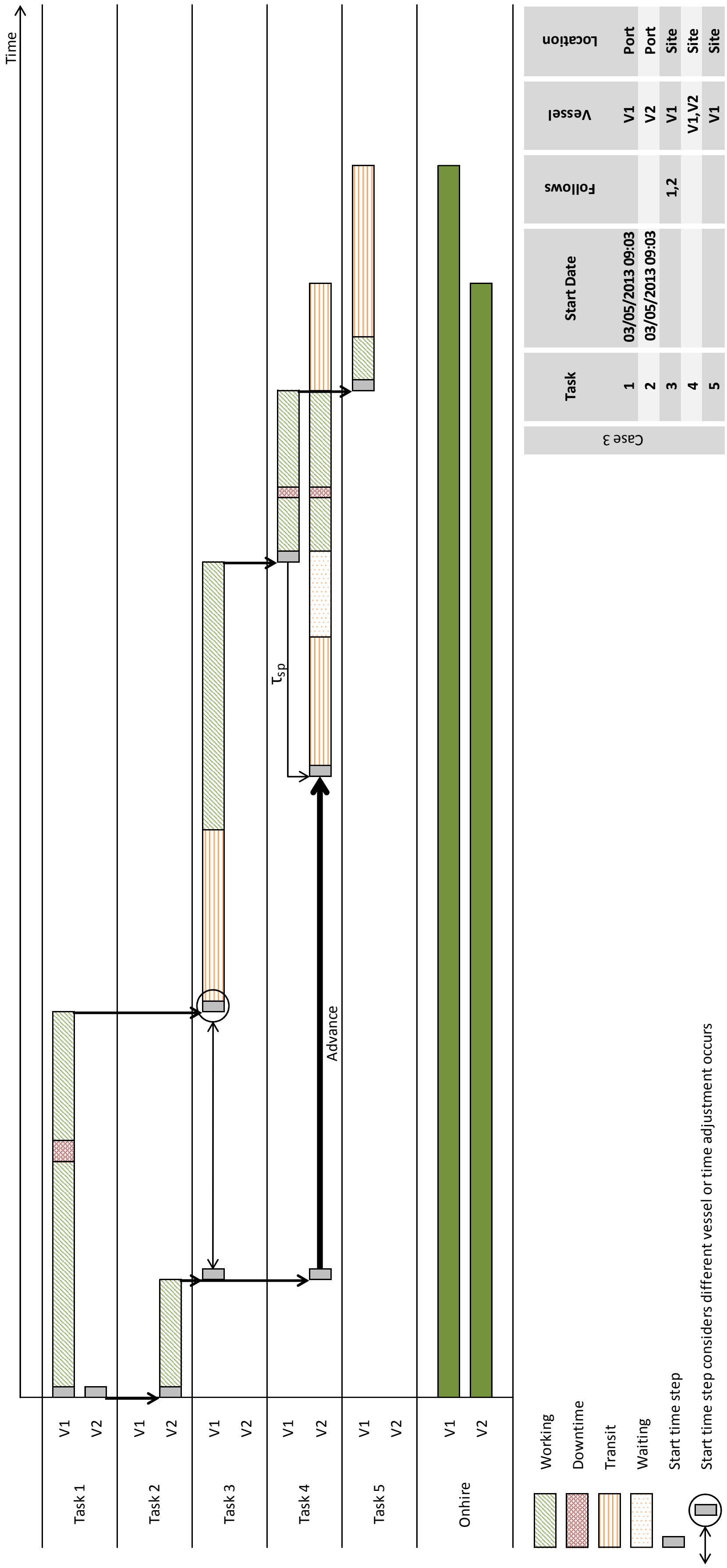


Figure 3-35: The effect of task list changes on scheduling - Case 2, showing the status of tasks relative to time, the interconnectivity of tasks and start dates and the vessel on hire time



Task	Start Date	Follows	Vessel	Location
1	03/05/2013 09:03		V1	Port
2	03/05/2013 09:03		V2	Port
3		1,2	V1	Site
4			V1,V2	Site
5			V1	Site

Figure 3-36: The effect of task list changes on scheduling - Case 3, showing the status of tasks relative to time, the interconnectivity of tasks and start dates and the vessel on hire time

3.4 Data outputs and the complete process

3.4.1 Outputs

Knowledge may be derived of where each vessel is in each time step and what that vessel is doing, thus eight “vessel states” are defined (Figure 3-37), these being:

- “In Port” – the vessel is quay side and no work is being performed;
- “Layup” – the vessel is at its defined safe haven and therefore no work is being performed;
- “Start Up In Port” – the vessel is quay side and preparing to work or to resume work;
- “Working In Port” – the vessel is quay side and performing work; progress is made;
- “Transit” – the vessel is changing location;
- “At Site” – the vessel is at its working location and no work is being performed;
- “Start Up At Site” – the vessel is at its working location and preparing to work or to resume work;
- “Working At Site” – the vessel is at its working location and performing work; progress is made.

Figure 3-37 presents an example of the vessel. The vessel state is presented for two vessels in an example analysis (with the x-axis representing the passage of time and the y-axis the vessel states). The solid line represents the relationship between the two with breaks representing the transition between tasks.

Considering Vessel 1; it can be seen that this vessel starts in port (as is required) and is immediately able to perform work, completing two in port tasks as can be seen by the, regularly occurring, step shape. This vessel then incurs downtime in port before transiting, arriving at site and performing work. This downtime is due to the site being inaccessible due to storm conditions.

Following this the vessel performs a series (three) tasks before changing location at site and performing further work. Lengthy at site downtime is then incurred before a series of tasks are completed. A transit home performed and demobilisation tasks executed.

The lower chart, for Vessel 2, can be interpreted in the same manner. It is worth noting here that Vessel 2 experiences long downtime on its second task. This is due to the required waiting before Vessels 1 and 2 work together (this can be observed from the fact that the task in question has an identical working profile on both charts). Since Vessel 1 is already at site it is possible to deduce from this output that the downtime it incurs on this, its eight task, is not due to its own limits but due to Vessel 2 been unable to access the site.

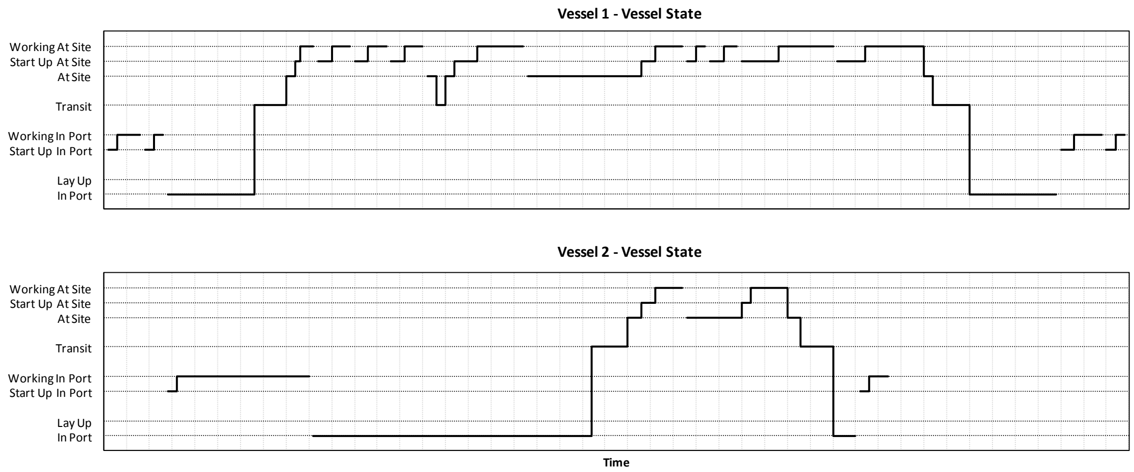


Figure 3-37: Vessel state outputs, the solid line represents the vessel status during current time step (x-axis)

This figure allows a detailed picture of the unfolding events to be formed, however there is still some lacking information. A main feature of this method is not just identifying downtime but determining the type, so that optimisation processes may be properly focused. When considering Figure 3-37 a number of downtime events were identified and based on the relationship between the vessel states it was determined that these downtime were due to an inaccessible site. This raises a number of questions:

- Firstly, is this downtime caused by an inaccessible site?
  - If this is true, is it hook up or station keeping limits which are directly responsible for the inaccessibility?
  - If this is not true what causes this delay?
- If task downtime occurs work is stopped, is any work performed at reduced efficiency?
- In both cases which of the metocean condition is causing the downtime?

In order to answer such questions and to shed further light on issues surrounding the installation process figures such as that presented in Figure 3-38 are produced. This example considers the effect of the three main considered metocean conditions and their cumulative effect. In each of the subplots four horizontal bands are presented with green cells representing a time step which does not cause downtime (100% efficiency), orange representing 50% working efficiency and red representing downtime. These bands are plotted for a selected vessel and represent:

- Top – The task limits which would be experienced were the vessel at site at the given time step. These limits change with and this can be seen in the tidal plot where peak tidal velocities do not always cause a reduction in working efficiency.
- Middle – The vessel station keeping ability. This is before any storm extension due to hook up/unhook requirements and therefore represents the time steps for which the storm actually occurs not the time steps spent off site.
- Bottom (Upper) – The unhook availability.
- Bottom (Lower) – The hook up availability.

The fourth subplot considers the overall effect on the vessel and therefore, as is the case within the method, takes the worse efficiency for each metocean condition in the time step and applies this.

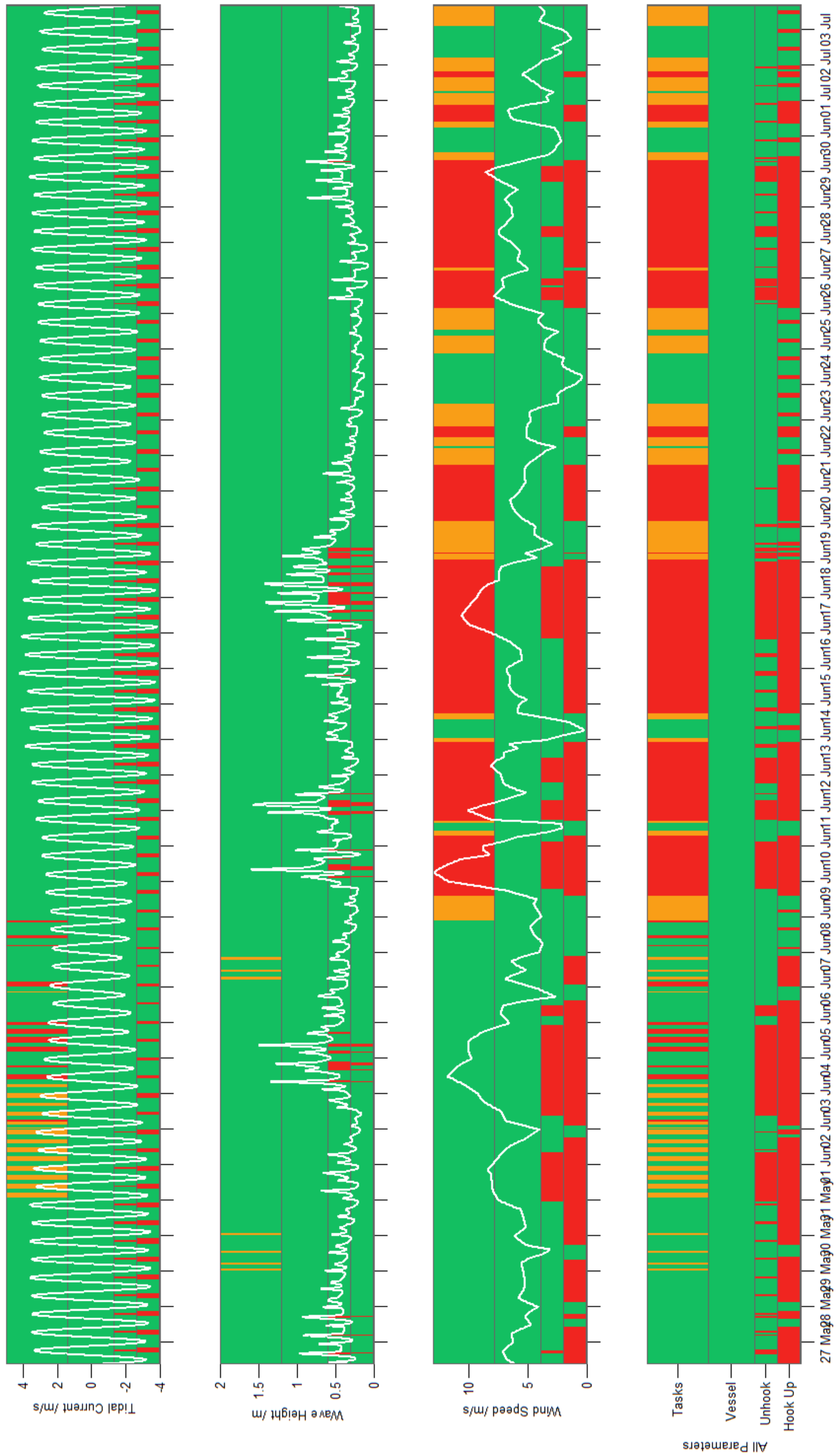


Figure 3-38: Limiting factor output considering efficiency/accessibility (0%/inaccessible - red; 50% - orange; 100%/accessible green) for operational elements (task efficiency, vessel stationkeeping, vessel hook up and unhook) for all metocean conditions and the total project

The eight vessel states previously discussed can, and in many cases should, be further extended. Coupled with a consideration of the downtime incurred, this can then lead to an even greater picture of the negative effect on the project being determined. It is possible to determine the time spent in each case and in turn focus effort in key areas.

The following states may be expanded:

- In port, to;
  - Weather downtime, these being the occasions for which the vessel cannot work on an in port task due to a task limit being exceeded;
  - Vessel/schedule downtime, these being occasions for which;
    - Scheduling leads to the vessel waiting on another vessel or task;
    - The vessel cannot hold station at site and is therefore in port;
  - Hook up/unhook, these being the occasions for which the vessel is preparing for or making safe following transit;
- At site, to;
  - Weather downtime, these being the occasions for which the vessel is at the working location and cannot work due to a task limit being exceeded;
  - Vessel/schedule downtime, these being occasions for which;
    - Scheduling or transit delays lead to the vessel waiting on another vessel or task;
  - Hook up/unhook, these being the occasions for which the vessel is preparing for or making safe following transit.

These expanded categories (in days in Figure 3-39) can be loosely deemed to be either states during which progress is made (shown in green), states which, despite being downtime, facilitate work (i.e. transit, shown in orange) or states which are absolute downtime (red). Figure 3-39 indicates that at site downtime is the largest burden on this example project and warrants further investigation/optimisation; whilst transit, for example, has a fairly minimal impact, meaning that obtaining a vessel which has greater cruising speed may not be worth any associated cost increase.

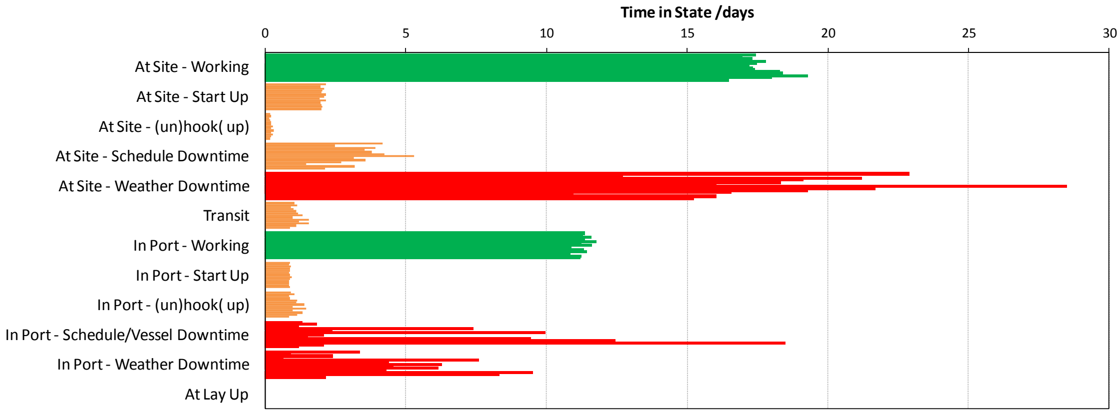


Figure 3-39: Comparing variability - time in vessel states (bar clusters) output for each year of analysis (individual bars) showing critical downtime (red), states which facilitate work without performing work (orange) and work (green)

3.4.2 Costs

Four cost points are incorporated:

- Vessel day rate;
- Vessel standby rate;
- Crew (excluding permanent crew) accommodation fees;
- Port fees.

Having performed an analysis process and possessing information regarding the vessel state at each time step it is possible to apply these rates and to determine a cost for each vessel in the analysis and in turn for the total project. Rates are applied based on the following assumptions:

- The day rate is applied if the vessel is in any state other than in port for any time step in a 24 hour period from midnight to midnight. The exception to this 24 hour period is the start day of the project (which is considered from start time to midnight) and the end day (which is considered from midnight to end time). The in port state represents the only state in which the vessel is not working and is not at sea, in cases where the vessel is working or at sea the day rate is incurred and the cost increased accordingly;
- The standby rate is applied in the converse situation, i.e. all time steps in the 24 hour period are in port and no work is performed. This means that a significant quantity of absolute downtime must be incurred for th standby rate to be applied;

- The vessel crew costs are included in the vessels rates, however projects often involve other personnel who are not covered by this expenditure. In this case an accommodation fee is added to the vessels overall cost on occasions where the vessel is away from port (in any state) for the period midnight to 6am;
- Port departure fees are incurred for every port departure the vessel makes during the installation project. This is identified via the transition of vessel state from in port to transit and a onetime fee is applied.

Clearly the economics of marine energy installation projects are not fully captured by this simplistic fiscal model and a number of cost points are not included. For example:

- No consideration is given to capital expenditure on materials, components, equipment, devices etc. This is a minor issue when it is considered that the purpose of these methods is the modelling of marine operation costs and whilst it is true that fiscal savings may be made in some of these areas it is not entirely necessary to consider this in the methods, instead using a post processing cost model;
- No consideration is given to fuel burn directly in the model, this may be a major point of expenditure and is perhaps a shortcoming of the method, however, obtaining detailed estimates of the fuel burn at site (i.e. on DP systems, generators etc.), in transit and on tasks (i.e. to operate cranes, grouting rigs etc.) is, whilst not impossible, difficult at a time step resolution. Instead a preferable approach may be to include a day by day estimate of fuel burn expenditure in the vessel day rate;
- No consideration is given to additional costs incurred as a result of using specialist equipment on tasks (e.g. if a drill rig, ROV or similar has been hired outside of the scope of the vessel charter for a limited period). This could be applied across the entire project by estimating a day rate increase; alternatively a post processing cost model could be utilized.

A number of key points are not included in the method’s capabilities at the time of writing and this is addressed further in Section 6.2. Whilst this is not of no concern it is certainly not a barrier to the application of these methods. Given that these methods handle the analysis of the operability of marine operations it is possible to extract useful and informative conclusions relating to the expenditure and cost reduction opportunities present on a project.

3.4.3 The process

Figure 3-40 presents the complete analysis process, including appropriate abort points for when a weather window cannot be obtained (i.e. Equation 3-24 is not satisfied). This figure indicates the looping through multiple years of metocean data and through multiple installation projects (e.g. as part of a large analysis and optimisation effort).

In Figure 3-40 all the afore mentioned methods are indicated with the links between these often representing a decision point. In practice these decision points are simple and seek to ensure that before work is performed all pre-requisites to work are satisfied. These decision points ensure that upon the completion of work appropriate steps are taken to prepare the pre-requisites for the following tasks, this is seen with the multiple instances of accessing the transit processes.

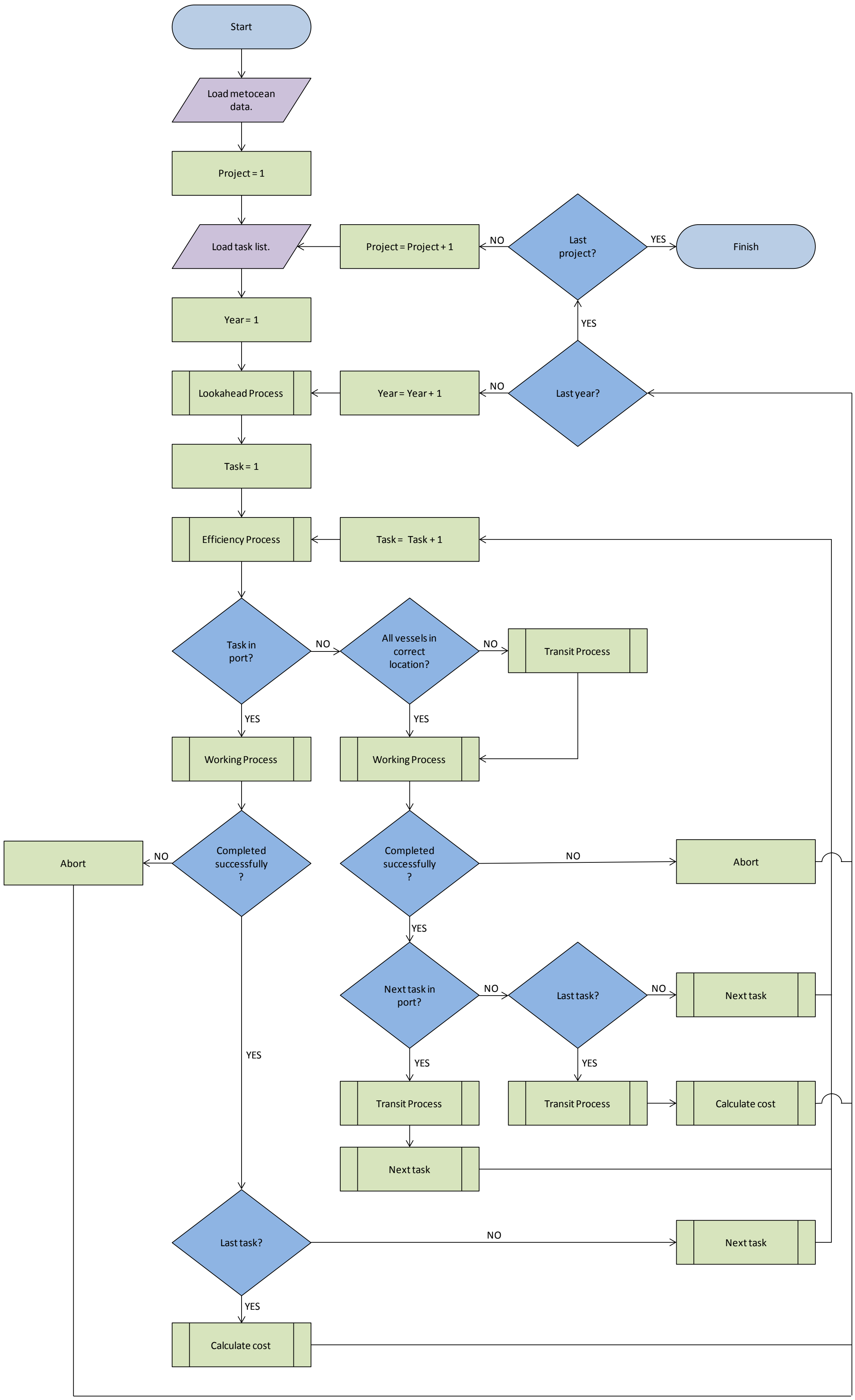


Figure 3-40: The complete process

3.5 Discussion, utilisation and uncertainty

It is possible to utilize the methods to analyse a single installation method with predefined assets, ports and logistics. By performing an analysis of this type it is possible to define the expected cost and duration of work. More power can be obtained from the methods, however, if an installation optimisation approach is utilized (as presented later in Section 5). A number of installation options exist, including changes to the installation method and assets. Trialling variations of this nature in the safe environment of a desktop computer is preferable to at sea. The cost and duration saving possible mean that this application of these methods in this type of process is a powerful utilisation.

A variety of uncertainties exist in the installation of marine energy devices, ranging from the availability of suitable working windows to the volatility associated with vessel day rates. Year on year metocean conditions vary and whilst the seasonal trends will broadly remain constant the timing of storm conditions against accessible tides and the scheduling of sensitive tasks can cause a high level of variation in installation cost and duration.

To capture this variation and obtain understanding of the uncertainty associated with the installation it is recommended that multiple years of metocean data are analysed (DNV, 2011). By performing an analysis across a range of years a spread of costs and durations can be obtained. It becomes apparent that there is less uncertainty and more confidence when the spread of results across these years is minimal. Operations which have low spread can be considered to be robust. These may represent a preferable installation method even when compared to one which has a lower minimum cost but a diverse range of results.

4 Comparison of methods

Considered here is the application of a case study installation operation performed at the Wave Hub with the aim of allowing the applicability of the numerical model described previously to be ascertained. Thought is also given to the importance of such analysis processes being performed; the applicability of the Weibull model discussed is compared alongside the time series approach.

Finally, the importance of analysing all phases of an installation operation, and particularly the transit phase is considered.

4.1 The Wave Hub

The Wave Hub is a "grid-connected offshore facility in South West England" (Wave Hub, 2013). Intended for the testing of marine energy generators at large scale the site holds a 25 year lease and covers 8km^2 of sea bed. An 11/33kV subsea cable allows grid connection.

To date, no marine operations have occurred at the Wave Hub, with the exception of the installation of the cable and subsea socket itself, however a number of developers of both wave and wind energy converters are in the process of preparing for deployment at this site. (Wave Hub, 2013a, 2013b & 2013c)

A number of existing methods for the analysis of installation operations have been presented (Section 1.5) along with the proposed new time domain simulation method developed herein (Section 3). In order to establish the suitability of the discussed methods an application is presented in which a simple deployment operation is performed at the Wave Hub site. This operation considers not only the at site conditions but also the transit phase of the operation, giving attention to the restrictions of towing a device. Key to this analysis are the metocean data (Section 4.2) and the requirements of the operation, these being the working durations and thresholds for each phase of the analysis.

This analysis considers the seasonal variation seen in metocean conditions and considers the impact on deployment duration and ultimately success. Comment is made as to the preferred method for this type of analysis and the role which multiple analysis methods may take.

4.2 Data sources

Two primary sources of data exist, modelled and recorded and it is thought that both are useful for this application; however there are some implications relating to each source. Obtaining recorded data is both time consuming and potentially costly. To obtain a large data set requires the deployment of an array of waverider buoys, or similar, over the required time frame. Whilst recorded data may be limited in these respects it is thought that the accuracy of this data is high. Modelling wave data is beneficial in that it is easier to obtain a large data set, both geographically and with respect to time. Whilst it would be necessary to deploy a large array or recording equipment to obtain data on multiple sites and transit routes a well-established model can produce this data. Ensuring accuracy, however, can be problematic and a detailed validation process alongside high quality input data is required. If these issues can be overcome obtaining a high resolution data set becomes a realistic possibility.

At the time of data collection responsibility for the Wave Hub lay with the South West Regional Development Agency (SWRDA) who, along with the University of Exeter, provided input data for this work. Two data types were obtained; computer modelled data was provided by SWRDA and is designated “modelled” throughout; the University of Exeter provided recorded data from Waverider and SeaWatch Mini Buoys; this input is designated “recorded” throughout.

The modelled data set contains 34105 data points, from 1988 to 2000, and the recorded data set 9930 data points, from 2005 to 2010, the distribution of which is indicated in Figure 4-1 and Figure 4-2. The figures show that the coverage of the two data sets is similar, particularly Figure 4-2 which considers the distribution of data points by wave height. It can be seen in both cases that the lowest period and lowest wave height waves are not covered and that the modelled data set covers wave up to 12 metres in height whilst the recorded set has an upper limit of approximately 7 meters. Whilst it may be true that there are few low height, low period waves at the Wave Hub it is these conditions which are most likely to be preferable for the execution of marine operations; therefore an absence of data in this area could bias the study. Considering that the waverider data set is recorded it is unlikely that a large number of smaller waves have been neglected, especially given that the recording equipment is capable of measuring these small waves. This, however, is the smaller data set and it is possible that a number of events, across the height spectrum may not have been recorded due to shorter deployments of the wave buoys than the modelled data.

It is not known how the modelled data was produced and what validation was performed, and whilst this causes some concerns it was decided that this data could be used in the study with caution.

The modal wave height is approximately 1.5m in both cases and that the range of periods covered by the data sets is equivalent. The larger modelled data set covers a greater range of wave heights.

The two data sets were processed separately for this study, however the decision was taken to also combine them into one large data set (designated "Combined Input"). It was thought that the size of the data set would have the most bearing on the accuracy of any results obtained, rather than the type of data (modelled or recorded). Whilst separately the data could be informative it would be more likely to be of use when combined.

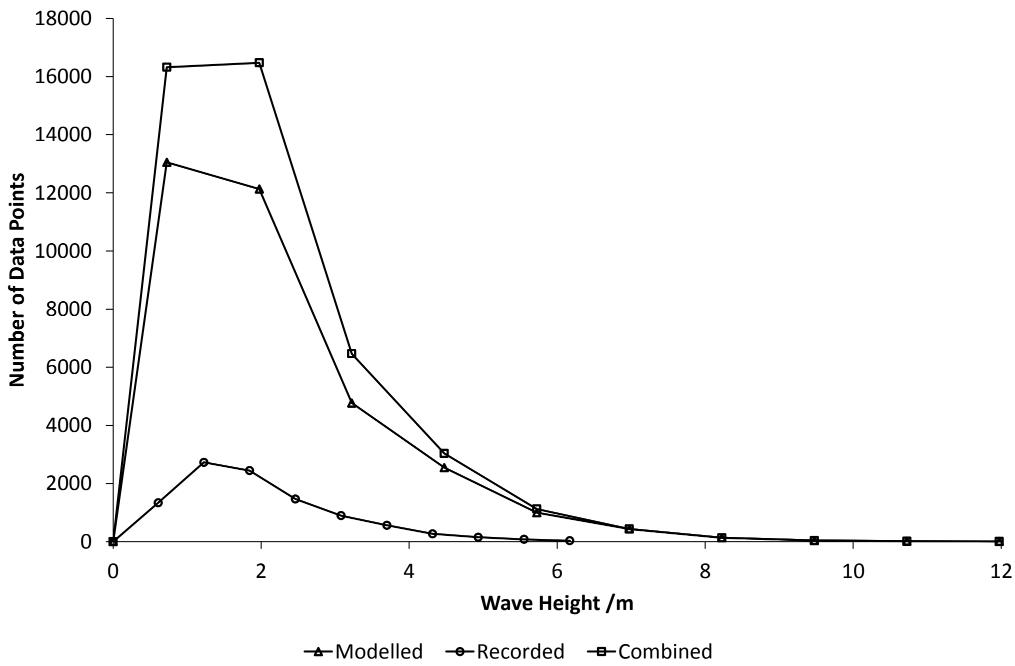


Figure 4-1: Data Coverage by wave height

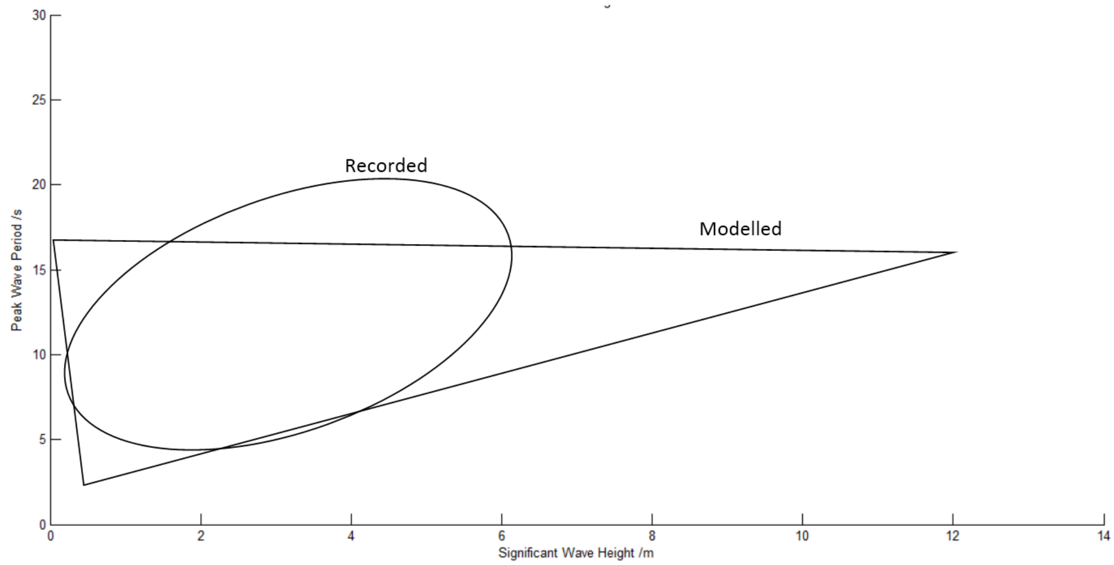


Figure 4-2: Data by wave height and period, area covered

Later, the University of Exeter developed a hindcast model for Cornwall. This data is produced using the SWAN (Simulating WAves Nearshore) model, 'a third-generation wave model for obtaining realistic estimates of wave parameters in coastal areas, lakes and estuaries from given wind, bottom and current conditions.' (The SWAN Team, 2011) This model produces metocean parameters for the seas surrounding the Cornwall peninsula as illustrated in Figure 4-3. Here the two computational grids can be seen, one for the entire Cornish peninsula (D0) and a finer resolution grid at the Wave Hub (D1). It should be noted that this data set is referred to as "hindcast" throughout and was produced for a number of locations throughout the grid D1.

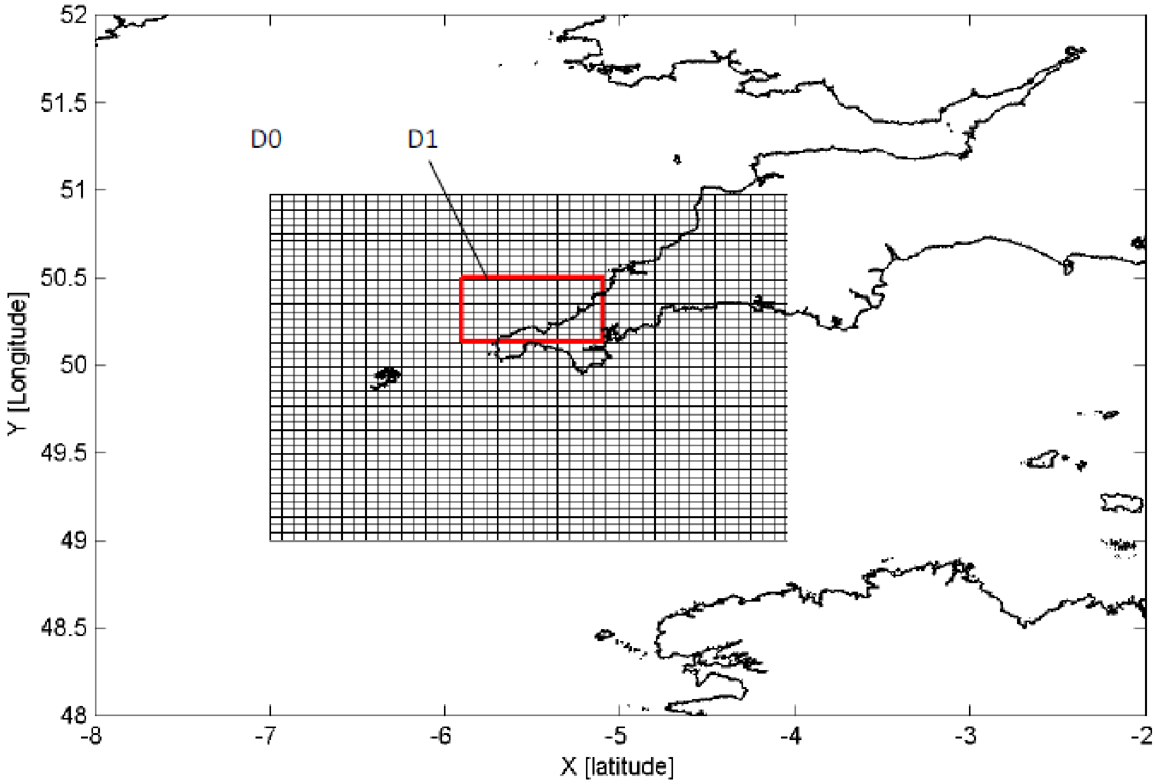


Figure 4-3: Hindcast model domain showing both D0, the Cornish peninsula grid, and D1 a finer resolution grid at the Wave Hub

The model covers the area of 4° to 7° west and 49° to 51° north. The model grid comprises the whole Cornwall coast and part of the Devon coast; the Isles of Scilly are included. A grid resolution of 1 km x 1 km is used for the model domain. Nests with smaller grid resolutions, down to 100 m x 100 m are used for nearshore areas of interest. Only the results from the main model domain are used in this study. The bathymetry for the model is constructed from the 200 x 200 m resolution bathymetry obtained from Marine DigiMap. The European Centre for Medium-Range Weather hindcast data is used for the wave and wind input. No water level variations and currents are taken into account. Figure 4-4 shows the bathymetry in a selection of the model domain. The SWAN output points relevant to this study are indicated by grey circles, the validation points are indicated by green squares.

The period between 1st January 1989 and 1st July 2011 was hindcasted with a time step of 60 minutes. The hindcast model set-up was validated against buoy data from 5 different buoys over the time periods where data is available. The buoys include two of the PRIMaRE wave buoys situated near the Wave Hub and three Coastal Channel Observatory buoys: Perranporth, Penzance and Looe Bay, Figure 4-4.

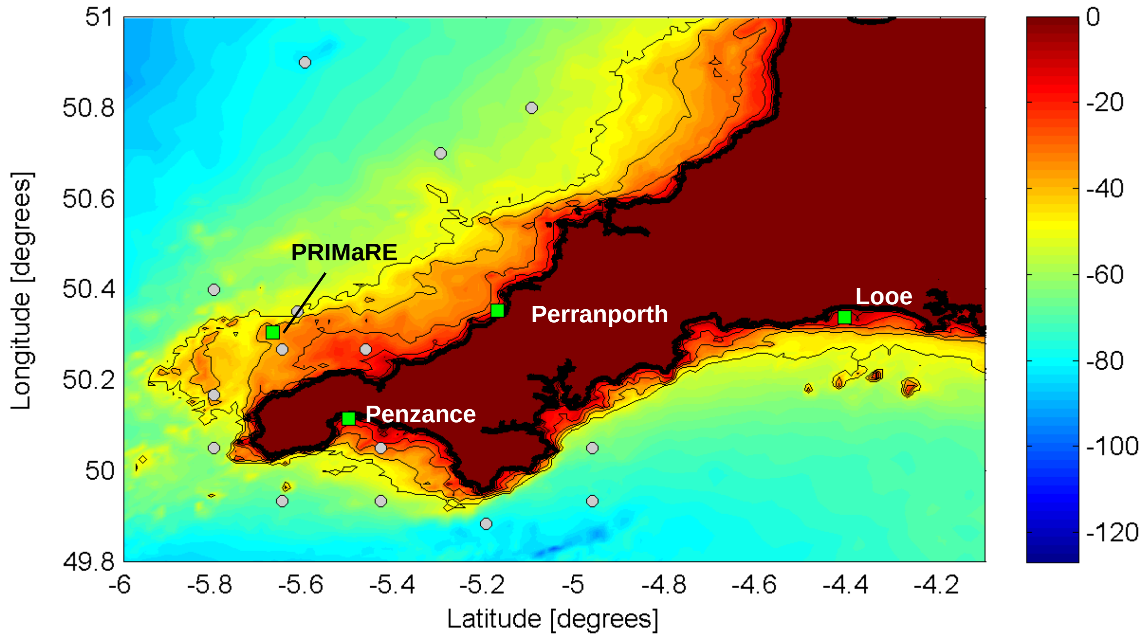


Figure 4-4: Output locations from the Cornish wave model relative to bathymetry

Figure 4-5 and Figure 4-6 show examples of the comparison between the measured and computed datasets for PRIMaRE wave buoy D and Looe Bay. These figures illustrate that the performance of the model compared to the measurements is best for medium range wave heights between 0.5 and 3 meters. Above and below these levels the wave heights were often underestimated by a few centimetres by the SWAN model.

For an analysis which is concerned with the workable windows at an offshore location the timing of up- and down-crossing events at a wave height threshold is more important that the level of match seen between peaks and troughs. Given thresholds of 1m, 1.5, and 3m, which are utilized later in this work, it can be seen that the timing of the crossing events is well match in both Figure 4-5 and Figure 4-6. Some discrepancies are visible at the 3m threshold in the comparison between PRIMaRE wave buoy D and the Cornish peninsular SWAN model. This can be seen particularly clearly during the wave height event which exceeds 4m on the 4th October (Figure 4-5).

A more detailed description of the model validation can be found in van Nieuwkoop (2012) and van Nieuwkoop *et al.* (2013). In conclusion, this validation demonstrates that the model is of sufficient accuracy to be acceptable for use in this study.

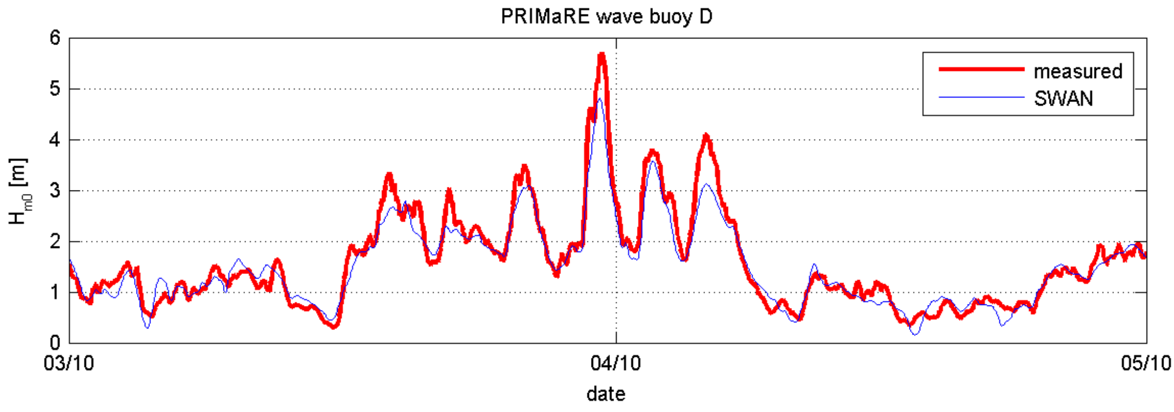


Figure 4-5: Comparison of measured (PRIMaRE wave buoy D) against modelled (SWAN at corresponding location)

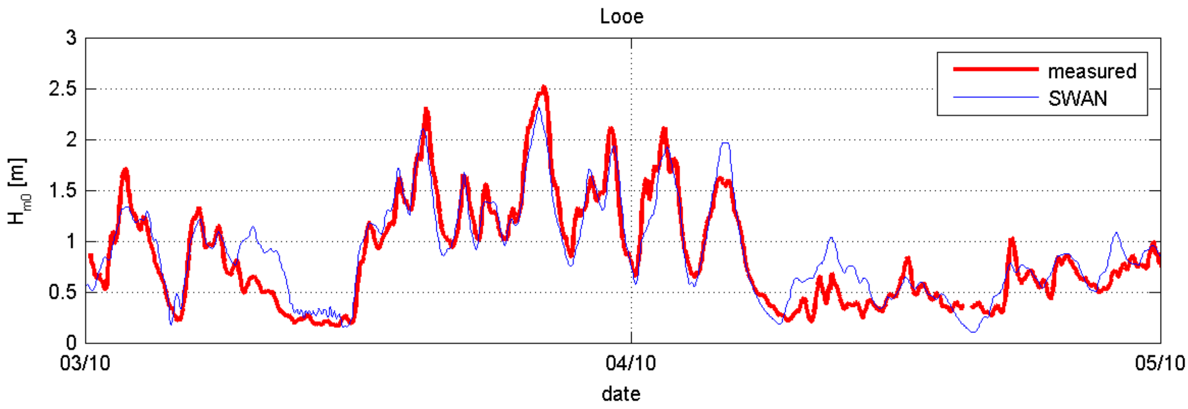


Figure 4-6: Comparison of measured (Looe Bay) against modelled (SWAN at corresponding location)

Studying the data produced by the Hindcast model, and considering the issues raised previously regarding data coverage, it was seen that the data coverage was significantly improved (Figure 4-7 and Figure 4-8). This new modelled data is high resolution (some 200,000 data points at hourly intervals over 20 years) and covers a full range of wave heights and periods, therefore mitigating the previous concerns of i) poor coverage at lower wave heights and periods and ii) data sets without sufficient data points to allow a high level of confidence in the study.

The new modelled data covers significant wave heights from approximately 0 metres to 10 metres and peak wave periods from 2 seconds to 16 seconds. Therefore this data incorporates both storm events, which are detrimental to the installation of wave energy converts and calm events, where site access is possible and workability is high.

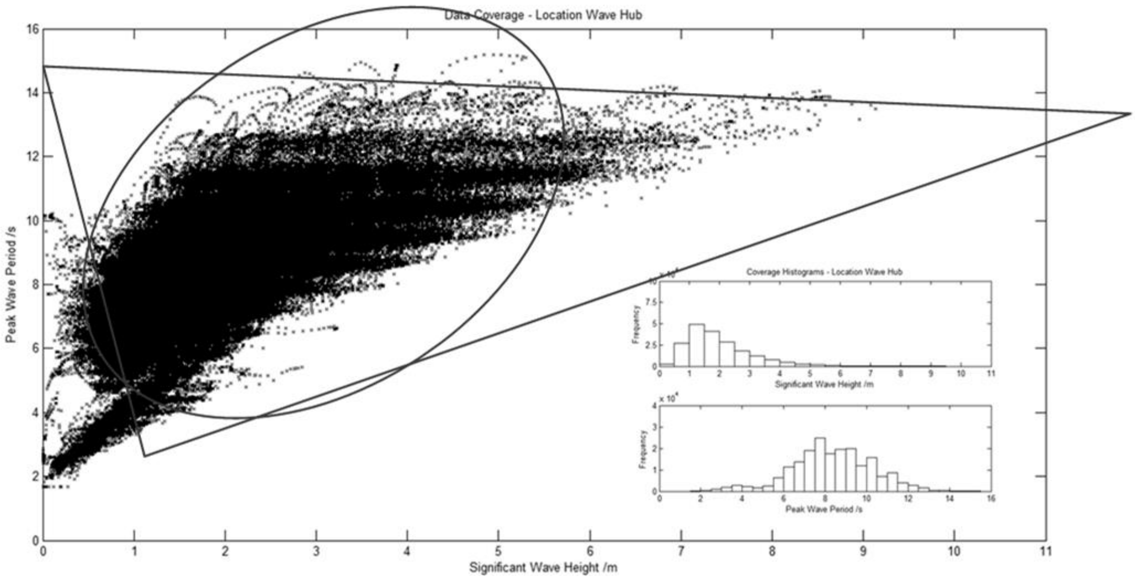


Figure 4-7: Data coverage at the Wave Hub, including previous data coverage overlay

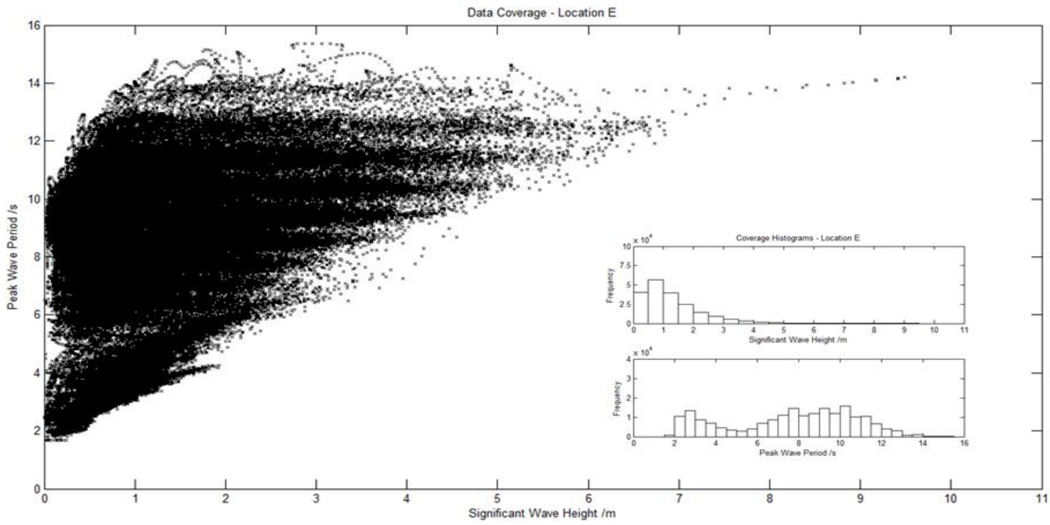


Figure 4-8: Data coverage on route to the Wave Hub

4.3 Weibull persistence application

The installation of a marine energy device can be subdivided into three distinct phases:

1. Mobilisation and transit to site, including towing the device;
2. On site activities, the actual installation process;
3. Demobilisation and transit to port.

Any analysis of the availability of weather windows for device deployment would be remiss if these three phases were not considered. Therefore a number of data points have been selected from the hindcast model to allow such an analysis to occur alongside a consideration of the modelled and recorded datasets which exist for the Wave Hub location.

Figure 4-9 shows a number of typical vessel tracks around the Wave Hub area. The green track represent tankers and cargo vessels and are limited to the shipping lanes, whose north and eastern limits are shown. The pink tracks represent fishing vessels and the blue tracks indicate tugs.

Figure 4-9: Indicative vessel tracks from Automatic Identification System showing tankers and cargo vessels (green), fishing vessels (pink), and tugs (blue). Also shown is the northern and eastern limits of the shipping lane in this area. (www.marinetraffic.com)

It was seen on the Automatic Identification System (AIS) that the fishing vessel journeying from Falmouth to the open sea to south of Wave Hub took 12 hours at a speed of 5 knots. It can be expected that towing a wave energy converter to the Wave Hub may also take 12 hours and it can be seen that the mobilisation and towing phase of an operation can be impacted upon by a lack of suitable conditions. It is thought that operations at the Wave Hub are likely to deploy from Falmouth, although Penzance and Hayle may be capable of handling smaller vessel (see Figure 4-9). Given the tracks seen and the possible port usage the data points indicated in Figure 4-10 and Table 4-1 were selected for analysis. The points *A* to *J* can be used to assess phases 1 and 3 of an operation whilst the Wave Hub data point is to be used for the actual installation process. Points *K*, *L*, *M* and *N* cover access down the Bristol Channel and can also be used to assess phases 1 and 3 of an operation, for example, for an operation deployed from Milford Haven, Wales.

Figure 4-10: Locations for data extraction from the University of Exeter Cornish Coast Wave Model

Table 4-1: Locations for data extraction from the University of Exeter Cornish Coast Wave Model

Data Point	West	North
A	4° 58’	50° 03’
B	4° 58’	49° 56’
C	5° 12’	49° 53’
D	5° 26’	49° 56’
E	5° 26’	50° 03’
F	5° 39’	49° 56’
G	5° 48’	50° 03’
H	5° 48’	50° 10’
I	5° 39’	50° 16’
J	5° 28’	50° 16’
Wave Hub	5° 37’	50° 21’
K	5° 48’	50° 24’
L	5° 18’	50° 42’
M	5° 06’	50° 48’
N	5° 36’	50° 54’

4.3.1 Results

Data concerning access and waiting hours was produced for all 15 locations specified in Table 4-1 for each month of the year. This produces some 360 data sets in addition to the 72 data sets produced from the modelled, recorded and combined data. A number of the hindcast data tables are reproduced in Access and waiting days and hours at the Wave Hub. These lookup tables present the number of access and waiting hours, to the nearest whole hour, for the range of significant wave heights analysed and for required calm event durations (the required window length) ranging from 6 hours to 240 hours (10 days).

Where the waiting time exceeds the number of hours in the month (for example 744 for 31 day months such as January and July) the waiting time is specified as being the number of hours in the month, this is as in Equation 1-14. In practice this means that those planning an operation would need to either deploy in another time frame, or would need to find means to allow deployment to occur in less favourable conditions (a shorter window or a larger significant wave height). By making concessions such as these it may be possible to deploy at the time of year originally specified. It is seen throughout this study that less waiting, and conversely more access, is available with i) a shorter required window length, ii) a larger wave height threshold, iii) a summer month.

Also included in these lookup tables are an underlay of contours. These contours specify the number of access or waiting days required at the corresponding height threshold and window length requirement. By incorporating these contours into the data it is possible to gain an impression of the trends present in the data. With regard to the access tables it is desirable to have high value contours at low wave heights. Conversely for the waiting tables it is desirable to see low value contours at low wave height. Studying the appended figures it can be observed that these more desirable trends are prevalent in July far more than January and it is not unreasonable to state that this is expected given the weather typically observed in these months in the UK.

Generally there is agreement between the hindcast data set and the modelled, recorded and combined data. The conclusions drawn from the modelled, recorded and combined data set are supported by those drawn from the hindcast data; that access days are almost twice more likely to occur in the summer months than in the winter months and waiting time is likely to be at least three times less. This has implications on the planning of marine operations and has cost implications based upon the time of year at which they can occur. Of particular interest here will be operations and maintenance work and unplanned interventions which may have to occur in the winter months, or the deployment of arrays which (given their size) may not be completely installed in a summer season.

Considering the trends seen in an individual month; windows with a threshold wave height of 0.5 metres are unlikely. Windows nearer to a threshold of 1.5 metres, which is probably a more realistic working threshold, are more likely. The trend seen is that the larger the threshold the more likely the window; however above 1.5 – 2 metres this is of little practical use.

Considering the availability of weather windows across the seasons it can be seen, perhaps unsurprisingly, that it is harder to find a window in the winter months and that more waiting time will be associated with these windows.

Windows of longer than 5 days are less likely to occur than short windows, and, as hypothesised previously, the longer the window the less access days and the more waiting time will be encountered, if the window occurs at all.

Considering Table 4-2 it can be seen that the modelled and recorded input data produce very similar access days and waiting time output, often within a 0.5 to 1 day range. Larger variation can be seen in some months in these cases approaching a 5 day range. It is believed that this is as a result of the significant difference in data set sizes.

Table 4-2: Comparison of access days and waiting time for the three metocean data sets for all months

Month	Modelled		Recorded		Combined	
	N_{ac}	N_{wa}	N_{ac}	N_{wa}	N_{ac}	N_{wa}
Jan	1.55	19.17	2.14	5.86	1.54	19.31
Feb	1.85	14.19	1.96	5.78	2.15	12.03
Mar	2.50	11.44	1.88	6.44	2.42	11.87
Apr	4.01	5.99	3.44	2.61	4.14	5.72
May	5.88	3.52	8.44	1.13	5.84	3.62
Jun	5.82	3.32	10.17	0.00	5.91	3.23
Jul	6.51	2.83	6.79	2.40	6.39	3.03
Aug	5.98	3.16	6.53	2.14	5.92	3.34
Sep	4.38	3.16	6.95	3.14	4.42	5.35
Oct	2.92	9.52	5.97	3.43	2.96	9.37
Nov	3.09	8.59	1.14	25.53	2.71	10.06
Dec	2.10	13.82	5.13	3.88	2.29	12.59

The modelled data set, which is the largest, tends to be more conservative. The data produces an estimate of less access days in most cases with more time spent waiting. In June the modelled date predicts almost half as many access days as the recorded data whilst in July the estimates are almost the same. The combined data tends towards the modelled data as the larger data set will influence the analysis more than the smaller recorded set.

To expect that the results from the combined data lie between the modelled and recorded data would be incorrect (as seen in April, for example). It is thought that the size of the data set is of most importance where the results are concerned. Also of importance for this method is the distribution of the data in the set due to the manner in which the Weibull fit is applied. This means that combining the data sets results in larger data sets with a better distribution of wave heights and periods. It is therefore recommended that large data sets of either modelled, recorded or a combination of both be used for this type of work, with the only caveat being that this input data is sufficiently accurate.

Figure 4-11 presents data for a 1.5 metre wave height threshold with a required length of 24 hours and here it can be seen that there is agreement in the trend seen between both studies, the hindcast and the combined data. The trend seen shares a similarity with the available monthly wave power reported from the hindcast model (Figure 4-12). Firstly, this validates the work performed here, ensuring that appropriate data is produced and that the trends are realistic. Secondly, given the comments previously made regarding the appropriateness of the input data and the expectation that the hindcast model used herein is superior the prior conclusions can be reconsidered and new expectations for the availability of weather windows at the Wave Hub formed.

Access days are twice more likely to appear in the summer months than in the winter months. Waiting time is likely to be four to five times less in the summer than the winter. The previous study placed this at three times, however this new data set reveals winter, and particularly January, to be much harsher than previously thought; the summer is marginally more favourable. This harsher winter leads to three primary concerns; i) operations and maintenance (O&M) interventions, ii) unplanned interventions, and iii) array deployments. It is possible that O&M interventions may not require wave thresholds as low as a deployment operation would require, however there still may be some considerable cost implication to a winter O&M schedule as downtime becomes a major factor of vessel hire.

Similarly, an unplanned intervention may not require the lowest of wave height thresholds, however this will depend on the nature of the intervention and should a tow to port be required a very low significant wave height threshold may be required, again leading to a cost implication through down time.

Finally, as the marine energy industry moves towards array deployments it may not be possible to complete a multi mega-watt marine park installation in a single summer season. This will leave project managers with some important decisions to make and a number of possible solutions will be available to them.

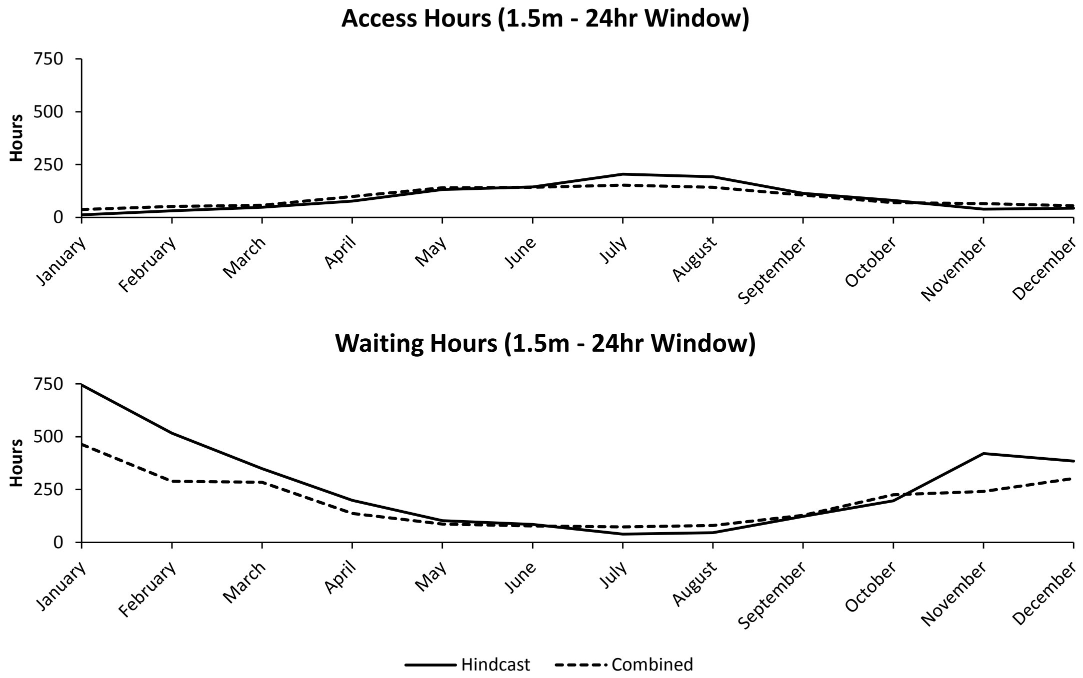


Figure 4-11: Access and waiting hours at the Wave Hub location demonstrating seasonality

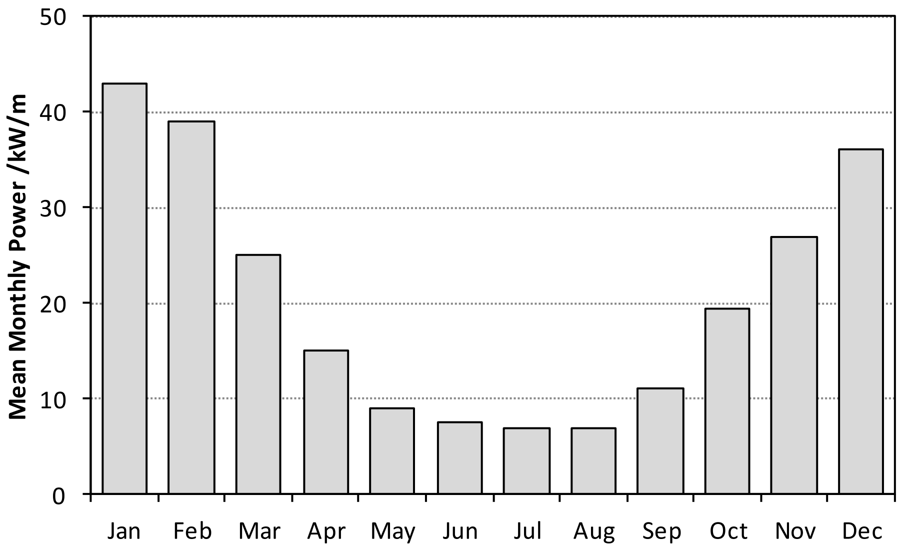


Figure 4-12: Mean monthly wave power at the Wave Hub site

Thus far the analysis has been concerned only with the conditions at the deployment site. It would be remiss of project manager to neglect the transit phases of the operation when considering the application of this process. Failure to consider the required transit conditions could lead to sever cost implications due to delayed deployment despite the occurrence of workable conditions at the site.

In this study deployment has been considered from Falmouth, on the south Cornwall coast, and from Milford Haven, in Pembrokeshire, Wales. Deployments have also been considered from the smaller ports of Penzance and Hayle, both in Cornwall, with Hayle being the nearest port to the Wave Hub site.

Table 4-3 details the data points which are considered to be on a transit route and it should be noted that there is limited data for transit from Milford Haven due to the geographic limits of the hindcast model.

Table 4-3: Access and waiting hours for the installation operation, including transit for all relevant data points for deployment from all four considered ports

Mobilised from Falmouth				
	January		July	
	Access	Waiting	Access	Waiting
A	82	200	300	0
B	23	744	196	62
C	14	744	136	110
D	16	744	215	50
F	9	744	168	82
G	8	744	227	43
H	9	744	218	48
I	14	744	181	72
WH	27	59	276	18
I	257	41	626	0
H	217	58	549	0
G	221	57	551	0
F	225	55	626	0
D	270	36	568	0
C	260	40	640	0
B	316	20	587	0
A	476	0	501	0

Mobilised from Penzance				
	January		July	
	Access	Waiting	Access	Waiting
E	65	744	268	23
D	16	744	215	50
F	9	744	168	82
G	8	744	227	43
H	9	744	218	48
I	14	744	181	72
WH	27	59	276	18
I	257	41	626	0
H	217	58	549	0
G	221	57	551	0
F	225	55	626	0
D	270	36	568	0
E	391	0	544	0

Mobilised from Hayle				
	January		July	
	Access	Waiting	Access	Waiting
J	28	627	174	78
WH	27	59	276	18
J	329	14	666	0

Mobilised from Milford Haven				
	January		July	
	Access	Waiting	Access	Waiting
M	21	744	127	120
L	16	744	181	72
WH	27	59	276	18
L	262	39	617	0
M	286	29	672	0

Having applied the Weibull method to all the data points Figure 4-13 and Figure 4-14 were produced. Here the window required at site was set at 1.5 metres for 12 hours, the window required for transit to site was set at 1 metre for 6 hours and the window required to leave site at the conclusion of the operation was set at 3 metres for 6 hours.

The assumptions made with the transit conditions were that a wave energy converter was to be towed to site, meaning that very clam conditions would be required due to the sensitivity of WECs to wave action. On the return journey the WEC would not be under tow as it will have been installed at the Wave Hub, therefore the vessel will be likely to be able to operate in more extreme conditions. Whilst the tow time from Milford Haven will be significantly greater than the tow time from Hayle, owing to the distances involved, it was decided to consider a 6 hour window at each data point. This is the shortest window analysed in this study, although it is possible to analyse shorter windows with this method, and by using this at each point it is possible to allow time for an aborted tow and return to port, should forecasts show inoperable states occurring once the tow has begun. In practice a safe holding area may be defined so that there is no requirement to return to port, particularly if inoperable conditions occur once an operation at the Wave Hub, which has deployed from Falmouth, for example, has started. However, this is not considered here where the primary aim is to demonstrate the applicability and importance of this method and of considering the transit phase of an operation.

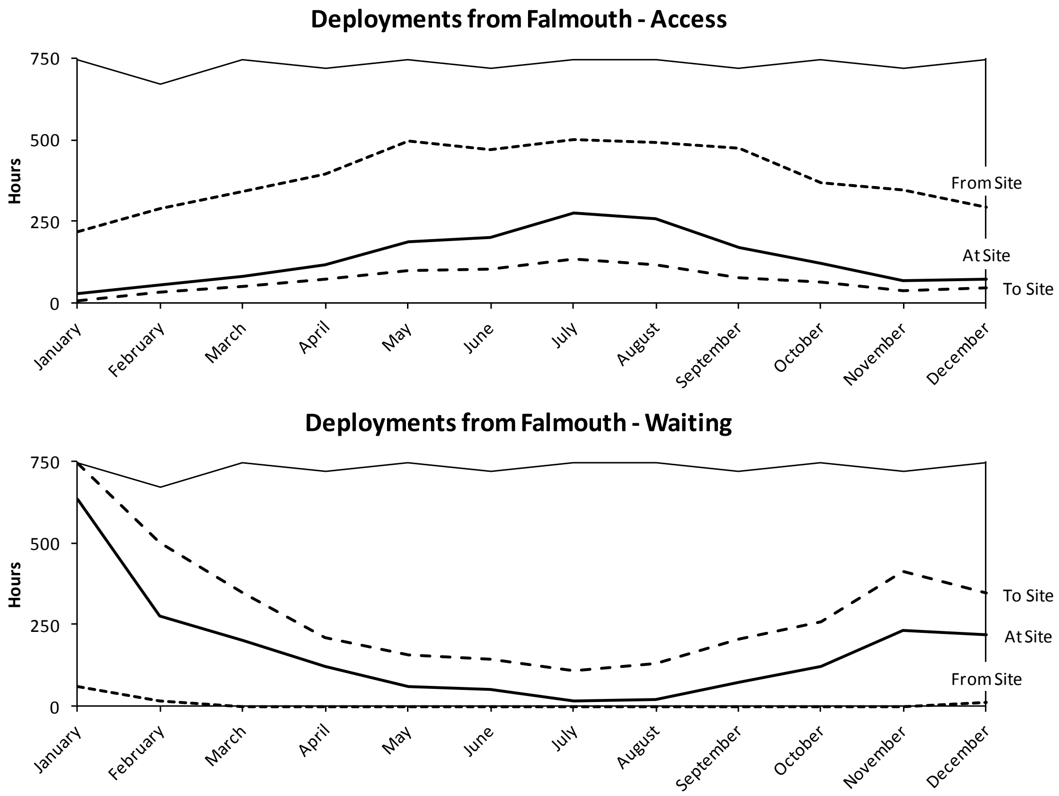


Figure 4-13: Access and waiting hours, deployment from Falmouth for all operation stages (transit to site, transit from site and at site work) demonstrating seasonality

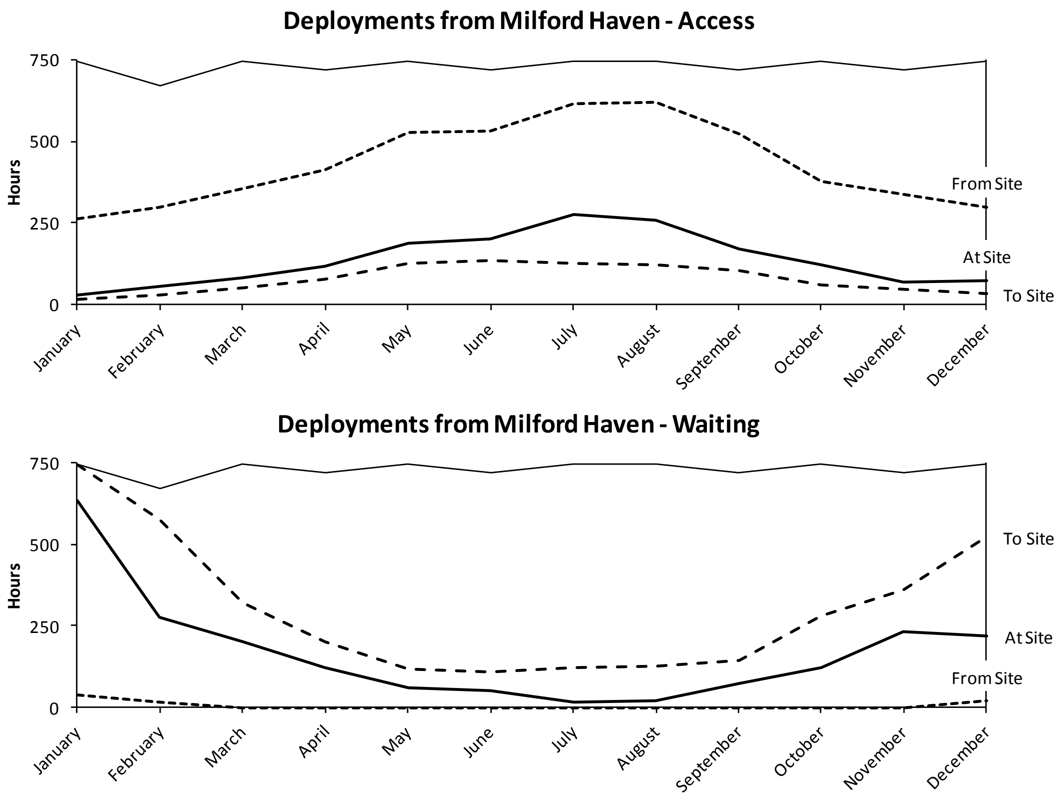


Figure 4-14: Access and waiting hours, deployment from Milford Haven for all operation stages (transit to site, transit from site and at site work) demonstrating seasonality

In the figures above the access and waiting hours for the three operation phases are shown for each month. To determine this, the maximum waiting time at any of the data points on the transit route is plotted, and similarly the minimum access time at any of the points is considered. Also indicated are the total hours in the month.

Trends seen previously regarding the availability of windows across the months are repeated here, with the summer season proving much more preferable than the winter months. Of greater importance is the trend seen for deployments from both ports, namely the relationships between the availability of windows for transit and for deployment. It is perhaps, given the conclusions drawn previously, unsurprising that the third operation stage is the easiest to execute, given the short window length and high wave height threshold. The limiting factor to the execution of this deployment is not the available window at the site but the available transit window. In this case there is a noticeable and substantial difference between the two, with access days at site being up to twice those to site for deployments from both ports.

Expanding on this, Table 4-3 details the access and waiting hours for deployments from all four ports for January and July, with the operability states as previously specified. In this table the access and waiting at each point on the transit is specified and it can be seen how the route selected and the consideration of the conditions for transit are vital to successful operation planning. Figure 4-15 shows this information for deployments from Falmouth. It can be seen how, firstly, a winter deployment is not possible under the current towing conditions, requiring re-specification as previously describe, and secondly, how, the transit to the site (when towing the WEC) is the limiting factor.

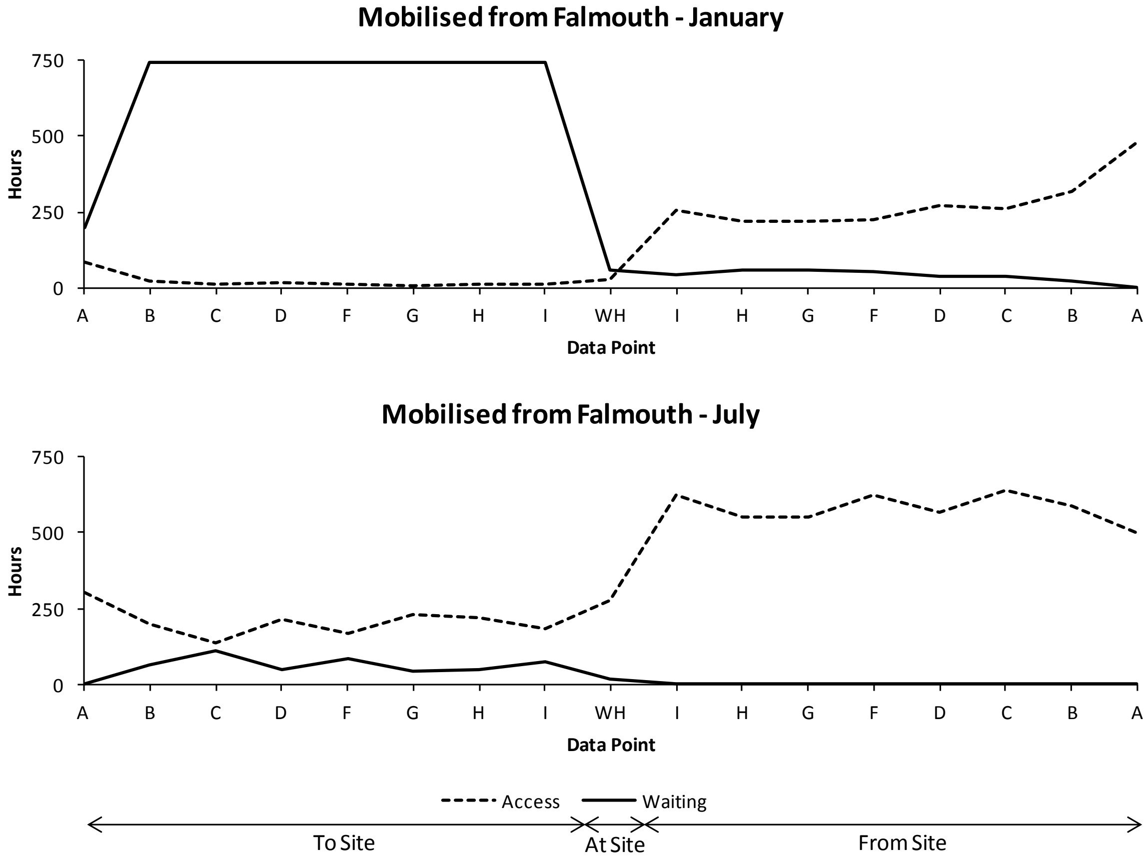


Figure 4-15: Access and waiting hours for July deployment from Falmouth showing the conditions at each point along the transit route

4.4 Time domain simulation application

To apply the newly described methods to a marine operation analysis three main data sources require definition, these being:

1. Geospatial data, including metocean conditions (Figure 4-16).
2. Vessel parameters (Figure 4-17).
3. Task information (Figure 4-19).

An extensive discussion of the possible inputs has been included previously in Section 3.1, here these inputs are discussed in relation to an operation at the Wave Hub site.

The metocean parameters used for this study are from the University of Exeter's hindcast model, as described in Section 4.2 and being located as indicated in Figure 4-16. Given the conclusions from the previous study, and the spatial range of this data set it was determined to be by far the most appropriate for this application, indeed the other data sets will not allow a detailed transit analysis to occur. At each location a time history of significant wave height is specified and whilst it is possible to consider wind speed and tidal current these are not included here. Also specified, and shown in the figure, are the transit routes from the four ports under consideration.

Figure 4-16: Transit routes to Wave Hub

Routes have been defined from these ports and where possible these are located close to the coastline. As noted in the analytical methodology the closest data point to the vessel location along a transit route is applied and whilst this means that in some instances a further offshore, and potentially more aggressive, data set is applied the distance travelled is as close to realistic as possible by utilising these tracks.

Given that these methods have no knowledge of the location of land, in this case the Cornish peninsula, south Wales and the Isle of Lundy it is necessary to define sufficient waypoints to ensure that passing between these does not result in a vessel running aground.

The defined project is the towing to site and installation of a single wave energy device. Upon completion of the project the vessel, which is assumed in this case to perform both the tow and installation operation, returns home. It is reasonable that this vessel will be capable of a slower transit when towing than post installation and therefore the vessel requires modelling in a manner which produces this. It is not possible to redefine a vessels parameters part way through an analysis, i.e. the change in characteristics cannot be directly modelled, however via the use of two vessels it is possible to replicate this type of behaviour. Defined below are two vessels, “Towing” and “Not Towing”. In both cases the crew team and fiscal rates are defined as zero as in this case study the duration of installation is of interest (thus allowing a more appropriate comparison with the previously applied Weibull persistence method).

For all limits wind and tide are specified at 100m/s, effectively removing this consideration. For both station keeping and hook up and unhook operations the wave height threshold is set at 1.5m, therefore matching the required conditions specified in the previous application.

The parameters are identical for both of the vessels, however, to capture the different transit speeds the velocity at different wave height limits varies, as indicated at the end of Figure 4-17 and graphically in Figure 4-18. These speeds have been selected to allow an approximate match to the window length specified for transit in the previous application, noting that the transit distance clearly affects the time required, a point not considered in the Weibull method.

Vessel Name	Towing				Not Towing			
Crew team	0				0			
Day Rate	£0				£0			
Standby Rate	£0				£0			
Overnight fees /person	£0				£0			
Port Fees /trip	£0				£0			
Station Keeping Limits	Tide /m/s	H_s /m	Wind /m/s		Tide /m/s	H_s /m	Wind /m/s	
	100	1.5	100		100	1.5	100	
Hook Up	Duration	Threshold			Duration	Threshold		
		Tide /m/s	H_s /m	Wind /m/s		Tide /m/s	H_s /m	Wind /m/s
αvs	0.5	100	1.5	100	0.5	100	1.5	100
βvs	0.5	100	1.5	100	0.5	100	1.5	100
αvp	0.5				0.5			
βvs	0.5				0.5			
Transiting	H_s /m	Speed /m/s			H_s /m	Speed /m/s		
	1	4			1	10		
	2	4			2	10		
	3	4			3	8		
	4	4			4	8		
	5	3			5	6		
	6	3			6	6		
	7	3			7	5		
	8	3			8	5		
	9	2			9	5		
	10	2			10	5		

Figure 4-17: Vessel inputs

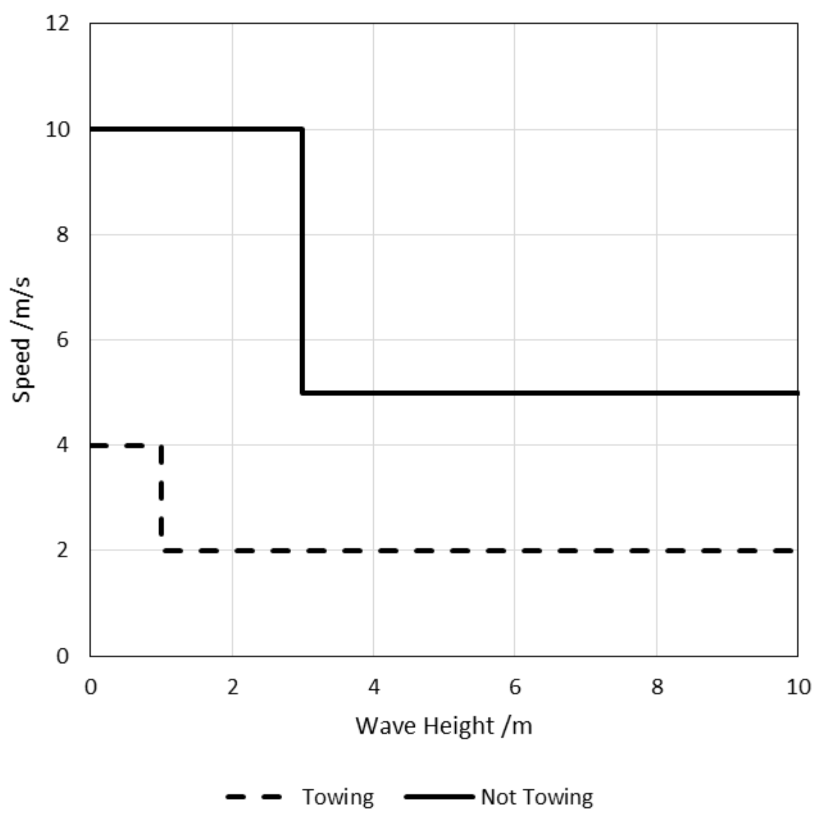


Figure 4-18: Comparison of cruising speeds for each element of the composite vessel

Whilst it is possible to define a series of tasks, therefore modelling the operation in high detail, this has been deemed unnecessary in this application and specifying only a single “At Site Operation” is sufficient to cause the vessel to access the site. This task is non-suspendable and has a duration of 12 hours with a start up of 0.01 hours (36 seconds). With a time step length of 3 minutes this places the operation at 241 time steps. The minimum duration for which it is acceptable to move to site has been set at 13 hours and given that the working efficiency in this specification may be 1 or 0 this ensures that transit results in task completion.

The start date of the operation has been set to 09:03am on the 1st, 7th, 14th, 21st and 28th of each month, producing 60 simulations per port with the coverage shown in Figure 4-20. By utilising a number of start dates it is possible to capture the seasonable variability of the installation operation and these dates may be fairly arbitrarily chosen with the only limiting factor to starting in each and every time step being the computational time.

Task	Start Date	Location (East)	Location (North)	Vessel	Durations /hours		Tide Limit /m/s		H_s Limit /m		Wind Limit /m/s	
					Start Up	Task Length	50%	0%	50%	0%	50%	0%
1 At Site Operations	01/01/2013 09:03	-5.6100	50.3500	Towing, Not Towing	0.01	12	100	100	1.5	1.5	100	100

Figure 4-19: Work to be performed (task list input)

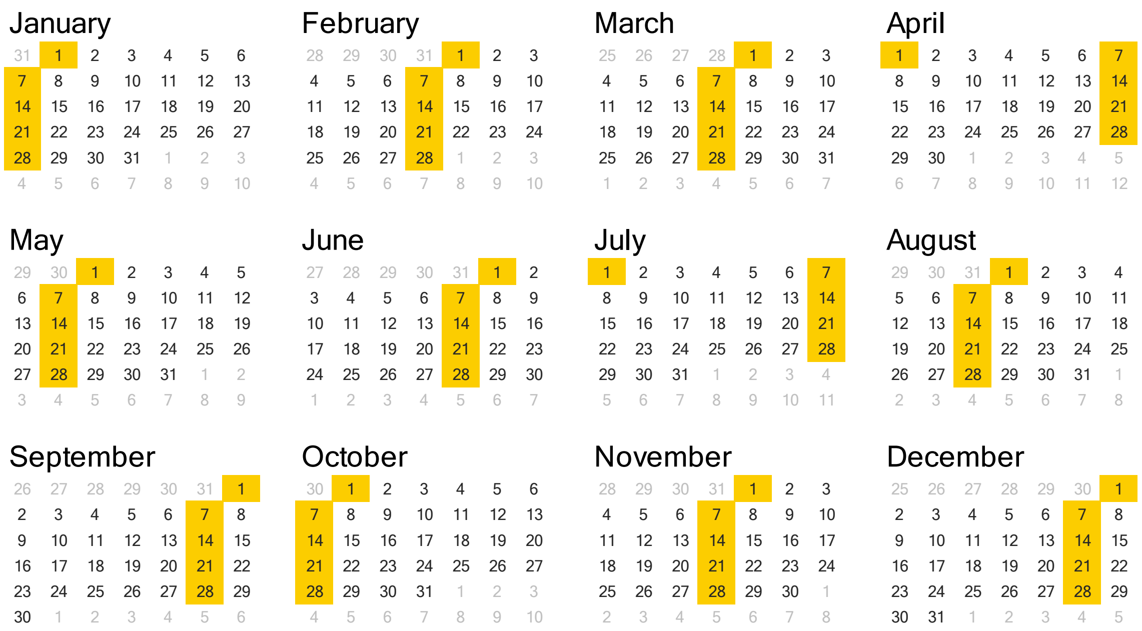


Figure 4-20: Start date coverage

To capture the changing speed of the vessel from towing to not towing the task is specified as requiring both vessels. By doing this both vessels will depart from port at an appropriate time as determined by the methods. Vessel 2, the vessel simulating not towing, will clearly arrive at site first due to its superior transit speed, however this vessel will be forced to wait for the arrival of the first vessel before work can commence. Once both vessels are at site and hooked up work may be performed and proceeds until completion, at this point both vessels access an appropriate unhook time step and begin their return to port. Again, it is clear that the not towing vessel will arrive home first, with the towing vessel taking some time longer. Via post processing it is possible to produce a resultant vessel, this being one which is "Towing" until the arrival at site and "Not Towing" once work has begun. The vessel state diagrams for both vessels and this resultant can be seen in Figure 4-21 with the differing transit lengths and waiting at site visible. Also visible here is the time which the vessel spends in port waiting for an appropriate window to occur.

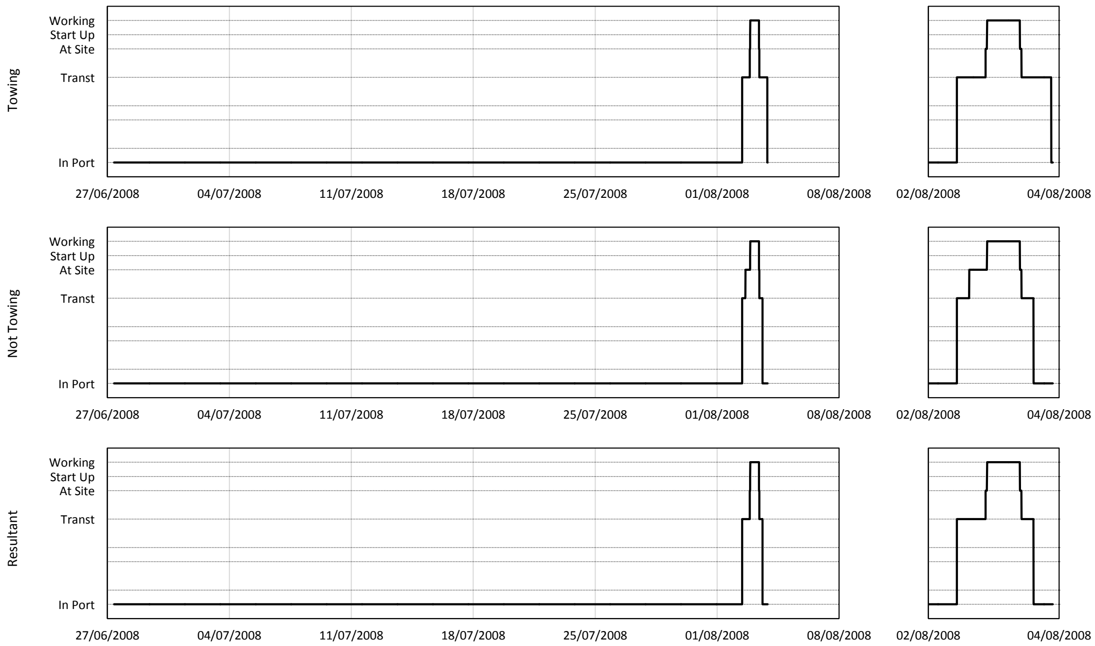


Figure 4-21: Vessel States – deployment from Falmouth. The top panel shows the "Towing" vessel, the middle panel the "Not Towing" vessel and the bottom panel the resultant vessel. The panels on the right focus on the operational element of the installation, including the variation in transit time.

4.4.1 Results

As noted the analysis was parameterised from a number of time steps and the duration of the project determined from the time at which the not towing vessel returned home. Presented in Appendix 2 and the figures below are two graphical outputs, these being:

1. The project duration from all analysed start points for each of the 22 years of analysis (one for each year of metocean data). This duration is indicated as a black bar;
2. The mean, 10th percentile and 90th percentile of project duration, calculated from the 22 years of data from each port. These plots include an indication of both the actual data and the trend of the curves.

The most apparent results seen in the project durations from all ports is the seasonal variability seen. Generally speaking the summer months (June to September) allow for the project to be completed in a shorter time and whilst some significant delays exist in some of the years of analysis these are a substantial amount shorter than the winter delays. Studying the Hayle data presented in Figure 4-22 and Figure 4-23, which is the port which experiences the least variability, the variation between summer and winter is still somewhat severe. Here a summer mean installation duration of only 3 days exists, with a winter mean duration of 22 days, some 7.3 times longer.

The figures appended demonstrate that the installation may take, considering mean values, between 3 and 46 days depending on the port and season. Furthermore there is a degree of volatility with a winter Milford Haven deployment ranging from approximately 3 days at the 10th percentile to 108 at the 90th. This year on year change leads to difficulties in scoping an accurate duration and cost for a project manager.

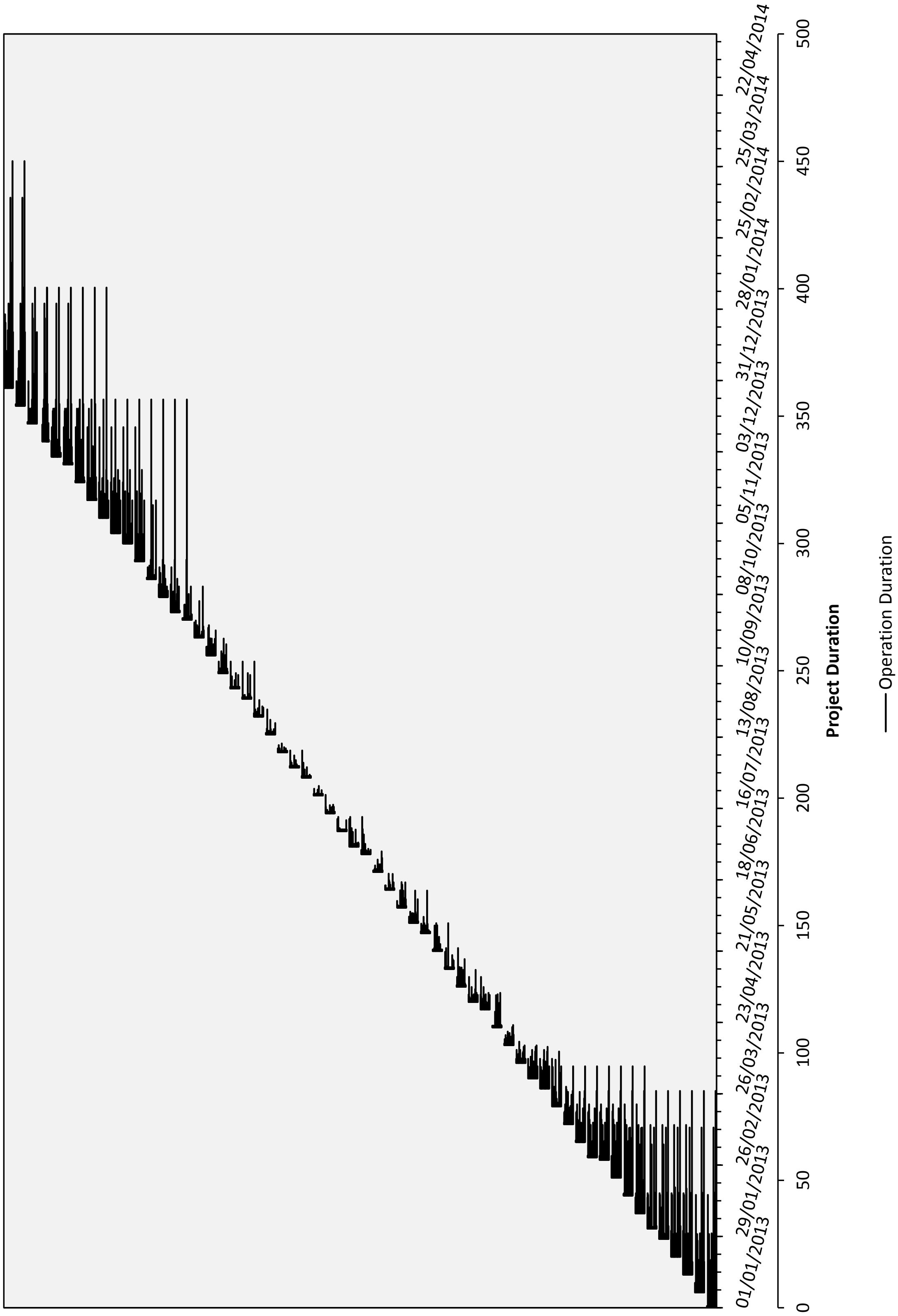


Figure 4-22: Duration of installation project - deployment from Hayle. Each small black bar represents time steps for which the vessel is waiting or working for each year of analysis and demonstrates the seasonality and year on year variation seen.

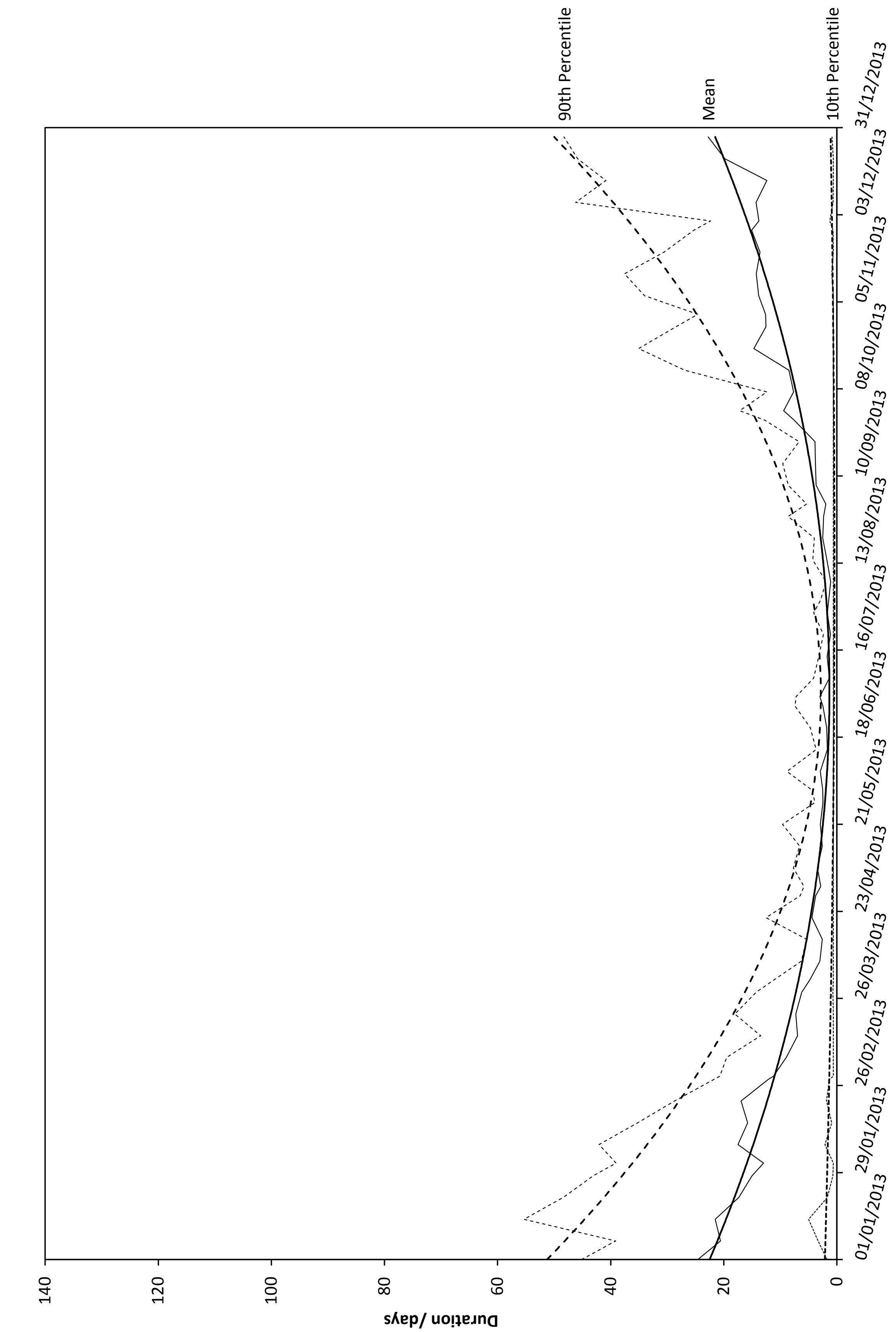


Figure 4-23: Duration of installation project at mean, 10th and 90th percentile - deployment from Hayle

Additionally it is worth considering the time composition of this project, this being the two transits and the required time working at site, the idealised (i.e. zero downtime) case from each port is shown in Table 4-4. Given the short duration of the start up period, the work at site takes half a day. It can be seen that towing to site, for the longer transits, comprises a large portion of the installation duration. In the case of deployment from Milford Haven, which has the longest transit route, this phase of the operation is longer, in an idealised situation, than the working phase. Similarly the return to port over these longer transits may be equal to 50% of the working time, a not insubstantial amount.

Table 4-4: Idealised (unweathered) installation cases for all ports

		Durations (days)				
Port	*Transit Distance (km)*	*Towing*	*Start Up*	*Working*	*Return to Port*	*Total Duration*
Falmouth	120.85	0.35	0.0004	0.50	0.14	0.99
Penzance	62.09	0.18	0.0004	0.50	0.07	0.75
Hayle	20.91	0.06	0.0004	0.50	0.02	0.59
Milford Haven	198.77	0.58	0.0004	0.50	0.23	1.31

Continuing to consider Milford Haven, it was observed that a winter installation takes a mean time of between 3 and 46 days, comparing this to the idealised duration of 1.49 days it quickly becomes apparent that a substantial quantity of downtime is being incurred; at this upper bound the mean installation takes almost 54 times longer than ideal.

Figure 4-24 shows the trend of the mean and maximum installation duration from all four of the ports. The longer the transit the longer the total installation duration. Whilst this most basic of conclusions would seem to nullify the requirement to apply any analysis method to this type of operation this is not true. The duration of the operation has been accurately calculated and the volatility surrounding these durations determined. Whilst the closer ports enjoy a shorter installation time additional factors may contribute to the selection of deployment port. It can be seen that the maximum installation duration from Penzance is only slightly in excess of the maximum installation from Hayle. The transits from these ports are just over 40km different in length, with Penzance's transit being almost three times that from Hayle. Given that the project duration is not three times greater the economics of day rates and port fees, plus the capabilities of the ports may be considered by a project manager who may be confident that moving significantly further from site will not substantially adversely affect deployment.

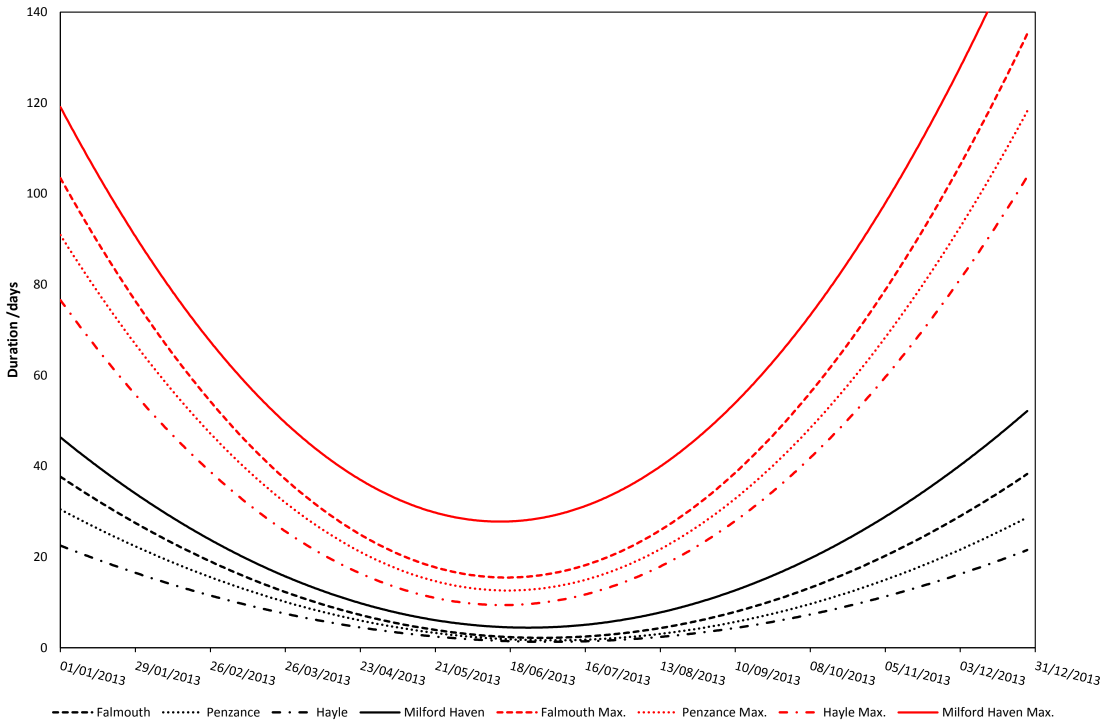


Figure 4-24: Duration of installation project – maxima (red) and means (black) - for deployment from all ports

4.5 Discussion and comparison of methods

There are two main conclusions which can be drawn from both aspects of this study. That performing an analysis, such as the ones described, is essential to the successful planning and scheduling of marine energy operations, particularly as the industry moved towards array deployments. That the entire operation, including mobilisation from port and the return to port, must be considered, particularly if sensitive equipment is to be towed.

When inoperable conditions prevail it may be possible to complete an installation program by:

1. Assigning additional resource to the tasks. This may, however, lead to a loss in working efficiency by saturating the space available at site and in port. If the local resource is not saturated additional time losses and risk may occur due to the increased complexity of many vessels and personnel working in close proximity;
2. Working over consecutive summer seasons. Whilst this will allow the work to be completed when the preferable working conditions are most readily available the length of time required to complete the marine energy park will increase dramatically due to the 6 months or so during which no work

is completed. Issues may arise with ensuring suitable vessel charters year on year;

3. Working during the winter. Whilst this will allow the work to be completed in one continuous operation the effect of downtime on the operation may be prohibitive (for example if a number of vessels are on hire but not working the fiscal impact may be substantial). This may be true even for the largest of wave height thresholds for the shortest of required windows.

Whilst it is not possible to comment on which route should be taken by the hypothetical project manager it is possible to draw one substantial conclusion. If adequate information relating to the availability of operable periods is unavailable it will be nearly impossible for the project manager to fully understand the impact of any decision taken. Whilst many experience mariners will have an understanding of the variability of metocean conditions seen at a site during the year this knowledge is likely to be qualitative, not quantitative and of little use for assigning cost and risk to a plan. The methods, however, allow for a good understanding of the conditions likely to be encountered to be developed and may be considered essential. This is particularly true given the seasonal variation seen in the case studies and the extent to which changes in required window length and wave height threshold affect the waiting time incurred.

Both methods demonstrated are quick, simple and easy to perform and remain highly informative. The main limiting factor of both methods is the availability of suitable input data and it is important to have a high quality and high quantity data set. In this study the use of the Cornwall hindcast model developed at the University of Exeter meets these needs, providing a high resolution validated data set, which covers a large geographic area and a sizeable time frame. This data was superior in these regards to the earlier utilized data sets and was the only one applicable to the latter simulation method.

Considering the Weibull method, it has been demonstrated that by applying a large data set and this method to the three phases of a simple operation any limiting areas, or bottlenecks, can be identified. Therefore, the resource used to increase the likelihood of finishing on time and on budget (or better) can be correctly focused.

Whilst this method allows an understanding of the likelihood of a window of a specified nature occurring it is limited in assessing the impact of windows on an operation, other than in terms of indicative downtime assessments. This is not to discredit this method which is of use, particularly early in a project and for comparative assessment of sites/seasons. The limitation of this method, however, is particularly evident were consecutive, adjacent and suspendable operations to be considered.

In addition the detail with which the individual phases can be analysed is limited. For example, when considering transit a window for which this may occur must be specified, however it is not known at this point how the prevailing conditions may impact on that window length, extending or reducing it. This places emphasis on the users to determine the time required to cover a distance and whilst this is a simple calculation it may be preferable to define a route and a speed.

Turning to the time domain simulation method, firstly the major shortcoming. The method utilized here does not allow for the transit efficiency to be set to zero, this means that transit is always possible regardless of the metocean conditions on route. This transit, however, will be performed at reduced efficiency as the magnitude of the metocean conditions increases (assuming, as is the case here, that the study specification reduces speed as wave height increases). This lack of a requirement to obtain a “transit window”, as utilized in the Weibull method, could clearly lead to inaccuracies in the analysis, particularly when long transit occur and particularly when this transit is across an area which may experience vastly different metocean conditions. An example of this is the case of a transit from Falmouth to the Wave Hub, upon rounding Land’s End, the western most point of the Cornish peninsula, different conditions may be encountered.

Whilst this is problematic the analysis of a transit in this time step wise efficiency based manner is an accurate and informative process. By calculating a transit which accesses a specified window the issue experienced with the Weibull method of having to scope a period of time which is sufficient to return to port if the site proves inaccessible is avoided. The utilisation of specific site station keeping windows and the requirement that hook up and unhook be possible add realism and detail which is lacking from the Weibull approach, where a user defined window only is considered.

This case study is simplistic and provides an introduction to the utilisation of these time domain methods. A single, non-suspendable task with transit, albeit at two different speed profiles, is a simple process for type of analysis. Conversely, this application is at the limits of the ability of the Weibull method. These new methods can consider many more aspects than the Weibull method, which may be considered an overviewing tool. Tasks may be deemed suspendable or non-suspendable; vessel station keeping may be modelled in a number of ways (capturing an array of vessel behaviours); transit and hook up can be considered with respect to metocean conditions. Complex scheduling can be achieved and multiple vessels may be utilized across an installation process which may be defined in terms of as many tasks as are required for sufficient detail to be incorporated into the analysis. Simple cost modelling can be performed directly with these methods, with export to more advanced cost models possible in the majority of cases. The Weibull method does not allow for any of these features.

Direct side by side comparisons of the results derived from each method are difficult given the differing manner in which they seek to answer the same question, although it is satisfying that the trends seen and the conclusions drawn regarding seasonality are seen in both data sets. Figure 4-25 and Figure 4-26 compare the results across the year for deployments from Falmouth, where the idealised durations are similar to the durations specified in the corresponding Weibull analysis when the transit windows are considered, and Milford Haven, which has the longest transit and therefore the most sensitivity to this element of the analysis, respectively. In these figures data relating the waiting time incurred during the deployment is presented as a proportion of the total working interval. In the case of the Weibull method this is the entirety of the month, in the case of the time domain simulation this may be more or less than one month given the nature of the analysis and the manner in which installations run to completion. A waiting to working proportion of 1 indicates that the month is entirely inaccessible, whilst a value of 0 indicates no downtime.

The trends seen are closely matched between the two methods with the summer being more accessible than the winter months. There is no consistent trend between optimistic and pessimistic access between the two methods (i.e. at times each of the methods is the most pessimistic). The Weibull method predicts more downtime in the winter months, with January and February being totally inaccessible for deployments from both Falmouth and Milford Haven and December being inaccessible for deployments from Milford Haven. The time domain simulation method predicts more downtime in the summer month for deployments from both ports.

This comparison provides a check on the sensibility of the produced data and illustrates the difficulties of comparing between the two methods, however, given the limitations of the Weibull method and the preference for the new process it seems redundant to apply the former method to any remaining studies included herein. Therefore, these new methods will be carried forwards and a presentation of its full capabilities presented in the following chapter.

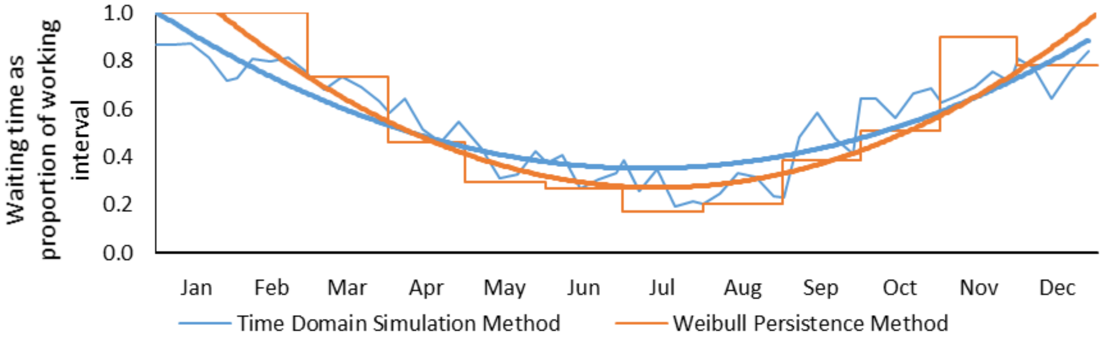


Figure 4-25: Waiting time as a proportion of working interval for both the time domain simulation method and the Weibull persistence methods, for deployment from Falmouth

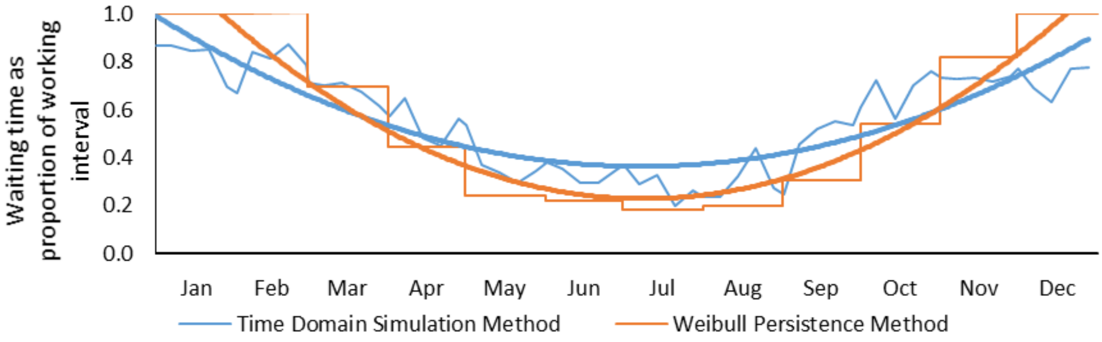


Figure 4-26: Waiting time as a proportion of working interval for both the time domain simulation method and the Weibull persistence methods, for deployment from Milford Haven

5 Tidal energy installation process – An application

To more fully demonstrate the capabilities of the described methods a case study tidal energy installation application is utilized. This both demonstrates the capability of the methods and investigates the influence of vessel limitations and task sequencing on the total duration of the installation of a tidal energy array. Particular attention is given to task and stationkeeping limits, the timing of the execution of critical tasks and the hook up time required to set up on station.

Tidal energy deployment sites are subject to extreme tidal current velocities and as a result efficient, effective operations must be performed to maximise the use of the accessible windows. Presented here is the installation of an array of six tidal turbine foundations. Discussion has been made (Section 1.2) regarding the appropriateness of gravity base structures; however, a number of early tidal deployments utilize this station keeping technology. Here consideration is given to a modular style foundation which utilizes a tripod sub-structure frame and three ballast blocks. The effect of this is to reduce the lift requirements, allowing smaller vessels/cranes to work, and to reduce the time required to lower items through the water column. This work could be expanded to consider the addition of nacelle, blades, cables and commissioning, and indeed further to considered O&M and decommissioning.

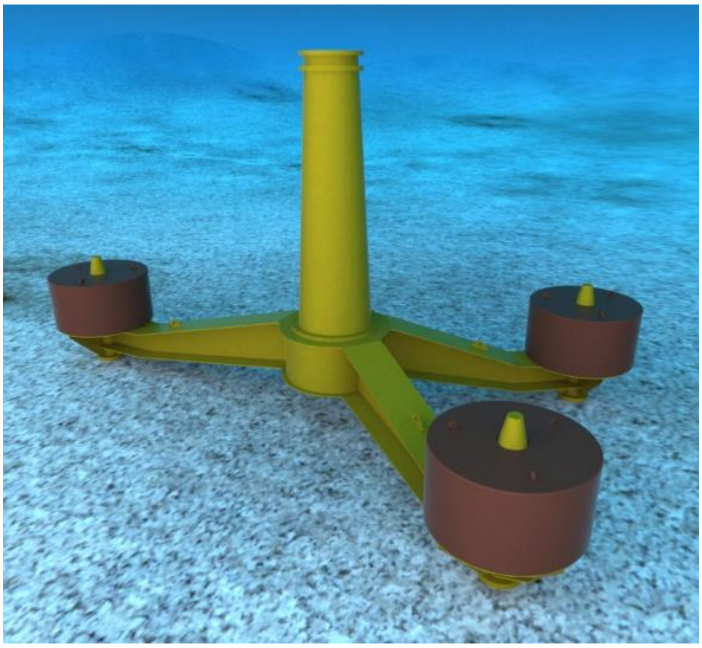


Figure 5-1: Installed modular gravity base foundation including three ballast weight units

In the course of the analysis four vessels are considered:

1. A Dynamic Positioning Offshore Construction Vessel (DP OCV);
2. A custom installation vessel, Mojo Maritimes Hi-Flow Installation Vessel (HF4);
3. A transport barge;
4. A tug, for manoeuvring the barge.

All vessels are considered to be capable of performing the required tasks, at a given set of limits, and the limits, both task and vessel station keeping, are introduced during the analysis process.

Figure 5-2: The North Sea Giant, a DP OCV

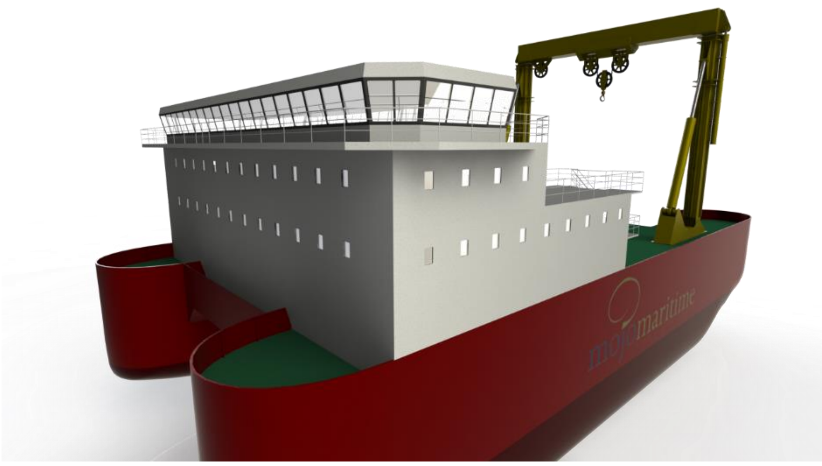


Figure 5-3: Mojo Maritime's HF4 Installation Vessel

Figure 5-4: Example barge and tug (Coles, 2002)

Two methods for the installation of the foundation units are utilized. These are designated Type A and Type B and are as follows (and in Figure 5-5):

A. Installation of a complete unit (i.e. substructure and three ballast blocks) before installation of the next complete unit;
B. Installation of all substructures before installation of the ballast blocks.

It is thought that Type B will be the more effective installation method. Often the intention when installing at a tidal energy site is to take a vessel on hire shortly before a preferable neap tide event, thus reducing the likely downtime due to high velocity currents. It is also known that the lowering of the substructures is a more sensitive task, requiring lower, more favourable metocean conditions for the successful execution of the installation. These conditions are more likely to occur early in the on hire time, due to the scheduling of the work relative to neap tides, and it is more likely that performing these sensitive operations early in the process will lead to success. The lowering of the ballast blocks, whilst not simple, is a less sensitive procedure and it is thought that this process can slip into spring tides with limited impact. In the scheduling, if installation Type A slips in to spring tides this will result in some additional down time as windows for substructure installation are sought.

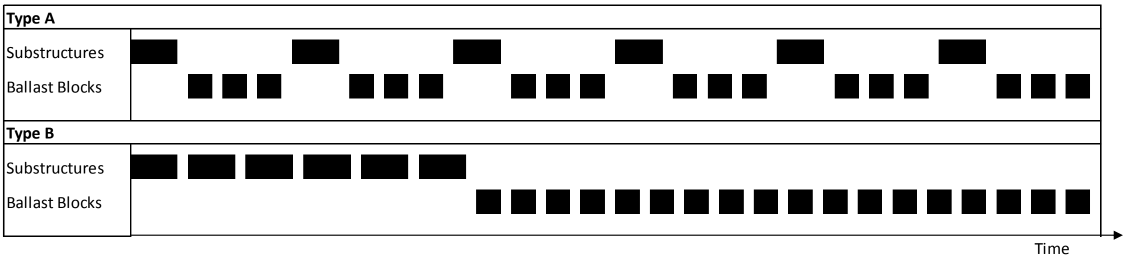


Figure 5-5: Installation methods, black bars represent working times

For the purposes of the analysis the DP OCV and HF4 are both rigged to allow the carrying of either one complete foundation (i.e. a single substructure and three ballast blocks), or two substructures, or six ballast blocks. Resupply via the barge also follows these loading requirements.
By considering these installation types, vessels and limits the following features are demonstrated:

- Transit;
- Storm calculation;
- Hook up evaluation;

- Non-suspendable task analysis;
- Multiple vessels;
- Simultaneous tasks;
- Day rates, crew costs and port fees;
- Vessel states;
- Default outputs.

5.1 Data sources

5.1.1 Geo-spatial data

The installation of these six foundations is assumed to take place at the European Marine Energy Centre (EMEC) in Orkney. Whilst EMEC, thus far, does not provide for the testing of arrays at its Fall of Warness tidal test site a good quality, complete metocean data set is held for this location.

Illustrated in Figure 5-6 are the locations of interest for this installation. Metocean data is held at the first turbine location and the remaining turbines have been positioned ensuring that a change location transit occurs between each installation phase. These locations are as in Table 5-1.

Kirkwall has been selected as the operating port and lay up location and the defined transit waypoints give a transit length of 22.5km to the first turbine location. Kirkwall has been used for marine energy deployments in the past and the harbour is being extended to allow for further, larger deployments to occur (Orkney Harbours, 2013).

Table 5-1: Turbine and metocean data point coordinates at EMEC

Data Point	West	North
Turbine 1 & Metocean	2.8600°	59.1600°
Turbine 2	2.8934°	59.1648°
Turbine 3	2.8711°	59.1757°
Turbine 4	2.9002°	59.1728°
Turbine 5	2.8854°	59.1814°
Turbine 6	2.8654°	59.1877°

Figure 5-6: Transit routes (Kirkwall to EMEC tidal berth), working locations and data points

5.1.2 Metocean data

Metocean data for the period 1986 to 1992 and 1994 to 2005 at three hour resolution was obtained from EMEC. This data (tide, wave and wind) was interpolated to 3 minute spacing, as recommended by DNV (2011) and provides 19 years in which the installation processes may occur (assuming a singular start date).

In all cases, and in an attempt to maximise success, a summer season installation has been selected and a start date of 1st July (9am) selected. However, unlike the Wave Hub application discussed previously, it is not simply a case of starting the installation on this date, or any other given date. The tidal current velocity is likely to be the main limiting factor and given the certainty with which tidal cycles can be forecast it is sensible to ensure that the target start date is appropriately matched to the predicted cycles. As can be seen in Figure 5-7, for Type A installations, and Figure 5-8, for Type B installations the 1st July often falls during a spring tide. Were the analysis started for this date in all years a number would incur unrealistic downtime immediately and result in an analysis of little or no value.

Given the manner in which the vessel decks are laid out, i.e. the type and quantity of foundation structures which may be carried, the mobilisation period is different for the two installation types. A conservative approach to determining a mobilisation time from the task lists is taken, therefore allowing for some downtime to be incurred during this process. Utilising these mobilisation times (7 days for Type A and 4 days for Type B) and identifying the target on site date, i.e. the start of the neap tides nearest to 1st July, a project start date can be determined. This is indicated in green in each of the figures and the start dates are in the range 11th June to 6th July.

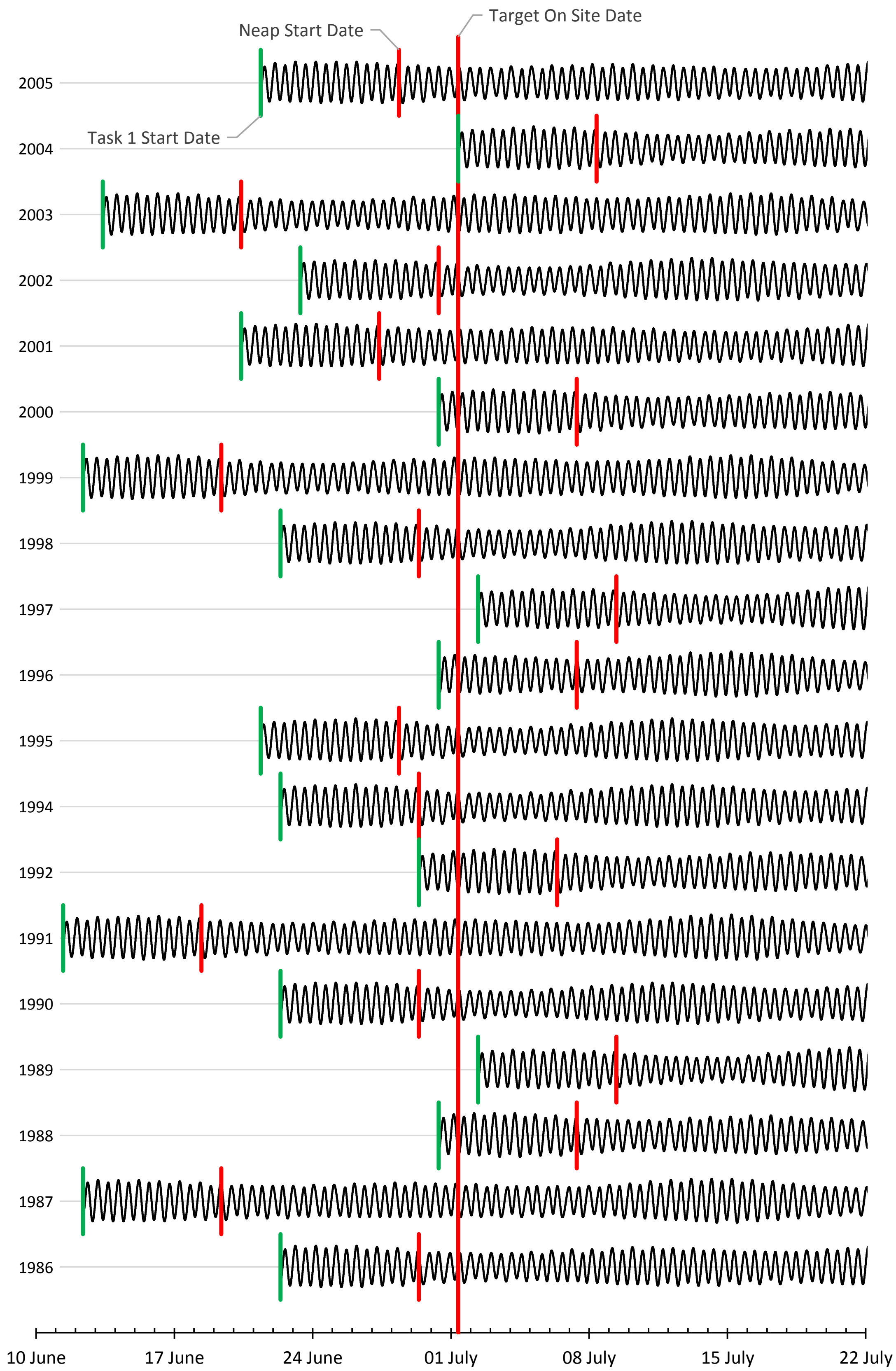


Figure 5-7: Start dates relative to tidal velocity conditions – installation Type A, including the target start date, the expected onsite (neap) start date and the project mobilisation start date

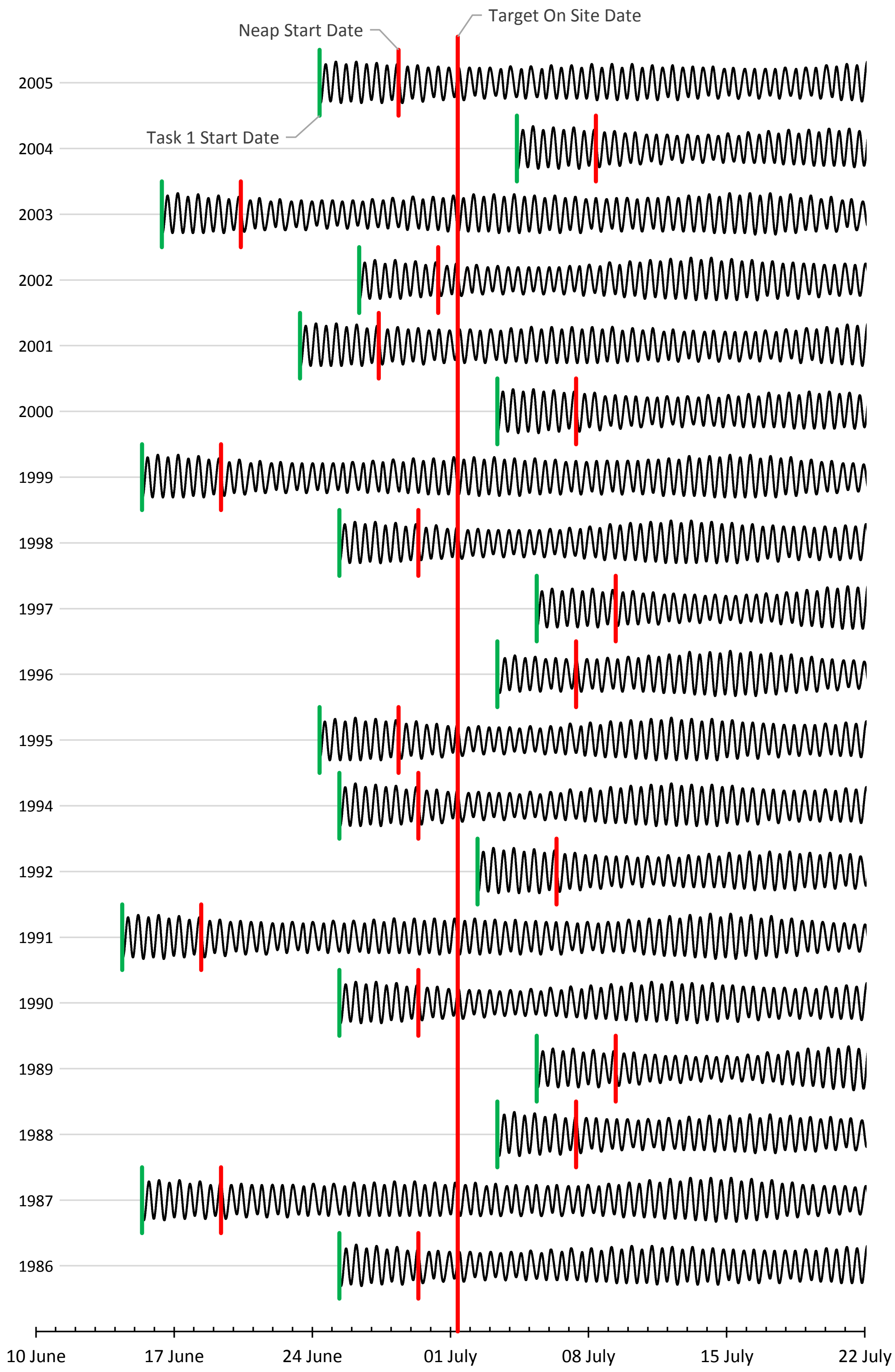


Figure 5-8: Start dates relative to tidal velocity conditions – installation Type B, including the target start date, the expected onsite (neap) start date and the project mobilisation start date

The full effect of the metocean conditions must be considered. Data sets exist for both significant wave height and mean wind speed and these are utilized in this analysis. Figure 5-9 shows the observed probability of exceedance of significant wave height for EMEC and for the Wave Hub site considered previously. This data is shown for the month of July (given the target start dates) and whilst this is a comparison between a wave energy facility and a tidal energy site it provides an indication of how benign the wave climate is at EMEC. This is perhaps not unsurprising given the length of fetch and relation of land to the prevailing wind. The result of this is that wave height sensitive operations are likely to be unaffected during these operations, although some small effect may be seen. It should be noted that, as previously observed (Section 1.5) probability of exceedance is not an appropriate metric for quantifying downtime on marine energy projects due to the lack of persistence of conditions. This lead to the development of these methods, however the overviewing capability of a probability of exceedance analysis is informative.

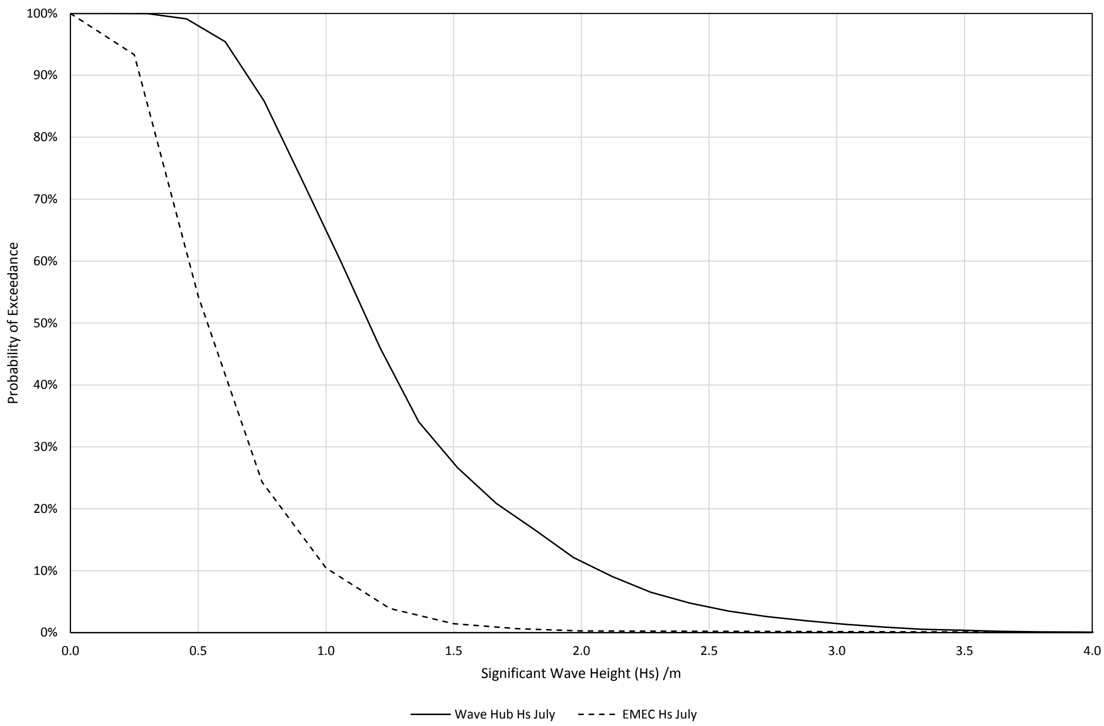


Figure 5-9: Probability of exceedance of significant wave height in July for EMEC (dashed line) and Wave Hub (solid line) showing the benign nature of waves at the EMEC tidal test site

Figure 5-10 details the wind speed for 1988, one of the nineteen years for which the analysis occurs. The wind speeds in July are low and, with the exception of some more extreme events, are unlikely to limit operations. Given the number of crane operations scheduled to occur, albeit at low lift heights, this is a pleasing observation. If the operations slip back in time, perhaps due to tidal current velocities impacting on the working efficiency, the periods of time for which the wind speeds are high appear short.

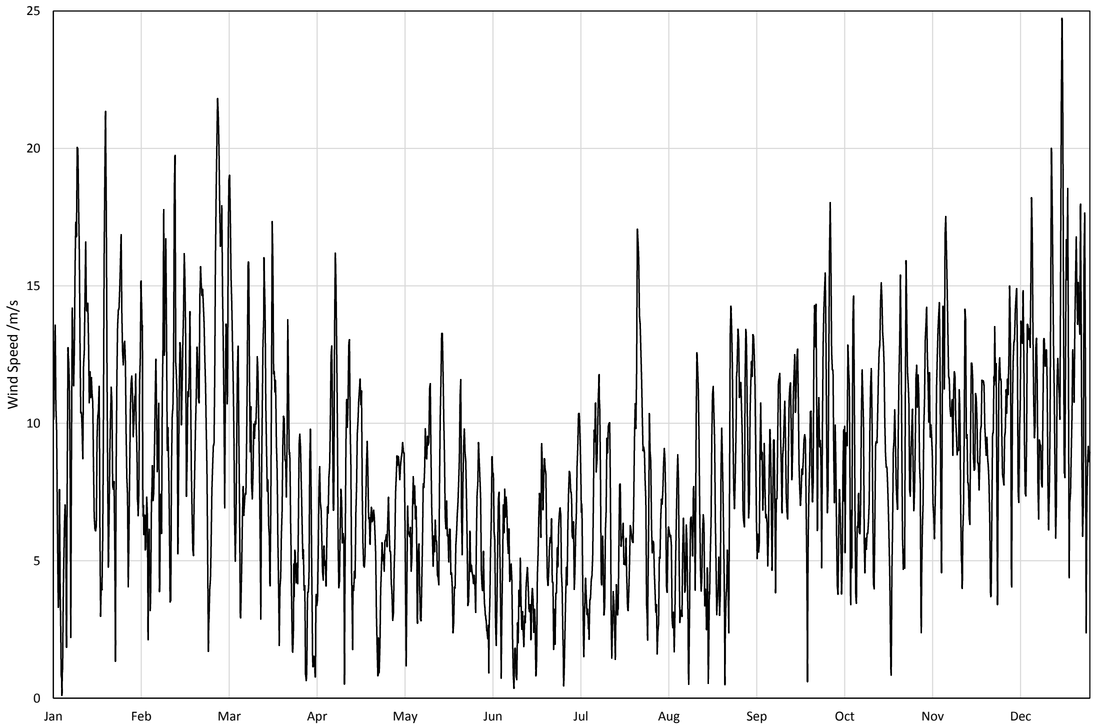


Figure 5-10: EMEC Wind Speed - 1988

5.2 Description of analysis scenarios

Fours scenarios were considered during this analysis process with each concerned with the optimisation of specific elements of the work.

- Scenario 1 represents and analysis of the existing specification available for work of this nature and may be considered to be a baseline analysis.
- Scenario 2 considers the influence of station keeping on the duration of installation. This is achieved by expanding the time for which a vessel is capable and permitted to work to include spring tides.
- Scenario 3 is concerned with the impact of repeated transit periods via the consideration of at site resupply of the installation vessel. This scenario, therefore, also considers the impact of offshore vessel-to-vessel lifts.
- Scenario 4 represents the impact of hook up time and working limits on the operation and considers the improvements which are possible via

optimisation in these areas. This is achieved via the introduction of a custom built vessel.

Each scenario is discussed further in the following sections with reference given to the working schedule and limitations applied and the vessel properties modelled. Reference is made to specific vessels, or vessel types and demonstrates the application of such an analysis process in the marine energy industry.

5.2.1 Scenario 1

The first analysis scenario is concerned with both installation types A and B, utilizes a DP OCV and works only on neap tide (often during the slack water period). To achieve this the vessel station keeping limits are set as indicated in Figure 5-11 with the exceedance time to indicate a storm set to 0.25 hours and the minimum workable length set to 1 hour. This has the effect of causing the vessel to only move to station during a neap tide cycle.

In addition to the station keeping limits the hook up and unhook limits are set as indicated and a vessel day rate of £75,000 is applied. The standby rate is set equal to this as it is assumed that a long term standard rate charter has been negotiated, resulting in no reduction in rate when not working. The day rate covers the cost of permanent crew members and additional systems required for installation and is considered to be very competitive. An additional crew team of 18 persons has been included at an additional cost of £150 per person per night and port fees, per departure, are set at £5,000.

Finally it is assumed that this OCV vessel can transit at 6m/s regardless of the prevailing wave conditions. This is a fair assumption given the size and capabilities of such a vessel.

Vessel Name	**OCV**			
Crew team	**18**			
Day Rate	**£75,000**			
Standby Rate	**£75,000**			
Overnight fees /person	**£150**			
Port Fees /trip	**£5,000**			
Station Keeping Limits	**Tide /m/s**	**H_s /m**	**Wind /m/s**	
	2	**2**	**15**	
Hook Up	**Duration**	**Threshold**		
		Tide /m/s	**H_s /m**	**Wind /m/s**
αvs	**0.5**	**2**	**1.5**	**12**
βvs	**0.5**	**2**	**1.5**	**12**
αvp	**1**			
βvs	**1**			
Transiting	**H_s /m**	**Speed /m/s**		
	1	**6**		
	5	**6**		

Figure 5-11: Vessel input – Scenario 1

The task lists used in both this scenario and scenario 2 (Section 5.2.2) are outlined in Figure 5-12 and Figure 5-13 for the Type A installation method and in Figure 5-14 and Figure 5-15 for the Type B installation. The task lists presented are, where appropriate, reduced in size for clarity and brevity.

For Type A installations the utilisation of the task repeating capabilities can be seen. Here the installation of two complete foundation structures is specified, with the second set of instructions repeated five times to achieve a total of six foundations installed.

A period of mobilisation can be seen (Tasks 1 to 4) where the vessel and crew are prepared for work. These tasks occur in port and are limited by wind, in the case of grillage installation, or unlimited, as it is assumed that inductions and the arranging of permits can be achieved regardless of the prevailing conditions.

This period of mobilisation is longer for Type A installations due to the requirement to carry both substructures and ballast blocks on board simultaneously. In the Type B installation the vessel is rigged to carry substructures and then modified part way through the process to carry ballast.

Having completed mobilisation tasks the vessel is loaded with the components to be installed. Again this is dependent on wind conditions for in port lifting operations, and transits to site (determined by the change in task coordinates).

At site the substructure is lowered to the seabed and sited (Task 12) and the ballast blocks are added (with the lift operations being Tasks 16, 18 and 20). These short operations are particularly limited with regard to metocean conditions, specifically tidal current velocity, with Task 12 being the most sensitive. This task requires a 1 hour window at less than 0.5m/s of current velocity, i.e. a slack water event. The ballast block installations also require a 1 hour window however this slack water period is larger owing to the less severe tidal restrictions.

Upon completion of the installation of the foundation a brief and tightly limited ROV (Remotely Operated Vehicle) inspection occurs before the vessel returns to port to resupply with the components required for the next foundation installation. Once the final turbine installation has been completed and the ROV inspection satisfactorily ended the vessel returns to port and a small number of demobilisation tasks are completed, these essentially being the undoing of the mobilisation tasks so that the vessel is made ready to proceed to its next job once off hire.

	Task	Start Date	Follows	Changing Location	Location (East)	Location (North)	Vessel	Durations /hours		Tide Limit /m/s		H_s Limit /m		Wind Limit /m/s		Task class number	Repeat
								Start Up	Task Length	50%	0%	50%	0%	50%	0%		
1	Vessel inductions	01/07/2013 09:03		0	-2.9600	58.9800	OCV	0.4	4	100	100	100	100	100	100	1	1
2	Arrange Permits			0	-2.9600	58.9800	OCV	0.3	3	100	100	100	100	100	100	1	1
3	Seafasten substructure grillage		1	0	-2.9600	58.9800	OCV	2.4	24	100	100	100	100	15	20	1	1
4	Seafasten ballast weight grillage		3	0	-2.9600	58.9800	OCV	3.2	32	100	100	100	100	15	20	1	1
5	Lift ballast weights (3x250t to deck)			0	-2.9600	58.9800	OCV	0.4	6	100	100	100	100	15	20	2	1
6	Lift substructure to deck			0	-2.9600	58.9800	OCV	0.6	4	100	100	100	100	15	20	2	1
7	Seafastening			0	-2.9600	58.9800	OCV	0.4	4	100	100	100	100	15	20	2	1
8	Deck inspection			0	-2.9600	58.9800	OCV	0.2	2	100	100	100	100	15	20	2	1
9	DP trials & MMO Clearance			1	-2.8600	59.1600	OCV	0.3	6	4	4	3	3	15	20	2	1
10	Surveyor verify site, set up station			1	-2.8600	59.1600	OCV	0.3	0.1	100	100	100	100	15	20	2	1
11	Lift frame clear of deck			1	-2.8600	59.1600	OCV	0.1	1	2	2	1	1	15	20	2	1
12	Lower to seabed and siting			1	-2.8600	59.1600	OCV	0.1	1	0.5	0.5	1	1	15	20	2	1
13	ROV survey			1	-2.8600	59.1600	OCV	0.025	0.25	0.5	0.5	2	2.5	15	20	2	1
14	recover rigging			1	-2.8600	59.1600	OCV	0.1	1	2	2	2	2	15	20	2	1
15	Rig BW 1			1	-2.8600	59.1600	OCV	0.1	1	2.5	2.5	2	1	15	20	2	1
16	Installl BW 1			1	-2.8600	59.1600	OCV	0.1	1	1.5	1.5	1	1	15	20	2	1
17	Rig BW2			1	-2.8600	59.1600	OCV	0.1	1	2.5	2.5	2	2	15	20	2	1
18	Install BW 2			1	-2.8600	59.1600	OCV	0.1	1	1.5	1.5	1	1	15	20	2	1
19	Rig BW 3			1	-2.8600	59.1600	OCV	0.1	1	2.5	2.5	2	2	15	20	2	1
20	Install BW3			1	-2.8600	59.1600	OCV	0.1	1	1.5	1.5	1	1	15	20	2	1
21	ROV survey			1	-2.8600	59.1600	OCV	0.05	0.5	0.5	0.5	2	2.5	15	20	2	1

Figure 5-12: Task list inputs – Installation Type A scenarios 1 and 2 (Part 1)

22	Resupply substructure			0	-2.9600	58.9800	OCV	0.4	4	100	100	100	100	15	20	3	5
23	Resupply ballast blocks			0	-2.9600	58.9800	OCV	0.6	6	100	100	100	100	15	20	3	5
24	Seafastening			0	-2.9600	58.9800	OCV	0.4	4	100	100	100	100	15	20	3	5
25	DP trials & MMO Clearance			2	-2.8934	59.1648	OCV	0.1	1	4	4	3	3	15	20	3	5
26	Surveyor verify site, set up station			2	-2.8934	59.1648	OCV	0.01	0.1	100	100	100	100	15	20	3	5
27	Lift frame clear of deck			2	-2.8934	59.1648	OCV	0.1	1	2	2	1	1	15	20	3	5
28	Lower to seabed and siting			2	-2.8934	59.1648	OCV	0.1	1	0.5	0.5	1	1	15	20	3	5
29	ROV survey			2	-2.8934	59.1648	OCV	0.025	0.25	0.5	0.5	2	2.5	15	20	3	5
30	recover rigging			2	-2.8934	59.1648	OCV	0.1	1	2	2	2	2	15	20	3	5
31	Rig BW 1			2	-2.8934	59.1648	OCV	0.1	1	2.5	2.5	2	2	15	20	3	5
32	Installl BW 1			2	-2.8934	59.1648	OCV	0.1	1	1.5	1.5	1	1	15	20	3	5
33	Rig BW2			2	-2.8934	59.1648	OCV	0.1	1	2.5	2.5	2	2	15	20	3	5
34	Install BW 2			2	-2.8934	59.1648	OCV	0.1	1	1.5	1.5	1	1	15	20	3	5
35	Rig BW 3			2	-2.8934	59.1648	OCV	0.1	1	2.5	2.5	2	2	15	20	3	5
36	Install BW3			2	-2.8934	59.1648	OCV	0.1	1	1.5	1.5	1	1	15	20	3	5
37	ROV survey			2	-2.8934	59.1648	OCV	0.05	0.5	0.5	0.5	2	2.5	15	20	3	5
38	Remove substructure deck grillage			0	-2.9600	58.9800	OCV	0.8	8	100	100	100	100	15	20	4	1
39	Remove ballast deck grillage			0	-2.9600	58.9800	OCV	2.5	25	100	100	100	100	15	20	4	1
40	Off Hire Inspection			0	-2.9600	58.9800	OCV	0.1	1	100	100	100	100	100	100	4	1

Figure 5-13: Task list inputs – Installation Type A scenarios 1 & 2 (Part 2)

The Type B installation (Figure 5-14 and Figure 5-15) follows a similar process to the Type A method, beginning with performing some mobilisation tasks to configure the vessel for carrying the foundation structures. In this case the vessel is prepared for only carrying substructures initially, with a reconfiguration taking place part way through the installation process (Task 47). The installation of the substructures in limited as before and all six substructures are installed consecutively (although only the installation of the first is detailed here). In this case shorter ROV inspections occur after these installations and not after the installation of the ballast blocks. As discussed previously, and as can be seen in the task list presented, the installation of these substructures is the most sensitive work and by performing this work first it is thought that it is possible to fully exploit the favourable conditions seen during the neap tides.

Once the substructures are installed the ballast blocks are added, with the vessel returning home to resupply after the installation of six ballast blocks or two substructures. Upon completion of the installation demobilisation tasks occur so that the vessel is returned to its original state and the vessel is then taken off hire.

	Task	Start Date	Follows	Changing Location	Location (East)	Location (North)	Vessel	Durations /hours		Tide Limit /m/s		H_s Limit /m		Wind Limit /m/s	
								Start Up	Task Length	50%	0%	50%	0%	50%	0%
1	Vessel inductions	01/07/2013 09:03		0	-2.9600	58.9800	OCV	0.4	4	100	100	100	100	100	100
2	Arrange Permits			0	-2.9600	58.9800	OCV	0.3	3	100	100	100	100	100	100
3	Install and Seafasten substructure grillages		1	0	-2.9600	58.9800	OCV	2.4	24	100	100	100	100	15	20
4	Lift 2 substructures to deck			0	-2.9600	58.9800	OCV	0.8	8	100	100	100	100	15	20
5	Seafastening			0	-2.9600	58.9800	OCV	0.4	4	100	100	100	100	15	20
6	Deck inspection			0	-2.9600	58.9800	OCV	0.2	2	100	100	100	100	15	20
7	Initial DP trials & MMO Clearance			1	-2.8600	59.1600	OCV	0.6	6	4	4	3	3	15	20
8	Surveyor verify site, set up station			1	-2.8600	59.1600	OCV	0.01	0.01	100	100	100	100	15	20
9	Lift frame clear of deck			1	-2.8600	59.1600	OCV	0.1	1	2	2	1	1	15	20
10	Lower to seabed and siting			1	-2.8600	59.1600	OCV	0.1	1	0.5	0.5	1	1	15	20
11	ROV survey			1	-2.8600	59.1600	OCV	0.025	0.25	0.5	0.5	2	2.5	15	20
12	recover rigging			1	-2.8600	59.1600	OCV	0.1	1	2	2	2	2	15	20
13	DP trials & MMO Clearance			0	-2.9600	58.9800	OCV	0.1	1	4	4	3	3	15	20
14	Surveyor verify site, set up station			0	-2.9600	58.9800	OCV	0.01	0.01	100	100	100	100	15	20
15	Lift frame clear of deck			2	-2.8934	59.1648	OCV	0.1	1	2	2	1	1	15	20
16	Lower to seabed and siting			2	-2.8934	59.1648	OCV	0.1	1	0.5	0.5	1	1	15	20
17	ROV survey			2	-2.8934	59.1648	OCV	0.025	0.25	0.5	0.5	2	2.5	15	20
18	recover rigging			2	-2.8934	59.1648	OCV	0.1	1	2	2	2	2	15	20

Figure 5-14: Task list inputs – Installation Type B scenarios 1 & 2 (Part 1)

47	Prepare vessel for ballast weights			0	-2.9600	58.9800	OCV	1.2	12	100	100	100	100	15	20
48	Load 6 ballast blocks			0	-2.9600	58.9800	OCV	1.2	12	100	100	100	100	15	20
49	Seafastening blocks			0	-2.9600	58.9800	OCV	0.4	4	100	100	100	100	15	20
50	DP trials & MMO Clearance			1	-2.8600	59.1600	OCV	0.1	1	4	4	3	3	15	20
51	Surveyor verify site, set up station			1	-2.8600	59.1600	OCV	0.01	0.01	100	100	100	100	15	20
52	Rig BW 1			1	-2.8600	59.1600	OCV	0.1	1	2.5	2.5	2	2	15	20
53	Installl BW 1			1	-2.8600	59.1600	OCV	0.1	1	1.5	1.5	1	1	15	20
54	Rig BW2			1	-2.8600	59.1600	OCV	0.1	1	2.5	2.5	2	2	15	20
55	Install BW 2			1	-2.8600	59.1600	OCV	0.1	1	1.5	1.5	1	1	15	20
56	Rig BW 3			1	-2.8600	59.1600	OCV	0.1	1	2.5	2.5	2	2	15	20
57	Install BW3			1	-2.8600	59.1600	OCV	0.1	1	1.5	1.5	1	1	15	20
58	DP trials & MMO Clearance			0	-2.9600	58.9800	OCV	0.1	1	4	4	3	4	15	20
59	Surveyor verify site, set up station			0	-2.9600	58.9800	OCV	0.01	0.01	100	100	100	100	15	20
60	Rig BW 1			2	-2.8934	59.1648	OCV	0.1	1	2.5	2.5	2	2	15	20
61	Installl BW 1			2	-2.8934	59.1648	OCV	0.1	1	1.5	1.5	1	1	15	20
62	Rig BW2			2	-2.8934	59.1648	OCV	0.1	1	2.5	2.5	2	2	15	20
63	Install BW 2			2	-2.8934	59.1648	OCV	0.1	1	1.5	1.5	1	1	15	20
64	Rig BW 3			2	-2.8934	59.1648	OCV	0.1	1	2.5	2.5	2	2	15	20
65	Install BW3			2	-2.8934	59.1648	OCV	0.1	1	1.5	1.5	1	1	15	20
102	Remove ballast deck grillage			0	-2.8654	59.1877	OCV	2.4	24	100	100	100	100	15	20
103	Off Hire Inspection			0	-2.8654	59.1877	OCV	0.1	1	100	100	100	100	100	100

Figure 5-15: Task list inputs – Installation Type B scenarios 1 & 2 (Part 2)

5.2.2 Scenario 2

In scenario 2 the vessel specification is re-scoped as defined in Figure 5-16. The only change made is to set the tide station keeping limit to 100m/s, this value, which will never be exceeded, essentially removes this limitation and allows the vessel to be on site throughout the entire tidal cycle. Now storms, in terms of whether the vessel can hold station, are determined only by wind and wave conditions giving the capability to potentially (task dependant) access a larger number of slack water periods. Incidentally the storm length threshold has been increased to 3 hours to achieve realistic behaviour in terms of leaving site. This vessel behaviour is considered to replicate a vessel being in one of two at site cases depending on the task limits applied. The vessel may be considered to be:

1) At site, not working due to task limits being exceeded;

2a) At site, working on tasks with generous limits (i.e. holding an approximate station whilst rigging for a lift);

2b) At site, working on tasks with strict limits (i.e. holding a specific station whilst performing a lift).

The scenario 2 analysis task lists are identical to the scenario 1 task lists with regard to individual activities durations and limits.

Vessel Name	OCV			
Crew team	18			
Day Rate	£75,000			
Standby Rate	£75,000			
Overnight fees /person	£150			
Port Fees /trip	£5,000			
Station Keeping Limits	Tide /m/s	H_s /m	Wind /m/s	
	100	2	15	
Hook Up	Duration	Threshold		
		Tide /m/s	H_s /m	Wind /m/s
αvs	0.5	2	1.5	12
βvs	0.5	2	1.5	12
αvp	1			
βvs	1			
Transiting	H_s /m	Speed /m/s		
	1	6		
	5	6		

Figure 5-16: Vessel input – scenario 2

5.2.3 Scenario 3

One potential area for increased performance is the resupply of the OCV. At present this vessel performs a short transit back to port, resupplies and returns to site. A potentially preferable working method is to resupply the OCV at site. To achieve this a “Barge and Tug” vessel is used, this has the properties shown in Figure 5-17. This vessel, which has no additional crew, has a day rate of £1000 and station keeping limits which match the OCV. The hook up limits are similar and slightly more favourable than those applied to the OCV and the unhook limits are more generous, it being considered that the barge leaving an alongside position is easier than entering it.

Vessel Name	**Barge and Tug**			
Crew team	**0**			
Day Rate	**£1,000**			
Standby Rate	**£1,000**			
Overnight fees /person	**£0**			
Port Fees /trip	**£100**			
Station Keeping Limits	**Tide /m/s**	**H_s /m**	**Wind /m/s**	
	100	**2**	**15**	
Hook Up	**Duration**	**Threshold**		
		Tide /m/s	**H_s /m**	**Wind /m/s**
αvs	**0.25**	**2.5**	**1.5**	**15**
βvs	**0.25**	**3**	**2**	**20**
αvp	**0.25**			
βvs	**0.25**			
Transiting	**H_s /m**	**Speed /m/s**		
	1	**4**		
	5	**4**		

Figure 5-17: Additional vessel input – scenario 3

The modified Type B task list is represented in Figure 5-18 and Figure 5-19. The bulk of the tasks are as previously, however there is now no requirement for the OCV to return to port to resupply, this now being performed at site in Tasks 19 and 64 by both the OCV and the barge and tug. This task utilizes multiple vessel and the barge is forced home upon completion of the job so that it may collect further supplies. The in port tasks of the barge are not modelled, there being sufficient time for their completion between trips to site (as seen during the mobilisation tasks) although it is not overly complex to add these.

The barge and tug is considered to be on hire from the start of its first resupply operation through to the end of its last, when it returns to port. The resupply operation is now marginally longer than previously given that this operation now occurs at sea and is therefore slightly more challenging than in scenario 2.

Finally the barge is considered to be capable of carrying sufficient supplies to allow the installation to progress as before (2 substructures or six ballast blocks are installed between resupplies).

	Task	Start Date	Follows	Changing Location	Location (East)	Location (North)	Vessel	Return Home	Durations /hours		Tide Limit /m/s		H_s Limit /m		Wind Limit /m/s	
									Start Up	Task Length	50%	0%	50%	0%	50%	0%
1	Vessel inductions	01/07/2013 09:03		0	-2.9600	58.9800	OCV	-	0.4	4	100	100	100	100	100	100
2	Arrange Permits			0	-2.9600	58.9800	OCV	-	0.3	3	100	100	100	100	100	100
3	Install and Seafasten substructure grillages		2	0	-2.9600	58.9800	OCV	-	2.4	24	100	100	100	100	15	20
4	Lift substructure to deck			0	-2.9600	58.9800	OCV	-	0.8	8	100	100	100	100	15	20
5	Seafastening			0	-2.9600	58.9800	OCV	-	0.4	4	100	100	100	100	15	50
6	Deck inspection			0	-2.9600	58.9800	OCV	-	0.2	2	100	100	100	100	15	20
7	Initial DP trials & MMO Clearance			1	-2.8600	59.1600	OCV	-	0.6	6	4	4	3	3	15	20
8	Surveyor verify site, set up station			1	-2.8600	59.1600	OCV	-	0.01	0.01	100	100	100	100	15	20
9	Lift frame clear of deck			1	-2.8600	59.1600	OCV	-	0.1	1	2	2	1	1	15	20
10	Lower to seabed and siting			1	-2.8600	59.1600	OCV	-	0.1	1	0.5	0.5	1	1	15	20
11	ROV survey			1	-2.8600	59.1600	OCV	-	0.025	0.25	0.5	0.5	2	2.5	15	20
12	recover rigging			1	-2.8600	59.1600	OCV	-	0.1	1	2	2	2	2	15	20
13	DP trials & MMO Clearance			2	-2.8934	59.1648	OCV	-	0.1	1	4	4	3	3	15	20
14	Surveyor verify site, set up station			2	-2.8934	59.1648	OCV	-	0.01	0.01	100	100	100	100	15	20
15	Lift frame clear of deck			2	-2.8934	59.1648	OCV	-	0.1	1	2	2	1	1	15	20
16	Lower to seabed and siting			2	-2.8934	59.1648	OCV	-	0.1	1	0.5	0.5	1	1	15	20
17	ROV survey			2	-2.8934	59.1648	OCV	-	0.025	0.25	0.5	0.5	2	2.5	15	20
18	recover rigging			2	-2.8934	59.1648	OCV	-	0.1	1	2	2	2	2	15	20
19	Resupply Installation Vessel			2	-2.8934	59.1648	OCV, Barge	Barge	1	10	2.5	2.5	3	3	15	20

Figure 5-18: Task list inputs – Installation Type B scenario 3 (Part 1)

↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
45	Prepare vessel for ballast weights			0	-2.9600	58.9800	OCV	-	1.2	12	100	100	100	100	15	20
46	Load ballast blocks			0	-2.9600	58.9800	OCV	-	1.2	12	100	100	100	100	15	20
47	Seafastening blocks			0	-2.9600	58.9800	OCV	-	0.4	4	100	100	100	100	15	20
48	DP trials & MMO Clearance			1	-2.8600	59.1600	OCV	-	0.1	1	4	4	3	3	15	20
49	Surveyor verify site, set up station			1	-2.8600	59.1600	OCV	-	0.01	0.01	100	100	100	100	15	20
50	Rig BW 1			1	-2.8600	59.1600	OCV	-	0.1	1	2.5	2.5	2	2	15	20
51	Installl BW 1			1	-2.8600	59.1600	OCV	-	0.1	1	1.5	1.5	1	1	15	20
52	Rig BW2			1	-2.8600	59.1600	OCV	-	0.1	1	2.5	2.5	2	2	15	20
53	Install BW 2			1	-2.8600	59.1600	OCV	-	0.1	1	1.5	1.5	1	1	15	20
54	Rig BW 3			1	-2.8600	59.1600	OCV	-	0.1	1	2.5	2.5	2	2	15	20
55	Install BW3			1	-2.8600	59.1600	OCV	-	0.1	1	1.5	1.5	1	1	15	20
56	DP trials & MMO Clearance			2	-2.8934	59.1648	OCV	-	0.1	1	4	4	3	4	15	20
57	Surveyor verify site, set up station			2	-2.8934	59.1648	OCV	-	0.01	0.01	100	100	100	100	15	20
58	Rig BW 1			2	-2.8934	59.1648	OCV	-	0.1	1	2.5	2.5	2	2	15	20
59	Installl BW 1			2	-2.8934	59.1648	OCV	-	0.1	1	1.5	1.5	1	1	15	20
60	Rig BW2			2	-2.8934	59.1648	OCV	-	0.1	1	2.5	2.5	2	2	15	20
61	Install BW 2			2	-2.8934	59.1648	OCV	-	0.1	1	1.5	1.5	1	1	15	20
62	Rig BW 3			2	-2.8934	59.1648	OCV	-	0.1	1	2.5	2.5	2	2	15	20
63	Install BW3			2	-2.8934	59.1648	OCV	-	0.1	1	1.5	1.5	1	1	15	20
64	Resupply Installation Vessel			2	-2.8934	59.1648	OCV, Barge	Barge	1.4	14	2.5	2.5	3	3	15	20
↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
98	Remove ballast deck grillage			0	-2.8654	59.1877	OCV	-	2.4	24	100	100	100	100	15	20
99	Off Hire Inspection			0	-2.8654	59.1877	OCV	-	0.1	1	100	100	100	100	100	100

Figure 5-19: Task list inputs – Installation Type B scenario 3 (Part 2)

5.2.4 Scenario 4

An additional consideration which may be made is the installation of the foundation units with a custom vessel. As introduced previously the Mojo Maritime HF4 is ‘an efficient and economic, fit for purpose installation vessel for tidal stream energy converters. The vessel has good dynamic positioning capabilities for operation in strong tidal currents thus broadening the operational window. […] A key criterion throughout the design process is minimizing the cost of the vessel to tidal turbine site developers.’ (Nicholls-Lee *et al.*, 2013). This vessel has been specified as outlined in Figure 5-20. Here the tidal limit is set to 100m/s again effectively removing this limitations (this is a fair reflection on the magnitude of the currents seen at the EMEC site and the capabilities of the HF4, these being 3.5m/s and 5m/s respectively). The wave height and wind speed limits are increased compared to the generously specified DP OCV and the hook up capabilities are greater. This is of particular use when considering the engaging of DP systems in a tidal race.

The crew team required to work from this vessel is reduced given the greater capabilities of the HF4 and the day rate is reduced due to the cost saving measures incorporated in the design.

The metocean limits applied to all tasks have been increased, expanding the working window of the HF4 relative to the DP OCV. The justification for this is twofold, firstly, the HF4 is more able to hold station, providing a more stable platform for the execution of work. Secondly, the HF4 is custom fitted for the installation of this type of tidal energy foundation and its A-frame and crane are extremely fit for purpose, resulting in the ability to work in larger tidal currents, wave heights and wind speeds. The increase in limits has been take as an additional 30% and can be seen in Figure 5-21 to Figure 5-24.

Vessel Name	**HF4**			
Crew team	**15**			
Day Rate	**£45,000**			
Standby Rate	**£45,000**			
Overnight fees /person	**£150**			
Port Fees /trip	**£3,000**			
Station Keeping Limits	**Tide /m/s**	**H_s /m**	**Wind /m/s**	
	100	**3**	**20**	
Hook Up	**Duration**	**Threshold**		
		Tide /m/s	**H_s /m**	**Wind /m/s**
αvs	**0.25**	**3**	**2**	**15**
βvs	**0.25**	**3**	**2**	**15**
αvp	**0.5**			
βvs	**0.5**			
Transiting	**H_s /m**	**Speed /m/s**		
	1	**5**		
	5	**5**		

Figure 5-20: Additional vessel input – Phase 4

	Task	Start Date	Follows	Changing Location	Location (East)	Location (North)	Vessel	Durations /hours		Tide Limit /m/s		H_s Limit /m		Wind Limit /m/s	
								Start Up	Task Length	50%	0%	50%	0%	50%	0%
1	Vessel inductions	01/07/2013 09:03		0	-2.9600	58.9800	HF4	0.4	4	100	100	100	100	100	100
2	Arrange Permits			0	-2.9600	58.9800	HF4	0.3	3	100	100	100	100	100	100
3	Install and Seafasten substructure grillages		1	0	-2.9600	58.9800	HF4	2.4	24	100	100	100	100	19.5	26
4	Lift 2 substructures to deck			0	-2.9600	58.9800	HF4	0.8	8	100	100	100	100	19.5	26
5	Seafastening			0	-2.9600	58.9800	HF4	0.4	4	100	100	100	100	19.5	26
6	Deck inspection			0	-2.9600	58.9800	HF4	0.2	2	100	100	100	100	19.5	26
7	Initial DP trials & MMO Clearance			1	-2.8600	59.1600	HF4	0.6	6	5.2	5.2	3.9	3.9	19.5	26
8	Surveyor verify site, set up station			1	-2.8600	59.1600	HF4	0.01	0.01	100	100	100	100	19.5	26
9	Lift frame clear of deck			1	-2.8600	59.1600	HF4	0.1	1	2.6	2.6	1.3	1.3	19.5	26
10	Lower to seabed and siting			1	-2.8600	59.1600	HF4	0.1	1	0.65	0.65	1.3	1.3	19.5	26
11	ROV survey			1	-2.8600	59.1600	HF4	0.025	0.25	0.65	0.65	2.6	3.25	19.5	26
12	recover rigging			1	-2.8600	59.1600	HF4	0.1	1	2.6	2.6	2.6	2.6	19.5	26
13	DP trials & MMO Clearance			0	-2.9600	58.9800	HF4	0.1	1	5.2	5.2	3.9	3.9	19.5	26
14	Surveyor verify site, set up station			0	-2.9600	58.9800	HF4	0.01	0.01	100	100	100	100	19.5	26
15	Lift frame clear of deck			2	-2.8934	59.1648	HF4	0.1	1	2.6	2.6	1.3	1.3	19.5	26
16	Lower to seabed and siting			2	-2.8934	59.1648	HF4	0.1	1	0.65	0.65	1.3	1.3	19.5	26
17	ROV survey			2	-2.8934	59.1648	HF4	0.025	0.25	0.65	0.65	2.6	3.25	19.5	26
18	recover rigging			2	-2.8934	59.1648	HF4	0.1	1	2.6	2.6	2.6	2.6	19.5	26

Figure 5-21: Task list inputs – Installation Type B scenario 4, without barge resupply (Part 1)

47	Prepare vessel for ballast weights			0	-2.9600	58.9800	HF4	1.2	12	100	100	100	100	19.5	26
48	Load 6 ballast blocks			0	-2.9600	58.9800	HF4	1.2	12	100	100	100	100	19.5	26
49	Seafastening blocks			0	-2.9600	58.9800	HF4	0.4	4	100	100	100	100	19.5	26
50	DP trials & MMO Clearance			1	-2.8600	59.1600	HF4	0.1	1	5.2	5.2	3.9	3.9	19.5	26
51	Surveyor verify site, set up station			1	-2.8600	59.1600	HF4	0.01	0.01	100	100	100	100	19.5	26
52	Rig BW 1			1	-2.8600	59.1600	HF4	0.1	1	3.25	3.25	2.6	2.6	19.5	26
53	Installl BW 1			1	-2.8600	59.1600	HF4	0.1	1	1.95	1.95	1.3	1.3	19.5	26
54	Rig BW2			1	-2.8600	59.1600	HF4	0.1	1	3.25	3.25	2.6	2.6	19.5	26
55	Install BW 2			1	-2.8600	59.1600	HF4	0.1	1	1.95	1.95	1.3	1.3	19.5	26
56	Rig BW 3			1	-2.8600	59.1600	HF4	0.1	1	3.25	3.25	2.6	2.6	19.5	26
57	Install BW3			1	-2.8600	59.1600	HF4	0.1	1	1.95	1.95	1.3	1.3	19.5	26
58	DP trials & MMO Clearance			0	-2.9600	58.9800	HF4	0.1	1	5.2	5.2	3.9	5.2	19.5	26
59	Surveyor verify site, set up station			0	-2.9600	58.9800	HF4	0.01	0.01	100	100	100	100	19.5	26
60	Rig BW 1			2	-2.8934	59.1648	HF4	0.1	1	3.25	3.25	2.6	2.6	19.5	26
61	Installl BW 1			2	-2.8934	59.1648	HF4	0.1	1	1.95	1.95	1.3	1.3	19.5	26
62	Rig BW2			2	-2.8934	59.1648	HF4	0.1	1	3.25	3.25	2.6	2.6	19.5	26
63	Install BW 2			2	-2.8934	59.1648	HF4	0.1	1	1.95	1.95	1.3	1.3	19.5	26
64	Rig BW 3			2	-2.8934	59.1648	HF4	0.1	1	3.25	3.25	2.6	2.6	19.5	26
65	Install BW3			2	-2.8934	59.1648	HF4	0.1	1	1.95	1.95	1.3	1.3	19.5	26
102	Remove ballast deck grillage			0	-2.8654	59.1877	HF4	2.4	24	100	100	100	100	19.5	26
103	Off Hire Inspection			0	-2.8654	59.1877	HF4	0.1	1	100	100	100	100	100	100

Figure 5-22: Task list inputs – Installation Type B scenario 4, without barge resupply (Part 2)

	Task	Start Date	Follows	Changing Location	Location (East)	Location (North)	Vessel	Return Home	Durations /hours		Tide Limit /m/s		H_s Limit /m		Wind Limit /m/s	
									Start Up	Task Length	50%	0%	50%	0%	50%	0%
1	Vessel inductions	01/07/2013 09:03		0	-2.9600	58.9800	HF4	-	0.4	4	100	100	100	100	100	100
2	Arrange Permits			0	-2.9600	58.9800	HF4	-	0.3	3	100	100	100	100	100	100
3	Install and Seafasten substructure grillages		2	0	-2.9600	58.9800	HF4	-	2.4	24	100	100	100	100	19.5	26
4	Lift substructure to deck			0	-2.9600	58.9800	HF4	-	0.8	8	100	100	100	100	19.5	26
5	Seafastening			0	-2.9600	58.9800	HF4	-	0.4	4	100	100	100	100	19.5	65
6	Deck inspection			0	-2.9600	58.9800	HF4	-	0.2	2	100	100	100	100	19.5	26
7	Initial DP trials & MMO Clearance			1	-2.8600	59.1600	HF4	-	0.6	6	5.2	5.2	3.9	3.9	19.5	26
8	Surveyor verify site, set up station			1	-2.8600	59.1600	HF4	-	0.01	0.01	100	100	100	100	19.5	26
9	Lift frame clear of deck			1	-2.8600	59.1600	HF4	-	0.1	1	2.6	2.6	1.3	1.3	19.5	26
10	Lower to seabed and siting			1	-2.8600	59.1600	HF4	-	0.1	1	0.65	0.65	1.3	1.3	19.5	26
11	ROV survey			1	-2.8600	59.1600	HF4	-	0.025	0.25	0.65	0.65	2.6	3.25	19.5	26
12	recover rigging			1	-2.8600	59.1600	HF4	-	0.1	1	2.6	2.6	2.6	2.6	19.5	26
13	DP trials & MMO Clearance			2	-2.8934	59.1648	HF4	-	0.1	1	5.2	5.2	3.9	3.9	19.5	26
14	Surveyor verify site, set up station			2	-2.8934	59.1648	HF4	-	0.01	0.01	100	100	100	100	19.5	26
15	Lift frame clear of deck			2	-2.8934	59.1648	HF4	-	0.1	1	2.6	2.6	1.3	1.3	19.5	26
16	Lower to seabed and siting			2	-2.8934	59.1648	HF4	-	0.1	1	0.65	0.65	1.3	1.3	19.5	26
17	ROV survey			2	-2.8934	59.1648	HF4	-	0.025	0.25	0.65	0.65	2.6	3.25	19.5	26
18	recover rigging			2	-2.8934	59.1648	HF4	-	0.1	1	2.6	2.6	2.6	2.6	19.5	26
19	Resupply Installation Vessel			2	-2.8934	59.1648	HF4, Barge	Barge	1	10	3.25	3.25	3.9	3.9	19.5	26

Figure 5-23: Task list inputs – Installation Type B scenario 4, with barge resupply (Part 1)

↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
45	Prepare vessel for ballast weights			0	-2.9600	58.9800	HF4	-	1.2	12	100	100	100	100	19.5	26
46	Load ballast blocks			0	-2.9600	58.9800	HF4	-	1.2	12	100	100	100	100	19.5	26
47	Seafastening blocks			0	-2.9600	58.9800	HF4	-	0.4	4	100	100	100	100	19.5	26
48	DP trials & MMO Clearance			1	-2.8600	59.1600	HF4	-	0.1	1	5.2	5.2	3.9	3.9	19.5	26
49	Surveyor verify site, set up station			1	-2.8600	59.1600	HF4	-	0.01	0.01	100	100	100	100	19.5	26
50	Rig BW 1			1	-2.8600	59.1600	HF4	-	0.1	1	3.25	3.25	2.6	2.6	19.5	26
51	Installl BW 1			1	-2.8600	59.1600	HF4	-	0.1	1	1.95	1.95	1.3	1.3	19.5	26
52	Rig BW2			1	-2.8600	59.1600	HF4	-	0.1	1	3.25	3.25	2.6	2.6	19.5	26
53	Install BW 2			1	-2.8600	59.1600	HF4	-	0.1	1	1.95	1.95	1.3	1.3	19.5	26
54	Rig BW 3			1	-2.8600	59.1600	HF4	-	0.1	1	3.25	3.25	2.6	2.6	19.5	26
55	Install BW3			1	-2.8600	59.1600	HF4	-	0.1	1	1.95	1.95	1.3	1.3	19.5	26
56	DP trials & MMO Clearance			2	-2.8934	59.1648	HF4	-	0.1	1	5.2	5.2	3.9	5.2	19.5	26
57	Surveyor verify site, set up station			2	-2.8934	59.1648	HF4	-	0.01	0.01	100	100	100	100	19.5	26
58	Rig BW 1			2	-2.8934	59.1648	HF4	-	0.1	1	3.25	3.25	2.6	2.6	19.5	26
59	Installl BW 1			2	-2.8934	59.1648	HF4	-	0.1	1	1.95	1.95	1.3	1.3	19.5	26
60	Rig BW2			2	-2.8934	59.1648	HF4	-	0.1	1	3.25	3.25	2.6	2.6	19.5	26
61	Install BW 2			2	-2.8934	59.1648	HF4	-	0.1	1	1.95	1.95	1.3	1.3	19.5	26
62	Rig BW 3			2	-2.8934	59.1648	HF4	-	0.1	1	3.25	3.25	2.6	2.6	19.5	26
63	Install BW3			2	-2.8934	59.1648	HF4	-	0.1	1	1.95	1.95	1.3	1.3	19.5	26
64	Resupply Installation Vessel			2	-2.8934	59.1648	HF4, Barge	Barge	1.4	14	3.25	3.25	3.9	3.9	19.5	26
↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
98	Remove ballast deck grillage			0	-2.8654	59.1877	HF4	-	2.4	24	100	100	100	100	19.5	26
99	Off Hire Inspection			0	-2.8654	59.1877	HF4	-	0.1	1	100	100	100	100	100	100

Figure 5-24: Task list inputs – Installation Type B scenario 4, with barge resupply (Part 2)

5.3 Results - impact on duration

5.3.1 Scenario 1

Performing the analysis of both Type A and B installations for all 19 years of data, on the start dates presented in the earlier figures produces an array of project durations; these results are presented in Figure 5-25. Here the black bar represents the range of the data and the markers the individual data points (noting that the variation in y-axis distribution is for readability and does not represent any data variation).

Considering these results; firstly, as hypothesised, there are similarities between both methods and the expected disparity between the two is not seen. The Type A installation has a number of outliers which dramatically increase the range of the data, the Type B installation has a single outlier which is similar to the comparable points from the first method.

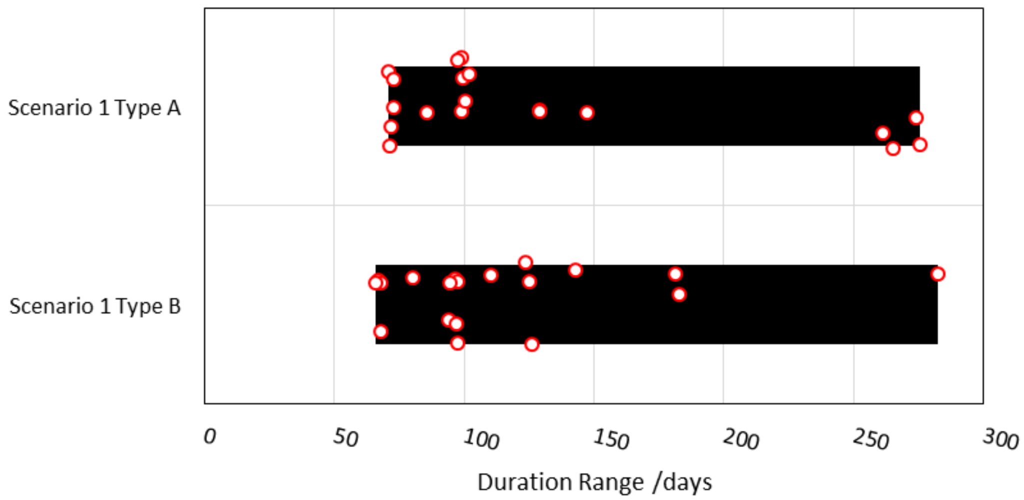


Figure 5-25: Summary results - scenario 1. The black bar represents the range of the data, the individual data points represent the results of one year of analysis.

Presented in Figure 5-26 are the vessel state diagrams for the OCV using both methods in year 5 (this being 1991). The duration of installations are:

- Type A – 71 days 3 hours;
- Type B – 67 days 20 hours.

Also presented in this figure is the tidal current velocity trace for the duration of the longest installation. It can be seen here that these installations take 5 neap tide cycles and that no work is performed on the Type B installation for the second neap tide event, this being a larger neap that those either side. The Type A installation manages a brief amount of work, the majority being in port due to a fortune of scheduling. The wave height and wind speed during this neap tide event are not extreme and that it is therefore the slightly elevated velocity which is to blame for the incurred downtime.

Looking at both installation types it can be seen that the mobilisation tasks ("Start Up In Port" and "Working In Port") are performed without incurring downtime during the execution of the task. It can also be seen that the early downtime incurred is due to a need to wait for a suitable at site window to occur. Whilst it is possible to reduce the mobilisation offset to reduce this period this is perhaps an unrealistic approach. Given that detailed metocean data is held it would be possible to calculate the mobilisation relative to the start of the neap tide event and adjust the start date accordingly. This, however, is not a luxury available to the project manager and it is more realistic to take the conservative approach used here.

During the fourth neap tide the benefit of installing the substructures in the early favourable conditions can be seen as here it is not possible for any work to occur on a Type A installation, due to the sensitive lift operations, whilst installation using the Type B method is able to occur unhindered. It is also possible to observe how the working time associated with the third, fourth and fifth neap is longer when these less sensitive operations occur.

As a final observation the extended in port working due to the reconfiguration of the vessel can be seen and whilst it is unfortunate that during this installation this falls during the later stages of a neap tide (where at site work could be performed) it can also be seen that it is possible to return to site and perform further installation tasks.

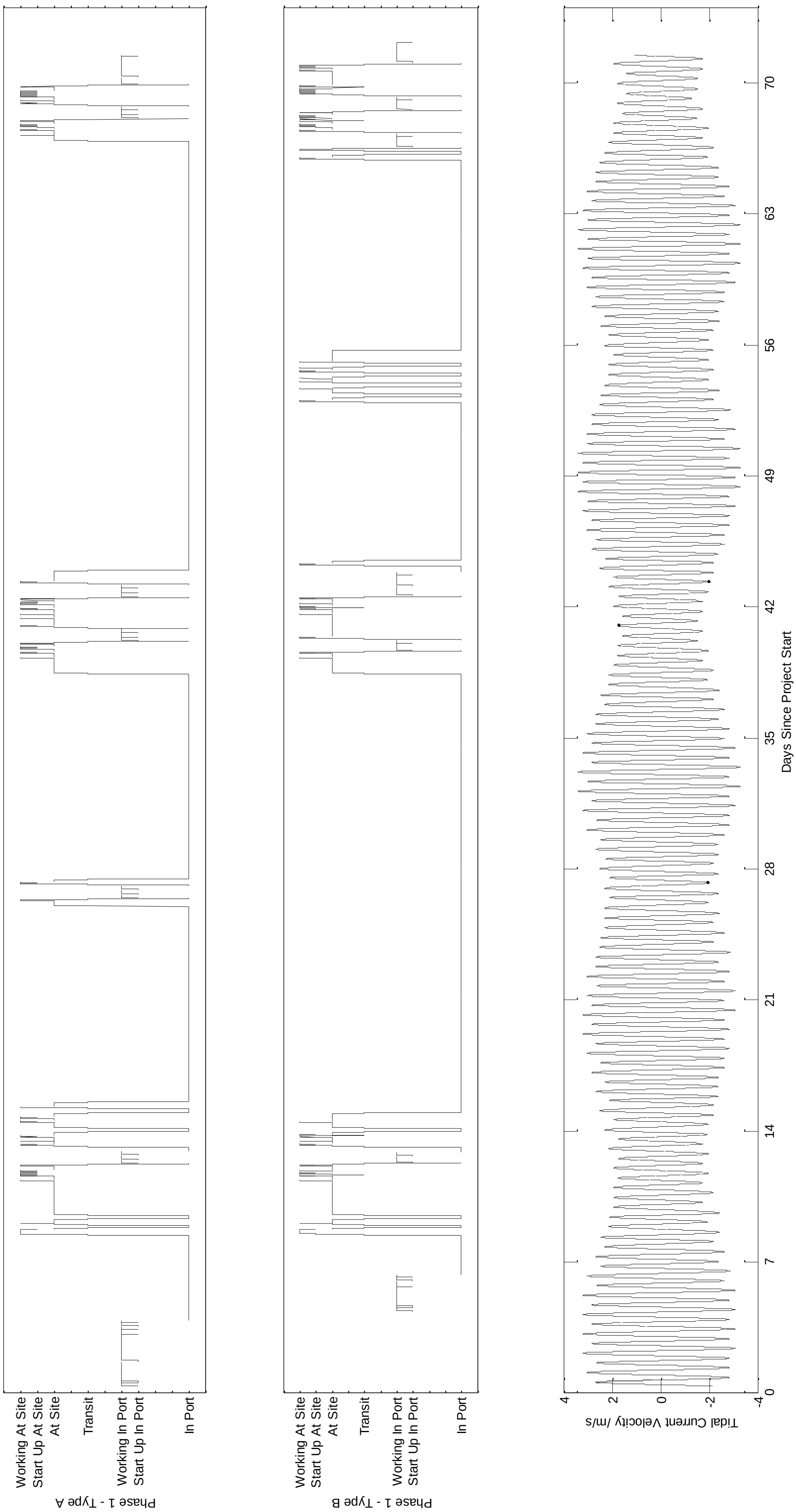


Figure 5-26: Scenario 1 vessel state outputs (year 5) including tidal current velocity at EMEC

Whilst it has been possible to determine a slight preference towards installation Type B it is fair to say that neither of these operations is optimal. Given the range of installation times observed (Type A: 71.11 to 275.44 days at a mean of 132.85 days; Type B: 65.95 to 282.43 days at a mean of 115.86 days) further work is required to obtain an appropriate installation duration. Requiring, at the lower end, some 10 days per foundation (at a vessel day rate cost of £3.75million per foundation) in the best case scenario is unacceptable, hence scenario 2.

5.3.2 Scenario 2

The approach utilized in Scenario 1, the access of site only during neap tide events, is unfavourable. This approach results in large periods of time being automatically written off as downtime and whilst it may be harder to work during spring tides there are still accessible slack water periods.

Again, summary results for this scenario are presented, these being in Figure 5-27. These results are presented alongside the corresponding results from scenario 1 to allow a direct comparison to occur.

The first observation which may be made from the data is that the slack water access approach used here is far superior to the neap tide only interventions utilized previously. The following can be seen:

- Type A: 45 days 13 hours to 89 days 0 hours;
- Type B: 42 days 3 hours to 80 days 22 hours.

In both cases this is a substantial reduction from the previous analysis and whilst these ranges are still reasonably large a greater degree of clustering can be seen with few outliers. This means that greater confidence in the range can be taken, noting that there is still significant variation. The clusters seen in the figures are closely related to the neap tides required to install the foundation structures.

Considering the merits of the two methods, Type A still incurs slightly longer durations and as a result greater costs, however the disparity between the two is small. That said, the shortest four installations, and ten of the shortest twelve are performed using installation Type B; thirteen of the slowest seventeen installations use the Type A method (Figure 5-28).

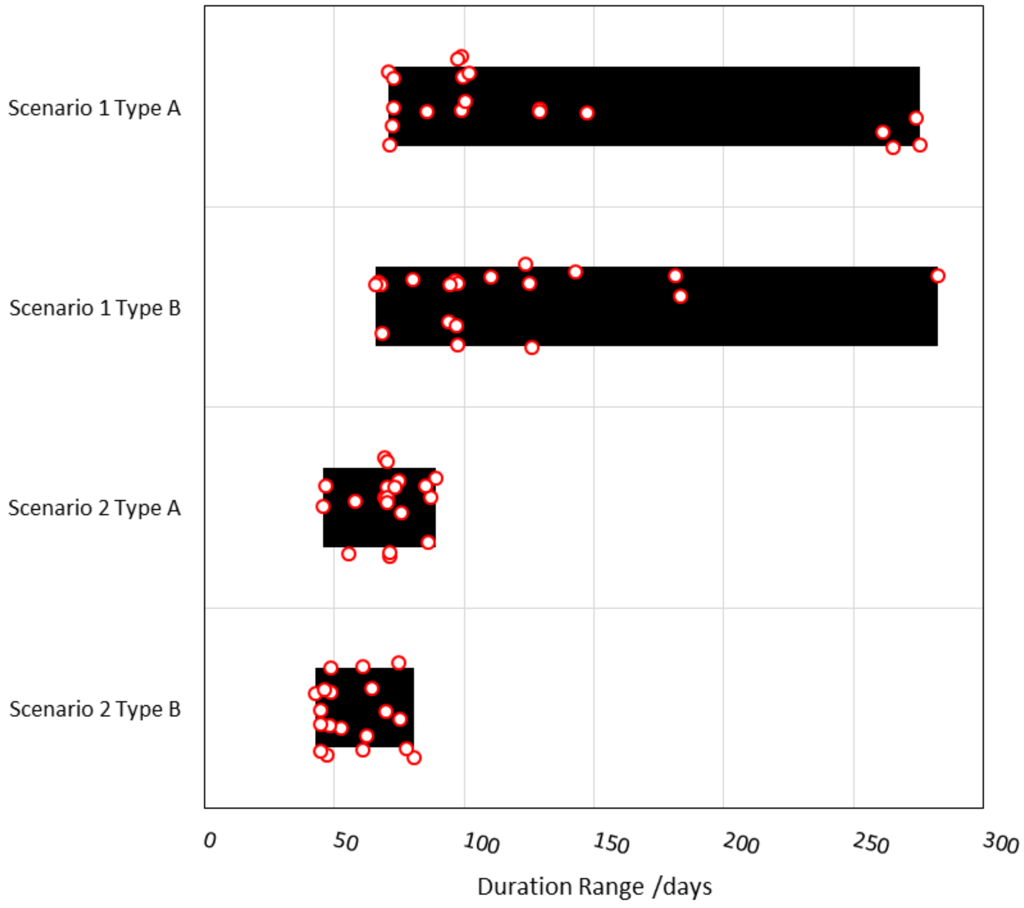


Figure 5-27: Summary results - Comparison between scenario 1 and 2. The black bar represents the range of the data, the individual data points represent the results of one year of analysis.

Rank	Duration /days	Type	Rank	Duration /days	Type
1	42.89	B	20	69.41	A
2	44.65	B	21	70.03	B
3	44.66	B	22	70.29	A
4	44.89	B	23	70.30	A
5	45.55	A	24	70.32	A
6	46.22	B	25	70.36	A
7	46.54	A	26	71.31	A
8	47.01	B	27	71.40	A
9	48.26	B	28	73.49	A
10	48.51	B	29	74.75	A
11	48.56	B	30	74.92	B
12	52.81	B	31	75.18	B
13	55.39	A	32	75.70	A
14	57.93	A	33	77.98	B
15	60.79	B	34	80.92	B
16	60.96	B	35	85.37	A
17	62.25	B	36	86.07	A
18	64.31	B	37	87.17	A
19	69.30	A	38	89.01	A

Figure 5-28: Ranked durations considering installation types

Again the vessel states for year 5 (1991) have been presented and this figure (Figure 5-29) vividly demonstrates the benefit of installing the substructures early on the preferable neap tides targeted for deployment.

This data, presented on the same time axes as Figure 5-26 for ease of comparison, covers five neap tide events and installation Type A requires all of these for a successful deployment to occur, being required to pause and wait for favourable conditions, when a substructure is due to be installed. This essentially rules out spring tide velocities for work and whilst not as poor as the scenario 1 installations this does incur a duration penalty. It should be noted here that waiting at site for such an extended period of time is unrealistic and highly unlikely to occur, especially given the short distance and transit time to port. This is currently a limitation of this analysis approach.

Turning attention to installation Type B, it can be seen that in port mobilisation occur as before with no downtime. The vessel, as in the Type A operation, performed a transit to site immediately as it has few station keeping limitations and hook up is available due to its short duration. DP trials and MMO clearance can occur immediately and then a short period of downtime is incurred, again in both cases, as the current velocity reduces and the neap tide begins. From this point very little downtime is incurred. The vessel is able to install all four of six substructures during the neap tide, installs the remaining two in the next available neap tide and is able to continue the process by installing the less sensitive ballast blocks during the following spring tide slack water events. This significantly reduces the operation duration.

Given the favourable installation durations obtained with the scheduling Type B this led to the Type A installation being rejected for future phases.

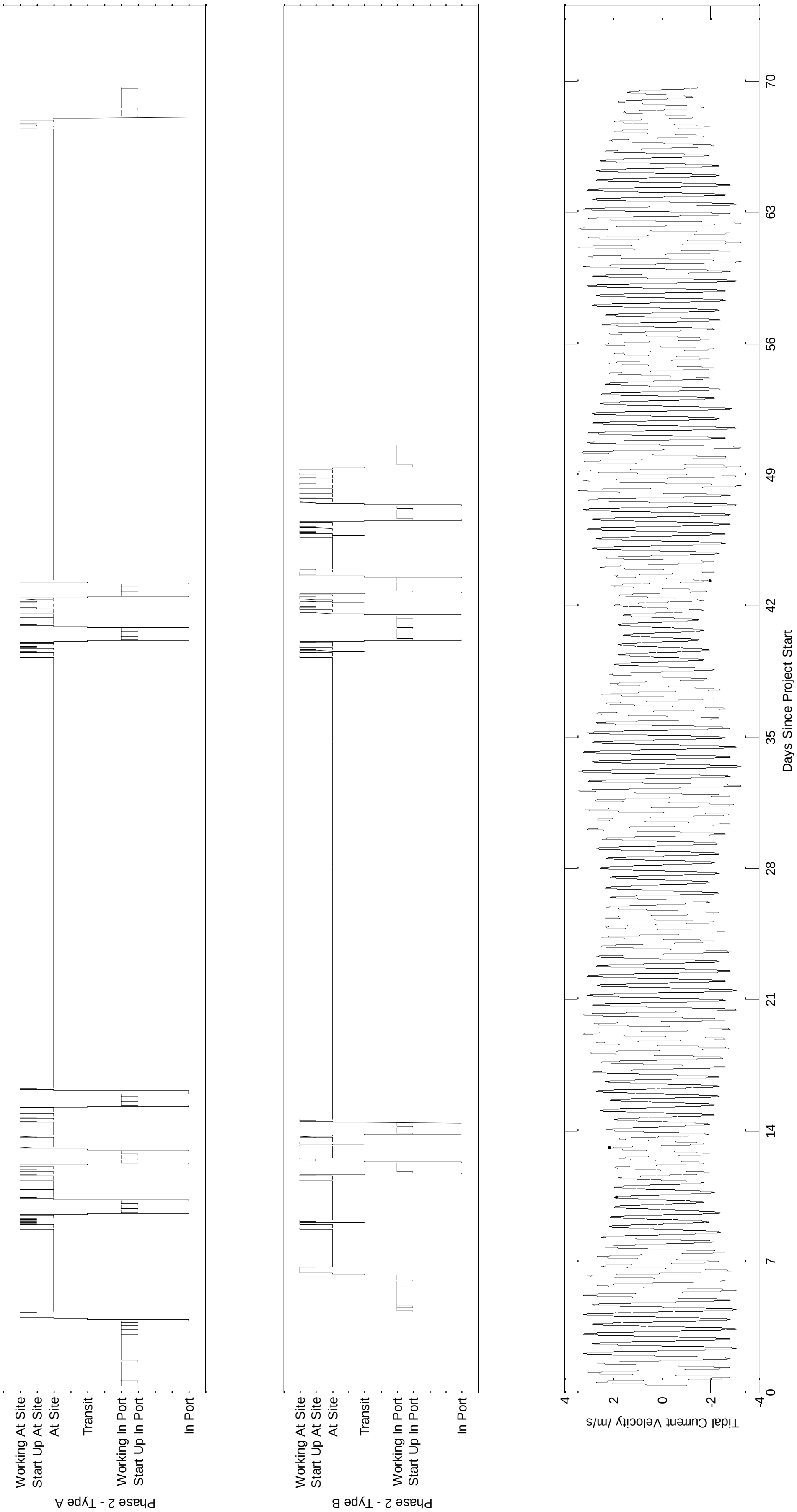


Figure 5-29: Scenario 2 vessel state outputs (year 5) including tidal current velocity at EMEC

5.3.3 Scenario 3

As with the previous scenarios the required installation duration of the project is presented in Figure 5-30. Furthermore, the results of the Type B installation analysed in scenario 2 are presented for comparison.

It can be seen that there is similarity between the two with the use of the barge resulting in a slightly longer operation. Much of the tight clustering, and increased certainty it brings, can still be seen but an extension of the duration is present none the less.

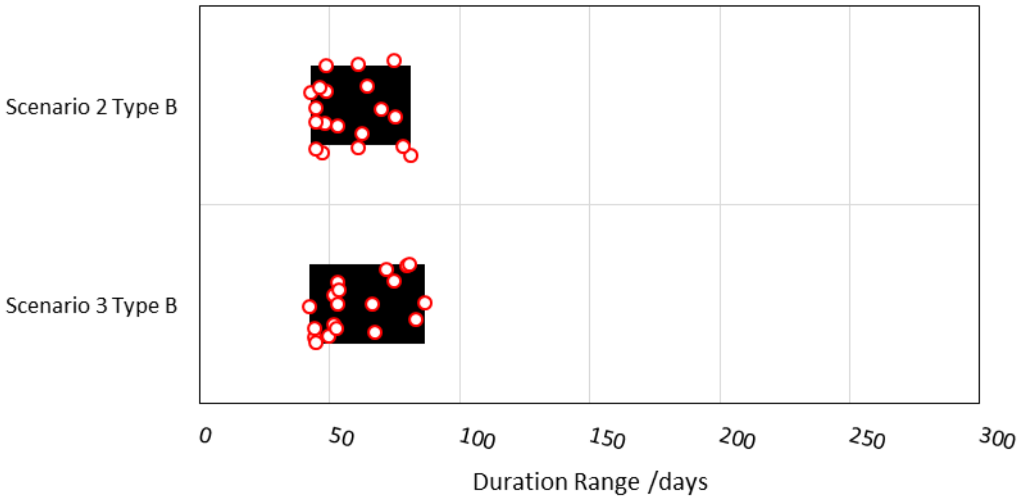


Figure 5-30: Summary results - Comparison between scenario 2 installation Type B and scenario 3. The black bar represents the range of the data, the individual data points represent the results of one year of analysis.

Considering, as with all scenarios, year 5. Generally, year on year there is a duration increase of 5 days as a result of utilising the barge. It is worth noting that, due to the additional OCV day rate and the cost of using the barge, a cost increase of £470,000 is seen (see Section 5.4). This is not an inconsequential figure given that the only change made here was to introduce at site resupply.
Figure 5-31 details the vessel states for both the OCV and the barge through this installation project. Two extended periods of at site downtime can be observed. The first of these occurs immediately after the initial DP trials as seen previously. The second, and longest, period of downtime occurs during the first at site ballast block resupply (the first resupply occurring in port when the OCV is reconfigured for the storage of these blocks). Here performing the transfer of components at site results in some 5 days of downtime, the bulk of the difference between this

and the previous scenarios. This downtime occurs during the later stages of a neap tide and is as a result of an elevated wave height and wind speed.

These durations and costs, which are similar but in excess of the comparative earlier costs are informative. A step which could be realistically expected to improve the operational performance has actually worsened it and whilst the magnitude of this increase may not be a large proportion of the overall project cost many companies in the marine renewable energy sector cannot happily allow £500,000 of capital expenditure to be used.

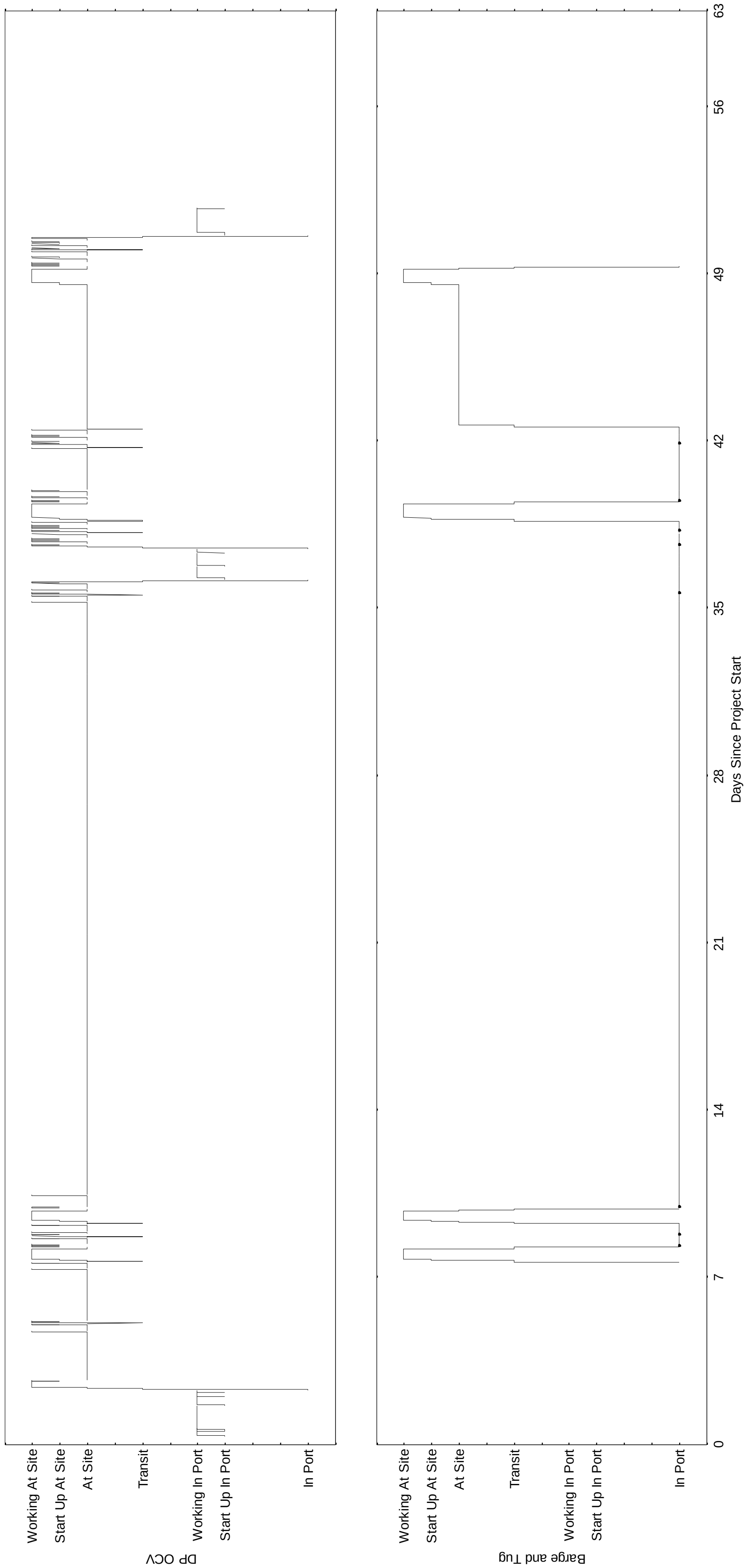


Figure 5-31: Scenario 3 vessel state outputs (year 5)

5.3.4 Scenario 4

The results of this analysis are somewhat startling. It is reasonable to assume that a significant increase in performance would be achieved via the use of this custom vessel, given its specific capabilities for this type of work, however the reduction in installation duration and cost is very large. The results of this installation, using HF4 and HF4 resupplied via a barge, are presented in Figure 5-32 alongside the OCV and OCV and barge results from scenarios 2 and 3. The following key facts regarding duration can be observed:

- OCV: 42 days 21 hours to 89 days 22 hours. Range 38.03 days;
- OCV with Barge: 42 days 3 hours to 86 days 8 hours. Range 44.2 days;
- HF4: 14 days 4 hours to 26 days 1 hours. Range 11.83 days;
- HF4 with Barge: 14 days 4 hours to 24 days 12 hours. Range 10.36 days.

There a large difference between the lower extreme of the OCV installations and the upper extreme of the HF4 durations. The range of installation durations with the HF4 is significantly smaller than any previous installation and allows a much greater confidence to be placed in the budgeting of the installation process. This said, a range of 10 days equates to some £450,000 in day rates and is indicative of the variability seen in the marine energy industry due to the working climate. Naturally the costs seen are less with the HF4 than with the OCV, the reasons for this being that the installation duration is less and the day rate of the custom vessel lower.

Considering the use of a barge alongside the HF4, once again a slight cost and duration difference is seen, however this is a reduction and somewhat minimal. This is likely to result in the decision to use a barge being based on logistical issues such as requirements to return to port for crew changes, refuelling and so on. This is not considered here but is an addition to the analysis which could be performed.

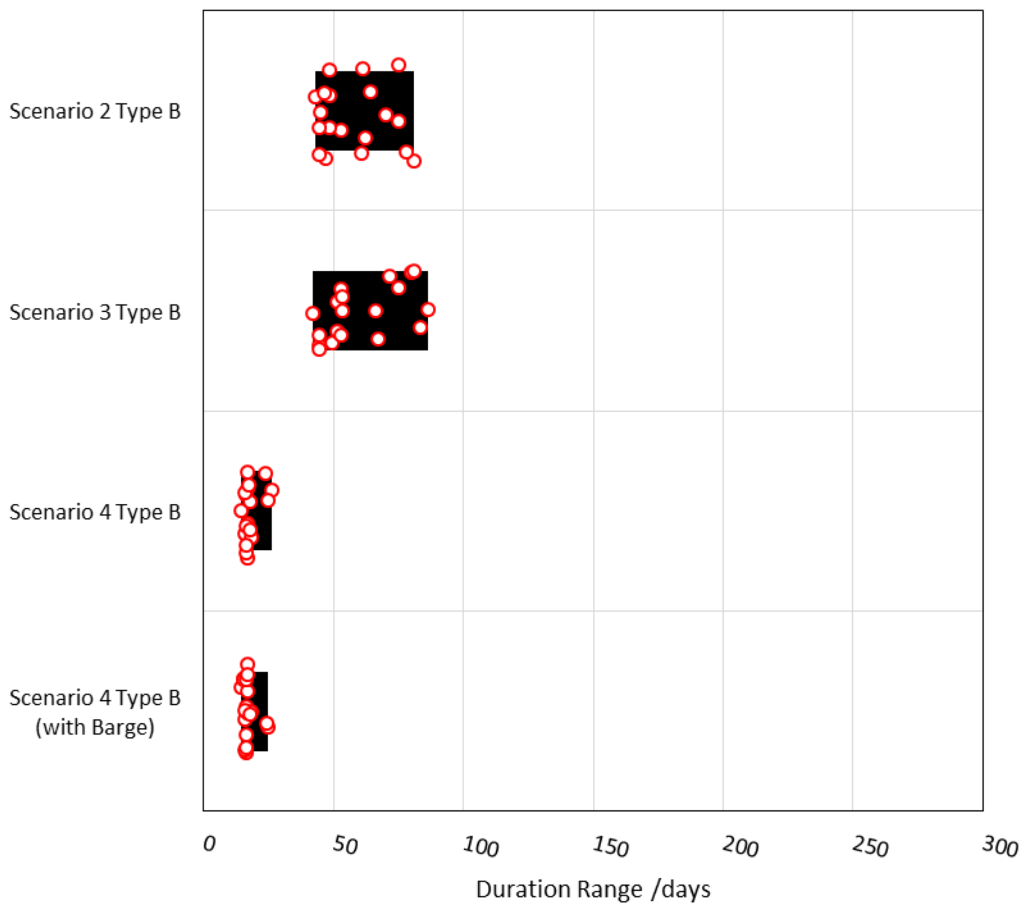


Figure 5-32: Summary results - Comparison between scenario 2 installation Type B and scenario 3 and 4. The black bar represents the range of the data, the individual data points represent the results of one year of analysis.

The vessel states have been included at it is clear that there is limited downtime during the operation (Figure 5-33). Mobilisation occurs efficiently and the vessel moves to site. This results in some downtime while waiting for a suitable tidal current velocity for the installation of the first substructure. From this point on downtime is limited to a few hours whilst awaiting slack water for the installation of additional substructures during the neap tide event. These short downtime periods continue during the installation of ballast blocks during the spring time, whilst waiting for a tidal current velocity of less than 2m/s. The selection of this vessel and this installation method largely desensitises the vessel to the tidal current and additional environmental parameters and ensures an operation which can be completed with a high chance of success. As previously, and more so due to the increase in hook up capabilities, the change location at site and return to port transits are completed efficiently and it can be seen that this is a highly capable installation option.

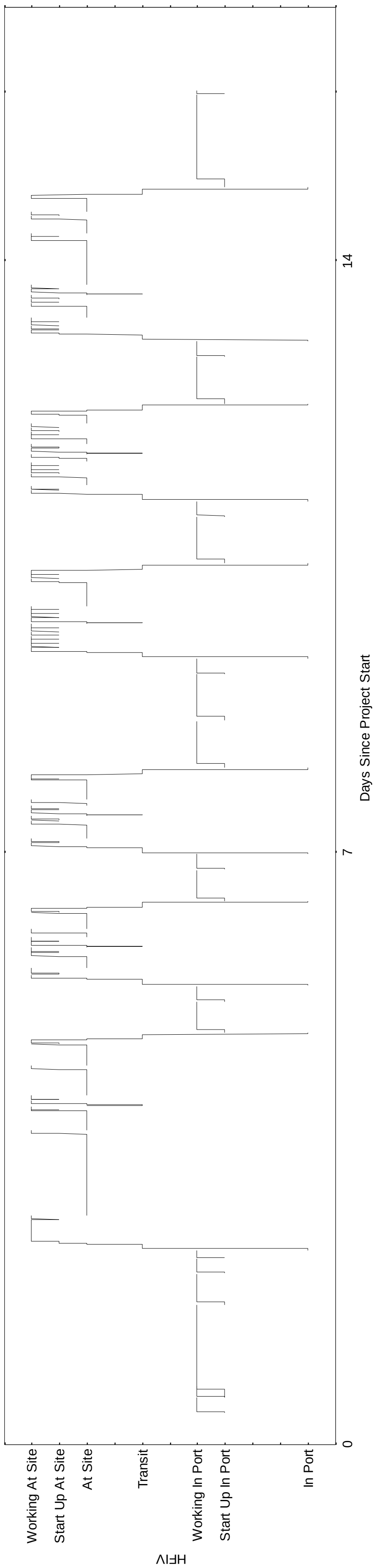


Figure 5-33: Scenario 4 vessel state outputs (year 5)

5.4 Discussion

Figure 5-34 presents an overview of all the analysis scenarios performed. It can be seen that as the process has progressed the duration and installation cost has reduced as inefficient vessels and installation methods are removed, resulting in a preferred option. The analysis presented here is reasonably simplistic and provides an overview of the capabilities of these methods. It can be appreciated that with a number of different foundation types, turbine installation methods, cable routing, ports, vessels and crew capabilities the level of complexity and the number of simulations required to obtain a grasp on the installation cost and duration increases.

The analysis performed has demonstrated a reduction in duration from 282 days, in the extreme worst case, to 14 days, in the extreme best case. A cost reduction of over £20 million occurs between these two and if, perhaps more fairly, consideration is given to the lowest scenario 1, Type B cost against the lowest scenario 4 cost a reduction of £4.4 million is seen. It is reasonable to consider this to be a significant reduction and one which can mean the difference not just between success and failure on an individual project but for a company's financial security as a whole.

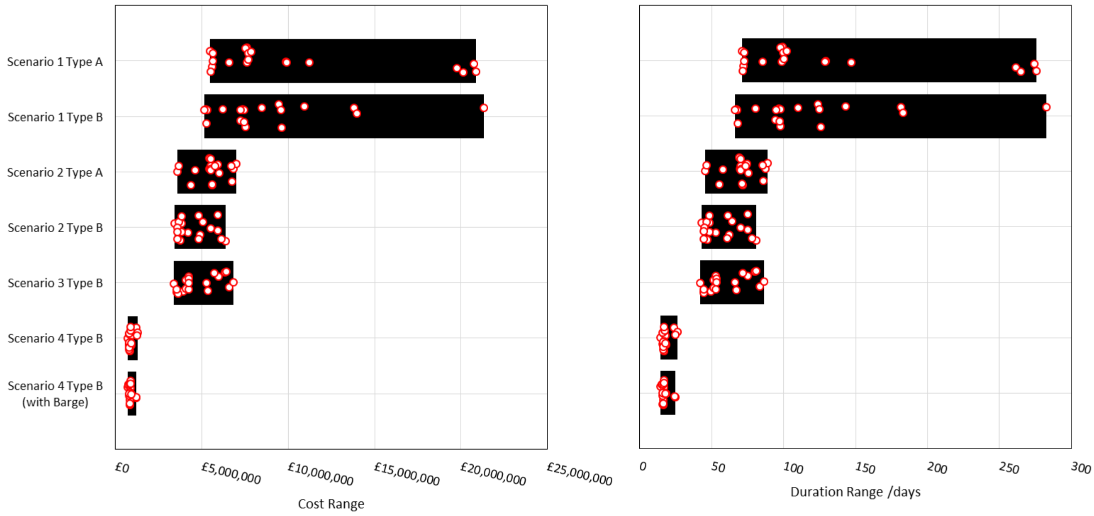


Figure 5-34: Summary results for all scenarios with cost (left) and duration (right). The black bar represents the range of the data, the individual data points represent the results of one year of analysis.

Throughout comment has been made regarding the effect of the tidal current velocity. The effect of waves and wind have been considered to be minimal.

Presented in Figure 5-35 and Figure 5-36 are metocean “barcode” plots which were first introduced in Section 3.4.3. The first of these plots is for the OCV installing during slack water events (scenario 2) using installation Type B. The data is presented for 1991 and relates to the vessel states presented in Figure 5-29. Also indicated in Figure 5-35 is the end point of the HF4 installation shown in Figure 5-36. This latter figure depicts data from scenario 4 (HF4, Slack Water, Type B).

In these plots a green background indicates that hook up, unhook and station keeping are possible. In the upper row, the task limits, the green background indicates that work would be possible if the vessel is in the working location and moored. Red area indicate the inverse.

It can be noted that the wind speed in both of these cases has absolutely no effect on the ability of either vessel to perform work and the wave height effect is limited. This is a reasonably benign site and the limits in these areas are not overly stringent; this is reflected in these outputs.

This means that the majority of downtime is as a direct result of the tidal current velocity and in both cases a reasonable quantity of downtime is seen in the tidal current plots. It can also be seen that the HF4 incurs significantly less downtime than the OCV and that the bulk of this downtime is related to waiting for slack water to execute tasks, rather than as a result of a vessel inability to hold station. There is no vessel station keeping downtime due to the limits being set at 100m/s and the hook up downtime is short in duration and occurs only on the largest spring tide.

Consideration of the vessel state and the prevailing metocean conditions can be highly informative, providing valuable information regarding where to focus optimisation efforts. In this case it can be seen that efforts relating to improved performance in elevated wind speeds would be wasted effort. Instead optimising for tide, as has been done with the HF4, improves the results. It would be possible at this point for the project manager, marine operations personnel or design team to identify that an optimisation of the lift and lower of the substructure would result in gains in terms of cost and duration and that any useful effort should be directed here.

Finally, this, and the previous, analysis inform requirements for further development and the limitations of the methods. In addition these analysis processes also highlight the strengths and benefits of the methods. This is discussed further in Section 6.2.

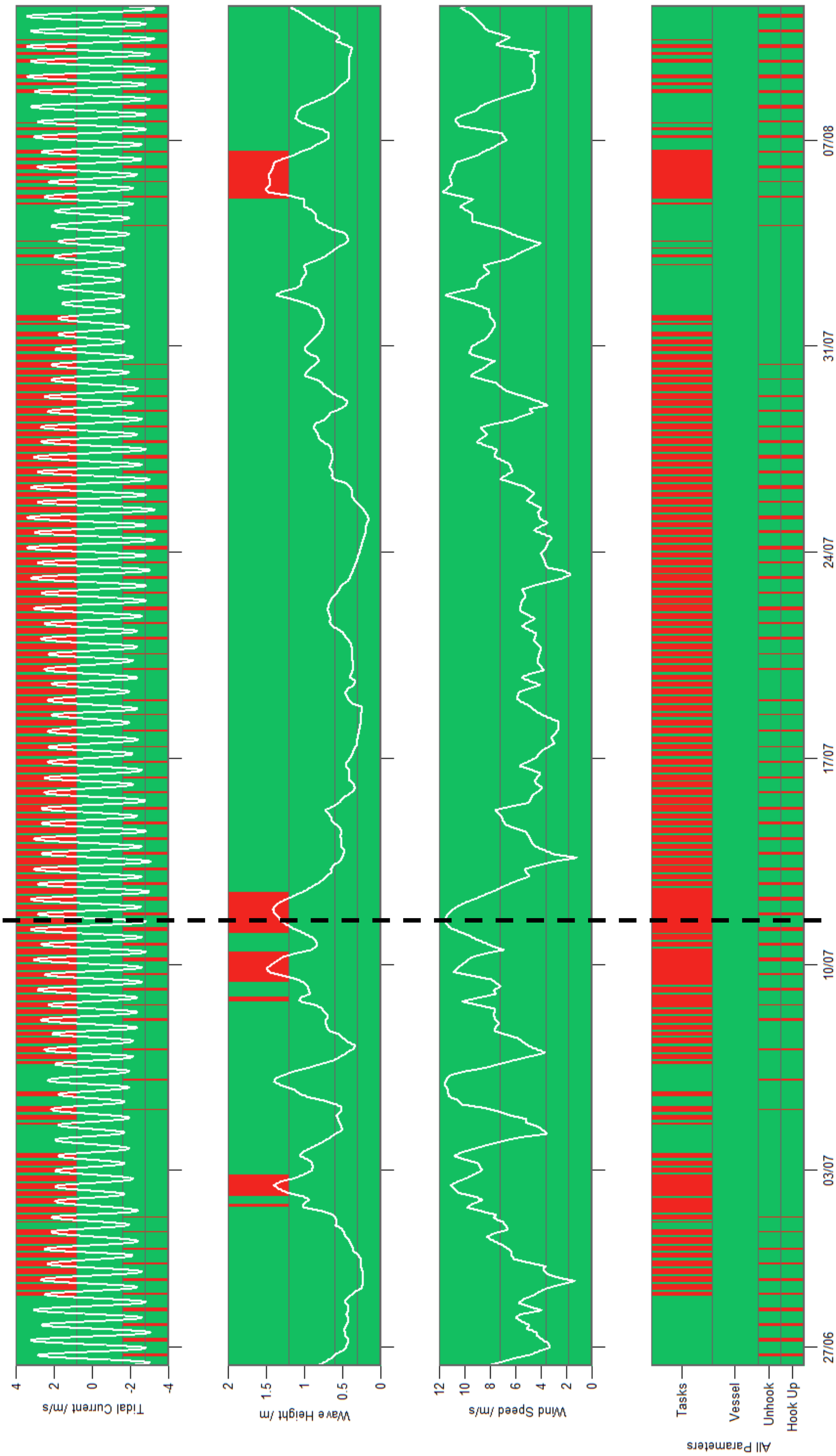


Figure 5-35: Metocean limitations for scenario 2, Type B (Year 5), detailing periods of zero workability

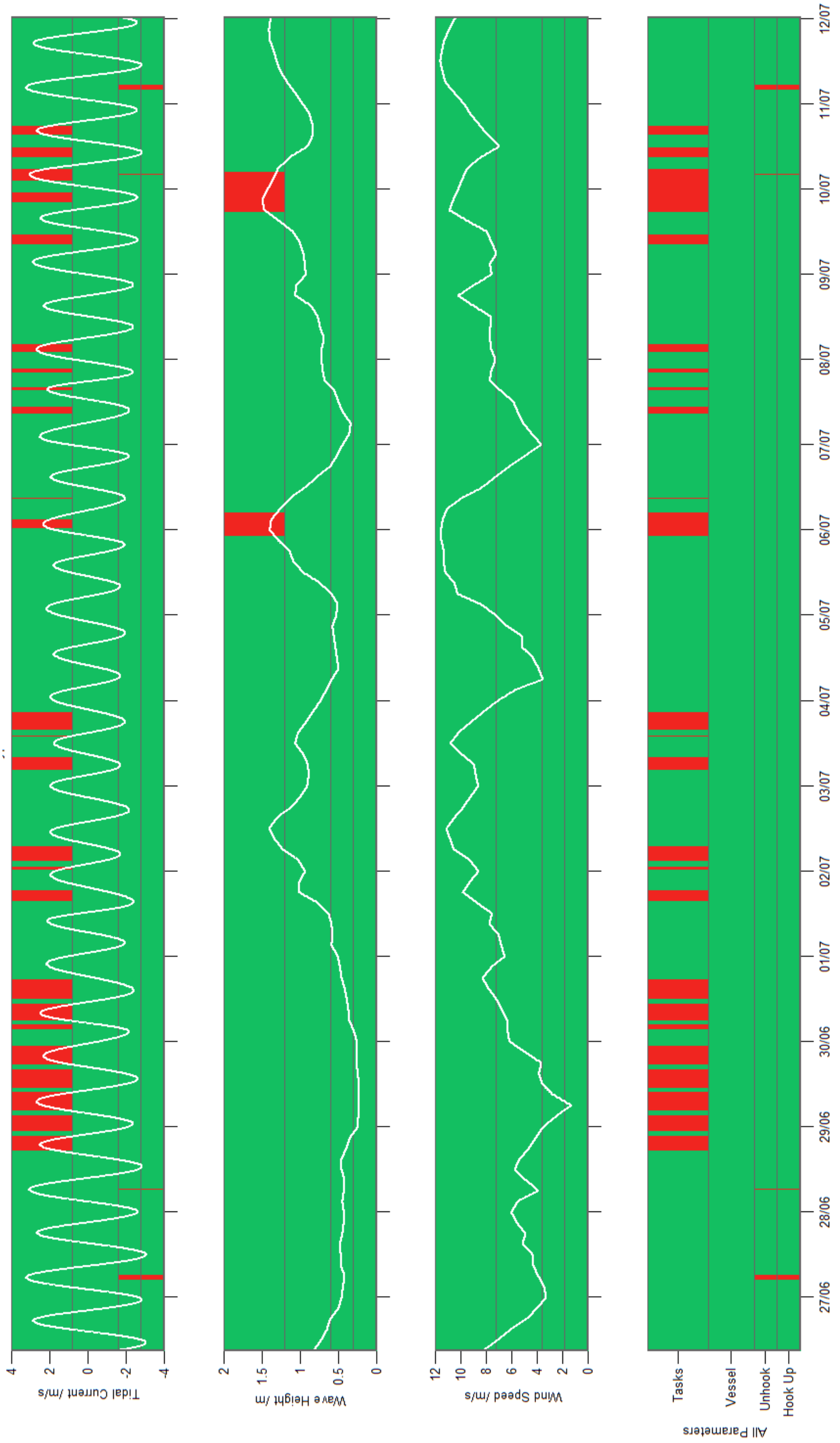


Figure 5-36: Metocean limitations for scenario 4, Type B (Year 5), detailing periods of zero workability

6 Conclusions

A series of methods have been developed, and packaged as a software tool, which allow for the simulation of offshore operations for marine energy devices. These methods achieve the aims and objectives outlined at the start of this thesis (Section 2.1) by determining the downtime incurred during marine energy installation operations and allowing steps to be taken to optimise operations and reduce costs.

In line with objective 4, these methods have already enhanced Mojo Maritime's capabilities and portfolio of services, and have provided assistance to the wider industry. A number of projects have already been performed, or are currently ongoing, which utilize these methods. The majority have been concerned with the selection of appropriate foundation times for marine energy converters or with the optimisation of installation and O&M methods to achieve a cost reduction.

6.1 Original contributions, findings and summary

Two major factors contributing not only to the cost but also at times presenting barriers to the successfully completion of an installation process were identified and recurred throughout this work. These being:

1. The vessel rates (day and standby);
2. The incurred weather downtime.

To some extent these barriers are directly linked. Whilst it is true that high day rates are an obstacle and that they will drive the cost of installation upwards (perhaps to unsustainable levels) it is when weather downtime leads to on hire vessels performing no work that the costs escalates without progress being made that the most severe results occur.

The novel elements of the method developed within this work, which address the barriers to installation, are the analysis of:

- Transit;
- Mooring operations;
- Working efficiency;
- Response to storms and waiting;
- Multiple vessels;
- Simultaneous tasks;

- Geo-spatial diversity.

The first three points above provide the capability to model all phases of an installation operation which is a key requirement of such work. The inclusion of vessel hook up and unhook is a novel feature and crucial to the analysis of certain operations, for example the use of a jack up barge may be limited more by this "getting on station" work than by the tasks performed. By including this analysis in the manner described the accessing and leaving site capabilities are assessed automatically each and every time a vessel moved, this is a benefit of these methods over existing time series analysis processes of this nature.

The combination of a task scheduling tool and time series weather window analysis in beneficial in answering questions relating to project planning and, critically, the success of intended work. Coupling this with the analysis types available, for example the consideration of suspendable and non-suspendable (i.e. critical) tasks leads to a powerful holistic analysis.

There are two main areas which these methods can be applied; the project (i.e. installation) planning phase and the device design phase. In both these phases the methods can be used to determine the cost and scheduling constraints of a given method or design (foundation for example). For marine operations and project managers, these time domain simulations can be used to gain an understanding of the risk and variability of cost and duration as demonstrated in Section 5.In addition to determining these elements and informing design and budgeting decisions the methods can be used by marine operations managers to optimise a design or installation method. This is the most powerful application of the methods and presents the main system for the reduction of the cost of installation and in turn the cost of the power produced. The use of the methods for optimisation was demonstrated thoroughly in Section 5 and most clearly in Figure 5-34 and whilst the utilisation of a custom vessel made the largest gains the optimisation process had been clearly demonstrated and the benefits can be seen, especially if savings are made via a change of method when a custom vessel is unavailable.

These methods can be applied early in a design procedure by mechanical or structural engineers and hydrodynamicists, informing the device design and engineering decision making. Consideration can be given not only to how and when a device is installed but to what type of device should be utilized. For example, presented here is the installation of a gravity base foundation unit. It may be seen that a drilled monopile would experience significantly lower costs, or indeed a driven monopile, pin pile and jacket foundation or any of a number of different station keeping devices. By employing these methods an informed decision on this aspect of design may be taken.

It is fair to say that these methods “think” less like a statistician and more like a marine operations manager, allowing for uptake and utilisation to occur, thus reducing installation costs across the industry.

Alternative methods have been highlighted in this work with one, the Weibull persistence method, being considered in detail. As noted, the merits of these methods are different and their application by personnel in the marine energy industry will vary. These statistical methods can be applied in order to determine weather window requirements and to provide a level of comparison between locations, seasons or limitations. These method may, however, be limited in assessing the impact of windows on a large more complex project and there is benefit in the application of a time domain simulation, similar to those describe here, when a more detailed assessment is required.

A number of findings have been demonstrated in this work, via a combination of the Weibull persistence method and the time domain simulation. It has been shown that a holistic analysis is required since the transit route may impose greater constrain on offshore operations than the conditions at site. It has also been shown that increasing the stationkeeping capabilities of a vessel leads to a reduction in the installation duration at a tidal stream site. This, however, can lead to unrealistically long offshore durations as individual task windows, i.e., the requirement to work during slack water, become the main limiting factor. Analysis of this nature identifies these limitations and assists in the remedying of delay.

A reduction in the hook up time allows for a greatly reduced installation schedule, this is due to the increased capability of a vessel to quickly access a weather window, and to then maximise the work which may be achieved in these favourable conditions.

6.2 Limitations and further work

The first areas of further work relate to the identified limitations of the model:

- Transit at 0% efficiency;

- Clustering of tasks into groups which must be finished together (e.g. the individual elements of an ROV survey);
- Crew, equipment and fuel resupplied.

In addition a number of other developments are possible:

- Storm intensity – a consideration of the magnitude by which a threshold has been exceeded rather than just the duration;
- Combined metocean effects – considering the effect of wind and wave, for example, together, not as discrete elements;
- Multiple port and layup locations;
- Mobile tasks – tasks which move during execution, for example cable laying;
- Cost model – expansion of the simple cost model to include additional features such as fuel burn, capital expenditure on installed components, drill rigs, etc.;
- Operational support – the development of a live mode which utilizes at site forecasts to inform decision making.

References

Aalbers, A.B. and van Dongen, C.J.G. (2008) "Weather Routing: Uncertainties and the effect of decision support systems", *Proceedings of the Marine Operations Specialty Symposium 2008,* Singapore.

Aalbers, A.B., Cooper, C.K., Nowak, S., Lloyd, J.R., Leenaars, C.E.J., and Vollen, F. *SafeTrans: A New Software System For Safer Rig Moves,* [Online], Available: http://www.marin.nl/upload_mm/a/a/b/1803898283_1999999096_TVW0213.pdf [15 May 2013].

AECOM (2009) *Environmental Assessment Registration Document – Fundy Tidal Energy Demonstration Project: Volume 1: Environmental Assessment,* Halifax: Author.

Anastasiou, K. and Tsekos, C. (1996a) "Operability analysis of marine projects based on Markov theory", *Applied Ocean Research*, vol. 18, issue 6 pp. 329-352.

Anastasiou, K. and Tsekos, C. (1996b) "Persistence statistics of marine environmental parameters from Markov theory, Part 1: analysis in discrete time", *Applied Ocean Research*, vol. 18, issue 4 pp. 187-199.

Aquamarine Power Limited (2009), *Underwater Foundation.* Inventor A.R. Thomson. International patent application, WO 2009/044161 A2. 5 October 2007.

aquamarinepowerltd (2010) *Oyster Wave Power Device Installation,* [Online], Available: www.youtube.com/watch?v=7ZVayyGnBSM [19 August 2010].

BBC (2010) *Pentland Firth tidal project set for development,* [Online], Available: http://www.bbc.co.uk/news/uk-scotland-highlands-islands-11636959 [14 May 2013].

Beegle, R. (2007) *Overview of Trends in the Tug Market,* [Online], Available: http://www.marcon.com/library/articles/2007/Tug%20Trends%20-%20Final%20color.pdf [17 August 2010].

Bowers, J.A. and Mould, G.I. (1994) “Weather Risk in Offshore Projects”, *Journal of the Operational Research Society,* vol. 45, no. 4, pp. 409-418.

BP (2000) *Gulf of Mexico Heavy Lift Vessel Summary,* [Online], Available: http://demo-dnet.com/final_offshore/Documents/01005FDH001.pdf [17 August 2010].

British Wind Energy Association (BWEA), (2009) *Marine Renewable Energy: State of the industry report – October 2009,* London: Author.

Bush, J. (2012) *Offshore wind – is it all about the maths?,* [Online], Available: http://www.connectingindustry.com/EnergyManagement/offshore-wind-is-it-all-about-the-maths.aspx [15 July 2012].

Callaghan, J. (2006) *Future Marine Energy: Results of the Marine Energy Challenge: Cost competitiveness and growth of wave and tidal stream energy.* London: Carbon Trust.

Carbon Trust *Capital, operating and Maintenance costs,* [Online], Available: http://www.carbontrust.co.uk/SiteCollectionDocuments/Various/Emerging%20technologies/Technology%20Directory/Marine/cost%20of%20energy/Capital,%20operating%20and%20maintenance%20costs.pdf [7 July 2010].

Catalani, M. (2009) “Ship scheduling and routing optimization. An application to Western Mediterranean area”, *European Transport,* no. 43, pp. 67-82.

Cheeseman, S. (2012) “UK tidal energy – greater investment needed?”, *Energy World*, No. 407, September, pp. 18-19.

Coles, D. (2002) *Barge A-390 & Tug*, [Online], Available: www.boatnerd.com [15 May 2013].

Collier, D., Whittaker, T. and Crowley, M. (2008) *The Construction of Oyster – A Nearshore Surging Wave Energy Converter.*

Darkes, D. (2008) *How long is the UK coastline?*, [Online], Available: http://www.cartography.org.uk/default.asp?contentID=749 [14 May 2013].

Deign, J. (2012) “Facing up to offshore wind’s cabling challenges”, *Offshore Wind Journal,* vol.1, issue 1, June, pp. 30-31.

Department of Energy and Climate Change (DECC), (2009) *The UK Renewable Energy Strategy,* Norwich: The Stationary Office.

Department of Energy and Climate Change (DECC), (2010) *Marine Energy Action Pan 2010: Executive Summary & Recommendations.*

Department of Energy and Climate Change (DECC), (2012) *The South West has today been named as the UK’s first Marine Energy Park, firmly placing the region on the international map for leadership,* [Online], Available: https://www.gov.uk/government/news/south-west-makes-splash-as-first-marine-energy-park [14 May 2013].

Det Norske Veritas (DNV), (2011) *Recommended Practice DNV-RP-H103: Modelling and Analysis of Marine Operations.*

Dudziak, G., Waltham, A., Barnes, J., Simmons, J. and Irvine, I (2009) *Marine Energy Supply Chain Survey.* [Online], Available: http://www.cambridge-resource-economics.co.uk/MEG%20Supply%20Chain%20Survey%20Report.pdf [14 May 2013].

Elliot, D. (2010) “Securing UK marine energy”, *Renewable Energy Focus*, May/June 2010, pp. 24-26.

Enviros (2009) *Banding the Renewables Obligation*, [Online], Available: http://www.enviros.com/PDF/BN020RenewablesObligation.pdf [25 August 2010].

European Marine Energy Centre (EMEC), (2010a) *Wave Developers*, [Online], Available: http://www.emec.org.uk/marine-energy/wave-developers/ [14 May 2013].

European Marine Energy Centre (EMEC), (2010b) *Tidal Developers*, [Online], Available: http://www.emec.org.uk/marine-energy/tidal-developers/ [14 May 2013].

European Marine Energy Centre (EMEC), (2010c) *Tidal Site,* [Online], Available: www.emec.org.uk/tidal_site.asp [5 July 2010].

European Marine Energy Centre (EMEC), *Tidal Test Site,* [Online], Available: http://www.emec.org.uk/pdf/emectidal_test_site.pdf [1 September 2010].

European Marine Energy Centre (EMEC), *Wave Test Site,* [Online], Available: http://www.emec.org.uk/pdf/emecwave_test_site.pdf [1 September 2010].

EVE and CIC energiGUNE *Biscay Marine Energy Platform (BIMEP): Infraestructura Singular de Investigación en Energías Marinas,* [Online], Available: http://www.cicenergigune.es/eng/pdf/marina.pdf [2 September 2010]

Fastnet Shipping Ltd. (2013) *Jack Up Barges,* [Online], Available: http://www.fastnetshipping.com/jack-up-barges.html [14 May 2013].

FORCE (2013) *FORCE Test Site,* [Online], Available: http://fundyforce.ca/about/force-test-site-2/ [14 May 2013].

Fraenkel, P. (2009) “SeaGen: Update on Developments”, All Energy ’09, Aberdeen.

Fugro GEOS (2005) *Weather Windows: Weather Windows User Guide*. Swindon: Author.

Fugro GEOS (2011) *Weather Windows*

Fugro Seacore (2013) *Jackup Platforms,* [Online], Available: http://www.seacore.com/specifications/jackup-platforms [14 May 2013].

Garrad Hassan (2013a) *Construction Phase Modelling*, [Online}, Available: http://www.gl-garradhassan.com/en/offshore/owners/ConstructionPhaseModelling%20.php [25 July 2013]

Garrad Hassan (2013b) *Operations and Maintenance Modelling,* [Online], Available: http://www.gl-garradhassan.com/en/offshore/owners/OandM.php [25 July 2013]

Glover, M. (2012) “Industry insight”, *International Sustainable Energy Review,* vol. 6, issue 2, pp. 35-37.

GustoMSC (2013) *Drilling Jack-ups*, [Online], Available: http://www.gustomsc.com/zoo/product-sheets/drilling-jack-ups.html [14 May 2013].

Hagerman, G., Fader, G., Carlin, G. and Bedard, R. (2006) *Nova Scotia Tidal In-Stream Energy Conversion (TISEC): Survey and Characterization of Potential Project Sites,* EPRI.

Halcrow (2006) *Interpretation of geotechnical and geophysical conditions at the Wave Hub site and offshore cable route,* Exeter: Author.

Houlsby, G.T. and Byrne, B.W. (2000) “Suction Caisson Foundations for Offshore Wind Turbines and Anemometer Masts, *Wind Engineering*, vol. 24, no. 4, pp. 249-255.

Institute of Mechanical Engineers (IMechE), *Marine Energy: More than just a drop in the ocean?* London: Author.

Jaurlaritza, E. and Vaszo, G. (2009) “Session Eight: Wave Energy Converters and Developing Projects”, *EFEF – Bilbao,* Bilbao.

Jeppesen (2013) *Commercial Marine Vessel Routing,* [Online], Available: http://ww1.jeppesen.com/marine/commercial/vessel-routing/index.jsp [15 May 2013].

Junginger, M., Faaij, J., and Turkenburg, W.C. (2004) “Cost Reduction Prospects for Offshore Wind Farms”, *Wind Engineering*, vol. 28, no. 1, pp. 97-118.

Marine Current Turbines Ltd (MCT), (2007) *Gravity Foundation for Tidal Stream Turbines.* Inventor: P.L. Fraenkel. International patent application, WO 2007/083105 A1. 18 January 2006.

Marine Scotland, The Scottish Government, AECOM, METOC *Pentland Firth and Orkney Waters Marine Spatial Plan Framework & Regional Locational Guidance for Marine Energy,* [Online], Available: http://www.scotland.gov.uk/Resource/Doc/295194/0096884.pdf [31 August 2010].

Maritime Journal (2010) *The ins and outs of a difficult deployment,* [Online], Available: www.maritimejournal.com/news/01/the-ins-and-outs-of-a-difficult-deployment [16 August 2010].

McMahon, T. (2010) *Historical Crude Oil Prices (Table),* [Online], Available: http://inflationdata.com/Inflation/Inflation_Rate/Historical_Oil_Prices_Table.asp [23 August 2010].

Mojo Maritime (2010a) *Installation Vessel Database.xlsx,* [Unpublished].

Mojo Maritime (2010b) *Operation Costs.xlsx,* [Unpublished].

Mojo Maritime (2010c) *Cast Study: SeaGen Installation Vessel*, [Online], Available: http://mojomaritime.com/case-studies/tidal/seagen-installation-vessel [20 August 2010].

Mojo Maritime (2012) *Hi-Flow Installation Vessel,* [Unpublished].

Mouslim, H. (2007) "SEM-REV Wave Energy Test Site: Project Development" *OREG Fall Symposium*, Whistler.

MPI Offshore (2013) *Equipment*, [Online], Available: http://www.mpi-offshore.com/equipment-1 [14 May 2013].

New Energy Focus (2008) *First Sea-Bed Mounted Tidal Turbine Deployed at EMEC,* [Online], Available: http://www.newenergyfocus.com/do/ecco/view_item?listid=1&listcatid=32&listitemid=1687 [17 July 2010].

NGI (2010) *Torpedo Anchors*, [Online], Available: www.ngi.no/no/Innholdsbokser/Referansjeprosjekter-LISTER0/Referanser/Torpedo-Anchors---A-new-anchor-Technology [24 August 2010].

NGI *Soil Investigation for Offshore Suction Anchors,* [Online], Available: http://www.ead.anl.gov/new/newsdocs/Lunne_lect6_suction_anchor.pdf [24 August 2010].

Nicholls-Lee, R., Hindley, S. and Parkinson, R. (2013) "Development of an economic and efficient installation vessel for tidal stream energy converter arrays", *Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering,* Nantes.

Nixon, J. (2004) "Salvage Claims", *International Marine Claims Conference,* Dublin.

O; Connor, M., Lewis, T., and Dalton, G. (2013) "Weather window analysis of Irish west coast wave data with relevance to operations & maintenance of marine renewables", *Renewable Energy,* vol. 53, pp. 57-66

Ocean Power Technologies, Inc., (2007) *Mooring of Arrays of Buoy-Like WECs.* Inventor: M.R. Draper. International patent application, WO 2007/106323 A2. 27February 2006.

Ocean Power Technologies, Inc., (2009) *Mooring of Multiple Arrays of Buoy-Like WECs.* Inventor: M.R. Draper and D.H. Silcock. International patent application, WO 2009/09400 A1. 22 January 2008.

Offshore Shipbrokers (2010) *Market Data*, [Online], Available: http://www.offshore-shipbrokers.co.uk/index.asp [24 August 2010].

Olstad, P.W., Åkerlund, J., Stempfle, I., Holtedahl, P., Frost, S., Daly, P., Kosine, O., Tenai, E., Ballesteros-Cruz, R., and Abecasis, R. (2009) *Energy from Wind and Ocean: A European Market Study 2009,* London: Innovation Norway.

Open Ocean (2013) *Ocean Compass: real-time operational solution*. [Online], Available: http://www.openocean.fr/drupal7/?q=compass# [15 May 2013].

OpenHydro Group Limited (2009) *An improved Installation Method.* Inventor: J. Ives and P. Dunne. International patent application, WO 2009/127425 A1. 17 April 2008.

OpenHydro IP Limited (2010a) *A Method of Installing a Hydroelectric Turbine Generator.* Inventor: J. Ives, D. Taaffe and P. Dunne. International patent application, WO 2010/069569 A1. 19 December 2008.

OpenHydro IP Limited (2010b) *A Hydroelectric Turbine with Aligning Means and Method of Deployment.* Inventor: J. Ives and P. Dunne. International patent application, WO 2010/069539 A1. 18 December 2008.

Orkney Harbours (2013) *Orkney Marine Services,* [Online], Available: http://www.orkneyharbours.com/ [15 May 2013].

Orme, J.A.C. and Masters, I. *Analysis and comparison of support structure concepts for tidal stream turbines*, [Online], Available: http://en4.swan.ac.uk/egmastersi/images/supportstructures.pdf [17 August 2010].

Peire, K., Nonneman, H. and Bosschem, E. (2009) "Gravity base foundations for the Thornton Bank offshore wind farm", *Terra et Aqua,* no. 115, June, pp. 19-29.

Pride International (2010) *Fleet Status Report,* [Online], Available: http://www.prideinternational.com/fw/main/Rig-Fleet-Overview-25.html [17 August 2010].

Red7 Marine (2013) *Jack up Barges/Self Elevating Platforms,* [Online], Available: http://www.red7marine.co.uk/marine-plant-hire-and-services/plant-hire/jack-up-barges-self-elevating-platforms/ [14 May 2013].

RenewableUK, (2010) *Manifesto – 2010: Policy actions for wind, wave and tidal energy in the UK.* London: Author.

RenewableUK, (2011) *Onshore and Offshore Wind: State of the Industry Report 2011*. London: Author.

Royal Academy of Engineering (2004) *The cost of Generating Electricity: A Commentary.* London: Author.

Saulnier, J-B., Maisondieu, C., Ashton, I. and Smith, G.H. (2012) “Refined sea state analysis from an array of four identical directional buoys deployed off the Northern Cornish coast (UK)”, *Applied Ocean Research,* vol. 37, August, pp. 1-21.

Scott, N.C., Smeed, M.R. and McLaren, A.C. (2009) *Pentland Firth Tidal Energy Project Grid Options Study,* Glasgow: Xero Energy.

Seadrill (2010) *Fleet Status Report*, [Online], Available: http://www.seadrill.com/stream_file.asp?iEntityId=1135 [17 August 2010].

SeaRoc (2013), *SeaPlanner*, [Online], Available: http://www.seaplanner.com/ [15 May 2013].

South West Regional Development Agency (SWRDA), (2010) *Wave Hub*, [Online], Available: www.southwestrda.org.uk/working_for_the_region/area/cornwall_isles_of_scilly/wave_hub.aspx [31 August 2010].

SPT Offshore *Suction Embedded Anchor,* [Online], Available: http://www.sptoffshore.com/bin/ibp.jsp?ibpZone=S8_SEA&ibpDisplay=view&ibpPage=S8_FocusPage&ibpDispWhat=zone& [14 May 2013].

Stallard, T., Dhedin, J-F., Saviot, S. and Noguera, C. (2010) *Procedures for Estimating Site Accessibility and Appraisal of Implications of Site Accessibility.* EQUIMAR.

Steenbuch, F. (2008) “First Mover in the Heavy Lift Installation Market”, *Pareto High Yield Conference,* London.
Sunrise/Sunset Algorithm, [Online], Available: http://williams.best.vwh.net/sunrise_sunset_algorithm.htm [15 May 2013].

Technology Strategy Board (TSB), (2010a) *Wave and tidal stream energy technologies: reducing cost and improving performance. Competition for collaborative R&D funding March 2010*. Swindon: Author.

Technology Strategy Board (TSB), (2010b) *Wave and tidal stream energy technologies: underpinning deployment. Competition for collaborative R&D funding September 2010.* Swindon: Author.

Technology Strategy Board (TSB), (2012) *Marine energy: Supporting array technologies. Competition for collaborative R&D funding March 2012.* Swindon: Author.

The Crown Estate *A Guide to an Offshore Wind Farm,* [Online], Available: http://www.thecrownestate.co.uk/guide_to_offshore_windfarm.pdf [17 August 2010].

The SWAN Team (2011) *SWAN User Manual*, [Online], Available: http://iod.ucsd.edu/~falk/modeling/swanuse.pdf [15 May 2013].

Tipex (2011) *Maps for your games,* [Online], Available: http://forums.white-wolf.com/default.aspx?g=posts&t=50155 [12 September 2012].

Tsekos, C. and Anastasiou, K (1996) "Persistence statistics of marine environmental parameters from Markov theory, Part 2: analysis in continuous time", *Applied Ocean Research*, vol. 18, issue 5 pp. 243-255.

van Nieuwkoop, J.C.C. (2012) *Long-term hindcast for Wave Hub, Cornwall – Validation and analysis of modelled Results*, University of Exeter. [Report].

van Nieuwkoop, J.C.C., Smith, H.C.M., Smith, G.H., and Johanning, L. (2013) "Wave resource assessment along the Cornish coast (UK) from a 23-year hindcast dataset validated against buoy measurements", *Renewable Energy*, vol. 58, pp. 1-14

Veness, C. (2012) *Calculate distance, bearing and more between Latitude/Longitude points,* [Online], Available: http://movable-type.co.uk/scripts/latlong.html [15 May 2013].

Vryhof Anchors (2010a) *Stevpris Mk6: The Industry Benchmark*, [Online], Available: http://www.vryhof.com/pdf_2010/VRYHOF-STYLE2010%20Brochure%20Mk6%20lowres.pdf [14 May 2013].

Vryhof Anchors (2010b) *Stevmanta VLA: Vertical Load Anchor,* [Online], Available: http://www.vryhof.com/pdf_2010/VRYHOF-STYLE2010%20Brochure%20Stevmanta%20lowres.pdf [14 May 2013].

Vryhof Anchors (2010c) *Anchor Manual 2010: The Guide to Anchoring*, 4th edition, Capelle ann den Yssel: Vryhof Anchors BV.

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

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

Wave and Tidal Energy (2009) *Fugro Seacore wins £2m Aquamarine installation contract,* [Online], Available: www.wave-tidal-energy.com/home/news-archive/35-wave-projects/170_fugro_seacore_wins_p2m_aquamarine_installation_contract [19 August 2010].

Wave Energy Centre *Potential and Strategy for the Development of Wave Energy in Portugal,* [Online], Available: http://www.wavec.org/client/files/Summary_DGGE_ingl.pdf [2 September 2010]

Wave Hub (2013a) *Cornish companies win bid to develop multi-million poind floating wind turbine project for Wave Hub,* [Online], Available: http://www.wavehub.co.uk/news/press-releases/cornish-companies-win-bid-to-develop-multi-million-pound-floating-wind-turbine-project-for-wave-hub/ [25 July 2013]

Wave Hub (2013b) *Wave Hub confirmed as preferred location for multi-million pound floating wind demonstrator,* [Online], Available: http://www.wavehub.co.uk/news/wave-hub-confirmed-as-preferred-location-for-multi-million-pound-floating-wind-demonstrator/ [25 July 2013]

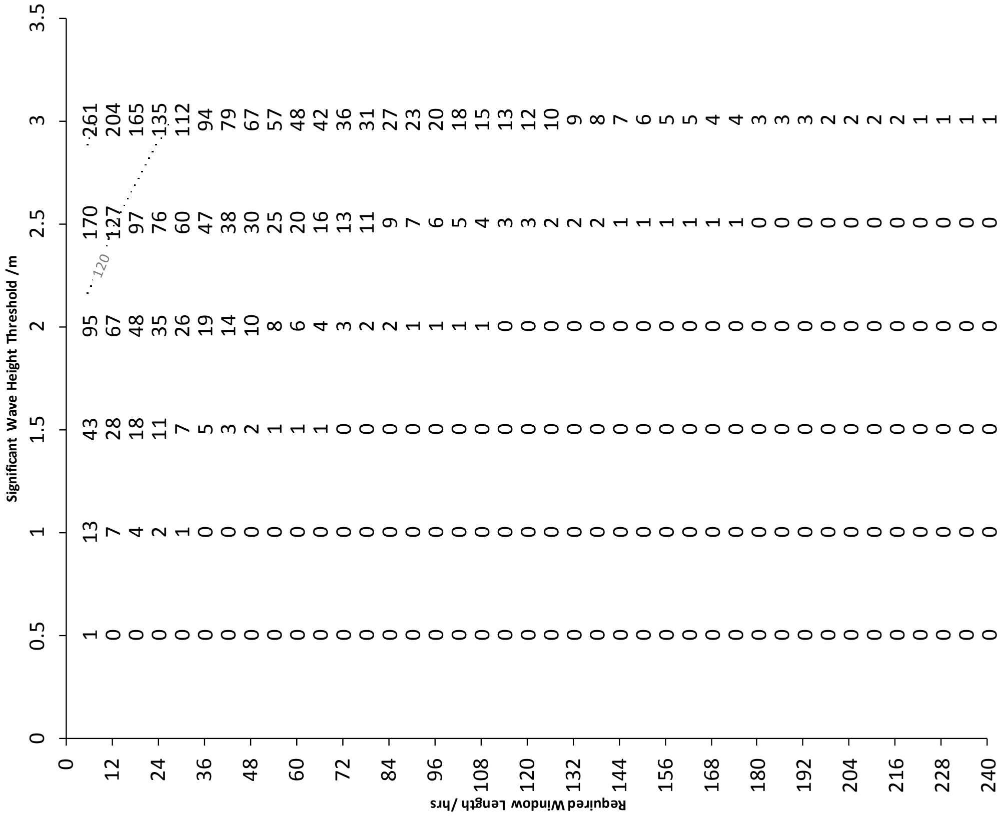
Wave Hub (2013c) *Marine licence approved for first Wave Hub deployment,* [Online], Available: http://www.wavehub.co.uk/news/press-releases/marine-licence-approved-for-first-wave-hub-deployment/ [25 July 2013]

Wave Hub *Wave Hub,* [Online], Available: www.wavehub.co.uk [25 July 2013]

Wilde, B. (2009) *Torpedo Anchors Enter the GoM,* [Online], Available: www.epmag.com/Magazine/2009/10/item45716.php [23 August 2010].

Wright, M. (2008) *Tidal Power and the "SeaGen" Tidal Stream Turbine: An Overview,* [Online], Available: http://www.taplondon.co.uk/bwea30/pdf/1_Martin%20Wright-web.pdf [14 July 2010].

A1. Access and waiting days and hours at the Wave Hub



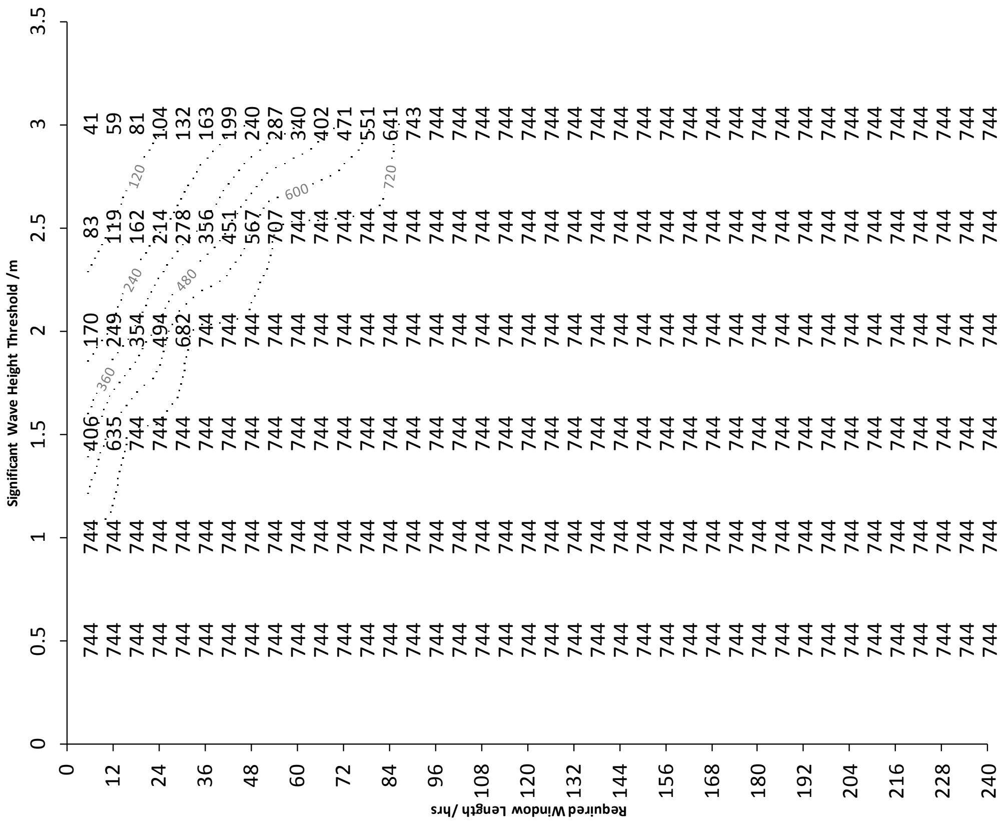
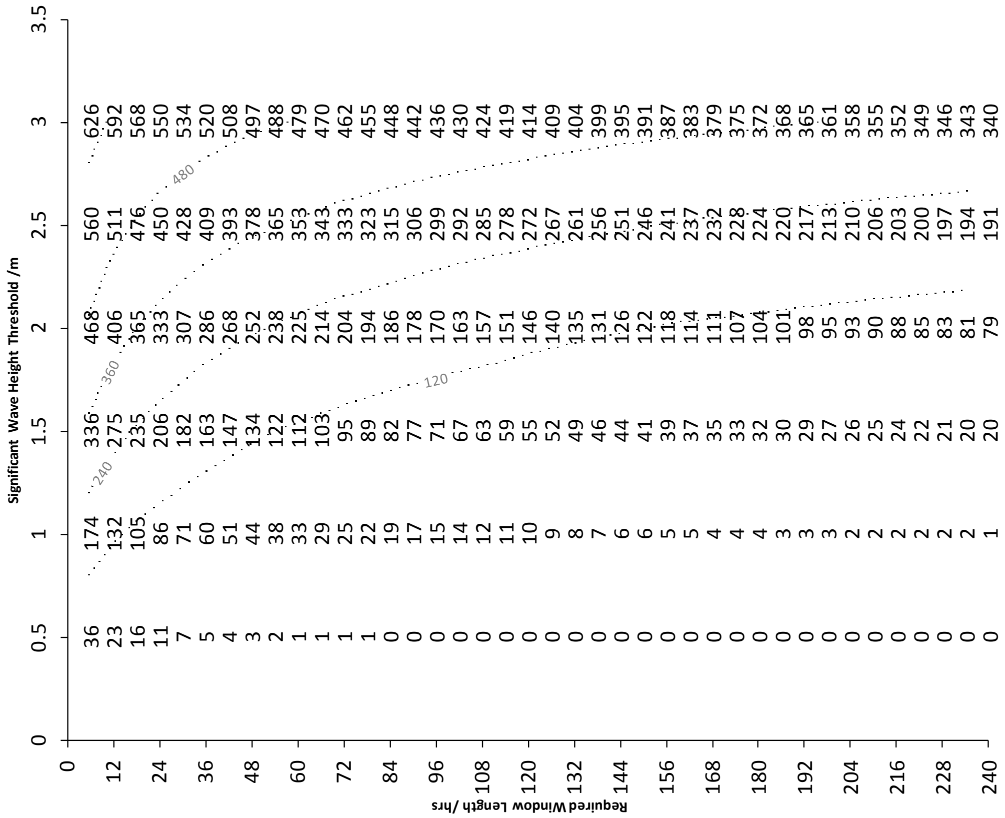


Figure A1-1: Access (upper) and waiting (lower) hours at the Wave Hub – January – Hindcast



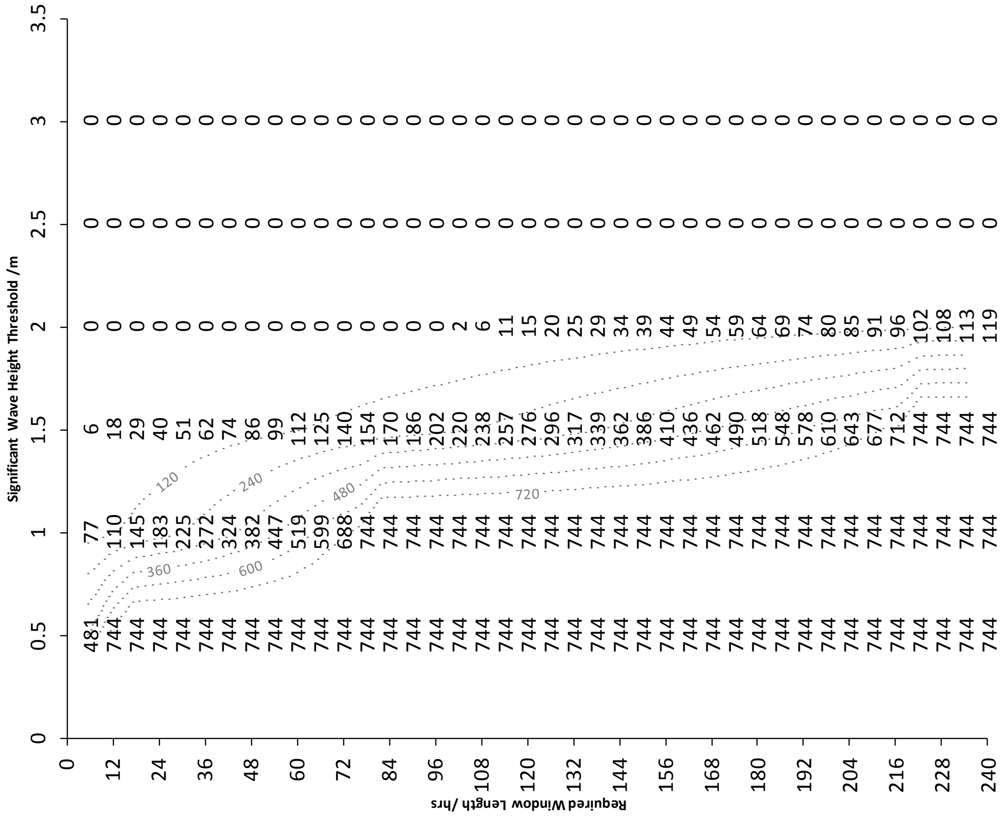
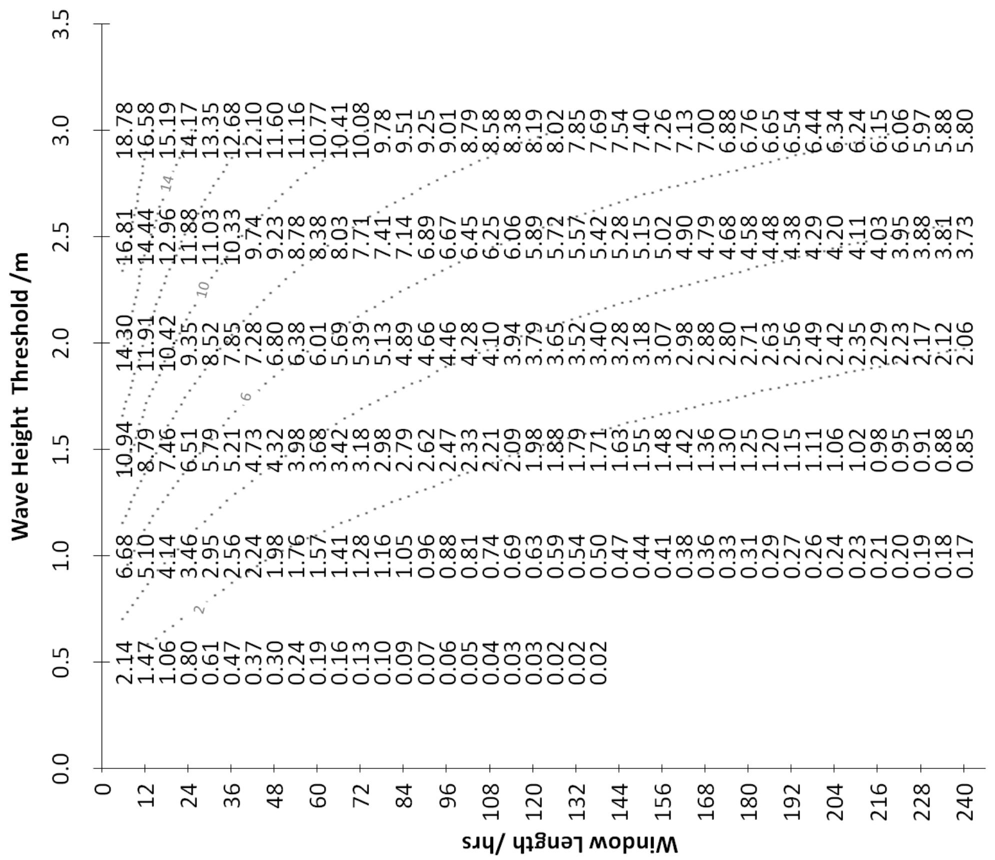


Figure A1-2: Access (upper) and waiting (lower) hours at the Wave Hub – July – Hindcast



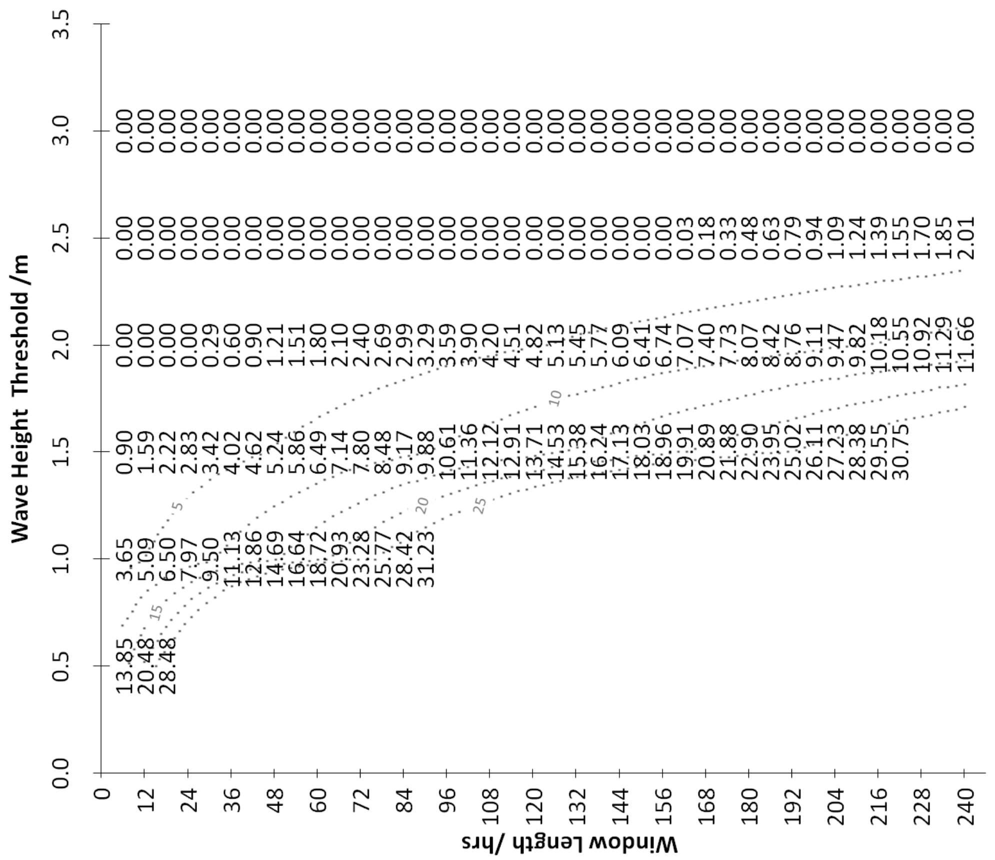
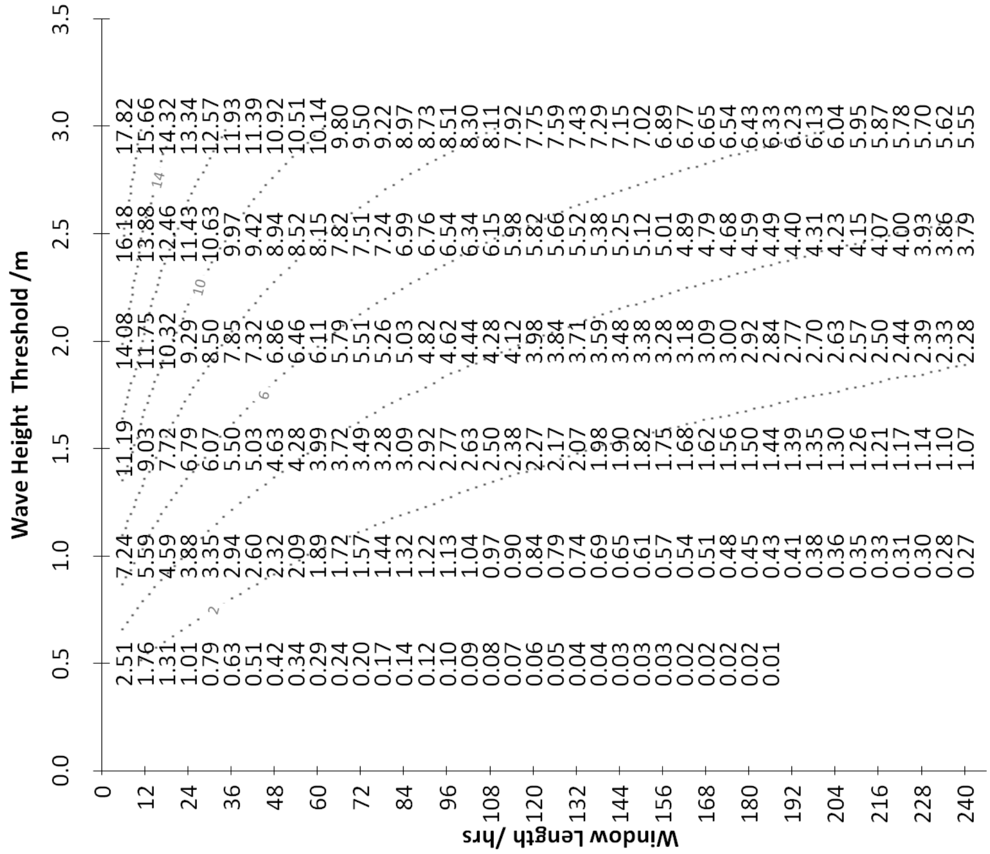


Figure A1-3: Access (upper) and waiting (lower) days at the Wave Hub – July – Modelled



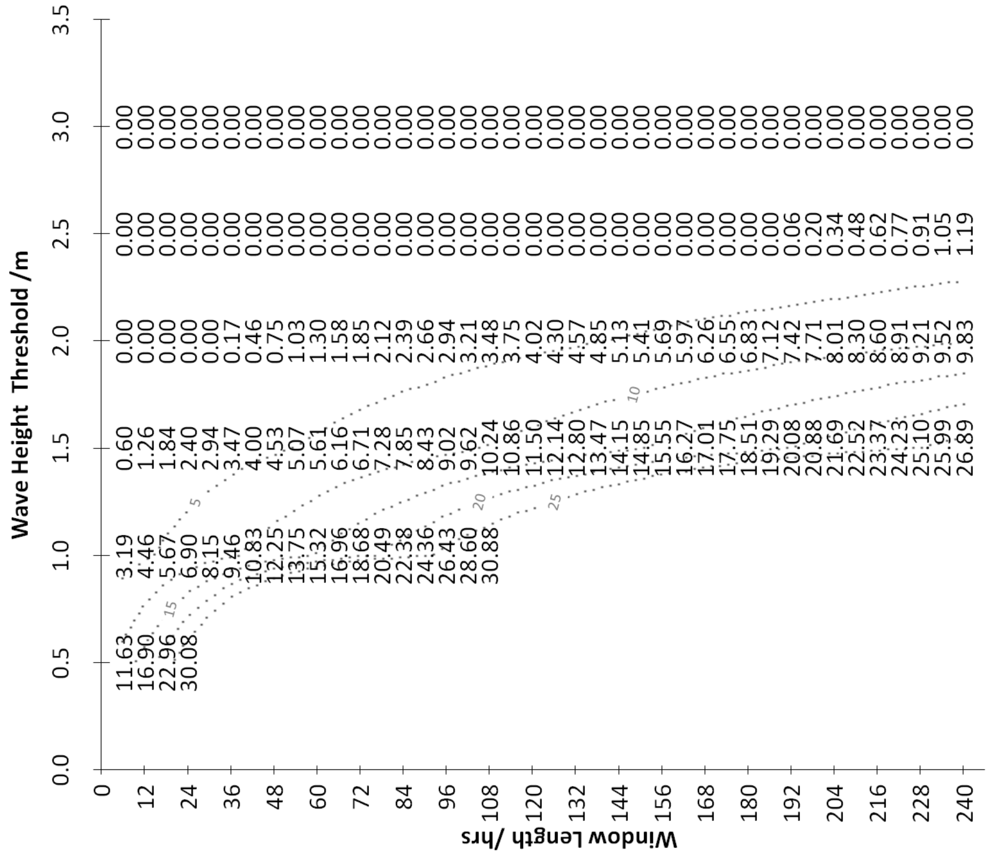
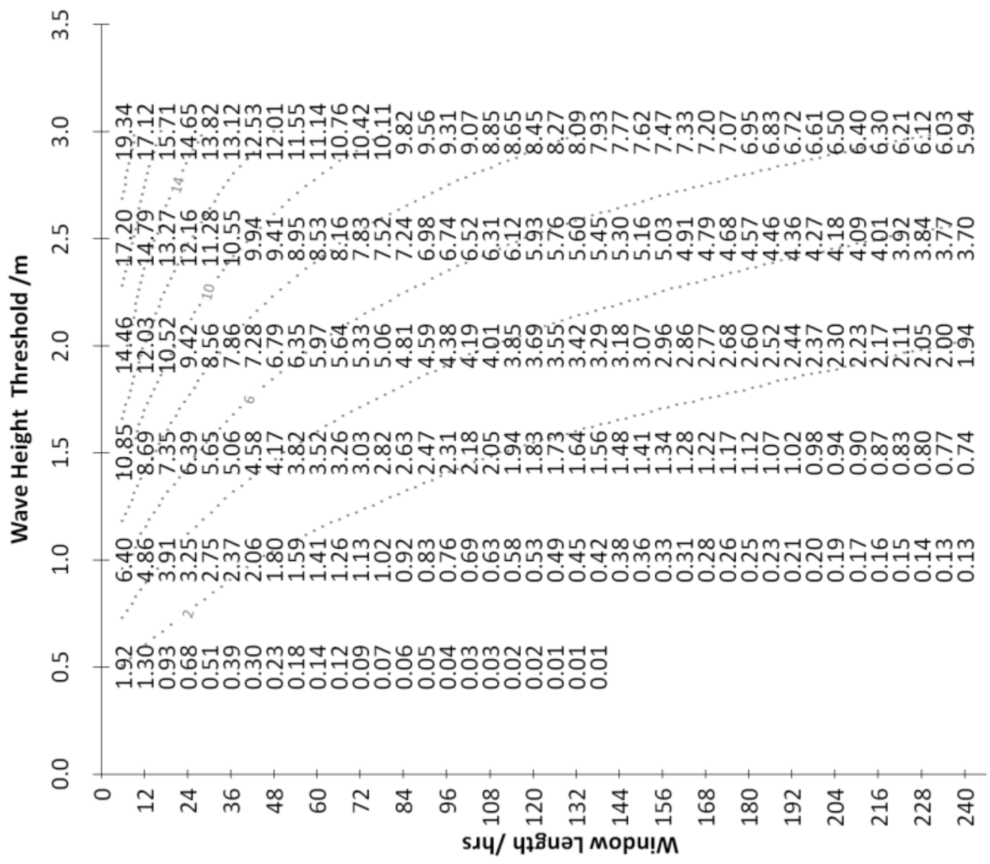


Figure A1-4: Access (upper) and waiting (lower) days at the Wave Hub – July – Recorded



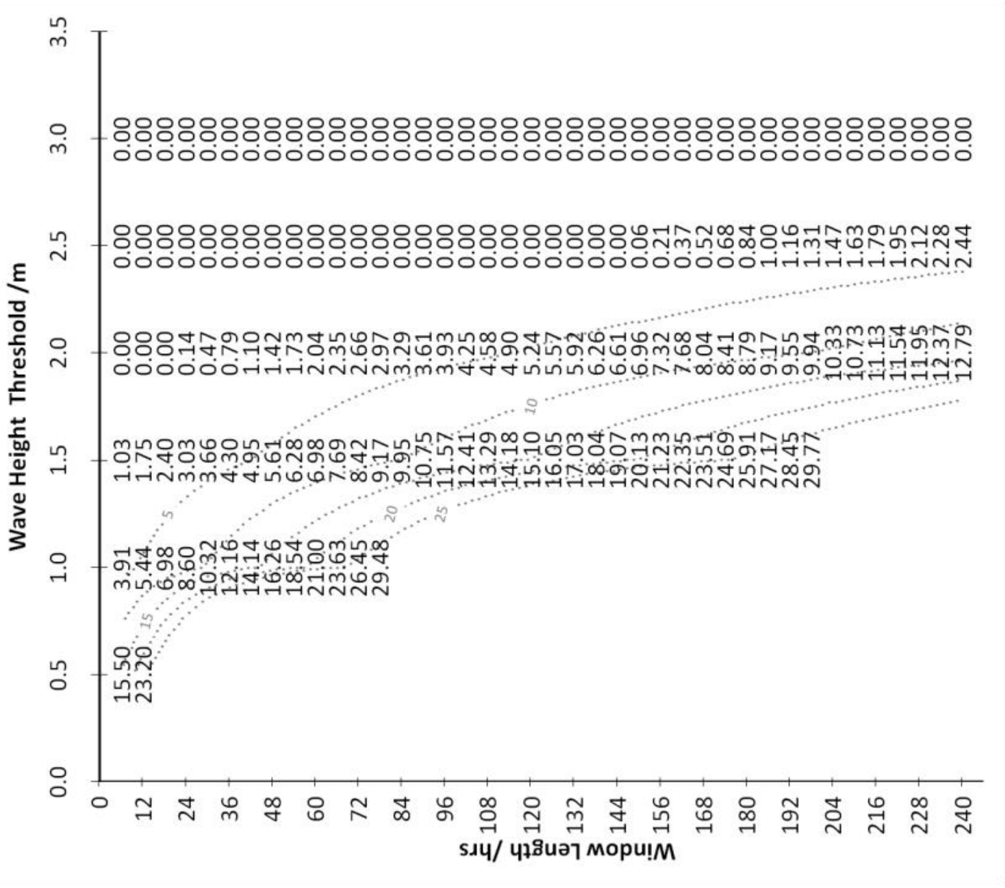
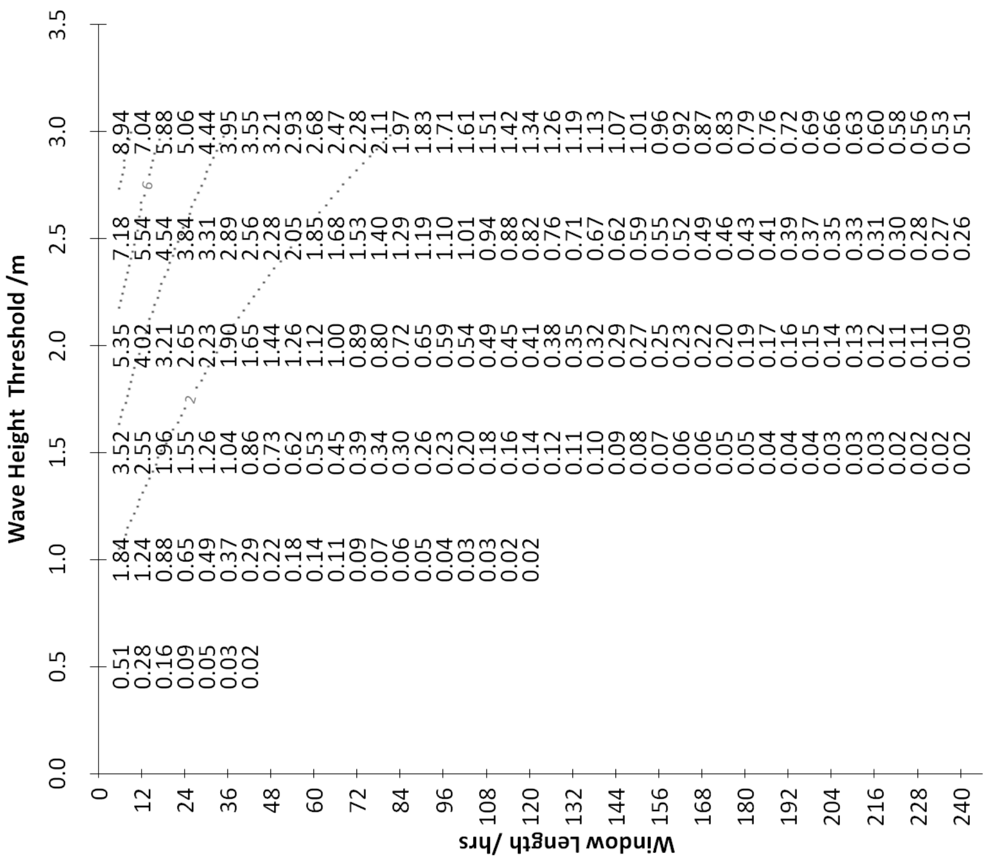


Figure A1-5: Access (upper) and waiting (lower) days at the Wave Hub – July – Combined



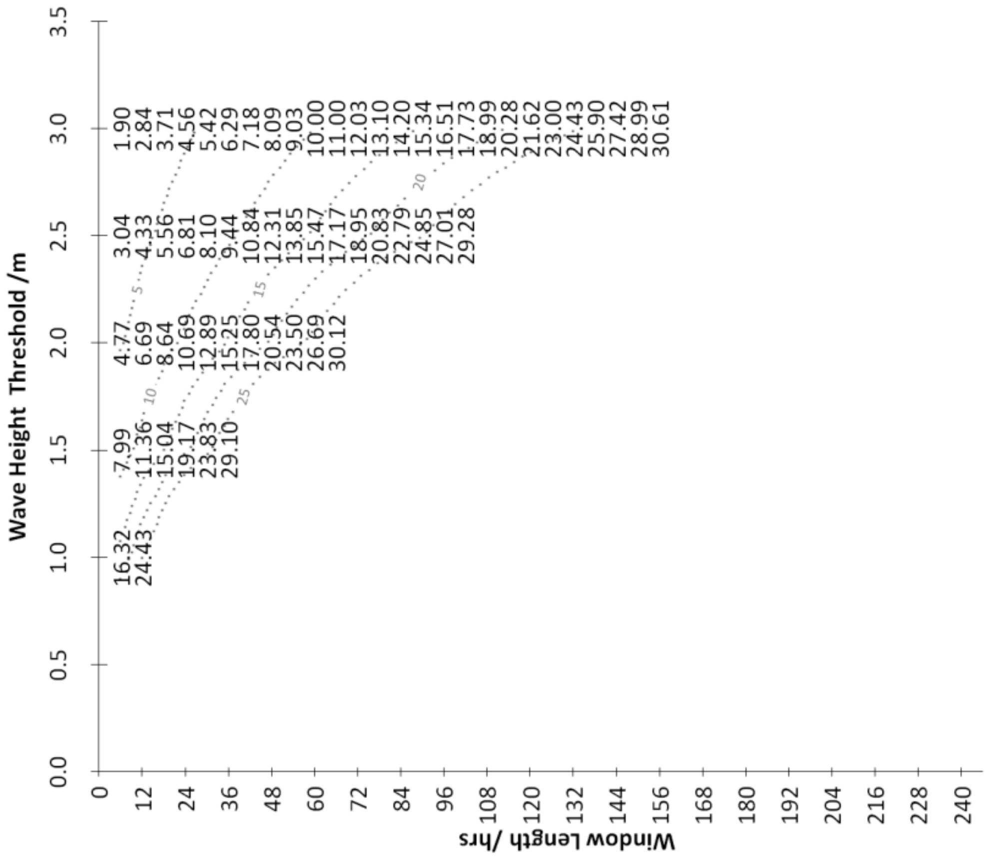
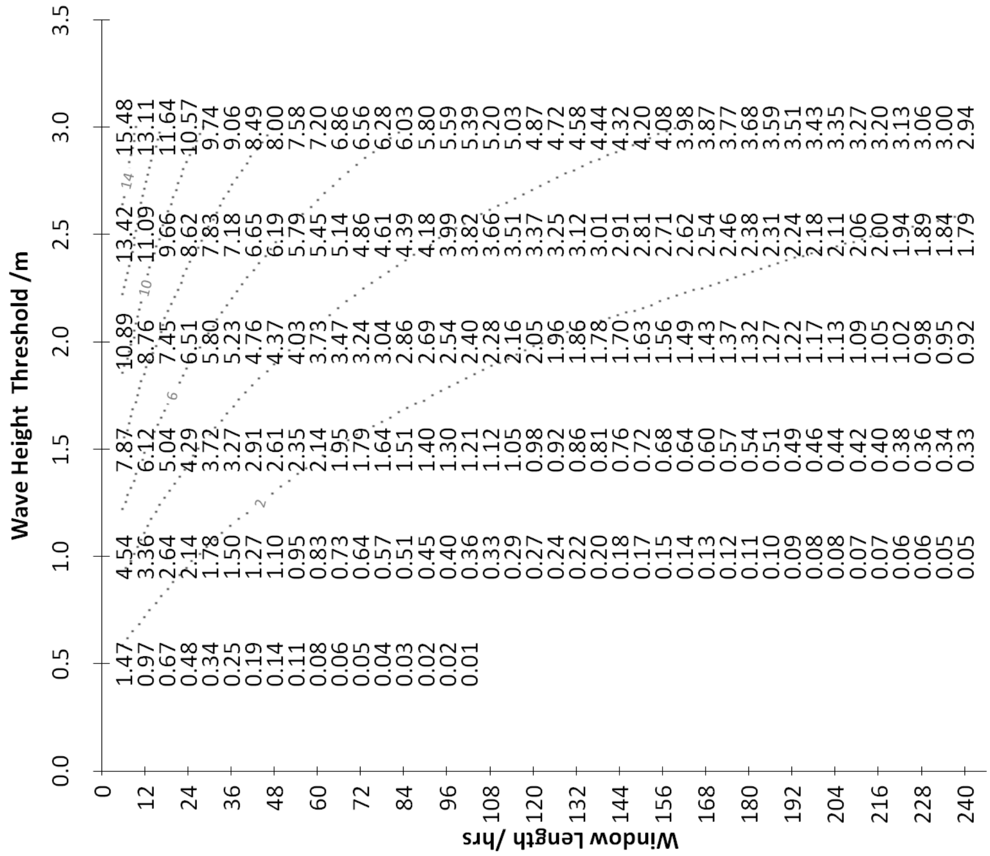


Figure A1-6: Access (upper) and waiting (lower) days at the Wave Hub – January –Modelled



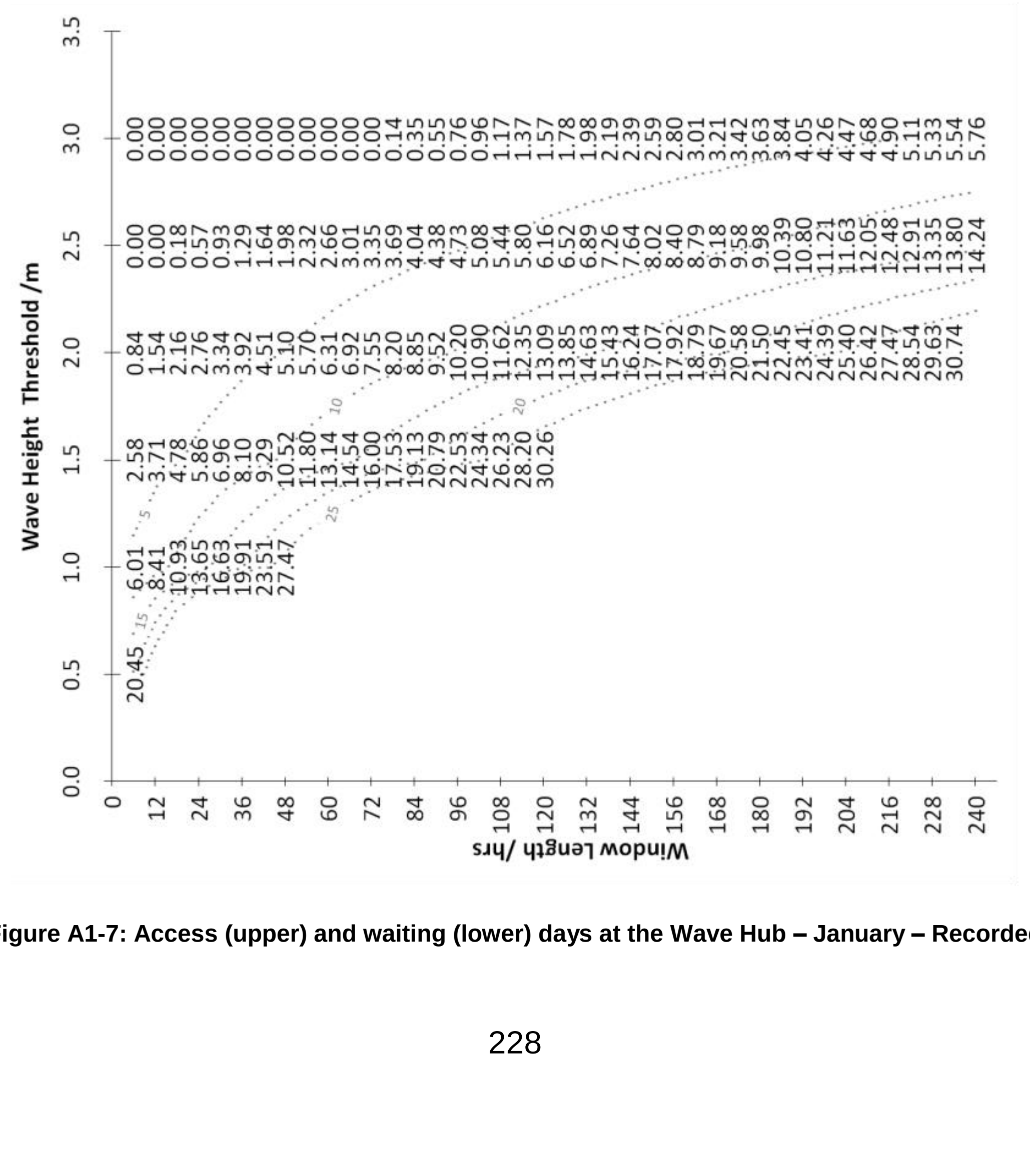
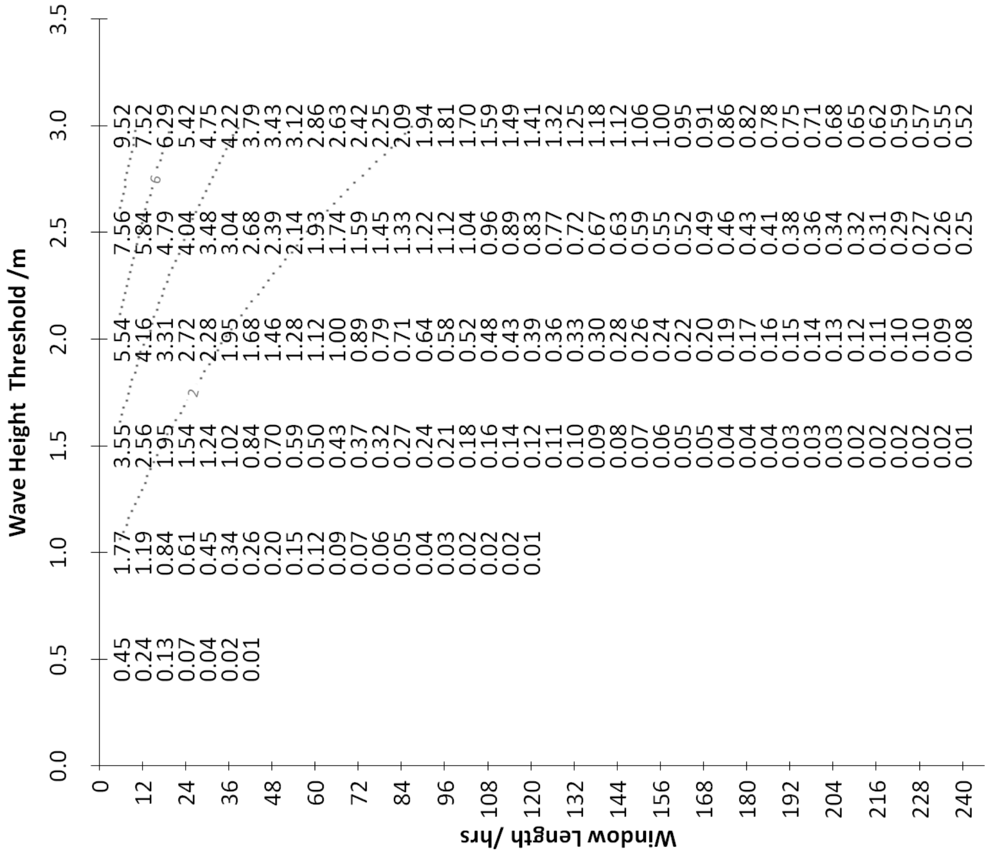


Figure A1-7: Access (upper) and waiting (lower) days at the Wave Hub – January – Recorded



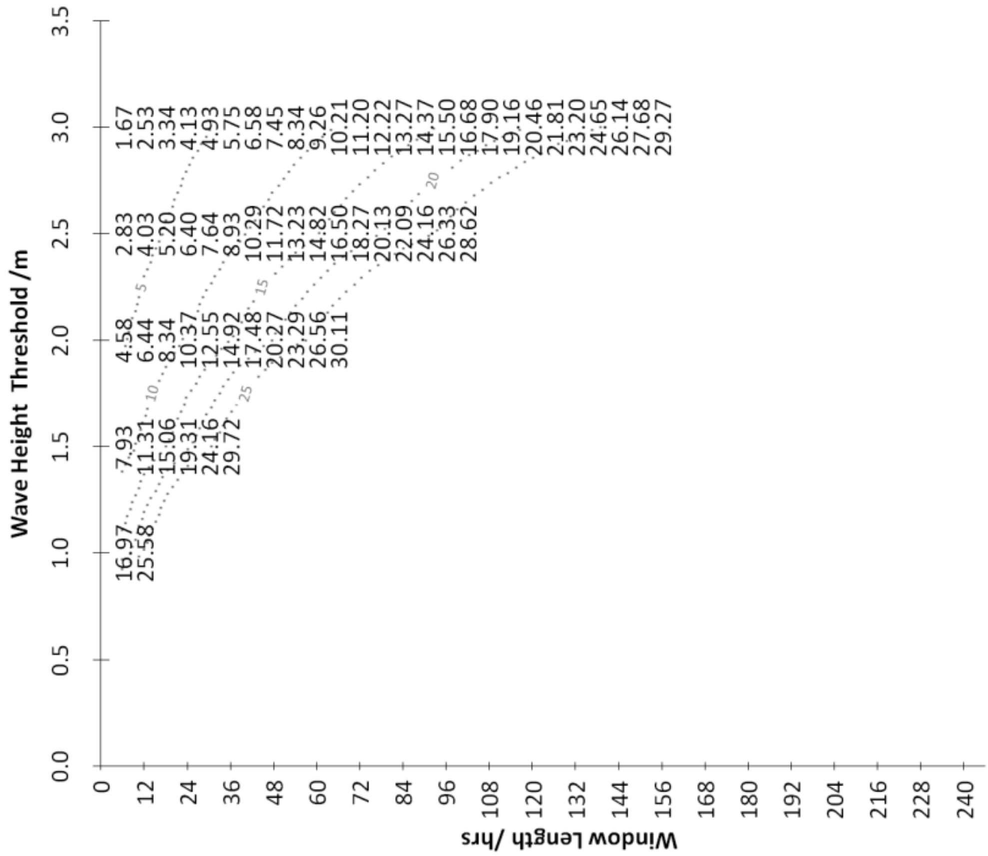


Figure A1-8: Access (upper) and waiting (lower) days at the Wave Hub – January – Combined

A2. Project duration and installation percentiles at the Wave Hub

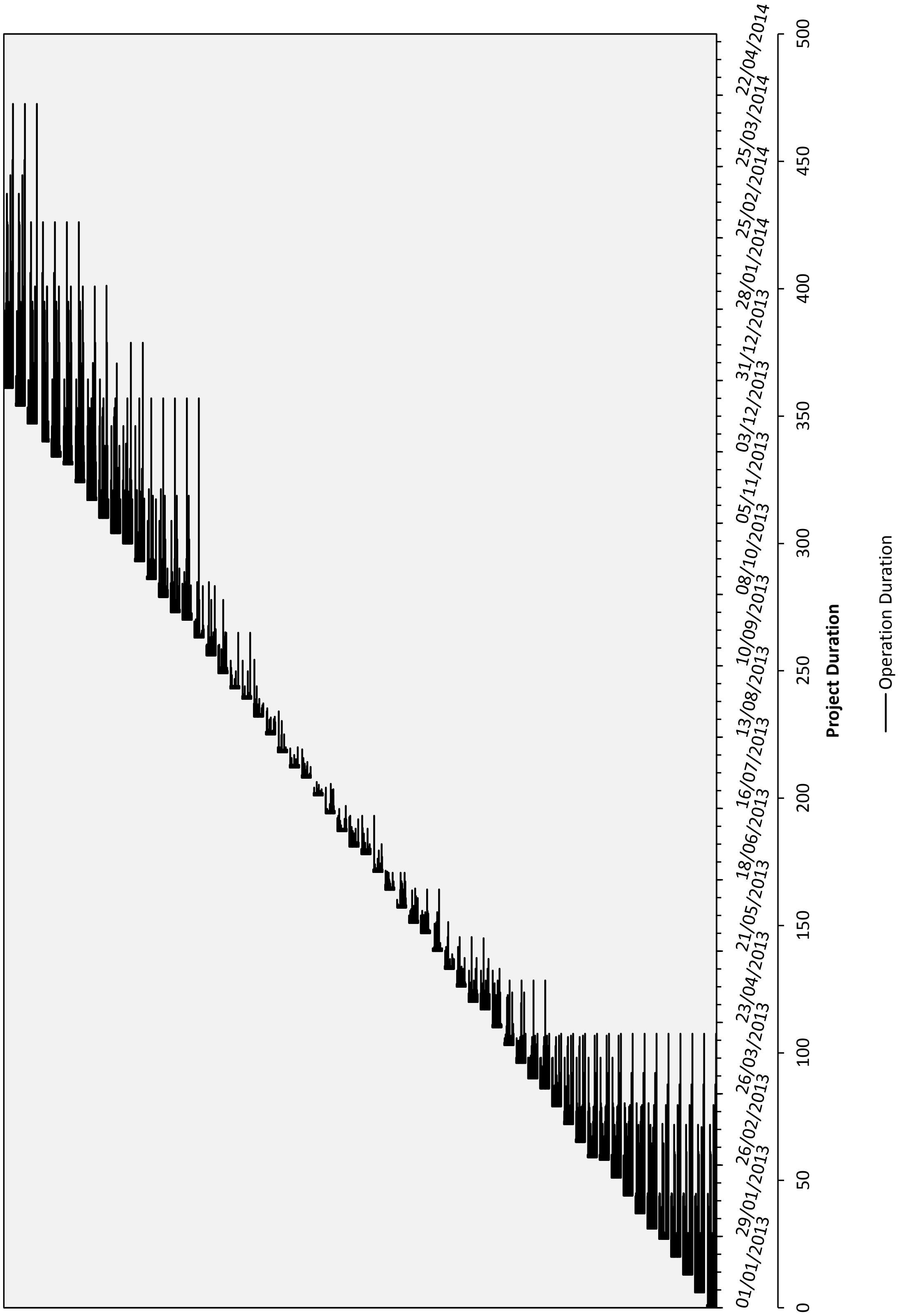


Figure A2-1: Duration of installation project - deployment from Falmouth

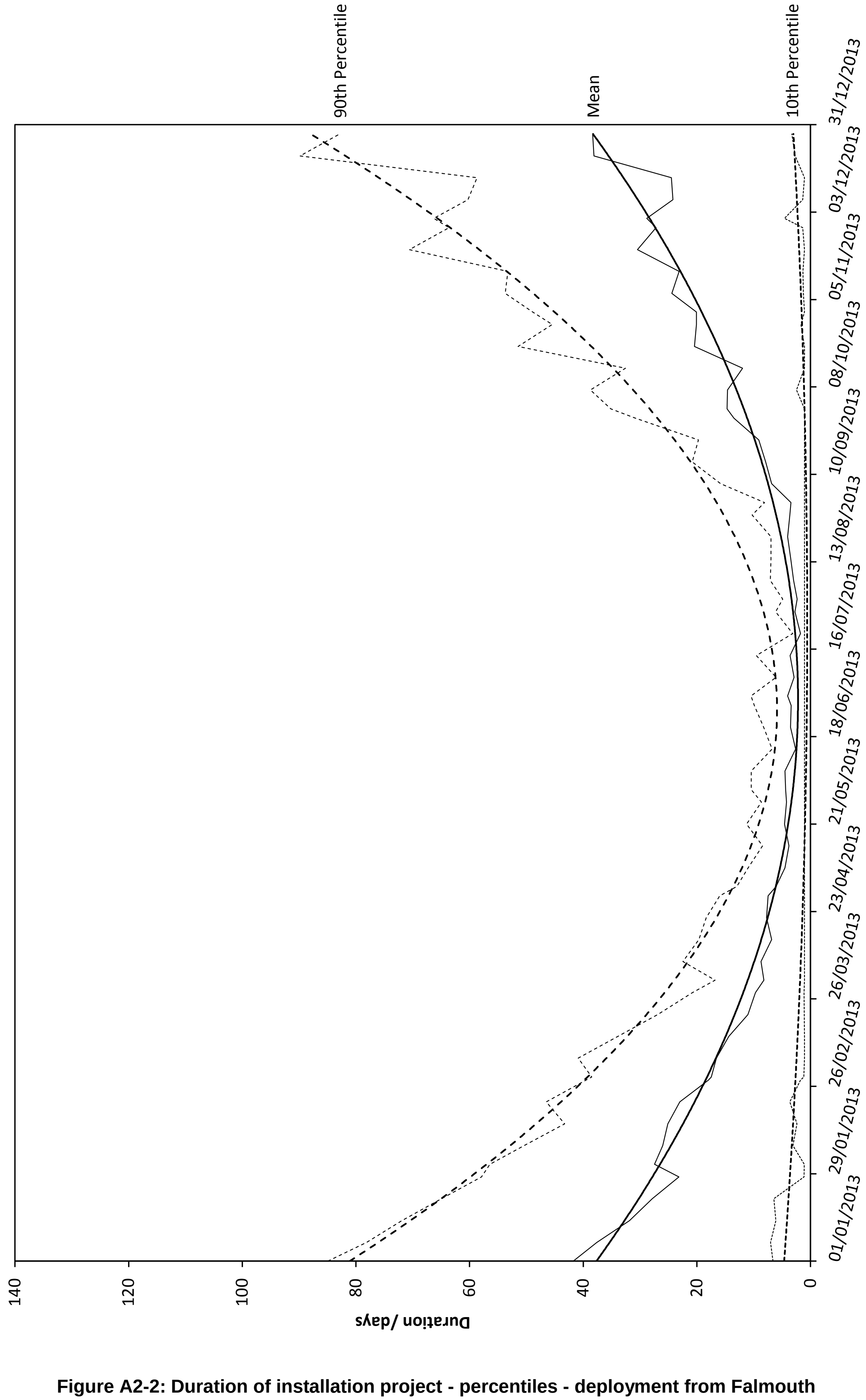


Figure A2-2: Duration of installation project - percentiles - deployment from Falmouth

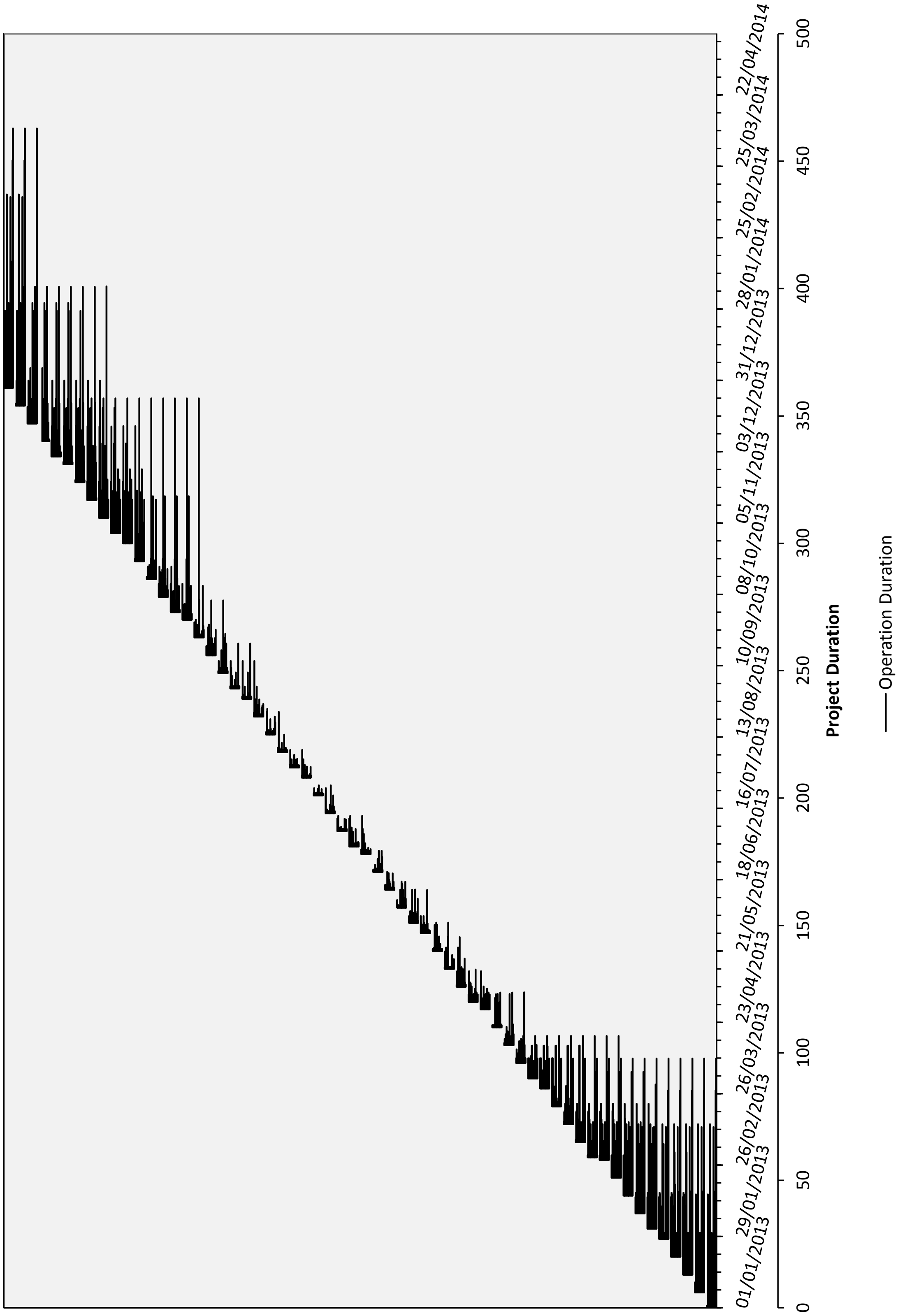


Figure A2-3: Duration of installation project - deployment from Penzance

Figure A2-4: Duration of installation project - percentiles - deployment from Penzance

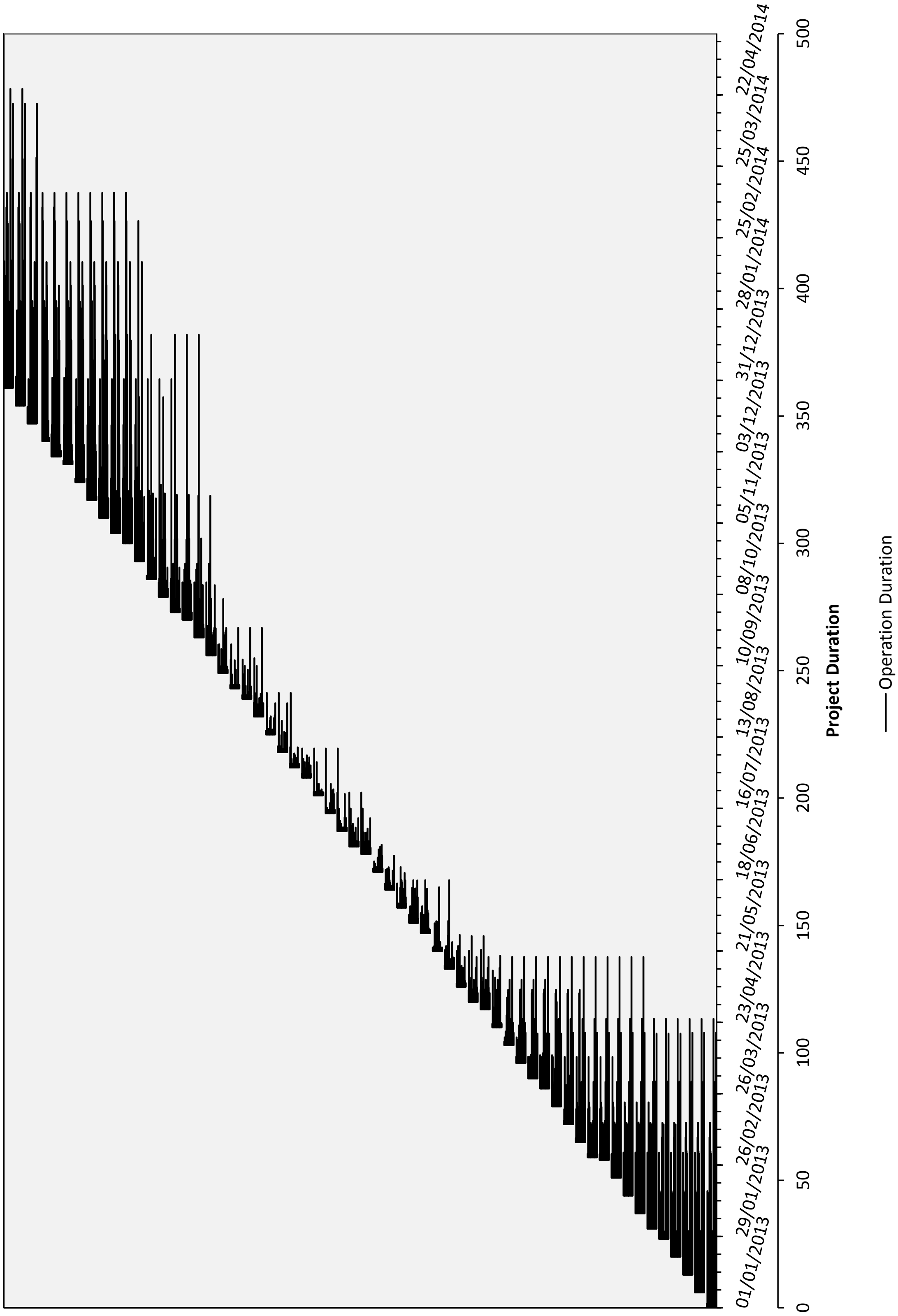


Figure A2-5: Duration of installation project - deployment from Milford Haven

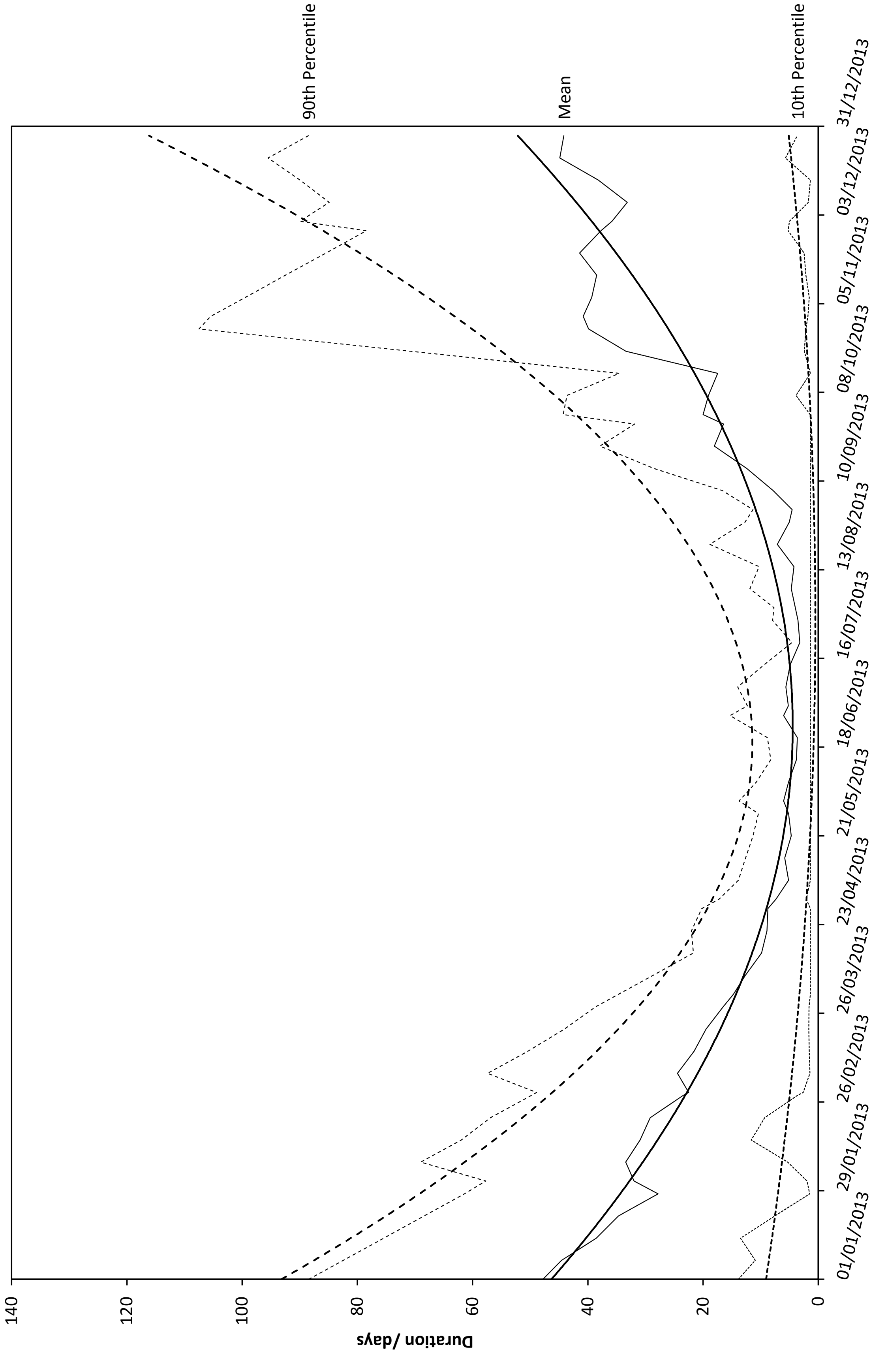


Figure A2-6: Duration of installation project - percentiles - deployment from Milford Haven