LiftWEC

DEVELOPMENT OF A NEW CLASS OF WAVE ENERGY CONVERTER BASED ON HYDRODYNAMIC LIFT FORCES

Deliverable D2.4

Specification of Design and Evaluation Support Software Tools

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EXECUTIVE SUMMARY

This document constitutes Deliverable D2.4 'Specification of Design and Evaluation Support Software Tools' of the LiftWEC project. LiftWEC is a collaborative research project funded by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 851885. It is the intention of the project consortium that the LiftWEC project culminates in the development of one or more promising configurations of a Wave Energy Converter operating through the use of one or more rotating hydrofoils that generate lift as the primary interaction with the incident waves. This report details a suite of *Concept Design* and *Concept Evaluation* support tools that will be developed to support the project in this goal.

Concept Design support tools are tools that will be used to provide a rapid, approximate, yet representative indication of system characteristics for one or more particular characteristics of a wave-driven rotating hydrofoil system. The Concept Design support tools will enable users to gain familiarity with the fundamental system physics and develop an initial understanding of the potential influence of key design decisions on system performance without the need to resort to complex, high fidelity, computationally expensive numerical methods. Thus, Concept Design support tools will not exhaustively model all relevant physical processes influencing the given system performance characteristic, but rather will allow rapid, iterative investigation of the design space to identify key variable interdependencies. It is intended that Concept Design support tools will be developed which can; (1) identify the *Optimum Hydrofoil Path*, (2) estimate the system *Power Capture,* (3) identify the magnitude and nature of *Cyclic/Reactive Energy* cycled within the system, (4) estimate the *Fundamental Reaction Forces*, (5) estimate the *Hydrofoil Reaction Torque*, and (6) estimate the *Annual Energy Production and Annual Structural Loading*. The specifications of these Concept Design support tools are presented in this document.

Noting that the LiftWEC project is characterised by the application of a three-phase iterative design and development exercise seeking to identify the most promising configuration(s) of a lift-based Wave Energy Converter, the *Concept Evaluation* support toolset will be used at the project Stage-Gates to assess the various LiftWEC concepts using a whole-systems approach. These evaluation exercises will be used to select those LiftWEC system configurations and sub-systems which are deemed to hold the greatest potential at each project Stage-Gate and forward them for further investigation. At each Stage-Gate, the evaluation exercise will be repeated incorporating the new design knowledge generated during the previous project phase, thus continually narrowing the work to focus on those systems which are thought to represent those with the greatest potential for successful development as a commercial entity. The specification of the Concept Evaluation toolset which will be used to conduct these assessments is also presented in this document.

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DEFINITION OF TERMS

Fundamental Reaction Force	The oscillatory wave-based/wave-induced loading experienced by the device which must be reacted to allow the system to remain in place. For more on the Fundamental Reaction Force the reader is referred to LiftWEC Deliverable D2.1 "Preliminary Synthesis of Design Knowledge".
Hydrofoil Reaction Torque	The unidirectional torque generated by the rotating hydrofoil as a result of lift which must be reacted to allow the system to remain in place. The different between the Fundamental Reaction Force and the Hydrofoil Reaction Torque is that the Fundamental Reaction Force is the oscillatory component of hydrofoil induced loading whereas the Hydrofoil Reaction Torque is the unidirectional torque generated on the rotor. Power capture is expected to be extracted from the Hydrofoil Reaction Torque. For more on the Hydrofoil Reaction Torque the reader is referred to LiftWEC Deliverable D2.1 "Preliminary Synthesis of Design Knowledge".
Phase Space	The range of possible phase angles between the fluid particle velocity vector due to the incident wave and the tangential velocity vector of the rotating hydrofoil. Typically, this is depicted as running between -180° and +180°.
Radial Thrust	The net, non-tangential components of lift and drag forces generated by the rotating hydrofoil which act along the operational radius of the hydrofoil i.e. the centripetal/centrifugal forces generated by the hydrofoil. For more on Radial Thrust the reader is referred to Section 3.2.2 and Section 3.2.3 of LiftWEC Deliverable D2.1 "Preliminary Synthesis of Design Knowledge" where the Radial Thrust is noted as the non-tangential components of lift and drag forces.
Cyclic/Reactive Energy	This is the energy entrained within the system which is cycled between states to permit operation of the device. For example, in a mass-spring system in undamped oscillation the Cyclic/Reactive Energy is the constant cycling of energy between the potential and kinetic form. This energy is typically 'controlled' to optimise system power capture. For a lift-based hydrofoil, it seems most likely that this would be energy used to either speed up or slow down the hydrofoil to keep it in the ideal phase relative to the wave. In power engineering this is termed *Reactive Energy*, however this document also uses *Cyclic Energy* due to unfamiliarity and the closeness of the term to the Fundamental Reaction Forces and Hydrofoil Reaction Torques which are very different concepts.

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1 INTRODUCTION

This document constitutes Deliverable '*D2.4 Specification of Design and Evaluation Support Software Tools'* of the LiftWEC project. LiftWEC is a collaborative research project funded by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 851885.

1.1 PROJECT OUTLINE

The LiftWEC project focuses on the development of a novel type of Wave Energy Converter (WEC), called LiftWEC, which is intended to utilise hydrodynamic lift forces to incite device motion and extract wave energy using one or more rotating hydrofoils, as opposed to the more traditional approach of exploiting buoyancy and diffraction force regimes. This radically different approach to the design of wave energy converters offers the opportunity of making a step-change in the potential of wave energy, and thus lead the way for its commercialisation, where no commercially viable wave energy system currently exists.

1.2 BACKGROUND

Within the LiftWEC project, it is intended that the consortium will collaborate to develop one or more outline Wave Energy Converter concepts that extract ocean wave energy through the exploitation of lift forces generated by one or more rotating hydrofoils. This will be achieved through an iterative design process consisting of cyclic knowledge building and re-integration. The process was formally initiated at the first project workshop, held in Project Month 6 (May 2020). At that workshop, a set of 17 *Preliminary LiftWEC Configurations* were independently developed using structured innovation techniques. Details on the workshop, the structured innovation exercises and the configurations developed can be found in LiftWEC Deliverable '*D2.3 Review of Current Lift-Based Wave Energy Converter Concepts and Specification of Preliminary Configurations'*.

Consideration of the *Preliminary LiftWEC Configurations* revealed significant commonality between many elements, or components, of the different configurations. That is, while each aggregate configuration was unique, configurations could typically be considered as an assemblage *of individual design elements* where almost all configurations had the majority of their *individual design elements* in common with one or more of the other configurations. Furthermore, it was noted that each *individual design element* typically provided a discrete solution to one (or more) particular fundamental requirements of the system. Interestingly, these solutions were approximately attributable to the range of requirements outlined in Deliverable *'D2.1 Preliminary Report on Synthesis of Design Knowledge'* suggesting potential modularity of the composite system.

It was therefore suggested that the best approach to continue development was not to consider each *Preliminary LiftWEC Configuration* in isolation, but rather to consider the LiftWEC system as an additive combination of a series of *individual design elements*. Then, the pre-requisites or design implications of each particular element dictate the potential combinations which can be achieved. This approach has the benefit of not limiting the consortium to consideration of particular pre-defined configurations and allows the identification of new, potentially more promising configurations as more knowledge is acquired on the various constituent components and system-wide requirements.

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This approach is detailed in Section 4 of project Deliverable D2.3, where the implications are discussed, and critical *individual design elements* or associated design knowledge requirements are identified for consideration by each of the main LiftWEC project work packages. It is therefore important that the project direction seeks to develop an understanding of the influence of these *individual design elements* on system performance and operation. As part of developing that understanding, a set of *Concept Design* and *Concept Evaluation* support tools will be developed to assist with determination of the influence of design decisions on system performance.

1.3 Purpose of Deliverable

This deliverable outlines the desired specification of both the *Concept Design* and *Concept Evaluation* support tools that will be developed and utilised within the LiftWEC project.

Concept Design support tools will exist as first principles implementations of system physics and will be used to assist with developing an outline understanding of the fundamental operational principles of a lift-based wave energy converter consisting of a series of rotating hydrofoils. These Concept Design support tools will be designed to be quick running, physical representations of the LiftWEC system capable of investigating the parameter space and will be informed by results obtained from higher fidelity computational methods which may not be best suited to exploration of the design space due to their computational and time resource requirements.

Concept Evaluation support tools will exist as a series of tools for completing comparative assessments of the viability of different LiftWEC sub-systems and configurations. Inputs will be obtained from the Concept Design support tools as well as from the higher fidelity computational models also being developed within the LiftWEC project.

It is intended that the development and implementation of the Concept Design and Concept Evaluation support tools will assist with identification of the most promising LiftWEC configurations. It is noted that this document is written as a *desired* specification for both the Concept Design and Concept Evaluation support tools. Thus, it is acknowledged that at this early stage, the authors may not yet know the most useful functionality of the tools which are to be developed. Indeed, it is expected that as the project continues and knowledge is developed, the desired functionality of Concept Design and Concept Evaluation support tools may change. The consortium therefore retains the right to modify the specification of Concept Design and Concept Evaluation in accordance with the development of new knowledge. This will ensure toolsets developed are guided by the science and not by a prior specification which is later found to be outdated on account of new information acquired. In all instances, tools will be developed which are thought to maximise the scientific learning and provide the greatest benefit to the LiftWEC project.

1.4 Structure of the Document

This document is divided into 3 main sections, including this introductory section. Section 2 presents the specification of tools to be developed for use as *design support* tools and includes an outline of the intended functionality of the various tools as well as details on the implementation of the tools. Section 3 presents the specification of tools to be developed for use in *evaluation* of device concepts, including details on the specific parameters required for evaluation, implementation of the tool and the use of results generated.

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2 Concept Design Support Tool Specification

2.1 Introduction

A series of *Concept Design* support tools will be produced to assist with developing an understanding of the fundamental hydrodynamics, operational requirements and engineering demands of a lift-based Wave Energy Converter. These tools will enable the project consortium to quickly identify and investigate the relationships which exist between design variables, and rapidly assess the impact of design decisions on a given system's performance, operation and effectiveness.

It is important that the tools developed do not incorporate bias and are designed to allow consideration of as many relevant design parameters as possible. Thus, the toolset developed should permit general exploration of the design space contained within the extent of the boundaries designated by the LiftWEC problem scope. The LiftWEC problem scope details the area of interest to the project consortium and is reproduced below for reference purposes.

> *"LiftWEC is a wave energy converter that extracts energy from the waves and converts it to electricity to be supplied at grid-scale to an underwater seabed cable. LiftWEC couples with the waves through lift forces generated by one or more hydrofoils that rotate in a single direction about one or more horizontal axes aligned orthogonally to the mean direction of wave propagation.*[1]*"*

Furthermore, to ensure appropriate coverage of requirements, the range of Concept Design support tools which will be developed has been decided based on the fundamental design knowledge requirements outlined in Deliverable D2.3.

As it is intended that the toolset will be used primarily for concept development and the generation of fundamental understanding, it is important that the design and implementation of specific tools support their intended function. That is, it is important to note the distinction between *Conceptual Design* and *Detailed Design* where the toolset described in this section falls within the *Conceptual Design* category. Thus, these tools are not intended to provide engineering appraisals of a particular configuration or sub-system. Rather the tools should inform on the implications of making particular design decisions in a relativistic manner. For example, it is not appropriate that Concept Design support tools would undertake any form of high-fidelity computational analysis as this would require excessive use of computational and time resources. Rather, Concept Design support tools should employ first principle physical representations to provide an outline understanding of the impact of specific design decisions on system features. Indeed, a range of high-fidelity computational models will also be developed within the LiftWEC project and, where appropriate, these will be used both to calibrate and validate the Concept Design support tools and further inform on more detailed aspects of design requirements. In addition, it would be impractical to attempt to develop a fundamental understanding of system physics using higher fidelity methods due to their fundamental nature and their associated operational restrictions. The remainder of this section details the intended function and implementation of the various Concept Design support tools which will be developed to serve the LiftWEC project.

[1] LiftWEC Problem Scope

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2.2 LIST AND INTERACTIONS OF CONCEPT DESIGN TOOLS

It is proposed that at least 6 tools will be developed to support concept design and development exercises. A very brief outline of each of the 6 tools is included below followed by an outline diagram depicting the interactions which exist between each of the various tools (Figure 1).

Tool 1: Determination of Optimum Hydrofoil Path

This tool will allow the user to identify the *optimum hydrofoil path* for a lift-generating rotating hydrofoil which is driven by wave-induced fluid flow. The optimum hydrofoil path simply refers to the path of travel which maximises the *hydrofoil power*, however it is proposed that alternative optimization parameters might prove more insightful at a later date and so functionality will be included to allow for future extension of the tool which allows users to consider alternative target optimizations. The tool will permit identification of variation in the hydrofoil path with a number of critical sea state and device design/control parameters. It is currently expected that the output from this tool will be used as an input into all other toolset.

Tool 2: Estimation of Power Capture

This tool will provide an estimate of the power capture of a particular implementation of a lift-based rotating hydrofoil operating under wave action. The power capture will generally be in the form of the hydrodynamic power capture, estimated before generator and other system losses are considered. This tool will allow the user to investigate the influence of sea state characteristics and device design and control parameters on the hydrodynamic performance of potential LiftWEC systems. Inputs for this tool will be taken from the outputs of the tool which determines the optimal hydrofoil path.

Tool 3: Estimation of Reactive/Cyclic Energy

This tool will estimate the level of cyclic/reactive energy required to maintain ideal motion of the hydrofoil. This is typically energy which will be required to be cycled by the control system in order to optimise performance. This tool will allow the user to identify the magnitude and nature of cyclic/reactive energy required to realise the Optimum Hydrofoil Path. Naturally this tool will therefore require inputs taken from the output of the tool which determines the optimal hydrofoil path. Considered alongside results obtained from the tool for estimation of Power Capture this tool will allow the user to determine the relative magnitude of control power required compared to that which can be extracted from the system.

Tool 4: Estimation of Fundamental Reaction Forces

This tool will provide an estimate of the Fundamental Reaction Forces experienced by a lift-based rotating hydrofoil which is driven by wave-induced fluid flow. The Fundamental Reaction Force is simply the oscillatory wave-induced loading experienced by the system which must be reacted to provide system stability. In particular this tool will seek to estimate the Fundamental Reaction Force occurring due to operation of the hydrofoil under wave action. As such this tool will not estimate contribution to the Fundamental Reaction Force due to other hydrodynamic processes such as viscous or form drag on the support structure. The tool will allow the user to investigate variation in Fundamental Reaction Forces due to variation in both sea state conditions and device design and control parameters. Inputs for this tool will be taken from the outputs of the tool which indicates the

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optimal hydrofoil path and thus it is important that simulation conditions are consistent across the two tools. Note that the Fundamental Reaction Force is separate to the Hydrofoil Reaction Torque.

Tool 5: Estimation of Hydrofoil Reaction Torques

This tool will give an estimate of the Hydrofoil Reaction Torque generated by a lift-based rotating hydrofoil operating under wave-induced flow. The Hydrofoil Reaction Torque is simply the moment-force generated by the rotating hydrofoil due to lift which must be reacted to ensure stability of the complete system. In the context of the complete LiftWEC system it may also be described as "Rotor Torque". One important difference between the Hydrofoil Reaction Torque and the Fundamental Reaction Force is that while the Fundamental Reaction Forces are typically expected to be oscillatory, the Hydrofoil Reaction Torque will be unidirectional. It is expected that the power-take-off will be extracted from this torque. The tool will allow the user to investigate variations in the Hydrofoil Reaction Torque due to variation in sea state conditions and device design and control parameters. Inputs for this tool will be taken from the outputs of the tool which provides the optimal hydrofoil path. It is therefore important that consistent simulation conditions are maintained across the tools.

Tool 6: Estimation of Annual Energy Production and Structural Loading

This tool will combine outputs from the majority of other tools and give an indication of Annual Energy Production (AEP) and typical annual structural loading of a given system. This will provide context for learning obtained relating to the effect of particular design variables in terms of their influence on the expected real-world operation of the system. The tool will allow consideration of all system variations permitted by previous tools and will give outputs both on an average and weighted sea state basis allowing the generation of scatter tables of performance and loading both in terms of the average for a given sea and their weighted influence on a given test site's wave climate.

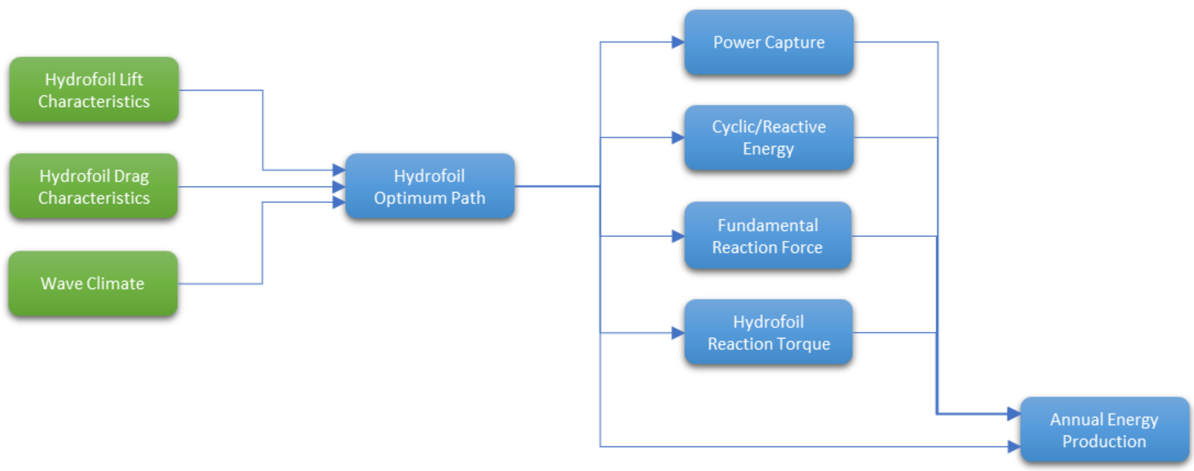

Figure 1: Outline of Interactions Between Concept Design Support Tools

2.3 SOFTWARE PLATFORM

Beta versions of the Concept Design support tools will be developed in Matlab. Whilst it is recognised that Matlab is a proprietary software distributed under commercial licence, it is thought that the simplicity of coding in Matlab and availability of specialist toolboxes likely outweigh the restrictions due to licencing. Indeed, only one project partner does not currently have organisational access to the

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Matlab platform, and this issue can be rectified if required. However, in order to support inclusion and permit use of the Concept Design support tools by all project partners, developers will endeavour to ensure that, if possible, software developed will also be suitable for use with Octave; an open source coding platform whose syntax is largely compatible with Matlab.

With beta versions of the Concept Design support tools completed, an assessment of their complexity and implementation will be conducted. Improvements to the design tools will then be considered prior to production of software for general release. This will include a decision on the feasibility and potential benefits of porting the tools to a more universally accessible platform such as Python.

2.4 FUNCTIONALITY

The functionality of a toolset defines its usefulness for a particular application. It is therefore important that the required functionality of a toolset is defined prior to its development such that its functional requirements, operational capabilities and allowable limitations are well defined and understood. This ensures that tools developed are appropriate for their intended use and thus should not mislead users in terms of the applicability and implications of results generated.

This section details the desired functionality of the Concept Design support tools that will be developed for the LiftWEC project. Common functionality of all Concept Design support tools is detailed in Section 2.4.1. Functionality for individual tools is subsequently outlined in Section 2.4.2 to Section 2.4.7. The reader is reminded that these are *desired* functionalities and may be later amended.

2.4.1 Common Toolset Functionality

In a general sense, the Concept Design support tools developed should benefit from the following common functionalities, regardless of their design, implementation or use. These may be thought of as guiding principles to be considered during toolset development.

Functional Specification

At the point of release, all tools will be accompanied by a Functional Specification which details the intended use case of the tool. The Functional Specification should outline the input requirements of the tool, including detail on user inputs and user-defined parameters. The Functional Specification should detail the methodology employed by the tool and provide citations to scientific literature where appropriate. Finally, the Functional Specification should describe the output of the tool including discussion of post-processing requirements.

Definition of Limitations

Typically, Concept Design support tools will be used to; (1) develop fundamental understandings of system physics, and (2) undertake investigations for the purpose of preliminary assessment of a given configuration's performance characteristics. It is not expected that Concept Design support tools will provide complete engineering appraisals of a system. Consequently, the expected limitations of the various tools should be documented. This may take the form of a list of modelling assumptions and known omissions. The benefit of this is that in many cases, experienced researchers will be able to qualitatively infer the expected impact of such limitations on results obtained. Thus, while it is acknowledged that the Concept Design support tools will often represent simplifications of the problem, some understanding should be given of the perceived impact of those simplifications.

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Speed of Assessment

All Concept Design support tools should be developed such that reliable results are obtained in a relatively small amount of time. More specifically, the tools should permit the rapid assessment of concept variations by a group of people seeking to investigate the design space in a collaborative environment. In quantitative terms, this might mean that tools should operate in real time, or much faster dependent on the particular tool. As guidance, it is noted that it is intended that the Concept Design support tools should be able to be used during project workshops and meetings to consider the implications of design decisions on system features.

Uncertainty/Accuracy & Precision

All tools developed should be both suitably *accurate* and *precise* such that they are suitable for their intended use and thus fulfil their *Functional Specification*. Accuracy refers to how close an estimate of the *quantity of interest* is to the true value. Precision refers to how close multiple estimates of the *quantity of interest* are to each other and, in this instance, is most likely to require consideration where statistical methods are employed. Combined, the level of accuracy and precision determine the *uncertainty* of a result. Allowable uncertainty therefore requires that the influence of uncertainty does not have a significant impact on outcome of the salient investigation being completed.

Ease of Use

All tools should be suitably user-friendly such that any informed member of the LiftWEC consortium could use the tool to carry out its intended function. This might require the production of documentation that explains the use of the tool. Documentation should include details on toolset inputs, assumptions, methods and outputs. Where appropriate, documentation should also include details on interpretation of results generated.

Interoperability

Where possible, tools should be produced which are interoperable across different operating systems. Furthermore, where practical, Concept Design support tools should be produced such that they are not dependent on specialist software, inputs or methods which are not typically available within the consortium. If a tool requires licenced software, input etc. it is advised the tool developer considers an alternative approach. For example, where allowable, many outputs from a licenced software could be pre-generated and supplied with the tool in the form of a look-up table or similar to simplify use.

Consistency of Inputs and Environmental Variables

As a number of tools take outputs from other tools as inputs, it is important that simulation conditions are maintained across the use of multiple tools. For example, it is important that outputs from the optimal hydrofoil path tool obtained for regular waves of 2m amplitude and 10s period are not used as inputs for the estimation of Fundamental Reaction Forces where simulation conditions for regular waves of 4m amplitude and 12s period are sought. Thus, a fail-safe mechanism should be included in the design of tools. Most likely this will exist in the form of a meta-data output file which will be generated by all tools and attributed to the results obtained for each individual running of the tool. All tools requiring inputs from other tools should then examine these meta-data files to ensure compatibility of inputs acquired and user-defined parameters for the investigation being completed.

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2.4.2 Optimum Hydrofoil Path

Prior to concerns regarding the practicality of extracting all available energy from a system, it is informative to first consider the optimum operating condition of the most fundamental element of that system. This provides the designer with a '*target state'* where an ideal system would fully realise this optimum operating condition. Details surrounding how this target state might be achieved or how such a system could be physically implemented should not be permitted to restrict investigation at this stage as the intention is not to produce an engineered solution, but rather to develop a fundamental understanding of the ideal system's physics. This in turn provides the designer with an understanding of the environmental and design variables which have the greatest impact on the ideal system's performance and thus allow identification of areas of priority and areas where compromise can be made without significant impact.

Evidently, the optimal operating condition will vary dependent on the specified optimization. For example, the optimal operating condition will likely not be the same if the optimization seeks to maximise energy extracted from a system, versus the case where the optimization seeks to minimise fluctuation in the instantaneous power capture.

In its most basic form, LiftWEC may be assumed as one or more hydrofoils which generate lift under wave action to drive rotation about an axis aligned orthogonal to the principle direction of wave propagation. The generation of lift and the resultant rotation of these hydrofoils represents the most fundamental function of this system as this is the mechanism through which energy is extracted from the fluid and transferred into the device. All other system processes are driven by the operation of this element. Thus, it is insightful to try to identify the *optimum hydrofoil path* as this will represent the 'target state' of the system.

Clearly, the *optimum* hydrofoil path will vary dependent on the *optimization parameter*. As the fundamental purpose of the system is to extract energy from ocean waves, it seems most appropriate that the primary optimization parameter considered during concept development should be the maximisation of hydrofoil power[2]. Maximisation of hydrofoil power has been selected as the primary optimization parameter as it is expected that this will also maximise the transfer of energy from the fluid to the device, thus presumably permitting the greatest potential level of energy extraction[3]. Thus, most fundamentally, a Concept Design support tool will be developed which permits the determination of the hydrofoil path which maximises hydrofoil power for a single rotating hydrofoil driven by a wave-induced fluid flow.

It is expected that the optimum hydrofoil path and motion in a steady state scenario (i.e. regular waves) will vary with; hydrofoil lift and drag characteristics, wave period, wave height, water depth and submergence. Thus, the toolset will be developed to permit investigation of variation in the optimum hydrofoil path for these variables. Observation of deviations in the optimum hydrofoil path

[2] Hydrofoil power is defined as the product of the hydrofoil angular velocity and hydrofoil torque about the rotational axis.

[3] Naturally, consideration of alternative optimization parameters such as minimizing the cost of energy produced is important, however, consideration of such alternatives represents system optimisation and the reader is reminded that these tools are intended to provide an understanding of the underlying system physics as opposed to providing direction for detailed engineering design. Consideration of such alternative optimization parameters is therefore not appropriate at this stage however will be more useful at a later stage in the design process when the implications of fundamental operational decisions are better understood.

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across a range of steady state conditions will assist with identification of the design variables which are most critical to optimising performance in non-steady state conditions (irregular sea states). For example, it will be important to determine the potential influence of variable pitch, operational radius and rate of rotation on the system's ability to follow the optimum hydrofoil path in the first instance. The toolset should therefore also permit demonstration of the degree of variation in the optimum hydrofoil path that occurs due to operation in irregular sea states. This knowledge will be used to hypothesize desirable control system requirements for later investigation of their influence on structural loading, power capture and annual energy production.

In order to determine the optimum hydrofoil path, it will be necessary to represent the operation of the hydrofoil thus the user will be able to define lift and drag characteristics as desired. If permissible, the toolset will be developed such that the influence of hydrofoil characteristics can be investigated without the need to pre-select specific hydrofoil forms. That is, it is intended that the hydrofoil properties will be defined based on a series of parameters which represent the influence of hydrofoil physical characteristics on their operational performance (i.e. on their lift and drag characteristics). Thus, the toolset will permit both investigation of the influence of generalised hydrofoil characteristics and the modelling of specific hydrofoil forms if desired.

As it is expected that the optimum hydrofoil path and motion will vary with elements of control, the tool will be developed such that the user will be able to permit or restrict real-time variation of the hydrofoil pitch, operational radius and rate of rotation. Thus, the user will be able to identify variation in the Optimal hydrofoil path where the system is somehow restricted.

Output from the toolset will include detail of the 2-dimensional positional coordinates (x and z locations) of the hydrofoil with time as well as the relative flow magnitude and direction. This will permit user identification of the optimal hydrofoil path shape and rate of travel across the phase space, thus providing an understanding of the necessary variations in operational radius and rate of rotation. The tool will also output details on the flow regime at the hydrofoil including the magnitude of the relative flow velocity on the foil and the angle of attack. Where hydrofoil pitch variation is permitted, detail of local pitch will also be output. Note that the system may or may not be constrained to operate with phase-locking. If it is thought to be of benefit to the project, the tool developers will consider extension of the tool to permit identification of the optimum path of multiple unidirectional rotating hydrofoils.

The intended operation and desired functionality of the toolset for identification of optimum hydrofoil path is summarised in Table 1.

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Table 1: Desired Toolset Functionality for Determination of Optimal Hydrofoil Path

<table>
<tr><th colspan="2">User Inputs</th></tr>
<tr><td colspan="2">• Hydrofoil lift characteristic with respect to angle of attack
• Hydrofoil drag characteristic with respect to angle of attack
• Wave characteristics</td></tr>
<tr><th colspan="2">Optimization Parameter</th></tr>
<tr><td colspan="2">• Maximum hydrofoil power</td></tr>
<tr><th colspan="2">User Specification</th></tr>
<tr><td colspan="2">• Hydrofoil pitch (options: fixed/variable/variation rate restricted)
• Radius of operation (options: fixed/variable/variation rate restricted)
• Rate of rotation (options: fixed/variable/variation rate restricted)</td></tr>
<tr><th colspan="2">Scenario Selection & Associated User Specifications</th></tr>
<tr><td>Regular Waves (Steady State)
• Wave period
• Wave height</td><td>Irregular Waves (Unsteady State)
• Representative wave period
• Significant wave height
• Spectral shape</td></tr>
<tr><th colspan="2">Parameters to be Investigated</th></tr>
<tr><td>• Wave height
• Wave period
• Spectral shape
• Water depth
• Submergence</td><td>• Hydrofoil pitch
• Radius of operation
• Rate of rotation</td></tr>
<tr><th colspan="2">Output</th></tr>
<tr><td colspan="2">• Optimal hydrofoil path
  ➢ 2-dimensional (x, z) hydrofoil co-ordinates with time
  ➢ Relative flow magnitude and angle of attack at the hydrofoil
  ➢ Rate of change of angle of attack
  ➢ Local hydrofoil pitch with time (if applicable)
• Optional - Optimal hydrofoil paths for multiple rotating hydrofoils</td></tr>
</table>

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2.4.3 Power Capture

Power Capture refers to LiftWEC's ability to extract and convert energy into a useful form from an incident sea. In its most basic form, Power Capture may be considered as the total hydrodynamic energy extracted from a wave and including consideration of generator or other conversion losses. This is different from the hydrofoil power calculated in the previous tool (Section 2.4.2) as this includes consideration of the conversion efficiency. Traditionally, the hydrodynamic power capture of a Wave Energy Converter may be calculated either directly or indirectly.

Direct estimation of the hydrodynamic power capture generally requires some understanding of the body motions and Power-Take-Off (PTO) arrangement. Where these are known or computed, the hydrodynamic power capture may be estimated in either the time or frequency domain. In the time domain, hydrodynamic power capture may be determined as the product of instantaneous body velocity and PTO force. In the frequency domain, the power capture must be estimated as a statistically representative average value for a given regular sea where the results for many regular wave frequencies may be combined to provide an estimation of power capture in an irregular sea.

Indirect estimation of the hydrodynamic power capture typically relies on representing the Wave Energy Converter's fundamental hydrodynamics in some other fashion where either the body motions, Power-Take-Off arrangement or both are either not known or not easily determined. A typical example of this approach uses the far-field hydrodynamics of a given system to estimate the potential hydrodynamic power capture where the far-field hydrodynamics can be represented as the linear super-positioning of the incident wave field and a radiated wave field that is propagating away from the device. Indeed, it can be shown that the maximum hydrodynamic power capture depends only on the radiation pattern generated by the Wave Energy Converter[4]. The relationships which can be developed between the incident wave field, the radiated wave field and the maximum potential hydrodynamic power capture are a consequence of the Haskind Relations, which link the incident wave field to the radiated wave field. Importantly, the Haskind Relations are derived from far-field considerations and so are not affected by *how* the far-field radiated waves are generated, simply how they may be related to the incident far-field waves[5].

It is possible that two separate Concept Design support tools will be developed for estimation of Power Capture; one employing a direct method of estimating power capture, and one employing an indirect method of estimating power capture. The results obtained should enable the user to quantitatively assess the impact of critical design variables on the potential power capture of the system and identify design variables which have the greatest impact on hydrodynamic performance. The system should permit consideration of those results in parallel with similar findings obtained relating to the Fundamental Reaction Forces and Hydrofoil Reaction Torques experienced.

The tools will be developed ensuring that estimates of hydrodynamic power capture will be possible for system operation in regular and irregular sea states. Tools will also permit modification of environmental variables such as wave height, period, spectral shape, water depth and submergence.

[4] Falnes, J. (2002). In Ocean Waves and Oscillating Systems: Linear Interactions Including Wave-Energy Extraction. Cambridge: Cambridge University Press.

[5] Although the near-field hydrodynamics associated with a rotating hydrofoil are very different to the hydrodynamics associated with traditional oscillatory Wave Energy Converters, it would seem reasonable that the optimum far-field hydrodynamics are not significantly affected by the type of interaction between the incident waves and driven body.

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Exploration of the design will be achievable through user specification of key device design parameters such as; hydrofoil lift/drag characteristics, hydrofoil length/span, hydrofoil pitch, operational radius, power-take-off force characteristics, number of hydrofoils and the application of any control. If possible, the tools will also permit consideration of system performance in both 2- and 3-dimensional scenarios.

In addition, as per guidance provided in Deliverable D2.3, functionality will be included which will allow for consideration of hydrodynamic power capture with variations in;

1) mode of operation (phase-locked/phase-independent),
2) rotor rigidity (fully fixed/compliant), and
3) PTO Characteristics[6] (hub-based/hydrofoil mounted).

The intended implementation and desired functionality for the Concept Design support tools with respect to the estimation of hydrodynamic power capture is summarised in Table 2.

[6] Consideration of the impact of having the Power-Take-Off mounted in the hub vs. mounted on the hydrofoil itself may require consideration of power capture beyond that of solely the hydrodynamic power capture. For example, it may be insightful to consider the influence of generator/conversion efficiency for each system. If possible, it would also be useful to consider the parallel influence on structural loading and load path requirements between the two cases however this is not considered a primary point of investigation.

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Table 2: Desired Toolset Functionality for Estimation of Hydrodynamic Power Capture

<table>
<tr><th colspan="2">User Inputs</th></tr>
<tr><td colspan="2">• Hydrofoil lift characteristic with respect to angle of attack
• Hydrofoil drag characteristic with respect to angle of attack
• Hydrofoil orientation and path (input from toolset element described in Section 2.4.2)</td></tr>
<tr><th colspan="2">Intended Calculation</th></tr>
<tr><td colspan="2">• Expected system power capture (typically hydrodynamic power capture)</td></tr>
<tr><th colspan="2">User Specification</th></tr>
<tr><td colspan="2">• Mode of Operation (Phase-locked/Phase-independent)
• Rotor Motions (Rotational axis: Fully fixed/Compliant)
• PTO Characteristics (Hub based/Hydrofoil mounted)</td></tr>
<tr><th colspan="2">Scenario Selection & Associated User Specifications</th></tr>
<tr><td>Regular Waves (Steady State)
• Wave period
• Wave height</td><td>Irregular Waves (Unsteady State)
• Representative wave period
• Significant wave height
• Spectral shape</td></tr>
<tr><th colspan="2">Parameters to be Investigated</th></tr>
<tr><td>• Wave height
• Wave period
• Wave regularity/spectral bandwidth
• Water depth
• Submergence
• Hydrofoil length/span
• Hydrofoil pitch
• Hydrofoil operational radius</td><td>• Number & orientation of hydrofoils
• Moment of inertia
• Power-take-off characteristics
• Phase relationship (body-wave)
• Control
   ➢ Pitch, radius, rate of rotation, moment of inertia</td></tr>
<tr><th colspan="2">Output</th></tr>
<tr><td colspan="2">• Expected system power capture (kW)</td></tr>
</table>

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2.4.4 Cyclic/Reactive Energy

Cyclic/Reactive Energy is the energy entrained within a mechanical system which must cycle between different states to permit the successful operation of that system. For example, consider a simple mass hanging on a spring. If the mass is displaced from its equilibrium position, a potential energy is generated within the spring. Upon release, the restoring force of the spring will convert that potential energy into kinetic energy. In the absence of any damping, the mass will continue to oscillate about its equilibrium position and the energy entrained within the system will continuously cycle between the potential and kinetic form. In this instance, Cyclic/Reactive Energy refers to the ongoing cycling of energy between the potential and kinetic states. In power engineering this is termed *Reactive Energy*. However, it is noted that use of the term Reactive Energy might introduce confusion between *Reactive Energy* and *Fundamental Reaction Forces* and *Hydrofoil Reaction Torques* which are very different concepts[7], hence the alternate naming convention adopted.

Typically, in wave energy applications, operators seek to ensure that the device achieves the correct velocity at the correct time. Often this will be in an attempt to ensure that the velocity of the device is 'in phase' with the velocity of the driving fluid particles, thus allowing the system to extract the greatest amount of energy possible. This target velocity has a particular magnitude and nature of associated energy. Where the actual kinetic energy of the system varies from that desired at any given time, the system performance will be sub-optimal. Consideration of the Cyclic/Reactive Energy of the system in its operational state compared to that of its desired state, clearly provides an indication of the level and nature of the divergence between the target system and that which has been observed. Control is often used to modify a system's performance characteristics such that this deviation between the target and actual system is reduced. Then, ideally, the overall efficiency of the system is increased. However, energy must be used to apply this control. This energy must be taken from that same system in some form and at a particular time. Consequently, it is therefore important to develop an understanding of the Cyclic/Reactive Energy of a system as this will allow the operator to determine the deviation in energy between the target and the actual state of the system, and perhaps assist with identification of a control strategy which might improve the performance. In other words, understanding the amount and nature of Cyclic/Reactive Energy is important because it typically needs to be controlled in order to maintain the correct phase of a system to maximise power capture[8].

However, with the control of Cyclic/Reactive Energy, there is the potential for system losses to occur due to imperfect conversion efficiencies and other dissipative effects. This dissipation limits the amount of energy which may be extracted from a system as there is only a finite amount of energy available and these losses must be made up from the 'excess' energy which could otherwise have been extracted. It is therefore also important to understand the Cyclic/Reactive Energy requirement of a system in relation to the level of energy extracted. This knowledge will help developers to determine whether or not the use of a particular phase control strategy is beneficial or indeed even viable in a real-world context. For example, if it was found that the Cyclic/Reactive Energy requirement for a system was ten times greater than the level of energy to be extracted, then even 2% losses experienced by the Cyclic/Reactive Energy system could mean a 20% reduction in power capture as those losses must be taken from the excess energy which would otherwise have been available for

[7] Fundamental *Reaction* Forces and Hydrofoil *Reaction* Torques refer to reaction of forces/moments against an external reference to provide stability whereas *Reactive* Energy refers to energy cycled between various sates within a given system.

[8] Note that the Cyclic/Reactive Energy is not typically extracted from a system.

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extraction. Thus, the greater the Cyclic/Reactive Energy requirements of a system, the less energy will typically be available for extraction. Furthermore, it may be expected that where Cyclic/Reactive Energy must be cycled within a mechanical system, increased cost will be incurred in order to provide the necessary mechanics to permit that energy transfer. Therefore, it is extremely important to develop a solid understanding of the Cyclic/Reactive Energy requirements of a system at an early stage in the design and development process.

It is expected that the Cyclic/Reactive Energy requirements of a rotating hydrofoil will be significantly reduced compared to those of more conventional Wave Energy Converters. Even in the simplest case of operation in regular waves, the entirety of the energy entrained within traditional reversal-based oscillatory systems must be cycled at least twice as a result of the stop-start kinematics of the system. A unidirectional rotating hydrofoil however requires no stop-starts in either regular or more complex irregular seas. Furthermore, it is expected that the inertia of a typical LiftWEC system will be smaller than that of other device types. As a result of the simplified motions and reduced inertia, it is expected that the Cyclic/Reactive Energy requirements of a rotating hydrofoil will be considerably smaller than those of more conventional Wave Energy Converters. Indeed, the only Cyclic/Reactive Energy requirement for a simple rotating hydrofoil without highly sophisticated control is the angular acceleration and deceleration of the system required to maintain oscillatory phase with waves of varied period in irregular sea states. At this early stage, it is envisaged that this may even be achievable through a mechanism as simple as intermittently reducing/increasing the power-take-off torque such that the instantaneous energy extracted is reduced at an appropriate point and then ‘re-captured’ at a more appropriate point later in time.

A Concept Design support tool will therefore be developed which allows investigation of the Cyclic/Reactive Energy requirements for a lift-based, wave-driven rotating hydrofoil. This will enable the consortium to determine the expected energy transfer required by the system. It is important that the tool permits this development of an understanding of Cyclic/Reactive Energy for even the simplest hydrodynamic implementation of the system, after which variation in the Cyclic/Reactive Energy requirements due to increased environmental and operational complexity can be determined. The toolset will permit estimation of Cyclic/Reactive Energy requirements in both regular and irregular sea states and with variation in water depth and system submergence. Functionality will be included for investigation of the influence of: hydrofoil operational characteristics (lift & drag), hydrofoil length/span, hydrofoil pitch, operational radius, moment of inertia, 3-dimensional effects, power-take-off characteristics and control. The intended implementation and desired functionality of the Concept Design support tool for investigation of the Cyclic/Reactive Energy cycling of a wave-driven rotating hydrofoil is presented in Table 3.

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Table 3: Desired Toolset Functionality for Estimation of Cyclic/Reactive Energy

<table>
<tr><th colspan="2">User Inputs</th></tr>
<tr><td colspan="2">• Hydrofoil lift characteristic with respect to angle of attack
• Hydrofoil drag characteristic with respect to angle of attack
• Hydrofoil orientation and path (input from toolset element described in Section 2.4.2)</td></tr>
<tr><th colspan="2">Intended Calculation</th></tr>
<tr><td colspan="2">• Quantity and characteristic of Reactive Energy cycles</td></tr>
<tr><th colspan="2">User Specification</th></tr>
<tr><td colspan="2">• Operational mode (options: production/survival - freewheeling)
• Hydrofoil pitch (options: fixed/variable/variation rate restricted)
• Radius of operation (options: fixed/variable/variation rate restricted)
• Rate of rotation (options: fixed/variable/variation rate restricted)
• Moment of inertia (options: fixed/variable/variation rate restricted)
• Number & orientation of hydrofoils (options: number, spacing)</td></tr>
<tr><th colspan="2">Scenario Selection & Associated User Specifications</th></tr>
<tr><td>Regular Waves (Steady State)
• Wave period
• Wave height</td><td>Irregular Waves (Unsteady State)
• Representative wave period
• Significant wave height
• Spectral shape</td></tr>
<tr><th colspan="2">Parameters to be Investigated</th></tr>
<tr><td>• Wave height
• Wave period
• Wave regularity/spectral bandwidth
• Water depth
• Submergence
• Hydrofoil length/span
• Hydrofoil pitch
• Hydrofoil operational radius</td><td>• Number & orientation of hydrofoils
• System moment of inertia
• Power-take-off characteristics
• Phase relationship (body-wave)
• Control
  ➢ Pitch, radius, rate of rotation, moment of inertia</td></tr>
<tr><th colspan="2">Output</th></tr>
<tr><td colspan="2">• Magnitude, nature and form of Cyclic/Reactive Energy requirements</td></tr>
</table>

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2.4.5 Fundamental Reaction Forces

Fundamental Reaction Force refers to the oscillatory wave-induced loading exerted upon the device which must be reacted. Historically, cost-efficient design for the transfer and grounding of Fundamental Reaction Forces has represented one of the most significant challenges for traditional Wave Energy Converter concepts. In particular, this difficulty has emerged due to the sizable magnitude of the Fundamental Reaction Forces experienced by devices which seek to extract energy through either the buoyancy or diffractive force regimes. It is thought however that the Fundamental Reaction Forces experienced by lift-based Wave Energy Converters could be lower than those for other devices due to their departure from 'force-interception' as an operating principle. It is therefore important to develop an understanding of both the magnitude and variability of Fundamental Reaction Forces experienced by lift-based systems.

Fundamental Reaction Forces will typically be generated by; (1) wave action on the support structure, (2) hydrostatic variations with surface undulation and (3) radial thrust[9] of the rotating hydrofoil(s). It is currently expected that radial thrust of the rotating hydrofoils will form the most significant component of the Fundamental Reaction Forces. Indeed, it is already known that symmetric 'cancellation' of radial thrust does not occur for a dual-hydrofoil system as might be expected. Rather, radial forces generated by dual-hydrofoil systems operating across an opposing phase space tend to coincide, thus doubling the Fundamental Reaction Force compared to that of a single hydrofoil system[10]. As a result of the perceived importance of radial thrust and due to the typically well understood nature of wave-induced loading on submerged rigid structures, the toolset developed will focus on estimation of the Fundamental Reaction Forces generated due to operation of the hydrofoil, a large part of which is expected to be the radial thrust loads. It is proposed that upon completion of the Concept Design support tool for estimating Fundamental Reaction Forces, assumptions made relating to prevalence of the operational hydrofoil forces over other Fundamental Reaction Force contributions will be checked.

A Concept Design support tool will be developed which is capable of providing an indication of the expected Fundamental Reaction Forces for a lift-based rotating hydrofoil. This will permit identification of the operation and design factors which most significantly influence Fundamental Reaction Forces. Load cases representing operational and survival modes will be considered for both production seas and storm events. Survival modes considered will include both "*fully-fixed*" and "*freewheeling*" survival strategies. In particular, it will be important to consider the influence of hydrofoil lift/drag characteristics, hydrofoil length, operational radius, moment of inertia, power-take-off characteristics and the number of hydrofoils on Fundamental Reaction Forces. Variation in loading will also be considered for hydrofoil operation throughout the extent of the phase space and with/without control of operational radius, hydrofoil pitch, rate of rotation and moment of inertia.

The intended implementation and desired functionality of the toolset for estimation of Representative Fundamental Reaction Forces[11] is summarised in Table 4.

[9] Radial thrust is used to describe the non-tangential components of lift and drag forces generated by the rotating hydrofoil.

[10] For more on the radial loading of one or more rotating hydrofoils the reader is referred to Section 3.2.2 and Section 3.2.3 of LiftWEC Deliverable *"D2.1 Preliminary Report on Synthesis of Design Knowledge"*.

[11] Representative Fundamental Reaction Force refers to an indication of either the mean or maximum force expected given a specific set of input parameters. Where appropriate, this may be accompanied by a statistical

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Table 4: Desired Toolset Functionality for Estimation of Fundamental Reaction Forces

User Inputs	
• Hydrofoil lift characteristic with respect to angle of attack • Hydrofoil drag characteristic with respect to angle of attack • Hydrofoil orientation and path (input from toolset element described in Section 2.4.2)	
Intended Calculation	
• Representative Fundamental Reaction Force due to hydrofoil operation (RFRF) ➢ RMS/Max of heave, surge & pitch loads/moments ➢ Statistical range of heave, surge & pitch loads/moments	
User Specification	
• Operational mode (options: *production/survival – freewheeling/survival – fully fixed*) • Hydrofoil pitch (options: *fixed/variable/variation rate restricted*) • Radius of operation (options: *fixed/variable/variation rate restricted*) • Rate of rotation (options: *fixed/variable/variation rate restricted*) • Moment of inertia (options: *fixed/variable/variation rate restricted*) • Number & orientation of hydrofoils (options: *number, spacing*)	
Scenario Selection & Associated *User Specifications*	
Regular Waves (Steady State) • *Wave period* • *Wave height*	**Irregular Waves (Unsteady State)** • *Representative wave period* • *Significant wave height* • *Spectral shape*
Parameters to be Investigated	
• Wave height • Wave period • Wave regularity/spectral bandwidth • Water depth • Submergence • Hydrofoil length/span • Hydrofoil pitch • Hydrofoil operational radius	• Number & orientation of hydrofoils • Moment of inertia • Power-take-off characteristics • Phase relationship (body-wave) • Control ➢ Pitch, radius, rate of rotation, moment of inertia
Output	
• Representative Fundamental Reaction Force (RFRF) ➢ Radial thrust load magnitudes ➢ *Optional – Variation in radial thrust load magnitudes* ➢ Non-radial thrust components of FRF due to hydrofoil operation ➢ *Optional – Variation in non-radial thrust force components*	

measure of the expected spread of the Fundamental Reaction Force. At this time there is no intention to develop a Concept Design Support Tool which would estimate the instantaneous Fundamental Reaction Force experienced by a given configuration, however, the possibility of developing such a tool will be explored if it is later found to be desirable and practical to do so.

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2.4.6 Hydrofoil Reaction Torques

The Hydrofoil Reaction Torque is the resistive torque that must be applied to the system to react against the torque generated by the rotation of the hydrofoil. It is largely expected that the useful output generated by the LiftWEC device will be extracted from this Hydrofoil Reaction Torque and thus, the Hydrofoil Reaction Torque would typically be provided by some form of power-take-off mechanism such as an electrical generator. In turn however this generator must have a reaction source to ensure system stability and permit the useful extraction of energy. It is therefore important to determine the expected magnitude of the torque generated by the hydrofoil's operation.

One important difference between the Hydrofoil Reaction Torque and the Fundamental Reaction Force is that while the Fundamental Reaction Forces are typically expected to be oscillatory, the Hydrofoil Reaction Torque will be unidirectional. This has a number of design implications which must be considered. For example, although it may seem sensible to make the Hydrofoil Reaction Source the same as the Fundamental Reaction Source, this may only be possible in the case where the reaction source is the seabed; while phase diversity and inertia could be used to provide Fundamental Reaction Forces, they are not suitable Hydrofoil Reaction Sources. Moreover, the use of the seabed for the Hydrofoil Reaction Source seems incompatible with the use of phase diversity or inertia for the Fundamental Reaction Source as this would negate the benefits that may come with the use of these other Fundamental Reaction Sources. Thus, it would seem that the Hydrofoil Reaction Source should be the seabed only if the Fundamental Reaction Source is also the seabed. The use of weight or buoyancy as the Hydrofoil Reaction Source however can be used with any of the Fundamental Reaction Sources [12].

A Concept Design support tool will be developed which can readily provide reasonable estimates of the Hydrofoil Reaction Torque generated by a lift-driven rotating hydrofoil [13]. This will permit identification of the design factors which most significantly impact Hydrofoil Reaction Torque. Load cases representing operational and survival modes will be considered for both production seas and storm events. The toolset will include functionality to consider the use of a *"freewheeling"* survival strategy. In this instance, there would appear to be no need for a *"fully-fixed"* survival strategy to be considered.

In addition, Concept Design support tools developed will allow investigation of the influence of hydrofoil lift/drag characteristics, hydrofoil length, operational radius, power-take-off characteristics, moment of inertia, number of hydrofoils and hydrofoil phase. Functionality will also be included to consider variation in loading for hydrofoil operation with/without control of operational radius, hydrofoil pitch, rate of rotation and moment of inertia.

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[12] For further discussion on the start-of-project understanding of Hydrofoil and Fundamental Reaction Sources as well as a list of potential reaction sources for each the reader is referred to LiftWEC Deliverable *"D2.1 Preliminary Report on Synthesis of Design Knowledge"*.

[13] Note that at the point of developing an understanding of system physics, it is inconsequential how the Hydrofoil Reaction Torque is provided. The toolset is not intended to provide an indication of the preferred engineering solution but rather is intended to permit investigation of the Hydrofoil Reaction Torque requirement and consideration of its magnitude in comparison to the Fundamental Reaction Forces developed for like systems. The combined consideration of Hydrofoil Reaction Torques and Fundamental Reaction Forces should assist with identification of the hydrodynamics driving the structural requirement after which time decisions on preferred structural arrangements can be made.

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The required functionality of the toolset for estimation of Representative Hydrofoil Reaction Torques[14] is summarised in Table 5.

Table 5: Desired Toolset Functionality for Estimation of Hydrofoil Reaction Torques

User Inputs	
• Hydrofoil lift characteristic with respect to angle of attack • Hydrofoil drag characteristic with respect to angle of attack • Hydrofoil orientation and path (input from toolset element described in Section 2.4.2)	
Intended Calculation	
• Representative Hydrofoil Reaction Torque (RHRT)	
User Specification	
• Operational mode (options: *production/survival – freewheeling*) • Hydrofoil pitch (options: *fixed/variable/variation rate restricted*) • Radius of operation (options: *fixed/variable/variation rate restricted*) • Rate of rotation (options: *fixed/variable/variation rate restricted*) • Moment of inertia (options: *fixed/variable/variation rate restricted*) • Number & orientation of hydrofoils (options: *number, spacing*)	
Scenario Selection & Associated *User Specifications*	
Regular Waves (Steady State) • *Wave period* • *Wave height*	**Irregular Waves (Unsteady State)** • *Representative wave period* • *Significant wave height* • *Spectral shape*
Parameters to be Investigated	
• Wave height • Wave period • Wave regularity/spectral bandwidth • Water depth • Submergence • Hydrofoil length/span • Hydrofoil pitch • Hydrofoil operational radius	• Number & orientation of hydrofoils • Moment of inertia • Power-take-off characteristics • Phase relationship (body-wave) • Control ➢ Pitch, radius, rate of rotation, moment of inertia
Output	
• Representative Hydrofoil Reaction Torque (RHRT) ➢ Magnitude of Hydrofoil Reaction Torque ➢ *Optional – Variation in Hydrofoil Reaction Torque*	

[14] Representative Hydrofoil Reaction Torque refers to an indication of either the mean or maximum torque expected given a specific set of input parameters. Where appropriate, this may be accompanied by a statistical measure of the expected spread of the Hydrofoil Reaction Torque.

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2.4.7 Annual Energy Production & Structural Loading

Annual Energy Production is a metric typically employed to determine the usefulness of a Wave Energy Converter as a utility scale energy generator. While the assessment of Power Capture allows ease of identification of the hydrodynamic performance of a system, it often does so in a detached manner. That is, without a reasonable understanding of a system's potential performance in a real-world scenario, the importance of particular aspects of the power capture variation with environmental or design variables can be difficult to determine. The use of Annual Energy Production, which couples an understanding of the system's power capture to an expected use case can often assist with placing the importance of particular performance features in context. For example, if it is found that the use of a very expensive and complex element of design would permit a doubling of the energy extracted in particular sea states, then it may not be worth spending considerable resources seeking to realise that potential if the overall contribution to Annual Energy Production is small. Thus, from a practical perspective, there is a significant benefit to considering the Annual Energy Production of a given system in parallel with developing further understanding of its potential power capture.

Annual Structural Loading will be used in a similar manner to the Annual Energy Production however where the Annual Energy Production sought to place the importance of particular power capture features in context, Annual Structural Loading will do so for the Fundamental Reaction Forces and Hydrofoil Reaction Torques. It is expected that the assessment of both the Annual Energy Production and the Annual Structural Loading will be conducted within a single tool. In short, this tool which will provide the user with an understanding of the implications of relationships determined between environmental and design variables and the power capture and structural loading of the system in terms of their expected impact on the real-world application of the technology. To provide a second example, this might allow the user to determine that an element of design which allows a significant reduction in structural loading in smaller seas might actually have a relatively small impact on the overall structural loading experienced by the system across its design life.

A Concept Design support tool will therefore be developed which permits the estimation of Annual Energy Production and Annual Structural Loading for a lift-based rotating hydrofoil system. Naturally this tool will require input from the majority of other tools and should allow the user to determine the perceived importance of potentially critical design variables at the point of system implementation. With the parallel availability of Fundamental Reaction Forces and Hydrofoil Reaction Torques it is noted that the combination of these results with the Annual Energy Production should allow for the development of a preliminary understanding of the system's critical performance/load ratios. The availability of this data should further assist with determination of potentially preferable system configurations and implementations. Furthermore, having the Fundamental Reaction Forces and Hydrofoil Reactions Torques separated should further assist with the identification of preferable power-take-off arrangements with respect to the co-location or otherwise of their necessary load paths.

This Concept Design support tool will provide functionality to assess the influence of key environmental and design variables including water depth, submergence, hydrofoil lift/drag characteristics, hydrofoil length/span, number of hydrofoils, power-take-off strategy, hydrofoil pitch, operational radius, moment of inertia and control. Naturally, the tool should permit ease of user specification/modification of the scatter matrix for which the system should be assessed. It is expected that the tool should provide both a simple scatter matrix style generic output across the various wave conditions considered as well as the previously discussed sea-weighted annual outputs.

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The intended implementation and desired functionality of a Concept Design support tool for Annual Energy Production and Annual Structural Loading is presented in Table 6.

Table 6: Desired Toolset Functionality for Estimation of Annual Energy Production and Annual Structural Loading

<table>
<tr><th colspan="2">User Inputs</th></tr>
<tr><td colspan="2">
• Hydrofoil lift characteristic with respect to angle of attack
• Hydrofoil drag characteristic with respect to angle of attack
• Hydrofoil orientation and path (output from toolset described in Section 2.4.2)
• Hydrofoil power capture characteristics (output from toolset described in Section 2.4.3)
• Fundamental Reaction Forces (output from toolset described in Section 2.4.5)
• Hydrofoil Reaction Torques (output from toolset described in Section2.4.6)
</td></tr>
<tr><th colspan="2">Intended Calculation</th></tr>
<tr><td colspan="2">
• Weighted Annual Energy Production (kWh/y)
• Weighted Annual Structural Loading due to Fundamental Reaction Forces
• Weighted Annual Structural Loading due to Hydrofoil Reaction Torques
• Sea State Performance (kW) and Efficiency (%)
• Sea State Loading Characteristics
</td></tr>
<tr><th colspan="2">User Specification</th></tr>
<tr><td colspan="2">
• Hydrofoil pitch (fixed/variable)
• Radius of operation (fixed/variable)
• Rate of rotation (fixed/variable)
</td></tr>
<tr><th colspan="2">Scenario Selection & Associated User Specifications</th></tr>
<tr><td colspan="2">
User Defined Scatter Matrix (Irregular Seas)
• Mean period
• Significant wave height
• Spectral shape
</td></tr>
<tr><th colspan="2">Parameters to be Investigated</th></tr>
<tr><td>
• Water depth
• Submergence
• Hydrofoil length/span
• Hydrofoil pitch
• Hydrofoil radius
</td><td>
• Number/position of hydrofoils
• Power-take-off characteristics
• Control
➢ Pitch, radius, rate of rotation, moment of inertia
</td></tr>
<tr><th colspan="2">Output</th></tr>
<tr><td colspan="2">
• Weighted Annual Energy Production (kWh/y)
• Weighted Annual Structural Loading due to Fundamental Reaction Forces
• Weighted Annual Structural Loading due to Hydrofoil Reaction Torques
• Sea State Performance (kW) and Efficiency (%)
• Sea State Loading Characteristics
</td></tr>
</table>

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2.5 RELATIONSHIP TO OTHER PROJECT TOOLSETS DEVELOPED

The LiftWEC project includes the development of various modelling tools to support the design of LiftWEC configurations. In general, these other tools involve the definition of a LiftWEC configuration and then simulating the response of this configuration to different system parameters and wave conditions. For example, the tools developed in Work Package 05 allow the effect of different control strategies on body response and power capture to be investigated. As such these other tools model the response of actual LiftWEC design to specific wave conditions. The design support tools developed in Work Package 02 are different because they do not attempt to model a response of a system. On the contrary, they are designed to identify what the optimal response or the consequences of a particular response may be, without explicit consideration of what is reasonable.

The key advantage of this is that the optimal response can be identified without consideration of practicalities, providing potentially valuable insight into the optimal design. However, it is likely that in producing these design tools it will be necessary to make some simplifications/assumptions that may or may not be reasonable. Clearly, for the insight to be valuable it is important that the consequences of the simplifications/assumptions are understood and the interpretation of the insight to be modified appropriately. The assessment of the validity of the simplifications/assumptions used in the design support tools will be done using the other tools that have been developed with the LiftWEC project.

For example, the fundamental reaction force design support tool may use the assumption that the only significant force that contributes to the fundamental reaction force is from the hydrofoil lift and drag forces that can be derived from lift and drag coefficients. The validity of this assumption can be assessed by comparing the fundamental reaction forces estimated by the design support tool with those obtained from a CFD model that will also be developed within the LiftWEC project.

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3 CONCEPT EVALUATION SUPPORT TOOL SPECIFICATION

3.1 OVERVIEW

The main objective of the LiftWEC project is to investigate the potential of lift-based Wave Energy Converters and, if possible, bring forward one or more lift-based WEC concepts from TRL 1 to TRL 3/4. The project approach is to begin by mapping out the design space covered by the LiftWEC Problem Scope[15] and target the generation of design knowledge to that which is thought to be most critical for the development of lift-based Wave Energy Conversion systems. This is followed by a three-phase, iterative design exercise based around structured innovation, knowledge capture and re-integration of learning into subsequent concept development and assessment. Throughout the project, a whole-systems and interdisciplinary approach is taken to knowledge generation and capture activities, ensuring configurations are not developed without input to both primary and secondary design drivers.

Following each phase of iterative knowledge generation, capture and concept development, previous design elements and concept configurations are evaluated based on knowledge generated in the preceding phase. As such, it is important that a fair, appropriate and consistent approach is taken to evaluation. Indeed, a previous LiftWEC project deliverable has already been produced which sought to develop a set of evaluation criteria suitable for use in the LiftWEC project[16]. This deliverable undertook an extensive literature survey to draw existing knowledge and learning from both the wave energy industry and further afield to develop these evaluation criteria. This section details the intended implementation and desired specification of the tools which will be used to undertake evaluation processes using those evaluation criteria.

As the LiftWEC project progresses and further information is acquired, it is expected that the methods and specifications employed for concept evaluation may become outdated. Consequently, these implementations and specifications represent the current understanding of the most useful evaluation approach and metrics. As such, the information contained in this section is subject to change pending further learning. This will allow the project direction to be suitably adjusted such that the scientific output remains aligned with that which is perceived to provide the greatest level of benefit to the wave energy industry and indeed the successful development of a lift-based Wave Energy Converter. It would not be ideal if favourable avenues of investigation could not be explored on account of a technicality due to retrospective identification of a previous oversight at an earlier stage of the project.

[15] LiftWEC Problem Scope: *"LiftWEC is a wave energy converter that extracts energy from the waves and converts it to electricity to be supplied at grid-scale to an underwater seabed cable. LiftWEC couples with the waves through lift forces generated by one or more hydrofoils that rotates in a single direction about one or more horizontal axes aligned orthogonally to the mean direction of wave propagation."*

[16] For more information on the relevance and selection of the LiftWEC evaluation criteria the reader is referred to LiftWEC Deliverable D2.2 *"LW-D02-02-1x0 Identification of Evaluation Criteria"*

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3.2 BIBLIOGRAPHY REVIEW

Prior to specification and development of the LiftWEC Concept Evaluation Support Tools it was intended that a review of pre-existing WEC assessment and evaluation criteria would be conducted. The culmination of that work is presented in LiftWEC Deliverable D2.2 *"LW-D02-02-1x0 Identification of Evaluation Criteria"*. Since its publication, the DTOceanPlus project released a new report [17] describing the Stage gate tools involved in the project. The report describes the evaluation thematic selected, the activities required at each stage to provide the necessary information for the evaluation, and the associated metrics.

WEC development is divided into 5 Stages, with Stage 0-1 covering the TRL up to TRL 3, and Stage 2 corresponding to technologies at TRL 4. Stages 3 to 5 covers the TRL up to TRL 9. The activities and metrics are adapted to each Stage. As the LiftWEC's scope covers the development of the concepts up to the TRL 4, the information related to the Stages 0, 1 and 2 are potentially relevant. However, the selection of LiftWEC candidate concepts will be conducted with configurations at TRL from 0 to 3, and only the selected concepts will be brought to TRL 4. The review of the information will, therefore, solely focus on the material related to the stages 0 and 1.

The DTOceanPlus report provides the list of evaluation criteria into 10 categories:

- Affordability
- Availability
- Reliability
- Maintainability
- Manufacturability
- Survivability
- Power Capture
- Power Conversion
- Installability
- Acceptability

For each category, a list of actions and type of information required to score the technology is provided. The list is summarised in Table 7.

Table 7: list of activities for Stage 0 and 1 of the DTOceanPLUS project.

Categories	Stage 0	Stage 1
AFFORDABILITY	Basic Capital Expenditure (CAPEX) estimate Additional CAPEX detail Target selection	CAPEX evaluation of Bill of Materials (BOM) Expand cost evaluation Calculate Levelized Cost of Energy (LCOE)
RELIABILITY	Evaluation of comparable technologies Novelty evaluation Target selection (reliability) Potential for control systems	Numerical model Structural component strength assessment Structural component safety factors Design limit states Identify failure modes
AVAILABILITY	Evaluation of comparable technologies Novelty evaluation Target selection for availability	Integrate FMEA and Operations and Maintenance (O&M) plan

[17] Wave Energy Scotland, The University of Edinburgh, ESC, WavEC, Tecnalia, "DTOceanPlus Deliverable D4.2 Stage Gate tool – Alpha version," DTOceanPlus, Edinburgh, 2020.

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Categories	Stage 0	Stage 1
MAINTAINABILITY	Potential for control systems Evaluation of comparable technologies Novelty evaluation Target selection for maintainability	Concept characterisation (maintainability) Develop high-level O&M process
MANUFACTURABILITY	Materials identification Sizing estimates for structure	Demonstration of manufacturing process (tank tests) Demonstration of manufacturing process (rig tests) Simple subsystem breakdown Outline manufacturing process Manufacturing feasibility assessment
SURVIVABILITY	Evaluation of comparable technologies Novelty evaluation Target selection for survivability	Concept characterisation Numerical model (extreme loads) Structural component strength assessment Structural component safety factors Design limit states for survivability
POWER CAPTURE	Basic hydrodynamic calculations Hydrodynamic performance estimates Device concept definition	Tank testing of energy capture technology Evaluation of tank testing Numerical model (hydrodynamic performance) Validate numerical model
POWER CONVERSION	PTO concept definition Additional energy transformation details	Rig testing of subsystems Numerical model for energy transformation
INSTALLABILITY	Impact of control systems on installability Evaluation of comparable technologies Novelty evaluation Target selection	High-level installation plan Concept characterisation (installability)
ACCEPTABILITY	Acceptability assessment	General acceptability evaluation

At Stage 0, the identification of the concepts novelty and target for each category should be conducted. At Stage 1, the requirement of completing an FMEA for all candidate concepts is compelling, as it will inform many of the categories and support the rating of the concepts.

Additional to the activities and metrics recommended to rate the technologies at each stage, a series of qualitative questions are presented in the deliverable.

3.3 Toolset Functionality Required

The aim of this tool is to enable the evaluation of several WEC configurations considering a set of comparison criteria. The main functionalities of the tool are the following:

- Weighting of the selection criteria based on a rational method
- Fractioned scoring of the WEC configurations
- Ranking of the WEC configurations scores
- Possibility to perform sensitivity analysis on the criteria weighting

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3.3.1 Categorising the concepts

The tools should allow the classification of the concepts as a function of the type of rotor, type of control, type of support structure and type of PTO. The classification of the concepts into different categories will allow the ranking of the concepts.

3.3.2 Weighting of the selection criteria by pairwise comparison

The tool should provide an automated method to estimate the weight of each evaluation criteria based on a predefined method using inputs from the LiftWEC partners. A pair wise comparison method is suggested as described in section 3.8.1.

3.3.3 Fractioned scoring of the WEC configurations

The tool should provide a standardised method for scoring the concepts regarding the different evaluation criteria presented in Table 8 to Table 15. Scoring will be completed by all LiftWEC partners and should therefore be built with the required flexibility.

The scoring of the concept should be relative and not absolute in order to facilitate the differentiation between the concepts. Therefore, the possibility to harmonize the scores and ensure that the full range of scoring is used for each category should be considered.

3.3.4 Ranking of the WEC configurations scores

Once the weighting of the criteria and the fractioned scoring of the WEC concepts is complete, the Concept evaluation Support tool should provide a ranking of the different concepts, for all the concepts together and as a function of the different categories identified for the categorisation of the concepts.

The ranking of the concepts should consider the possibility to perform a sensitivity analysis on the weights of the criteria in order to provide an indication of the variability of the final scoring and ranking associated to each concepts.

3.4 Toolset Inputs

3.4.1 Evaluated configurations

List of the scenarios to be assessed.

Note: for example, 18 scenarios combining several ‘categories:

- WEC rate power (0.2MW, 0.5MW, 0.8MW)
- WEC type (horizontal blades, vertical blades)
- WEC foundation (fixed in seabed, gravity-based, floating semisub)

3.4.2 Evaluation criteria

List of the evaluation criteria, considering

- Specific criteria: some criteria will be specific to one ‘category’ (for example, a criterion ‘ability to adapt to different soil conditions’ will be scored on the WEC foundation category, independently from other categories of the configuration)
- Transverse criteria: some criteria must be assessed considering the complete configuration

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The objective is to have not too many transverse criteria or try to split them into specific criteria as much as possible.

3.5 Engagement with LiftWEC partners

The evaluation and selection of concepts within the LiftWEC consortium is a crucial tasks, and all partners should be provided the means to take ownership of the decision process. Additionally, all partners of the project will have different experiences and appreciation for the aspects required to assess the different concepts. It is therefore important that inputs from the partners at all the steps of the evaluation process (weighting of the criteria, fractional scoring of the concepts, selection from ranking) are considered.

The pairwise comparison used for the weighting of the criteria can be obtained from the independent efforts of all the team involved. The variability of the comparisons between the different teams will be considered as inputs for the sensitivity analysis defined in section 3.3.4.

Similarly, the fractional scoring of the concepts can be obtained by asking all the partners to independently score the concepts against the different criteria, and then averaging the results. Such process can be built within the tool from the onset.

Once the ranking of the concepts will be obtained, the selection of the concepts must involve all the partners. This is not properly a requisite of the evaluation tool, but of the evaluation process itself.

3.6 Software Platform

The Concept Evaluation support tool will be implemented as a simple spreadsheet workbook that provides evaluation guidance and allows for direct user input of evaluation scores for the range of evaluation criteria defined in LiftWEC Deliverable D2.2 "*LW-D02-02-1x0 Identification of Evaluation Criteria".* Spreadsheets offer significant functionality and flexibility in organization, analysis, storage and presentation of small, interactive, user-driven datasets. Indeed, spreadsheet-based datasets are one of the most commonly used formats for collection, manipulation, and presentation of data across many industries and platforms. It is therefore expected that all project partners are familiar with their construction and use.

Data held within a spreadsheet is typically readable by both proprietary and open-source spreadsheet applications, as well as by a significant number different programming languages. Thus, whilst it would be possible to develop a bespoke, project-orientated software with an associated database, it is thought that the use of a simple spreadsheet application will better serve the purpose of the Concept Evaluation support tool and ensure that the toolset is accessible to all project partners.

The evaluation tool is an Excel spreadsheet gathering the different steps of the evaluation process.

3.6.1 Spreadsheet Structure

3.6.1.1 Sheet 1 – List of configurations

List of all the detailed considered configurations, with the required categories

3.6.1.2 Sheet 2 – List of evaluation criteria

List of the criteria with their definitions, also defining if they are specific or transverse

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3.6.1.3 Sheet 3 – Criteria weighting
Pairwise comparison matrix and weighting matrix. This will include the possibility to obtain inputs from the different partners

3.6.1.4 Sheet 4 – Specific criteria scoring matrices
Scoring of the specific criteria for each category of criteria. This will include the possibility to obtain inputs from the different partners

3.6.1.5 Sheet 5 – Main scoring matrix
Global matrix:

- Criteria weighting automatically filled in (from criteria weighting sheet)
- All specific scores automatically filled in (from specific criteria scoring sheet)
- Scoring of the transverse criteria

Global scores for each configuration and ranking are also included in this sheet.

3.6.2 Spreadsheet Inputs required
The following inputs are required:

- List of the configurations (sheet 1)
- List of the criteria (sheet 2)
- Pairwise comparison matrix (sheet 3)
- Specific criteria scores (sheet 4)
- Transverse criteria scores (sheet 5)

3.6.3 Spreadsheet Outputs Required
The following outputs are provided:

- Overall score for each configuration
- Ranking of the configurations

3.7 Parameter Specification

The parameters against which LiftWEC configurations are to be evaluated were initially proposed and described in LiftWEC deliverable D2.2 *"LW-D02-02-1x0 Identification of Evaluation Criteria"*. For more information on the relevance and selection of these criteria, as well as further descriptive text, the user is referred to that publication. This section details the approach to be taken by the LiftWEC consortium during evaluation of LiftWEC concept configurations. Details are given for each parameter identified in LiftWEC Deliverable D2.2.

As stated previously, it is acknowledged that there may be reason to modify the scoring criteria or indeed even the evaluation parameters themselves as the project progresses and further design knowledge is generated. To ensure that the impact and implications of such changes are both understood and appreciated, all variations in evaluation parameters or scoring criteria should be logged in the evaluation toolset documentation and a new release version of the toolset issued. Furthermore, any output generated by the toolset should ensure that all assessment exercises are accompanied by an identifier which details the evaluation toolset version employed in a given assessment. This should help to ease identification of re-evaluation requirements when

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improvements are applied to the toolset, thus in turn ensuring that previously assessed configurations do not continue to be unduly criticised or mistakenly recommended on account of outdated understanding. If practical, the toolset should also be designed to provide an output indicating configuration assessments that should be reconsidered following toolset updates and revisions.

Prior to presentation of the parameter specification the reader is reminded that the LiftWEC project seeks to develop a lift-based Wave Energy Converter, and the intended purpose of the evaluation exercise is not to allow potential LiftWEC configurations to be benchmarked against traditional WECs, nor is it intended to identify one specific optimum configuration from those generated. Rather, the purpose of the evaluation exercise is to rank the potential design elements and configurations developed. It is intended that the evaluation toolset should allow identification of instances where one or more sub-systems within a configuration significantly increases or decreases that configuration's rank, thus permitting extraction of the relevant design knowledge for inclusion in future research efforts if desired. In addition, the reader is advised that, as outlined in Deliverable D2.2, the evaluation process is not intended to be conducted at the current state of development, however with the foresight of consideration of the configuration's potential at the point of commercial roll-out.

The remainder of this section is comprised of a series of tables which detail the evaluation approach taken to each of the evaluation criteria as presented in LiftWEC deliverable D2.2. The parameters are grouped into five key areas as outlined in Deliverables D2.2. The five key areas for evaluation are; (1) Energy Production, (2) Survivability, (3) Affordability, (4) Acceptability and (5) Developability. Evaluation parameters and scoring criteria for *Energy Production* are presented in Table 8. Evaluation parameters and scoring criteria for *Survivability* are presented in Table 9. Evaluation parameters and scoring criteria for *Affordability* are presented in Table 10, Table 11, Table 12 and Table 13. Evaluation parameters and scoring criteria for *Acceptability* are presented in Table 14. Evaluation parameters and scoring criteria for *Developability* are presented in Table 15.

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Table 8: Evaluation Criteria Specification for Energy Production

Criteria Level 1	Criteria Level 2	Evaluation Specification/Scoring Criteria	
Energy capture	Energy absorption potential	Input:	Capture Width Ratio (**%**).
		Source:	Concept Design support tools, low/high fidelity numerical models, physical experiments.
		Notes:	Capture Width Ratio defined as percentage of wave energy absorbed across device span in design sea.
	Control potential	Input:	Numeric score (**1 – 10**, *1 – no control, 5 – fair control, 10 – perfect control*)
		Source:	Evidence based manual assessment.
		Notes:	Score given according to impact of control on *Energy absorption potential*.
	Load shedding abilities	Input:	Numeric score (**1 – 10**, *1 – no shedding, 5 – fair shedding, 10 – complete shedding*)
		Source:	Evidence based manual assessment.
		Notes:	Score given according to ability of system to shed extreme loads during large seas. Consideration to be given to the ability to continue operation in large seas.
	Versatility	Input:	Numeric score (**1 – 10**, *1 – no versatility, 5 – fair versatility, 10 – strong versatility*)
		Source:	Evidence based manual assessment.
		Notes:	Score given according to ability to perform equally well across a wide range of sea states and environmental conditions.
Energy conservation	Storage	Input:	Numeric score (**1 – 10**, *1 – no versatility, 5 – fair versatility, 10 – strong versatility*)
		Source:	Evidence based manual assessment.
		Notes:	Score given according to ability to store some energy within the PTO chain prior to exportation. Rotor inertia can be interpreted as a energy storing ability.
	Efficiency	Input:	Efficiency of power train (**%**)
		Source:	Evidence based manual assessment.
		Notes:	Defined as the efficiency of hydrodynamic to electrical energy conversion

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Table 9: Evaluation Criteria Specification for Survivability

Criteria Level 1	Criteria Level 2	Evaluation Specification	
Load shedding abilities	Rotor shedding abilities	Input:	Numeric score (**1 – 10,** *1 – no shedding, 5 – fair shedding, 10 – complete shedding*)
		Source:	Evidence based manual assessment.
		Notes:	Score given according to ability to limit rotor (hydrofoil) loading through active or passive control or by any other means.
	Structural support abilities	Input:	Numeric score (**1 – 10,** *1 – no limiting, 5 – fair limiting, 10 – complete limiting*)
		Source:	Evidence based manual assessment.
		Notes:	Score given according to ability to limit loads on support structure through active or passive control or by any other means.
Loads in extreme event	Extreme loads	Input:	Numeric score (**1 – 10,** *1 – severe extreme loads, 5 – fair extreme loads, 10 – no/reduced extreme loads*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of the severity of extreme fundamental reaction and hydrofoil torque loads experienced by the system in survival mode. Should consider option for disengaging power take off. Note reduction of extreme loads refers to reduction below operational loads.
	Snap loads/End-stop risks	Input:	Numeric score (**1 – 10,** *1 – severe snag/snag/end-stop risks, 5 – fair snag/snag/end-stop risks, 10 – no snag/snag/end-stop risks*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of risk of impulsive loads due to snap or snag loads or end-stop risks etc. Should consider use of survival mode and option for disengaging power take off.

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Table 10: Evaluation Criteria Specification for Affordability

Criteria Level 1	Criteria Level 2	Evaluation Specification	
Structural requirement	Rotor structural requirement	Input:	Numeric score (**1 – 10,** *1 – high requirement, 5 – fair requirement, 10 – very low requirement*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of rotor structural requirement due to fatigue and ultimate limit state
	Support structure structural requirement	Input:	Numeric score (**1 – 10,** *1 – high requirement, 5 – fair requirement, 10 – very low requirement*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of support structure structural requirement due to fatigue and ultimate limit state
	Structural versatility	Input:	Numeric score (**1 – 10,** *1 – no versatility, 5 – some versatility, 10 – very high versatility*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of versatility in structural material choice, manufacturing processes etc.
Station keeping requirement	N/A	Input:	Numeric score (**1 – 10,** *1 – high complexity/risk, 5 – fair complexity/risk, 10 – very low complexity/risk*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of complexity of- and risk to- the station keeping system.
Installability	Safety	Input:	Numeric score (**0 – 10,** *0 – extremely unsafe, 5 – adequately safe, 10 – very safe*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of safety of installation operations and procedures. Note scoring less than 5 results in concept considered as *inadequate*.
	Transport to site requirement	Input:	Numeric score (**1 – 10,** *1 – extremely difficulty, 5 – fair difficulty, 10 – no difficulty*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of ease and cost of system transport from port to installation site. May account for transport vessel requirements, distance travelled etc.

Table 11: Evaluation Criteria Specification for Affordability (cont.)

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Criteria Level 1	Criteria Level 2	Evaluation Specification	
Installability (cont.)	Boats/asset requirement	Input:	Numeric score (**1 – 10,** *1 – extreme requirements, 5 – fair requirements, 10 – very minor requirements*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation related to specialist vessel, asset and diver requirements for farm installation. Should consider complexity of operations, availability of specialist vessels, diver & ROV requirements etc.
	WEC installation time	Input:	Numeric score (**1 – 10,** *1 – excessive requirements, 5 – fair requirements, 10 – very minor requirements*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of time required to install a single WEC as a sum of all actions required including preparation, manoeuvring, installation, attachment etc. Does **not** include accountancy for availability of weather windows.
	Farm installation time	Input:	Numeric score (**1 – 10,** *1 – excessive requirements, 5 – fair requirements, 10 – very minor requirements*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of time required to install complete wave farm including weather window availability.
Manufacturability	Rotor	Input:	Numeric score (**1 – 10,** *1 – excessive complexity, 5 – fair complexity, 10 – no complexity*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of complexity for mass production of rotor. Consideration of blade length, size, profile, mounting structure, electronics incorporation, materials etc.

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Table 12: Evaluation Criteria Specification for Affordability (cont.)

Criteria Level 1	Criteria Level 2	Evaluation Specification	
Manufacturability (cont.)	Support structure	Input:	Numeric score (**1 – 10,** *1 – excessive complexity, 5 – fair complexity, 10 – no complexity*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of complexity for manufacture of support structure. Consideration of size, shape, functionality, component interdependence, modularity, materials etc.
	PTO	Input:	Numeric score (**1 – 10,** *1 – excessive complexity, 5 – fair complexity, 10 – no complexity*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of the complexity for manufacture of the Power Take Off unit. Consideration of size, form, implementation, modularity, availability, materials etc.
Maintainability	Connection/disconnection requirement	Input:	Numeric score (**1 – 10,** *1 – extreme difficulty, 5 – fair difficulty, 10 – no difficulty*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of difficulty in retrieval/redeployment of a single WEC for maintenance purposes. Should consider weather window availability.
	Modular O&M	Input:	Numeric score (**1 – 10,** *1 – no modularity, 5 – fair modularity, 10 – complete modularity*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of modularity and implementation of concept for ease of maintenance.
	Boats/asset requirement	Input:	Numeric score (**1 – 10,** *1 – extreme requirements, 5 – fair requirements, 10 – very minor requirements*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation related to specialist vessel, asset and diver requirements for maintenance operations. Should consider complexity of operations, availability of specialist vessels, diver & ROV requirements etc.

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Table 13: Evaluation Criteria Specification for Affordability (cont.)

Criteria Level 1	Criteria Level 2	Evaluation Specification	
Maintainability (cont.)	Safety	Input:	Numeric score (**0 – 10,** *0 – extremely unsafe, 5 – adequately safe, 10 – very safe*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of safety of maintenance operations and procedures. Note scoring less than 5 results in concept considered as *inadequate*.
	Critical elements	Input:	Numeric score (**1 – 10,** *1 – no redundancy/excessive vulnerability, 5 – fair redundancy/fair vulnerability, 10 – high redundancy/very minor vulnerability*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of redundancy/requirement for operation of critical elements without which device would not function/survive.
Reliability	Prime mover/structural	Input:	Numeric score (**1 – 10,** *1 – very poor reliability, 5 – fair reliability, 10 – very good reliability*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of reliability of rotor, support structure, station keeping system etc.
	PTO	Input:	Numeric score (**1 – 10,** *1 – very poor reliability, 5 – fair reliability, 10 – very good reliability*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of reliability of Power-Take-Off and control units.

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Table 14: Evaluation Criteria Specification for Acceptability

Criteria Level 1	Criteria Level 2	Evaluation Specification	
Regulatory & environmental	N/A	Input:	Numeric score (**0 – 10,** *0 – regulatory acceptance not possible, 5 – fair acceptability, 10 – very acceptable*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of system acceptability from regulatory and environmental perspectives. Should consider device size, materials, manufacturing processes, carbon embodiment, ecological impact, installation/maintenance/decommissioning operations, impact on coastal processes etc.
Societal impact	N/A	Input:	Numeric score (**0 – 10,** *0 – regulatory acceptance not possible, 5 – fair acceptability, 10 – very acceptable*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of system acceptability from societal perspective. Should consider impact on local landscapes, shipping, marine economies etc.

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Table 15: Evaluation Criteria Specification for Developability

Criteria Level 1	Criteria Level 2	Evaluation Specification	
Physical test requirements	N/A	Input:	Numeric score (**1 – 10,** *1 – unrealistic requirements, 5 – fair requirements, 10 – easily achievable requirements*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of physical test requirements to develop concept through to the point of commercial roll-out. Include consideration of small-scale physical tests, small scale bench tests, full scale PTO bench tests, small/medium/full scale prototype tests. Include consideration of expected cost and resource requirements.
Numerical modelling complexity	N/A	Input:	Numeric score (**1 – 10,** *1 – unrealistic requirements, 5 – fair requirements, 10 – easily achievable requirements*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of numerical model development for assistance with development, design and optimization of entire concept to commercial roll-out.
Scalability	N/A	Input:	Numeric score (**1 – 10,** *1 – not scalable, 5 – fair scalability, 10 – excellent scalability*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of system scalability in terms of suitability for mass production, increased rate of manufacture, lowering cost of energy through development of products and procedures, potential to benefit from economies of scale etc.
Secondary markets	N/A	Input:	Numeric score (**1 – 10,** *1 – not suitable, 5 – fair suitability, 10 – extremely suitable*)
		Source:	Evidence based manual assessment.
		Notes:	Evaluation of system suitability for adaption to serve secondary markets such as powering oceanographic instruments, offshore platforms, island communities, niche markets, alternative uses etc.

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3.8 METHODS FOR EVALUATION

3.8.1 Criteria weighting by pairwise comparison

3.8.1.1 Conceptual description of the method

The aim of the pairwise comparison is to establish individual weighting in a list of criteria, by comparing each of them to all the others. The methods originate from industrial practices with which INNOSEA has been involved in the past. For the comparison of two criteria, the relative importance/impact of criterion 1 is assessed compared to criterion 2.

Criterion 1 can be Much Stronger (MS) / Stronger (S) / Neutral (N) / Weaker (W) / Much Weaker (MW) than criterion 2. An example is given in Table 3-16.

Table 3-16: example of pairwise comparison between criteria

	Crit. A	**Crit. B**	**Crit. C**
Crit. A	N	MS	S
Crit. B	MW	N	MW
Crit. C	W	MS	N

This matrix should be understood as following:

- Crit. A is much stronger than Crit. B (or Crit. B is much weaker than Crit. A – grey cell)
- Crit. A is stronger than Crit. C (or Crit. C is weaker than Crit. A – grey cell)
- Crit. B is much weaker than Crit. C (or Crit. C is much stronger than Crit. B – grey cell)

Values $s(j;k)$ are attributed to each pair of criteria, relatively to the importance (MS = 3 / S = 2 / N = 1 / W = 0.5 / MW = 0.33).

Table 3-17: method to calculate the s_i weights for each criteria from the pairwise comparison.

j \ k	1	…	k	…	n
1	$s(1;1)$				
…					
j			$s(j;k)$		
…					
n					
SUM	$s_1 = \sum_{j=1}^{n} s(j;1)$		$s_k = \sum_{j=1}^{n} s(j;k)$		

For each pair of criteria, a ratio of the pair value $s(j;k)$ over the sum of the values S_k is performed. The final criterion weighting is the mean Sf_k as shown in the table below.

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j \ k	1	…	k	…	n	SUM
1	$\frac{s(1;1)}{s_1}$					$Sf_1 = \frac{1}{n}\sum_{k=1}^{n}\frac{s(1;k)}{s_1}$
…						
j			$\frac{s(j;k)}{s_k}$			$Sf_k = \frac{1}{n}\sum_{k=1}^{n}\frac{s(j;k)}{s_k}$
…						
n						

With this method the individual weight of one criterion among all criteria is assessed. The method provides a way to simply rank the criteria one against each other without having to consider its overall weight within the scoring system

3.8.1.2 Application of the method to the LiftWEC criteria

Two options are possible to apply the method, mainly depending on the number of the evaluation criteria:

- Pairwise comparison between all criteria one to each other (better for a limited number of criteria)
- multi-levels pairwise comparison: level 1 to weight categories one against each other, level 2 to weight criteria one against each other inside a category

The evaluation criteria identified in LiftWEC Deliverable D2.2 *"LW-D02-02-1x0 Identification of Evaluation Criteria"* are already within thematics, and then each thematics contains up to 2 levels of criteria. A multi-level pairwise comparison is therefore considered, and the "thematic" level is ignored.

3.9 CONFIGURATIONS SCORING

At the level or TRL of the LiftWEC project, a typical score scale for each criterion can be defined from 0 to 5. The precision of the score should not exceed half-point values (0.5, 1, 1.5, …. 4.5, 5)

Scores are relative between the configurations: considering a given criterion, the most efficient/adapted configuration should be attributed a score of 5 and the least efficient/adapted one should be attributed a score of 1. If a configuration is unable to fulfil the criterion, it should be attributed a score of 0 and considered eliminated.

3.9.1 Specific criteria scoring

Specific criteria are relative to a single category of the scenario. Thus, the options in each category are scored in a matrix independently from the rest of the scenario.

3.9.2 Transverse criteria scoring

Transverse criteria are relative to an overall concept scenario. Scores are given for each of the scenarios to be assessed.

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3.10 Sensitivity Analysis on the Weighting of Criteria

The weighting of the selection criteria is a contentious area, with no absolute answer to the system. The pairwise method selected to weight the criteria intends to rationalise the process, and the involvement of all the partners in the process is aimed at ensuring that all the involved parties take ownership of the process.

However, depending on the experience and priorities of the different group involved in the LiftWEC, it is possible that the weighting of the criteria obtained from the pairwise comparison performed by each group will vary significantly. In such cases, the possibility to consider a sensitivity analysis of the ranking of the concepts to the weighting of the criteria will be considered.

The range of weights obtained for each criteria using the pairwise comparison from each LiftWEC partner will be used to define the range of variability of the weights.

A Monte Carlo type of analysis can then be conducted, where many realisation of the concept ranking can be obtained. For each realisation, the weights of each criteria will be selected randomly within their range of variability.

This method might provide some insight into the influence of each criteria, and it will help to have a fuller view of the concept scores when deciding which concepts should be kept for the following phases.

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