Techno-economic WEC system optimisation – Methodology applied to Wavebob system definition

J. Weber[1], R. Costello[1], F. Mouwen[1], J. Ringwood[2] and G. Thomas[3]

[1] Wavebob Ltd.,
H3, Maynooth Business Campus, Maynooth, Co. Kildare, Ireland
E-mail: jochem.weber@wavebob.com

[2] Dept. of Electronic Engineering
NUIM Maynooth, Co. Kildare, Ireland
E-mail: john.ringwood@eeng.nuim.ie

[3] Dept. of of Applied Mathematics
University College Cork, Cork, Ireland
E-mail: g.thomas@ucc.ie

Abstract

The overall system optimisation of wave energy converters remains a challenging task. Firstly, this is associated with the large number of system parameters and their related constraints, secondly, the complexity of numerical system representations capturing overall system behaviour and, thirdly, the uncertainties in the prediction and formulation of appropriate overall economic system performance objectives.

The parameterisation and the modelling challenges require a staged approach for an overall system optimisation. This ranges from simplified system representations exposed to variations within a large parameter space to more sophisticated system models subject to evaluation for a reduced and focused parameter zone. The description of the system dynamics, operation and performance needs to capture the key characteristics of the WEC concept functionality, the technical implementation and the economic application from the beginning and throughout the optimisation and development process.

The paper describes the problems that are associated with the widely employed sequential development of wave energy converter (WEC) systems from concept through technology to economic application and presents the methodology applied to the overall techno-economic system optimisation and development process of Wavebob WECs.

Keywords: Economic performance, technology development, WEC system optimisation

1. Problem description

This paper considers the optimisation of WEC systems and focuses on WEC technology development rather than upon site or project development. Therefore, resource, environmental and operational conditions of a site or sites are regarded as a given and the system of WECs is required to satisfy and exploit such conditions in an economic and optimal defined manner. Site selection and development, where WEC technologies are regarded as given, are not within the scope of these considerations on technology optimisation. Notwithstanding the justified focus on technology development, it is recognised that both development processes are not decoupled. This is particularly evident for WEC technologies targeting particular site types with, for example, minimum water depth, or on the other hand, near- or onshore bottom mounting requirements.

Rightly, development protocols such as in [1], call for the WEC development process to be conducted in a well structured and sequential manner commencing with a focus on absorber concept viability and performance improvement. Over the development process, the systems are considered at increasing scale and with increasing detail. Technological development then follows the completion of absorber concept development and optimisation. Subsequently, with WEC technology design variations in hand, economic considerations receive increasing attention to achieve economic viability. These three broad development stages - targeting conceptual, technological and economic viability and performance - and the manner in which they build upon each other is briefly depicted in Fig. 1.

Over the years, a number of WEC technology developments have suffered considerable setbacks or failure, often associated with the omission of the required, important steps in these development stages.

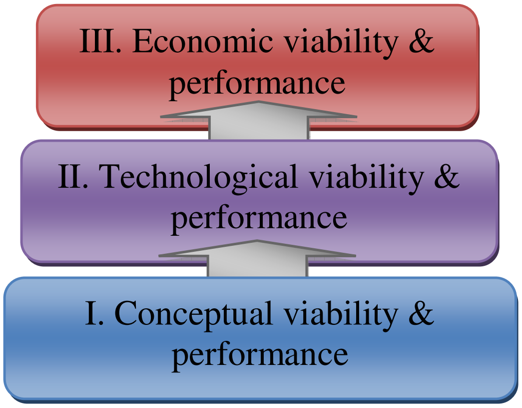

Figure 1: Sequential system development approach.

Notwithstanding the recognised benefits of the sequential development, an undesirable phenomenon - not precluded by a sequential approach - is becoming increasingly evident in WEC developments. This is associated with the belated consideration of technological and economic system performance criteria, resulting in setbacks with potential failure of achieving technological or economic viability. As concept and absorber developments advance and reach largely defined embodiments, the consideration of technological and economic criteria may be low and their viability thresholds may be difficult to achieve.

Even the sequential optimisation of just two power conversion steps in the conversion chain of a WEC system, or the sequential consideration of absorber shape and power take-off (PTO) control of a WEC can lead to considerable penalty on overall system performance; this has been shown by Weber & Thomas [2], Babarit [3] and Gilloteaux & Ringwood [4].

The overall techno-economic WEC optimisation needs to overcome such a sequential consideration of key technological subsystems and advance to a simultaneous consideration of all key performance features and an integrated optimisation of the WEC technology in their economic application. The persisting range and variation of WEC species under development is a testament of the challenge of satisfying the economic performance goals and of the requirement for such an integrated approach.

2. Approach

Techno-economic system optimisation is referred to as the process of defining a WEC system technology that is best suited to satisfy the economic requirements, and thereby implied technical requirements, with respect to a defined application scenario. This scenario is captured in the concept of operation (CONOPS), as in [5], and describes the entire lifecycle representation of the system including manufacture, deployment, operation, O&M and decommissioning.

From these overall system requirements, systems engineering provides the methodology to identify subsystem requirements and formulate functional interfaces between the subsystems.

Wavebob is in the process of advancing its system optimisation to reflect on the integral technology development process in an overall techno-economic system optimisation. At the heart of this system optimisation is the simultaneous consideration of conceptual, technological and economic viability and performance criteria subject to the concept of operation requirements. This integrated approach, as opposed to the sequential approach, is expressed in Fig. 2 and can be epitomised in the following key principles.

- For a system to be viable: conceptual, technological and economic viability thresholds are *sine qua non*.
- Conceptual viability is a necessary but not a sufficient condition for technological viability.
- Technological viability is a necessary but not a sufficient condition for economic viability.
- Economic, technological and conceptual constraints and conditions of viability, need to be satisfied at all stages of conceptual, technological and economic development and optimisation.

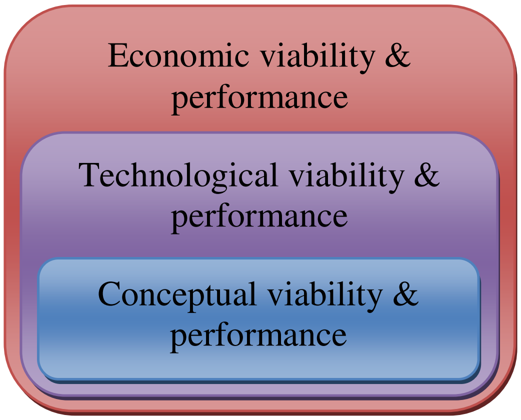

Figure 2: Integral system development approach.

For the implementation of this integrated system optimisation approach, it is important to recognise that performance quantities and conditions of all system levels need to be formulated at the earliest stage possible. This provides a means of avoiding the cul-de-sac of sub-system development or part-criteria optimisation paths. An extended set of system models for the prediction of the essential quantification of concept, technology and economics performance is required.

3. Modelling

With the focus towards an integrated system optimisation, the models, used in the optimisation, aim to include all aspects of the WEC system with significant effect on the technological and economic system performance. It is clear that, at the onset of a development and in the absence of detailed system designs, the prediction of technological and economic performance is subject to considerable uncertainty. These increased uncertainties in the models are initially accepted. As the WEC development proceeds the system definition is refined and the detail of the modelling is increased, so that greater accuracy and higher certainty in the system performance prediction is achieved.

The following subsections give a brief outline of the different system descriptions, simulation models and performance representations.

3.1 Parameter space

A wide range of system parameters are subject to overall system optimisation. Building on the formalised structure introduced in [6] these are grouped by function and type. Key examples include

- Design parameters (e.g. geometrical, structural),
- Slow control parameters (sea state to sea state),
- Fast control parameters (e.g. instantaneous PTO),
- Operational parameters (e.g. procedural)
- Economic parameters (e.g. cost of material).

Parameter constraints include

- Independent constraints (interval or discrete),
- Combined constrains.

The parameters a chosen to describe an identified WEC specie, specified by its associated concept. This allows the correlation of key system properties and features to characteristic parameters.

3.2 System dynamics

Numerical modelling and simulation tools of the system dynamics, employed and under development, are listed in [5]. These are supported by empirical test data and model validation. The models primarily describe motion, energy flow and load flow through the system, with a central element being the determination of the energy output in wave-to-wire simulation. Production sea states are fed into deterministic system models for simulation and power prediction. Combined with the scatter diagrams of sea states, the occurrence of power production levels and energy yields are determined.

A fundamental example of system optimisation, with simultaneous consideration of conceptual and technological properties, is an optimisation of absorber shape, slow and fast control parameters towards maximal yield of energy output, while satisfying PTO constraints of relative motion, velocity and force, reflecting technological limits of different PTO types and PTO component selection. The optimisation results show significant influence of the magnitude of the PTO technology constraints on the optimised absorber shapes. In the extreme cases of weak and stringent PTO constraints the system optimisations lead to evidently different operational principles within the same device species. This provides an illustrative example where conceptual intuition, with a focus on the fundamentals of one working principle, may bring about an incompatibility with technological requirements.

3.3 Operation and uncertainty

The modelling of operational conditions and WEC system states is most appropriately achieved using statistic models; this is due to the stochastic nature of the underlying processes.

Primarily, wave, current and wind data from measurements and models are used to identify the occurrence and distribution of a range of environmental conditions over a complete lifecycle. The categories of device states and associated models include deployment, idle, production, access, maintenance, recovery and decommissioning conditions.

All operational conditions are considered along with WEC system properties to identify required system states and modes and to derive standard operating procedures (SOP). In order to identify reliability, availability, maintainability and safety characteristics of the WEC system, different statistical analysis and modelling methods are used. The failure mode effects and criticality analysis (FMECA), as e.g. presented in [7], plays a central role in risk analysis, determination of system availability and definition of operation & maintenance (O&M) requirements and associated cost. A plethora of detailed technical WEC system events, including subsystem and component failure, are considered via Monte-Carlo simulation to determine statistical information on overall system states. These are combined with planned and unplanned O&M procedures and statistics of weather windows to arrive at system availability and downtime. Life Cost-Based FMEA, described in [8], is used to determine risk in terms of O&M cost. The decrease in uncertainty of the availability prediction is schematically depicted in Fig. 3. Clearly, detailed system state representation in an FMEA process prior to the availability of detailed system design and experience from pilot operation is a challenging task. However, the value of the utilisation of such simulation tools at the earliest possible stage in the development process has proven significant in the Wavebob technology development and needs to play a core part in the integral development approach and in overall techno-economic system optimisation.

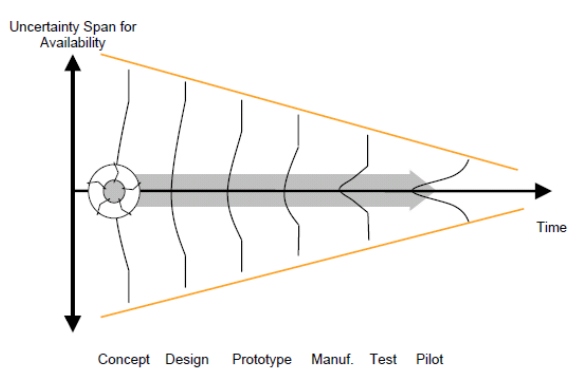

Figure 3: Increased certainty of availability prediction over WEC system development process, from [9].

3.4 Optimality and economics

Most real-world optimisation problems involve the simultaneous optimisation of multiple, usually competing, objectives. A common solution is to employ a single performance function, where individual objectives are typically balanced by assigning relative linear weights. If the problem is well understood and there is some consistency between objectives (e.g. units, nature of variables, etc), for example, as formulated in the optimal control cost function [10], good results can ensue, especially if there is an intuitive relationship between the weights and the solution [11].

In many cases, however, such as in the techno-economic optimisation of WECs, the performance function is not well understood. In such cases, the problem should be formulated as a true multi-objective one, with non-commensurable objectives. This can lead to the achievement of a number of solutions which can provide the engineer with some insight into the problem, prior to the selection of a final solution. Multi-objective (MO) optimisation tries to optimise the components of a vector-valued performance function. Unlike single objective optimisation, the solution to the MO problem is a *Pareto-optimal* [12] set of solutions. Each of the solutions in the set is (Pareto) optimal in the sense that no improvement can be obtained in any of the vector components without adversely affecting one or more of the other components. Concurrent search methods, such as genetic algorithms [13] have been demonstrated [14] to be a contender for the solution of MO optimisation problems.

Key financial performance quantities include Cost of Electricity (CoE), Net Present Value (NPP), Internal Rate of Return (IRR), describing different features of an economic WEC technology application. Common to all are the objectives to

- Maximise availability and predicted annual energy output,
- Minumise Capital Expenditure (CapEx) and Operational Expenditure (OpEx).

The partial dichotomy of the resulting multi-objective is evident. For instance, for a particular WEC absorber geometry, a PTO controller can be found to maximise energy capture on a wave-to-wave basis. However, this is likely to impose significant extra loading on the device structural and the optimal control of the PTO depends on the relative merits of achievable availability, power output, required CapEx and OpEx.

3.5 Complexity and evaluation

The large multi-dimensional parameter spaces, the challenges in the numerical system modelling in a variety of domains and the uncertainties in the performance prediction pose an optimisation problem of considerable complexity. It is therefore of crucial importance that knowledge gain and increased understanding of the system properties goes along with a gain in system performance. A variety of system behaviour visualisation codes have been implemented and are in continued use to facilitate the evaluation and interpretation of simulation results from numerous parameter configurations. These include

- Automated reports presenting all relevant spectral motion, forces, power quantities as transfer functions based on frequency domain simulation and a range of characteristic scalar statistic performance quantities for given site conditions and a range of device scales (FD report),
- Automated reports presenting all relevant motion, forces, power quantities as time traces, histograms and exceedance curves based on time domain simulation for individual control settings and associated parameter constraints for given site conditions and each sea state for the associated scatter diagram (TD report),
- Automated reports presenting all relevant spectral motion, forces, power quantities as transfer functions and system responses based on frequency domain simulation for individual control settings and associated parameter constraints for given site conditions and for each sea state of the scatter diagram (FD spectral matrix report).

An example of a FD spectral matrix report is displayed in Fig. 4, showing one page of spectral transfer functions for each sea state of the scatter diagram with labelling suitable for overview and focussed zoom.

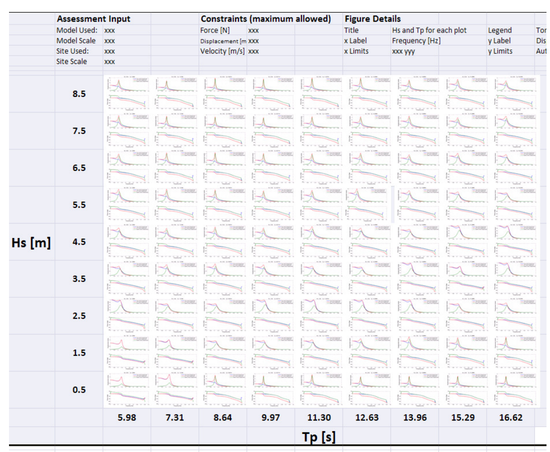

Figure 4: FD spectral matrix report.

Furthermore, one and two dimensional combined sensitivity analysis graphs are an essential visualisation tool for the evaluation of system performance quantity variations due to parameter deviations from a reference point.

Additional representations of the system behaviour can provide valuable insight into subsystem performance. Main examples are listed below.

- Power flow - Display of the power flow along the wave-to-wire energy conversion chain; representations of subsystem power and efficiency are valuable.

- Load flow - Display of forces/moments along the load paths, both through and past the PTO; this shows e.g. mooring load introduction, structural loading and the key force-separation provided by a mechanical bearing system, to deliver the appropriate sole working force introduction into the PTO. This may be conducted for operational, fatigue and extreme loading.
- Cost/benefit flow - Display of cost and benefit flow through the WEC system. Individual Capex, OpEx, operational revenue and availability, can be attributed to subsystems and expressed as economic performance quantities; displayed over the WEC system structure.

4. Conclusion

The advancement from a power conversion system optimisation to an integrated process of overall techno-economic system optimisation is a crucial step in the improvement of a technology development approach. The shift from the isolated focus on a WEC absorber concept that sets the route of the development towards an overall system development with a simultaneous refinement of all subsystems, with the absorber at its heart, is imperative, as it is crucially important that the technological and economic requirements and constraints are identified and incorporate into the WEC development process at the earliest possible stage. Development risks and barriers are identified early in the development process and the route to commercial application of wave energy may be considerably shortened. On the contrary, the chance of success, employing a purely sequential development path from concept through to technical considerations and subsequently to the imposition of economic criteria is greatly reduced. Thus, an integrated system optimisation where concept, technology, operation and economics are considered and guide the development process and system refinement at all stages is required. As the system definition is rather unrefined and uncertain at the beginning of a development, the system is defined with greater and increasing detail and certainty over the time of the development process.

Equally, as technology, operation and economics need to be considered when the WEC concept is under development, conceptual characteristics need to be subject to improvement when the integrated system optimisation identifies needs and opportunities that have an impact on the system concept. This may include an incremental development step or an improvement and refinement in WEC type or species.

The development and refinement of Wavebob WEC technology is benefiting from both, the adaptation of a systems engineering development process and the advancement of the system simulation tools towards an integrated techno-economic system optimisation. Both methods are complementary and effectively provide combination and synchronisation of aspect of the technology development including numerical and empirical system modelling, continued technology evaluation and refinement, subsystem development and overall system integration.

References

[1] HMRC & Marine Institute (2003): Ocean Energy: Development and Evaluation Protocol, Ireland.

[2] J. Weber, G.P. Thomas (2006): Turbine type & design selection in the context of multi-parametric overall system optimisation of Oscillating Water Column wave energy converters. Proc. Ocean Energy International Conference, Bremerhaven, Germany, 213 – 224.

[3] A. Babarit. (2005): Optimisation hydrodynamique et contrôle optimal d'un récupérateur d'énergie des vagues. Ph.D. Thesis, École Centrale de Nantes, France.

[4] J.-C. Gilloteaux, J.V. Ringwood. (2010): Control-informed geometric optimisation of wave energy converters, Proc. IFAC Conf. on Control Applications in Marine Systems, Rostock, Germany.

[5] J. Weber, F. Mouwen, A. Parish and D. Robertson. (2009): Wavebob – Research & Development Network and Tools in the Context of Systems Engineering. Proc. Eighth European Wave and Tidal Energy Conference, Uppsala, Sweden.

[6] J. Weber. (2006): Optimisation of the hydrodynamic-aerodynamic coupling of an oscillating water column wave energy converter. Ph.D. Thesis, University College Cork, Ireland.

[7] E. Zio, P. Baraldi, E. Patelli. (2006): Assessment of the availability of an offshore installation by Monte Carlo simulation. Intl. Journal of Pressure Vessels and Piping, 83, 312-320.

[8] S.J. Rhee, K. Ishii. (2003): Using cost based FMEA to enhance reliability and serviceability. Advanced Engineering Informatics, 17, 179-188.

[9] J. Gidlund. (2010): Standpoint - Wavebob design risk assessment. Internal report, Vattenfall, Stockholm, Sweden.

[10] H. Kwakernaak and R. Sivan. (1972): Linear Optimal Control Systems, Wiley-Interscience.

[11] J. Weber, G. Thomas (2003): Some aspects of the design optimisation of an OWC with regard to multiple sea states and combined object functions. Proc. Fifth European Wave Energy Conference, Cork, Ireland, 141-148.

[12] Y. Descotte, and J. Latombe (1985). Making compromises among antagonist constraints in a planner. Artificial Intelligence 27, pp. 183-217.

[13] D.E Goldberg. (1989): Genetic algorithms in search, optimisation and machine learning, Addison-Wesley.

[14] C.M. Fonseca and P.J. Fleming. (1993) Genetic algorithms for multiobjective optimisation: Formulation, discussion and generalization, Proc. 5th Intl. Conf. on Genetic Algorithms, Sam Mateo, CA: Morgan-Kaufmann.