SE in Wave Energy Technology

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The design of effective and economically viable wave energy devices involves complex decision-making about the product based on conceptual design information, including stakeholder requirements, functions, components and technical parameters. The great diversity of concepts makes it extremely difficult to create fair comparisons of the relative merits of the many different designs. Conventional design approaches have proved insufficient to guarantee wave energy technologies meet their technical and economic goals. Systems engineering can provide a suitable framework to overcome the obstacles towards a successful wave energy technology. The main objective of this work is to review the well-established systems engineering approaches that have been successfully implemented in complex engineering problems and to what extent they have been applied to wave energy technology development.

Keywords: concept design ; design domains ; decision-making ; matrix-based design methods ; metrics ; requirements ; stakeholders ; sustainable development ; systems engineering ; wave energy

1. Introduction

Humankind has always tried to make the world a better place through engineering, technology and innovation. The fundamental human needs (e.g., health, food, shelter, clean water and energy) have hardly changed over the centuries and throughout the world, but new challenges are posed as our society steadily evolves [1]. This is the case of the Covid-19 pandemic, which is confronting the world with a deep health, social and economic crisis that is upending business-as-usual. Emerging energy technologies have a broad role to play in enabling a strong forward-looking recovery and accelerating the shift to a sustainable and resilient climate-neutral economy.

Today's engineering solutions often lead to large complex products that can only be successful if they are able to meet individuals' demands, are environmentally acceptable and provide value to society. In maximising the value to stakeholders, engineers must cope with greater levels of complexity and interdependence of system elements. Although complexity and interdependence are characteristics that, by themselves, provide no intrinsic value, they produce vulnerabilities and risks that need adequate analysis and timely exposure to decision-makers.

The early stages of technology development are crucial in order to meet system cost and performance expectations. Actually, many authors agree that around 70–80% of the product lifetime costs are determined during the conceptual design phase [2][3][4]. The implication is that early design decisions are much more significant than later product development ones. Too little time spent in the conceptual design phase can lead to gaps in understanding the problem requirements, limited opportunities for novel concept generation and wasted time and money developing a concept that is unable to perform well enough to become a viable solution [5].

In order to reduce the undesirable gap between committed costs and system-specific knowledge at the early design stages, it is essential to design a process that integrates and applies the technological activities of synthesis, analysis and evaluation iteratively over the system life cycle [6]. Design traceability is also needed, as much knowledge and investment is lost at the project life cycle phase boundaries and between different projects [7]. During the design phase, the engineer is responsible for developing a comprehensive list of requirements and evaluation criteria. Thus, key metrics are established that identify the specific measures of system performance and assist in decision-making [8]. These metrics are used to scope or constrain the technical solutions. The system concept is then formalised by functional and physical architectures that meet the initial requirements. However, the process of converting stakeholder requirements into a successful design is critical. To make decisions effectively, several approaches have been developed, such as case- or knowledge-based reasoning, decision tree and matrix-based modelling methods. Amongst these approaches, the matrix-based methods are the most commonly used by engineers due to their simplicity, effectiveness and efficiency [9].

2. Application of SE Methods to Wave Energy

Wave energy converters (WECs) are complex engineering systems, and product development is inevitably multidisciplinary. So far, wave energy development experience shows that excellence in each discipline is a necessary but not sufficient condition to achieve a viable product. SE provides a suitable framework for a holistic approach that might allow progress towards a successful wave energy technology [10].

The need for a more comprehensive systems perspective to the development of wave energy technologies was also highlighted in a recent workshop on the identification of future emerging technologies in the ocean energy sector [11]. The report points out that some practical aspects neglected at an early stage can become a problem if taken up at a later stage, and therefore, technology developers should move from a sequential to a system design process. In order to overcome failures previously experienced in the sector, an integrated systems approach is required to develop wave energy systems; subsystems cannot be developed in isolation.

Similarly, the application of SE principles has been recognised by sector experts as a way to accelerate marine energy research [12]. Survey results of this research recommended focusing on common components to enable affordable ways to harvest marine energy and not on specific technologies. Experts also suggested proving that a system works reliably, checking its functionality in the early project stages and, consequently, focusing on end-user requirements.

As presented in Section 3, WEC concepts span a wide design space. The great variety of concepts makes it extremely difficult to identify common design approaches. Moreover, there is little published work on the specific design methods used in developing these devices, since most of the technology developers are private companies.

Nevertheless, a small fraction of technology developers does claim to have used a SE approach in their development process. The authors have identified the following five practical examples in the literature review:

- Wavebob [13] described the concept of SE in its application to WEC design. The method ensures the essential identification of technological barriers at an early stage of the system development, alleviating unnecessary technology cost and reducing development, operational and corporate risk, while shortening the development time.
- Martifer [14] implemented SE for the systematic selection of candidate architectures and the definition of functional requirements for system design and development.
- The utility company PG&E [15] used a formal SE approach in the development of WaveConnect, a wave energy pilot project, to demonstrate the long-term viability of harnessing ocean wave energy for electricity generation on a commercial scale.
- Waves4Power has used SE to propose new mooring solutions for the WaveEL device and array systems regarding their survivability, serviceability and profitability [16].
- AWS has applied a SE approach to the front-end engineering design activities of the AWS-III WEC [17].

Even though some companies seem to be aware of existing SE methods, it is a strikingly recent phenomenon (only documented in the last 10-year timeframe). Additionally, the application of SE might have been limited and fragmented, since these technology developers have not been free from suffering expensive, high-risk, slow, rigid and discontinued technology developments.

The application of SE to wave energy technology development is reviewed in more detail in the following subsections.

2.1. Environmental Analysis

The environmental domain recognises that the wave energy system exists within a context in which multiple SD are influencing its conception, planning, and operation. The SD include the political, economic, social, technical and environmental factors that constrain, enable or alter the design solution.

The authors of [18] presented the context diagram used to define the external systems that can directly influence the success of a grid-connected wave energy farm. This list identifies the factors that are out of the control of the external systems and the farm (i.e., political, social and economic climates). It is pointed out that the overarching context can influence the external systems and the success of the farm. However, the SD are not specifically analysed.

The authors of [19] analysed the critical factors to the commercial viability of WECs in off-grid luxury resorts and small utilities using political, economic, social, technological, legal and environmental (PESTLE) tools and Porter’s five competitive forces. Factors like the available wave resource, distance from shore, existing infrastructure, power demand, supply chain logistics, alternative energy sources and current cost of energy were found to have large impacts. The authors acknowledged that the factors discussed may not affect the viability of off-grid systems in the same way as in grid-connected systems.

The authors of [20] carried out a similar analysis to reveal the risks and uncertainties that face large-scale grid-connected wave and tidal energy projects. This work showed that, although the political, economic and social aspects have great importance, the technological barriers are key in order to attract investors.

The Pacific Northwest National Laboratory (PNNL) and National Renewable Energy Laboratory (NREL) are conducting a three-year project to review the grid value for marine energy development at scale on an intermediate-to-long-term horizon. Grid values are arranged into three categories: the spatial or locational aspects of marine energy, the temporal or timing aspects and special applications to ensure most situational benefits are captured [21].

Finally, the H2020 DTOceanPlus project presented a summary of nontechnical barriers and enablers to wave and tidal stream commercialisation in its public deliverable D8.1 [22]. The factors listed from literature sources comprise private and public financing, insurance, continued cost reduction, supportive consenting and regulation, infrastructure, standards and certification, innovation and cross-sectoral interlinkages, together with ethical and environmental concerns.

Attributes that characterise the SD are fairly covered for wave energy, but there is no reference to how these SD interact among each other and are prioritised.

2.2. Stakeholder Analysis

The stakeholder domain aims to define the design problem in the language of the customer and other related actors. Wave energy stakeholders can be defined as individuals, collectives and organisations who have an interest in wave energy technologies, who can influence project development or be affected by the project, as well as those who can directly or indirectly impact the decision-making processes [23]. Key stakeholders will be those who can significantly influence the technology and project development or are central to its final success.

The stakeholder analysis involves the identification and prioritisation of stakeholder groups, eliciting and ranking SR, as well as defining system merits or MOEs.

The review of the literature reveals very diverse classifications of stakeholders for marine energy projects. For instance, in [24], the following six main stakeholder groups are identified:

- project designers and developers;
- national, regional and local governments and public authorities;
- potential member companies and partners;
- financial institutions;
- knowledge institutes and
- environmental organisations.

However, the FP7 EQUIMAR project [25] considers stakeholders during the entire project life

cycle. At the initial stages of project development, owners, developers, suppliers, employees, the government, unions and individuals or whole communities located near or at the vicinity have a key influence. When operational, creditors and end energy users can be included as well, stakeholders are then grouped into four categories:

- Statutory consultees: authorities, agencies, groups or bodies defined in local, national or international legislation, which the developers are obliged to consult.
- Strategic stakeholders (nonstatutory consultees): local, regional, national or international organisations (and their representatives) who have important information, experience and expertise.
- Community stakeholders: any individual, groups of individuals or organisations whose lives, interests and welfare can be affected by the development.
- Symbiotic stakeholders: owners or organisations who may have an interest on or may have mutual benefits from a co-development.

More recently, in [26], twenty-six wave energy stakeholders are identified who are grouped into four categories:

- Highest-level stakeholders. Customers of the wave energy project (e.g., utility companies but, also, investors and financiers) or stakeholders that do not have direct economic interest in it.
- Core stakeholders. Project developer, owner, construction company and farm operator.

- First-tier suppliers. These stakeholders have direct interaction with the WEC farm core stakeholders by providing major services or subsystems required to build the wave energy project (e.g., WEC units or marine operations).
- Low-tier suppliers. They do not interact directly with the core stakeholders. They are suppliers to the first-tier suppliers.

Although the above shows some underpinning research to assist in the identification of wave energy stakeholders, to the best of our knowledge, there is no public reference on stakeholder prioritisation in this sector. Stakeholder mapping techniques, usually based on two or three dimensions (e.g., power, interest and urgency), have been used in other sectors to determine the priority of identified stakeholders [27][28].[29]

The elicitation of SR largely depends on the type of market being addressed. As explained in the Section 5.1, the environmental domain accounts for the factors linked to the added value to the intended market.

Both Wavebob and utility company PG&E mention the use of SE to reflect end-user needs and to develop the top-level requirements.

To date, the Wave-SPARC project has produced the most comprehensive analysis of the wave energy stakeholder domain. Wave-SPARC has delivered a complete and agnostic formulation of a utility-scale wave energy project through the application of SE and a stakeholder analysis. The analysis of stakeholders' needs in [26] led to seven high-level SR and a total of 33 low-level SR. Costs and risks are clearly identified as two of the high-level requirements. The other five categories contain a mixture of benefits (reliable for grid operations), opportunities (benefit society and deployable globally) and risks (acceptability and safety).

SR are not ranked/weighted according to their relative importance. However, the concept of requirement flexibility is introduced to carry out their aggregation into higher-level requirements [26]. A technical solution may not fully satisfy one low-level requirement, but a trade-off with another requirement may make the higher-level requirement still viable. Four degrees of flexibility are identified, ranging from high flexibility to none.

SR identify specific properties of the system that are needed to satisfy the end-user or stakeholder. Once the critical system properties are established, metrics must be assigned to offer the system engineer a means by which to assess various solutions. The list of requirements that have been developed in Wave-SPARC serve as the components of the technology performance level (TPL) metric [30]. The seven capabilities groups meet the seven high-level SR and constitute the ultimate metrics a utility-scale wave energy project must satisfy:

- C1: Have market-competitive cost of energy.
- C2: Provide a secure investment opportunity.
- C3: Be reliable for grid operations.
- C4: Benefit society.
- C5: Be acceptable to permitting and certification.
- C6: Be safe.
- C7: Be globally deployable.

In order to rank SR, [31] took a different approach. They applied the Delphi method to assess the economic requirements and their relative importance for the development of the wave and tidal energy technologies based on the experts' judgment. Operational costs and revenue were ranked as the most important criteria from the experts' points of view. Preoperation costs and investment, incentives, profitability and externalities were ordered in the next priorities, respectively. It is worthwhile noting that both the incentives and externalities are SD and, thus, should belong to the environmental domain.

2.3. Functional Analysis

The functional analysis in SE has the objective of defining the functional architecture of the system and characterising its functional behaviour. FR are the bridge between the stakeholders and technical teams, and they shall be specified at each stage of the system life cycle. Thus, a necessary step is to identify all these stages.

Wavebob defined operational scenarios right through from transportation, assembly, installation and commissioning to operation, maintenance, support and decommissioning. More recently, [30] identified six life cycle stages for a wave energy farm: engineering, procurement, construction, installation, operations and disposal.

The authors of [32] proposed a systematic approach for the design of WECs, identifying the functions, selecting those having an important bearing on cost and trying to find ways of performing those functions economically. This systematic approach for the early or conceptual stages of design is described in [33]. The design of WECs is exemplified through the analysis possible combinations of three main functions: provide a working surface, provide a reaction force and extract power. Providing the reaction force is the dominant function in designing affordable devices. It results, apparently, in this approach focusing on the specification of FR during the operational phase of the technology.

The University of Uppsala has applied a systems approach to develop ways to harness wave energy, which considers manufacturing, maintenance and compatibility with the natural environment early in the design process [34]. These criteria are not normally used for down-selecting a concept from a set of solutions that achieve a desired functionality.

Technology developer Martifer implemented a SE approach for the systematic selection of candidate architectures and a definition of FR for system design and development. Similarly, the utility company PG&E developed a set of functional block diagrams to identify functional relationships between system infrastructure segments and to external systems in the WaveConnect project. The authors of [35] described the functions performed by the OWC power plant to convert wave power into electricity.

Partial coverage of FR can be found in [36], where FR are formulated in the context of wave energy conversion but only for the mooring system, and [37], who has produced a comprehensive landscaping report for wave energy Scotland (WES) on FR for WEC controls. The authors of [38] presented a functional analysis of the submergence system for a Spar OWC in the form of an octopus diagram, exposing the elements interacting with the system and the main functions (service and constraint). The functional analysis resulted in a set of functional specifications showing the expected system functions, the judgement criteria, the levels of these criteria and the flexibility.

The authors of [30] presented a full taxonomy of FR for a wave energy farm. The five top-level functions identified what the wave energy farm must do to meet its mission. The subfunctions below the top levels further decomposed the top-level functions (e.g., WEC or electrical substation). These subfunctions identified the unique aspects that must be achievable to satisfy the higher-level function. A further breakdown was given to subfunctions in the form of sub-subfunctions, further focusing in on the details that were needed (e.g., power take-off (PTO) within a WEC). At each level, the functions were mapped to capabilities through MOPs.

In 2009, EMEC introduced some guidelines for functional performance measures of marine energy conversion systems, such as reliability, maintainability and survivability [39]. At a high level, performance metrics require design and systems engineering, and, at a lower level, components are able to fulfil these requirements. This is not necessarily captured by the contemporary TRL (technology readiness level) assessment. This is the reason why [40] examines the key performance metrics that underpin Levelised Cost of Energy (LCOE) (i.e., Capital Expenditure (CAPEX), Operational Expenditure (OPEX), yield, reliability, cost of finance, survivability, durability and project size).

Since 2014, Wave-SPARC [39] has been developing and applying holistic and quantitative technoeconomic assessment metric systems to identify technology weaknesses and strengths to, ultimately, advance technology towards their markets applications. This de-risking approach is applicable to all WEC systems that are currently under development and to the novel systems invented in the project. The system performance is measured through the TPL metric. The development of TPL assessment criteria, methods and tools was first introduced in [41], further developed in [42], and practically applied and enhanced in the Wave-SPARC project.

Similarly, since 2016, WES has been promoting the development of performance metrics and tools for ocean energy technologies via workshops with a wide international cross-sector input [43]. This work is being further developed within the EU H2020 funded project DTOceanPlus [44] and International Energy Agency Collaboration Programme for Ocean Energy Systems (IEA-OES) Task 12 on an International Technology Evaluation Framework for Ocean Energy [45]. The authors of [46] contributed to gaining an international consensus by compiling a list of existing ocean energy performance metrics for the farm level; the wave energy device and its main subsystems (e.g., structure, PTO, control and mooring).

The analysis of FR for wave energy systems is reasonably well-covered in the literature. There is also a growing awareness on the need to define functional performance measures to judge the success of wave energy technologies beyond the TRL assessment [47] Based on US and EU progress, there is ongoing work to gain an international consensus on the development of performance metrics. Although this is very positive, there is still the need for methods that establish the relative importance of FR and their interactions.

2.4. Technical/Physical Analysis

The technical and physical domains describe the physical embodiment required to achieve the system functions. Functional architectures contain logical decompositions of high-level functions into lower-level functions. High-level functions occur in the operational environment, which dictates how the system must work at the level of operators. Lower-level functions are allocated to the physical architecture of the system . Therefore, TR are dependent on the design solution.

An overview of the key subsystems that require consideration for wave energy systems is provided in [48], [49] and [50]. According to these sources, the WEC can be characterised in five main subsystems, namely the reaction system, power take-off, hydrodynamic system, power transmission and control. Due to the large number of existing WEC devices, it is impossible to analyse all potential decompositions. Alternatively, a high-level system breakdown in [48] identified eight different categories of combinations between the diverse hydrodynamic and reaction systems relevant to the WEC industry.

The authors of [51] presented a comprehensive functional analysis, technical breakdown and mapping of the system requirements to the main cost centres of a WEC, i.e., the rotor, PTO, substructure, installation and maintenance operations. However, all technology developers are required to develop a system decomposition and functional allocation, either implicitly or as a result of a more systematic process.

Wavebob and Waves4Power are two examples of technology developers where system decomposition and functional allocation has been documented. In the case of Wavebob, this process was mainly driven by reliability concerns. The analysis of the failure mode effects provided the quantitative information on system availability to inform on the need for increased system redundancy or modularity, in turn providing invaluable information on the appropriateness of system designs at an early stage of the development. As regards Waves4Power, this process was used to propose new mooring solutions for the WaveEL device and array systems in terms of their survivability, serviceability and profitability. Evaluation matrices were used to compare alternative mooring concepts.

There are several standards and guidelines that have been produced to assist in the development of the TR and assessment of technical performance:

- EMEC has issued some guidelines for the grid connection of marine energy conversion systems [52].
- International Electrotechnical Commission (IEC) TS 62600-2:2019 provides design requirements to ensure the engineering integrity of wave, ocean, tidal and river current energy converters, collectively referred to as marine energy converters [53]
- IEC TS 62600-100:2012 provides a systematic method for assessing the electrical power production performance of a WEC [54]
- IEC TS 62600-30:2018 specifies the electrical power quality requirements of a marine energy (wave, tidal and other water currents) converter unit [55]

As TR are quite specific to the design solution, there is little information on the TPMs used to make decisions on the design options explored and sizing of the components.

2.5. Process Analysis

The process domain determines the process variables, manufacturing requirements and activities that enable the production of specific components and assemblies to achieve the final system. Manufacturing readiness levels (MRL) are commonly used to measure progress on the effectiveness of producing specific components and assemblies[56]. The identification of manufacturing risks must begin at the earliest stages of technology development and continue vigorously throughout each stage of the system design.

There are no references in the literature to the development of MR specific for WEC devices. The EMEC has produced some guidelines for manufacturing, assembly and testing of marine energy conversion systems [56]. This document does not contain a list of MR, but it could be used to inspire the development of MR.

2.6. Evaluation and Selection

Evaluation throughout the wave energy technology development path has usually been based on the TRL assessment, as presented before. Several TRL definitions specific to wave energy have been proposed [57][58]. However, readiness levels assess the maturity and risks within the wave energy development process rather than its quality, technical or economic performances.

Evaluation methodologies based on the LCOE have been at the very centre of wave energy technology development. LCOE combines in a single metric two important stakeholder requirements, namely lifetime costs and energy production. This method is akin to well-known cost-benefit analyses.

Reversed LCOE engineering [59] is a methodology to explore the limits for the technical parameters of a WEC. In this approach, an LCOE target is set, and the upper cost limits for the main subsystems of the WEC are obtained. Learning rates due to factors such as the production volume and automation can also be considered in order to assess whether the cost limits for a subsystem can be reached from the current costs. This methodology relies on prior knowledge of the allocation of cost centres to the physical realisation. It provides guidance for existing prototypes on how to improve their commercial attractiveness but does not guarantee the stakeholder value is maximised.

The authors of [60] proposed a new methodology that can be used to account for both risk and the LCOE to give a clearer picture of the feasibility of a WEC development.

Beyond costs and risks, proposed an integrated TPL metric. The lowest level system capabilities are scored and progressively aggregated following a mathematical calculation. There are three different ways of combining the lowest level scores: arithmetic mean, geometric mean and multiplication with normalisation. The overall score is calculated from scores for the seven high-level capabilities arranged into three categories (weighted average of individual geometric means). However, due to the scoring complexity, this approach requires expert assistance to perform the assessment. In the public version of the tool, the weighting of the different criteria is fixed. The TPL assessment cannot be adapted to changing market conditions or stakeholders' expectations, which will incidentally hinder the traceability of system requirements across domains.

Inherent to the performance assessment, there is the concept of staged development. Stages are loosely related to the TRL scale. At each stage-gate, an evaluation of the relevant metrics is done. Different stage frameworks have been proposed. The most common one consists of five stages. This systematic development plan was initially proposed for WECs of a buoyant type to mitigate the financial and technical risks during development at the Hydraulics & Maritime Research Centre of the University College Cork (HMRC) [61]. Later, it was adopted as the best practice by IEA-OES [62] and FP7 EQUIMAR [63] and, finally, recommended by the IEC [64]. A WEC or subsystem must fulfil the stage-gate criteria at the end of each stage before passing to the next development stage. A simplified approach consists of three stages. The project and/or the technology deployment are split into early, mid and late stages [65].

The authors of [66] presented a series of considerations to specify the requirements of relevant, realistic and effective assessment criteria, methodologies and tools for wave energy technologies. Among them are the measurability, level of accuracy, granularity, validation, reference values and thresholds for the assessment criteria.

The authors of proposed a set-based design (SBD) approach for concept selection. Designers can avoid choosing a concept based on imprecise data by developing many concepts and eliminating the inferior ones instead of selecting one concept for further development and iteration. Trade-offs and preferences can be included when evaluating concepts by combining the utility analysis with SBD methods. When applying utility-based decisions in SBD, designers create a utility function that weighs each attribute of the concept. Within each attribute, the concept is given an interval score. The interval score allows the designers to account for the span of possible values given the imprecision of the conceptual design.

The project SEAWEED is also developing a structured approach to concept creation and selection [67] focused on the direction of early stage concept creation activity towards promising areas of investigation rather than the definition and evaluation of detailed technical solutions.

Finally, DTOceanPlus is developing design tools for the assessment of ocean energy arrays, devices and subsystems at different development stages. Assessments are grouped into four main categories, namely SPEY (System Performance and Energy Yield); RAMS (reliability, availability, maintainability and survivability); SLC (system lifetime costs) and ESA (Environmental and Social Acceptance). These assessments will feed into a stage-gate metric tool for the overall assessment of ocean energy technologies.

Wave energy system development, evaluation and selection is moving progressively from simplified approaches such as assessing the technology maturity and cost to more holistic performance measures. Selection at intermediate stages of the system design contributes to reducing the risks. Iterations at low TRLs until the desired performance is achieved will contribute to the analysis of the solution space and production of more cost-effective designs.

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