Novel methodology for holistic assessment of wave energy design options

Pablo Ruiz-Minguela, Jesus M. Blanco, Vincenzo Nava

Abstract— **Harnessing wave energy is widely recognised to pose substantial engineering challenges. Conventional methodologies focused on evaluating technology maturity have proved insufficient to guarantee Wave Energy Converters (WEC) meet their technical and economic goals.**

This paper presents a novel methodology for the assessment of wave energy design options based on sound Systems Engineering and Multicriteria Analysis principles. This approach is particularly useful during the first stages of technology development where up to 75% of the final product cost can be committed.

To guarantee stakeholder requirements are fully traceable throughout the design process, the methodology proposes a sequential mapping among three different domains (i.e. Stakeholder, Functional, Physical world). Using a combination of well-established tools, the relative importance of each of the design domain criteria is assessed and the relationship matrix between domains filled out.

This methodology is accompanied by a case study to show it can be used by wave energy stakeholders to inform their decision-making process, as it provides a structured method for the analysis of wave energy design options at early design stages. It is also suggested that this methodology can be used by technology developers both to identify wave energy concepts with greatest potential and to prioritise their design improvement efforts.

Keywords— **Decision-making, Functional Analysis, Stakeholders, Systems Engineering, QFD, Wave Energy.**

I. INTRODUCTION

DESPITE significant efforts in the last decades, Wave Energy technologies have not reached commercial maturity yet [1]. Wave Energy is not competitive with other renewable energy sources mainly due to its poor performance, low reliability levels and high costs. Conventional methodologies focused on Technology Readiness Levels (TRL) have proved insufficient to guarantee wave energy technologies meet their technical and economic goals.

Systems Engineering methods [2], [3], [4], [5] have been successfully applied in other industrial sectors (e.g. automotive, aerospace) to develop innovative products meeting very diverse and demanding customer needs.

Likewise, Multicriteria Analysis [6], [7] has been applied to inform the decision-making process in early design phases of complex engineering problems, particularly when alternative solutions can be heterogeneous.

Stakeholders play an important role in the development of system innovations as their expectations greatly influence the future of such innovations until the potential benefits are realised through practical application [8]. Therefore, it is paramount that stakeholder requirements are fully traceable throughout the design process.

To guarantee traceability, the proposed approach is based on a sequential mapping process among three different domains of the design world: i) **Stakeholder Domain**, where stakeholders define what they would like to see in their system design; ii) **Functional Domain**, where the functions that satisfy those requirements are identified; iii) **Physical Domain**, in which functions are mapped to physical realisations.

The successful transition from different domains require effective design synthesis and analysis. The engineer's synthesis activity transforms *what* the stakeholders want the design to achieve to *how* to achieve it. The engineer's analysis activity supports validation and verification.

The paper proceed as follows. Section II highlights the major works on measuring performance of wave energy technologies at early stages. Section III outlines the novel methodology that is practically demonstrated in Section IV. Finally, results of this case study are discussed and concluded in sections V and VI respectively.

II. RELATED WORK

Methodologies based on the Levelized Cost Of Energy (LCOE) have been at the very centre of wave energy technology development. LCOE combines in a single

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metric two important stakeholder attributes, namely lifetime costs and energy production. This method is akin to well-known cost-benefit analyses [9]. The reversed LCOE engineering [10] is a methodology to explore the limits for the technical parameters of a Wave Energy Converter (WEC). In this approach, an LCOE target is set and the upper cost limits for the main subsystems of the WEC are obtained. This methodology relies on prior knowledge on 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 stakeholder value is maximised.

Parametric scanning of the design space [11] has also been proposed for early stage decision-making. This method models the different elements of the LCOE formula based on a multiplicity of technical parameters. In this case, multicriteria decisions may be extremely difficult as the number of solutions grow exponentially with the parameters considered.

Acknowledging that there is a diversity of criteria a wave energy technology must achieve, there is an ongoing process of building understanding, acceptance and clarity in the approach to measuring and assessing the key targeted areas. To date, Wave Energy Scotland has developed a set of stage gate metrics to be used in wave energy technology development programmes to objectively measure technology performance [12]. The common evaluation framework establishes metrics and how to calculate them at different stages of technology development, but not their relative importance to stakeholders. Besides, allocation to sub-systems and thresholds still remain unclear.

Finally, it is worthwhile mentioning Technology Performance Level (TPL) Assessment Methodology [13]. Based on System Engineering principles, the performance of any specific WEC design is measured through a set of criteria associated with the performance of the solution. Hence, as the TPL is assessed on a holistic level, trade-offs are embedded. However, due to the scoring complexity, this approach requires expert assistance to perform the assessment. In the public version of the tool, it cannot be adapted to changing market conditions, which will impact the mapping of stakeholder requirements into engineering parameters and consequently the final ranking.

III. DESCRIPTION OF THE METHODOLOGY

A. Mapping process

This novel methodology proposes a sequential mapping among three of the four different domains in the design world [14]:

- Stakeholder Domain, defined by the Stakeholder Attributes (SA) the customer and associated stakeholders would like to see in their system.
- Functional Domain, where requirements are transformed in a comprehensive Functional Specification (FS).
- Physical Domain, in which the Engineering Parameters (EP) emerge. They describe the physical embodiment or realisation to achieve the above functions.

Since this research is manly focused on the early design phases of wave energy technologies where little knowledge of the manufacturing and logistics is known, the mapping of the Physical Domain onto the Process Domain will not be considered.

Design domains are mapped as shown in Fig. 1.

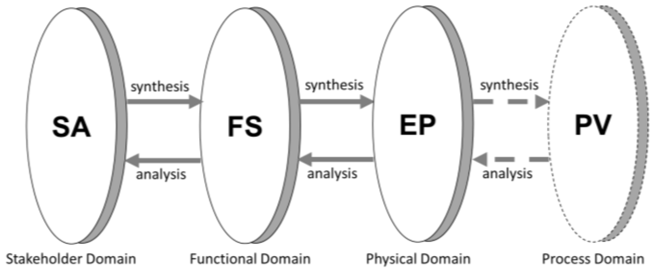

Fig. 1. Domains of the Design World (adapted from [14]).

Moving from left to right illustrates the engineer's synthesis activity from *what* to *how* achieve the design. Conversely, moving from right to left shows the engineer's analysis activity, which supports validation and verification. It is worth noting that the first three domains are also consistent with the "Vee model" in a traditional top-down Systems Engineering method [3] and the systematic design process proposed by Pahl [9].

The mapping is done following a matrix-based modelling approach. Using a combination of well-established tools, the relative importance of each of the design domain criteria is evaluated and the relationship matrix between domains filled out.

Fig. 2 illustrates this process, which guarantees the traceability of requirements throughout the various design domains and phases.

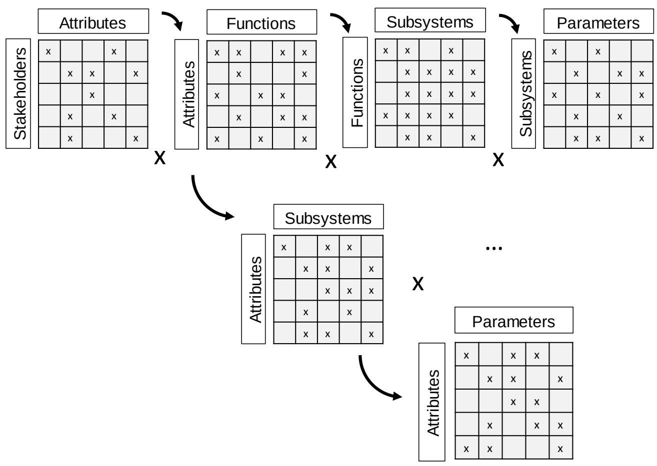

Fig. 2. Matrix-based Modelling Approach.

Stakeholder domain analysis involves identifying and understanding who the key stakeholders of wave energy are, their roles, relationships and needs. In the stakeholder domain, the design problem is defined in the language of the customer, which is still general, ambiguous and highly unmeasurable. Main steps in the stakeholder domain are as follows:

1. Identify wave energy stakeholders, their interactions and groupings.
2. Prioritise stakeholders according to their influence. Various stakeholder dimensions are assessed, namely stakeholder power, interest and urgency.
3. Elicit stakeholder roles and expectations. Stakeholders have challenges that need to be addressed.
4. Prioritise Stakeholder Attributes (SA).

Functional domain analysis produces a technology-agnostic definition of the design problem. It involves the definition of wave energy functional requirements and their allocation to standard sub-system/component classes. Main steps in the functional domain are as follows:

1. Define system boundaries and list the elements of the external environment in relation with the system (external functional analysis). The context diagram visualizes the environment in which the system exists during and out of operation.
2. Obtain the hierarchy of Functional Requirements (FR) through the functional decomposition process (internal functional analysis). The function tree diagram provides an organized approach to identifying the essential features of a system that must be addressed by its design.
3. Map Functional Requirements (FR) to Stakeholder Attributes (SA).
4. Decompose the wave energy system in a standard functional architecture. Critical Interfaces between Sub-Systems/Components are identified.
5. Allocate Functional Requirements (FR) to Sub-systems/Components.

Finally, the **physical domain analysis** specifies the design problem in specific, precise and measurable terms. The different Sub-Systems/Components are defined by quantifiable Engineering Parameters (EP). Main steps in the physical domain analysis are as follows:

1. Identify Engineering Parameters (EP) and variability ranges.
2. Develop Value Functions which model fundamental relationships between the physical Engineering Parameters and the actual value provided to stakeholders.
3. Compare wave energy design options to identify design alternatives with greatest potential, set up minimum thresholds and suggest improvement areas.

A combination of several matrix-based modelling tools is used, mainly Quality Function Deployment [15], Analytical Hierarchical Process [16] and Design Structure Matrix [17]. Value functions are modelled upon a reduced set of parameters.

B. *Matrix-based Modelling Tools*

The Quality Function Deployment (QFD) method helps generate the information needed in the product definition phase of the design process. QFD originated in Japan and was first introduced at the Kobe shipyards of Mitsubishi Heavy Industries in 1972 [15]. The most important information that the QFD provides is the weights of evaluating criteria, which are derived by the importance ratings of stakeholder requirements together with the relationship weightings between stakeholder needs and evaluating criteria. The House of Quality (HoQ), the basic design tool in QFD, is built in the following steps.

1. Identify the stakeholders.
2. Determine the stakeholder requirements.
3. Determine relative importance of the requirements.
4. Build a benchmark.
5. Generate evaluating criteria.
6. Relate stakeholder requirements to evaluating criteria.
7. Set evaluating criteria targets and importance.
8. Identify relationships between evaluation criteria.

Traditionally, the evaluation criteria consisted of engineering specifications, but other QFD matrices can be built by considering factors such as design parameters, product characteristics, functions, failure modes or manufacturing processes. Moreover, these matrices can be linked in a waterfall manner as previously shown in Fig. 2.

QFD was combined with the Analytic Hierarchy Process (AHP) to deal with incomplete and imprecise information in stakeholder requirements [18]. Instead of using specific symbols in step 3, the strength of the relationship is obtained through the general AHP pairwise comparisons (see Table I).

TABLE I
GRADATION SCALE FOR QUANTITATIVE COMPARISON

Importance	Definition	Explanation
1	Equal	Factors contribute equally to the objective
3	Moderate	One factor is slightly favoured over another
5	Strong	One factor is strongly favoured over another
7	Very strong	Evidence exists for a factor dominance
9	Extremely strong	Highest possible validity of a factor
2, 4, 6, 8	Intermediate values	For compromise between the above values

Lastly, the Design Structure Matrix (DSM) was used to represent the elements comprising a system and their interactions, thereby highlighting system architecture or design structure. DSM is characterised as a square *nxn* matrix, showing the interactions among a given set of *n* system elements. DSM offers a highly compact, easily scalable, and intuitively readable representation of a system architecture.

IV. APPLICATION CASE STUDY

The application of this novel methodology is showcased in a utility-scale wave energy project. The selection of this case study has been motivated by the size of the market opportunity. Grid-connected electricity generation is expected to be the dominant market for wave power technologies and actually the majority of technologies are being developed to generate electricity at utility-scale. Partial results are only illustrated in the last steps of the case study due to the large size of matrices.

A. Wave Energy Stakeholders

The traditional view of measuring a project success has evolved through time to include stakeholder satisfaction. Wave energy stakeholders can be defined as individuals, collectives and organisations who have an interest in wave energy technologies, can influence project development or be affected by the project, as well as those who can directly or indirectly impact the decision-making processes.

A utility-scale wave energy project will generally involve the creation of Special Purpose Vehicle (SPV) company to develop, build, maintain, and operate the wave energy project for its lifetime [19]. The SPV is the project owner and central administrative entity. It acquires financing, hires a developer, organise power purchase agreements, and maintains overall responsibility for the profitability of the project and for meeting obligations stipulated by regulators in the site lease.

The shareholders of this company are the sponsor(s) of the project, and their percentage of ownership in the company is proportional to the equity that they have invested. When the project is fully developed, the SPV will secure funds to pay the construction mainly with loans.

The Government can provide investment and generation incentives to develop the project. Common support mechanisms in renewable energy projects are competitive bidding (i.e. tender or auctioning schemes), renewable energy targets, feed-in tariffs or feed-in premiums, capital subsidies, and tax incentives.

Project developers are contracted by the owner to plan and develop the wave energy farm, often from the beginning stages of site assessment through the final stage of commissioning. The project developer will acquire project rights for sitting and permitting of the farm. Independent bodies will assess conformity of the project with regards to international standards.

During the consultation process, pressure groups may play an important role in setting further conditions for project approval. Project developers will also engage organisations that have a strategic interest in wave energy or represent the interest of other groups, even if not required to do so by law. This can include any groups that may significantly influence the development, either with their support or their opposition (e.g. environmentalists, political parties, community bodies, trade associations, unions, media).

The SPV will enter into different agreements with specialised firms for construction, operation and maintenance of the project. Generally, risks are transferred to these contractors. Low-tier suppliers provide various goods and services to the main contractors. An insurance company is chosen to provide coverage during the construction and operation phases.

Finally, the broader consumer body includes individuals and organisations that consume energy and/or pay taxes. The project charges end-users for the energy produced, collects payments and uses that revenue to cover its costs. Prior construction, a Power Purchase Agreement (PPA) can be signed with an off-taker, often a utility company, who ultimately sells it to consumers. If lenders can see the company has a purchaser of its production, it makes it easier to obtain financing.

Considering the stakeholder interactions described above, wave energy stakeholders can be grouped in four broad categories presented in Table II.

TABLE II
WAVE ENERGY STAKEHOLDERS

Group	Stakeholders	Roles
Financiers	Sponsors Lenders Government	Provide economic resources or incentives to develop the project
Condition setters	Regulators Independent bodies Pressure groups	National, regional and local bodies and groups setting conditions, required to be consulted or influencing the direction of the project
Developers	Project developer Construc. company Operating company Suppliers Insurance company	Direct interest in how things are managed on the project. Provide key resources, advice, services or assets
Energy users	Off-taker Grid operator Consumers	Direct participation in the flow of energy

Stakeholder mapping techniques, usually based on two or three dimensions, can help managers determine the priority of identified stakeholders [20]. The selected stakeholder dimensions for this research are power, interest and urgency.

As shown in Fig. 3, up to eight categories can be established according to the number of dimensions stakeholders possess.

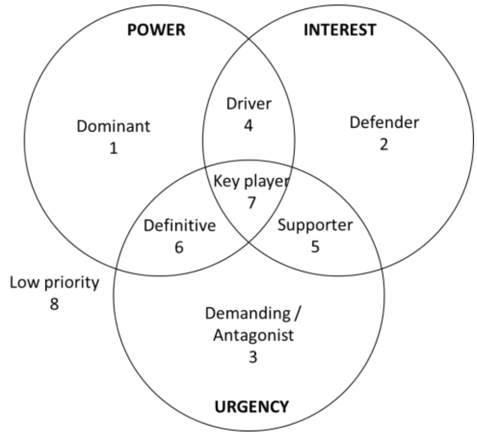

Fig. 3. Stakeholder Classification (adapted from [20]).

Latent stakeholders (1, 2 & 3) possess only one of the three dimensions and it is recommended to keep them informed or satisfied. Expectant stakeholders (4, 5, & 6) possess two of the three dimensions. In this case, it is recommended to keep a close and good relationship. Key players (7) possess the three dimensions and the project must consider the needs of these stakeholders. Marginal stakeholders (8) possess none of the dimensions and therefore it is recommended to monitor them with minimal effort.

QFD-AHP has been used to prioritize wave energy stakeholders. The numerical scale 1 to 9 denotes gradation from weak to very strong relationship between the stakeholder and the corresponding dimension. However, in this case aggregation is done using geometric mean as power, interest and urgency are quasi-independent dimensions.

Lenders, who score the highest with regards to power, are dominant stakeholders closely followed by the Government and Regulators. Project developers are expectant stakeholders who can support the project as they score the highest in interest and urgency. Pressure groups may have significant interest but lack power to become a driving force. Full results are presented below in Fig. 4.

Stakeholder Group		Stakeholders		Dimensions: Power	Interest	Urgency	Stakeholder Prioritisation Rating	
Financiers	26.2%	S1.1	Sponsors	3	5	5	4.22	11.6%
		S1.2	Lenders	9	1	1	2.08	5.7%
		S1.3	Government	7	5	1	3.27	9.0%
Condition Setters	22.4%	S2.1	Regulators	7	3	3	3.98	10.9%
		S2.2	Independent bodies	1	3	1	1.44	4.0%
		S2.3	Pressure groups	1	7	3	2.76	7.6%
Developers	37.0%	S3.1	Project developer	1	9	9	4.33	11.9%
		S3.2	Construct. company	3	5	3	3.56	9.7%
		S3.3	Operating company	3	5	1	2.47	6.8%
		S3.4	Suppliers	1	5	1	1.71	4.7%
		S3.5	Insurance company	3	1	1	1.44	4.0%
Energy users	14.3%	S4.1	Off-taker	3	3	1	2.08	5.7%
		S4.2	Grid operator	5	1	1	1.71	4.7%
		S4.3	Consumer	1	3	1	1.44	4.0%
			Totals				**36.48**	**100.0%**

Fig. 4. Wave Energy Stakeholder Prioritisation.

B. Stakeholder Attributes

The main goal of a utility-scale wave energy project is to convert wave energy into grid-compliant electricity in a competitive and acceptable manner during its lifetime [13].

The expectations of individual stakeholders might address favourable and unfavourable concerns. The favourable sure concerns are called benefits (B) while the unfavourable ones are called costs (C). The uncertain concerns of a decision are the opportunities (O) that the decision might create and the risks (R) that it can entail. Benefit and cost attributes can be considered as immediate features of an alternative, whereas opportunity and risk attributes represent what could be expected from this alternative. In sustainable energy a benefit is a driver, cost is a constraint, an opportunity is policy and risks create sensitivity. The analysis of benefits, opportunities, costs and risks (BOCR) offers a structural framework to get all necessary information for effective decision-making [20].

The analysis of stakeholders' needs presented in [13] leads to seven high-level stakeholder requirements. 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, deployable globally) and risks (acceptability and safety).

The expectations of individual stakeholders have been reorganised into a distilled list of Stakeholder Attributes (SA) that ensure the wave energy system addresses all favourable and unfavourable concerns.

Wave Energy Benefits

B1.1 Energy production: The amount of electricity production is an essential driver to the value of a wave energy project as it is the way to create revenues.

B1.2 Controllability: The electricity market requires prediction of energy production for grid operation, correlation to the daily demand and load control or adaptation.

B1.3 Availability: Downtime is produced by repair activities due to system failures (unreliability) and logistic delays. A high availability will increase the energy production value over its lifetime.

B1.4 Profitable business: Private stakeholders seek a secure return on investment, dividend, interest rate or commercial margin. Public stakeholders should ensure an efficient use of public resources.

Wave Energy Opportunities

O1.1 Economic growth and job creation: Wave energy projects may boost employment by directly influencing the creation of stable and highly specialized jobs.

O1.2 Climate change mitigation: Wave energy technologies produce little GHG emissions over its entire lifecycle.

Wave Energy Costs

C1.1 Capital costs: It includes all costs that occur until the farm starts producing electricity (i.e. development, manufacturing, transport, assembly, installation and commissioning).

C1.2 Operational costs: This includes all costs necessary to operate and maintain the farm over its entire service life (i.e. inspection, operation, maintenance, repair, and preventing any other harms).

C1.3 End-of-life costs: It includes costs to decommission, recycle, reuse and dispose.

C1.4 Financial costs: This includes costs to finance and insure the wave energy systems.

Wave Energy Risks

R1.1 Survivability: Due to the stochastic nature of the environment, conditions that are beyond design limits may happen. Survivability is the degree to which a system continues to fulfil its mission despite external hazards.

R1.2 Commercial risks: Uncertainties may make costs, energy production, and availability deviate from expectations. Long term agreements and contracts can mitigate them.

R1.3 Acceptability: This attribute comprises compliance with regulation and avoidance of negative environmental, social and industrial impacts.

Again, Stakeholder Attributes have been ranked using QFD-AHP. A relationship matrix has been built representing how each stakeholder category relates to a Stakeholder Attribute. The strength of this relationship is expressed using the same gradation scale.

The relative weight of the individual stakeholder attributes is presented in Fig. 5.

Stakeholders		Stakeholder Prioritisation Rating	B1.1 Energy production	B1.2 Controllability	B1.3 Availability	B1.4 Profitable business	O1.1 Economic growth & job creation	O1.2 Climate change mitigation	C1.1 Capital costs	C1.2 Operational costs	C1.3 End-of-life costs	C1.4 Financial costs	R4.1 Survivability	R4.2 Commercial risks	R4.3 Acceptability
S1.1	Sponsors	11.6%	7	5	7	9	1	3	7	5	3	9	9	9	3
S1.2	Lenders	5.7%	7	1	3	7	0	0	7	7	3	9	5	9	1
S1.3	Government	9.0%	7	1	3	5	9	9	5	5	7	3	5	7	9
S2.1	Regulators	10.9%	3	7	3	0	0	0	0	0	1	0	9	0	9
S2.2	Independent bodies	4.0%	1	1	1	0	0	0	0	0	1	0	9	0	9
S2.3	Pressure groups	7.6%	3	5	5	1	9	9	1	1	3	0	9	1	9
S3.1	Project developer	11.9%	9	7	7	9	5	5	7	7	3	5	7	1	5
S3.2	Construct. company	9.7%	0	0	0	9	1	0	9	3	1	0	5	3	3
S3.3	Operating company	6.8%	0	0	7	9	1	1	3	9	1	0	1	3	3
S3.4	Suppliers	4.7%	0	0	0	7	1	1	5	5	1	0	3	1	0
S3.5	Insurance company	4.0%	5	1	5	7	0	0	7	7	3	7	5	9	0
S4.1	Off-taker	5.7%	9	5	9	7	1	3	0	0	0	3	3	5	1
S4.2	Grid operator	4.7%	5	9	7	5	0	0	0	0	0	0	0	3	0
S4.3	Consumer	4.0%	7	0	9	0	1	1	0	0	1	5	1	1	7
	Totals	100.0%	4.72	3.48	4.69	5.75	2.50	2.75	4.15	3.74	2.25	3.06	5.73	3.74	4.65
			9.2%	6.8%	9.2%	11.2%	4.9%	5.4%	8.1%	7.3%	4.4%	6.0%	11.2%	7.3%	9.1%
			36.4%				10.3%		25.8%				27.6%		
			Benefits				Opportunitie		Costs				Risks		

Fig. 5. Wave Energy Stakeholder Attributes.

C. *Functional Requirements*

Functional analysis is the next step after the analysis of stakeholder needs. It aims to identify what wave energy system functions shall be provided, what structure these functions should follow, and how these functions shall interact in an optimal manner to satisfy stakeholder needs efficiently. Functional analysis provides a picture of what functions the wave energy system should perform, not how these functions have to be implemented [3].

There are two types of functional analysis. Whereas the external analysis is focused on the system user and the identification of its service functions, the internal analysis is focused on the system designer; it involves transforming service functions into technical or internal functions.

A full understanding of system functions is needed for a complete description of the system in the form of a functional architecture.

A primary function is defined as the principal reason for the existence of that system. Secondary functions need to be performed to realise the primary function, whilst the loss of the primary function causes loss of the market value of a system [21]. In fact, the system can be perceived as an instrument to modify the features of an external entity (primary functions). Likewise, the system may have to adapt to the external environment to operate (secondary functions).

The external entities depicted in Fig. 6 interact with the wave energy system.

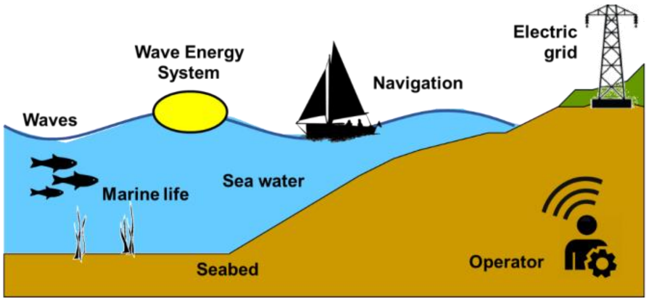

Fig. 6. Elements of the Environment.

As presented before, the main goal of a utility-scale wave energy project is to convert wave energy into grid-compliant electricity in a competitive and acceptable manner during its lifetime. Accordingly, the primary function of a wave energy system is stated as follows:

Fp1: Convert wave energy into grid-compliant electricity

The system interacts with two external entities, i.e. the waves and the electric grid as represented in Fig. 7.

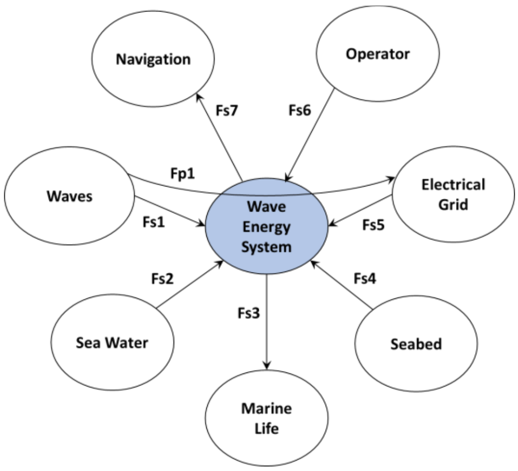

Fig. 7. Context Diagram for the Wave Energy System.

The rest of functions are secondary. They link a single external entity with the system and are listed below:

Fs1: Survive extreme wave loading

Fs2: Avoid corrosion caused by sea water

Fs3: Withstand biofouling caused by marine life

Fs4: Maintain position with respect to seabed

Fs5: Be supplied back-up power

Fs6: Be monitored and controlled by an operator

Fs7: Avoid collision risk with surrounding navigation

To examine internal functionality, Function Analysis System Technique (FAST) is used [21]. A FAST diagram is built from left to right in the logic of *why* to *how*. Any function to the left of another function is a higher-level function, since reading the FAST model in the why direction will lead to the primary function. Conversely, any function to the right of another function is a lower-level function and represents a means that is needed (how) to achieve the function being addressed. The level of detail expands until it terminates at an actionable level. An actionable or measurable level of detail is one on which an engineer can begin the development work.

Main output of FAST is therefore the identification of the basic functions through the decomposition of the higher-level functions. The basic functions help defining or refining the functional requirements of system, as each basic function can be rewritten as a Functional Requirement (FR).

Fig. 8 presents the FAST diagram for the wave energy system. It can be observed that this internal analysis has produced a further decomposition of one secondary function identified in the external analysis (Fs4), grouped together Fs1, Fs2 and Fs3 in an intermediate level, and completed the list of basic functions.

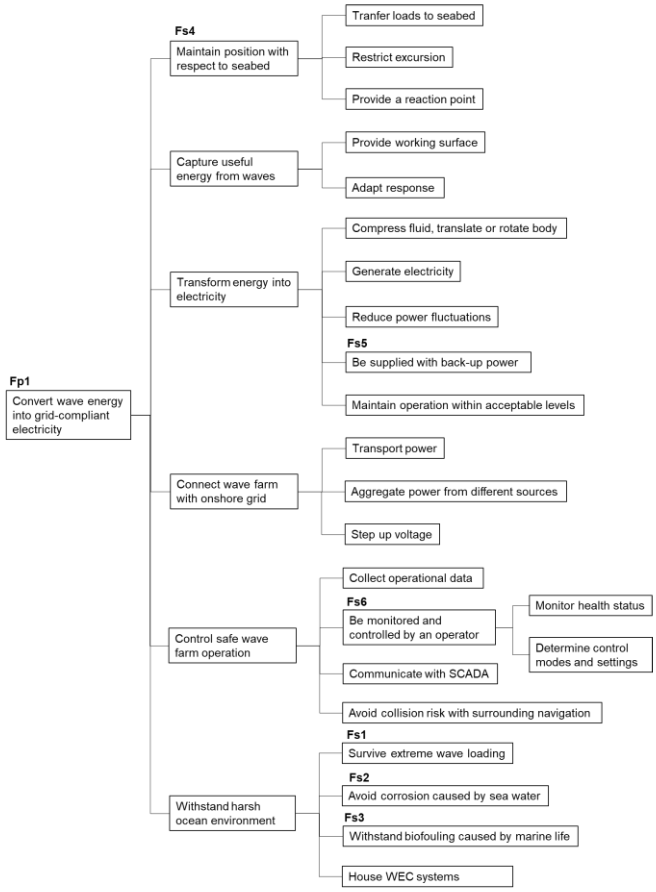

Fig. 8. FAST Diagram for the Wave Energy System.

Low-level functional requirements have been ranked using QFD-AHP. A relationship matrix has been built representing how each Stakeholder Attribute relates to a Functional Requirement. Similarly as with stakeholder attributes, the strength of this relationship is expressed using a 0-9 gradation scale (none to extremely strong).

The relative weight of the individual functional requirements is presented in Fig. 9.

Stakeholders Attributes		*Prioritisation Rating*	F1.1 Transfer loads to seabed	F1.2 Restrict excursion	F1.3 Provide a reaction point	F2.1 Provide working surface	F2.2 Adapt response	F3.1 Compress fluid, translate or rotate body	F3.2 Generate electricity	F3.3 Reduce power fluctuations	F3.4 Be supplied back-up power	F3.5 Maintain operation within acceptable levels	F4.1 Transport power	F4.2 Aggregate power from different sources	F4.3 Step up voltage	F5.1 Collect operational data	F5.2 Monitor health status	F5.3 Determine control modes and settings	F5.4 Communicate with SCADA	F5.5 Avoid collision with surrounding navigation	F6.1 Withstand extreme loading conditions	F6.2 Avoid corrosion caused by sea water	F6.3 Withstand biofouling caused by marine life	F6.4 House WEC systems
B1.1	Energy production	9.2%	1	0	5	9	9	9	9	7	1	7	5	5	5	3	0	3	0	0	1	0	0	0
B1.2	Controllability	6.8%	0	1	0	0	9	5	5	7	1	9	1	3	5	3	3	9	3	0	5	0	0	0
B1.3	Availability	9.2%	0	0	0	0	5	7	9	1	0	5	3	3	3	1	1	7	1	0	3	3	3	5
B1.4	Profitable business	11.2%	0	0	3	5	7	7	9	9	0	9	9	9	3	3	3	7	1	5	9	5	7	3
O1.1	Economic growth & job creation	4.9%	3	5	3	9	5	5	5	3	0	3	9	7	7	1	1	1	0	0	3	1	1	1
O2.2	Climate change mitigation	5.4%	0	0	0	9	9	9	9	7	0	5	9	9	9	0	0	1	0	1	0	0	0	0
C1.1	Capital costs	8.1%	3	3	5	9	3	3	3	3	1	1	9	7	7	1	1	3	1	1	9	1	1	3
C1.2	Operational costs	7.3%	1	3	5	1	3	7	5	3	1	3	1	5	3	5	7	5	1	5	1	3	3	1
C1.3	End-of-life costs	4.4%	9	5	1	1	1	1	1	1	1	1	9	9	9	1	1	0	0	0	1	3	3	1
C1.4	Financial costs	6.0%	3	3	3	1	5	7	5	9	1	7	1	3	5	1	1	5	1	1	9	3	3	1
R1.1	Survivability	11.2%	7	9	7	3	7	1	1	3	0	9	1	1	1	5	5	7	3	7	9	7	7	3
R1.2	Commercial risks	7.3%	1	3	1	1	7	3	1	5	0	5	1	3	1	3	9	7	1	1	5	3	3	1
R1.3	Acceptability	9.1%	9	7	1	5	1	5	1	1	0	5	7	5	3	1	1	3	1	9	9	5	7	1
	Totals	**100.0%**	**2.80**	**3.03**	**2.88**	**4.08**	**5.60**	**5.33**	**4.96**	**4.58**	**0.42**	**5.73**	**4.82**	**5.07**	**4.18**	**2.38**	**2.68**	**4.89**	**1.12**	**2.79**	**5.44**	**2.95**	**3.36**	**1.76**
			3.5%	3.8%	3.6%	5.0%	6.9%	6.6%	6.1%	5.7%	0.5%	7.1%	6.0%	6.3%	5.2%	2.9%	3.3%	6.0%	1.4%	3.5%	6.7%	3.7%	4.2%	2.2%
			10.8%			12.0%		26.0%					17.4%			17.2%					16.7%			
			Maintain position with respect to seabed			Capture useful energy from waves		Transform energy into electricity					Connect wave farm with onshore grid			Control safe wave farm operation					Withstand harsh ocean environment			

Fig. 9. Wave Energy Functional Requirements.

D. *Allocation of Functional Requirements*

Generally, the Wave Energy System will be composed by a number of WECs. An overview of the key components that require consideration for wave energy systems is provided in [22], [23], [24]. According to these sources, the WEC can be characterized as follows:

Reaction System: Structural reference elements that maintain the spatial position of the device within the marine environment and transfer loads to the seabed.

Power Take-Off (PTO): Means by which the primary captured energy extracted from the waves is converted into a more useful form of energy.

Hydrodynamic System: This is the main interface through which the device interacts with the energy source. It provides the surface area for wave power absorption and actively transfers its motions and forces to both the Reaction and PTO systems.

Power transport: It is done by connecting individual devices with inter-array cables and then to an export cable which brings electricity to shore.

Control: Hardware, software and instrumentation to safeguard the device, control its hydrodynamic response and optimise power capture under a wide range of operating conditions.

Fig. 10 presents a two-level hierarchical decomposition of a wave energy system.

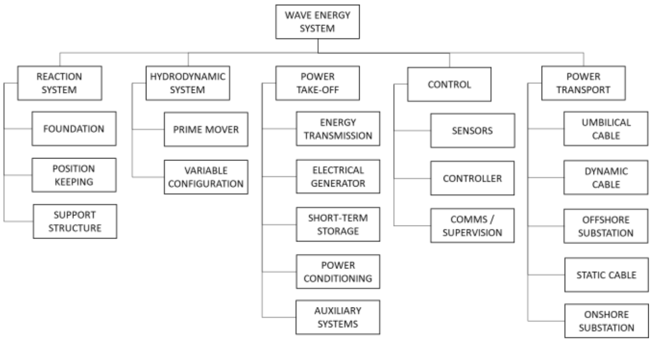

Fig. 10. Hierarchy of Wave Energy Subsystems.

Critical interfaces with external entities in the wave energy system are:

- Hydrodynamic system with wave resource
- Reaction system with seabed
- Control with the operator (SCADA system)
- Power transport with electrical grid

Functional architectures are 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 [25]. Functional analysis produces a detailed definition of the system functions. To implement these functions, system components are needed to perform these functions.

Fig. 11 presents the functional allocation at system level.

	Systems	Reaction System	Hydrodynamic System	Power Take-Off	Power cables	Control
Functions		C1	C2	C3	C4	C5
Maintain position with respect to seabed	F1	1				
Capture useful energy from waves	F2	1	1			
Transform energy into electricity	F3			1		
Connect wave farm with onshore grid	F4				1	
Control safe wave farm operation	F5					1
Withstand harsh ocean environment	F6	1	1	1	1	1

Fig. 11. Wave Energy Functional Allocation.

There is an on-to-one allocation of functions to components except for "capture useful energy" and "withstand harsh ocean environment". In the case of fixed referenced devices, the reaction system serves both to maintain position and capture useful energy. On the other hand, withstanding the harsh ocean environment is a distributed function across all sub-systems/components.

This functional allocation has been also performed at sub-system level, but not shown in this paper.

Fig. 12 presents the mapping of Stakeholder Attributes to Components (Co). It has been obtained by multiplying the matrix of Stakeholder Attributes to Functional Requirements (Fig. 9) by the one of Functional Requirements to Component allocation at sub-system level (Fig. 11).

Stakeholders Attributes	Prioritisation Rating	C1.1 Foundation	C1.2 Position Keeping	C1.3 Support Structure	C2.1 Prime Mover	C2.2 Variable Configuration	C3.1 Energy Transmission	C3.2 Electrical Generator	C3.3 Short-term Storage	C3.4 Power Conditioning	C3.5 Auxiliary Systems	C4.1 Umbilical Cable	C4.2 Dynamic Cable	C4.3 Offshore Substation	C4.4 Static Cable	C4.5 Onshore Substation	C5.1 Sensors	C5.2 Controller	C5.3 Comms/ Supervision
B1.1 Energy production	9.2%	2	2	15	10	10	10	10	17	13	7	6	6	16	6	11	4	3	3
B1.2 Controllability	6.8%	5	6	5	5	14	10	10	21	13	9	6	6	14	6	11	8	12	12
B1.3 Availability	9.2%	3	9	14	14	14	13	15	9	7	8	6	11	12	6	9	10	8	8
B1.4 Profitable business	11.2%	9	21	32	29	28	21	23	25	17	19	18	21	30	18	21	24	10	13
O1.1 Economic growth & job creation	4.9%	6	13	18	15	10	9	9	11	11	4	12	13	26	12	19	6	2	1
O2.2 Climate change mitigation	5.4%	0	0	9	9	9	9	9	16	16	6	9	9	27	9	18	0	1	2
C1.1 Capital costs	8.1%	12	17	28	23	14	13	13	15	12	3	18	21	32	18	25	12	4	5
C1.2 Operational costs	7.3%	2	11	14	9	10	11	9	7	10	11	2	3	10	2	5	12	12	11
C1.3 End-of-life costs	4.4%	10	21	10	9	8	5	5	3	14	4	10	11	28	10	19	8	1	0
C1.4 Financial costs	6.0%	12	21	20	17	20	19	17	23	18	11	10	11	18	10	15	16	6	7
R1.1 Survivability	11.2%	16	39	36	29	30	17	17	19	11	23	10	13	12	10	11	28	12	17
R1.2 Commercial risks	7.3%	6	15	14	13	18	11	9	17	9	9	6	7	10	6	7	14	16	9
R1.3 Acceptability	9.1%	18	37	28	27	22	19	15	11	9	19	16	17	24	16	19	22	4	13
Totals	**100.0%**	**8.24**	**17.58**	**20.48**	**17.59**	**17.35**	**13.72**	**13.35**	**15.62**	**12.13**	**11.47**	**10.25**	**12.02**	**19.50**	**10.25**	**14.43**	**14.12**	**7.58**	**8.81**
		3.4%	7.2%	8.4%	7.2%	7.1%	5.6%	5.5%	6.4%	5.0%	4.7%	4.2%	4.9%	8.0%	4.2%	5.9%	5.8%	3.1%	3.6%
		18.9%			14.3%		27.1%					27.2%					12.5%		
		Reaction System			Hydro-		Power Take-Off					Power Cabling					Control		

Fig. 12. Mapping of Stakeholder Attributes to Components.

E. Engineering Parameters

Engineering Parameters (EP) represent the behaviour characteristics of both the whole system and each individual subsystem. An engineering parameter is a generalised characteristic representing an engineering situation. The list of 39 generic engineering parameters established in TRIZ [26] is taken as a reference for identification of wave energy technical parameters.

The Hydrodynamic system has been selected in the case study for illustrative purposes. Engineering parameters relevant to the Hydrodynamic system are:

- Displaced volume (m3)
- Aspect ratio
- Breaking load
- Design life (years)
- Technology class
- Control type
- Unit cost (€/kg)
- Origin of materials (local, national, international)

Engineering Parameters have been ranked using QFD-AHP. A relationship matrix has been built representing how each engineering parameter relates to a particular component. The strength of this relationship is expressed using a 0-9 gradation scale (Fig. 13).

			EP.1	EP.2	EP.3	EP.4	EP.5	EP.6	EP.7	EP.8
	Components	***Prioritisation Rating***	Displaced volume (m3)	Aspect ratio	Breaking load (kN)	Design life (years)	Technology class	Control type	Unit cost (€/kg)	Origin (local, nat'l, int'l)
C2.1	Prime Mover	7.2%	9	3	7	9	9		7	3
C2.2	Variable Configuration	7.1%				7	5	9		
	Totals	**14.3%**	**0.65**	**0.22**	**0.50**	**1.14**	**1.00**	**0.64**	**0.50**	**0.22**
			13.3%	4.4%	10.3%	23.5%	20.6%	13.1%	10.3%	4.4%

Fig. 13. Hydrodynamic System to EP Matrix.

To conclude, Fig. 14 presents the mapping of Stakeholder Attributes to Engineering Parameters. It has been obtained by multiplying the matrix of Stakeholder Attributes to Components (Fig. 12) by the matrix of Components to Engineering Parameters (Fig. 13).

			EP.1	EP.2	EP.3	EP.4	EP.5	EP.6	EP.7	EP.8
	Stakeholders Attributes	***Prioritisation Rating***	Displaced volume (m3)	Aspect ratio	Breaking load (kN)	Design life (years)	Technology class	Control type	Unit cost (€/kg)	Origin (local, nat'l, int'l)
B1.1	Energy production	9.2%	90	30	70	160	140	90	70	30
B1.2	Controllability	6.8%	45	15	35	143	115	126	35	15
B1.3	Availability	9.2%	126	42	98	224	196	126	98	42
B1.4	Profitable business	11.2%	261	87	203	457	401	252	203	87
O1.1	Economic growth & job cr	4.9%	135	45	105	205	185	90	105	45
O2.2	Climate change mitigation	5.4%	81	27	63	144	126	81	63	27
C1.1	Capital costs	8.1%	207	69	161	305	277	126	161	69
C1.2	Operational costs	7.3%	81	27	63	151	131	90	63	27
C1.3	End-of-life costs	4.4%	81	27	63	137	121	72	63	27
C1.4	Financial costs	6.0%	153	51	119	293	253	180	119	51
R1.1	Survivability	11.2%	261	87	203	471	411	270	203	87
R1.2	Commercial risks	7.3%	117	39	91	243	207	162	91	39
R1.3	Acceptability	9.1%	243	81	189	397	353	198	189	81
	Totals	**100.0%**	**158.34**	**52.78**	**123.15**	**279.79**	**245.09**	**156.15**	**123.15**	**52.78**

Fig. 14. Mapping of Stakeholder Attributes to EP.

The Stakeholder Attributes to Engineering Parameter (EP) matrix provides a summary of how the performance of the system is related to the subsystems in the system. The engineering characteristics represented in this matrix are identical to the engineering parameters in the traditional QFD.

V. Discussion

It is commonly accepted that a system performance must be determined in the context of the established stakeholder needs. However, stakeholder needs are general, ambiguous, highly unmeasurable and thus the design cannot be easily assessed. The sequential mapping among three different domains of the design world enables full traceability of stakeholder needs. This approach is particularly useful during the first stages of technology development where up to 75% of the final product cost can be committed [27].

The application case study shows this approach can be used by various stakeholders to inform their decision-making process in a utility-scale wave energy project.

The systematic analysis of the first design domain (Stakeholders Attributes) produced a prioritised grouping of wave energy stakeholders and expectations or attributes. Project developers are the highest ranked stakeholder group, followed by Financiers and Condition setters. Energy users obtain the lowest rating. Sponsors (11.6%), Regulators (10.9%), Project developer (11.9%) and Off-taker (5.7%) have the highest rating within their respective stakeholder group. It is worth noting that even though the main goal of a utility-scale wave energy project is to convert wave energy into grid-compliant electricity the group of stakeholders comprising energy users are merely drivers but not key players.

It can be observed that benefits account for more than 1/3 of stakeholder requirements, whereas costs slightly above 1/4. Risks, uncertain concerns of the investment decision, are equally important as costs (sure concerns). A conventional cost-benefit analysis would have missed these important factors. The highest ranked stakeholder concerns in each category are a Profitable business (11.2%), Climate change mitigation (5.4%), Capital costs (8.1%) and Survivability (11.2%).

The analysis of the second design domain (Functional Requirements) resulted in the essential features the wave energy system must address, a hierarchy of wave energy subsystems and an allocation of these functions to the physical embodiment.

Transforming wave energy into electricity account for more than 1/4 of functional requirements. In fact, capturing, transforming and connecting to the grid total 55% of functional requirements. Mapping of Stakeholder Attributes to components reflect a similar weight of PTO and power cabling systems. This is consistent with the primary function of the wave energy project.

Lastly, the analysis of the third design domain (Engineering Parameters) for the Hydrodynamic system of the WEC, highlights the importance of both Design life and Technology class for the survivability of the farm and a profitable business.

VI. Conclusions and Further Work

The development of wave energy systems involves complex decision-making about the product based on conceptual design information including stakeholder needs, functions, components and engineering parameters. Several Systems Engineering design methods have been developed for structuring conceptual design information using matrices, including requirements, functions, components and engineering parameters. However, existing methods do not provide a means for mapping non-adjacent information domains.

The matrix-based modelling approach presented in this paper was developed to address the current shortcomings. This novel method for wave energy enables a systematic design approach, a traceable mapping of non-adjacent design domains, a visualisation of complex system information and customisation to changing market conditions. The main contribution is to provide designers with a flexible tool to focus attention on key properties and target areas in the system. For instance, results from the application case study highlight the significant importance of risks factors in wave energy design, which normally are hidden in traditional cost-benefit approaches.

The methodology consists of three primary-level matrices, namely the SA-to-FR matrix, the FR-to-Co matrix, and the Co-to-EP matrix. Additional matrices are computed through matrix multiplication from the primary matrices. Particularly the SA-to-EP matrix can be used to compare alternative design solutions.

This work is part of a broader PhD research project. Further work will be focused on identifying wave energy design alternatives with greatest potential. To that purpose, a set of value functions will be developed to model fundamental relationships between the engineering parameters and the actual value provided to stakeholders. The methodology will also be validated by involving representatives of the different stakeholder groups to refine the relationship strength in the matrices.

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