Using Structured Innovation Techniques to Assess and Develop Potential Technology for Wave Energy Power Conversion

Anna Stegman#1, Henry Jeffrey#2, Lars Johanning#3, Stuart Bradley#4

#1IDCORE, Energy Technologies Institute, Loughborough, UK anna.stegman@eti.co.uk
#2 Institute of Energy Systems, University of Edinburgh, Scotland, UK
#3 College of Engineering, Mathematics and Physical Sciences, University of Exeter, Penryn, UK
#4 Energy Systems Catapult, Derby, UK

Abstract- **This paper proposes a method that could be of use to developers when considering designs improvements, or to investors considering a range of opportunities. The methodology shows how improvements to designs can be developed using systematic problem solving tools and the Theory of Inventive Thinking (TRIZ). The methodology is demonstrated in this study, using high level functional requirements for a wave energy converter, and a range of commonly used design metrics. The simple example uses baseline data from published developers, and results are calculated, using Monte Carlo analysis, to show potential scenarios that would offer an overall improvement. In this case, the mass, level of control, and load variation are shown to be the parameters with the greatest impact on the overall design score, and are used as initial examples to apply the TRIZ tools.**

***Keywords*: Wave Energy, Structured Innovation, QFD, TRIZ**

I. INTRODUCTION

For wave energy to be a commercially viable technology there needs to be a significant cost reduction, and improvement in performance from previously developed devices [1]. It is been the general consensus for a number of years, that to achieve this, a step change in the technology is required, and that incremental design improvements are unlikely to meet targets for levelised cost of energy [2]–[6]. By using a structured, systematic approach, it is hoped that areas for improvement that provide the greatest impact to the overall design will be identified, to help achieve this level of step change, and encourage the greatest value from investments.

Systems engineering tools place the customer requirements at the forefront of the design and development process [7]-[8]. Stakeholder requirements were defined in [9] for a commercial WEC farm and included, at high level;

- Have competitive cost of energy
- Provide secure investment opportunity
- Be reliable for grid operations
- Benefit society
- Be acceptable for permitting and certification
- Be acceptable regarding safety
- Be globally deployable

This analysis assumed that multiple wave energy farms have been deployed, and that there are multiple proven technologies to choose from. These are clearly important factors for large scale deployment, however this present study aims to focus on the technological aspects which would lead to the development of these proven technologies from which to choose.

This study aims to show a potential method that could be used i) by developers to improve the next design iteration, and ii) investors to compare options, by developing a modified Quality Function Deployment (QFD) model. The method provides an evidence base to why certain design choices have been made, and therefore has potential to add value, perhaps to attract investors, exploit the technology, and develop Intellectual Property. The outputs from the QFD can be used to show key design conflicts, and these can be translated into a Theory of Inventive Thinking (TRIZ) format to help identify solutions.

TRIZ is a common technique developed from a rigorous patent study in Russia [10]. The general approach by TRIZ is that the problem is not unique, and it is most likely that it has been encountered before, in another field, and a way to solve it has already been developed. This encourages thinking across industries, and thereby can accelerate progression by using ideas implemented in other sectors.

The technique is widely used in other industries to aid design development including aerospace, electronic design, and wind turbines [11]–[15].

This paper is comprised six sections. The methodology will be briefly described, followed by the definition of the functional requirements model. The QFD model will be developed using a general example as a demonstration. The possible design conflicts will be identified and the TRIZ contradiction matrix, [16], will be applied to solve these, and show how this could be integrated into the design process. The final sections will then discuss the limitations and conclusions.

II. METHODOLOGY

The overall approach developed in this study is summarised in Fig. 1 and this section will discuss each stage in further detail.

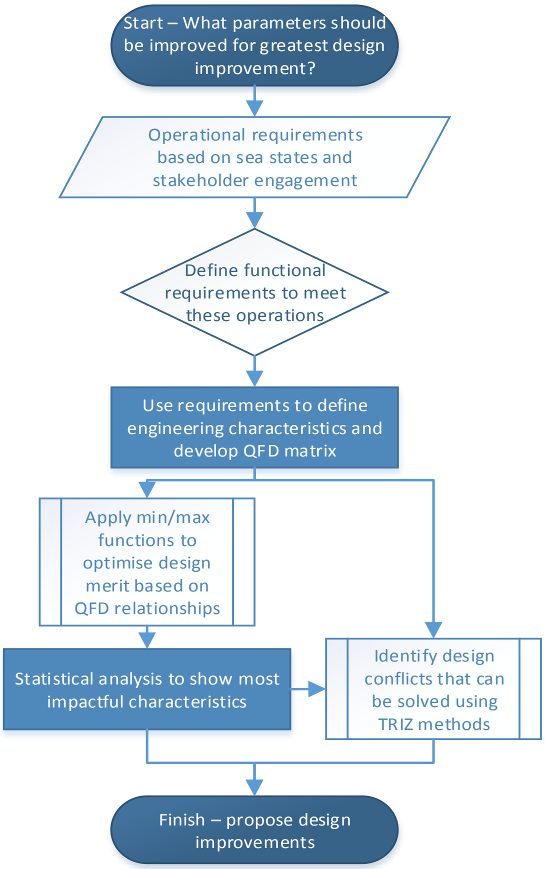


Fig. 1. Flowchart to show methodology applied in study

A. *Define functional requirements at device level*

The requirements are defined, initially, based on the operational modes that are necessary for a wave energy device. At this scale, the predominant focus is on the technology requirements, and the political, societal, environmental and economical are not included. There is some overlap with the requirements defined in [9] from stakeholder engagement.

B. *Quality Function Deployment (QFD) model*

The requirements, (r_n), form the basis of the QFD matrix and therefore ensure that these are considered early in the design stage. Engineering characteristics (e_n) are then defined by considering how the requirements can be satisfied. The matrix is completed by assigning a qualitative value to the strength of the relationship between the requirement and characteristic (9: strong, 3: moderate, 1: weak, 0: none). These scores are used to calculate a weighting, to indicate impact on the overall design.

In this study, a function is applied to each engineering characteristic; maximise or minimise. Some studies have used optimise and variations of maximise and minimise [17], however to demonstrate the method, it will be kept relatively simple. These functions require a neutral point, and a parameter value. In this case, the neutral point will be based on a published data relating to the Pelamis device, and the parameter values will be a range, broadly based on possible values from other devices [18].

The function output gives a merit value (mv_n) as a fraction, and when this is multiplied by the weighting from the relationship matrix, it gives an overall score for that characteristic (s_n). The sum of the scores give an overall design merit score (ODM) as a %.

A monte carlo analysis is completed for the parameter ranges and statistical analysis can show what scenarios are required to achieve a higher overall score. If there were a number of choices that were being compared, a smaller number of scenarios with discrete values could be used, and this would enable a direct comparison would be possible. This would depend however, on having the input data available.

The methodology is summarised below;

$$\begin{bmatrix} e_1 & e_2 & \cdots & e_n \end{bmatrix}$$

$$QFD\ Matrix: \quad \begin{bmatrix} r_1 \\ r_2 \\ \vdots \\ r_n \end{bmatrix} \times \begin{bmatrix} w.e_{11} & w.e_{12} & \cdots & w.e_{1n} \\ w.e_{21} & w.e_{22} & \cdots & w.e_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ w.e_{n1} & w.e_{n2} & \cdots & w.e_{nn} \end{bmatrix} = \begin{bmatrix} sc_1 \\ sc_2 \\ \vdots \\ sc_n \end{bmatrix}$$

$$\begin{bmatrix} m_1 & m_2 & \cdots & m_n \end{bmatrix}$$

$$\begin{bmatrix} f_1 & f_2 & \cdots & f_n \end{bmatrix}$$

$$\begin{bmatrix} mv_1 & mv_2 & \cdots & mv_n \end{bmatrix}$$

$$\begin{bmatrix} s_1 & s_2 & \cdots & s_n \end{bmatrix}$$

$$OMD\ (\%) = \sum_{i=1}^{n} (mv_n\, s_n) \times 100$$

Where

$r =$ requirement weighting

$e =$ engineering characteristic

$w.e =$ qualitative relationship score between the requirements and engineering characteristic (9: strong, 3: moderate, 1: weak, 0: none)

$sc =$ score check to verify weightings and importance ranking $s_{1=} \sum r_1\, w.e_{1n}$

$m =$ metric definition as a measure for the engineering characteristic

$f =$ function to apply to metric

$$Maximise: \quad 1 - \left(\frac{1}{2^{\frac{\rho}{\eta}}}\right)$$

$$Minimise: \quad 1 - \left(\frac{1}{2^{\frac{\eta}{\rho}}}\right)$$

$\eta =$ neutral point

$\rho =$ parameter value

mv = merit value = function output

ODM (%) = overall design merit

C. *Solving Conflicts with TRIZ*

Another facet of the QFD method is to consider the relationship between each engineering characteristic, termed the house of quality. A strong or moderate positive, or strong or moderate negative is generally used as a qualitative assessment. For example, if a parameter is to maximise structural volume, but another is minimise mass, these would have a strong negative relationship to each other.

A tool used in TRIZ is the contradiction matrix which lists 39 technical parameters, and shows the most common inventive principles used to solve these, from a list of 40 [10]. To continue the example of a low mass, high volume structure, the matrix recommends applying the inventive principles;

- Taking out
- Copying
- Pneumatics and hydraulics
- Composite materials

These principles are vague to allow the same matrix to be applicable in a wide range of cases, therefore to develop solutions, they do require a level of inventiveness, creative thinking, and expertise. To be able to apply these principles there needs to be reason behind the choices, for example, a a large volume maybe required as this will increase the amount of wave energy captured, and low mass is preferable as it implies a low cost structure and ease of installation and transportation. However, in the case of wave energy, if the different operating cases are considered (Fig. 3), a large volume would be required when operating in the average seas and mass would not be as important, and a small volume for peak storms to lower the loads on the system, and a small volume and mass for transportation and installation.

Taking out – could imply that the mass isn't there during installation, but is while operating, so seawater could be used as ballast in a rigid, or flexible body. Or the volume could be increased by using an inflatable or folded/origami type structure. This is just a simple example and in a real scenario would require workshops with a number of individuals to fully explore each inventive principle suggested, and would depend on the technology being considered.

III. APPLICATION AND ANALYSIS

A. *Functional Model Analysis*

To ensure an appropriate technology, it is necessary to first consider the operational requirements based on resources and site conditions. These can then be translated into functional requirements for the overall system, and subsystems. Fig. 2 shows an example of the annual variation of wave energy, in this case taken from Orkney [19]. There are power peaks in winter of up to 65 kW/m, whereas it doesn't typically go above 5 kW/m in summer months. The sea state information can be used to define what operating cases are required, and are summarised in Fig. 3.

A system level functional diagram is defined, in this case being technology and working principle agnostic, Fig. 4. By just considering the working principle and conversion principle inputs and outputs, a general sub-system functional diagram, Fig. 5, has been completed indicating the relationships between each requirement, and the inputs and outputs.

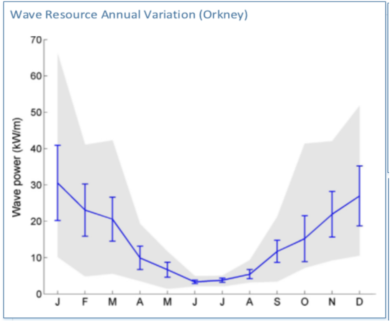
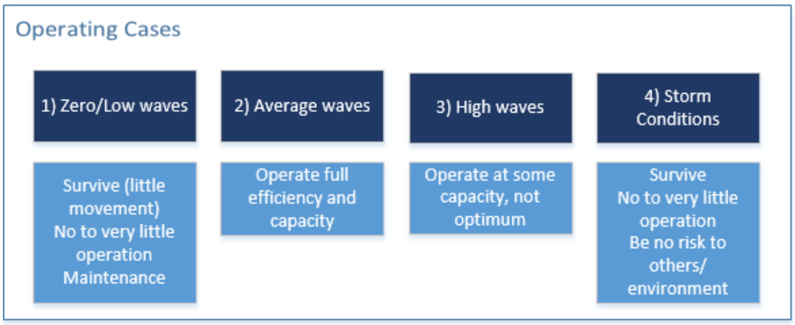


Fig. 2 Annual wave resource variation – Orkney [19]



1) Zero/Low waves	2) Average waves	3) High waves	4) Storm Conditions
Survive (little movement) No to very little operation Maintenance	Operate full efficiency and capacity	Operate at some capacity, not optimum	Survive No to very little operation Be no risk to others/ environment

Fig. 3 Operational requirements for a wave energy converter

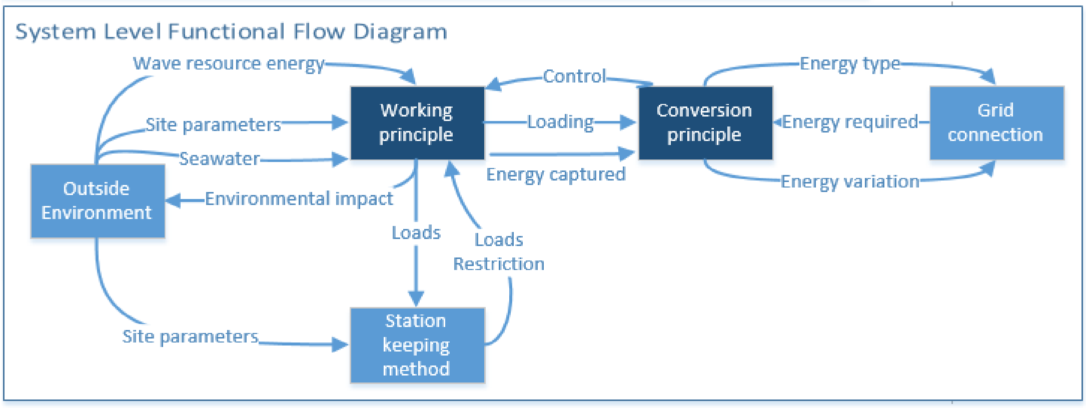


Fig. 4 System level functional requirement diagram

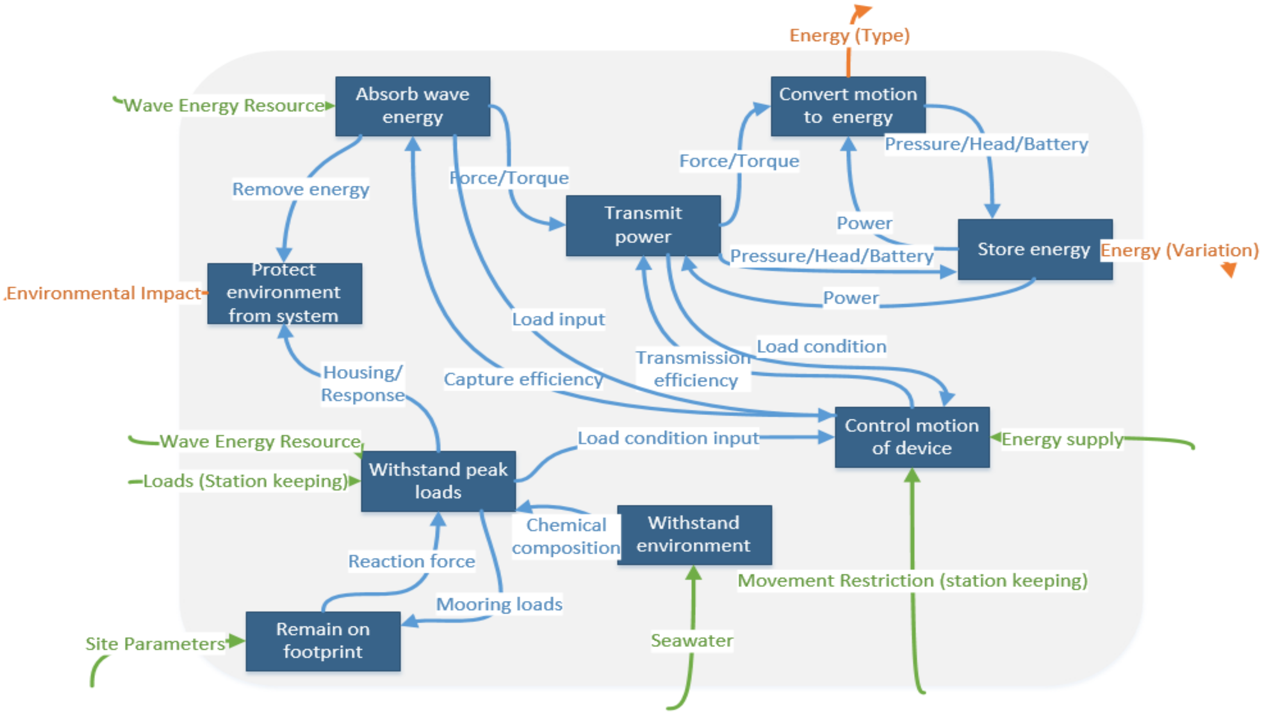


Fig. 5 Sub-system level functional requirement diagram of the working principle and power conversion with inputs (green), outputs (orange) and relationships (blue)

B. *QFD Model Analysis*

The subsystem functional requirements are used as inputs to the QFD analysis. In this example, all requirements were given an equal weighting, however this could be altered using stakeholder engagement and the Analytical Hierarchy Process (AHP). If this method was applied to a particular technology, a greater level of detail could be included, and the level of uncertainty, and potential subjective bias reduced by applying known numerical values and relationships.

In this case study the functional requirements from the sub-system level diagram, Fig. 5, are used as the initial input. Engineering characteristics are defined based on metrics that have previously been used as a way to describe wave energy converters [20]-[21]. A summary of the engineering characteristics is given in Table 1 with details of the range of function values applied. The full table is given in Appendix A.

By applying a range of parameter values to each characteristic, a Monte Carlo analysis could be carried out for assessing the overall design merit score. In this case, 1000 simulations were completed.

Based on these parameters, the ODM ranged from 35 to 68%. The aim of the process is to maximise the ODM, and therefore the results could be statistically analysed to show what has the greatest impact to the score. Based on the input data and equations, the neutral figures would give an ODM of 50% and therefore it is important to choose relevant reference data for the analysis. Fig. 6 shows the relative impacts of each characteristic to the final score, and shows structural mass, control, and load variation to have the greatest.

To explore this further, the simulations are considered in subsets based on the range of the overall design merit score and are summarised in Fig. 7 for each parameter.

TABLE 1 EXAMPLE OF METRICS USED FOR DEMONSTRATION

n	Characteristic	Metric	Function	Neutral point (approx. Pelamis data)	Min	Max
1	Capture width ratio	%	Maximise	20	5	60
2	Structure volume	m^3	Maximise	500	300	1500
3	Mass	tonne/MW	Minimise	1000	200	5000
4	No. conversion stages	Number	Minimise	4	1	5
5	Known materials/technology subcomponents	TRL	Maximise	7	1	9
6	Storage capability	% of rated power	Maximise	15	0	100
7	Control of system	% degree of controllability	Maximise	30	0	100
8	Load shedding strategy	Peak: average load ratio	Minimise	15	10	60
9	Degree of load variation through systems	%	Minimise	50	0	100
10	Material durability	Qualitative measure – fatigue, robustness	Maximise	4	1	5
11	Material strength	Qualitative measure – tensile strength: Young's modulus	Maximise	3	1	5
12	Mooring system and installation methods	Qualitative measure - Use of specialised vessels	Minimise	3	1	5

While Fig. 7 shows the results in terms of merit values to show the degree of impact from each parameter, Fig. 8 translates this into the real values used in the analysis to show what sort of region a device would have to fall within to achieve this scoring level. This indicates that a lower mass is required, in the range 500 to 1800 tonnes/MW, and a high structural volume between 900 and 1300m^3.

The results here given here are purposefully general and simplified, and should not be taken as reference values. This is a demonstration of the potential use of the methodology to add value to a design process.

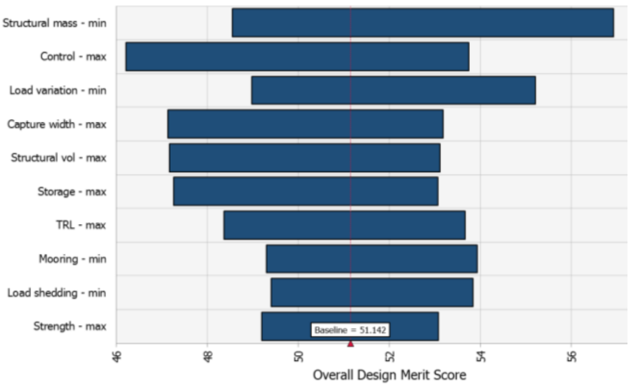


Fig. 6 Inputs ranked by effect on output mean

C. *Conflicts and Solutions*

Appendix A shows the conflicts between the engineering parameters in the house of quality, above the relationship matrix. This is useful as it can identify design areas, that if improved, would have the greatest effect on other characteristics. In this case it is assessed in a qualitative way, however the details could be improved if a specific technology was being considered.

In this study, only the strong negative relationships will be considered which are summarised in Table II, along with the TRIZ translations and suggested inventive principles to consider.

These inventive principles are challenging to apply to a high level problem, as it is often easier to solve more defined problems with tighter boundaries [22], however could be of use if this process was applied to a certain WEC or subsystem.

For example, if a floating oscillating water column type device was being considered and it was found the most important factor was to increase the volume to capture a greater amount of energy, without increasing the force intensity on the structure and mooring systems. One suggested inventive principle is ‘dynamics’. A subsection of this option is to change the object or outside environment for optimal performance at every stage of operation. Changing the outside environment could relate to the position of the device, or opening, in the water column, or optimising the performance could mean changing the dimensions of the opening using a flexible material, tuned to behave depending on the loading condition.

Another suggested principle for the same contradiction is ‘parameter change’ which includes; physical state, concentration or density, flexibility, temperature, volume, or pressure. The internal pressure of the air chamber could be controlled to optimise the response of the water column and potentially could be used as a tuning device. This would limit the air flow through the turbine, but could act as a sort of buffer or cushion to protect the more sensitive components against a wide load variation.

These two suggestions are to demonstrate the method, however clearly more analysis would be needed to fully understand the benefits and limitations of new concepts.

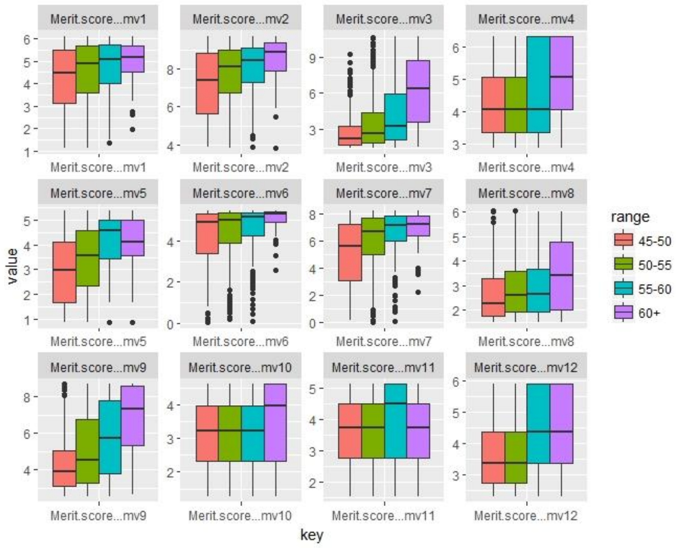


Fig. 7 Merit scores for each parameter

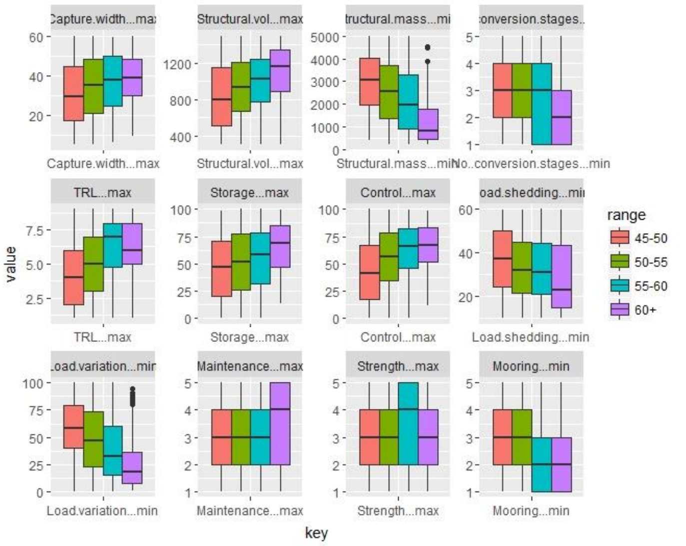


Fig. 8 Range of values for each parameter (value units are related to metric in Table 1)

TABLE II TRIZ INVENTIVE PRINCIPLES SUGGESTED

Parameter to improve	Without making this worse	TRIZ parameter	TRIZ parameter	Inventive principles suggested	
Increase structure volume	Decrease mass	Volume of moving object	Weight of moving object	2	Taking out
				26	Copying
				29	Pneumatics/ hydraulics
				40	Composite materials
Increase structure volume	Decrease mooring costs	Volume of moving object	Force (Intensity) as the mooring methods have to withstand greater forces from a larger device	15	Dynamics
				35	Parameter change
				36	Phase transition
				37	Nested doll
Decrease structure mass	Increase material strength	Weight of moving object	Strength	28	Replace mechanical system
				27	Cheap, short living objects
				18	Mechanical vibration
				40	Composite materials

IV. DISCUSSION

The analysis in this case study has been based on a combination of qualitative and quantitative data to demonstrate the strengths and weaknesses of using such a method.

The initial requirement definition was done at a high level, and could be applied to many different technology areas. The analysis in this case, did not include any weighting, however this could be achieved by employing analytical hierarchy process [8], which allows stakeholders to rank the relevant importance of each requirement against the other.

The definition of engineering characteristics and relationship matrix score is input by the user and is subjective. If this method was being used in practice, either by a developer, or investor considering opportunities, this would need a team to contribute to reduce the subjectivity and any bias. While this may be a time consuming step in a design process, the output will be a useful step to compare potential options and record reasons behind discounting certain options. The end result is also likely to conform to the customer requirements to a greater degree, and have a greater chance at being a successful product compared to the competition.

The choice of metric, function, and parameter values, may also have an element of subjectivity that would affect the overall design merit score. In this case, data relating to Pelamis was used, where available, as a neutral point, and a range of parameter values were applied using Monte Carlo analysis techniques to provide statistical data. Other studies have proposed a wider range of functions such as optimising towards a specific value, or applying different rates of minimising or maximising [17], [7], however this would require a greater understanding of the relationships between parameters.

The application of the TRIZ inventive principles to solve design conflicts may be more relevant to technology developers, as they are easier to apply to more defined problems. They give quick ideas for solving commonly found conflicts however, and can aid any workshops or brainstorming sessions for concept development.

V. CONCLUSIONS AND FURTHER WORK

The aim of this study is to show a potential methodology of combining systems engineering tools, and applying to the case of wave energy, to improve the quality of technical solutions. While it is demonstrated at a relatively simple, high level in this case to be technology agnostic, it could have relevance to a subsystem, whole device, or to compare and rank different technology options. The analysis could also include manufacturing, social, and environmental design aspects as increasing the level of detail may alter the final results. It is important to state the boundaries and assumptions used in the process, and define a base level comparison if using quantitative data.

ACKNOWLEDGEMENTS

The author gratefully acknowledges funding support from ETI and the EPSRC RCUK Energy program for the Industrial Doctoral Centre for Offshore Renewable Energy (IDCORE). Furthermore, they would like to thank Wave Energy Scotland for the discussions, and input to the analysis.

REFERENCES

[1] S. Bradley. (ETI), “Wave Energy Insights from the Energy Technologies Institute Key findings.” 2014.

[2] Carbon Trust, “Future Marine Energy,” 2006.

[3] A. Stegman, A. De Andres, H. Jeffrey, L. Johanning, and S. Bradley, “Exploring Marine Energy Potential in the UK Using a Whole Systems Modelling Approach,” 2017.

[4] ETI and UKERC, “Marine Energy Technology Roadmap Technology roadmaps are tools that provide a framework for stimulating term vision , target or goal Marine Energy Technology Roadmap.” 2014.

[5] DECC, “UK Renewable Energy Roadmap”, 2011.

[6] SI Ocean, “Ocean Energy : Cost of Energy and Cost Reduction Opportunities,” May, 2013.

[7] M. H. Eres, M. Bertoni, M. Kossmann, and J. Scanlan, “Mapping customer needs to engineering characteristics: an aerospace perspective for conceptual design,” *J. Eng. Des.*, vol. 25, no. 1–3, pp. 64–87, 2014.

[8] K. L. Yung, “Application of Function Deployment Model in Decision Making for New Product Development,”

Concurr. Eng., vol. 14, no. 3, pp. 257–267, 2006.

[9] A. Babarit, D. Bull, K. Dykes, R. Malins, K. Nielsen, R. Costello, J. Roberts, C. B. Ferreira, B. Kennedy, and J. Weber, “Stakeholder Requirements for Commercially Successful Wave Energy Converter Farms,” *Renew. Energy*, 2017.

[10] K. Gadd, “TRIZ For Engineers : Enabling Inventive TRIZ For Engineers : Enabling Inventive Problem Solving.” 2011.

[11] V. Souchkov, “Accelerate Innovation with TRIZ,” 2013.

[12] I. M. Ilevbare, D. Probert, and R. Phaal, “Technovation A review of TRIZ , and its benefits and challenges in practice,” *Technovation*, vol. 33, no. 2–3, pp. 30–37, 2013.

[13] I. M. Ilevbare, “Integration of TRIZ and roadmapping for innovation , strategy , and problem solving,” no. July, pp. 1–45, 2011.

[14] V. Nikoli, S. Sajjadi, D. Petkovi, S. Shamshirband, Ž. Ć, and L. Yee, “Design and state of art of innovative wind turbine systems,” vol. 61, pp. 258–265, 2016.

[15] Y. Borgianni and D. T. Matt, “Applications of TRIZ and Axiomatic Design : a Comparison to Deduce Best Practices in Industry,” vol. 39, pp. 91–96, 2016.

[16] Oxford Creativity, “TRIZ Contradictions Matrix.” 2010.

[17] E. Papageorgiou, M. H. Eres, and J. Scanlan, “Value modelling for multi-stakeholder and multi-objective optimisation in engineering design,” *J. Eng. Des.*, vol. 27, no. 10, pp. 697–724, 2016.

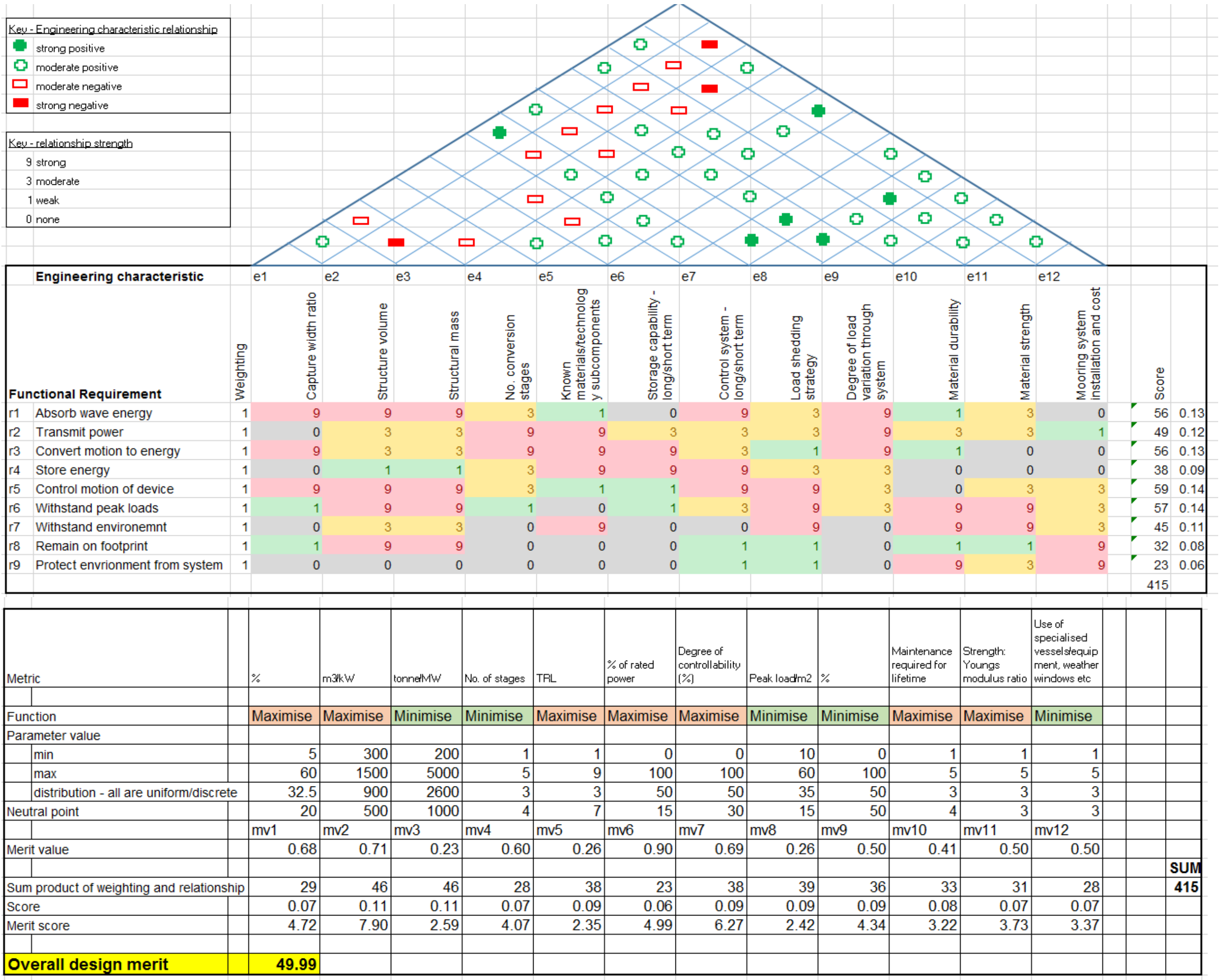
[18] A. De Andres, E. Medina-lopez, D. Crooks, O. Roberts, and H. Jeffrey, “International Journal of Marine Energy On the reversed LCOE calculation : Design constraints for wave energy commercialization,” *Int. J. Mar. Energy*, vol. 18, no. 2017, pp. 88–108, 2018.

[19] S. P. Neill, M. J. Lewis, M. R. Hashemi, E. Slater, J. Lawrence, and S. A. Spall, “Inter-annual and inter-seasonal variability of the Orkney wave power resource,” *Appl. Energy*, vol. 132, pp. 339–348, 2014.

[20] D. Bull, R. Costello, A. Babarit, K. Nielsen, C. B. Ferreira, B. Kennedy, R. Malins, K. Dykes, J. Roberts, and W. Pi, “Technology Performance Level Assessment Methodology Version 3,” April, 2017.

[21] EERA, ERA-NET Ocean Energy, Wave Energy Scotland, and OES, “Workshop on Stage Gate Metrics for Ocean Energy Technology Development,” no. September, pp. 1–20, 2016.

Appendix A Quality Function Deployment Model



Key - Engineering characteristic relationship
- ● strong positive
- ○ moderate positive
- ▭ moderate negative
- ■ strong negative

Key - relationship strength

9	strong
3	moderate
1	weak
0	none

	Engineering characteristic		e1	e2	e3	e4	e5	e6	e7	e8	e9	e10	e11	e12		
	Functional Requirement	Weighting	Capture width ratio	Structure volume	Structural mass	No. conversion stages	Known materials/technology subcomponents	Storage capability - long/short term	Control system - long/short term	Load shedding strategy	Degree of load variation through system	Material durability	Material strength	Mooring system installation and cost	Score	
r1	Absorb wave energy	1	9	9	9	3	1	0	9	3	9	1	3	0	56	0.13
r2	Transmit power	1	0	3	3	9	9	3	3	3	9	3	3	1	49	0.12
r3	Convert motion to energy	1	9	3	3	9	9	9	3	1	9	1	0	0	56	0.13
r4	Store energy	1	0	1	1	3	9	9	9	3	3	0	0	0	38	0.09
r5	Control motion of device	1	9	9	9	3	1	1	9	9	3	0	3	3	59	0.14
r6	Withstand peak loads	1	1	9	9	1	0	1	3	9	3	9	9	3	57	0.14
r7	Withstand environemnt	1	0	3	3	0	9	0	0	9	0	9	9	3	45	0.11
r8	Remain on footprint	1	1	9	9	0	0	0	1	1	0	1	1	9	32	0.08
r9	Protect envrionment from system	1	0	0	0	0	0	0	1	1	0	9	3	9	23	0.06
															415	

Metric	%	m3/kW	tonne/MW	No. of stages	TRL	% of rated power	Degree of controllability (%)	Peak load/m2	%	Maintenance required for lifetime	Strength: Youngs modulus ratio	Use of specialised vessels/equipment, weather windows etc	
Function	Maximise	Maximise	Minimise	Minimise	Maximise	Maximise	Maximise	Minimise	Minimise	Maximise	Maximise	Minimise	
Parameter value													
min	5	300	200	1	1	0	0	10	0	1	1	1	
max	60	1500	5000	5	9	100	100	60	100	5	5	5	
distribution - all are uniform/discrete	32.5	900	2600	3	3	50	50	35	50	3	3	3	
Neutral point	20	500	1000	4	7	15	30	15	50	4	3	3	
	mv1	mv2	mv3	mv4	mv5	mv6	mv7	mv8	mv9	mv10	mv11	mv12	
Merit value	0.68	0.71	0.23	0.60	0.26	0.90	0.69	0.26	0.50	0.41	0.50	0.50	
													SUM
Sum product of weighting and relationship	29	46	46	28	38	23	38	39	36	33	31	28	**415**
Score	0.07	0.11	0.11	0.07	0.09	0.06	0.09	0.09	0.09	0.08	0.07	0.07	
Merit score	4.72	7.90	2.59	4.07	2.35	4.99	6.27	2.42	4.34	3.22	3.73	3.37	
Overall design merit	**49.99**												