A Set-Based Design Approach for the Design of High-Performance Wave Energy Converters

Ali M. Trueworthy, Bryony L. DuPont, Benjamin R. Maurer, and Robert J. Cavagnaro

Abstract—[1] **The objective of this paper is to introduce an approach for designing wave energy converters (WECs) that can be implemented early during the conceptual design phase, enabling downstream convergence on higher performance concepts. Currently, WEC concepts span a wide design space which includes a high number of functionally dissimilar devices. Concept-agnostic assessment of WEC techno-economic performance using the Technology Performance Level (TPL) metric** [1] **allows for these concepts to be assessed during the late stages of the design process; however, this assessment itself is not intended to be a design approach. As TPL assessment requires detailed designs, it cannot guide design engineers in concept generation and refinement. This leaves WEC designers with limited guidance in the early stages of the design process, often resulting in premature commitment to a single functional concept that can limit device performance, even if later-stage design optimization techniques are used.**

This paper proposes a Set-Based Design approach to WEC design which can enable the generation of high-performance concepts faster and with less expense. Set-Based Design is a design process in which engineers ideate a large set of potential solutions and work with critical stakeholders to ensure convergence on an optimal concept [3]. The process was chosen specifically due to its ability to directly facilitate design decision making. We tested the design method through a design workshop in which participants were given design requirements and asked to generate WEC concepts. The group which used Set-Based Design generated a concept which scored higher on the TPL assessment than the concepts generated by the control groups. Though the workshop was constrained by time, number of participants, and background of participants, it was a good proof of concept for the applicability of this design methodology and provided insight on how to continue developing WEC design methodologies. SBD is a methodology that can help designers understand and design to the conflicting requirements of WEC design. SBD also allows designers to avoid making decisions based on imprecise information, which may ultimately lead to more efficient generation of high-performance concepts.

Keywords—**Conceptual design, Set-Based Design, utility analysis, utility function, wave energy converter**

I. Introduction

Wave energy has a long history, with some of the first modern device designs emerging in the 1970s [1]. Despite this, wave energy has not yet become a substantive contributor to the global energy generation profile. The primary challenges that limit expansion if wave energy conversion are the constraints of marine operation, the costs of building and testing new devices, the difficulty for electrical grids to accommodate the influx of renewable energy generation, and the unknown environmental impacts of wave energy development. Overcoming these challenges will require further exploration of the fundamental wave energy converter design, with focus on increased power generation performance. One means of enabling designers to focus on improved power generation during WEC design is to apply conceptual-design-phase design methods, which are largely underapplied to these systems.

Conceptual design methods allow designers to analyse the problem, ideate new solutions, and select the best solution for continued development. Too little time spent in the conceptual design phase can lead to (1) gaps in understanding the trade-offs and specific requirements of the problem, (2) limited opportunities for novel concept generation, and, (3) wasted time and money developing a concept which does not perform well enough to be a viable solution to the problem. The current state of wave energy converter development reflects many of these problems. Implementing a design approach which encourages more time to be spent in the conceptual design phase can mitigate these issues while helping industry remain flexible to advancements in research.

WEC design is a complex problem with conflicting customer requirements and technically challenging

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functional requirements. We hypothesize that structuring the early design phase of WEC design using established engineering design practices will allow more rapid and informed advancement of WECs.

A. WEC Design and Assessment

WEC concepts span a wide design space, which includes both floating and shore mounted oscillating water column devices, heave, surge, and pitch oscillating body devices, and overtopping devices [1]. The European Marine Energy Center lists 227 wave energy developers across the world [2]. Since most of these developers are private companies, there is no published work regarding the specific design processes used in developing the devices. Despite this, some industry patterns of WEC design have been recognized in [3] and [4]. Poor device performance has been connected to the technology readiness-driven funding on which small wave energy companies depend. Obtaining patents and displaying a readiness for marine operations through laboratory and open water testing are important parts to gaining and maintaining funding sources for small WEC developers. The push toward development causes the early design stages to be neglected and funding to be spent building and testing devices with sub-optimal performance [3].

The first step in a successful design process is to understand stakeholders and their needs and be able to translate these needs into functional requirements. These customer requirements help drive assessment— a concept that meets all the customer requirements would be considered high-performing. In WEC design, this part of the design process requires an intricate understanding of many trade-offs and challenges which are unique to wave energy. For example, larger WECs can better capitalize on larger wave resources to develop power but require substantially higher capital costs than smaller devices. To facilitate that understanding and to give designers a metric by which to measure the performance of their devices, researchers and the National Renewable Energy Lab and Sandia National Labs created the Technology Performance Level (TPL) Assessment[5]. The TPL metric, which exists in three versions and continues to be improved, provides a cohesive set of capabilities- or customer requirements- for wave energy devices as well as a large set of questions which indicate which parameters impact which capabilities [5]. Despite its content and ability to help designers understand the requirements of a high-performing WEC, TPL is not a design process and does not give designers a path to follow to design high-performing devices.

When a design approach is implemented early in the conceptual design phase, it enables downstream convergence on higher performance concepts [cite]. Conceptual design-phase methods for WEC design could enable designers to generate higher-performing WECs. We have identified a design methodology, Set-Based Design, as an approach to conceptual design that could be applied to WEC design to improve device performance across the industry.

B. Set-Based Design

The Set-Based Design approach stands out from traditional, point-based design. It allows designers to develop multiple concepts concurrently, putting off commitment to a single concept while assembling more information about the problem. The approach was first presented as-named by Ward et al. in 1997 [6] as a method for solving design problems which have high levels of uncertainty. It focuses on eliminating inferior concepts and iteratively adding detail until convergence on a single concept. By developing many concepts and eliminating inferior concepts instead of selecting one concept for further development and iteration, designers avoid choosing a concept based on imprecise data. Concepts are, by definition, imprecise. SBD's iterative path to conceptual design allows designers to model at higher fidelity at each subsequent stage. As concepts become more precise, designers keep only the concepts that meet the requirements and avoid wasting resources on inferior concepts.

SBD capitalizes on two significant paradigm shifts in engineering design by allowing designers to maintain and refine a large set of foundationally independent concepts. First, it has been shown that engineering design entities that do not focus on a single concept early in the design phase (and instead generate many concepts) design more efficiently in terms of time and cost [7]. In traditional design, feedback from downstream entities (such as manufacturers and end users) usually happens after upstream entities (design engineers) have committed to a concept, so changes can only be minor. Analysing and refining many concepts— while potentially adding time during the early design phase— leads to higher- performance solutions that are more quickly implementable, and effectively reduces the need for iteration in later stages of design [7]. Secondly, SBD is a conceptual-phase analog to design optimization. Like design optimization, SBD uses a large set of potential solutions that thoroughly explore the solution space and use refinement methods to converge on a single, optimal design.

When applying a SBD approach designers will:

1. Brainstorm a wide set of functionally varied concepts.
2. Iterate the Set A with various stakeholders from early on, removing or refining concepts that don't meet the stakeholder's requirements.
3. Form Set B from refined concepts. Add detail to the concepts in Set B and iterate again with stakeholders. Repeat these steps, adding fidelity to the design each time, until a final set has emerged.
4. Employ design convergence methods to analyse viability of each concept in the final set

5. Select most viable concept for further design refinement and development.

SBD is an approach to conceptual design which has received some attention in literature, but mostly as a theory, without details on how to organize, reduce, refine, and model concepts. Little has been published on the *application* of SBD. A technical paper from the American Society of Naval Engineers by David J Singer discusses SBD and its potential application in ship design [8]. Singer et al. have also published on design optimization algorithms based on SBD [9]. Toyota Motor Company has been highlighted by Ward and Sobek et al. as an example of success of SBD, the specific application called Set-based Concurrent Engineering [10], [7]. These reports provide support for the structure of SBD, but no guidance on the actual implementation of SBD in practice.

One major shortcoming of SBD theory is that, for design problems where there are multiple attributes that must be satisfied, SBD does not give clear means for incorporating trade-offs and preferences [11]. Malak et al. outline a strategy which combines utility-based decision theory with set-based design to give designers a means for incorporating trade-offs and preferences [11].

To apply SBD to WEC design, we developed a method for applying SBD theory which includes some of the methodology presented by Malak et al. [11]. We simplified the application so that it could implemented and studied in a short period of time.

C. *Utility Analysis in Set-Based Design*

Combining methods of utility analysis with SBD gives designers a way to include trade-offs and preferences when assessing concepts. Unlike standard utility analysis which focus on selecting the best concept through its measured or estimated utility in a variety of attributes, the method presented by Malak et al. focuses on eliminating inferior concepts by answering the questions "will I ever choose Alternative X?"

When applying utility-based decisions in SBD, the designers create a utility function which weights 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 conceptual design. Applying the utility function to each interval, designers can assess the utility of each sub-concept as well as the whole concept. The utility intervals of different concepts can be compared using interval dominance criteria to reduce the set. The interval domination criteria from says that a dominated concept is one for which the expected utility, no matter where it lands on the interval, will always be less than the expected utility of another concept. This domination criteria can be applied to both concepts and sub-concepts, but for sub-concepts may be result in a change or improvement of the sub-concepts rather than its elimination. [11] also presents a method for accounting for shared uncertainty when assessing concepts for dominance. Malak et al. write, "when uncertainty is shared among all possible actions, it means that a particular future condition or event is independent of the current decision." An example of shared uncertainty in WEC design could be the rate paid to vessel personnel for maintenance activities. The

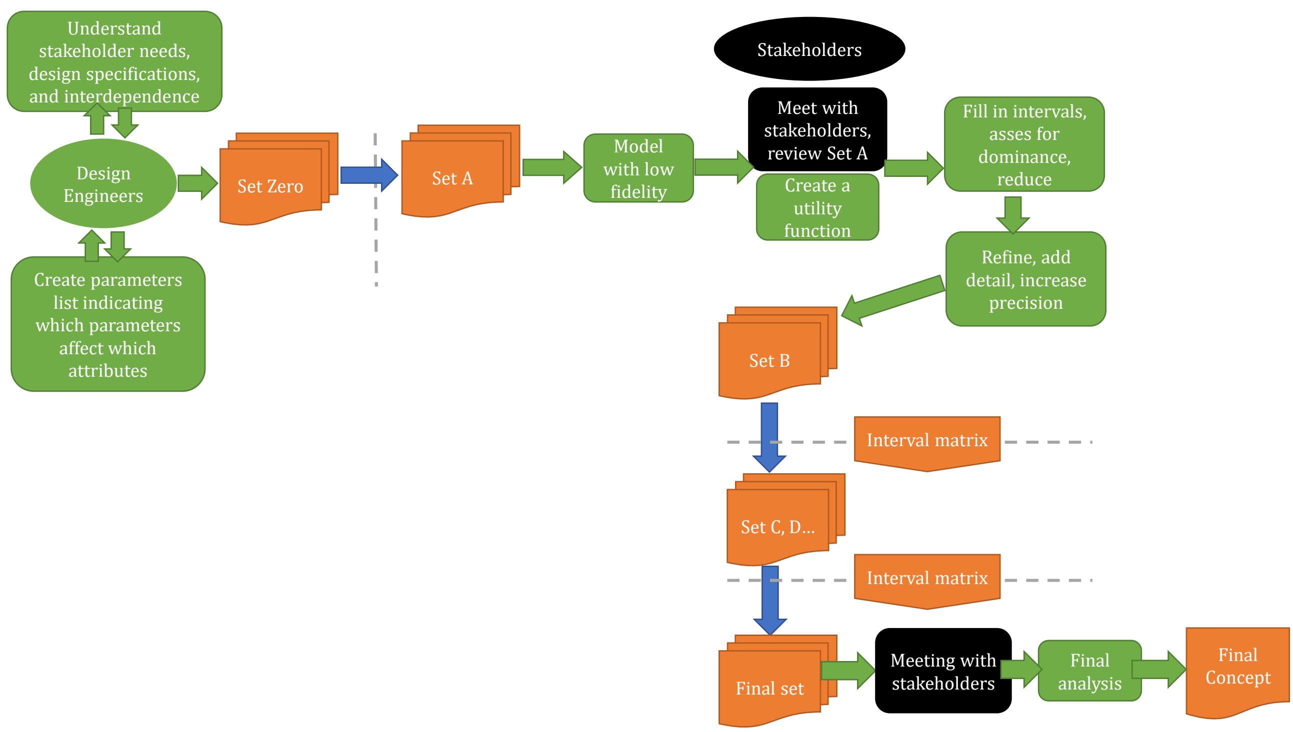

Fig. 1. Flow chart describing steps in SBD with Utility Analysis. Green sections indicate action by designers, black indicate action by designers and stakeholders, orange represent a specific element, and blue indicate an area where one must break out and follow steps indicated in Fig. 2.

uncertainty in the rate of pay would contribute to a widening of the interval value of operational costs, which may result in overlap of the operational costs of different concepts. To account for shared uncertainty, one could plot the utility as a function of personnel pay rate. If at every possible pay rate, concept A has a higher utility than concept B, than concept A dominates concept B and concept B should be eliminated.

It may not always be possible to eliminate concepts based on the dominance criteria. In this case, Malak et al. recommend refining the problem, dividing the concept into sub-concepts, and adding detail to concepts to decrease imprecision. Beneficially, this iteration aligns with the iterative nature of SBD.

II. SET-BASED WEC DESIGN

The industry status and unique challenges of WEC design led us to apply SBD theory to WEC design. We have also chosen to employ some of the decision-making criteria from [11]. This section shows the process we tested to implement SBD and highlights some specific examples of how SBD is well suited to applications in WEC design.

continuously throughout the design process. As designers model WECs, meet with stakeholders, and perform comparisons of different concepts, they will improve their understanding of stakeholder needs and the effects of individual parameters on system performance. To create the initial set, designers should first ideate freely, creating a broad set of imprecise concepts. Malak et al. define a concept as, "not a highly detailed product, but rather a general approach to implementing a function or system"[11]. The initial set is called Set Zero. The top half of Fig. 2 shows the steps to develop Set A from Set Zero.

Once the initial set has been ideated, designers will remove infeasible concepts. With the remaining concepts, designers should identify how the concept performs each function, the details of which should be very general. This step is included to ensure that each concept can perform all required functions of the device. It also helps the design team to identify any areas in which they may need to put more emphasis. For example, if half the concepts in Set Zero do not have an identifiable method of position control, the design team may consider looking again at the project requirements and parameters and searching for any gaps in their own understanding which may have led to the oversight. For the concepts that may not meet

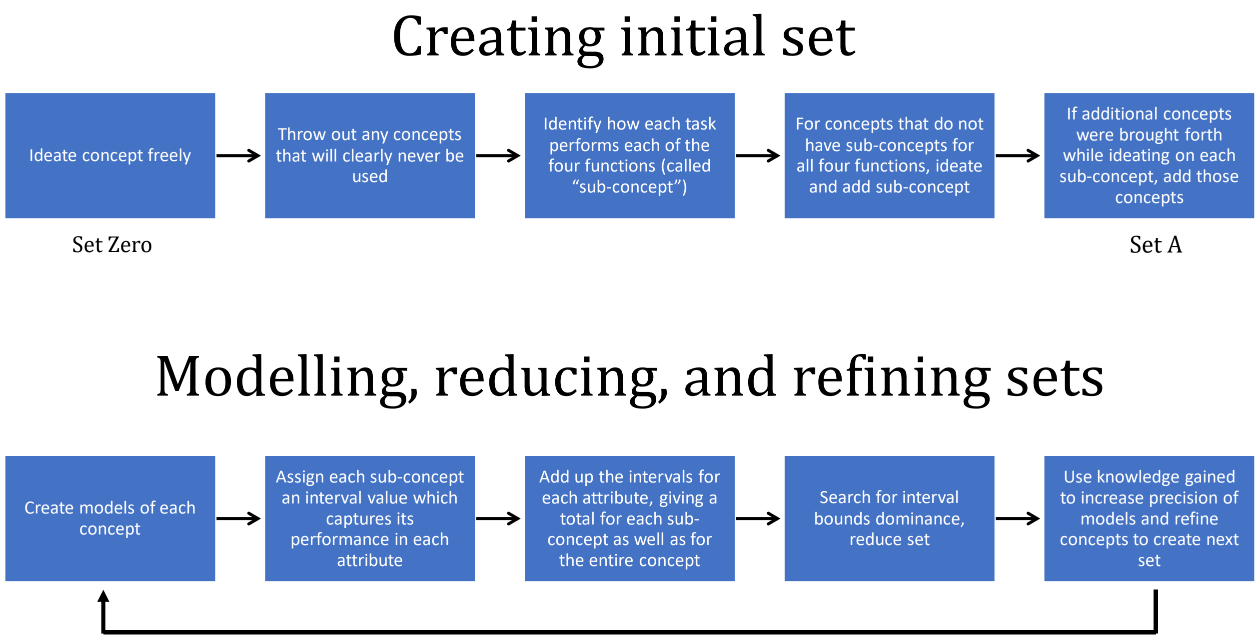

Fig. 2. Flow chart describing steps in SBD with Utility Analysis for creating and initial set (top) and modelling, reducing, and refining sets (bottom). Within the SBD process, these steps should be followed as indicated in Fig. 1.

D. Application of Set-Based Design and Utility Analysis

Fig. 1 shows a flow chart for the implementation of SBD. On the left, "understand stakeholder needs, design specifications, and interdependence" and "create parameters list indicating which parameters affect which attributes" are two tasks that should be done

some functional requirements, detail should be added. The mechanism through which a concept performs a certain function is called a sub-concept. For example, if a linear generator is used for power conversion, the linear generator would be the sub-concept that satisfies the power conversion functional requirement. It may be necessary, when ensuring that each concept has a sub-concept that satisfies each functional requirement, to ideate a single sub-concept. If completely new concepts emerge from this ideation, they should be added to the set. This completes the creation of Set A.

Once Set A has been defined, designers model, reduce, and refine the concepts iteratively, increasing precision with each iteration until they have converged on a final set. The methods for modelling, reducing, and refining sets are described in the bottom half of Fig. 2. The concepts should be improved and modelled increased fidelity as designers proceed through the design process— beginning with back-of-the-envelope calculations and moving toward computational models. Models of the sub-concepts should be made with the intention of filling the cells of a design matrix, such as that in Fig. 3, with interval values as described in Section C. The interval should become more precise as higher fidelity modelling is performed. The units of the values are at the discretion of the designers. Once the sub-concepts have been modelled in Set A, designers meet with stakeholders. Stakeholder feedback should be used to create a utility function for the attributes. The utility function gives weights to each attribute, and later in the design process could be individualized by sub-concept. Using the utility function, designers can assess the utility of each sub-concept as well as the concept. Referring to the design matrix in Fig. 3, the expected utility of each sub-concept can be calculated as

$$[x_{T1}(Aa)\ y_{T1}(Aa)] = \left[\sum_{0}^{n} U(x_{1n})\ \sum_{0}^{n} U(y_{1n})\right] \tag{1}$$

And the utility of each concept can be calculated as

$$[x(Aa)\ y(Aa)] = \left[\sum_{0}^{n} U(x_{nT})\ \sum_{0}^{n} U(y_{nT})\right] \tag{2}$$

Or

$$[x_{T1}(Aa)\ y_{T1}(Aa)] = \left[\sum_{0}^{m} (x_{Tm})\ \sum_{0}^{m} (y_{Tm})\right] \tag{3}$$

Where U is the utility function. And concept Aa is concept a in Set A. If X(Aa) > Y(Ab) Concept Aa dominates concept Ab, so concept Ab should be eliminated. If $x_{T1}(Aa) > y_{T1}(Ab)$ sub-concept Aa_1 dominates sub-concept Ab_1, so sub-concept Ab_1 should be refined or possibly eliminated. Dealing with sub-concept dominance is ultimately up to the designers.

Designers then compare utility intervals and remove any dominated concepts. Once the concepts have been assessed for dominance criteria, further refinement should be done using knowledge gained, and the refined concepts make up the next set. The concepts should then be modelled with increased precision, and the process repeated. Stakeholder meetings need not be held at each iteration, but at a minimum should occur to discuss Set A before the team establishes the utility function, any time the designers feel they may need to alter the utility function, and close to the end of the process when the designers converge on a final concept from the final set.

Concept Aa m n	Collects Wave power	Controls position	Converts power	Delivers power	Interval sum in each attribute
Capital Expense	$[x_{11}(Aa)\ y_{11}(Aa)]$				$[x_{1T}(Aa)\ y_{1T}(Aa)]$
Operational Expense					
Electricity Generation					
Availability					
Uncertainty					
Survivability					
Expected Total Utility	$[x_{T1}(Aa)\ y_{T1}(Aa)]$				[X(Aa) Y(Aa)]

Expected utility of sub-concept

Total expected utility of concept

Fig. 3. Interval utility design matrix filled out by designers using SBD to calculate expected utility of each sub-concept and total expected utility of the concept.

E. *Advantage of SBD for WECs*

SBD has features which make it suitable for addressing the specific challenges of WEC design. Primarily , SBD allows for adjustment of the concept to changing requirements or infrastructure. This feature is suitable for the energy market given the many stakeholders and the volatility of customer requirements. Rising concerns regarding anthropogenic climate disruption and energy security leave the energy markets susceptible to changes in local to international government policy. Supporting technology being developed for the energy market, such as autonomous underwater vehicles, energy storage, and grid integration systems, could also have significant effects on the cost of WEC development. SBD allows designers to develop a set of concepts, so changes in the design requirements are easier to adjust to. Even if a design team has converged on a single concept, they have a whole set of other concepts that have been well fleshed out should there be a change in the supporting technology or energy market which leads to the chosen concept to no longer be the best. Another aspect of wave energy that could impact WEC design is the knowledge of environmental impacts and the permitting processes. Since these are being developed alongside WECs, flexibility in WEC design to adhere to new regulations or permitting processes is important. For example, knowledge of environmental impacts in certain regions could create significant costs increases for WECs that exceed threshold noise levels or permitting processes could restrict vehicle use for installation. Both scenarios could lead to significant changes in the ability of a concept to meet customer requirements.

SBD combined with utility analysis as described in [11] as well as this paper, allows for development of multiple concepts even when knowledge is imprecise or incomplete. Due to the harsh environment in which wave energy systems are deployed, the importance of system reliability is heightened, as maintenance in an offshore environment is expensive and often confined to a small weather window. Utility analysis lets designers explore the impacts of reliability while SBD allows them to continue developing multiple concepts while knowledge of the concept's reliability remains imprecise.

There are many trade-offs for WEC systems, which could be better understood with the use of utility analysis in SBD. For example, while good PTO control can improve the efficiency of a WEC, it also increases the complexity, which can result in decreased reliability, increases maintenance costs, and increased structural fatigue [cite]. Understanding which trade-offs to make is a lot like an optimization problem, to which SBD is a conceptual analog. SBD's conceptual optimization is also suitable for WEC design given the abundance of existing concepts, as it is a good method of comparing the many them without performing high fidelity modelling and costly testing.

III. Design Workshop

To test this SBD approach, we held a workshop with 12 engineering students at Oregon State University. From here on these students will be referred to as "designers." The purpose of the workshop was to assess whether the SBD approach has the potential to increase WEC device performance when applied in the early stages of conceptual design. It also functioned as a trial for the applicability of the presented application of SBD theory, which was important given the lack of published work on method of applying SBD. Assessing the applicability and effectiveness of the SBD approach in the early stages in a small-scale, controlled setting allowed us to understand how we need to continue to develop the approach for application in industry.

F. Methodology

We assembled 3 groups of 4 designers, all engineering students at Oregon State University. The designers were tasked with developing grid-scale WEC concepts to meet the functional and customer requirements presented to them at the beginning of the workshop. The requirements were derived from the Technology Performance Level metric. We identified 4 functional requirements/functions and 6 customer requirements/attributes, shown in Fig. 3, to which the participants will design WEC concepts. In an industry environment, the designers would establish these requirements, and design requirements could change based on the stage in the design process. Mapping customer requirements to functional requirements is another significant area of design study which is not explored here. The requirements were chosen to best suit the time and knowledge limitations of designers. The four functional requirements are: 1). Collect wave energy, 2). Control position, 33). Convert wave energy to electrical energy, and 4). Transport energy to shore. The customer requirements/attributes are 1). Capital Expense, 2). Operational Expense, 3). Electricity Generation, 4). Availability, 5). Uncertainty, and 6). Survivability. Each customer requirement was defined for the participants along examples of the contributing parameters. For example, operational expense was defined as, "the costs

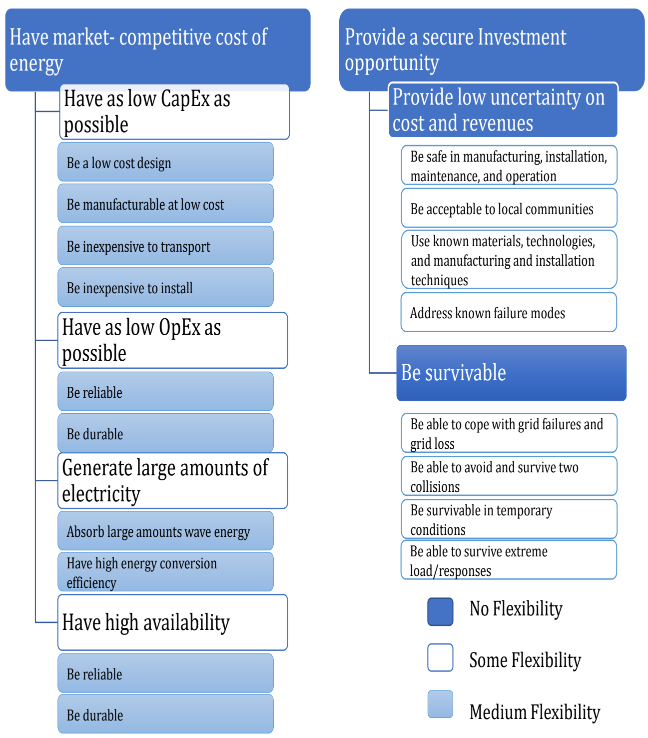

Fig. 4. Taxonomy of Customer Requirements altered from example provided in TPL documentation.

incurred during operation and maintenance," and the parameters that participants were given to consider were technology class of components, ease of maintenance, depth and distance from shore, size and weight of parts that need to be moved, vessels and personnel required for maintenance, availability of spare parts, and durability. The requirements were presented to all participants before they were divided into teams. A taxonomy of the customer requirements, Fig. 4, was presented to designers to break down and indicate the flexibility of each requirement. The taxonomy is presented in a manner similar to that in which the full TPL taxonomy is presented in the TPL assessment documentation [12].

Once the designers were briefed on the problem, they were split into groups and given three different sets of design instructions. The first control group, C1, was instructed to produce a single WEC concept. C2, is the second control group, . This group was instructed to produce 3 WEC concepts and was also given access to the decision matrix. Both C1 and C2 were given a simple decision matrix to use if they wanted. W1, the workshop group, was instructed to follow the SBD application presented in this paper. They were asked to present 3 concepts which were included in their final set and indicate the single concept upon which they converged. It was made clear to W1 that all their concepts were to be evaluated, not just the one they indicated to be the best. The groups submitted their concepts via a Technical Submission Form which was altered from the original TPL Technical Submission Form developed by the U.S. Department of Energy Wave-SPARC project team [13]. The submission form given to designers only included questions and requests specific to Technology Readiness Level 1-2 concepts. We included a description and some data about the theoretical site that the designers were working with at the beginning of the form. Given that power generation estimates are not simple to make for WEC concepts, we also supplied designers with a look-up table of capture width ratios (CWRs) according to characteristic dimension for different types of WECs, which was based on data presented by Babarit in [14]. To avoid pre-populating designers with existing WEC concepts, we abstracted the labels of the type of WEC to the type of wave motion they capture and their location in the water column. Once they looked up the CWR, designers used Eq. 1 to calculate power generation in a 40kW/m sea.

$P=J*CWR*B$ (4)

Authors Ali Trueworthy and Dr. Bryony DuPont acted as stakeholders for the designers. At the end of the workshop, designers were also asked to fill out a post-workshop survey.

Authors Dr. Benjamin Maurer and Dr. Rob Cavagnaro performed TPL assessment of each concept. (note: waiting on assessment by Cavagnaro). TheyThese assessors were not aware of which group generated which concept(s). The Technical Submission form and the questions that make up the TPL assessment were altered simplified to match the customer requirements presented to designers. The designers were only assessed based on those customer requirements rather than the full taxonomy of requirements included in the TPL assessment version 3.01. We chose the requirements based on what the designers could comprehend and address given the time constraints, and what could be assessed in low fidelity concepts. We focused on the first two capabilities of the TPL assessment, "Have a market-competitive cost of energy," and "Provide a secure investment opportunity." The scoring tool used to assess the concepts was altered from the available version of the TPL scoring tool to match the taxonomy shown in Fig. 4. The sections were weighted according to the number of questions and the flexibility indicated on the taxonomy.

G. Workshop Constraints and Limitations

The workshop functioned as a proof-of-concept for the SBD design method rather than an accurate representation of how SBD would be applied in industry. The time constraints and lack of background of the participants lead us to scale the problem significantly. Typically, given a new design methodology, the methodology should dictate the time taken to produce concepts, and this type of concept generation is conducted on the order of days, and not hours. In this workshop, we constrained designers in both the methodology and time. The limited sample size and the time constraints preclude any determination of which design approach is best in industrial application.

Given the alterations done to the TPL assessment and submission form to better align with the scope of the workshop, the TPL scores presented should only be considered relative to one another. They should not be compared to assessments done on other devices using different versions of the assessment. The nature of the TPL assessment is not entirely objective, especially for such low fidelity concepts.

H. Results and Conclusions

Group C1, tasked with putting forth one WEC concept, ideated several concepts to begin the workshop. After ideating a set of general concepts, they settled on one concept to move forward with. Feedback from the group indicated that they did not consider the design requirements again until after they had chosen a concept, at which time they used the requirements as a guide when adding detail to their design. They submitted one concept as requested. It received a TPL score of 4.2.

Group C2, tasked with producing three concepts, followed a similar methodology as C1. They ideated 11 initial concepts, and then selected from those 11 the three they would like to further develop. They did not use any quantitative assessment when choosing the three concepts they would develop. They proceeded to develop the concepts one at a time, like C1, using the requirements as a guide when adding detail. C2 did not submit 3 concepts as requested. Rather, they submitted one highly developed concept. It received at TPL score of 4.3.

Group W1 ideated an initial set of concepts, but unlike C1 and C2, they narrowed that set down to five rather than one. With the five concepts, they identified how each concept performed each function. They presented those five concepts in the first stakeholder meeting. Although they were assigned to follow the presented SBD method, they were still inclined to indicate their favourite concept to stakeholders at the first meeting. The stakeholders reminded them that their task was not to choose one concept right away. In the first stakeholder meeting, W1 focused on telling stakeholders how each concept performed each function. They did not give information on costs, availability, uncertainty, or survivability. After the meeting, they continued to follow the iterative steps of SBD, though they some input intervals into the design matrix were neglected. Instead, they entered a single, scaled value. Set B consisted of 3 concepts, narrowed by 3 from Set A. They refined those 3 concepts then held another stakeholder meeting. At this meeting, scores in each attribute category were presented to the stakeholders, and W1 converged on a final set. Set C contained 2 concepts which they submitted, indicating the one concept which they assessed to be superior (the "final concept"). The final concept scored 4.5, while the second concept scored a 3.8. Interestingly, the concept that W1 indicated to be their favourite in the first stakeholder meeting did not end up being their final concept. This indicates that SBD succeeded in increasing designers' understanding of the problem and that the method of eliminating inferior concepts rather than choosing one single concept to refine and develop is promising for WEC design.

	C1 Concept 1			C2 Concept 1			W1 Concept 1			W1 Concept 2		
CapEx	3.9	4.6	4.2	4.1	4.2	4.3	4.3	4.8	4.5	4.2	3.8	3.5
OpEx	4.8			3.8			4.4			3.4		
Electricity	6.0			4.4			6.0			5.4		
Availability	3.9			4.2			4.3			2.6		
Uncertainty	4.4	3.4		3.5	4.5		3.9	3.9		2.5	2.8	
Survivability	2.5			5.6			3.8			3.0		

Table 1. TPL Scores of each submitted concept broken down by attribute. The second column for each concept shows the scores in "Cost of Energy" and "Investment Opportunity" which are calculated from attribute scores. The last column is total TPL score.

The scores in each category are shown in Table 1. Though W1 generated the highest scoring concept, they only have the best score in two out of the six attributes. C1 also has two of six highest scores, and W1 Concept 1 and C1 tie for the highest score in electricity generation. No single concept performed better than others in all categories.

There were some similarities in results across concepts. Three of the four concepts got the highest score in the electricity generation attribute compared to the other attributes. For C2 survivability was highest followed by electricity generation. The two lowest scoring concepts were the only ones that had a score less than 3 for any attribute.

IV. Conclusions and Future Work

This work shows that SBD theory can be applied to WEC design problems. It is some of the first work implementing SBD. The scale at which we tested the methodology could not effectively prove all our hypothesises regarding how SBD can improve WEC conceptual design and ultimately WEC performance, but our findings indicate that we should continue developing the design methodology on a larger scale. The feedback from designers in the workshop as well as their submitted concepts made it clear that the conflicting requirements of WEC design may not be well understood just by reading them in an assessment document such as TPL. For designers to design to conflicting requirements, they need a design methodology that guides them in doing so and helps them gain a better understanding of the problem as they refine concepts. So far, our research shows that SBD can provide the necessary guidance.

Future work will be done developing tools for comparing imprecise WEC concepts with SBD. Group W1 showed that SBD and utility analysis can guide designers in comparison of multi-attribute imprecise concepts, but as concepts increase in detail and fidelity, the tools implemented in the methodology should also increase in detail and fidelity.

We hope to partner with WEC designers in industry to further test and improve the SBD process. It is our conclusion that the methodology should continue to be developed and implemented on larger scales given its theoretical potential and the initial implementation presented in this paper.

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References

[1] A. F. d. O. Falcão, "Wave energy utilization: A review of the technologies," *Renew. Sustain. Energy Rev.*, vol. 14, no. 3, pp. 899–918, 2010.

[2] "Wave developers : EMEC: European Marine Energy Centre." [Online]. Available:

http://www.emec.org.uk/marine-energy/wave-developers/. [Accessed: 28-Feb-2019].

[3] J. Weber, "WEC Technology Readiness and Performance Matrix – finding the best research technology development trajectory," *Int. Conf. Ocean Energy, ICOE*, no. OCTOBER 2012, pp. 1--10, 2012.

[4] J. Weber and D. Laird, "Structured innovation of high performance Wave Energy Converter technology," *11th Eur. Wave Tidal Energy Conf.*, pp. 1–7, 2015.

[5] D. Bull *et al.*, "Scoring the Technology Performance Level (TPL) Assessment," 2017.

[6] W. W. Finch and A. C. Ward, "A Set-Based System for Eliminating Infeasible Designs in Engineering Problems Dominated by Uncertainty," *ASME Int. Des. Eng. Tech. Conf.*, pp. 1–12, 1997.

[7] D. Sobek and J. K. Liker, "Toyota's Principles of Set-Based Concurrent Engineering," *MIT Sloan Managment Review*.

[8] D. J. Singer, N. Doerry, and M. E. Buckley, "What is set-based design?," *Nav. Eng. J.*, vol. 121, no. 4, pp. 31–43, 2009.

[9] S. Hannapel, N. Vlahopoulos, and D. Singer, "Including Principles of Set-Based Design in Multidisciplinary Design Optimization," in *12th AIAA Aviation Technology, Integration, and Operations Conference*, 2012.

[10] A. Ward, J. K. Liker, J. J. Cristiano, and D. K. Sobek, "The second Toyota paradox: How delaying decisions can make better cars faster," *MIT Sloan Managment Review*, vol. Spring, 1995.

[11] R. J. Malak, J. M. Aughenbaugh, and C. J. J. Paredis, "Multi-attribute utility analysis in set-based conceptual design," *Comput. Des.*, vol. 41, no. 3, pp. 214–227, Mar. 2009.

[12] D. Bull *et al.*, "Systems engineering applied to the development of a wave energy farm," *2nd Int. Conf. Renew. Energies Offshore*, no. April, pp. 189–196, 2016.

[13] K. Nielsen, B. Kennedy, D. Bull, R. Costello, J. Roberts, and J. Weber, "Technical Submission Form Technical Specification of a Wave Energy Farm," 2017.

[14] A. Babarit, "A database of capture width ratio of wave energy converters," *Renew. Energy*, vol. 80, pp. 610–628, Aug. 2015.