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Much like wind energy in its early years, marine energy has vast potential, and wave energy converter (WEC) concepts are constantly in development. Consequently, wave energy faces many challenges for expansion and has a wide-ranging design space of WEC concepts. The large design space demands new methods for understanding the potential performance of early-design stage concepts. The Technology Performance Level (TPL) metric has been a proposed method for early-stage concept assessment. However, previous research has shown that the TPL is not designed in such a way that it is able to distinguish between multiple early-stage, low-fidelity concepts. Therefore, we created a conceptual design tool to complement the TPL assessment to help wave energy developers during the design stage, rather than a quantitative assessment metric. The tool integrates knowledge from TPL and a blue economy emerging market stakeholder analysis. The tool guides marine energy developers during the conceptual design of a wave energy converter by presenting designers with established practices, asking if their concept is able to meet these practices and constraints, and providing design feedback based on the answers. Previous sustainable product design research shows tools that help designers integrate knowledge at the concept stage positively impact deliberate sustainable design decisions. Through the tool's feedback, we hope

to help designers identify specific changes and actions to improve their system early in the design process, subsequently leading to improved TPL ratings during device embodiment design. We worked closely with Oregon State University's 2020-2021 Marine Energy Collegiate Competition team to understand the tool's ability to create awareness and improve concepts. In this paper, we document the architecture, content, and results from our first tests of the tool. While this study is limited by the number of participants, it serves as a proof of concept for the effectiveness of this tool and provides insight for further improvement of the tool's structure and content. Creating awareness of oversights early in the design process will help wave energy developers effectively engage stakeholder requirements, increasing the appeal of a wave energy converter concept to marine energy stakeholders.

# A Conceptual Design Tool for High-performance Wave Energy Converters for Blue Economy Applications

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Don't forget to love each other

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# Chapter 1: Introduction

In response to the global climate crisis and ever-increasing global energy consumption [1], renewable energy sources such as marine energy continue to be developed. Wave energy in particular has vast potential because the ocean's waves have a technical potential of 1,400 TWh/yr within the United States' exclusive economic zone [2], which is enough energy for 130 million homes for an entire year [2]. Harnessing this energy does not require significant land use compared to other renewable energy technologies [3], is close to the world's population-dense coastal regions, and can provide a reliable carbon-free energy source to remote coastal communities and other emerging market or *Blue Economy* applications [2]. The Blue Economy focuses on "improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities" [4] and Blue Economy applications often refer to non-electrical grid (hereafter referred to as grid-scale) markets like aquaculture, desalination, and ocean observation. Despite this potential, there are still gaps in knowledge that researchers and developers need to overcome to make wave energy an economically viable energy alternative.

Wave energy faces many challenges for expansion that contribute to these knowledge gaps. It is a complex engineering problem and it has a wide-ranging design space of WEC concepts. The large WEC design space demands new methods for understanding the potential performance of early-design stage concepts. Understanding the performance of WECs early allows designers to make changes and increase performance with little impact on the overall cost of the WEC. This will help WECs become an economically viable energy alternative. Our research focuses on how to embed stakeholder and industry experiential knowledge at the concept generation phase. Embedding knowledge early in the design process will help wave energy developers effectively engage stakeholder requirements – increasing the appeal of a wave energy converter concept to marine energy stakeholders.

## 1.1 Paradigms in Wave Energy Converter Design

Early peer-reviewed literature in wave energy focused on grid-scale wave energy converter development and provides a good foundation for designing a WEC. Previous literature puts a significant focus on problem definition through resource assessments that help define the operational ranges of the WEC [3, 5–8]. Researchers also conduct economic analyses [9–11] and local community surveys [12, 13], which help determine the stakeholder requirements for WECs. All of this previous work helps researchers investigate WEC concepts and methods for designing optimal WECs. However, even with this body of work it is unclear how much industry focuses on the conceptual design of grid-scale WECs.

In their recent literature review and industry survey of grid-scale WEC design, Trueworthy and DuPont [14] found that many wave energy developers commit to an archetype before conceptual design begins. Trueworthy and DuPont [14] also found that over half of respondents selected spiral design when asked *What design approaches have you used to shape your overall design process?*. Spiral design stems from software development and is an iterative process that follows a design-build-test cycle [15]. In mechanical design this methodology is heavily limited by timelines and budgets, reducing the number of possible iterations and often resulting in a sub-optimal design [16]. Publications also suggests that few developers are conducting concept evaluations before model validation [14, 17]. These findings illustrate a potential paradigm with wave energy converter design: many developers are spending little time engaging with early design and are instead opting to follow a design-build-test cycle that limits the performance of their concepts.

With the help of existing literature, we can begin understanding why the wave energy sector may spend little time in early design. Wave Energy is a multi-disciplinary field and the design of wave energy converters integrates aspects of multiple design problems, like the stakeholder input of product design and the subsystem integration of systems design [18]. Moreover, the wave energy sector is also not at a stage of design convergence, like wind energy with three-blade, horizontal-axis turbines. There are many archetypes of WECs, and varying designs within those categories of archetypes -

leading to a large design space, or potential set of complete solutions. Trueworthy and DuPont [14] observe that there is a limited selection of early concept evaluation tools. The lack of such tools means there are few opportunities for effectively employing information early in the design process. While not a clear explanation of why WEC designers spend little time in early design, this does indicate that researchers need to test and develop design methodologies that better address the challenges of WEC design. According to Weber [19], WEC developers commit to an archetype early because fast demonstrations of technological readiness is crucial for funding in the wave energy sector. By pressuring developers to demonstrate technological readiness, the wave energy sector is setting an incentive to skip early design stages. Skipping early design puts the sector into a continuous design-build-test paradigm where the discovery of a major problem late in design can lead to longer development, costly redesign, and lower technological performance. This paradigm may limit wave energy developers to the overall performance constraints of the initial concept, making it very difficult to change design directions and/or redesign. Individual setbacks stall development of the marine energy sector as stakeholders may lose trust in the robustness of marine energy. Therefore, efforts are needed to help wave energy developers produce high-potential designs.

Government-funded projects such as WaveSPARC (Systematic Process and Analysis for Reaching Commercialization) and DTOcean/DTOceanPlus projects seek to provide the wave energy industry with development methodologies and tools to enable innovation. We analyze these tools in further detail in Chapter 2. The WaveSPARC project specifically establishes the Technological Performance Level (TPL) metric which is used alongside the Technology Readiness Level (TRL) metric to plot the trajectory of a technology [19]. The WaveSPARC team predicts that the current trajectory of grid scale WECs are less cost competitive than other energy sources by market entry, but hopes to drive innovation at early TRL levels, so that the TPL of a WEC is cost-competitive by market entry [19, 20]. This interest in driving innovation has many developers and researchers investigating emerging market or Blue Economy applications.

Blue Economy applications are particularly interesting for wave energy as they provide an opportunity to develop competitive, carbon-free energy technologies at a significantly smaller scale than grid-scale applications. Interest in these applications will alleviate one of the primary aforementioned shortcomings of the current design-build-test paradigm for wave energy – these prototypes are smaller, substantially cheaper, and much easier to iterate and improve with new design decisions. These emerging market WECs (hereafter referred to as EM-WECs) may also provide a stepping stone for grid-scale WEC development, helping wave energy mirror the technological growth path of wind and other renewable energy technologies. It is important to note that using EM-WECs as a stepping stone for grid-scale development assumes that EM-WECs have the same growth path as a grid-scale WEC - that is for any TRL level, an EM-WEC and grid-scale WEC will have the same TPL. However, engineering design shows us that EM-WECs will have different requirements than grid-scale WECs. Therefore, it is critical that the design of these EM-WECs does not fall into the same design-build-test paradigm of grid scale, as this may stifle the technology growth trajectory.

## 1.2 Improving Design Thinking with Engineering Design

From product discovery to end of life, engineering design encompasses techniques enabling high-quality and cost-effective products [15]. Engineering design research includes varying definitions of product design stages, but all have a similar focus on the early design phase of product discovery [15]. Conceptual design is one phase in product discovery, covering the steps of concept generation, concept evaluation, and concept selection. The goal of these steps is to produce a concept or "an idea that is sufficiently developed to evaluate the physical principles that govern its behavior" [15]. Concept generation is the process of developing the idea, designers often refine their ideas clarifying functions and making changes. Then, designers evaluate how well the idea meets the project goals and product requirements during concept evaluation. These steps often overlap, with a designer going through the multiple generation and evaluation cycles before selecting a final design, ending the conceptual design phase.

Many engineering design studies focus on how to improve our design thinking during the product discovery phase. While engineering design methods and research began growing during the late 1980s/early 1990s [21], the idea of design thinking was popularized in 2008 by Tim Brown [22] who defined design thinking as:

> "a discipline that uses the designer's sensibility and methods to match people's needs with what is technologically feasible and what a viable business strategy can convert into customer value and market opportunity."

The consumer product sector employs this design thinking philosophy alongside early phase engineering design methods to create widely successful products. The design of complex systems can be more challenging than traditional consumer product design. Nonetheless, there is much the wave energy community can learn to improve the development process and our design thinking. We look to product design, because this an internationally successfully field that with many parallels to EM-WEC design. Product designers consider many factors and stakeholders to create successful products; all while using engineering design methodologies. Employing engineering design methodologies can lead to a 35% to 75% decrease in manufacturing costs - while comprising only 5% of the manufacturing budget [15]. This is often attributed to the fact that designers are considering the entire life cycle of a product during the concept generation phase. Thus, it is critical that the wave energy sector applies engineering methodologies to EM-WECs.

Making changes early in the design process when little is known about the function of the device may seem counter-intuitive and detrimental to the success of a product. Dieter and Schmidt [23] describe this as "a paradox inherent in the design process between the accumulation of problem (domain) knowledge and the freedom to improve the design" [23]. This paradox creates an inflection point during the design process that represents the optimal point for making changes to a concept. The inflection point is late enough in the process that the designer understands both the customer requirements and engineering characteristics needed to make a successful product. This is also early enough that the changes have a minimized impact on development costs. Previous work demonstrates that design tools and guidelines can help increase a designer's focus on goals and requirements [24], and that better design practices lead to better products [15]. This is due to the fact that these practices provide designers with a structure that helps encourage early consideration of later design challenges, which can help designers avoid costly redesigns. Engaging with these engineering design methods will help WEC developers effectively integrate knowledge at early stages of design, which can help increase the quality and performance of their concept.

Engineering design practices are also employed in many established industries. For instance, Toyota and the automotive industry heavily employ Quality Function Deployment to investigate customer requirements that inform a company's design choices [25]. This product definition methodology is stakeholder focused, and forces the designers to think about stakeholder needs and how these translate into engineering requirements. In the case of Toyota, these design decisions are finalized early and few changes are made after the first 12 months of development [25]. Making these changes early is inexpensive, allowing developers to explore a wide variety of concepts and select the one that best fits their customer and functional requirements. It is crucial that wave energy designers engage with early design as these methods may help developers find high-potential archetypes.

## 1.3 Overview of Work

Little work to date applies the findings of engineering design literature to wave energy. Trueworthy and DuPont [14] found that few WEC developers are employing early engineering design methodologies and suggest researchers work on converting existing methodologies for Wave Energy. Furthermore, tests of existing WEC design tools find that these tools have a hard time differentiating between multiple low fidelity designs [26]. These findings indicate a need for more research in wave energy on best practices that enable the design of high-potential WEC concepts. Other sectors, like product design, provide insight into the type of tools that may aid in improving our early design practices. Identifying oversights early in the design process will help wave energy developers effectively engage stakeholder requirements – increasing the appeal of a wave energy converter concept to marine energy stakeholders. In this work, we propose the Blue Economy Quiz, a conceptual design tool for wave energy developers. The core of the Blue Economy Quiz is a knowledge repository of stakeholder needs, functional requirements, and experiential knowledge for emerging market wave energy converters. This is a repository of knowledge that Blue Economy WEC designers might not have, allowing us to provide developers with feedback to help improve concepts. It is important to note that this is not meant to be a quantitative metric of the WEC's satisfaction of stakeholder requirements. This is a design tool for that can be used during concept generation and concept evaluation. The goal of this research is to help wave energy developers make sure they are not missing stakeholder information from early design stages and ensure that designers can incorporate experiential knowledge from later design stages into the concept generation and concept evaluation stages.

The Blue Economy Quiz employs a similar methodology to an existing sustainable product design tool, the GREEn Quiz (Guidelines and Regulations for Early design for the Environment). This tool presents designers multiple choice questions related product guidelines and asks the user to pick how well their concept meets the requirement. Previous work with the GREEn Quiz demonstrates that it increases sustainable design decisions during concept generation [27, 28]. However, the complexity of the wave energy converter design problem requires more research to provide guidelines and tools that enable the development of high-potential WEC concept. Since wave energy and the Blue Economy is such a multidisciplinary space, we hope the Blue Economy Quiz can help developers by being an accessible design tool that provides experiential knowledge to help improve concepts. It is important to provide this knowledge during concept generation and evaluation because making changes early in the development is less costly, and incorporating this knowledge early should help increase stakeholder satisfaction with wave energy. Additionally, since the GREEn Quiz is for product design, it is unclear if this methodology will be effective at impacting a change during conceptual WEC design. As we hope to increase design decisions during concept generation, we must research and test the Blue Economy Quiz to understand its impact on concept generation. We choose to analyze design decisions as these are features that designers indicate follow one or more ideas. Thus, if design decisions increase during concept generation, developers will have more opportunities to integrate stakeholder and industry knowledge into their designs. We also intend for this work to be useful for researchers who wish apply existing engineering design methodologies to emerging market WEC design.

In Chapter 2 of this work, we review concept evaluation tools in engineering design, specifically focusing on product design and Design for X, and the state of the art in wave energy concept and product evaluations. In Chapters 3 and 4, we outline the contents and implementation of the Blue Economy Quiz as well as the proof of concept testing conducted with the Oregon State University Marine Energy Collegiate Competition team. In Chapter 5, we discuss the results of this proof of concept testing. The results of this testing help us determine if this tool can impart change during concept generation for Wave Energy Converters and provide insight about the tool's effectiveness to impart change compared to other redesign interventions. Moreover, the results provide insight on possible limitations of this tool and future research paths for this methodology. To conclude, we identify that this methodology is capable of increasing the design choices made during concept generation, how to increase the utility of the tool during concept generation, and how future research can determine the impact this tool has on EM-WEC development.

# Chapter 2: Literature Review

## 2.1 Concept Evaluation Tools in Engineering Design

Before proceeding, it is important to define *concept evaluation*. In engineering design, concept evaluations often make comparisons between multiple ideas against the requirements of the project. The methods often provide a structure for determining what should be the best concept to use for product development. Evaluations can help with making design decisions, allowing the designer to refine or improve a concept. These comparative methods are numerous, including Pugh charts, concept screening, fuzzy set theory, and utility analysis [29]. Another category of concept evaluation analyzes an individual idea against design requirements. These methods are often similar to product evaluations, but early concept evaluation tools require less information about the design. In this paper we will examine individual concept evaluation tools that are used to improve design decisions during concept generation.

Design for X (DfX) is the application of design processes toward typically later-design-stage objectives, allowing designers to focus on a particular objective or set of objectives. These categories can cover many areas such as Design for Manufacturing (DfM), Design for Environment (DfE), Design for Assembly (DfA), and Design for Reliability (DfRL)[30]. Many DfX tools integrate the knowledge of a specific area into preexisting methods to help designers achieve the goals of said area. Novel methods are also developed, though Benabdellah et al. [30] found that many novel methods are complex, time consuming, and often do not consider the entire life cycle of a product.

As an example DfX approach and as a close analogy to the consideration of diverse design objectives in the design of wave energy converters, Design for Environment research has focused on these issues as they relate to product design [27, 31–34]. DfE studies find that early incorporation helps reduce the environmental footprint of a product [33]. DfE specifically integrates knowledge that helps reduce environmental degradation caused by poor design decisions. Tools for DfE fall into many categories, the most recognizable being the life-cycle assessment/analysis (LCA). LCAs are used in many industries and help designers understand the overall environmental impact of an existing product. While the LCA is helpful in understanding the detailed impact across the product's life, the need for a completely finished product does not make this a good early concept evaluation tool. Other engineering design work investigates incorporating LCAs earlier in product development, yet these are still completed after establishing a concept[31] and cannot be used during the concept generation phase.

Other DfE tools include guidelines and checklists which are generally comprised of generic information that designers can apply to their concept. One popular version of this tool is "The Ten Golden Rules," which is a tool that covers holistic life cycle aspects designers should consider [34]. These types of tools are useful for designers because it prompts them to apply these rules to the specifics of their product and can be used multiple times during conceptual design [34]. The issue here is that designers often need some experience to apply these guidelines and develop solutions for their concept [34].

The GREEn Quiz (Guidelines and Regulations for Early design for the Environment) is a novel DfE tool for helping designers integrate knowledge at the concept stage [27, 28]. This tool compiles DfE knowledge from multiple sources, like established DfE checklists and guidelines, into an accessible concept evaluation tool for designers of all skill levels. The GREEn quiz uses a search tree to prompt designers with multiple choice questions about established DfE knowledge and, based on the answers selected, provides a feedback report[27]. The feedback presents the designer with recommendations on how to make the concept more sustainable [27]. This methodology was compared against using no tools or even using established DfE checklists and guidelines, with the results demonstrating a positive impact on the number of deliberate sustainable design decisions designers make during concept generation [27, 28].

The positive impact of the GREEn Quiz falls in line with other studies demonstrating that structured design tools help increase a designer's focus on goals and requirements[24]. This effect can be explained through priming, a subject studied extensively in engineering design and other fields [35–37]. Priming is a psychological method that presents information that engages a mindset impacting a subsequent activity [38]. In engineering design, many studies look at how priming can be used to effect the concept generation process and find that priming helps generate innovative designs with no decrease in feasibility [39].

The marine energy sector has few early design phase tools, and lacks any like the GREEn quiz that: (1) presents designers with existing stakeholder requirements to evaluate how the concept engages stakeholder requirements and (2) provide designers with actionable design feedback for improving their WEC concept. The lack of such a tool inhibits developers' ability to integrate knowledge and create high-performing, innovative designs. The inherent multi-disciplinary nature of WEC design makes it difficult for developers to generate a concept that satisfies stakeholder requirements. There are also no widely commercially successful WEC designs, meaning the industry needs to learn from later design stage failures to help increase the likelihood of success. Therefore, it is important that developers have the ability integrate experiential knowledge and stakeholder requirements during early design stages. To make such a tool for WEC design, we must first explore existing evaluations.

## 2.2 Wave Energy Design and Concept Evaluation

There is a large potential set of complete solutions—commonly called the *design space*—for wave energy converters. Each WEC archetype harnesses the ocean's energy differently, and each design concept within that archetype can use different kinds of wave motion. This variety already implicates a large number of research and development topics such as shape, controls, mooring, and electricity conversion. Wave energy developers must embrace innovation and economic value while simultaneously considering numerous stakeholder requirements in order to become a competitive energy alternative. When this already-complex design space is combined with growing interest in Blue Economy applications, it is clear there is a need for design strategies that aid developers in tackling these challenges. It is important to note that as of writing we are aware of only one design or concept evaluations intended for Blue Economy applications[40]. While there are other concept evaluations for WECs, most concept evaluations are intended for grid-scale applications. Research groups like the WaveSPARC (Systematic Process and Analysis for Reaching Commercialization) and DTOcean/DTOceanPlus projects seek to provide the industry with development methodologies and tools that enable innovation.

The WaveSPARC project is comprised of teams at at the National Renewable Energy Laboratory and Sandia National Labs and is funded through the United States Department of Energy. The goal of this project is to provide industry with tools and methodologies to develop high performance wave energy converters that also integrate stakeholder requirements [19, 20]. The WaveSPARC teams developed the Technology Performance Level (TPL) assessment to quantify how well a technology performs in relation to its holistic economic capability [19]. The TPL assessment has undergone many revisions since its initial development as a grid-scale WEC evaluation, and is continuing to be developed by the WaveSPARC team. Through our collaboration with the WaveSPARC team, research recently began on a Blue Economy version of the assessment [40]. The TPL assessment requires an assessor to answer questions about seven distinct categories, with each category addressing aspects impacting the techno-economic performance of a wave energy converter. Each of these categories were determined by identifying customer requirements through a stakeholder analysis. The categories for the grid-scale TPL assessment are [19]:

1. **Cost of Energy:** This entails the factors that contribute to a competitive energy cost, such as capital expense and operating expense.

2. **Investment Opportunity:** This includes the uncertainty associated with the cost of energy and factors relating to how well a WEC can survive at sea.

3. **Grid Operations:** This answers the question, “Will the WEC be good for grid-scale use?”

4. **Benefit to Society:** This incorporates the impact on local communities and environmental impact over the entire life cycle of the WEC.

5. **Permitting and Certification:** This determines the environmental and ecological impact and the ability of the WEC to coexist with other ocean users.

6. **Safety and Function:** This discusses the safety over the entire lifecycle of the WEC.

7. **Globally Deployable:** This considers the conditions that determine where the WEC can be deployed.

For the Blue Economy version of the TPL assessment, the WaveSPARC team adjusted the categories. Based on our recommendations [41], the *Cost of Energy* category was changed to *Cost of Concept* making this category more generalized [40], capturing the variety of Blue Economy applications for WECs. The *Grid Operations* category was removed also from the assessment and replaced with *Use Integration* at our recommendation [41].

The questions in both versions of the TPL assessment require extensive information from developers in order to choose accurate responses. This information is submitted prior to the evaluation, allowing for a WEC expert assessor to review and ask for any additional information they may need to accurately score the technology [42, 43]. Often, the assessment is conducted by multiple experts who collaborate.

The Technology Readiness Level (TRL) metric determines how ready a technology is for the market by measuring the maturity of the technology, or how far along it is in development. The scores range from 1-9, with 1 meaning a "majority of [the technology's] key performance characteristics and cost drivers do not satisfy, and present a barrier to, potential economic viability" [40] and 9 meaning the technology is "competitive with other energy sources without special support mechanism." [40]. The creators of the TPL assessment employ it alongside the TRL metric to help drive WEC technology to high-performance at early readiness levels [20, 42]. Starting early development at a high TPL will provide wave energy developers with a footing to reach the highest TPL by the time the WEC is ready for market entry [19]. Reaching the highest TPL means that the technology will be cost competitive with other energy technologies without the need for subsidies, enabling wave energy to be a viable alternative.

The TPL assessment report is designed to help developers identify areas of improvement and increase the performance of the device through redesign. However, the complexity of the WEC design problem requires the evaluation and feedback to be more tailored to the design stage. Previous research dictates that early concept changes have a low impact on the TRL, and that while using engineering design methods during concept generation can increase the technological performance level, the TPL assessment does not quantitatively differentiate between multiple low fidelity designs [26]. This is due to the amount of technical information that is required by TPL assessment to complete the evaluation. Many of the TPL assessment's questions require information that designers might not have during concept generation. The lack of information makes it difficult for assessors to accurately judge a concept and raises uncertainty in the evaluation. The use of expert assessors to complete the evaluation also makes the TPL assessment a difficult tool for conceptual design. Many concept generation methods encourage the production of multiple concepts, which would require multiple TPL assessments and consequently demands more time from assessors. This makes it difficult to use the tool during concept evaluation.

The report designers receive allows them to review how they scored in each category, subcategory, sub-subcategory, and question. While this is helpful as they can see what is required to score better on each question, there is no feedback helping the designer understand how to start improving their concept. As a concept evaluation tool, this limits the ability of designers to act on feedback. It is not always straightforward how to start improving a concept - so knowing what metrics you need to achieve is not as helpful as how to begin redesigning your concept. As previously discussed, early guidance helps designers create better concepts. Thus, the feedback needs to both orient designers on best practices and provide actionable feedback. It is important to note that the TPL assessment is a good product evaluation tool for the product development phase. This is when developers have selected a design and are refining the characteristics through hydrodynamic modeling, control system modeling, and scaled testing. The TPL assessment is ideal for this phase as developers will have the knowledge necessary for the assessment and it helps the designer understand their design's techno-economic performance potential.

The DTOcean and DTOceanPlus projects are comprised of international teams of academic, government, and private researchers and are funded through the European Union's FP7 and Horizon 2020 program, respectively. The goal of these projects is to provide open-source design tools for the "development and deployment of ocean energy systems, aligning innovation and development processes with those used in mature engineering sectors" [44] across all stages of WEC development. There are many modules of DTOceanPlus, with the tools relating to concept evaluation being:

1. **Structured Innovation tool:** This uses established design methods to help with concept generation and selection [45, 46].

2. **Assessment Design tools:** These calculate parameters used for technology benchmarking [47].

3. **Stage Gate tool:** This uses metrics to evaluate technology development [48].

Like the TPL assessment, the Stage Gate and Assessment Design tools are very helpful for the development of a concept because they accumulate wave energy design knowledge into a set of tools. However, these creators intend these tools for use during product development, meaning the tool is appropriate for a refined design and would prove difficult for a low-fidelity design [47, 48]. Thus, these tools could also have trouble differentiating between low fidelity designs.

DTOceanPlus' Structured Innovation design tool combines Quality Function Deployment (QFD), the Theory of inventive problem solving (TRIZ), and Failure Modes and Effects Analysis (FMEA) into a design tool for the sector [45, 46]. QFD is a stakeholder-focused project definition methodology that helps designers understand the design problem [15]. Through the process designers cover eight steps [15] and complete a House of Quality [25]. These steps cover:

1. Customers and customer requirements: This covers steps one through three of

QFD, where designers identify the customers, what they want (the requirements), and the relative importance of these requirements.

2. Benchmarking against current products: This covers step four of QFD, where designers identify some competition in their design space and then evaluate each product against the identified customer requirements.

3. Translating customer requirements to engineering specifications: This covers steps five through eight, where designers generate engineering specifications, relate customer requirements to specifications, set target values for specifications, and identify specification relationships.

TRIZ is a concept generation methodology that is based on the idea that many problems engineers face have already been solved and analyzes patents to define inventive principles [49]. The methodology has designers identify contradictions in a design to discover which intersecting principles can help improve a product [49, 50]. FMEA falls under Design for Reliability, and is a five step technique [15] that many industries employ during both conceptual design and product development [23].

The FMEA portion of the Structured Innovation design tool has users enter all information needed for the analysis and the results page tells the user which failure modes need redesign [45]. The QFD/TRIZ portion of the tool has users enter all information for QFD outlined above. Then the tool uses the functional requirements of QFD for TRIZ feedback and benchmarking against current solutions [45, 46]. This design tool is still in development and shows promise for wave energy developers, as it is applying widely successful engineering design methods. The QFD/TRIZ portion specifically provides marine examples for solutions to TRIZ suggestions, the intent being that these help redesign the identified failure modes [45, 46]. The marine energy examples are also important as they orient the designer to the state of the art. Nonetheless, this tool has limitations that arise with the user-driven input. These are: (1) user-driven input limits the accessibility of the tool and (2) there is a potential for oversight of stakeholder requirements and functional requirements. Reducing accessibility limits who can use the tool. The Blue Economy is a multidisciplinary space, meaning there is a vast amount of experiential knowledge that may unknowingly get overlooked while using the tool. If the developer accidentally overlooks requirements during the project definition stage, this tool will not catch the mistake. These oversights could lead to low-performance concepts and potentially more negative public perception of wave energy, since the designers are not effectively engaging with all stakeholders. Thus, this tool may best serve those with well-established wave energy converter design knowledge.

Outside of these projects, wave energy researchers are also investigating other methods for WEC concept evaluations. Bubbar et al. [51] employ Falnes' method for analytically solving the optimal linear power capture with a mechanical circuit representation [52] to create a novel concept evaluation. This methodology allows developers to calculate the power capture of their device by solving an analytical impedance matching problem between the WEC and the power take-off (PTO) [51]. This provides developers with the ability to determine their concept's power capture and compare it to the power capture of other device configurations [51]. While this methodology provides a novel way to calculate power capture without the need of detailed simulations, the sole focus on power capture requires other evaluations to determine how well the device satisfies other stakeholder requirements. Heikkilä et al. [53] build upon their previous work in [54, 55] where they employ multiple methodologies to help WEC design focus on reliability. The methodologies they investigate are FMEA, reliability modeling and simulation using reliability block diagrams (RBDs), and life cycle cost (LCC) calculations [53–55]. In their paper, Heikkilä et al. apply these methodologies to the development of a oscillating surge wave energy converter, which allows them to model and predict failures of the device's power take off system [53]. While increasing the reliability of WECs is important to the success of the sector, this methodology requires detailed design data that is often not considered during early conceptual design. This system is better for product development when developers are are working on the configuration of their selected design. With modifications, it is possible that this systems could be used at the the end of conceptual design when developers are evaluating a few high-fidelity concepts.

# Chapter 3: Methods

Performance evaluations for WEC design often require extensive information about a concept. These details can include anything from deployment plans to the maximum power capture, or a combination of maximum power capture and a proxy for cost, such as device volume. Such evaluations require models, simulations, and, occasionally, tank testing validation. At the early design phase, developers may not have clarified details to calculate maximum power or considered details such as installation and deployment.

As part of our collaboration with the WaveSPARC team, we suggested the creation of a conceptual design tool that employs the knowledge of the TPL assessment to help developers embed crucial design knowledge early in WEC design. Instead of asking designers how they plan to deploy a WEC and then provide feedback based on the answer, a concept-phase WEC design tool should present designers with the restrictions of established practices and ask if their concept is able to meet these restrictions. This format is more accessible to designers of all skill levels and provides fast feedback during the early design stage. As previously stated, the early incorporation of guidelines helps designers focus on goals during design without reducing originality and feasibility. Catching oversights early in the design process will help designers effectively engage stakeholder requirements and increase the appeal of a wave energy converter concept to parties involved in the marine energy sector.

## 3.1 Design Tool

### 3.1.1 Structure and Content

The Blue Economy Quiz is a tool which reflects knowledge from both the Systems Engineering approach to grid-scale WEC design conducted by the WaveSPARC team and an emerging market stakeholder analysis performed by this research team at the

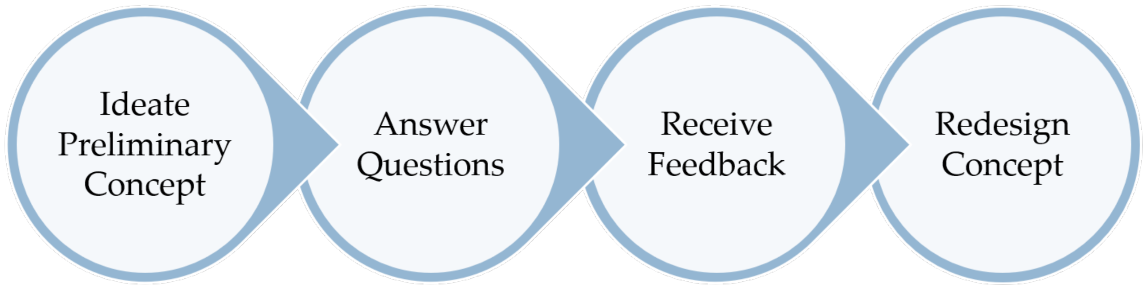


Figure 3.1: The intended use of the Blue Economy quiz is to provide designers with a tool that can help increase the performance potential of their concepts early in the design process. It achieves this function by presenting multiple choice questions related to established design practices and asks the user to pick how well their concept meets the requirement. These answers determine a feedback report to help redesign the concept.

Pacific Marine Energy Center (PMEC). The tool that provides designers of varied skill levels with the knowledge needed to improve low-fidelity concepts for emerging market applications. The Blue Economy Quiz is not an assessment tool for emerging markets, but a design tool for marine energy developers that can be used alongside other design methods.

The Blue Economy Quiz follows the format of the aforementioned GREEn Quiz, asking designers questions about their concept and providing design feedback based on the answers provided. This format enables understanding the extent that users are engaging stakeholder requirements, and is accessible to users of all skill levels as potential responses are pre-populated. Fig. 3.1 illustrates how the tool is designed to be incorporated into concept generation. Questions are divided into six categories related to the Blue Economy:

1. Cost of Concept
2. Investment Opportunity
3. Use Integration
4. Benefit to Society

5. Safety and Function

6. Permitting and Global Deployability

These sections generally align with the categories of the TPL assessment, with some notable distinctions. We changed *Cost of Energy* to *Cost of Concept* because the scale and capabilities of Blue Economy devices dictates that there are variety of factors separate from the cost of energy. In a grid-scale WEC, the energy produced is sold. However, in an emerging market WEC the cost of energy produced might not be as important as the overall cost of the device. One new category, *Use Integration*, covers requirements and practices that increase the capabilities of a device. Since there are a variety of sectors in the Blue Economy *Use Integration* is important to evaluate if designers are including features that increase the capabilities of a WEC. The *Use Integration* category achieves this by asking questions about the capabilities important to Blue Economy stakeholders and to WEC development in general. These adjustments align with the suggestions we made in [41] for ongoing work towards adapting the TPL assessment to Blue Economy applications [40]. We also chose to combine the *Permitting and Certification* and *Globally Deployable* sections of the TPL assessment because these topics extensively overlap.

Through our collaboration with the WaveSPARC team, we conducted a stakeholder analysis for Blue Economy emerging market WECs (EM-WEC) [41]. This stakeholder analysis followed the first few steps of Quality Function Deployment [15] to define the stakeholder requirements of an EM-WEC in ocean observation, desalination, and autonomous underwater vehicles. Through the stakeholder analysis, we gained key insights about the differences between grid-scale WECS and EM-WECs. With these insights, we processed the questions of the TPL assessment - determining which questions are directly transferable, which questions need modifying, and which are not applicable for EM-WECs. These TPL assessment questions are not solely applicable to grid-scale devices and will be useful for all Blue Economy WEC developers [41]. A more thorough discussion about this evaluation and the customer requirements for EM-WECs can be found in [41].

The basis for many of the Blue Economy Quiz questions comes from the results of the previously discussed analysis and our research on wave energy. These questions were made by taking the EM-WEC requirements and asking how well a designer incorporates the requirement into their concept. See Table 3.1 for an example question from each category. Some questions in each section of the Blue Economy Quiz are also the transferable questions from the TPL assessment identified in [41]. Again, the goal here is to present designers with known functional requirements and check how well their concept satisfies this limitation. Clarifications and definitions are included within the question prompt to provide the user with more comprehensive knowledge, making the questions: (1) easier to answer during the concept generation stage, and (2) more accessible to designers with varying levels of wave energy design knowledge. The multidisciplinary nature of marine renewable energy makes easy to answer and accessible questions important for a concept generation tool because this means that there is a low barrier of entry to determine how well a WEC design satisfies stakeholder requirements. A lower barrier of entry provides designers the ability to evaluate more WEC concepts during early design because they do not need to spend a lot of time developing models to analyze the concept.

Each question is paired with a set of user responses that indicate how well the concept satisfies the question, with some questions including an option of not having considered the topic. The number of responses varies for each question, with responses tailored to both the question's topic and the complexity of how a designer may have incorporated the idea, as seen in Table 3.1. See Appendix A for the complete list of content in the Blue Economy Quiz. These answers are scored on a scale from zero to one, with zero indicating the designer has not considered the requirement or has not incorporated the requirement into their design, and one indicating the designer has fully incorporated the requirement. In this paper we refer to the zero scoring answers as "low" scoring, the answers between zero and one as "medium" scoring, and the one scoring answers as "high" scoring. Currently, all question receive the same weighting, but future versions of the Blue Economy Quiz will include the ability to change question weights. This functionality will allow the tool to adapt the importance of requirements to better reflect stakeholder opinions.

Table 3.1: An example question from each section of the Blue Economy Quiz

| Category | Question | Answer | Score | Feedback |
|---|---|---|---|---|
| Cost of Concept | Is the concept easily deployable by a common workboat? | We have not considered deployment of the concept | 0 | Outline the deployment (and maintenance) process early in design such that adjustments can be made to ensure that the device is deployable by common workboat. For the field in which you are working, determine limits for volume, weight, and mobility of a device. |
| | | The concept is not deployable by a common workboat | 0 | Outline the deployment (and maintenance) process early in design using storyboarding techniques. You might consider adding modularity, switching to lighter material, changing mooring design, or making the device tow-able by boat. It may be beneficial to reach out to experts early in the process, such as the crew on ocean research of installation vessels. Reduce the costs of renting or buying specialized equipment. DTOceanPlus offers a Logistics and Marine Planning tool that you may find helpful later in the design process. |
| | | The concept has few components with life spans shorter than that of the device | 0.5 | – |
| | | The concept has no components with life spans shorter than that of the device | 1 | – |
| Investment Opportunity | Are most of the components of the system technologies which are already used in the marine environment? | Few/none of the components of the system are already used in the marine environment | 0 | Consider replacing some components with others which are already used successfully in the marine environment. These could be identified by looking at existing marine industries. Meeting with stakeholders such as marine contractors could help you identify components that could be replaced. |
| | | Most of the components of the system are already used in the marine environment | 0.5 | – |
| | | All components of the system are already used in the marine environment | 1 | – |

Table 3.1: (continued)

| Category | Question | Answer | Score | Feedback |
|---|---|---|---|---|
| Use Integration | Can the concept provide real-time data to operators? | We have not considered provide real-time data to operators | 0 | Determine if providing real-time data would increase the capability of the system. Meeting with stakeholders such as purchasers and operators could help with this decision. Looking at existing marine devices that provide data, such as ocean observation buoys, could help with the determining needed systems. When considering the system, remember to determine the energy needs of electronics. |
| | | The concept cannot provide real-time data to operators | 0 | Consider whether the adding the ability to provide real-time data to operators could increase the capability of the system to perform its intended functions (within the design requirements). Meeting with stakeholders such as purchasers and operators could help with this design decision. |
| | | The concept can provide limited real-time data to operators | 0.5 | – |
| | | The concept can provide real-time data to operators | 1 | – |
| Benefit to Society | Will the device lead to a reduction in carbon emissions during the early life cycle (manufacturing, assembly, lifting, transport, installation) of the device? | We have not considered the reduction in carbon emissions | 0 | List all life stages (from design, manufacturing, assembly, lifting, transport, installation) and consider sources of carbon emissions. Try replacing unsustainable materials with environmentally friendly alternatives and reducing reliability of harmful manufacturing practices, Involving manufacturers and marine contractors can provide important insight into how to make your system environmentally friendly. For more information regarding environmentally friendly design, refer to literature on Design for Environment and Design for Sustainability. |
| | | The device will not lead to a reduction in carbon emissions | 0 | Consider ways to reduce carbon emissions during the early life cycle of the system. Try replacing unsustainable materials with environmentally friendly alternatives and reducing reliability of harmful manufacturing practices. For more information regarding environmentally friendly design, refer to literature on Design for Environment and Design for Sustainability. |
| | | The device will lead to a reduction in carbon emissions | 1 | – |

Table 3.1: (continued)

| Category | Question | Answer | Score | Feedback |
|---|---|---|---|---|
| Safety and Function | Can the concept be detected by other vessels/people at sea? | The concept cannot be detected by others | 0 | Consider redesigning your system so that it is easy to detect by marine vessels or other people at sea. Interviewing other marine environment users may help you ideate ways to improve the system's ability to be detected. You may find common concept generation methods such as brainwriting or morphological matrices to be helpful with this redesign. |
| | | The concept can be detected by others | 1 | – |
| Permitting and Global Deployability | Can the concept be disassembled/easily distributed? | We have not considered disassembly of the concept | 0 | Create a storyboard the disassembly of the process. This may help you understand potential issues that need redesigned. Replace components that cannot be disassembled or easily distributed with more mobile, modular components. Try to design components that require no advanced or uncommon manufacturing techniques and can be disassembled for transportation. Standardize dimensions and refer to Design for Assembly and Design for Manufacturing literature for further guidance. |
| | | The concept cannot be disassembled or easily distributed | 0 | Consider replacing the components that cannot be disassembled or easily distributed with more mobile, modular components. This can be achieved by designing components that requires no advanced or uncommon manufacturing techniques and can be disassembled for transportation. Standardize dimensions and manufacturing steps, and refer to Design for Assembly and Design for Manufacturing literature for further guidance. |
| | | The concept can be partially disassembled but requires oversize vehicles for distribution | 0.5 | – |
| | | The concept can be disassembled and easily distributed | 1 | – |

When a user takes the quiz, questions are served to them by category and the answers to each question are saved. Once a user has answered all the questions, the quiz compiles the scores for each category and normalizes the scores to ten, with higher scores indicating that a concept embeds more stakeholder requirements.The design tool does not provide feedback for all answers, and is limited to the most relevant information that will improve the user's concept. The quiz provides designers with section scores and feedback if they selected low scoring answers - meaning they have either not considered or have not incorporated a stakeholder requirement. The initial feedback page shows only the two lowest scoring categories for this same reason - the lower a category score, the worse their concept satisfies the requirements in that category. Our experience with engineering design and the guidelines, rules, and feedback of other engineering design studies – discussed in section 2.1 – formulates the basis for the feedback. The feedback includes:

1. **Design strategies:** These are specific improvements designers can make to their system.

2. **Suggestions:** These are broad recommendations designers can make for improvement.

3. **Design methods:** These are actions designers can take to reach certain performance requirements.

Users also have the option to view feedback for the entire quiz, which is downloadable as a PDF for later viewing. The initial feedback page is cached so users can revisit the feedback page and download their feedback later if needed. Through the feedback, the tool will help designers identify specific changes and actions they can take to improve their system.

### 3.1.2 Web-based Implementation

The Blue Economy Quiz is currently hosted [56] using the free web-hosting service Heroku and functionality is achieved through the open-source Django application *django-quiz* [57]. Django is a free and open-source web framework from Python [58]. This package is a Django application we built, providing users with the functionality to build similar concept stage design tools and host the tool online.

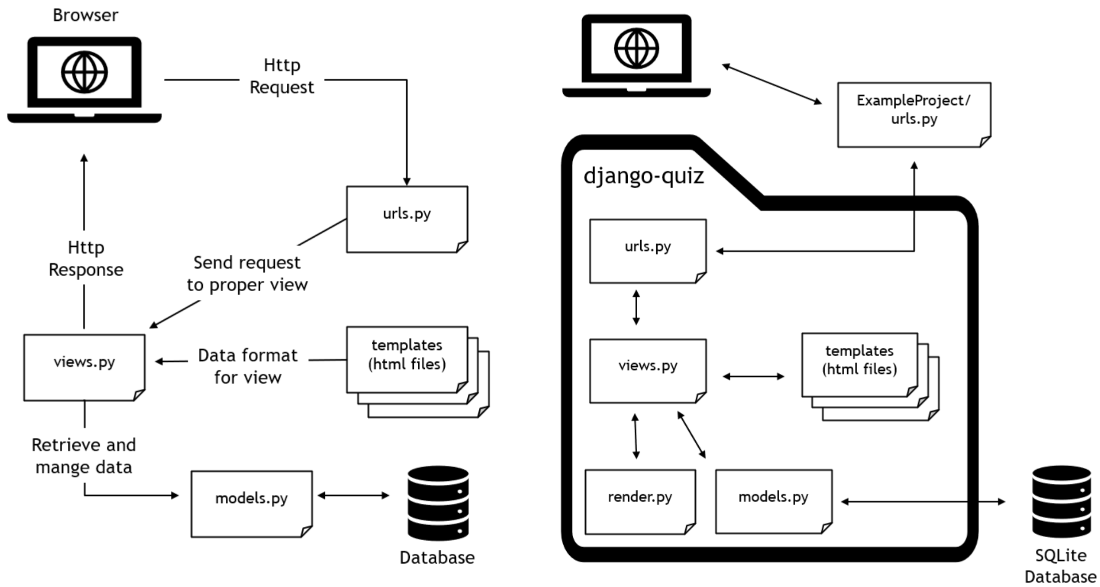


Figure 3.2: Functionality of Django Applications (left) and *django-quiz* package (right)

Our *django-quiz* package follows Django's models, templates, and views structure to create the desired functionality seen in Figure 3.2 [59]. Models are the objects that determine that structure of the database. This provides users the ability to manage and query contents in the database. This file contains all the functions that will handle HTTP requests. The *views.py* file contains functions that access needed data through the models file and then send the queried data to the templates to get the rendering format seen in browser. For the *django-quiz package* this covers all backend functions, including creating user responses, saving or updating user feedback, starting a new quiz session, processing a selected answer, normalizing the session scores to a scale of zero to ten, and retrieving session data for a view function. Moreover, this file contains methods for renders the entire frontend users and superusers will experience. The *templates.py* file defines the structure of the data to be rendered on screen. In this case, we use templates to render webpages as well as PDFs in browser. The *django-quiz* package also contains a render file, which is not existent in traditional Django packages and was created following a tutorial on rendering a html template to a pdf [60]. Render sets the render class, which has a static method for generating a pdf in-browser using a template and data. We update this package concurrently with the Blue Economy Quiz to maintain feature parity.

In this package each version of a design tool is called a quiz and is defined in the models by six quiz-related classes:

1. Quiz: This stores the name of the quiz, the date it was created, a description of the build, and whether the quiz is active.

2. Category: This stores the category's parent quiz, the category name, and a description of the category.

3. Question: This stores the question's parent quiz, category, and the question text.

4. Answer: This stores the answer's parent quiz, parent category, parent question, answer text, and answer weight.

5. Feedback: This stores all related parent objects (quiz, category, question, and answer) and the feedback text.

6. User Response: This stores the parent quiz for the response, a unique id number, and the response data. A function generates the unique identification number by combining the (database assigned) quiz identification number and a choice from set of numbers from zero to 999. The function removes existing identification numbers from the selection pool before choosing a new number, eliminating the chance of duplicates. The identification number functionality will be changed for larger deployments.

After installing and hosting *django-quiz* on a server, this package requires interaction through the browser to create/modify/delete quizzes. The superuser generates quizzes with a comma-separated-value (csv) file or can manually create quizzes in-browser. Response data is stored within the database and can be exported using third-party SQL database navigation programs. Participants can anonymously visit the site, look at the details of each quiz build, and decide which quiz to take. Employing this functionality allows multiple users to simultaneously access the quiz online in an easy to use format. See Appendix B for more information on functionality and setting up the package.

# Chapter 4: Experimental Design

The version of the tool presented in this paper is still in the early stages of development and there are planned improvements to the structure, content, and implementation. Nonetheless, it is important to investigate the efficacy of the current version of the quiz - in order to see how well the tool can help designers identify and make changes to their design. As the validity of this approach has been demonstrated in the product design space [27, 28], it is important to determine whether or not this methodology can be an effective tool for the wave energy sector. To test this, we hosted two design workshops for members of Oregon State University's (OSU) Marine Energy Collegiate Competition (MECC) team - one in Spring 2021 and another in Fall 2021. These human studies had IRB approval (**IRB Number:** IRB-2019-0426, **Title:** Design Methods For Marine Energy Emerging Markets) through our collaboration on the WaveSPARC project covered in Chapter 2. We also worked alongside the OSU and University of Washington's MECC teams to get user feedback on potential improvements for the tool. The MECC program is funded by the United States Department of Energy and run by the National Renewable Energy Laboratory that tasks multidisciplinary teams of graduate and undergraduate students with designing, testing, and pitching a marine energy device for a Blue Economy application [61].

## 4.1 Design Workshop: Spring 2021

The purpose of the first design workshop is to test the efficacy of the Blue Economy Quiz to impact change during concept generation. In engineering design studies, this is often achieved by analysing design decisions. Design decisions are choices that a designer makes during concept generation. These can be very specific, such as changing the number of sensors on a WEC, or general, such as making the hull diameter larger. To test the Blue Economy Quiz and investigate how well it impacts the design process, we analyze the design decisions before and after designers use the Blue Economy Quiz to see how the provided feedback drives decisions during redesign. In the workshop, we asked participants to use text callouts to annotate their concept drawings. This allows us to differentiate what is and is not a design decision. For example, "direct pressurization - more efficient than electrical conversion, lower cost" is considered a design decision because it demonstrates a comparison being made during concept generation. Whereas, "substrate to prevent large marine animals but house smaller organisms" is not considered a design decision because the statement does not indicate other methods were considered during concept generation.

It is important to note that we are not looking at the total number of design decisions. Instead, we are looking at the scope of design decisions across the categories of the Blue Economy Quiz - meaning each group makes at least one decision per category. It is important that an EM-WEC tool for concept generation and evaluation makes designers aware of a holistic set of customer requirements because the Blue Economy is multidisciplinary. An increase in decisions across categories after taking the Blue Economy Quiz will indicate that the tool's feedback is orienting designers, whereas no change or a decrease in decisions will indicate that the Blue Economy Quiz may limit redesign.

Table 4.1: Design Objective and Constraints from Spring 2021 Workshop

| | |
|---|---|
| Design Objectives | Reliable energy production<br>Low capital cost<br>Safe<br>Serves populations in need of water |
| Design Constraints | Tens of megawatts<br>Either provide power for pumping water to desalination plant, or provide direct pressurization<br>Provide tens of million gallons of desalinated water per day |

In the workshop, the participants were paired into four groups and tasked to sketch a design of a wave-powered device for large scale desalination that satisfied a given a set of design objectives and constraints. These objectives and constraints, in Table 4.1 came from our stakeholder analysis for EM-WECs [41].

After completing concept generation, each group used the Blue Economy Quiz to get feedback on their design. Then groups were instructed to use the feedback report to redesign their concept. Finally, each group was asked to use the Blue Economy Quiz a final time to evaluate their revised concept. The final attempt of the Blue Economy Quiz allows us to compare our analysis on design decisions to how the groups self-assess their changes. From this workshop, we can make initial observations about the impact that the Blue Economy Quiz has on design decisions.

## 4.2 Design Workshop: Fall 2021

The purpose of the second design workshop is to compare the how the Blue Economy Quiz impacts design against other methods of priming designers during concept generation. This is achieved by analysing design decisions for three types of redesigned concepts:

1. A concept redesigned with no intervention
2. A concept redesign with an intervention that provides designers with similar knowledge that is contained in the Blue Economy Quiz
3. A concept redesign with the feedback from the Blue Economy Quiz

In this workshop, the 15 participants were assigned to three groups of two members and three groups of three. This division was made to distribute preexisting engineering design and wave energy converter design knowledge as evenly as possible. All groups were tasked to sketch two designs of a wave-powered device for ocean observation and navigation that satisfied a given set of design objectives and constraints, in Table 4.2. These objectives and constraints came from our stakeholder analysis for EM-WECs

[41]. We directed groups to make the two concepts at the same time to avoid the participants using knowledge from the first concept's redesign process in their second concept's initial design.

After completing the two concepts, the groups were tasked with redesigning one concept. Groups 1, 2, and 3 were given no information for the redesign, while groups 4, 5, and 6 were provided materials with more information about their design task. This included: (1) an excerpt from [41] discussing ocean observation and navigation and the importance of various stakeholders and (2) an updated list of design objectives and constraints, which are in bold in Table 4.2. These updated requirements also come from our stakeholder analysis [41] and are also captured in the Blue Economy Quiz so we are confident that the update will provide minimal priming effect for the redesign of the second concept. The excerpt from [41] and the updated the objectives and constraints also simulates a traditional redesign intervention because developers often gain more information on their design problem over the course of a project. For instance, developers may present concepts to stakeholders and get feedback which will dictate changes developers make during redesign.

Table 4.2: Design Objective and Constraints from Fall 2021 Workshop: bold entries were provided after the initial design was completed

| | |
|---|---|
| Design Objectives | Reliable energy production<br>Safe<br>Low operational cost<br>**Low capital cost**<br>**Easy to install and recover** |
| Design Constraints | Tens of Watts<br>Cause no environmental disruption<br>Adaptable to many instruments<br>**Survivable**<br>**Flexible in a variety of wave conditions** |

Once the groups finished the redesign of their first concept, they used the Blue Economy Quiz for their second concept. Groups were directed to use the feedback from the tool to redesign their second concept. Due to time constraints we elected to not have the participants take the Blue Economy Quiz a second time. Based on the results of the workshop in Section 4.1 we predict that the Blue Economy Quiz intervention will be more effective at increasing design decisions than either of the methods, and that the intervention will preform better than no intervention. From this workshop, we can make observations and compare the impact that the Blue Economy Quiz with other concept generation interventions.

# Chapter 5: Results & Discussion

## 5.1 Limitations and Assumptions

The Spring 2021 design workshop functioned as a proof-of-concept and user experience test for the Blue Economy Quiz. The limited sample size does not permit a statistical study of the tool's effectiveness or a comparison with existing methodologies. In this case, the workshop was hosted for two and a half hours. The time constraints of the workshop limited the feedback that could be acted upon during the redesign. For instance, one question suggests the designer complete a functional decomposition to reduce operational redundancies. Since the workshop was a few hours total, it would be difficult to fully follow this feedback for informed design decisions. Ideally, the start of the workshop would include an introduction to the design methods mentioned in the quiz's feedback and provide ample time for the design activity. Despite these potential shortcomings, the workshop successfully provided a preliminary test of the Blue Economy Quiz and helped to steer development plans and testing of the tool.

The Fall 2021 design workshop functioned as further proof-of-concept by comparing the Blue Economy Quiz with: 1) a redesign without an intervention, and 2) a redesign with an intervention that provides the designer with more information. This overcomes a limitation of the first design workshop. While the sample size is larger than the first workshop, the sample size does not permit a statistical study into the tool's effectiveness compared to existing methodologies. This workshop was also limited by time, as it was hosted in two one-hour sessions with the first concept's redesign being assigned between meetings. Written instructions were provided to all groups to ensure each had the same guidelines for the redesign activity's duration. However, one group misunderstood these guidelines resulting in that group's data being discarded further shrinking the sample size. Future workshops can avoid this limitation by hosting the workshop in one extended session allowing for additional clarifications and guidance.

Like the first workshop, the duration of the redesign activity using the Blue Economy Quiz limited how much feedback participants could fully follow. While we attempted to mitigate priming designers during their first concept redesign by using requirements integrated into the Blue Economy Quiz, it is possible that groups incorporated the updated requirements from the first concept into their second concept redesign - even if they did not receive feedback about these specific requirements. Ideally, the design workshop would be long and large enough to have each group only work with one concept and one redesign method to minimize the chance of priming participants. Despite these potential shortcomings, this workshop provided good insight into how the Blue Economy Quiz compares to traditional methods and helped cement development plans and testing of the tool.

It is also important to note that using the OSU MECC team may also skew the data to be more favorable to the Blue Economy Quiz. The tool is meant to evaluate how well a concept satisfies Blue Economy customer requirements. A less knowledgeable sample group could lead to the perception that the Blue Economy Quiz has a larger impact on redesign. However, part of the MECC is educating the students on wave energy. When combined with the fact that some team members are graduate students who are researching wave energy, we believe that the MECC is a good proxy for the multidisciplinary space of the Blue Economy.

## 5.2 MECC Workshops

### 5.2.1 Spring 2021

As discussed in Section 4.1, this workshop tasked members of the Oregon State University Marine Energy Collegiate Competition team to design and redesign a wave powered device for large scale desalination. The setup of the workshop allows for measuring the decision-making ability of each group before and after taking the Blue Economy Quiz. Prior to using the Blue Economy Quiz, few groups addressed design decisions relating to the Blue Economy Quiz categories in their initial concept. An example of a design decision could be a unique feature or a text annotation, like in

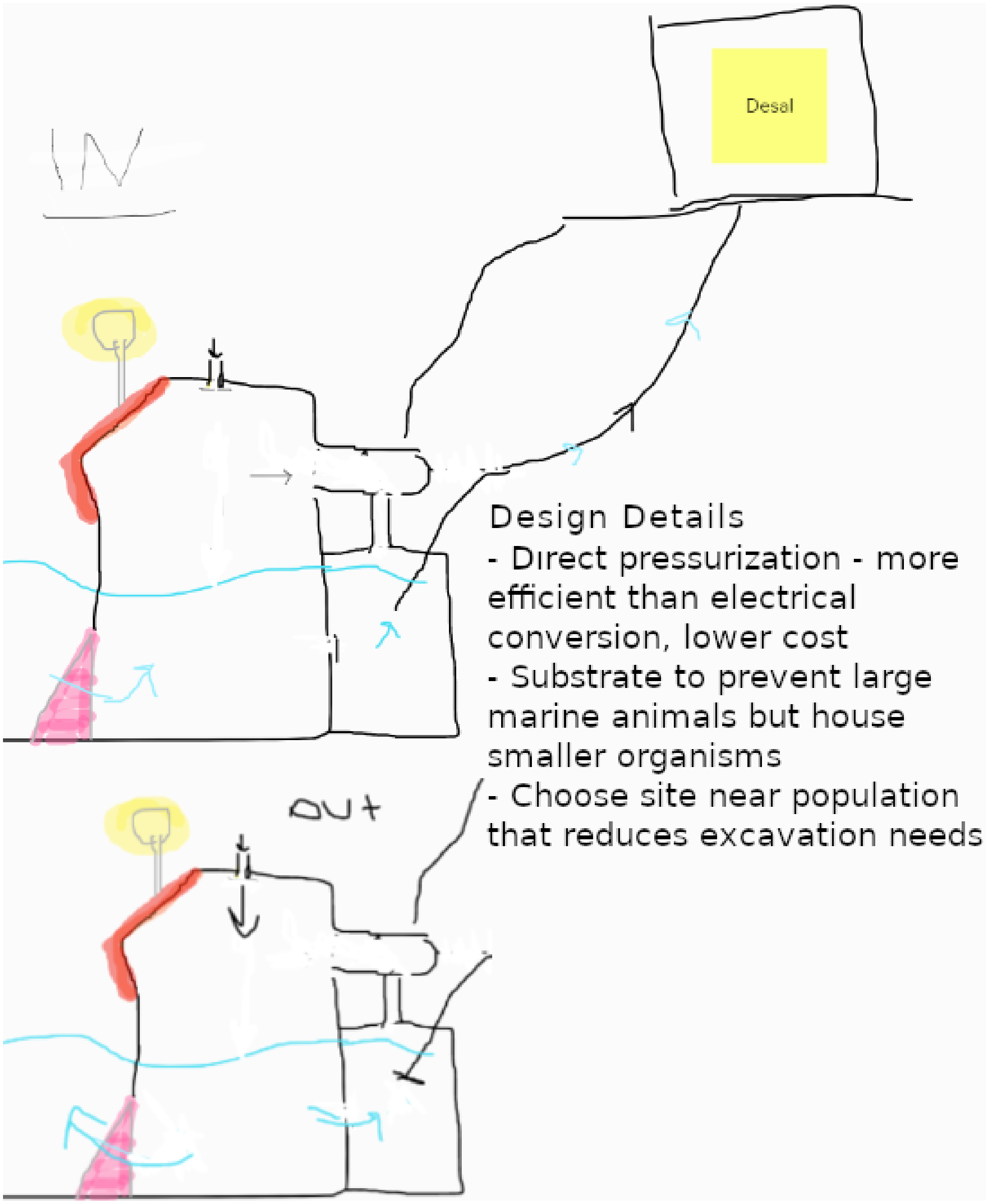


Figure 5.1: A sketch of a WEC concept from the OSU MECC design workshop, before taking the Blue Economy Quiz. This group provided text callouts to help explain multiple design decisions. Note: the "Design Details" text of the image was enhanced to improve legibility.

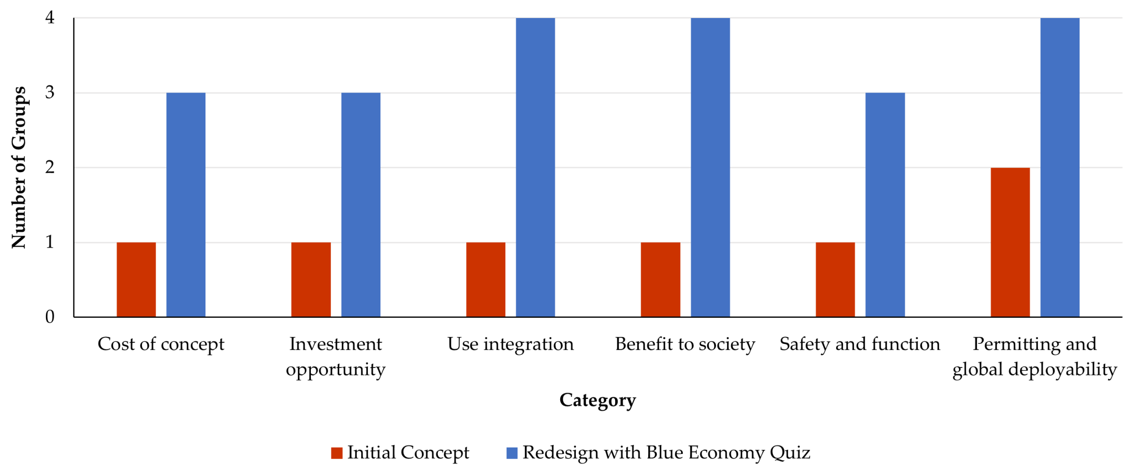


Figure 5.2: Design decisions referenced in the concept sketch for each category, before and after taking the Blue Economy Quiz. These design decisions were only counted once per group in a section, even if they referenced multiple aspects within a category in their sketch.

Fig. 5.1, that explains the function of the device.

The results of the design workshop with members of the Oregon State University MECC team are shown in Fig. 5.2 and Fig. 5.3. Fig. 5.2 shows the number of groups that reference a category within the Blue Economy Quiz, both before (Red) and after (Blue) using the tool to evaluate their concept. A group is only counted once per section, even if they referenced multiple aspects within a category.

Fig. 5.3 shows the change in answer composition by category of low scoring, medium scoring, and high scoring questions. As seen in Fig. 5.2, all categories except permitting and global deployability had a design decision by one group in the initial design. Four of the six category design decisions were made by one group, with all other groups only making one design decision in the initial design. After taking the quiz, three out of the four groups mentioned at least one design decision relating to every category. This indicates that even with limited time to process the tool's feedback, the knowledge is in a format that is easy to translate into design decisions. Furthermore, these results indicate that the questions of the Blue Economy Quiz cover

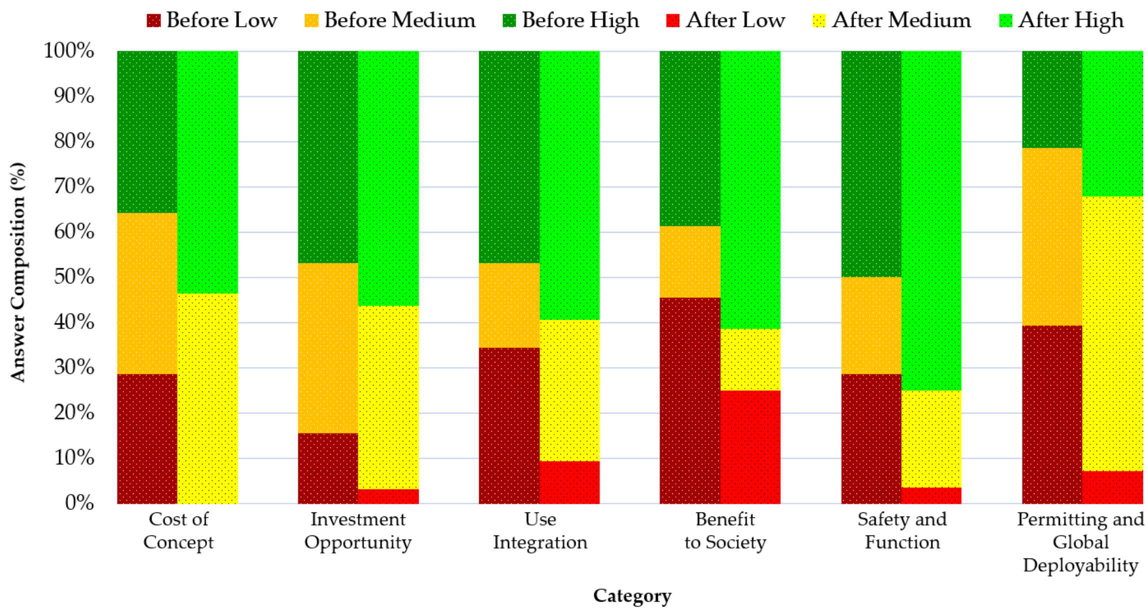


Figure 5.3: Division of score breakdown by category before (dark color with white dots) and after (light color with black dots) taking the quiz for: (a) low scoring questions, (b) medium scoring questions, and (c) high scoring questions.

topics that the designers had not initially considered. While the increase in design decision breadth follows the results found by tests of the GREEn Quiz [27], it is clear that we need more testing of this tool to determine the tool's effectiveness across a broad range of designers and a broad range of Blue Economy emerging markets.

As seen in Fig. 5.3, we see that the participants decreased the proportion of low scoring answers in each category. On average, the groups increased the medium and high scoring answers through their redesign. The decrease in low scoring answers is expected. Low scoring answers often include an option for not considering the requirement presented and we expect designers to make design changes to satisfy requirements. Nonetheless, this further indicates that the Blue Economy Quiz helps designers consider how they can refine their design to incorporate the requirements presented. While these results are not statistically significant due to the small sample size, the group choices can provide insight regarding focused testing and development of the quiz. It is important to note that each category does not have the same number of questions, so this analysis is only on the evolution of answer composition on a per-category basis and is not intended to compare answer composition between categories.

Based on these preliminary results, we could consider developing feedback for mid-level answers when a category score reaches a certain score threshold. This would help improve designs during structured concept generation methods, like Set-Based Design. Designers often refine concepts a few times in these methods, so providing mid-level feedback after a certain score threshold may help concepts reach a higher performance level. Future testing could incorporate a longer study, which could allow us to investigate not just if the feedback for low and medium scoring answers impacts a change on the design but also if that change is beneficial to the performance and stakeholder satisfaction of the design.

As discussed in Section 2.1, engineering design studies show that early incorporation of guidelines helps prime designers to focus on goals during design while maintaining originality and feasibility. Since the Blue Economy Quiz appears to achieve our goal of helping designers incorporate requirements, it is important that we are vigilant in keeping these stakeholder requirements current. Incorporating dated or incorrect information may decrease the overall performance of a design and could be detrimental to the stakeholder's perception of a concept.

### 5.2.2 Fall 2021

As discussed in Section 4.2, this workshop tasked members of the Oregon State University Marine Energy Collegiate Competition team to design and redesign wave powered devices for ocean observation and desalination. The setup of the workshop allows for measuring the decision-making ability of each group before and after intervention during the design processes. The raw data for the workshop are illustrated in Figures 5.4, 5.5, and 5.6 which show the number of groups that reference a category within the Blue Economy Quiz, both before (Red) and after (Blue) using the tool to evaluate their concept. A group is only counted once per section, even if they referenced

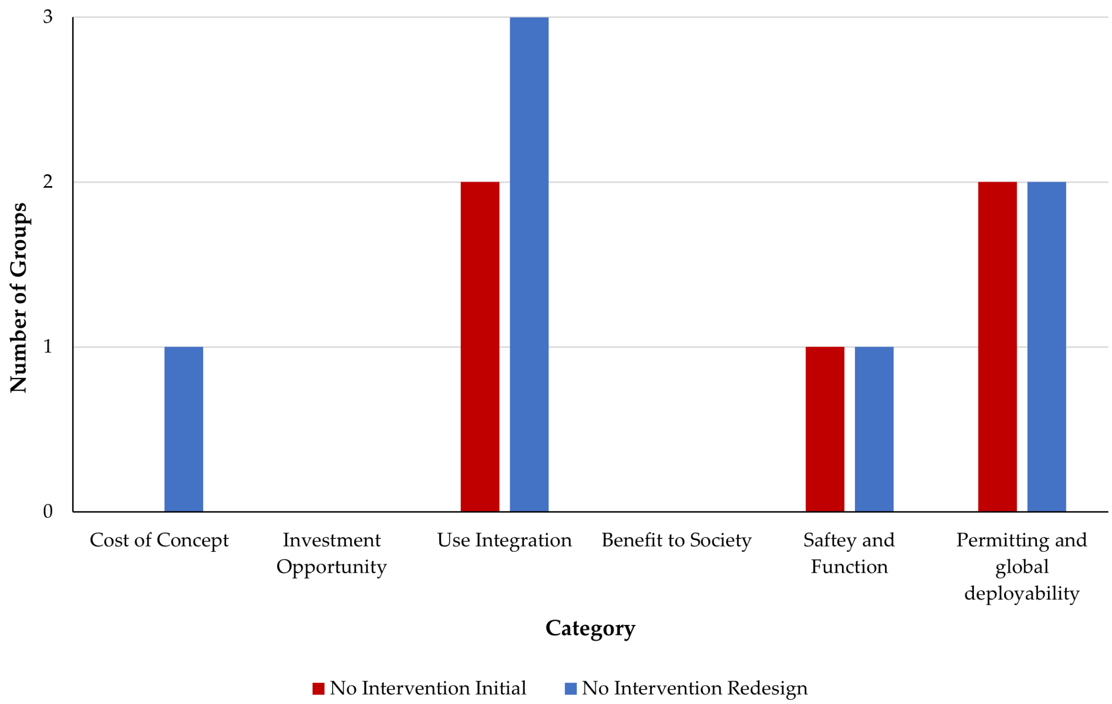


Figure 5.4: No-intervention design decisions referenced in the concept sketch for each category covered by the Blue Economy Quiz. These design decisions were only counted once per group in a section, even if they referenced multiple aspects within a category in their sketch.

multiple aspects within a category.

As seen in Fig. 5.4, the groups with no intervention only have two instances of new design decisions being made during redesign, one instance in *Cost of Concept* and one in *Use Integration*. These results are expected as the groups still had access to the original design prompt, which provided design objectives and limitations within both of these categories. While a smaller sample size, the intervention data allows us a preliminary look at how design decisions are impacted by other forms of presenting information to designers. Fig. 5.5 shows us three instances of increased design decisions in *Cost of Concept*, *Safety and Function*, and *Permitting and Global Deployability*. This is expected because these topics are covered in the updated design objectives

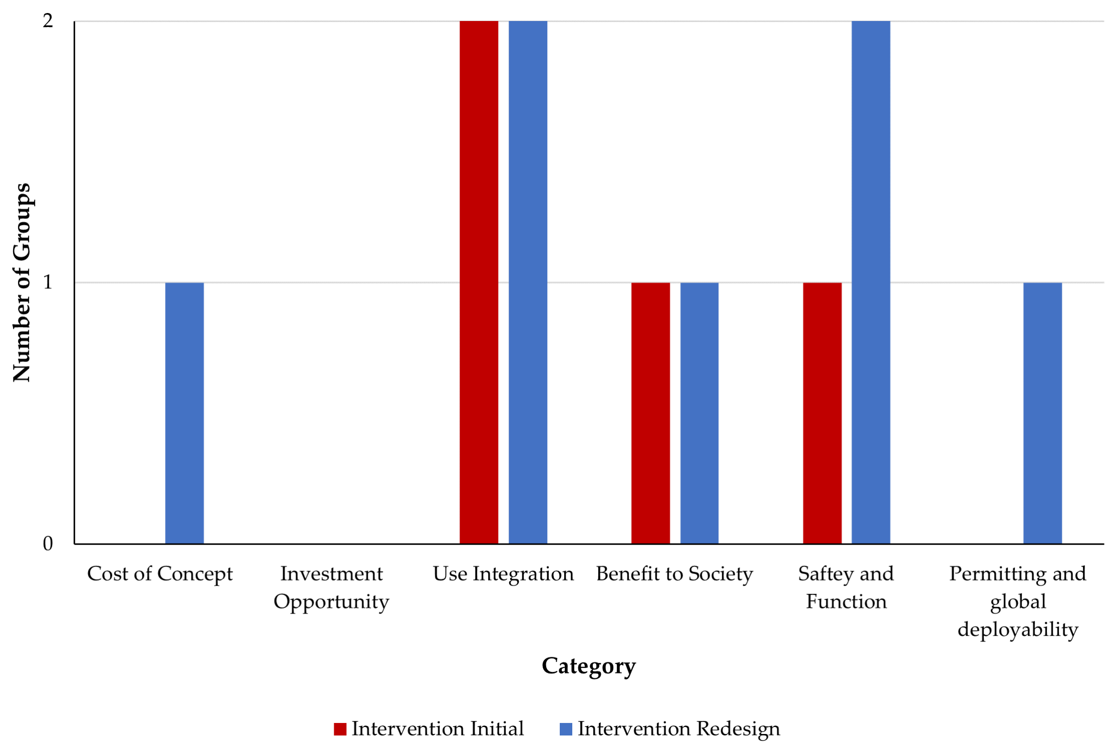


Figure 5.5: Intervention design decisions referenced in the concept sketch for each category covered by the Blue Economy Quiz. These design decisions were only counted once per group in a section, even if they referenced multiple aspects within a category in their sketch.

and information. The Blue Economy Quiz redesign intervention sees an increase in design decisions across all categories of covered by the tool. For instance, only one out of five groups initially consider *Cost of Concept*, *Investment Opportunity*, *Benefit to Society*, and *Safety and Function*. After taking the Blue Economy Quiz, over half of the groups made design decisions in these categories. These results support and expand upon the findings of our first test.

The fact that almost every team increased design decisions across each category of the Blue Economy Quiz, as seen in Fig. 5.6, is promising. This indicates that even with limited time to process the feedback of the Blue Economy Quiz, the knowledge

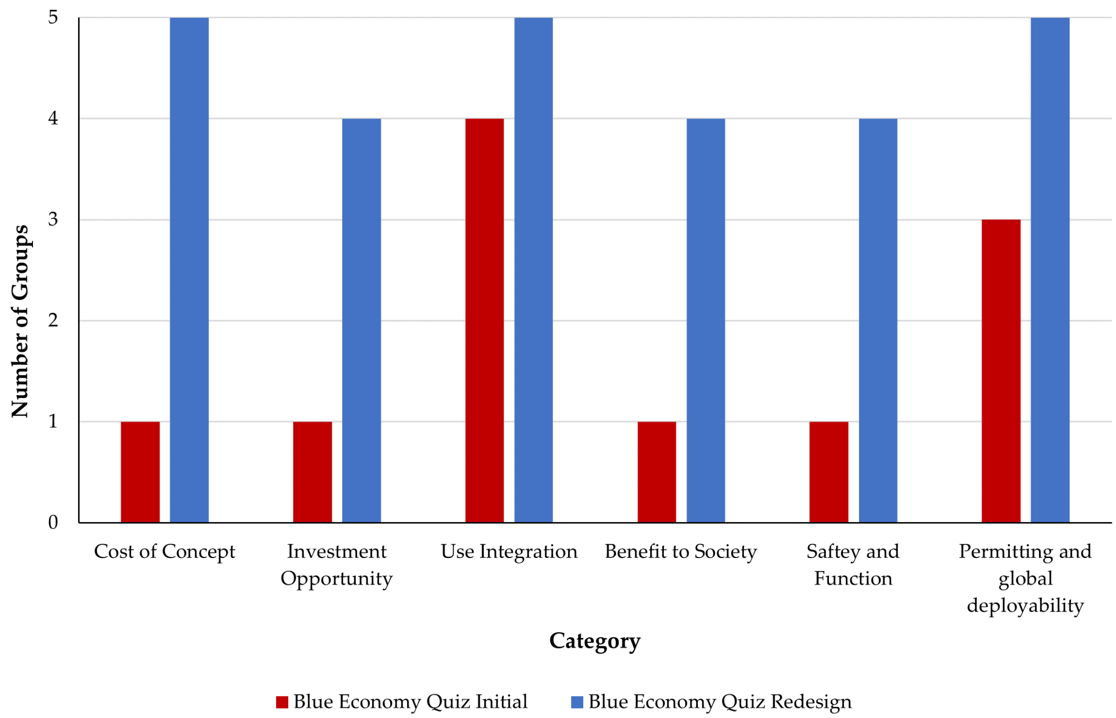


Figure 5.6: Blue Economy Quiz intervention design decisions referenced in the concept sketch for each category covered by the Blue Economy Quiz. These design decisions were only counted once per group in a section, even if they referenced multiple aspects within a category in their sketch.

is in a format that is easy to translate into design decisions. Furthermore, even when similar information is presented to designers, it appears that the Blue Economy Quiz's approach is more effective at helping designers synthesize information. The results also further support that the questions of the Blue Economy Quiz cover topics that designers do not initially consider during concept generation. The results also bring to light an interesting observation: We see that across almost all groups, the participants' initial concepts focus on *Use Integration*. The phenomena is understandable due to the priming effect of the design limitation we initially provide, which asks for the concept to be "adaptable to many instruments." This falls under the *Use Integration* category. Thus, future testing should be aware of the priming effect the initial workshop instructions can have on workshop participants.

Based on these results future testing should focus a few different goals. First, we should establish whether or not the Blue Economy Quiz is more effective than just providing designers with all of the information within the tool in another format. This test would provide more concrete evidence about the impact of the tool's format. Next, we should compare the Blue Economy Quiz with a popular concept generation method such as TRIZ. This test could also include the list of guidelines generated using the entirety of the knowledge in the Blue Economy Quiz. While we believe the Blue Economy Quiz would be more effective at increasing design decisions, a larger comparison with an existing methodology is important for benchmarking and demonstrating the tool's impact to industry.

## 5.3 User Feedback

During the workshops we also received feedback on the Blue Economy Quiz's user experience. Workshop participants stated that the topics and feedback of the quiz are helpful, as it reveals topics they had not considered during initial concept generation. The OSU MECC team said this feedback impacted conversations the team had throughout the rest of the competition. The workshop participants also stated that some questions were hard to answer for their concept, either because the question did not directly apply to their concept or because they did not have enough information to answer the question. For instance, during the Spring 2021 workshop one group designed a desalination device that used an onshore oscillating water column. The deployment site made some of the questions hard to answer. This problem reveals a potential limitation of the tested Blue Economy Quiz build. Currently, the quiz delivers the same question set to each participant regardless of the project, WEC archetype, deployment site etc. While we intended the tool to be site and sector agnostic - not all projects have the same requirements. The wave resource at a deployment site can change a vast number of WEC design parameters, and the importance of customer requirements changes based on the application. If the wrong requirements are presented to designers, this could lead to bad design decisions that may hinder the performance and stakeholder satisfaction of the WEC.

We can ensure that the right requirements are present to the user by incorporating filtering questions. These filtering questions will change the structure of the quiz to a search tree, allowing us to deliver more specific questions to the user and provide further clarification on restrictions of established practices. Currently, all questions in the Blue Economy Quiz are of equal weighting, so individual weights for questions can help provide relevant design feedback. These filtering questions alongside a weighting system will help designers know which stakeholder requirements are the most important to incorporate in their concept. Additionally, some users stated that it may be helpful to have features to track progress such as numbering questions or a progress bar. Participants stated that this feature would help with time management and would help them keep track of questions to focus on answering accurately if using the Blue Economy Quiz multiple times. These progress-tracking suggestions align with literature on user-focused survey design [62] and the improvements will ensure that taking the quiz is an effective use of time and will keep users engaged.

# Chapter 6: Conclusions

In this thesis, we present an early-design-phase wave energy converter design tool that presents designers with known practices for designing for Blue Economy applications and provides design feedback based on user answers. The tool is based on an existing product concept generation tool that successfully help designers make sustainable design decisions and incorporates wave energy converter design knowledge. This addresses a need for more early concept evaluation tools identified in previous work [14, 26]. The proposed tool provides designers with actionable feedback that helps designers improve their designs to better satisfy stakeholder requirements. We tested this tool in two case studies with the Oregon State Marine Energy Collegiate Competition team. The Spring 2021 testing provided us with key insights for future testing, and the Fall 2021 testing provides a qualitative comparison with other methods. The results of both experiments show a positive relationship between using the Blue Economy Quiz and making design decisions that capture a wider breadth of stakeholder requirements. The Spring 2021 answer composition data indicates that this tool can be expanded to increase its utility across multiple uses in early design. Through the Fall 2021 testing, we see that the Blue Economy Quiz may be more effective at priming designers than other methods of presenting customer requirements. However, future testing is needed for a clearer determination. The results from these tests indicate that such a tool may be helpful for wave energy developers in emerging markets.

Future work on this tool will incorporate feedback from the OSU MECC team, most of which aligns with existing literature on survey design to increase participant engagement [62]. These additions will also help ensure that using the Blue Economy Quiz is an effective use of time. We also plan to make the quiz more versatile by adding filtering questions and weights to individual questions. Filtering questions allow us to serve an initial set of high level questions to determine what detailed questions should be asked of the concept. This will change the structure of the quiz from a more general survey to a search tree structure. The search tree will eliminate asking questions that are irrelevant to a design's application and could reduce the number of questions a user needs to answer. For instance, if a concept has functionality currently on the market, we should also ask if the designer has benchmarked the concept against competition. Weights for individual questions will allow us to present the most important feedback for a designer. Additionally, we will continue to update the contents of the tool to reflect current literature on stakeholder requirements in emerging markets. This is important, as stakeholder needs change over time. We plan to add more user-friendly features, such as a progress bar that designers can view as they take the quiz. We hope to test this tool with a larger group to have a more detailed investigation on the impact of the tool during concept generation. This larger test should compare the Blue Economy Quiz with other established concept generation and evaluation methodologies as we need more detail on how methodologies impact making design decisions that capture a wider breadth of stakeholder requirements. It would also be interesting to test what kind of feedback and what amount of feedback is most helpful during concept generation. Currently, users have access to the entirety of the feedback from the Blue Economy Quiz. While this can be helpful for a comprehensive redesign, there is the possibility that the amount of information could overwhelm a design team and lead to lower performing concepts. Thus, investigating impact that the amount of feedback has on design could be helpful in determining the focus of future development.

After more development and testing, it is pertinent to conduct longer tests with the Blue Economy Quiz where we have participants complete all design stages up though concept selection. After concept selection, we can then evaluate concepts that used the Blue Economy Quiz and concepts that followed traditional design methodologies. Estimating manufacturing costs, performance, and stakeholder acceptance of these concepts will help us understand the impact of the Blue Economy Quiz on WEC development. This research will help us provide a tool for wave energy developers that improves the performance of their concepts and engages all stakeholders.

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# APPENDICES

# Appendix A: Blue Quiz Contents

Table A.1: Cost of Concept

| Question | Answer | Score | Feedback |
|---|---|---|---|
| Does the concept have any components with life spans shorter than that of the device? | The concept has many components with life spans shorter than that of the device | 0 | Consider replacing components that have a lifespan shorter than that of the device with components with longer lifespans. This could be achieved by changing materials reducing loading or preventing exposure to the marine environment. |
| | The concept has few components with life spans shorter than that of the device | 0.5 | – |
| | The concept has no components with life spans shorter than that of the device | 1 | – |
| Does the concept require battery storage to operate essential device electronics? | We have not considered if the concept will require battery storage to operate essential device electronics | 0 | Approximate the energy needs of onboard electronics and determine if a battery will be needed. |
| | The concept requires more than 5kWh battery storage to operate essential device electronics | 0 | Consider ways to reduce needs for battery storage such as powering electronics directly, eliminating non-essential electronics, or moving some functions to shore. When selecting and sizing a battery, be sure minimize maintenance needs (will your battery last the entire deployment?), and avoid environmental hazards (is there a chance of leaking or corrosion?). |
| | The concept requires less than 5kWh battery storage to operate essential device functions | 0.5 | – |
| | The concept does not require battery storage to operate essential device electronics | 1 | – |
| Does the concept have components requiring planned maintenance at sea? | We have not considered if the concept will have components that require planned maintenance at sea | 0 | Select components that have long windows between routine maintenance. You can minimize the cost of planned maintenance by combining/simplifying tasks or making autonomous maintenance possible. Try creating a maintenance storyboard in order to determine your maintenance needs. |

Table A.1: Cost of Concept (continued)

| Question | Answer | Score | Feedback |
|---|---|---|---|
| | The concept has many components requiring planned maintenance at sea | 0 | Minimize the cost of planned maintenance by combining or simplifying tasks or making autonomous maintenance possible. Consider replacing components that need routine maintenance. Creating a storyboard of the process for device maintenance may help you understand potential maintenance costs. |
| | The concept has few components requiring planned maintenance at sea | 0.5 | – |
| | The concept does not have components requiring planned maintenance at sea | 1 | – |
| Can the concept continue operating if damaged? | We have not considered if the concept can continue operating if damaged | 0 | Consider outlining the subsystems that are most likely to be damaged during operation and determine ways to mitigate the chances of damage. Consider adding redundancy for the components that are most likely to be damaged and interrupt operation. Performing a Failure Modes and Effects Analysis can help with these steps. |
| | Components cannot sustain damage and continue operating | 0 | Add redundancy to the system for the parts that are most likely to be damaged. Determine ways to mitigate the chances of damage such as survival configuration or materials change. Performing a Failure Modes and Effects Analysis will help you to understand where maintenance might be necessary. |
| | A few components can continue operating if damaged | 0.5 | – |
| | Most significant components can continue operating if damaged | 1 | – |
| Is the concept easily deployable by a common workboat? | We have not considered deployment of the concept | 0 | Outline the deployment (and maintenance) process early in design such that adjustments can be made to ensure that the device is deployable by common workboat. For the field in which you are working, determine limits for volume, weight, and mobility of a device. |

Table A.1: Cost of Concept (continued)

| Question | Answer | Score | Feedback |
|---|---|---|---|
| | The concept is not deployable by a common workboat | 0 | Outline the deployment (and maintenance) process early in design using storyboarding techniques. You might consider adding modularity, switching to lighter material, changing mooring design, or making the device tow-able by boat. It may be beneficial to reach out to experts early in the process, such as the crew on ocean research of installation vessels. Reduce the costs of renting or buying specialized equipment. DTOceanPlus offers a Logistics and Marine Planning tool that you may find helpful later in the design process. |
| | The concept can be deployed by a common workboat, but will require special systems for installation | 0.5 | – |
| | The concept is easily deployable by a common workboat without special systems for installation | 1 | – |
| Can the concept be transported by the highway system and manufactured in typical manufacturing facilities? | We have not considered transportation and manufacturing | 0 | Consider each component of the system and check if they require advanced or uncommon manufacturing techniques. Estimate weights and volumes and compare to weight and volume limits for air/land/water transport (whichever you may need). |
| | The concept has multiple components which cannot be transported on the highway system nor manufactured at on-site manufacturing facilities | 0 | Redesign or replace components that cannot be transported by highway or built at standard, on-site manufacturing facilities. This could be achieved by designing a system that requires no advanced or uncommon manufacturing techniques (simplify shapes, materials, high-tech components) or can be disassembled for transportation. You may find common concept generation methods such as brainwriting or morphological matrices to be helpful with this redesign. |
| | The concept is not transportable on the highway system but all components can be manufactured in typical manufacturing facilities; or the concept is transportable on the highway system but require manufacturing facilities that are not available in many areas | 0.5 | – |

Table A.1: Cost of Concept (continued)

| Question | Answer | Score | Feedback |
|---|---|---|---|
| | The concept can be transported by the highway system and manufactured in typical facilities | 1 | – |
| How many energy conversion steps are there from power absorption to usable power? | We have not considered how many energy conversion steps there are from power absorption to useable power | 0 | Consider performing a functional decomposition of the system. This may help you visualize the conversion steps and identify opportunities for increased efficiency. |
| | More than four steps | 0 | Consider reducing the number of conversion steps to increase efficiency. Performing a functional decomposition for the system may help you visualize the necessary conversion steps and recognize opportunities for increased efficiency. |
| | Three to four steps | 0.5 | – |
| | Two or fewer steps | 1 | – |
| Does the station keeping system interrupt the ability of the device to absorb energy? | We have not considered if station keeping system will interrupt the device's ability to absorb energy | 0 | Explore options for the the station keeping subsystem and estimate how they will interact with the energy absorbing/converting subsystems of the device. |
| | The station keeping system significantly reduces the device's ability to absorb energy | 0 | Consider redesigning the station keeping system to reduce its impacts on the part of the device that absorbs energy. This could include moving connection points, altering ranges of motion, or changing the size, shape, or material of the station keeping system. Determine the requirements of the mooring system, and sketch potential solutions, comparing each to the requirements using decision matrices. |
| | The station keeping system interrupts the ability of the device to absorb energy but only slightly | 0.5 | – |
| | The station keeping system does not interrupt the ability of the device to absorb energy | 1 | – |
| Does the system require a grid connection for survival or continued production? | The system requires a grid connection for survival | 0 | Consider redesigning or replacing components that require the device to have a grid connection. Performing a functional decomposition for the system may help you visualize the necessary inputs and recognize opportunities for decreased grid reliance. |
| | The system requires a grid connection for continued production but can survive without a grid connection | 0.5 | – |

Table A.1: Cost of Concept (continued)

| Question | Answer | Score | Feedback |
|---|---|---|---|
| | The system does not require a grid connection for survival nor for continued production | 1 | – |
| Does the concept require components that have to be custom made? | The concept requires many components that must be custom made | 0 | For components that must be custom made, simplify manufacturing processes as much as possible. This can be done by designing the component and the manufacturing method concurrently. Standardize dimensions and manufacturing steps, and refer to Design for Manufacturing and Design for Assembly literature for further guidance. |
| | The concept requires a few components that must be custom made | 0.5 | – |
| | The concept does not require components that must be custom made | 1 | – |
| Can the device function in a wide range of wave resources? | The device can convert energy only within a resource range less than 5 kW/m | 0 | Consider increasing the range of wave resource in which the device can convert energy. Outline the process of energy conversion and use this to identify the limiting components or subsystems. Replace or redesign the limiting components and subsystems, you may find using a Morphological Analysis beneficial to this process. |
| | The device can convert energy in a limited range (5-10 kW/m) of wave resources | 0.5 | – |
| | The device can convert energy in a wide range (>15k W/m) of wave resources | 1 | – |
| Are components designed to endure extreme loads? | Most components are not designed to endure extreme loads | 0 | Redesign the components likely to face the highest load to be able to endure extreme load common in the marine environment. At the conceptual stage, it is important to identify the location of high point load so that they can be modeled later on. |
| | Components at areas of point load are designed to endure extreme loads | 0.5 | – |
| | All components are designed to endure extreme loads | 1 | – |
| Is the concept able to be integrated into coastal infrastructure? (Such as piers, jetties, groins, breakwaters) | The concept is unable to be integrated into existing coastal infrastructure | 0 | Consider the kind of coastal infrastructure available and the potential to use that infrastructure to improve your design by use in maintenance or deployment, cost reduction, or improvement of production. |

Table A.1: Cost of Concept (continued)

| Question | Answer | Score | Feedback |
|---|---|---|---|
| | The concept can be partially integrated into existing coastal infrastructure | 0.5 | – |
| | The concept can be fully integrated into existing coastal infrastructure | 1 | – |
| Does the concept contain materials that are rare or difficult to source? | We have not considered the materials of the concept | 0 | Consider each component of the system and check if they require rare materials. Try to replace rare materials with common materials and refer to Design for Manufacturing and Design for Sustainability literature for further material selection guidance. |
| | Most of the materials for the concept are rare or difficult to source | 0 | Consider replacing rare or difficult to source materials with common materials. Meeting with stakeholders, such as manufacturers, could help you identify materials should be replaced. |
| | Some of the materials for the concept are rare or difficult to source | 0.5 | – |
| | Only a few materials are rare or difficult to source | 1 | – |

Table A.2: Investment Opportunity

| Question | Answer | Score | Feedback |
|---|---|---|---|
| Can the concept be deployed/installed/maintained with standard port infrastructure? | The concept requires new port infrastructure | 0 | Adjust deployment/installation/maintenance processes to be done with standard port infrastructure. Involving stakeholders such as marine contractors, port workers, and workboat crew early in the design process could help you make informed design decisions regarding these processes and the infrastructure available. |
| | The concept requires some changes to standard port infrastructure | 0.5 | – |
| | The concept requires standard port infrastructure | 1 | – |
| Does the concept provide power where it is the most cost-effective generation option? | We have not compared the costs of power converted by our device to other forms of generation. | 0 | Explore options for power generation its area of application and compare the cost of power generation. Then approximate your device's power generation costs. Early in the design process, cost estimates are highly uncertain. You may use previous estimates from marine energy reference models for the US Department of Energy to guide your estimates. |
| | The concept provides power where it is not a cost-effective generation option | 0 | Consider ways to make your system more cost-effective in its area of application. Meeting with end-users and purchasers to determine their needs could help you determine ways to make more cost-effective design decisions. |
| | The concept provides power where it is one of a few cost-effective generation options | 0.5 | – |
| | The concept provides power where it is the most cost-effective generation option | 1 | – |
| Can the concept be adapted to be part of an array? | We have not considered if the concept can be adapted into an array | 0 | Consider the area of application for the device and if array operation could be beneficial. Meeting with end-users and purchasers to determine needs could help you make this decision. When redesigning, consider what changes to the mooring, transmission, and use area are needed. Remember to consider other users of the marine environment (fisheries, shipping, etc.). |

Table A.2: Investment Opportunity (continued)

| Question | Answer | Score | Feedback |
|---|---|---|---|
| | The concept cannot be adapted to be part of an array | 0 | Meet with end-users and purchasers to determine if array operation is beneficial. Minimizing the use area of the array will help make this a cost-effective design decision. Remember to consider other users of the marine environment (fisheries, shipping, etc.). |
| | The concept can be adapted to be part of an array if there are some adjustments | 0.5 | – |
| | The concept can be adapted to be part of an array as designed | 1 | – |
| Can the concept be scaled? Meaning, if the concept is designed for grid operation, can it be scaled for emerging markets (or vice versa) | We have not considered the concept can be scaled | 0 | Look at the emerging markets listed in both the U.S. Department of Energy's Powering the Blue Economy Report, and the potential markets listed in DTOcean Plus' Potential Markets for Ocean Energy. Consider how customers change between markets and potential design modifications that might be needed. |
| | The concept cannot be scaled | 0 | Consider if scaling the concept would be beneficial for potential end-users. Meeting with purchasers and end users outside of your intended market may help determine if this would be a beneficial design decision. |
| | The concept can be scaled, but there is a limit to the extent | 0.5 | – |
| | The concept can be scaled to any operational need. | 1 | – |
| Are most of the components of the system technologies which are already used in the marine environment? | Few/none of the components of the system are already used in the marine environment | 0 | Consider replacing some components with others which are already used successfully in the marine environment. These could be identified by looking at existing marine industries. Meeting with stakeholders such as marine contractors could help you identify components that could be replaced. |
| | Most of the components of the system are already used in the marine environment | 0.5 | – |
| | All components of the system are already used in the marine environment | 1 | – |

Table A.2: Investment Opportunity (continued)

| Question | Answer | Score | Feedback |
|---|---|---|---|
| Are there any rare materials/-materials prone to major price fluctuations used in the device? | We have not considered if there will be rare materials or materials prone to major price fluctuations | 0 | Consider each component of the system and check if they require rare materials or materials that are prone to major price fluctuations. Try finding alternative materials with stable prices and refer to Design for Manufacturing, Design to Cost, and Design for Sustainability literature for further material selection guidance |
| | There are rare materials/materials prone to major price fluctuations used in the device | 0 | Find alternate materials to replace any rare materials or materials prone to major price fluctuations. Meeting with stakeholders such as manufacturers and marine contractors could help you identify alternative materials. |
| | There are few rare materials/materials prone to major price fluctuations used in the device | 0.5 | – |
| | There are no rare materials/materials prone to major price fluctuations used in the device | 1 | – |
| Can the output of the entire system (freshwater, seaweed, offshore power, etc.) be produced at a competitive price? | The output of the entire system cannot be produced at a competitive price | 0 | onsider ways to reduce the price of the output of the system. Identify outside circumstances that may impact your system's ability to produce at a competitive price. Compare your concept to existing products that perform similar functions using Pugh Charts or a Decision Matrix. Use the results to identify and redesign the most expensive components. |
| | The output of the entire system can be produced at a price slightly above market price | 0.5 | – |
| | The output of the entire system can be produced at a competitive price | 1 | – |
| Can the concept be monitored from shore?,The concept can be fully monitored from shore | The concept cannot be monitored from shore | 0 | Consider adding features that allow the device to be monitored from shore. Examine existing marine devices that can be monitored from shore, such as ocean observation buoys, to assess your options. When considering the system, remember to determine the energy needs of electronics. |
| | The concept can be monitored from shore, but with limited capability | 0.5 | – |
| | The concept can be fully monitored from shore | 1 | – |

Table A.3: Use Integration

| Question | Answer | Score | Feedback |
|---|---|---|---|
| Does the concept have energy storage capacity? | We have not considered energy storage for this device | 0 | Determine the design requirements of the intended end users and purchasers of your device. This can be done by completing a House of Quality. If the intended use case would benefit from energy storage, consider the cases where the storage will be used. How much power will you need and for how long? Using this information, you can effectively select the most cost-effective energy storage method. When selecting, be sure minimize maintenance needs (will a battery last the entire deployment?), and avoid environmental hazards (is there a chance of leaking, corrosion, or damage?). |
| | The concept has no energy storage capacity | 0 | Consider whether adding energy storage capacity could increase the capability of the system to perform its intended functions (within the design requirements). Meeting with end-users and purchasers could help with this decision. When selecting, be sure minimize maintenance needs (will your battery last the entire deployment?), and avoid environmental hazards (is there a chance of leaking or corrosion?). |
| | The concept has minimal energy storage capacity | 0.5 | – |
| | The concept has energy storage capacity at the scale of its generation capacity | 1 | – |
| Can the concept be integrated with other renewable installations? | The concept cannot be integrated into other renewable installations | 0 | Consider whether the adding the ability to be integrated with other renewable installations could increase the capability of the system to perform its intended functions within the design requirements. Refer to literature on colocated offshore renewable energy farms for more information. |
| | The concept can be integrated into some renewable installations | 0.5 | – |
| | The concept can be integrated into any renewable installation | 1 | – |

Table A.3: Use Integration (continued)

| Question | Answer | Score | Feedback |
|---|---|---|---|
| Can the concept provide real-time data to operators? | We have not considered provide real-time data to operators | 0 | Determine if providing real-time data would increase the capability of the system. Meeting with stakeholders such as purchasers and operators could help with this decision. Looking at existing marine devices that provide data, such as ocean observation buoys, could help with the determining needed systems. When considering the system, remember to determine the energy needs of electronics. |
| | The concept cannot provide real-time data to operator | 0 | Consider whether the adding the ability to provide real-time data to operators could increase the capability of the system to perform its intended functions (within the design requirements). Meeting with stakeholders such as purchasers and operators could help with this design decision. |
| | The concept can provide limited real-time data to operators | 0.5 | – |
| | The concept can provide real-time data to operators | 1 | – |
| Is the connection between the system that converts wave power to usable power permanently attached to the subsystem that uses the power? | The connection is permanent | 0 | Consider potential failures that could come from a not-permanent connection and whether their might be a way to reduce that potential failure by making the connection permanent, avoiding needless connect and disconnect, or protecting the connection from salt water and extreme loads. |
| | The connection is not permanent | 1 | – |
| Is the point of the interconnection exposed to salt water? This is the connection between the WEC and the system it is powering. | The point of interconnection is exposed to seawater | 0 | Consider designing the system to protect the point of interconnection from seawater. Alternatively, consider using TRIZ to generate new concepts for reducing risk associated with sea water exposure. |
| | The point of interconnection is not exposed to seawater | 1 | – |
| Is there a physical subsystem responsible for transferring material or energy to shore? What ratio of the total system volume is this subsystem? | We have not considered if there will be a physical subsystem responsible for transferring material or energy to shore | 0 | Outline if a physical subsystem for transferring material or energy to shore is needed. You may find common concept generation methods such as brainwriting or morphological matrices to be helpful with this process. |

Table A.3: Use Integration (continued)

| Question | Answer | Score | Feedback |
|---|---|---|---|
| | There is a subsystem that takes more than 15% volume | 0 | Consider ways to reduce the size of the subsystem responsible for device-to-shore transfer. Compare your subsystem to existing designs using Pugh Charts or a Decision Matrix. Use the results to identify redesign solutions and reduce the volume of this subsystem. |
| | There is a subsystem that takes less than 15% volume | 0.5 | – |
| | There is no subsystem | 1 | – |
| Is the system able to generate more power than it consumes? | The system generates less power than it consumes | 0 | Consider making design decisions to increase your device's power production. Performing a functional decomposition for the device and its subsystems may help you visualize the necessary conversion steps and recognize opportunities for increased efficiency. |
| | The system generates as much power as it consumes | 0.5 | – |
| | The system can generate more power than it consumes | 1 | – |
| Is the point of interconnection subject to extreme loads? This is the connection between the WEC and the system it is powering. | The point of interconnection is subject to extreme loads under normal operating conditions | 0 | Consider re-configuring your system so that the integration point is not subject to extreme loads.This could be done by using TRIZ to generate new concepts for reducing extreme loads on the point of interconnection. |
| | The point of interconnection is subject to extreme loads during installation, survival mode, or other alternate operating conditions | 0.5 | – |
| | The point of interconnection is not subject to extreme loads | 1 | – |

Table A.4: Benefit to Society

| Question | Answer | Score | Feedback |
|---|---|---|---|
| Can the concept provide ancillary benefits such as prevent coastal erosion, etc.? | The concept cannot provide ancillary benefits | 0 | Consider potential ancillary benefits of your system. These benefits could influence the cost, acceptability, and the benefit to society of the system. Ideas for potential ancillary benefits could come from conversations with stakeholders. |
| | The concept provides some ancillary benefits | 0.5 | – |
| | The concept provides many ancillary benefits | 1 | – |
| Can the concept provide real-time data to the public/user? | The concept cannot provide real-time data to the public | 0 | Consider adding capabilities to provide real-time data to the public. Meeting with end-users could help with this design decision. Compare existing products that provide real-time data to the public using Pugh Charts or a Decision Matrix. Use the results to identify and add capability to your design. |
| | The concept provides real-time data to the public | 1 | – |
| Have you assessed the potential disruptions of your device to fishing/marine farming? | We have not considered potential disruptions of our device for fishing and marine farming | 0 | Consider involving these stakeholders early in the design process. You might consider conducting interviews, surveys, or market research to help ideate ways to improve the system's ability to work with other users of the marine environment. |
| | We have considered fishing and marine farming users, and determined that the concept is disruptive. | 0.33 | Consider involving these stakeholders early in the design process. Interviewing aquaculture companies or fisheries may help ideate ways to improve the system's ability to work with other users of the marine environment. |
| | We have considered fishing and marine farming users, and determined that disruption is minimal. | 0.66 | – |
| | We have used feedback from fishing and marine farming users to determine that disruption is minimal. | 1 | – |
| Have you assessed the potential disruptions of your device to marine recreation? | We have not considered potential disruptions of our device for fishing and marine farming | 0 | Consider involving these stakeholders early in the design process. You might consider conducting interviews, surveys, or market research to help ideate ways to improve the system's ability to work with other users of the marine environment. |

Table A.4: Benefit to Society (continued)

| Question | Answer | Score | Feedback |
|---|---|---|---|
| | We have considered recreational users of the marine environment, and determined that the concept is disruptive | 0.33 | Consider involving these stakeholders early in the design process. Interviewing surfers or recreational boaters may help ideate ways to improve the system's ability to work with other users of the marine environment. |
| | We have considered recreational users of the marine environment, and determined that disruption is minimal | 0.66 | – |
| | We have used feedback from recreational users to determine that disruption is minimal. | 1 | – |
| Have you assessed the potential disruptions of your device to protected species? | We have not considered potential disruptions of our device on protected species | 0 | Consider involving these stakeholders early in the design process. You might consider conducting interviews, surveys, or market research to help ideate ways to improve the system's ability to work with other users of the marine environment. |
| | We have considered protective species in the marine environment, and determined that the concept is disruptive. | 0.33 | Consider involving these stakeholders early in the design process. Interviewing marine wildlife protection organizations may help ideate ways to improve the system's ability to work with other users of the marine environment. |
| | We have considered protective species in the marine environment, and determined that disruption is minimal. | 0.66 | – |
| | We have used feedback from marine species protection organizations to determine that disruption is minimal. | 1 | – |
| Have you assessed the potential disruptions of your device to marine shipping and transportation? | We have not considered potential disruptions of our device for shipping and transportation | 0 | Consider involving these stakeholders early in the design process. You might consider conducting interviews, surveys, or market research to help ideate ways to improve the system's ability to work with other users of the marine environment. |
| | We have considered marine shipping and transportation users of the marine environment, and determined that the concept is disruptive. | 0.33 | Consider involving these stakeholders early in the design process. Interviewing shipping companies may help ideate ways to improve the system's ability to work with other users of the marine environment. |

Table A.4: Benefit to Society (continued)

| Question | Answer | Score | Feedback |
|---|---|---|---|
| | We have considered marine shipping and transportation users of the marine environment, and determined that disruption is minimal. | 0.66 | – |
| | We have used feedback from marine shipping and transportation users of the marine environment to determine that disruption is minimal. | 1 | – |
| Will the device lead to a reduction in carbon emissions during the early life cycle (manufacturing, assembly, lifting, transport, installation) of the device? | We have not considered the reduction in carbon emissions during the early life cycle | 0 | List all life stages (from design, manufacturing, assembly, lifting, transport, installation) and consider sources of carbon emissions. Try replacing unsustainable materials with environmentally friendly alternatives and reducing reliability of harmful manufacturing practices, Involving manufacturers and marine contractors can provide important insight into how to make your system environmentally friendly. For more information regarding environmentally friendly design, refer to literature on Design for Environment and Design for Sustainability. |
| | The device will not lead to a reduction in carbon emissions during the early life cycle | 0 | Consider ways to reduce carbon emissions during the early life cycle of the system. Try replacing unsustainable materials with environmentally friendly alternatives and reducing reliability of harmful manufacturing practices. For more information regarding environmentally friendly design, refer to literature on Design for Environment and Design for Sustainability. |
| | The device will lead to a reduction in carbon emissions during the early life cycle | 1 | – |
| Will the device lead to a reduction in carbon emissions during operation of the device? Be sure to consider maintenance needs too. | We have not considered the reduction in carbon emissions during operation | 0 | List all life stages (operation, maintenance) and list sources of carbon emissions. Try using TRIZ to ideate more reliable concepts. Involving stakeholders such as marine contractors can provide important insight into how to reduce carbon emissions. For more information regarding environmentally friendly design, refer to literature on Design for Environment and Design for Sustainability. |

Table A.4: Benefit to Society (continued)

| Question | Answer | Score | Feedback |
|---|---|---|---|
| | The device will not lead to a reduction in carbon emissions during operation | 0 | Consider ways to reduce carbon emissions during operation of the system. Try increasing time between required maintenance. For more information regarding environmentally friendly design, refer to literature on Design for Environment and Design for Sustainability. |
| | The device will lead to a reduction in carbon emissions during operation | 1 | – |
| Will the device lead to a reduction in carbon emissions during the end of life stages of the device? Be sure to consider removal, decommissioning, repurposing, etc. | We have not considered the reduction in carbon emissions during during end of life stages | 0 | List all life stages (removal, decommissioning, repurposing, etc.) and outline sources of carbon emissions. Involving stakeholders who might be ask risk such as marine contractors and disposal workers, etc. provide important insight into reducing carbon emissions. For more information regarding environmentally friendly design, refer to literature on Design for Environment and Design for Sustainability.List all life stages (removal, decommissioning, repurposing, etc.) and outline sources of carbon emissions. Involving stakeholders who might be ask risk such as marine contractors and disposal workers, etc. provide important insight into reducing carbon emissions. For more information regarding environmentally friendly design, refer to literature on Design for Environment and Design for Sustainability. |
| | The device will not lead to a reduction in carbon emissions during end of life stages | 0 | Consider ways to reduce carbon emissions during the end stages of the system. For more information regarding environmentally friendly design, refer to literature on Design for Environment and Design for Sustainability. |
| | The device will lead to a reduction in carbon emissions during end of life stages | 1 | – |
| Are the materials used for the device recyclable or reusable? | None of the materials used for the device are recyclable or reusable | 0 | Consider replacing components that are not reusable or recyclable with ones that are. For more information regarding materials selection, refer to literature on Design for Environment and Design for Sustainability. |
| | Some of the materials used for the device are recyclable or reusable | 0.5 | – |

Table A.4: Benefit to Society (continued)

| Question | Answer | Score | Feedback |
|---|---|---|---|
| | All the materials used for the device are recyclable or reusable | 1 | – |
| Does the device provide end users with functionality that is not currently possible? | The device does not provide end users with functionality that is not currently possible | 0 | Consider how your proposed system can be better than what is currently available. Could your system open up new possibilities? Try performing a SWOT analysis or benchmarking against current products to identify opportunities for your concept. |
| | The device provides end users with functionality that is not currently possible | 1 | – |

Table A.5: Safety and Function

| Question | Answer | Score | Feedback |
|---|---|---|---|
| Does the concept consist of many moving parts exposed to seawater? | The concept consists of many exposed moving parts | 0 | Protect components from seawater exposure and/or reduce the number of moving parts. Alternatively, consider using TRIZ to generate new concepts for reducing risk associated with contact between moving parts and sea water. |
| | The concept consists of few exposed moving parts | 0.5 | – |
| | The concept consists of no exposed moving parts | 1 | – |
| Can the concept be detected by other vessels/people at sea? | The concept cannot be detected by others | 0 | Consider redesigning your system so that it is easy to detect by marine vessels or other people at sea. Interviewing other marine environment users may help you ideate ways to improve the system's ability to be detected. You may find common concept generation methods such as brainwriting or morphological matrices to be helpful with this redesign. |
| | The concept can be detected by others | 1 | – |
| Have you listed all of the potential threats to human health and safety during life cycle stages? (Consider all life stages from design, manufacturing, assembly, lifting, transport, installation, operation, maintenance, removal, decommissioning, etc.) | We have not considered potential threats to human health and safety | 0 | List all life stages (from design, manufacturing, assembly, lifting, transport, installation, operation, maintenance, removal, decommissioning, etc.) and consider threats to human health and safety. Involving stakeholders who might be ask risk such as marine contractors, manufacturers, disposal workers, etc can provide important insight into how to make your system safe. |
| | Yes, and there is significant threat to human health and safety during life cycle stages | 0.33 | Reduce threats to human health and safety. Involving stakeholders who might be ask risk such as marine contractors, manufacturers, disposal workers, etc can provide important insight into how to make your system safe. |
| | Yes, and there is some threat to human health and safety during life cycle stages | 0.66 | – |
| | Yes, and there is no threat to human health and safety during life cycle stages | 1 | – |

Table A.5: Safety and Function (continued)

| Question | Answer | Score | Feedback |
|---|---|---|---|
| Can the concept survive extreme conditions? | We have not considered the survivability of the concept | 0 | Perform a Failure Modes and Effects Analysis for your concept. This will help you to identify the most important potential failures to address. Look at literature on Design for Reliability for more information on increasing the survival of the device. Water pressure, salinity (air and water), temperature variations, marine life, and extreme wave events are all environmental factors that may cause failures. |
| | The concept cannot survive exposure to extreme conditions | 0 | Improve your concept's survivability. This could involve including a survival configuration or replacing components with more durable, reliable components. Performing a Failure Modes and Effects Analysis will help you to understand design changes to improve survivability. Look at literature on Design for Reliability for more information on increasing the survival of the device. |
| | The concept is designed to survive limited exposure to extreme conditions | 0.5 | – |
| | The concept is designed to survive prolonged exposure to extreme conditions | 1 | – |
| Does installation or maintenance require divers? | Yes, installation and maintenance require divers | 0 | Identify ways to avoid needing divers for installation or maintenance. Involving stakeholders that would be involved in installation and maintenance may help with this redesign. Creating a storyboard of the process for device installation and maintenance may help you ideate potential changes. |
| | Yes, installation or maintenance requires divers | 0.5 | – |
| | No, neither installation nor maintenance require divers | 1 | – |
| What is the likelihood that the system will be lost to sea? | No offshore subsystems (including moorings) have been designed for conditions worse than expected and no plan has been put in place for the possibility that the device becomes free | 0 | Consider designing offshore components for extreme conditions and making a plan for device retrieval. Meeting with stakeholders involved with device retrieval, such as marine contractors, may help with understanding design decisions. Creating a storyboard of the device retrieval process may help you understand the process. |

Table A.5: Safety and Function (continued)

| Question | Answer | Score | Feedback |
|---|---|---|---|
| | Some offshore subsystems (including moorings) have been designed for conditions worse than expected and no plan has been put in place for the possibility that the device becomes free | 0.33 | Consider making a plan for device retrieval. Creating a storyboard of the process for device retrieval may help you understand the steps for retrieval. |
| | Some offshore subsystems (including moorings) have been designed for conditions worse than expected and a plan has been put in place for the possibility that the device becomes free | 0.66 | – |
| | All offshore subsystems (including moorings) have been designed for conditions worse than expected and a plan has been put in place for the possibility that the device becomes free | 1 | – |
| Does the device have a survival mode? | The device does not have a survival mode | 0 | Consider how your device will respond to extreme conditions and how you can design your system to survive them. A survival mode could be a way to do this. Performing a Failure Modes and Effects Analysis will help you to understand design changes to improve survivability. |
| | The device has a survival mode | 1 | – |

Table A.6: Permitting and Global Deployability

| Question | Answer | Score | Feedback |
|---|---|---|---|
| Can the concept be deployed in environmentally sensitive areas? | We have not considered the concept's impact on environmentally sensitive areas | 0 | Meet with potential environmental stakeholders, such as environmental regulators, to help you address environmental concerns and refer to literature on Design for Environment for further guidance. GIS or marine spatial planning resources may help you identify sensitive or protected marine areas. |
| | The concept causes environmental concerns and cannot be deployed in environmentally sensitive areas | 0 | Consider addressing environmental concerns early in the design process. Meeting with potential environmental stakeholders, such as environmental regulators, could help you make informed design decisions. Refer to databases such as the Wave & Tidal Knowledge Network for literature on the environmental impacts of marine energy. |
| | The concept causes some environmental concerns and will have restrictions on where it can be deployed; but overall materials and high-tech components may help you recognize opportunities for reduced complexity. | 0.5 | – |
| | The concept causes no environmental concerns and can be deployed in environmentally sensitive areas | 1 | – |
| Does the concept require disruptive infrastructure to the seafloor/water column/sea surface? | We have not considered if the concept requires disruptive infrastructure | 0 | Outline the infrastructure your concept requires. Meeting with environmental stakeholders and marine contractors could help you understand the impacts of such infrastructure and identify alternatives. Identify the function(s) of disruptive infrastructure and brainstorm alternative concepts which can complete the same necessary functions. |
| | The concept requires infrastructure that is disruptive to the seafloor/water column/sea surface | 0 | Consider reducing your system's dependence on disruptive infrastructure. Meeting with environmental stakeholders and marine contractors could help you understand the impacts of such infrastructure and identify alternatives. Identify the function(s) of disruptive infrastructure and brainstorm alternative concepts which can complete the same necessary functions. |

Table A.6: Permitting and Global Deployability (continued)

| Question | Answer | Score | Feedback |
|---|---|---|---|
| | The concept requires some infrastructure that could be disruptive to the seafloor/water column/sea surface | 0.5 | – |
| | The concept does not require infrastructure that is disruptive to the seafloor/water column/sea surface | 1 | – |
| Does the concept provide power for essential services that are used globally? e.g. telecom services, electricity, food etc. | The concept provides power for services that are sight specific or inessential | 0 | Improve the global deployability of your system by making it compatible for use with services that are necessary to most populations. To begin understanding end user needs, you might consider conducting interviews, surveys, or market research. |
| | The concept can provide power for services that are important to many communities | 0.5 | – |
| | The concept can provide power for services that are essential globally | 1 | – |
| Can the concept be deployed in areas with a low marine energy resource? | The concept cannot be deployed in areas with a low marine energy resource | 0 | Determine how often your likely deployment sites will have low marine energy resource. Use this knowledge to estimate the availability of the device. Low availability can decrease a device's ability to meet functional requirements and can decrease income from energy output. Be sure to look at changes in marine resource over seasons as well as other marine patterns. |
| | he concept can be deployed in areas with low marine energy resource, but will operate in a reduce capacity | 0.5 | – |
| | The concept can be deployed in areas with a low marine energy resource | 1 | – |

Table A.6: Permitting and Global Deployability (continued)

| Question | Answer | Score | Feedback |
|---|---|---|---|
| Can the concept be disassembled/easily distributed? | We have not considered disassembly of the concept | 0 | Create a storyboard the disassembly of the process. This may help you understand potential issues that need redesigned. Replace components that cannot be disassembled or easily distributed with more mobile, modular components. Try to design components that require no advanced or uncommon manufacturing techniques and can be disassembled for transportation. Standardize dimensions and refer to Design for Assembly and Design for Manufacturing literature for further guidance. |
| | The concept cannot be disassembled or easily distributed | 0 | Consider replacing the components that cannot be disassembled or easily distributed with more mobile, modular components. This can be achieved by designing components that requires no advanced or uncommon manufacturing techniques and can be disassembled for transportation. Standardize dimensions and manufacturing steps, and refer to Design for Assembly and Design for Manufacturing literature for further guidance. |
| | The concept can be partially disassembled but requires oversize vehicles for distribution | 0.5 | – |
| | The concept can be disassembled and easily distributed | 1 | – |
| Does the concept generate light or noise pollution? | The concept generates significant light or noise pollution | 0 | Reduce the light and/or noise created by your device. Meeting with marine contractors could help identify design decisions to reduce excess light or noise pollution. |
| | The concept generates minimal light or noise pollution | 0.5 | – |
| | The concept generates no light or noise pollution | 1 | – |
| Is the system negatively disrupted by changes to tidal range, current, or temperature (within the range of temperatures present in ocean environments)? | We have not considered the device's sensitivity to tidal range, current or temperature. | 0 | Approximate your system's sensitivity to changes in the tidal range, current, or temperature and determine if it is negatively impacted by disruptions. |

Table A.6: Permitting and Global Deployability (continued)

| Question | Answer | Score | Feedback |
|---|---|---|---|
| | The system is very sensitive to tidal range, current or temperature | 0 | Brainstorm ways of reducing your system's sensitivity to tidal range, current or temperature using methods such as brainwriting or TRIZ. Rate alternatives against customer requirements in a decision matrix. In cases where there are multiple, potentially equivalent options, consider continuing through the design process with multiple concepts and reassessing when you have a higher level of certainty. |
| | The system is somewhat sensitive to tidal range, current or temperature | 0.5 | – |
| | The system is not sensitive to tidal range, current or temperature | 1 | – |

# Appendix B: *django-quiz* Package Information

## B.1 Library Dependencies

The current build of *django-quiz* requires the Python 3 core datetime, random, io, and csv libraries. In addition to a full install of the current Django 3 build, this package also requires a few external library dependencies.

### B.1.1 Jsonfield

This library is a model field that allows for storing JSON to a model [63]. When this project started, I was actively learning about django and relational databases. Thus, I decided to use the default SQLite database and did not realize the need for JSON support until later.

### B.1.2 nested_admin

This allows for nesting admin inlines in Django [64]. This allows for one-page populating of the quiz name, category name, question test, answers text, and answer weighting. Figure 3 is a screenshot of nest_admin's functionality.

### B.1.3 xhtml2pdf

This is a library that allows a user to format an html file for rendering a pdf [65]. Since Django projects are online and use html templates for rendering the webpage, this simplified the process of formatting and rendering a pdf.

### B.1.4 pytest and pytest-django

These two libraries are paired together because Django has existing testing functionality that needs replicated in pytest. Pytest-django provides the replication, allowing for pytest use in Django [66]. Pytest is a package that makes testing in python straightforward [67].

## B.2 Functionality

Current functionality of *django-quiz* allows for complete control over the creation of a quiz. When using the csv upload for quiz creation, quizzes are automatically activated for participant access. Participants can view the quiz index to see the active quizzes and can look at the details of a quiz. Once the participant has decided which quiz to take, they click “Take Quiz” on the quiz index page. This starts a new session for the quiz and will load the first question of the first category. The participant can then navigate through the quiz, answering one question at a time. When the participant has answered all the questions, the initial feedback page will load. This is a cached page that renders the feedback for the two lowest scoring categories. Clicking “Get full Feedback Report” will load a cached PDF of all feedback for that participant’s quiz session. The following sections will follow this process in more detail.

### B.2.1 Superuser Functionality

After the user sets up their Django project and installs *django-quiz* and its dependencies, they can login at the admin panel. Once logged in, the user can navigate to the csv upload page by adding “upload-csv/” to the end of the base URL. In this case, the base URL is our local server 127.0.0.1:8000/ - if the app is hosted on public server the base URL will be different.

From here, the user can browse their computer for the csv of the quiz they wish to create. When they have selected their file, click upload. This page will catch if the file is not a csv and will ask for the correct filetype. If the csv is not formatted properly, the page will stop the quiz creation process and will ask the user to check the csv format. The page will reload with a message telling the user the if the upload is successful. Quizzes created via csv are automatically marked active and ready for participants.

### B.2.2 Participant Functionality

Starting at the quiz index, participants can browse and look at the details of each quiz build. The details page lists the quiz name, the description, all the quiz categories, and the questions belonging to those categories. This functionality is designed with the idea that *django-quiz* user may have multiple quiz builds relating to a single subject. The details page allows participants to look at each quiz and decide which they want to take.

After selecting "Take Quiz," *django-quiz* will start a new quiz session and page through the quiz question by question. If a participant tries to go to the next question before selecting an answer, the page reloads and displays a message reminding the participant to select an answer.

Once the participant has answered all the questions, *django-quiz* compiles all the answers and fetches the appropriate feedback. The initial feedback page is cached for 15 minutes. The caching time can be changed in the code, but future updates will make this available to change on the admin panel.

The feedback page displays the two lowest scoring sections, and only displays feedback for the answers with feedback. This means if the superuser enters "No Feedback" as the feedback answer, then nothing will render on the feedback page.

Selecting "Get Complete Feedback Report" tells *django-quiz* to render a PDF of the participant's feedback. This page is cached for an hour, but the PDF can be downloaded immediately. The feedback report provides a complete breakdown of the quiz. The top of the page has the scores for each category, which are displayed with each question, the answers selected, and the feedback. If "No Feedback" was entered for the answer, then the feedback report will render "No feedback for this question."

## B.3 Setting up *django-quiz* for your Django project

These instructions assume you do not have an existing Django project. If you do, skip step 1.

1. After installing Django, create a project. For more information on installing Django, visit the project's GitHub for detailed instructions CITE. In your command line run:

```
django-admin startproject project name
```

   You can substitute *project name* with whatever you want the project to be called.

2. Now navigate to the django-quiz folder and install the requirements. This command should ensure all the libraries you need for this project are installed.:

```
pip install -r requirements.txt
```

3. Also run:

```
python setup.py install
```

4. Then add *'quizzes'* and *'nested_admin'*, to your *INSTALLED_APPS* in the `settings.py` file.

5. Add the following to your project's `urls.py file`:

```
from django.contrib import admin
from django.urls import path, include
from quizzes.views import quiz\_upload

urlpatterns = [
    path('quizzes/', include('quizzes.urls')),
    path('admin/', admin.site.urls),
path('nested\_admin/', include('nested\_admin.urls')),
path('upload-csv/', quiz\_upload, name="quiz\_upload"),
]
```

   You can substitute *'quizzes'* to whatever you want the base quiz url to be named.

6. Now, navigate back to your project directory. Make your migrations and migrate your data with:

```
python manage.py makemigrations
```

and

```
python manage.py migrate
```

7. If you have not done so already, create a superuser to access the admin site:

```
python manage.py createsuperuser
```

8. You can now run your local server to start the Django app:

```
python manage.py runserver
```

Visit *127.0.0.1:8000/admin* to log-in and see the admin panel. After following the csv formatting instructions in below, visit *127.0.0.1:8000/upload-csv* to upload your quiz build csv. If you receive an error trying to access *127.0.0.1:8000/upload-csv*, your admin session expired – so you will need to login again.

## B.4 Generating a quiz with a csv

1. To create a test csv open TextEdit, Notepad, or your text editor of choice.

2. On the first line type copy and paste the following:

```
QUIZ NAME,YYYY-MM-DD,DESCRIPTION OF QUIZ
```

Replacing *QUIZ NAME* with the name of your quiz, the date field with the date, and *DESCRIPTION OF QUIZ* with brief description of your quiz. If you plan on using a comma in the description, use the quote character | around the entire description.

3. The rest of the csv is formatted as follows:

```
QUIZ NAME,CATEGORY 1 NAME,QUESTION 1 TEXT,ANSWER 1 TEXT,ANSWER WEIGHT,FEEDBACK TEXT FOR ANSWER 1\\
QUIZ NAME,CATEGORY 1 NAME,QUESTION 1 TEXT,ANSWER 2 TEXT,ANSWER WEIGHT,FEEDBACK TEXT FOR ANSWER 2\\
QUIZ NAME,CATEGORY 1 NAME ,QUESTION 1 TEXT,ANSWER 3 TEXT,ANSWER WEIGHT,FEEDBACK TEXT FOR ANSWER 3\\
```

Questions can have as many answers as you want. If you do not want feedback for an answer, type "No Feedback." Currently weighting should be on a scale of zero to one, with one being the best answer and zero being the worst.

When formatting the csv file, if you plan on using commas for the text of questions/answers/feedback, you must surround the text with the quote character | around the text for said question/answer/feedback. *It is also important to note that current functionality requires all questions to have unique answers in a quiz.* This bug will be addressed in a future update.

Template and example csv files can be found on the GitHub repository [57].