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WaveSPARC: Evaluation of Innovation Techniques for Wave Energy

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Abstract— **The Wave Systematic Process and Analysis for Reaching Commercialization (WaveSPARC) project aims to deliver "seed concepts" of high-confidence and high-performance in wave energy conversion. The intention is that these seed concepts will subsequently undergo industrial development to full commercial application and economic viability. The activities in the WaveSPARC project include Invention, assessment, identification, verification and validation of novel and high techno-economic-potential WEC technology concepts.**

The WaveSPARC project has via Structured Innovation derived several new ideas for WEC concepts. The concepts have been evaluated using a TPL assessment methodology developed as part of the project. At this stage several new ideas for WEC concepts have been derived. When the concept development has reached the desired high TPL score models will be build and tested in model scale.

This paper provides a critical review of the Innovation process used. The initial approach includes a specification of requirements for the WEC, selection of critical sub functions and then using the inventive technique TRIZ to find new and innovative sub function solutions combined into a new WEC designs.

Keywords: **WEC, Innovation, TRIZ, WaveSPARC**

I. Introduction

THIS paper gives an overview of the application of TRIZ tools to date in the WaveSPARC project and a discussion of future tools that have either been identified as holding promise for use in future phases of the project or have been considered and discounted.

At this phase of writing:

- a substantial Systems Engineering effort has been completed,
- the TPL assessment has been revised,
- the TRIZ methodology has been applied to the wave energy design problem in three different approaches, and
- several proposals for improved application of TRIZ and other design processes have been formulated.
- several alternative design processes and innovation toolboxes have been considered for relative strengths and/or complementarity to TRIZ.

In the context of the above this document summarises the status of the project with respect to use of invention/design methodologies learnings of this initial approach will be described.

II. Historical context

Over the years many WECs have been proposed and significant effort been expended to determine which WEC concept is better than the others. The first systematic exploration of wave energy was the UK Wave energy program, in 1973–1979, during this program several WECs were proposed and the cost of energy from a 2000MW wave power plant was calculated based on numerical or experimental results.

The range of wave energy devices has always been very large and there is still no clear consensus on which systems are likely to prove successful. Even within the generic sub-systems there is still a wide diversity of designs and ideas i.e. of methods of power take off and station keeping. This is to a greater part a result of the inventiveness of wave energy device designers. Understandably, each designer is a champion for their own technology and usually wants to push their technology through to the prototype stage as soon as possible. This results in a wide variety of devices being tested at large scale within a very limited budget. This way forward is very inefficient (high risk) and other methods of proceeding should be looked at, e.g. the Danish Wave Energy program [2] which excluded many devices at the laboratory-scale testing stage based on quantification of some simple parameters and an agreed methodology for testing and development. The pioneer of wave energy, Stephen Salter, put it this way [3]:

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"You need to have a transparent method of assessing the designs….. That is the first step. I think the second step is, you must do very good model testing and computer modelling, the computers are getting very good at predicting the way things behave in waves, they are much better than they were just a few years ago. So, I would like to see rigorous model tests and computer tests and spread sheets for cost prediction. We need also to get a more precise way of working out what things cost. Much of that information is a commercial secret.... We need to find ways of getting that information, to optimize the designs. Then you can then make really very good decisions. If this data is done well enough and presented well enough and clearly enough, in a uniform way, I think you can then make much more rapid progress than by building bigger devices and testing them at sea, with the risk that you may have overlooked something."

The above experience and observations agree with the views of the authors and are typical of well-reasoned reflections on commercial wave energy development efforts to date. The Wave SPARC project is motivated to address these problems and to develop alternative approaches, specifically the Technology Performance Level (TPL) approach to assessment and the structured innovation approach to concept initiation.

III. Application of TRIZ to WEC Innovation

To date the WaveSPARC project has applied TRIZ techniques to the wave energy innovation challenge using two approaches and a third approach is in preparation for application in 2019 Q3. Each of the approaches has sought to build on the comprehensive stakeholder requirements analysis material developed in the Systems Engineering exercise undertaken by the WaveSPARC team in 2016 & 2017. We believe that this Systems Engineering exercise is the most comprehensive requirements analysis ever completed for wave energy. Each of the approaches also seeks to build on the experience gained in the earlier approaches. This section will present a summary of the methodologies and the perceived strengths and weaknesses of these three approaches to applying TRIZ to wave energy.

A. Approach 1

This approach sought to apply the TRIZ contradictions matrix in a comprehensive way to a selected subset of the sub-functions identified using Systems Engineering.

Methodology

- Requirements specification (System Engineering effort & Functional Requirements)
- Selection of multiple critical and high innovation potential sub-functions
- Apply TRIZ to selected sub-functions to invent solutions
- Assess the subfunction solutions and down-select through TPL assessment
- Check for possible combinations of solutions for different subfunctions to compose novel concept
- Identify multiple system concepts
- Evaluate and down-select system concepts through TPL assessment for further development

1) Pros

- Very comprehensive requirements specifications & analysis exercise completed
- Direct application of TRIZ to find solutions to contradictions
- Intended to deliver a rich variety of sub-function solutions with possibility to cross-combine these to form new concepts
- High quality sub function solutions were produced using this methodology

2) Cons

- Several sub function solutions are not compatible (e.g. hinged barge + pneumatic PTO)
- When multiple sub-functions are considered the dimensions of the problem search space are enormous and direct application of formal tools to multiple sub-functions is very resource intensive
- Due to the resource intensive nature of the larger problem, despite generating high quality sub-function solutions, combining sub-function solutions was not achieved using this methodology.

3) Conclusion

While this approach generated useful outputs, our experience was that the overall large dimensions of the problem made the complete application of this methodology very resource and time consuming and based on this experience a more targeted approach was sought. Experience with this Approach 1 led us to formulate Approach 2 detailed below.

B. Approach 2

This approach sought to apply the TRIZ contradictions matrix in a more targeted way than approach 1.

1) Methodology

- Requirements specification
- Select multiple critical sub-functions
- Rank selected critical sub-functions in terms of potential for impactful innovation
- Apply TRIZ to the highest ranked sub-function (Primary sub-function)
- Assess these subfunction solutions and down-select through TPL assessment
- Take a high-potential solution to Primary sub-function and expand the focus of the innovation to include another sub-function (Secondary sub-function)
- Apply TRIZ to the Secondary subfunction extending the priority subfunction solution with multiple secondary subfunction solutions (In this case the Secondary subfunction is directly tailored to the Primary subfunction solution therefore avoiding problems due to the large design space)

• Evaluate combined primary and secondary subfunctions solutions and down-select through TPL assessment for further TRIZ application and development

• Proceed with added subfunction solution innovations until WEC system concept is complete

• Evaluate combined, complete system solutions and down-select through TPL assessment for further development

2) Pros

• Secondary sub-function solutions are tailored to be combinable with the Primary sub-function solution.

• The problems relating to the very large design space are avoided and the TRIZ tools are applied to manageable numbers of design candidates or solutions.

• High quality concepts were produced using this methodology

3) Cons

• Design space is partitioned to exclude infeasible solution combinations, but this may also exclude some feasible solutions. This is a necessary consequence of reducing the design space.

4) Conclusion

Useful outputs were generated using this approach. In addition, further insights into the nature of the wave energy design problem were gained through the application of TRIZ tools within this methodology. In applying TRIZ contradiction matrix to the Primary-Secondary sub-function combinations we observed that the contradictions are not universal. (See section "Contradictions" below for more info on contradictions). Contradictions that are relevant to a sub-function in the context of one solution may not be relevant in the context of another solution. This insight leads to suggestions for refined methodologies, below in Approach 3 and also in the next section on "Additional uses of TRIZ tools".

C. Approach 3

This approach is designed to take advantage of the observations made in the previous approach of the properties of the wave energy design space with respect to the TRIZ tools especially the contradiction matrix.

Methodology

• Scan existing WEC technology design space and Identify promising high potential WEC technology concept classes/architypes

• Down-select to most promising concepts through TPL assessment

• Identify the core weaknesses of these concepts

• Apply TRIZ to the weaknesses of these concepts in order to Improve these concepts their class OR Invent novel WEC classes the solving, dissolving of the key contradictions

• It has been shown in our work that the power of TRIZ offers the capability to breakout of an archetype by solving the weakness through breaking a contradiction and either jumping to another archetype or inventing potentially superior new archetypes

• Evaluate combined, complete system solutions and down-select through TPL assessment

1) Pros

• Uses available material & stock of WECs

• High likelihood of avoiding re-inventing existing concepts

2) Cons

• Does not start from a clean sheet therefore may have reduced freedom for achieving novelty (although this is debatable, the opposite is also arguably true).

IV. Additional uses of TRIZ tools

During the Wave SPARC project, we have applied TRIZ intensively to the wave energy innovation challenge. This section will detail the TRIZ techniques that we have not yet used but nevertheless have identified as holding potential relevant to the wave energy problem.

Overall TRIZ is a very suitable technique for the wave energy innovation challenge. Fig. 1 and Fig. 2 give graphical summaries of two of the essential properties of the TRIZ methodology. Fig. 1 represents the ability of TRIZ to offer a lens to view all problems in terms of generalized conceptual problems with well-known generalized conceptual solutions that can be used to assist arriving at solutions to specific real-world problems.

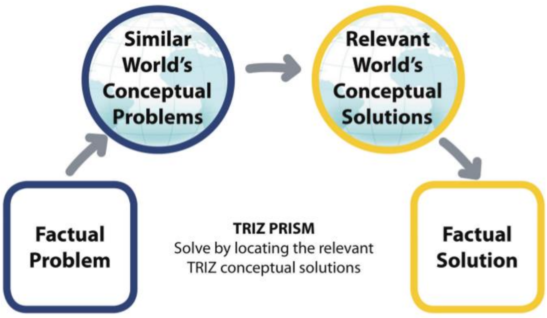

Fig 1. TRIZ. Left, conceptualizing lens.

Fig. 2 shows the distribution of inventions across five levels of increasing difficulty of invention, all levels can benefit from TRIZ but problems in levels 1 & 2 are usually solved by brainstorming without TRIZ, the TRIZ methodology offers the strongest advantages in the higher levels but especially level 3 & 4 [1]. It is apparent to the Wave SPARC team that initiation of wave energy concepts is not a level 1 or level 2 activity and is level 3 or 4 and maybe level 5.

In addition, our experience to date with using TRIZ reassures us that the procedures and processes that TRIZ encourages are productive. More specifically, besides the innovative outputs produced to date there are two observations that give a very high degree of confidence in the effectiveness of TRIZ and motivate us to pursue use of the additional aspects of TRIZ that we have not used to date. These are, firstly, TRIZ activities to date have led us to produce chains of reasoning that we recognise as familiar "fertile ground" in terms of the teams experience of solving problems in past projects (some in other sectors).

And secondly, that following the TRIZ methodology has led us to systematically "rediscover" old inventions and existing classes of wave energy devices. These points give us confidence is finding new high potential innovations and give us motivation to apply the TRIZ tools described below that have not been applied to date.

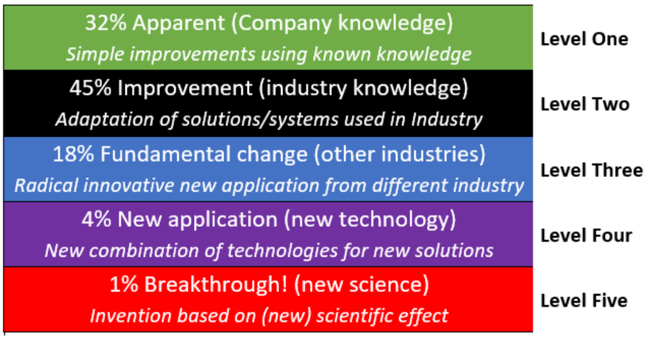

Fig 2. The 5 levels of Innovation.

Specific TRIZ techniques that we would use in the coming phases of WaveSPARC are:

- Innovation checklist
- "Ideality" & the ideal WEC

In addition to these standard TRIZ tools work to date has allowed us to identify several unique characteristics of the wave energy innovation problem and design space. These insights present opportunities for adaptation of the TRIZ innovation disciplines and practices to the application area. These are:

- Tailoring the TRIZ tools to the multi-architype nature of the wave energy design space.
- Special treatment of high number of "must have" WEC requirements identified in [4].

D. Innovation checklist

The innovation checklist is a structured approach that allows the actual state of a problem to be captured in a standardized manner. The technique also aims to generate some initial ideas through analytical thinking. The Innovation Checklist documents the physical system and how it is connected to its environment. Reference [2] described the Innovation Checklist procedure in detail. The Technology Performance Level and Systems Engineering work completed to date in the Wave SPARC project significantly overlap with the suggested scope and procedure for an Innovation Checklist, the following description focuses on the benefits of undertaking the additional work needed to complete an Innovation Checklist.

Both the TPL assessment system with imbedded metrics and the Systems Engineering (SE) documents are directly concerned with identifying the stakeholder requirements and the ability of system to meet these requirements. The TRIZ Innovation Checklist allows a broader view of the problem in several key areas and therefore may lead to insights to the problem that did not arise from the TPL and SE exercises.

TABLE I
TRIZ INNOVATION CHECKLIST, ADAPTED FROM [3]

1. Information about the system
1.1. System designation
1.2. Primary useful function of the system
1.3. Current or desirable system structure
1.4. Mode of operation of the system
1.5. System environment
2. Available resources
3. Information about the problem situation
3.1. Sought improvement of the system
3.2. Mechanism or mode of the dis-advantage
3.3. History of evolution of the problem
3.4. Other problems to be solved
4. Modification of the system
4.1. Permitted modifications
4.2. Limits of system modification
5. Selection criteria for solution concepts
5.1. Sought technical properties
5.2. Sought economic properties
5.3. Sought time schedule
5.4. Expected innovative features
5.5. Other selection criteria
6. History of solution attempts
6.1. Previous attempts to solve the problem
6.2. Other systems with a similar problem

The suggested activities in an Innovation Checklist are summarized in Table 1. There are two principle areas in the checklist that are not fully included in the TPL and SE work to date. These are firstly point 2.0 and (partly) 1.5 and secondly points 3.3, 6.1 & 6.2.

Points 2 and 1.5 relate to the environment and Resources. In the current TPL and SE work the environment is primarily considered in so far as it supplies a) wave energy to be captured b) extreme events to be survived and d) acceptability. In the TRIZ meaning of Resources the environment supplies many other ostensibly banal but potentially crucial things (for example, air, water, buoyancy, heat, temperature, inertia and many other material or phenomenological properties) that may play a role, weather subtle or not, in the invention or functioning of new concepts. Analysis of Resources is a key principle of TRIZ and additional work in this area may be very fruitful for Wave SPARC.

Points 3.3, 6.1 & 6.2 relate to the history of the application area in terms of evolution of the problem and solution attempts as well as history of other similar problems in other sectors of the economy. The SE and TPL work to date do not cover these activities and there is likely to be some beneficial insights in analysing the strengths, weaknesses and trends in past wave energy innovations as well as seeking parallel efforts in other sectors.

Overall, we propose that following the full Innovation Checklist as a formal activity will be beneficial and complimentary to the work completed to date and will be undertaken before FY19 Q3.

E. "Ideality" & the ideal WEC

A TRIZ technique to help uncover/clarify the true system requirements is to describe an Ideal Outcome. This TRIZ technique also helps to uncover/clarify the contradictions that make real world system less than ideal. The TRIZ approach holds that constraints/ contradictions/ costs/ harms are rendered irrelevant when describing ideal outcomes.

Describing an Ideal Outcome allows us to temporarily ignore or switch off the constraints, harms and costs. This approach allows us to clearly define Requirements where Constraints or concerns about Harms/Costs might have been blocking clarity about the Ideals or Requirements. For example, rejecting a perfect solution because it is impossible might prevent us from identifying a similar and nearly perfect solution that is in fact possible. The intention, therefore, in using this approach is to use descriptions of impossible idealised solutions, firstly, to identify real world practical solutions with nearly ideal properties and secondly to identify more precisely the reasons why existing solutions are not ideal or why ideal solutions are not possible. Identifying both these Ideal but impossible and related real and possible solutions contributes to the Requirements clarification and to the stock of potential partial solutions.

According to [1], conceptually, if the Ideal system is visualized as a mountain peak and the current system to be improved is visualized as a base camp then the best real-world practical system is on the mountain between base camp and the ideal summit and:

- If we start with the system we've got then we must "hike up" to the real system that we want.
- If we start with the ideal system then we can "ski down" to the real system that we want.

According to [3] the hypothesis of ideality serves:

- as a vision of an ideal end-state in which all contradictions are resolved,
- for comparison of solution ideas,
- for assessing the further development of technical systems and determining which directions should be taken in working on system improvements, not only for incremental but also for radical progress or discontinuous respectively disruptive innovations.

In addition, the description of ideality is an abstraction and is complimentary to the TRIZ lens Fig.1 and supports the use of TRIZ tools for structured and oriented search for solution ideas.

The work to date in the Wave SPARC project on TPL, Systems Engineering and the "Contradictions Matrix" are significantly overlapping with the ideality concept described in this section. Nevertheless, there is reason to believe that a dedicated effort in this area, possibly in conjunction with the work described in the next section, will yield positive results and will contribute to the Wave SPARC goals.

F. Special treatment of multi archetype design space

An outcome of the WaveSPARC work to date is recognition of the multi-archetype nature of the wave energy design space. This characteristic is evident in the diversity of concepts in the wave energy patent records and is most likely a result of the genuine complexity of the physical phenomena in water waves and in wave-body interactions.

Contradictions or conflicts are a key concept in TRIZ and much of the power and utility of TRIZ is derived from providing mechanisms for elimination of these contradictions and conflicts. This is the difference between optimization and innovation, while optimization will seek the *least bad compromise* due to a contradiction, innovation will seek to avoid compromise by removing the contradiction.

A challenge, that we have encountered in the Wave SPARC work to date, in applying TRIZ tools to wave energy is that different contradictions apply to different wave energy design archetypes. For example, a heaving WEC often embodies contradictions related to a hydrostatic stiffness that is too high, while a surging WEC often embodies contradictions related to a hydrostatic stiffness that is too low. The requirements and contradictions apply differently to different modes of oscillation, differently to surface piercing and subsurface bodies, differently to rigid bodies and to flexible bodies, differently to thin geometries compared to bluff bodies and differently to different types of reaction frame (single-body/multi-body/absolute-reference/internal-mass/OWC). Due to the nature of Froude scaling laws the contradictions related to resonance and bandwidth, which are of key importance, also apply differently at different scales.

We have designed a workplan to take advantage of this multi-archetype nature of the wave energy innovation challenge. The intention is to exploit the newly identified structure of the design space to gain new insights into which options are the most promising. We think it is possible to develop more detailed or more precise contradictions that are relevant to any given subset of the archetypes. We have identified a list of 48 "starting points" for wave energy converter designs. These are enumerated by considering power absorption in the 6 modes of motion and 8 design options generated by permutations of three selected design alternatives. The design alternatives considered are: Surface-piercing/subsurface, Self-reacting/bottom-reacting, Rigid/ Flexible.

It is important to mention that the application of TRIZ in the Structured Innovation/Wave-SPARC project has shown that the solution of contradictions of a specific WEC archetype through the application of TRIZ inventive principles can lead to new archetypes. That TRIZ not only offers the potential to improve a WEC concept within an archetype but TRIZ generated improvements can also lead to a transformation or jump from one archetype to another including innovation of new archetypes.

G. Special treatment of must have requirements

The requirements as captured in the Wave SPARC Systems Engineering exercise already completed [4] has generated very many "must have" requirements. Arguably all these requirements equally merit assessment and verification in the TPL assessment. However, not all of these requirements merit equal priority in the structured innovation activities. This reality has been implicit in the application of the TRIZ contradiction matrix in Wave SPARC work to date. This work focused on the numbered function F1.1.1 "Capture wave energy" (See [4] p30) and some interacting functions while deferring consideration of many other requirements/functions/capabilities. This selectivity is necessary to make progress because a side effect of the volume of requirements and level of detail produced by the Systems Engineering effort is that it tends to hide or "crowd out" the areas that need real innovation. A reflection on progress to date is that some functions that hold high innovation potential has been identified but a deeper search remains, with a more explicit and formal exploration of how unequally allocated innovation focus on the many must have requirements will be beneficial.

V. Alternative Invention Methodologies

The WaveSPARC project has heavily invested in development of the Technology Performance Level (TPL) assessment metric and in combining the TPL with Systems Engineering approaches. Furthermore, the Wave SPARC project has committed to using structured innovation techniques in general and TRIZ with reference to TPL scoring as an assessment methodology. This section of the report will present other methods of structured innovation and a commentary on their comparison and complementarities with TRIZ and/or TPL. Some of these methods are selected as possibly beneficial to Wave SPARC while others are found to be either less comprehensive or less powerful than the methods that are already in use. Some of the comparisons between these other methods presented and the methods already selected for Wave SPARC explain the status given to TRIZ within the Wave SPARC project.

H. Overview

Most systems for promotion or management of invention, design or innovation typically combine processes like:

a) Requirements capture/analysis
b) Solution/concept generation
c) Solution assessment/ranking/selection

Many systematized approaches exist to assist in these steps, many of these are focused on requirements analysis (Systems Engineering, Axiomatic design, Quality Function Deployment, Morphological analysis) still more are focused on solution assessment and ranking (design matrices, decision matrices, Pugh matrices, trade study tools, set based design) however relatively few systematized approaches are focused on solution or concept generation. Most, if not all, concept generation approaches are closely related to either Brainstorming or TRIZ.

There are some commonalities between Brainstorming and TRIZ, primarily that premature selection of solutions is strongly discouraged in both methodologies. In Brainstorming ideas must not be criticized too harshly too early, participants must not "strangle the new-born", while in TRIZ ideas must not be prematurely selected, participants must treat all their ideas as "ugly babies" and continue to develop more alternatives. Nested within the commonality is a diametric opposite, Brainstorming expects to generate low value ideas and the discipline needed is to keep them alive while TRIZ expects to generate high value ideas and the discipline needed is to avoid calling off the search too early.

I. Contradictions

To understand structured innovation, it is important to understand the concept of contradiction. At the heart of every difficult problem are one or more contradictions, these contradictions are what make the problem difficult. Without contradictions an invention challenge or design problem is simply a matter of defining requirements and ticking these off a check list for each solution and ranking solutions if more than one meets all requirements. Many design and invention methodologies are written as if this simplistic contradiction free view is realistic. Examples of contradictions include; a component needs to be very strong and very light; two components need to be in the same place at the same time; a component needs to be rigid/heavy/impermeable for one requirement and simultaneously elastic/light/permeable for another requirement. Most challenges have contradictions of one type or another. Most innovation methodologies or design processes do not address these contradictions and leave them undocumented and implicit. In these cases, good solutions are still eventually found by Brainstorming or by individual talent and the innovation methodology or design process is useful in the steps leading up to and after invention but not during the inventive step.

While brainstorming is structured and systematic in the way that ideas are captured and in how the brainstorming rules are applied, it is specifically unstructured in how new ideas are generated and in how participants are encouraged to think. In this sense brainstorming is the opposite of structured innovation. Crucially Brainstorming does not address contradiction.

While contradictions are what make difficult problems difficult, thinking about contradictions also stimulates creative solutions. Michael Michalko, author of Thinkertoys: Handbook of Creative Thinking Techniques says "It appears that thinking in terms of contradictions and paradoxes triggers creativity… and creates the conditions for a new point of view to bubble free from your mind." [5].

TRIZ, and its offshoots, are the only methods that we have discovered so far in the Wave SPARC project that directly address contradictions and provide a series of tools for exploring, unpicking and resolving contradictions. Consideration of contradictions is a key background to our reflections on some of the alternative invention and design methodologies included below.

J. Decision-matrix method

The decision-matrix method, or Pugh Concept Selection, is a qualitative technique used to rank the multi-dimensional options of an option set. A basic decision matrix consists of establishing a set of criteria options which are scored and summed to gain a total score which can then be ranked. Importantly, it is not weighted to allow a quick selection process.

A weighted decision matrix operates in the same way as the basic decision matrix but introduces the concept of weighting the criteria in order of importance. The resultant scores better reflect the importance to the decision maker of the criteria involved. The more important the criteria the higher the weighting it should be given. Each of the potential options are scored and multiplied by the weighting given to each of the criteria to produce a result.

The advantage of the decision-making matrix is that subjective opinions about one alternative versus another can be made objective. Another advantage of this method is that sensitivity studies can be performed. An example of this might be to see how much your opinion would have to change for a lower ranked alternative to outrank a competing alternative.

In the context of the Wave SPARC project the Pugh matrix or decision matrix is a very general-purpose tool that is significantly overlapping with the TPL scoring tool which has been specially developed by the Wave SPARC project for assessing and ranking wave energy innovations. The project team have developed a new TPL scoring spreadsheet with, not only weightings, but also threshold values and a methodology for combining scores that reflects the impact of each sub-category on the cost of wave energy. We do not anticipate that a general-purpose approach will be more applicable than the purpose designed TPL scoring spreadsheet.

K. Quality Function Deployment (QFD)

Quality Function Deployment (QFD) is a structured approach defining requirements and translating them into specific plans to produce products to meet those needs. The “voice of the customer” is the term to describe these stated and unstated customer needs or requirements.

In 1976, the Union of Japanese Scientists and Engineers (JUSE) saw the need for tools to promote innovation, communicate information and successfully plan major projects. A team researched and developed the seven new quality control tools, often called the seven management and planning (MP) tools, or simply the seven management tools. Not all the tools were new, but their collection and promotion were.

- Affinity Diagram: organizes many ideas into their natural relationships.
- Relations Diagram: shows cause-and-effect relationships and helps you analyze the natural links between different aspects of a complex situation.
- Tree Diagram: breaks down broad categories into finer and finer levels of detail, helping you move your thinking step by step from generalities to specifics. (For root–cause analysis: “What causes this?” or “Why does this happen?” this is used in TRIZ)
- Matrix Diagram: shows the relationship between two, three or four groups of information and can give information about the relationship, such as its strength, the roles played by various individuals, or measurements.
- Matrix Data Analysis: a complex mathematical technique for analyzing matrices, often replaced in this list by the similar prioritization matrix. One of the most rigorous, careful and time-consuming of decision-making tools, a prioritization matrix is an L-shaped matrix that uses pairwise comparisons of a list of options to a set of criteria to choose the best option(s).
- Arrow Diagram: shows the required order of tasks in a project or process, the best schedule for the entire project, and potential scheduling and resource problems and their solutions.
- Process Decision Program Chart (PDPC): systematically identifies what might go wrong in a plan under development.

In the context of the Wave SPARC project the QFD approach is significantly overlapping with the Systems Engineering exercise already completed. Within the market applications targeted we are confident that the stakeholder requirements have been thoroughly identified and analysed so there is no advantage in pursuing QFD in addition to the Systems Engineering work already completed.

L. Set-Based Design

Set based design is described in detail for design and concept selection in [8]:

“Designing a system can be viewed as establishing the values for a vector of design variables that define the design solution. In SBD the design solution emerges from systematically eliminating combinations of design variable values shown through analysis to NOT be a good solution. As rigorous analysis eliminates more and more of the solution space, feasible solutions become apparent. The first step in SBD is defining bounds for regions of the solution space. This can be either a bounding variable range, such as length or speed, or discrete states of design such as electric drive or traditional reduction gear driven vessel. Once the regions are established, different specialties explore trade-offs by designing/evaluating multiple alternatives within their domain. As the specialists explore the design alternatives they communicate their analysis-based preferences for different regions of the design space to the study integrators. The study integrators integrate the domain solutions produced and evaluated by specialists into total system solutions.”

Three principle concepts for implementing SBD [9] are:

1. consider many potential solutions
2. have specialists evaluate sets of solutions from their own perspective, and
3. intersect the sets to optimize a global solution and establish feasibility before commitment.

The optimization process can consider physical performance of a solution, as well as other attributes such as manufacturability and complexity of systems integration.

The SBD process does not focus on solution or idea generation specifically but rather on generation and evaluation of combinations of subsystems or partial solutions. It may be possible to combine some of the SBD processes with consideration of contradictions identified using the TRIZ tools and methodologies.

The SBD process is potentially complimentary to the TRIZ based methods that have been used to date in the Wave SPARC project. For example, graphical outputs, like those in reference [8], could be generated using the TPL scores already produced in the Wave SPARC project to better communicate the outputs of the project. The SBD process is also potentially complementary to analysis of the multi-architype nature of the design space already identified in the previous sections and potentially useful in analysis of the high number of “must have” requirements in wave energy is recognized and has been a key motivator in the early development of the TPL methodology

M. WSTAT

The Whole System Trades Analysis Tool (WSTAT) is a tool which supports the systems engineering technical management process of decision analysis by identifying compromises, revealing opportunities, while communicating the impacts of decisions across a system's development lifecycle.

“The data base of components Pareto optimality" is a formally defined concept used to determine when an allocation is optimal. An allocation is not Pareto optimal if there is an alternative allocation where improvements can be made to at least one participant's well-being without reducing any other participant's well-being. If there is a transfer that satisfies this condition, the reallocation is called a "Pareto improvement." When no further Pareto improvements are possible, the allocation is a "Pareto optimum."

The challenge that we anticipate in applying WSTAT to the wave energy innovation problem is that the input data is not available in enough detail or with sufficient independence between different types of data to allow the tool to be effective. The point about independence of data is critical, if data is not truly independent then decisions about combining different sub-systems or design choices in wave energy systems may invalidate data describing those elements, e.g. if the data was generated in test cases that rely on certain combinations of sub systems then the data will not be relevant for other combinations. Cost data and material data can be readily made independent but dynamic characteristics, survival characteristics and energy absorption performance, which is key to wave energy assessment, are much more difficult to make independent since several subsystems must work together to generate an estimate of energy absorption or other dynamic performance. We may nevertheless make a more detailed evaluation of suitability of this tool.

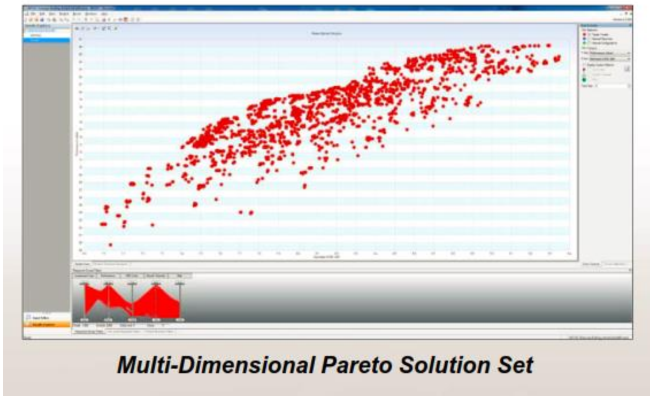

Figure 3. WSTAT Whole System Trades Analysis Tool.

I. CONCLUSION

The WaveSPARC project is systematically identifying innovative solutions to the conversion of Ocean Wave Energy as a sustainable power source.

Experience in wave energy development is that structured innovation techniques are necessary.

In this paper we have presented the TRIZ techniques used to date in the WaveSPARC project, together with the TRIZ techniques planned in the next stages of the project. In addition, several alternative approaches have been outlined and the compatibility and complementarity of these with TRIZ has been discussed.

In the past much, work in wave energy has relied on unstructured innovation leading to premature large-scale demonstration technologies. We aim to apply TRIZ and other complementary structured innovation tools to generate WEC concepts that are worthy of large-scale prototypes.

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