Advanced Design Tools for Ocean Energy Systems Innovation, Development and Deployment

Deliverable D3.2

Structured Innovation design tool – Alpha version

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EXECUTIVE SUMMARY

The Structured Innovation (SI) design tool forms part of the DTOceanPlus suite of second-generation open source design tools for ocean energy. The SI tool comprises innovation methodologies which can enhance concept creation and selection in ocean energy systems (including sub-systems, energy capture devices and arrays), enabling a structured approach to address complex ocean energy engineering challenges where design options are numerous, and thus it can facilitate efficient evolution from concept to commercialisation.

Deliverable D3.2 "Structured Innovation design tool – Alpha version" of the DTOceanPlus project includes the details of the Structured Innovation design tool, and it represents the result of the work developed during task T3.2 of the project. The present document summarises both the functionalities and supporting theory, as well as the more technical aspects of the code implemented for this tool.

The Structured Innovation design tool within the DTOceanPlus suite is one of a kind beyond the current state-of-the-art, that will enable the transfer and adaptation of the QFD/TRIZ and FMEA methodologies (described below) to the ocean energy sector. For a sector such as ocean energy, where the number of design options is still very high, the open-source Structured Innovation design tool is needed to help users to understand the complexity and interdependencies of the engineering challenge – resulting in a more efficient evolution from concept to commercialisation.

- The Quality Function Deployment (QFD) methodology defines the innovation problem and identifies trade-offs in the system.
- The Theory of inventive problem solving (TRIZ), a systematic inventive problem-solving methodology, generates potential solutions to the often-contradictory requirements raised from the QFD.
- The output from the integrated QFD/TRIZ component comprises of design requirements along with target engineering metrics.
- The Failure Modes and Effects Analysis (FMEA) assesses the technical risks associated with the proposed design concepts.

The SI tool produces a set of metrics and assessments; a conflicts and impact report; and a design report. The metrics and assessments include both ideality (a measure of what might be theoretically possible to achieve) and development values (how difficult it would be to implement the selected solution), relevant to the benchmark assessments of ideal innovative concepts for wave and tidal renewable energy projects at different stages of development. The design report then includes requirements, specifications and gap analyses.

The SI tool can be used either as a standalone tool or within the framework of design tools of the DTOceanPlus project. It offers two main design modes, a new concept mode – to give an estimate of costs and performance at an early stage in the concept creation / design process, and an improvement cycle mode – for more detailed assessment of innovation within an existing device/project development path.

The Business Logic of the code, comprising of the functions of the SI tool, has been implemented in Python 3. An Application Programming Interface (API) was developed following the Open API specifications, in order to interact and communicate with the other modules of the DTOceanPlus design suite.

The Graphical User Interface (GUI) of the tool is developed in harmony with the other modules, in Vue.js, allowing the user to interact easily with the Structured Innovation design tool, inputting data and visualising results.

The Business Logic has been verified through the implementation of unit tests, guaranteeing easy maintainability for future developments of the tool. The preliminary tests and verifications performed are presented in this document.

Examples of the capabilities of the SI tool are included throughout the document.

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ABBREVIATIONS AND ACRONYMS

AD	Axiomatic Design
AEP	Annual Energy Production
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
API	Application Programming Interface
BS	British Standards
CAPEX	Capital Expenditure
CFD	Computational Fluid Dynamics software
CFP	Carbon Footprint
CFMEA	Concept-design Failure Modes and Effects Analysis
CSV	Comma Separated Values
DET	Detection
DOE	Design of Experiments
DOORS	Dynamic Object-Oriented Requirement System
EIA	Environmental Impact Assessment
ESA	Economic and Social Acceptance
ESC	Energy Systems Catapult
ET	Energy Transformation
ETI	Energy Technology Institute
FMA	Function Means Analysis
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Mode Effects and Criticality Analysis
GUI	Graphical User Interface
HoQ	House of Quality matrix
IFR	Ideal Final Results
IP	Intellectual Property
IRR	Internal Rate of Return
ISO	International Organization for Standardisation
KPI	Key Performance Indicator
LCOE	Levelised Cost of Energy
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
OCC	Occurrence
OEC	Offshore Energy Converter (aggregate term for WEC & TEC)
OEM	Original Equipment Manufacturer
OES	Ocean Energy Sector
OPEX	Operational Expenditure
PTO	Power Take-Off
QFD	Quality Function Deployment
R&D	Research and Development
RAMS	Reliability, Availability, Maintainability, Survivability
RC&M	Requirements Capture and Management
RPN	Risk Priority Number
SE	Systems Engineering
SEV	Severity
SPEY	System Performance and Energy Yield

SR	Stakeholder requirement
TEC	Tidal Energy Converter
TRIZ	*Teoriya Resheniya Izobretatelskikh Zadatch*, (theory of inventive problem solving)
TRL	Technology Readiness Level
TS	Technical Solution
UEDIN	University of Edinburgh
UI	User Interface
UML	Unified Modelling Language
VOC	Voice of the Customer
WEC	Wave Energy Converter
WES	Wave Energy Scotland
WP	Work Package

DEFINITION OF TERMS

Structured Innovation Methodology

A technique to stimulate rigour, organised and consistent innovative thinking, technology selection and impact assessment. This technique combines functions such as understanding the mission, the future vision, the market (including the potential for commercial exploitation, competition, differentiation, social value etc.) and the development of potential solutions. This is broadly described in British Standard BS7000-1, "Design Management Systems, Part 1 – Guide to Managing Innovation" amongst others. The methodology is in accordance with the concept shown in Figure 0.1

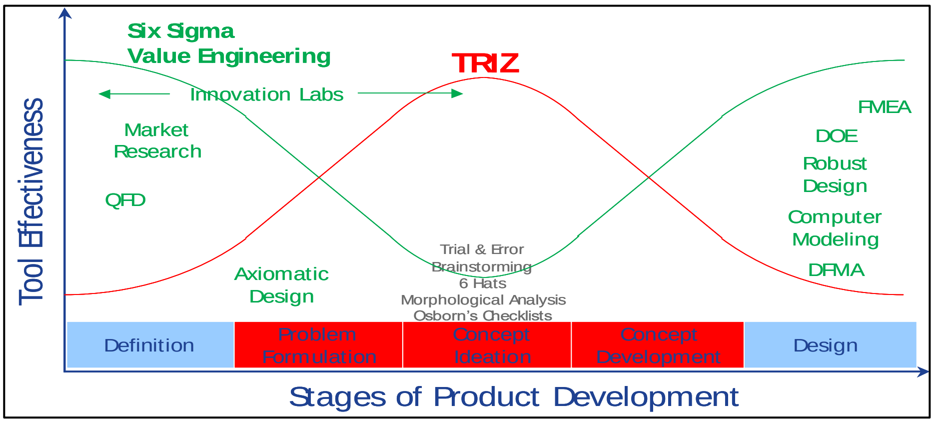

FIGURE 0.1: TOOL EFFECT VS PRODUCT DEVELOPMENT STAGE [1]

Quality Function Deployment (QFD)

A structured methodology used to identify, prioritise customers' requirements and translate them into suitable technical requirements for each stage of product development and production. It is achieved using the House of Quality (HoQ) which is a matrix used to describe the most important product or service attributes or qualities.

Theory of Inventive Problem (TRIZ)

A systematic problem-solving approach based on universal principles of creativity, patents, and research. The methodology looks to identify the generic concept problems and solutions, and to eliminate the technical and/or physical contradictions.

Failure Modes and Effects Analysis (FMEA)

A methodology used as a risk analysis and mitigation tool to improve development ventures. At concept and design phases, the concept or design FMEA mitigates risks associated with the various concept selections.

Customer requirements

Quality can be defined as meeting customer needs or requirements. These requirements, also known as 'the voice of customers,' are captured in a variety of ways such as customer specifications, surveys, interview.

Design parameters	The design parameters are technical characteristics or functional requirements defined to meet the customer requirements. These parameters are measurable, and meaningful, stated in such a way that particular solutions are implied.
Target values	The target values of the design parameters provide the quantitative technical specifications for these parameters to satisfy the customer requirements.
Ideality	Ideality is best defined as the aspirational State-of-the-art parametric values, that can drive innovation and identify opportunity, and newness relative to current capability. In other words, an ideal state of a system is a system where all its functions are achieved with no harm caused.
Functional fixedness	This is the cognitive bias that adults employ to understand quickly the operation of an object (for example, we might think of the 'natural' way of using a Smartphone, but might not consider using it as a hammer as a toddler might – even if this is not its intended use, there might be instances when its destruction is irrelevant compared to the gain).
Contradictions/ Conflicts	Contradictions occur between two or more features, with one feature to be improved, and the other worsened. An example of this could be: to generate more electricity, a bigger turbine might be required (improved features), but this will result in heavier machine, increasing its costs (worsened features).
Art-of-the-possible	These are values of ideal technology (ideal solutions beyond constraints-competing interests). The art-of-the-possible rather than the state-of-the-art takes into consideration the ideality of devices or processes only limited by physics (e.g., the Betz limit, yield strength) and extreme conditions to provoke new concepts
Occurrence	In FMEA, occurrence is defined a ranking number associated with the likelihood that the failure mode and related causes will be present in the function being considered
Severity	In FMEA, severity is the ranking associated to the extremely severe effect of failure modes.
Detection	The probability of detecting a failure before the effect is realised is determined by the current controls of the systems. Detection raking is associated with how likely a failure can be detected.
Risk Priority Number (RPN)	The RPN, the product of occurrence, severity, and detection rankings, is a measure used when assessing risks to help identify critical failure modes. Caution is required when assessing risks using RPN values.

1. INTRODUCTION

1.1 SCOPE AND OUTLINE OF THE REPORT

This report is deliverable D3.2 of the DTOceanPlus project, which provides details of the Structured Innovation (SI) design tool, and it presents the result of the work developed during tasks T3.1 and T3.2 of the project. This document serves as the technical manual of the alpha version of the SI tool, including the data requirements, main functions, interfaces and all the pertinent technical details. The alpha version of this tool is a fully functional version of the tool in terms of implementation of the calculations covered by the SI tool (Business Logic). However, it has limited functionality in terms of Application Programming Interface (API) since the other modules are still under development. The alpha version has incomplete functionality in terms of Graphic User Interface (GUI), and this will be further developed during the integration phase.

The remainder of this report is structured as follows:

- Supporting **concepts, definitions** and underlying assumptions behind the Structured Innovation tool is given in Chapter 2.
- **User groups**, **use cases** within the suite of tools, and **functionalities** of the Structured Innovation design tool are covered in Chapter 3, both for the new concept and improvement cycle modes.
- The actual **implementation** of the tool describing the architecture, business logic, API, GUI and some examples is described in Chapter 0.
- Finally, **future work** is discussed in Chapter 5

The Structured Innovation design tool is one of the newly added tools in DTOceanPlus, which were not present in DTOcean [1] to provide structured methodologies for concept creation and selection, as well as improvements to existing designs.

1.2 SUMMARY OF THE DTOCEANPLUS PROJECT

The Structured Innovation design tool belongs to the suite of tools "DTOceanPlus" developed within the EU-funded project DTOceanPlus [2]. DTOceanPlus aims to accelerate the commercialisation of the Ocean Energy sector by developing and demonstrating an open source suite of design tools for the selection, development, deployment and assessment of ocean energy systems (including sub-systems, energy capture devices and arrays) and at various levels of complexity (Early/Mid/Late stage).

At a high level, the suite of tools developed in DTOceanPlus will include:

- **Structured Innovation tool (SI)**, for concept creation, selection, and design.

- **Stage Gate tool (SG)**, using metrics to measure, assess and guide technology development.

- **Deployment tools**, supporting optimal device and array deployment:
  - Site Characterisation (SC): to characterise the site, including metocean, geotechnical, and environmental conditions.
  - Machine Characterisation (MC): to characterise the prime mover;
  - Energy Capture (EC): to characterise the device at an array level;
  - Energy Transformation (ET): to design PTO and control solutions;
  - Energy Delivery (ED): to design electrical and grid connection solutions;
  - Station Keeping (SK): to design moorings and foundations solutions;
  - Logistics and Marine Operations (LMO): to design logistical solutions and operation plans related to the installation, operation, maintenance, and decommissioning operations.

- **Assessment Tools**, to evaluate projects in terms of key parameters:
  - System Performance and Energy Yield (SPEY): to evaluate projects in terms of energy performance.
  - System Lifetime Costs (SLC): to evaluate projects from the economic perspective.
  - System Reliability, Availability, Maintainability, Survivability (RAMS): to evaluate the reliability aspects of a marine renewable energy project.
  - Environmental and Social Acceptance (ESA): to evaluate the environmental and social impacts of a given wave and tidal energy projects.

These will be supported by underlying common digital models and a global database, as shown in Figure 1.1.

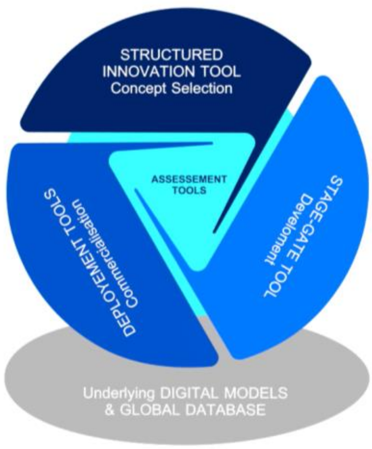

FIGURE 1.1: REPRESENTATION OF DTOCEANPLUS TOOLS

2. THEORY, DEFINITIONS AND ASSUMPTIONS

2.1 OVERVIEW

The Structured Innovation (SI) design tool is intended to provide the designer with a process, information, validated data, analysis, and comparative assessments, to generate new or improved concepts of a sub-system, device, or array. The process of using the SI tool provokes the designer to consider the interactions between technical solutions to a problem, and the necessary compromises that are required to meet the design intent or requirements, and the interactions with the competent person. In this context, the process needs to be carefully considered to avoid constraining opportunistic innovation and innovation that is created by systematic thinking. The tool aims to encourage the break-down of functional fixedness – a cognitive bias that is commonly employed to understand quickly the operation of an object. This fixedness, which impedes creativity or innovation, is countered by many features within the tool, including the TRIZ component.

The Structured Innovation design tool, is built upon three methodologies:

- Quality Function Deployment (QFD)
- Theory of Inventive Problem Solving (TRIZ)
- Failure Modes and Effects Analysis (FMEA).

The Quality Function Deployment module defines the innovation problem and identifies trade-offs in the system. TRIZ, a systematic inventive problem-solving module, generates potential solutions to the contradictions raised from the QFD requirements. The outcome from the QFD and TRIZ processes (which are combined into a single module) generates several design requirements along with target engineering metrics. The FMEA process (which is the second module) is used to assess the technical risks associated with the proposed design concepts. The following section 2.2 has been adapted from Deliverable D3.1 [3] and previous work [4].

2.2 CONCEPTS

The ability of a company to put forward an idea of a higher value can be a source of competitive advantage and represents the reason for which a customer may opt for one company to the disadvantage of another. Nowadays, most companies developing new products or services use a form of innovation process to identify, create, and develop innovative solutions, measure 'success' against their competitors and manage the uncertainties and risks associated with the implementation processes.

In Deliverable D3.1, an analysis of innovative best practices was described across a wide variety of sectors. Despite the positive impacts of structured innovation approaches across some of the mature sectors (e.g. automotive, aerospace), the application is less evident in the ocean energy sector [3]. Organisations such as Wave Energy Scotland, and the US-based National Renewable Energy Laboratory (NREL) and Sandia National Laboratories, use structured innovation approaches to identify and develop new wave energy converter concepts with high techno-economic performance potentials. From the horizon scanning of the various sectors in [3], it is seen that most sectors are benefiting from using one, or a hybrid of two, of the three QFD/TRIZ/FMEA methods to implement a structured innovation approach to their designs. Each methodology can be applied standalone. However, when applied together, the limitations of one methodology are overcome by the strength of the others (e.g. the QFD-TRIZ hybrid combination with customer-driven and innovation-driven design) [5] [6].

2.2.1 QUALITY FUNCTION DEPLOYMENT (QFD)

Developed in the late sixties in Japan, QFD is a structured methodology used to identify customers' requirements, prioritise them, and translate them into suitable technical requirements for each stage of product development and production [7]. This is achieved using the House of Quality (HoQ), which is a matrix used to describe the most crucial product or service attributes or qualities. The HoQ matrix is used to translate the customer needs into design characteristics using a relationship matrix and demonstrates the strength of the relationship between the customer needs (WHATs) and the design parameters (HOWs). This approach allows collaboration between the various teams and the ability to capture and visualise information in one place. The HoQ matrix is data-intensive and allows the team to capture a large amount of information in one place [4] [7].

2.2.1.1 Building a HoQ matrix

The HoQ matrix, as shown in Figure 2.1 overleaf, is built in consecutive steps by determining each of the following sections:

WHATs captures what the customer needs – the customer requirements. The identification of who the customers are is crucial to the deployment of the tool. This should include customers/stakeholders who are directly or indirectly involved or affected by the product/service. The requirements of the multitude of stakeholders could originate from market research, interviews, laws and regulations, contracts, operational concepts, site conditions, external interfaces and utilities, industrial codes and standards, operator needs, the public interest and other sources [4]. The WHATs are listed down the left-hand side of the HoQ matrix.

Importance – also known as priority, evaluates the importance of each of the customer needs relative to the others by generating a ranking scale.

HOWs – describes how to meet the customer' needs using design requirements, also known as technical solutions. These design requirements are translated from refining the customer requirements into parameters that can be achieved, measured, and with measurable target values. This shows how customer needs can derive from various sources (interview, regulations, and references) and are then refined to design requirements that provide parameters and information meaningful to and measurable by, a system [8]. The HOWs are listed across the top of the HoQ matrix.

The Roof of the HoQ (**HOW vs HOW**) – indicates how the design requirements interact with each other in synergy or conflicting with each other. Different studies use various rating scales to indicate the positive impacts and negative impacts of the correlations of one design requirement with another (e.g. strong positive interaction (++), strong negative interaction (--), no relationship (0 or -)).

Main Body (WHAT vs HOW) – provides a relationship and correlation matrix carried out to find out the relative importance of each parameter (HOW) against the customer requirement (WHAT) rankings.

HOW-MUCH – also known as target values or metrics, describes the ideal values of each of the design requirements. These can be used to trigger or provoke innovation. The competing solutions/products (whether in-house design alternatives or those of commercial competitors) can then also be assessed against these target values to determine whether and how closely each solution meets the target criteria and requirements.

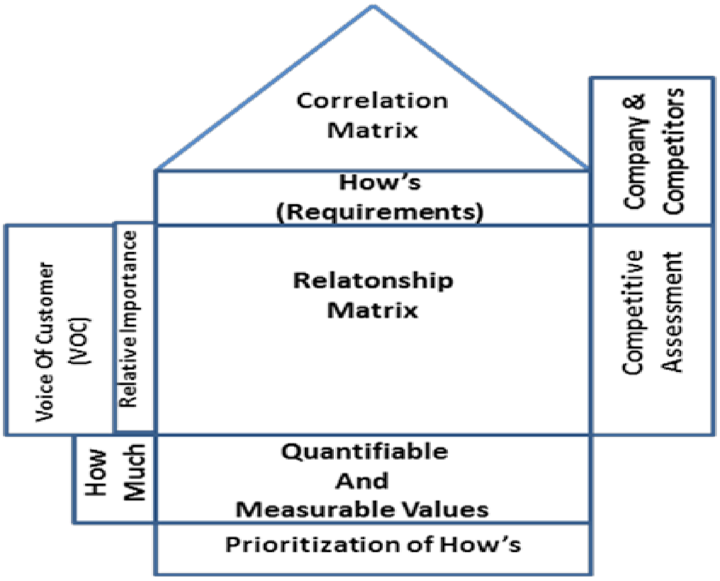

FIGURE 2.1: QUALITY FUNCTION DEPLOYMENT (HOUSE OF QUALITY) [9]

2.2.1.2 Phases of the House of Quality

The deployment of the QFD is a 4-phase process that uses the HoQ matrix to translate the stakeholder requirements into technical requirements. The technical requirements of the system of interest are then refined into specific requirements for the subsystems and components. The 4 phases, as illustrated in Figure 2.2, are:

- Phase-1, Design requirement phase: defines the stakeholder needs and translates them into high-level design requirements to meet the needs. This level is also known as Top-Level HoQ. It includes a competitive analysis against the state-of-the-art technologies or processes, as well as ideal target values against which to compare.

- Phase-2, Product or Part requirement phase: uses the technical requirements defined in the top-level HoQ as requirements that need to be met. These technical requirements are refined into product or part characteristics of the sub-systems.
- Phase-3, Process or Manufacturing phase: defines manufacturing or assembly requirements for the product or part characteristics defined in the HoQ phase-2.
- Phase-4, Production or Quality Control phase: identifies the critical elements of the subsystems or components and the specific requirements for production or deployment. This step could include inspection for quality assurance or condition testing.

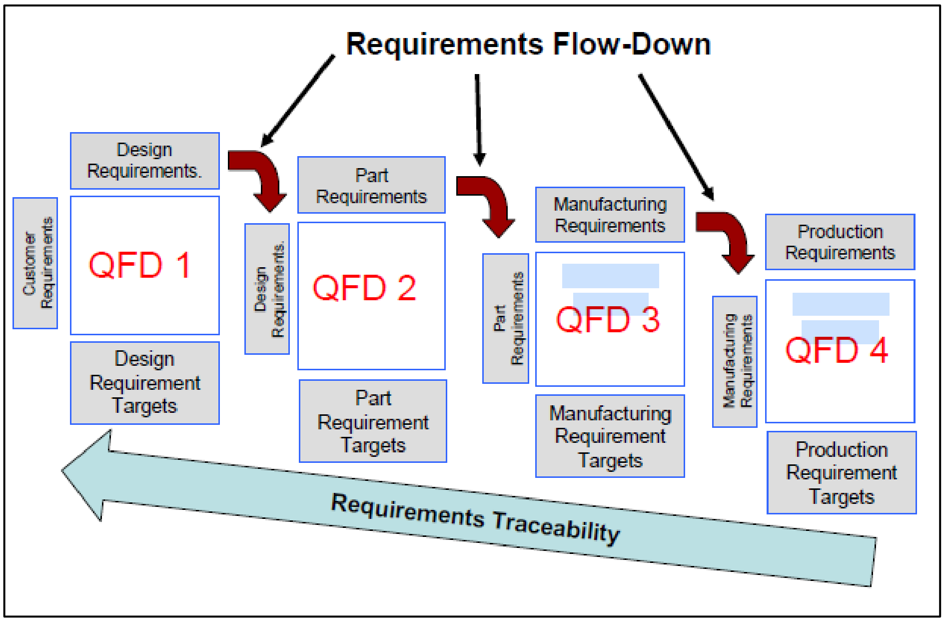

FIGURE 2.2: QFD 4-PHASES PROCESS [4]

2.2.1.3 QFD process within the SI tool

As highlighted in Figure 2.2, the QFD is a multi-level analysis that enables an experienced user to follow this process in each phase, in order to develop design requirements, to gain insight into conflicts and to propose innovative solutions, all of which in turn inform the next phase.

As the user refines their design or functional requirements into more detailed and specific requirements, the same QFD process is implemented as described in Section 2.2.1.1.

Within the Structured Innovation tool implemented in the DTOceanPlus suite of tools, the user carries out Phase-1 of the HoQ. Once the phase-1 analysis is complete, the user may then choose to take this to Phase-2 by starting a new study and transferring only the relevant impactful functional requirements from the Phase-1 analysis into the Phase-2 study. The same process may be implemented for all phases to Phase-4 with the relevant details.

2.2.2 THEORY OF INVENTIVE PROBLEM SOLVING (TRIZ)

TRIZ, a Russian acronym for "*Teoriya Resheniya Izobretatelskikh Zadatch*" translates to the Theory of Inventive Problem Solving. It is a systematic innovation problem-solving tool that goes beyond intuition, to used logic, data and research derived from the study of patterns of invention in the global patent literature [10] [11]. Invented by Genrich Altshuller, TRIZ was developed from several designs and patent inputs conducted by Vladimir Petrov who studied the history of its evolution. TRIZ has been used for over 50 years as a problem-solving technique and tool to supplement or improve product designs. To increase ideality, TRIZ through problem-solving works out the benefits of achieving an output against the costs and harms of achieving it [10] [11].

The process provides inventive inspiration for the designer – encouraging the user to look for existing solutions to similar problems at different scales and times. This allows the user to think of adoption of principles that might offer idealised solutions from other industries, countries, times in history. "Someone somewhere has already solved your problem" [12]. The methodology makes use of past inventions, problems and solutions, evolution trends and patents in areas of science and technology and across different industries to define a knowledge-based database of 40 inventive principles, a contradiction matrix, 76 standard solutions, and trends of evolution that can be used as brainstorming tools to solve any contradiction and/or incremental problems.

As a systematic innovative tool, TRIZ attempts to eliminate the compromises and trade-offs usually accepted in a system or process at the early stages of the design. The specific problems or innovation needs are simplified to TRIZ conceptual problems using the TRIZ knowledge database (the inventive principles and standard solutions), and the solution is then evaluated for the specific problem.

The TRIZ process is executed in steps: the first step analyses the specific problem and formulates generic problems, from which generic solutions are then identified using the TRIZ library, and these are then translated to solutions relevant to the initial problem. This is illustrated in Figure 2.3 overleaf. The TRIZ database consists of various tools and information such as the 40 Inventive Principles, the technical contradiction matrix, the separation principles, the 76 standard solutions, evolution patterns, and substance-field analysis.

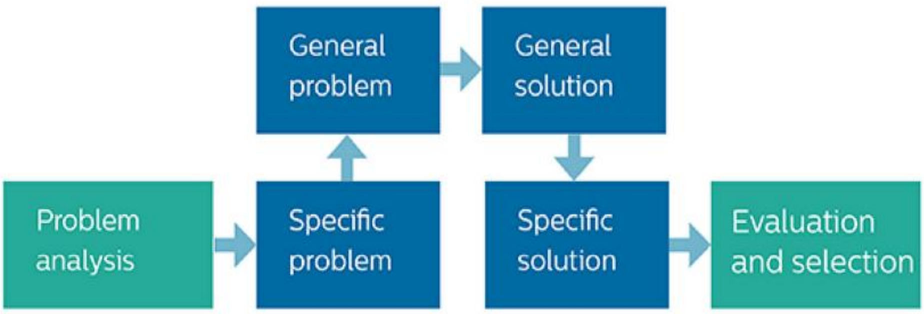

FIGURE 2.3: SOLVING TECHNICAL PROBLEMS USING TRIZ [11]

2.2.2.1 TRIZ Contradiction Matrix

The contradiction matrix, also known as the 39 Engineering Parameters, consists of specific parameters identified by Altshuller that can improve or worsen the design of a system. The 39×39 contradiction matrix presents these parameters based on their ability to either improve or worsen each of the other parameters, and thus the design or operational conditions [4] [11].

The contradiction matrix, presented in Figure 2.4 and Figure 2.5, represents the improving features in the first column and potentially worsening features in the top row. Each of the corresponding squares in the body of the matrix contains a list of inventive principles that can resolve the contradiction, by improving one parameter without worsening the other.

Various software tools have implemented this matrix into algorithms following a step-by-step process to solve the contradictions (e.g. TechOptimizer, Goldfire Innovator, CreaTRIZ, TriSolver, TRIZ Explorer, TRIZContrasolve, Guided Brainstorming [13]) – although none has combined this with QFD and FMEA, as the DTOceanPlus Structured Innovation tool has done.

Improve this one without making this one worse

Contradiction Matrix for Solving Technical Contradictions

39 Technical Parameters

No.	Parameter	Weight of moving object	Weight of Stationary Object	Length of moving object	Length of Stationary object	Area of moving object	Area of stationary object	Volume of moving object	Volume of stationary object	Speed	Force (Intensity)	Stress or pressure	Shape	Stability of the object's composition	Strength	Duration of action of a moving object	Duration of action of a stationary object	Temperature	Illumination intensity	Use of energy by a moving object	Use of energy by a stationary object	Power	Loss of energy	Loss of substance	Loss of Information	Loss of time	Quantity of substance	Reliability	Measurement accuracy	Manufacturing precision	Object-affected harmful factors	Object-generated harmful factors	Ease of manufacture	Convenience of Use	Ease of repair	Adaptability or versatility	Device complexity	Difficulty of detecting and measuring	Extent of automation	Productivity
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
1	Weight of moving object		-	15 8 29 34	-	29 17 38 34	-	29 2 40 28	-	2 8 15 38	8 10 18 37	10 36 37 40	10 14 35 40	1 35 19 39	28 27 18 40	5 34 31 35		6 29 4 38	19 1 32	35 12 34 31		12 36 18 31	6 2 34 19	5 35 3 31	10 24 35	10 35 20 28	3 26 18 31	3 11 1 27	28 27 35 26	28 35 26 18	22 21 18 27	22 35 31 39	27 28 1 36	35 3 2 24	2 27 28 11	29 5 15 8	26 30 36 34	28 29 26 32	26 35 18 19	35 3 24 37
2	Weight of stationary object	-		-	10 1 29 35	-	35 30 13 2	-	5 35 14 2	-	8 10 19 35	13 29 10 18	13 10 29 14	26 39 1 40	28 2 10 27		2 27 19 6	28 19 32 22	19 32 35		18 19 28 1	15 19 18 22	18 19 28 15	5 8 13 30	10 15 35	10 20 35 26	19 6 18 26	10 28 8 3	18 26 28	10 1 35 17	2 19 22 37	35 22 1 39	28 1 9	6 13 1 32	2 27 28 11	19 15 29	1 10 26 39	25 28 17 15	2 26 35	1 28 15 35
3	Length of moving object	8 15 29 34	-		-	15 17 4	-	7 17 4 35	-	13 4 8	17 10 4	1 8 35	1 8 10 29	1 8 15 34	8 35 29 34	19		10 15 19	32	8 35 24		1 35	7 2 35 39	4 29 23 10	1 24	15 2 29	29 35	10 14 29 40	28 32 4	10 28 29 37	1 15 17 24	17 15	1 29 17	15 29 35 4	1 28 10	14 15 1 16	1 19 26 24	35 1 26 24	17 24 26 16	14 4 28 29
4	Length of stationary object	-	35 28 40 29	-		-	17 7 10 40	-	35 8 2 14		28 10	1 14 35	13 14 15 7	39 37 35	15 14 28 26		1 40 35	3 35 38 18	3 25			12 8	6 28	10 28 24 35	24 26	30 29 14		15 29 28	32 28 3	2 32 10	1 18		15 17 27	2 25	3	1 35	1 26	26		30 14 7 26
5	Area of moving object	2 17 29 4	-	14 15 18 4	-		-	7 14 17 4	-	29 30 4 34	19 30 35 2	10 15 36 28	5 34 29 4	11 2 13 39	3 15 40 14	6 3	-	2 15 16	15 32 19 13	19 32		19 10 32 18	15 17 30 26	10 35 2 39	30 26	26 4	29 30 6 13	29 9	26 28 32 3	2 32	22 33 28 1	17 2 18 39	13 1 26 24	15 17 13 16	15 13 10 1	15 30	14 1 13	2 36 26 18	14 30 28 23	10 26 34 2
6	Area of stationary object	-	30 2 14 18	-	26 7 9 39	-		-	-	-	1 18 35 36	10 15 36 37		2 38	40		2 10 19 30	35 39 38		-		17 32	17 7 30	10 14 18 39	30 16	10 35 4 18	2 18 40 4	32 35 40 4	26 28 32 3	2 29 18 36	27 2 39 35	22 1 40	40 16	16 4	16	15 16	1 18 36	2 35 30 18	23	10 15 17 7
7	Volume of moving object	2 26 29 40	-	1 7 4 35	-	1 7 4 17	-		-	29 4 38 34	15 35 36 37	6 35 36 37	1 15 29 4	28 10 1 39	9 14 15 7	6 35 4		34 39 10 18	2 13 10	35		35 6 13 18	7 15 13 16	36 39 34 10	2 22	2 6 34 10	29 30 7	14 1 40 11	26 28	25 28 2 16	22 21 27 35	17 2 40 1	29 1 40	15 13 30 12	10	15 29	26 1	29 26 4	35 34 16 24	10 6 2 34
8	Volume of stationary object	-	35 10 19 14	19 14	35 8 2 14						2 18 37	24 35	7 2 35	34 28 35 40	9 14 17 15		35 34 38	35 6 4				30 6		10 39 35 34		35 16 32 18	35 3	2 35 16		35 10 25	34 39 19 27	30 18 35 4	35		1		1 31	2 17 26		35 37 10 2
9	Speed	2 28 13 38		13 14 8		29 30 34		7 29 34			13 28 15 19	6 18 38 40	35 15 18 34	28 33 1 18	8 3 26 14	3 19 35 5		28 30 36 2	10 13 19	8 15 35 38		19 35 38 2	14 20 19 35	10 13 28 38	13 26		10 19 29 38	11 35 27 28	28 32 1 24	10 28 32 25	1 28 35 23	2 24 35 21	35 13 8 1	32 28 13 12	34 2 28 27	15 10 26	10 28 4 34	3 34 27 16	10 18	
10	Force (Intensity)	8 1 37 18	18 13 1 28	17 19 9 36	28 10	19 10 15	1 18 36 37	15 9 12 37	2 36 18 37	13 28 15 12		18 21 11	10 35 40 34	35 10 21	35 10 14 27	19 2		35 10 21		19 17 10	1 16 36 37	19 35 18 37	14 15	8 35 40 5		10 37 36	14 29 18 36	3 35 13 21	35 10 23 24	28 29 37 36	1 35 40 18	13 3 36 24	15 37 18 1	1 28 3 25	15 1 11	15 17 18 20	26 35 10 18	36 37 10 19	2 35	3 28 35 37
11	Stress or pressure	10 36 37 40	13 29 10 18	35 10 36	35 1 14 16	10 15 36 28	10 15 36 37	6 35 10	35 24	6 35 36	36 35 21		35 4 15 10	35 33 2 40	9 18 3 40	19 3 27		35 39 19 2		14 24 10 37		10 35 14	2 36 25	10 36 3 37		37 36 4	10 14 36	10 13 19 35	6 28 25	3 35	22 2 37	2 33 27 18	1 35 16	11	2	35	19 1 35	2 36 37	35 24	10 14 35 37
12	Shape	8 10 29 40	15 10 26 3	29 34 5 4	13 14 10 7	5 34 4 10		14 4 15 22	7 2 35	35 15 34 18	35 10 37 40	34 15 10 14		33 1 18 4	30 14 10 40	14 26 9 25		22 14 19 32	13 15 32	2 6 34 14		4 6 2	14	35 29 3 5		14 10 34 17	36 22	10 40 16	28 32 1	32 30 40	22 1 2 35	35 1	1 32 17 28	32 15 26	2 13 1	1 15 29	16 29 1 28	15 13 39	15 1 32	17 26 34 10
13	Stability of the object's composition	21 35 2 39	26 39 1 40	13 15 1 28	37	2 11 13	39	28 10 19 39	34 28 35 40	33 15 28 18	10 35 21 16	2 35 40	22 1 18 4		17 9 15	13 27 10 35	39 3 35 23	35 1 32	32 3 27 15	13 19	27 4 29 18	32 35 27 31	14 2 39 6	2 14 30 40		35 27	15 32 35		13	18	35 24 30 18	35 40 27 39	35 19	32 35 30	2 35 10 16	35 30 34 2	2 35 22 26	35 22 39 23	1 8 35	23 35 40 3
14	Strength	1 8 40 15	40 26 27 1	1 15 8 35	15 14 28 26	3 34 40 29	9 40 28	10 15 14 7	9 14 17 15	8 13 26 14	10 18 3 14	10 3 18 40	10 30 35 40	13 17 35		27 3 26		30 10 40	35 19	19 35 10	35	10 26 35 28	35	35 28 31 40		29 3 28 10	29 10 27	11 3	3 27 16	3 27	18 35 37 1	15 35 22 2	11 3 10 32	32 40 28 2	27 11 3	15 3 32	2 13 28	27 3 15 40	15	29 35 10 14
15	Duration of action by moving object	19 5 34 31	-	2 19 9	-	3 17 19	-	10 2 19 30	-	3 35 5	19 2 16	19 3 27	14 26 28 25	13 3 35	27 3 10		-	19 35 39	2 19 4 35	28 6 35 18		19 10 35 38		28 27 3 18	10	20 10 28 18	3 35 10 40	11 2 13	3	3 27 16 40	22 15 33 28	21 39 16 22	27 1 4	12 27	29 10 27	1 35 13	10 4 28 15	19 29 39 35	6 10	35 17 14 19
16	Duration of action by Stationary object	-	6 27 19 16	-	1 40 35	-		-	35 34 38	-				39 35 3 23		-		19 18 36 40		-		16		27 16 18 38	10	28 20 10 16	3 35 31	34 27 6 40	10 26 24		17 1 40 33	22	35 10	1	1	2		25 34 6 35	1	20 10 16 38
17	Temperature	36 22 6 38	22 35 32	15 19 9	15 19 9	3 35 39 18	35 38	34 39 40 18	35 6 4	2 28 36 30	35 10 3 21	35 39 19 2	14 22 19 32	1 35 32	10 30 22 40	19 13 39	19 18 36 40		32 30 21 16	19 15 3 17		2 14 17 25	21 17 35 38	21 36 39 31		35 28 21 18	3 17 30 39	19 35 3 10	32 19 24	24	22 33 35 2	22 35 2 24	26 27	26 27	4 10 16	2 18 27	2 17 16	3 27 35 31	26 2 19 16	15 28 35
18	Illumination Intensity	19 1 32	2 35 32	19 32 16		19 32 26		2 13 10		13 19 10	26 19 6		32 30	32 3 27	35 19	2 19 6		32 35 19		32 1 19	32 35 1 15	32	13 16 1 6	13 1	1 6	19 1 26 17	1 19		11 15 32	3 32	15 19	35 19 32 39	19 35 28 26	28 26 19	15 17 13 16	15 1 19	6 32 13	32 15	2 26 10	2 25 16
19	Use of energy by moving object	12 18 28 31	-	12 28	-	15 19 25	-	35 13 18	-	8 15 35	16 26 21 2	23 14 25	12 2 29	19 13 17 24	5 19 9 35	28 35 6 18	-	19 24 3 14	2 15 19		-	6 19 37 18	12 22 15 24	35 24 18 5		35 38 19 18	34 23 16 18	19 21 11 27	3 1 32		1 35 6 27	2 35 6	28 26 30	19 35	1 15 17 28	15 17 13 16	2 29 27 28	35 38	32 2	12 28 35
20	Use of energy by stationary object	-	19 9 6 27								36 37			27 4 29 18	35				19 2 35 32	-				28 27 18 31			3 35 31	10 36 23			10 2 22 37	19 22 18	1 4					19 35 16 25		1 6
21	Power	8 36 38 31	19 26 17 27	1 10 35 37		19 38	17 32 13 38	35 6 38	30 6 25	15 35 2	26 2 36 35	22 10 35	29 14 2 40	35 32 15 31	26 10 28	19 35 10 38	16	2 14 17 25	16 6 19	16 6 19 37			10 35 38	28 27 18 38	10 19	35 20 10 6	4 34 19	19 24 26 31	32 15 2	32 2	19 22 31 2	18 2 35	26 10 34	26 35 10	35 2 10 34	19 17 34	20 19 30 34	19 35 16	28 2 17	28 35 34
22	Loss of energy	15 6 19 28	19 6 18 9	7 2 6 13	6 38 7	15 26 17 30	17 7 30 18	7 18 23	7	16 35 38	36 38			14 2 39 6	26			19 38 7	1 13 32 15			3 38		35 27 2 37	19 10	10 18 32 7	7 18 25	11 10 35	32		21 22 35 2	21 35 2 22		35 32 1	2 19		7 23	35 3 15 23	2	28 10 29 35
23	Loss of Substance	35 6 23 40	35 6 22 32	14 29 10 39	10 28 24	35 2 10 31	10 18 39 31	1 29 30 36	3 39 18 31	10 13 28 38	14 15 18 40	3 36 37 10	29 35 3 5	2 14 30 40	35 28 31 40	28 27 3 18	27 16 18 38	21 36 39 31	1 6 13	35 18 24 5	28 27 12 31	28 27 18 38	35 27 2 31			15 18 35 10	6 3 10 24	10 29 39 35	16 34 31 28	35 10 24 31	33 22 30 40	10 1 34 29	15 34 33	32 28 2 24	2 35 34 27	15 10 2	35 10 28 24	35 18 10 13	35 10 18	28 35 10 23
24	Loss of Information	10 24 35	10 35 5	1 26	26	30 26	30 16		2 22	26 32						10	10		19			10 19	19 10			24 26 28 32	24 28 35	10 28 23			22 10 1	10 21 22	32	27 22				35 33	35	13 23 15
25	Loss of Time	10 20 37 35	10 20 26 5	15 2 29	30 24 14 5	26 4 5 16	10 35 17 4	2 5 34 10	35 16 32 18		10 37 36 5	37 36 4	4 10 34 17	35 3 22 5	29 3 28 18	20 10 28 18	28 20 10 16	35 29 21 18	1 19 26 17	35 38 19 18	1	35 20 10 6	10 5 18 32	35 18 10 39	24 26 28 32		35 38 18 16	10 30 4	24 34 28 32	24 26 28 18	35 18 34	35 22 18 39	35 28 34 4	4 28 10 34	32 10 1	35 28	6 29	18 28 32 10	24 28 35 30	
26	Quantity of Substance	35 6 18 31	27 26 18 35	29 35 14 18		15 14 29	2 18 40 4	15 20 29		35 29 34 28	35 14 3	10 36 14 3	35 14	15 2 17 40	14 35 34 10	3 35 10 40	3 35 31	3 17 39		34 29 16 18	3 35 31	35	7 18 25	6 3 10 24	24 28 35	35 38 18 16		18 3 28 40	3 2 28	33 30	35 33 29 31	3 35 40 39	29 1 35 27	35 29 25 10	2 32 10 25	15 3 29	3 13 27 10	3 27 29 18	8 35	13 29 3 27
27	Reliability	3 8 10 40	3 10 8 28	15 9 14 4	15 29 28 11	17 10 14 16	32 35 40 4	3 10 14 24	2 35 24	21 35 11 28	8 28 10 3	10 24 35 19	35 1 16 11		11 28	2 35 3 25	34 27 6 40	3 35 10	11 32 13	21 11 27 19	36 23	21 11 26 31	10 11 35	10 35 29 39	10 28	10 30 4	21 28 40 3		32 3 11 23	11 32 1	27 35 2 40	35 2 40 26		27 17 40	1 11	13 35 8 24	13 35 1	27 40 28	11 13 27	1 35 29 38
28	Measurement Accuracy	32 35 26 28	28 35 25 26	28 26 5 16	32 28 3 16	26 28 32 3	26 28 32 3	32 13 6		28 13 32 24	32 2	6 28 32	6 28 32	32 35 13	28 6 32	28 6 32	10 26 24	6 19 28 24	6 1 32	3 6 32		3 6 32	26 32 27	10 16 31 28		24 34 28 32	2 6 32	5 11 1 23			28 24 22 26	3 33 39 10	6 35 25 18	1 13 17 34	1 32 13 11	13 35 2	27 35 10 34	26 24 32 28	28 2 10 34	10 34 28 32
29	Manufacturing Precision	28 32 13 18	28 35 27 9	10 28 29 37	2 32 10	28 33 29 32	2 29 18 36	32 23 2	25 10 35	10 28 32	28 19 34 36	3 35	32 30 40	30 18	3 27	3 27 40		19 26	3 32	32 2		32 2	13 32 2	35 31 10 24		32 26 28 18	32 30	11 32 1			26 28 10 36	4 17 34 26		1 32 35 23	25 10		26 2 18		26 28 18 23	10 18 32 39
30	Object affected harmful factors	22 21 27 39	2 22 13 24	17 1 39 4	1 18	22 1 33 28	27 2 39 35	22 23 37 35	34 39 19 27	21 22 35 28	13 35 39 18	22 2 37	22 1 3 35	35 24 30 18	18 35 37 1	22 15 33 28	17 1 40 33	22 33 35 2	1 19 32 13	1 24 6 27	10 2 22 37	19 22 31 2	21 22 35 2	33 22 19 40	22 10 2	35 18 34	35 33 29 31	27 24 2 40	28 33 23 26	26 28 10 18			24 35 2	2 25 28 39	35 10 2	35 11 22 31	22 19 29 40	22 19 29 40	33 3 34	22 35 13 24
31	Object-generated harmful factors	19 22 15 39	35 22 1 39	17 15 16 22		17 2 18 39	22 1 40	17 2 40	30 18 35 4	35 28 3 23	35 28 1 40	2 33 27 18	35 1	35 40 27 39	15 35 22 2	15 22 33 31	21 39 16 22	22 35 2 24	19 24 39 32	2 35 6	19 18 22	2 35 18	21 35 2 22	10 1 34	10 21 29	1 22	3 24 39 1	24 2 40 39	3 33 26	4 17 34 26							19 1 31	2 21 27 1	2	22 35 18 39
32	Ease of manufacture	28 29 15 16	1 27 36 13	1 29 13 17	15 17 27	13 1 26 12	16 40	13 29 1 40	35	35 13 8 1	35 12	35 19 1 37	1 28 13 27	1 13 11	1 3 10 32	27 1 4	35 16	27 26 18	28 24 27 1	28 26 27 1	1 4	27 1 12 24	19 35	15 34 33	32 24 18 16	35 28 34 4	35 23 1 24		1 35 12 18		24 2			2 5 13 16	35 1 11 9	2 13 15	27 26 1	6 28 11 1	8 28 1	35 10 28 1
33	Convenience of Use	25 2 13 15	6 13 1 25	1 17 13 12		1 17 13 16	18 16 15 39	1 16 35 15	4 18 39 31	18 13 34	28 13 35	2 32 12	15 34 29 28	32 35 30	32 40 3 28	29 3 8 25	1 16 25	26 27 13	13 17 1 24	1 13 24		35 34 2 10	2 19 13	28 32 2 24	4 10 27 22	4 28 10 34	12 35	17 27 8 40	25 13 2 34	1 32 35 23	2 25 28 39		2 5 12		12 26 1 32	15 34 1 16	32 26 12 17		1 34 12 3	15 1 28
34	Ease of repair	2 27 35 11	2 27 35 11	1 28 10 25	3 18 31	15 13 32	16 25	25 2 35 11	1	34 9	1 11 10	13	1 13 2 4	2 35	11 1 2 9	11 29 28 27	1	4 10	15 1 13	15 1 28 16		15 10 32 2	15 1 32 19	2 35 34 27		32 1 10 25	2 28 10 25	11 10 1 16	10 2 13	25 10	35 10 2 16		1 35 11 10	1 12 26 15		7 1 4 16	35 1 13 11		34 35 7 13	1 32 10
35	Adaptability or versatility	1 6 15 8	19 15 29 16	35 1 29 2	1 35 16	35 30 29 7	15 16	15 35 29		35 10 14	15 17 20	35 16	15 37 1 8	35 30 14	35 3 32 6	13 1 35	2 16	27 2 3 35	6 22 26 1	19 35 29 13		19 1 29	18 15 1	15 10 2 13		35 28	3 35 15	35 13 8 24	35 5 1 10		35 11 32 31		1 13 31	15 34 1 16	1 16 7 4		15 29 37 28	1	27 34 35	35 28 6 37
36	Device complexity	26 30 34 36	2 26 35 39	1 19 26 24	26	14 1 13 16	6 36	34 26 6	1 16	34 10 28	26 16	19 1 35	29 13 28 15	2 22 17 19	2 13 28	10 4 28 15		2 17 13	24 17 13	27 2 28 29		20 19 30 34	10 35 13 2	35 10 28 29		6 29	13 3 27 10	13 35 1	2 26 10 34	26 24 32	22 19 29 40	19 1	27 26 1 13	27 9 26 24	1 13	29 15 28 37		15 10 37 28	15 1 24	12 17 28
37	Difficulty of detecting and measuring	27 26 28 13	6 13 28 1	16 17 26 24	26	2 13 18 17	2 39 30 16	29 1 4 16	2 18 26 31	3 4 16 35	36 28 40 19	35 36 37 32	27 13 1 39	11 22 39 30	27 3 15 28	19 29 39 25	25 34 6 35	3 27 35 16	2 24 26	35 38	19 35 16	19 1 16 10	35 3 15 19	1 18 10 24	35 33 27 22	18 28 32 9	3 27 29 18	27 40 28 8	26 24 32 28		22 19 29 28	2 21	5 28 11 29	2 5	12 26	1 15	15 10 37 28		34 21	35 18
38	Extent of automation	28 26 18 35	28 26 35 10	14 13 17 28	23	17 14 13		35 13 16		28 10	2 35	13 35	15 32 1 13	18 1	25 13	6 9		26 2 19	8 32 19	2 32 13		28 2 27	23 28	35 10 18 5	35 33	24 28 35 30	35 13	11 27 32	28 26 10 34	28 26 18 23	2 33	2	1 26 13	1 12 34 3	1 35 13	27 4 1 35	15 24 10	34 27 25		5 12 35 26
39	Productivity	35 26 24 37	28 27 15 3	18 4 28 38	30 7 14 26	10 26 34 31	10 35 17 7	2 6 34 10	35 37 10 2		28 15 10 36	10 37 14	14 10 34 40	35 3 22 39	29 28 10 18	35 10 2 18	20 10 16 38	35 21 28 10	26 17 19 1	35 10 38 19	1	35 20 10	28 10 29 35	28 10 35 23	13 15 23		35 38	1 35 10 38	1 10 34 28	18 10 32 1	22 35 13 24	35 22 18 39	35 28 2 24	1 28 7 19	1 32 10 25	1 35 28 37	12 17 28 24	35 18 27 2	5 12 35 26	

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FIGURE 2.4: TRIZ 39X39 CONTRADICTION MATRIX IN SI TOOL [11]

Figure 2.5 represents an instance of using the contradiction matrix: The user wants to increase the area of their device (improved feature) resulting in increasing the weight of the device (worsening feature). The 39x39 contradiction matrix guides the user to consider specific inventive principles for this particular contradiction – in this case principles 2, 29, 17 or 4, discussed further in Section 2.2.2.2. The complete 39x39 contradiction matrix fully implemented in the SI tool is presented in Figure 2.4.

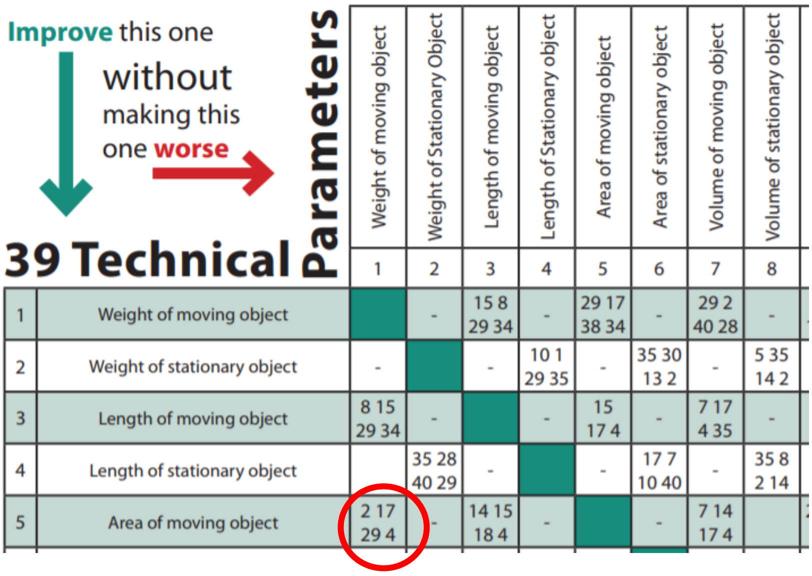


FIGURE 2.5: EXAMPLE OF THE TRIZ 39×39 CONTRADICTION MATRIX

These contradictions can be grouped into physical contradictions and technical contradictions.

- Physical contradictions refer to functions of a system which are subject to contradictory, opposing requirements. For example, a car should be user-friendly and simple enough to drive, but at the same time it could have the most advanced and complex features.
- Technical contradictions, on the other hand, are typical trade-offs in the system, where an ideal state cannot be reached due to another feature in the system preventing it; e.g. direct-drive generator machines are more reliable than geared machines, but heavier.

2.2.2.2 TRIZ Inventive Principles

It is normal that, when contradictions arise during the design of products or processes, a trade-off between design parameters occurs. The standard or traditional approach involves a brainstorming and/or trial-and-error process, resulting potentially in the inability to resolve contradictions beyond existing knowledge and experience. Altshuller reviewed hundreds of thousands of patents and inventions and came up with the distinguished 40 Inventive Principles based on breakthrough inventions. These inventive principles are solutions achieved to overcome the contradiction patterns described in the 39X39 contradiction matrix [4] [11]. The contradictions and inventive principles are generic enough to apply to various sectors.

Each matrix cell points to inventive principles, as shown in Figure 2.5, that have previously been used to resolve the contradictions. These principles (Table 2.1) should be evaluated by the user to determine the most relevant one for the system.

Table 2.1: TRIZ 40 inventive principles [14]

Inventive Principles			
1	Segmentation	21	Rushing through
2	Separation or extraction	22	Blessing in disguise (harm to benefit)
3	Local quality	23	Feedback
4	Asymmetry	24	Intermediary
5	Merging or combining	25	Self-service
6	Universality	26	Copying
7	Nesting dolls	27	Cheap disposable
8	Counter-weight	28	Replace a mechanical system
9	Preliminary counter-action	29	Pneumatics or hydraulics
10	Preliminary action	30	Flexible films or membranes
11	Previously placed pillow	31	Porous materials
12	Equipotential	32	Optical changes
13	Other way around	33	Homogeneity
14	Spherical shapes	34	Recycling (rejecting and regenerating)
15	Dynamism	35	Physical or chemical properties
16	Partial or excessive action	36	Use phase changes
17	Moving to another dimension	37	Thermal expansion
18	Mechanical vibration	38	Strong oxidants
19	Periodic action	39	Inert environment
20	Continuity of useful action	40	Composite materials

2.2.2.3 TRIZ Separation Principles

In some cases, there may be contradictions within a parameter. For instance, a wave energy converter should have a large displaced volume but low mass, TRIZ separation principles consider problems in time, in space, between parts and whole, and upon conditions. The physical contradictions are resolved by separating the contradictory requirements.

In time, the schedule of operations may be arranged so that requirements are met at each time or phase of operation (one example of that would be the traffic lights). In space, the contradictory requirements are defined in phases, where a particular phase or sub-system does not require a specific implementation of parameters (e.g., a seesaw, or bi-focal reading glasses). The separation between part and a whole considers using the characteristics of a system to be represented as parts of the system, meaning that "at the same critical moment in time and in the same space, a grouping of objects can have a collective property, and its parts can have the opposing property [14]". This enables minimal critical interaction with some parts of the system.

2.2.2.4 QFD/TRIZ integration in the SI tool

In the process of obtaining and assessing innovative solutions, the user might be tempted to only assess those solutions that they might come across quickly, or perhaps pre-meditating the solutions by only considering the advantages of their competitors' products. This might lead to functional fixedness, and a lack of differentiation between products. The SI tool within the DTOceanPlus does not reinvent the TRIZ processes, instead the state-of-the-art comes from integrating the TRIZ into the QFD process.

The integration of TRIZ into QFD in the SI tool allow the user to quickly create innovative solutions by using the TRIZ methods and inventive solutions within the QFD process. For example, if there is a lack of impact in the user's solutions, TRIZ might allow the user to think of alternative, impactful solutions by reference to the TRIZ processes – thinking of past, present and future inventions that meet a similar problem, or perhaps with difference of scale – micro or macro.

The TRIZ examples implemented in the SI tool, presented in Annex Table 0.1 to Table I.0.3 , show typical or exemplary solutions, but also a list of similar Marine Energy-related solutions that has been produced. TRIZ can be triggered to support the initial requirement exploration, during conflict assessment where a solution is seen as a block, or where there is a lack of quality in the solution provision, and in impact analysis.

2.2.3 FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

Widely used in engineering design, Failure Mode and Effect Analysis (FMEA) is a methodology used to identify and eliminate potential system failures. It provides a means to compare various system configurations by identifying possible root causes of failure(s), failure modes and estimation of relative risks, to drive towards higher reliability, quality and enhanced safety [15]. The tool aids in developing robust design and control measures to prevent potential failures from occurring.

There are two main approaches to performing an FMEA: one is based on the physical structure of the system (e.g. details of variation in design data), and one based on its functional structure [16]. The latter (Concept/Design FMEA) is used as part of the DTOceanPlus Structured Innovation tool for design or concept assessments. The methodology assesses the system to highlight potential risks associated with failure of the system and of its functions, and to identify ways to resolve them before actual designs are implemented.

The FMEA is conducted as follows:

- The key functional requirements of a given conceptual design are first determined.
- For each functional requirement, potential failure modes are determined.
- The Occurrence probability of each failure is established.
- Additionally, the Severity of each failure is determined, indicating the consequential effects of that failure mode.

- Finally, the likelihood that controls will detect that a failure has occurred (Detection), is determined for each failure based on the existing detection and control system in place.
- The criticalities of failures are then determined using the Risk Priority Number (RPN), which is calculated by multiplying the Severity (SEV), Occurrence (OCC), and Detection (DET) rankings associated with each failure: RPN = SEV*OCC* DET.
- This RPN is then used to prioritise risks, and suitable follow-up corrective actions are proposed to reduce the criticality of potential failures by implementing the corrective actions. These corrective actions can be obtained from the QFD alternative solutions, specific actions for the system (e.g. proposed design review, enhanced material properties), and background literature (e.g. measures implemented in other sectors).
- The RPN is then re-calculated to establish the impact of the corrective actions on the system and the level of criticality of the system with the proposed measures.
- These mitigation actions should then be implemented in the design of the systems.

A scoring matrix with a scale of 1-10 for Severity, Occurrence and Detection is defined either by using the standard pre-defined FMEA scaling matrix, or by adopting a user-defined one agreed at the outset of the project.

An example of Severity categories and corresponding severity rankings implemented in the SI tool are given below in Table 2.2.

TABLE 2.2: EXAMPLE OF SEVERITY RATING [16]

Severity Rating	Severity Definition	Severity Level	Ranking Value
Minor	It would be unreasonable to expect that the minor nature of this failure would cause any real effect on system capability. The failure might not be noticed.	Minor	1
Low	The nature of the failure causes only a slight deterioration of system capability that may require minor rework action.	Minor	2, 3
Moderate	Failure causes some deterioration in System capability which may generate the need for unscheduled rework /repairs or may cause a minor health hazard or minor injury to user.	Marginal	4, 5, 6
High	Failure causes loss of system capability or may cause a serious health hazard or serious injury to the user.	Critical	7, 8
Very High	A potential failure could cause complete system loss and/or death of user(s).	Major	9, 10

The complete scaling matrix implemented in the SI tool for Severity, Occurrence and Detection is presented overleaf in Table 2.3,

Table 2.4 and

Table 2.5.These definitions are taken from ISO 12132 standard [17]. A template of an FMEA worksheet is shown in Figure 2.6.The generic FMEA library implemented in the SI tool is presented in the Annex at Table 0.7 to Table I.11.

TABLE 2.3: SEVERITY RANKING

Severity	Description
1	No effect
2	Minor performance loss, defect noticed only by close inspection
3	Minor performance loss, defect noticed only by most observers
4	Minor performance loss, defect apparent
5	Device operable, but minor performance loss, end-user experience some dissatisfaction
6	Device operable, but auxiliary performance lost
7	Device operable, but with reduced performance level, end-user dissatisfied
8	Device inoperable, primary function lost
9	Device inoperable, safe function lost with warning
10	Device inoperable, safe function lost without warning

TABLE 2.4: OCCURRENCE RANKING

Occurrence	Description	Event occurrence - e.g. 1 in 1000 hours / days etc.
1	Failure unlikely	1 in 1000000
2	Relative few failures	1 in 250000
3	Relative few failures	1 in 20000
4	Occasional failures	1 in 1000
5	Occasional failures	1 in 400
6	Occasional failures	1 in 80
7	Repeated Failures	1 in 20
8	Repeated Failures	1 in 8
9	Failure inevitable	1 in 4
10	Failure inevitable	> 1 in 2

TABLE 2.5: DETECTION RANKING

Detection	Process FMEA	Design FMEA
1	Detection is almost certain	Design controls will detect a potential cause / mechanism and failure mode
2	Detection is highly likely	Very high chance that DC can find the failure mode and cause
3	High chance that the defect can be found	high chance that DC can find the potential failure mode and cause
4	Moderately high chance that the defect will be detected	Moderately high chance
5	Moderate chance that detection is possible	Moderate chance
6	Low chance of detection	low chance
7	Very low chance of detection	Very low chance
8	Remote chance of detection	Remote chance
9	Very remote chance of detection	Design control is unlikely to predict failure mode or cause
10	Total uncertainty of detection	Design control cannot detect the potential cause and failure mode, or there is no design control

Potential
Failure Mode and Effects Analysis
(Design FMEA)

___System
___Subsystems
___Component
Model Year / Vehicle(s):
Core Team:

Design Responsibility :
Key Date :

FMEA Number :
Prepared by :
FMEA Date (Orig.) :
(Rev.) :

Item / Function	Requirements	Potential Failure Mode	Potential Effects of Failure	SEV	CLASS	Potential Causes / Mechanisms of Failure	Current Design Controls Prevention	OCC	Current Design Controls Detection	DET	RPN	Recommended Actions	Responsibility & Target Completion Date	Action Results				
														Actions Taken	SEV	OCC	DET	RPN

Figure 2.6: Template of an FMEA worksheet

3. USE CASES AND FUNCTIONALITIES

This section describes the main use cases of the tool, and the functionalities implemented in it. This section also discusses the two design modes of the SI tool: standalone and integrated.

3.1 USER GROUPS

The overarching use case for the Structured Innovation design tool is for concept creation and design improvement. The SI tool will enable users to:

- Scan the design space and identify attractive areas for innovation
- Create new concepts and identify areas of opportunities
- Identify and solve the contradictions arising from the proposed solutions
- Mitigate the potential technical risks associated with the attractive concepts
- Improve existing design concepts.

In Deliverable D3.1, the Technical Requirements of the SI tool were presented, and the use cases were listed for the different types of users identified [3]. Three key user groups were identified as part of the development of the functional requirements [18]:

i. **Technology Developers** – to assess areas of improvement and technical challenges
ii. **Project Developers** – to assess novelty in technology at any level of aggregation, and
iii. **Public or Private Investors** – to identify attractive areas of innovation for investment.

3.2 USE CASES

In this section, use cases are described from an operational perspective, in respect to what the user decides to do and which modules to run. The execution of the runs will require an experienced user to make informed decisions at each stage or mode of operation of each module – QFD/TRIZ and FMEA. An operational use case can be summarised as shown in Figure 3.1.

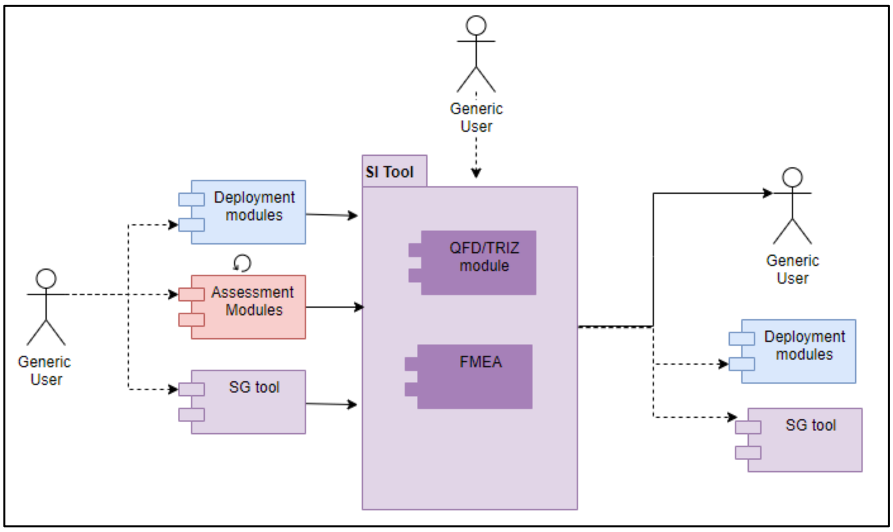


FIGURE 3.1: OPERATIONAL USE CASE FOR USING THE STRUCTURED INNOVATION TOOL

In this generic use case, the user will be able to:

1. Run the SI tool if innovative improvements are required after running the set of Deployment Design & Assessment tools of DTOceanPlus
2. Run the SI tool within the framework of the Stage Gate Design tool.
3. Use the SI tool in standalone mode.

By considering the three use cases above mentioned, Table 3.1 summarises the dependencies of the SI tool with the other modules in DTOceanPlus.

TABLE 3.1: DEPENDENCIES OF SI TOOL WITH OTHER MODULES IN DTOCEANPLUS

Consumes from	Consumed by
Stage Gate tool All Deployment tools All Assessment tools	Stage Gate tool

3.2.1 USE CASE AFTER DEPLOYMENT DESIGN TOOLS

Within DTOceanPlus, the Structured Innovation tool will be used for concept creation or for improvement at various maturity levels, and at different levels of aggregation of a system. All the design tools within the DTOceanPlus suite of tools can be used to identify innovation needs or opportunities (within existing designs or new concepts) based on the design specifications and shortfalls.

In this case, the user will run one or more Deployment Design tools as required, run the assessment modules to carry out the specific assessments, and if innovative improvements are required, the user will then be directed to the Structured Innovation tool. As shown in Figure 3.2, the results will be shown to the user who can then assess further the potential innovative concepts and re-assess their new/improved design.

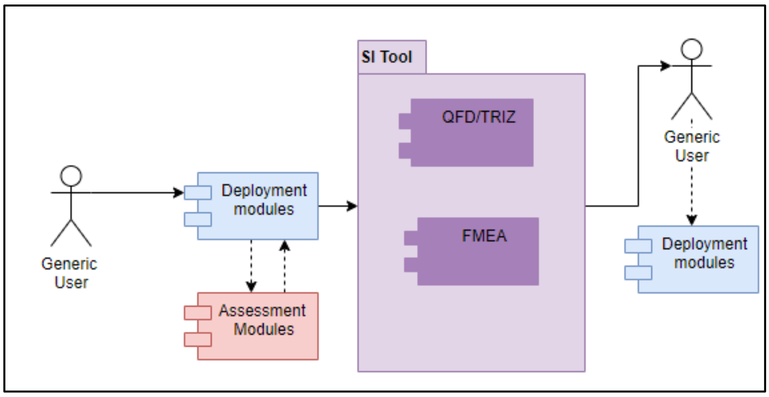


FIGURE 3.2: USE CASE FOR USING THE SI TOOL AFTER RUNNING THE DEPLOYMENT TOOLS

3.2.2 USE CASE WITHIN THE FRAMEWORK OF STAGE GATE TOOL

In this case, the Structured Innovation tool will be integrated with the Stage Gate design tool to allow the user to assess the areas that require improvement, and then to launch the Structured Innovation tool for (one or more) improvement cycles as seen in Figure 3.3. The following steps are identified for this use case:

1. The user runs the framework of the SG tool. The Deployment and Assessment tools may be used to provide design information and calculate key metrics which are fed back into the stage gate design tool.
2. The SI tool is triggered when the results of the stage gate assessment highlight specific Evaluation Areas that need to be improved.
3. The SI tool will be run, and it will check that the needed information is available (from other modules); if it is not, it will request the user to input the information.
4. The user will complement the information and then generate (one or more) innovative solutions using the SI tool.
5. The SI tool will provide the innovative assessments to the SG tool to complete the SG framework.

6. The SG tool will show the outcome to the user.

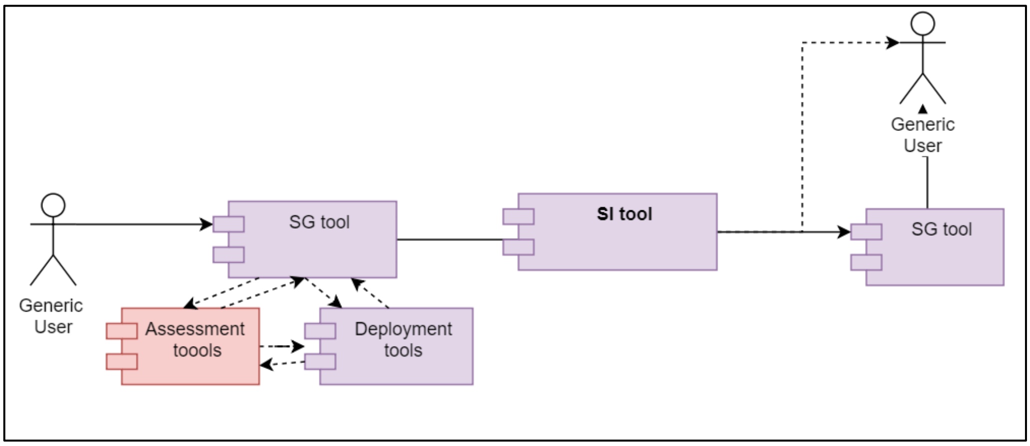


FIGURE 3.3: USE CASES FOR SI TOOL WITHIN THE FRAMEWORKS OF THE SG TOOL

3.2.3 USE CASE IN STANDALONE MODE

In this case, the user would like to explore the design space in order to identify attractive areas of innovation (without specific input from other modules). The user will provide all the required inputs in this case, and will be presented with the overall results of the innovative assessment as shown in Figure 3.4 .

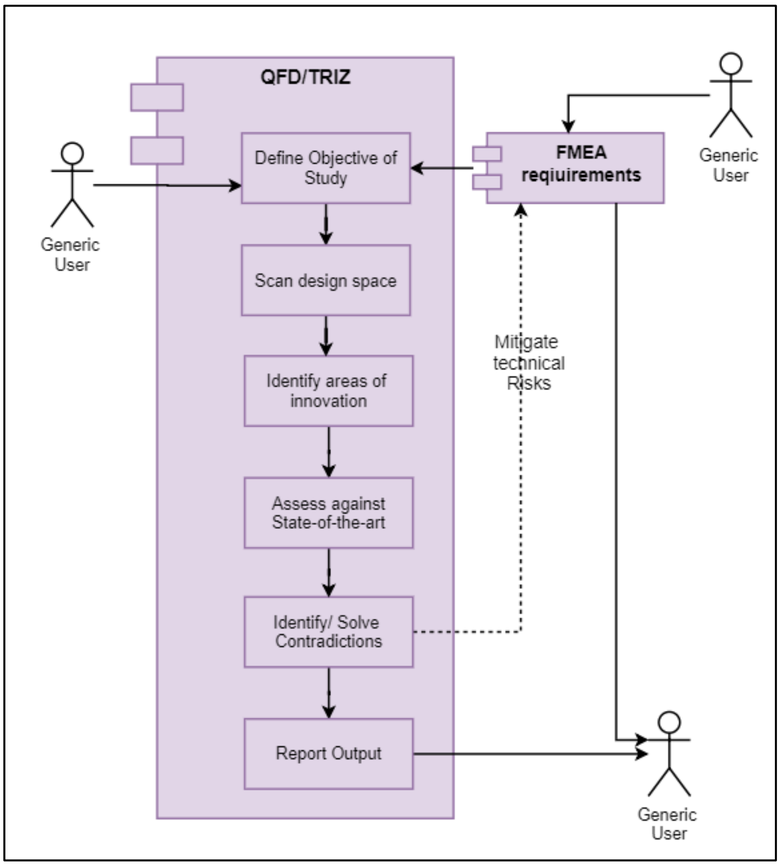


FIGURE 3.4: STANDALONE MODE OF THE STRUCTURED INNOVATION TOOL

3.3 THE FUNCTIONALITIES

The Structured Innovation tool has six major functionalities:

1. **Defining objectives of the study:** This stage captures the project objectives and the list of the stakeholder needs (WHATs) broadly defined. In the context of developing a new product, this is a list of customer requirements. These requirements – often very general, vague, and difficult to implement directly – are prioritised in order of importance.

2. **Scanning the design space:** The QFD/TRIZ module of the SI tool is used for two purposes. Firstly, to scan the design space by mapping options for each of the key parameters which make up ocean energy concepts or projects, then ranking the attractiveness of these options through high level physical and economic assessments. Secondly, to define the innovation problem space representing the voice of the customer and make immediate objective assessment of the best solutions which fit the users' requirements.
    a. **Definition of functional requirements:** This is the stage where the customer needs are translated into measurable functional requirements (HOWs) that can satisfy the needs.
    b. **Definition of Impacts:** In this stage, the relationships between the stakeholder needs (WHATs) and the functional requirements (HOWs) are determined using a predefined scale. Many of the HOWs identified affect more than one WHAT.
    c. **Requirement interactions:** This establishes the interdependencies between functional requirements (HOWs). The purpose is to identify areas where trade-off decisions, conflicts and innovation may be required.

3. **Identifying attractive areas of innovation:** The SI tool is developed to include fundamental relationships between key parameters in ocean energy concepts, evidence from the first ocean energy arrays, and a standard library of problem solution inter-relationships. QFD uses a set of requirements (WHATs) and answers them with a set of functional requirements (HOWs). There will be a variety of solutions to solve each requirement, with each solution being aimed at producing the best requirement improvement. These solutions may contradict each other, and the QFD/TRIZ methodology allows these contradictions to be identified, and their impact assessed.
The possible concepts will be ranked in order of importance and achievability, highlighting options which would be attractive investment opportunities. Evaluation of these options will be based on high-level metrics.

4. **Assessing contradictions:** The TRIZ component of the SI tool is used to produce solutions to the QFD requirements where an improvement is needed, or if there is no existing solution, or if the key performance indicators are not satisfactorily met. The TRIZ methodology can be used to ensure completeness in the key parameters which define the design space with, for example, use of the Effects Database and in the series of provocative prompts to provide the well-known forty inventive principles and other tools to solve contradictions contained within the QFD. The QFD

and TRIZ components are integrated into a single component within the SI tool to allow visualisation of areas of opportunity and risk.

5. **Assessing technical risk:** Technical risks are framed using the 'concept' or 'design' FMEA tool. The tool provides ratings for each defect or failure in terms of severity, occurrence, and detection. The FMEA uses a database of validated defect parameters to improve understanding of technical risk during the design assessment process, but also to offer opportunities for both risk mitigation and cost reduction. In the SI tool, the structured innovation process will conclude with a visualisation method to represent the process and results obtained, and deviation from the key performance metrics. The results will be expressed in terms of a ranking of attractive options and in presentation of the QFD requirements. The overall result will be an acceptability rating that allows objective assessment of the design.

6. **Reporting outputs:** This generates a summary page of all the outputs including a list of proposed innovative functions, their metrics, conflicts and interrelationships, and impact. This can be in report format or as a set of data files for further analysis and updates in the future.

Further details for each of these functionalities are given in the following sections.

3.3.1 DEFINING OBJECTIVES OF THE STUDY

The user starts the Structured Innovation tool by defining the project study and mission statement. The QFD/TRIZ module is then initiated to define or review the objectives (stakeholders' needs) and priorities of their study, potentially including improvement requirements captured during the design stages or the technology assessment in the Stage Gate tool.

The following processes, illustrated in Figure 3.5, are undertaken:

- The user defines the top-level objectives and relative priorities that trigger the potential for innovation. These objectives are the result of design needs (Design limitations), the art-of-the possible of the designs and/or from threshold values from the SG tool.
- The SI tool could also be initiated by the requirements identified from the FMEA technical risks and required mitigation measures. The FMEA functions will be inputted into the tool to obtain innovative solutions to the design functions with "unacceptable" technical risks.

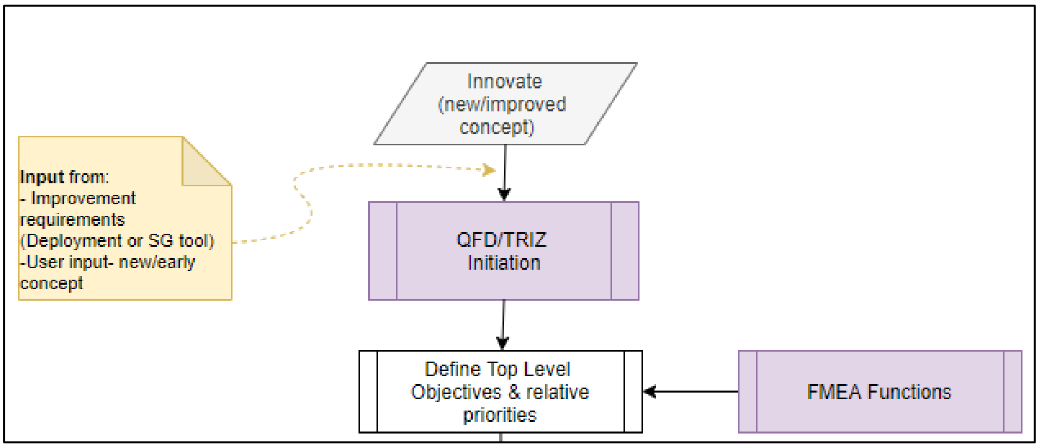


FIGURE 3.5: DEFINING TOP OBJECTIVES & RELATIVE PRIORITIES

These objectives define the user requirements. In the context of developing a new product for example, this is a list of the customer requirements which are usually general, vague, and difficult to implement directly; they require further detailed definition. An example is shown in Table 3.2:

TABLE 3.2: EXAMPLE DEFINING TOP OBJECTIVES

Mission statement	Stakeholder needs
Identify attractive business cases for exploitation of wave energy resources	Cost of energy Security of power supply Environmental impact

3.3.2 SCANNING THE DESIGN SPACE

After capturing the objectives of the study, the user assesses the potential innovative solutions based on the objectives. The steps taken to achieve these innovative solutions are expanded in the sections below:

3.3.2.1 Functional requirements

The captured objectives described in Section 3.3.1 are refined into the next level of detail by listing one or several functional requirements for each objective (i.e. How are we going to satisfy the needs?). The objective of this refinement is to identify actionable functional requirements - ones that have clear actions to satisfy the needs. For each need, the user defines functional requirements. These requirements can be either directly inputted by the user or selected from the solution hierarchy pre-defined in the SI tool. Section 0 provides more details on the solution hierarchy and data required to run the SI tool.

The desired direction of improvement is also determined for each functional requirement (is higher or lower better?). Using the example in Table 3.2, the direction of improvement can be as shown in Table 3.3.

TABLE 3.3: EXAMPLE DIRECTION OF IMPROVEMENT

Stakeholder needs	Direction of Improvement
Cost of energy	Lower is better
Security of power supply	Higher is better
Environmental impact	Lower is better

SOLUTION HIERARCHY

The solution hierarchy is a multi-level list of potential solutions for ocean energy systems that starts with the energy trilemma as requirements: delivering secure, affordable, and environmentally sustainable energy; and lists potential solutions for each requirement. The intention is to offer this hierarchy as a structured set of prompts, and to help the user to consider multiple solutions to different QFD levels – the user can then understand the potential for ideality and innovation, and thoroughness. An example of a solution hierarchy is shown in Figure 3.6.

L1	L2	L3	L4	L5
		← Design Flexibility →		
Lowest Lifetime costs	Capital costs	Material costs	Manufacturing methods	Insulation system
	Operational costs	Material amount	Material Strength	I^2R loss
	Decommissioning costs	Machine efficiency	Active material attributes	Windage and friction loss
	Energy Conversion	Reliability	Conversion efficiency	
			Repairability	
			Losses	

FIGURE 3.6 EXAMPLE OF APPLICATION OF SOLUTION HIERARCHY

This example shows several design selection decisions for the first level requirement – minimal lifetime cost. The example is associated with the reduction of the operational costs, and the links between the Levels of hierarchy. The user has design flexibility over levels 3 to 5, with the top two levels being influenced by external stakeholders and legislation. The full list of the solution hierarchy is presented in Annex Table I.4 to Table I.6.

FUNDAMENTAL RELATIONSHIPS

The Beta version of the SI tool being developed is to include fundamental relationships between key parameters in ocean energy concepts, evidence from the first ocean energy arrays, and trends observed in the industry.

The fundamental relationships are the engineering, physics and fundamental economic relationships which drive the earliest stages of assessing the attractiveness of concepts. These relationships enable the user to evaluate more widely how to deliver the concept creation use cases.

When running in 'Integrated' mode, the Structured Innovation design tool will work alongside the Stage Gate design tool to assess the fundamental engineering parameters of the proposed concepts against the topic areas in the stage gate metrics framework. In this mode, the Structured Innovation design tool also requires use of relevant Deployment and Assessment design tools to compute parameters to inform the engineering, physics, and economic fundamental relationships, and to provide tools which support the evaluation of requirements and solutions in the QFD/TRIZ modules.

New concepts created as part of the Structured Innovation design tool will utilise the simplest versions of the assessment and deployment tools to assess these concepts. These may be based on fundamental engineering, physics and economics relationships, or stripped-down versions of the assessment tools with default values for many of the variables.

There is likely to be some qualitative data and little quantitative data available about the performance of a technology. The Structured Innovation design tool assessment method will be linked to the ability to work with the Stage Gate, Deployment and Assessment tools to execute assessments at low Technology Readiness Level, by using fundamental engineering, physics and economics relationships through the high-level assessment of concepts as part of the Structured Innovation design tools.

An example illustrating fundamental relationships in some of the modules of DTOceanPlus is presented in Table 3.4.

TABLE 3.4: EXAMPLE OF FUNDAMENTAL RELATIONSHIPS IN DTOCEANPLUS MODULES

Defining parameters	Fundamental relationships
Transformed Energy	Relationships between- PTO type, efficiency, and energy yield
Describing mooring and foundations	Fundamental physics on the loads expected
Lifetime costs of project	Cost proxies relating to major sub-assemblies instead of LCOE (e.g. ACE= ACCW/CCE described below)

At the earliest stage of assessment, there is usually little data available making it difficult for the user to calculate some parameters such as the Levelised Cost of Energy (LCOE). Cost proxies, in these cases, can be calculated using fundamental relationships, for example the ACE:

$$ACE = \frac{\mathrm{ACCW}}{\mathrm{CCE}}$$

ACE, being the ratio of the **A**verage climate capture width (ACCW) to the **C**haracteristic capital **E**xpenditure (CCE), is a benefit-to-cost ratio which can be used to assess the economics of wave and tidal energy systems. The fundamental relationship between ACE and the LCOE is presented in Figure 3.7.

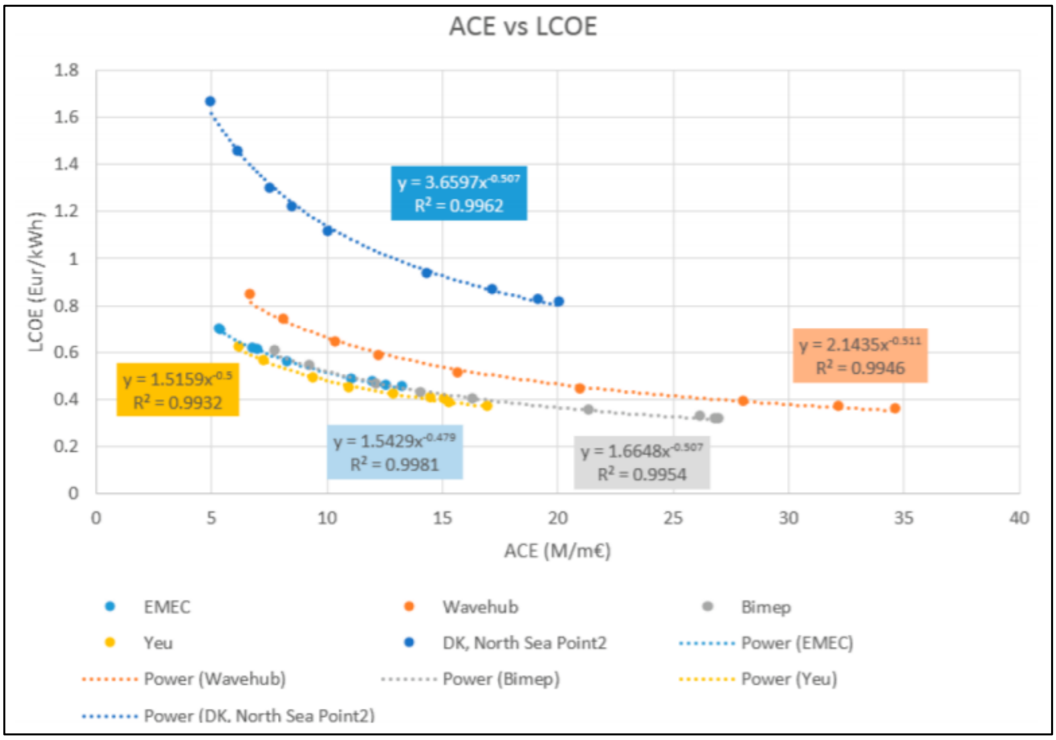


FIGURE 3.7: COMPARISON BETWEEN ACE AND LCOE METRICS FOR WAVE ENERGY CONVERTERS DEPLOYED IN DIFFERENT LOCATIONS. [19]

3.3.2.2 Impacts

This function determines the relationships of the stakeholder objectives (WHAT) and the functional requirements (HOWs) where each intersect. Many of the HOWs identified affect more than one WHAT. The strength of relationship between each of the needs and functional requirements is determined using a simple scale: high (9), medium (4), low (1), none (0). It is crucial to verify that all major WHATs are connected with one or more HOW, otherwise a review of the functional requirements is required.

3.3.2.3 Correlations

The correlation (interdependencies) between the functional requirements (HOWs) is determined in order to identify areas where trade-off decisions, conflicts and innovation may be required. Pre-defined scales are used to describe the strength of the relationships between the functional requirements (High-medium-low-no relationship) and positive or negative.

3.3.3 IDENTIFYING ATTRACTIVE AREAS OF INNOVATION

The possible concepts will be ranked in order of importance and achievability, highlighting those which would be attractive investment opportunities. Evaluation of these options will be based on high-level metrics such as Internal Rate of Return (IRR) of investment, Payback time, Cost of Energy, etc.

3.3.3.1 Ideality assessment

For each potential area of innovation, target values are established. At this stage, the team or the designer determines HOW MUCH each functional requirement can be ideal. These target values allow users to assess the potential for innovation of concepts, support comparisons against the state-of-the-art, and provoke innovation and invention processes.

The Structured Innovation tool uses reference data to provoke innovation through its QFD/TRIZ and FMEA modules. One example of this is the concept of ideality, which is often used in TRIZ. The QFD functions will assess ideality by using target values for some of the quantitative parameters (e.g. % losses in a cable). These target values could take one of the four data types, namely the state-of-the-art, commercial acceptance targets, ideal technology values or benchmark data. Qualitative values can be used by conversion to quantitative scale by application of conversion ratings. The data required for ideality assessment are shown in Table 3.5 and described overleaf.

TABLE 3.5: DATA REQUIRED FOR IDEALITY ASSESSMENT

Data required	Reference Data Type
Target values to identify areas of achievement shortfall and to provoke innovation	State-of-the-art
	Commercial acceptance targets
	Ideal technology values – the art-of-the-possible
	Benchmark data – performance data

The user can set these targets for each of the functional requirements. For example, they might set a target for capital cost that they want to achieve. Alternatively, the list of targets required by the SI tool can be obtained from the Stage Gate tool to give the user the option of using the same targets as metric thresholds within a Stage Gate Framework.

STATE-OF-THE-ART DATA

The state-of-the-art data refer to leading edge technology or design data including newest ideas and features. These reference data can be inputted by the user, or obtained (if available) from the Design and Assessment modules, or the data catalogue containing static data, including information about components such as electrical components, moorings, foundations, vessels, and ports.

COMMERCIAL ACCEPTANCE TARGETS

These data refer to quantifiable measures to evaluate performance objectives. They are also known as Key Performance Indicators (KPI) e.g. LCOE, AEP, other commercial or environmental targets. These data can be inputted by the user, or if available obtained from the DTOceanPlus catalogues.

ART-OF-THE-POSSBLE DATA

These are values of ideal technology (ideal solutions beyond constraints- competing interests). art-of-the-possible rather than the state-of-the-art takes into consideration the ideality of devices or processes only limited by physics (e.g., the Betz limit, yield strength) and extreme conditions to provoke new concepts.

BENCHMARK DATA

A performance benchmarking database will assist the users of the Structured Innovation design tool to provoke innovation whilst improving performance and reliability. The benchmark database will provide key performance indicators to help demonstrate the potential for innovation against standard or targeted benchmark performance credentials.

The benchmarking is focused on the operational performance and reliability of ocean energy technologies. Data such as performance, availability, reliability, and maintenance metrics across a range of dimensions, such as regional geography, turbine type and age, etc. will make the benchmark catalogues. Thereby, providing a detailed analysis of a project current performance against the competitors or the State-of-the-art to enable identification of areas for innovation or optimisation. Benchmark catalogues will be updated to provide the most comprehensive and current cross sector view of ocean energy operations.

3.3.3.2 Development assessment

This function rates the organisation's difficulty in engineering and delivering (make, supply, deliver) these ideal functional requirements. Some of the attributes might have direct conflicts with the organisation. Mass production may be in conflict with the existing organisation capacity, for example.

The SI tool requests the user to select from the pre-defined scale (Very high (5) -very low (1)), the level of difficulty to engineer and to deliver the ideal functions, and to assess the organisational impacts of implementing the potential concepts.

3.3.4 ASSESSING CONTRADICTIONS

In the process of obtaining and assessing innovative concepts, the user might be tempted to only assess those solutions that they might come across quickly, by only considering the advantages of their competitors' products. This might lead to functional fixedness, as described in the definition of terms, and a lack of differentiation between products.

This function examines the relationships between each functional requirement as described in Section 3.3.2.3, and helps the user to eliminate the contradictions associated with the strong negative relationships.

The integrated TRIZ/QFD process enables the user to create innovative concepts by using the TRIZ functions and inventive solutions within the QFD process. For example, if there is a lack of impact in the user's concepts, TRIZ might allow the user to think of alternative, impactful solutions by reference to the TRIZ toolkit – thinking of past, present and future inventions that meet a similar problem, or perhaps with difference of scale – micro or macro. The TRIZ examples show the typical or exemplary solutions, but also a list of similar Marine Energy-related solutions has been produced.

TABLE 3.6: EXAMPLE OF MARINE RELATED SOLUTIONS USING TRIZ

Inventive Principles		
Number	**Description**	**Marine Energy Example from existing practice**
4	Asymmetry	WEC floats, blade sections, sub-frame stringers using prime number spacing
5	Merging or combining	Bearing cooler acts as a heat sink
6	Multi-functionality	Generator acts as a brake

3.3.5 ASSESSING THE TECHNICAL RISKS

The user initiates the FMEA module to systematically assess and mitigate potential risks associated with the proposed new or improved concept(s):

1. By defining the scope and the system boundaries of the study: Interfaces, elements within the system, and elements outside the system
2. By providing the functional requirements of the system under study
3. By completing the FMEA worksheet to identifying the potential failure modes/effects, and defining the current design and control process of the system.

The FMEA process within the SI tool is presented in the UML diagram in Figure 3.8 overleaf.

The library of generic data used is presented in the Annex at Table 0.7 to Table I.11.

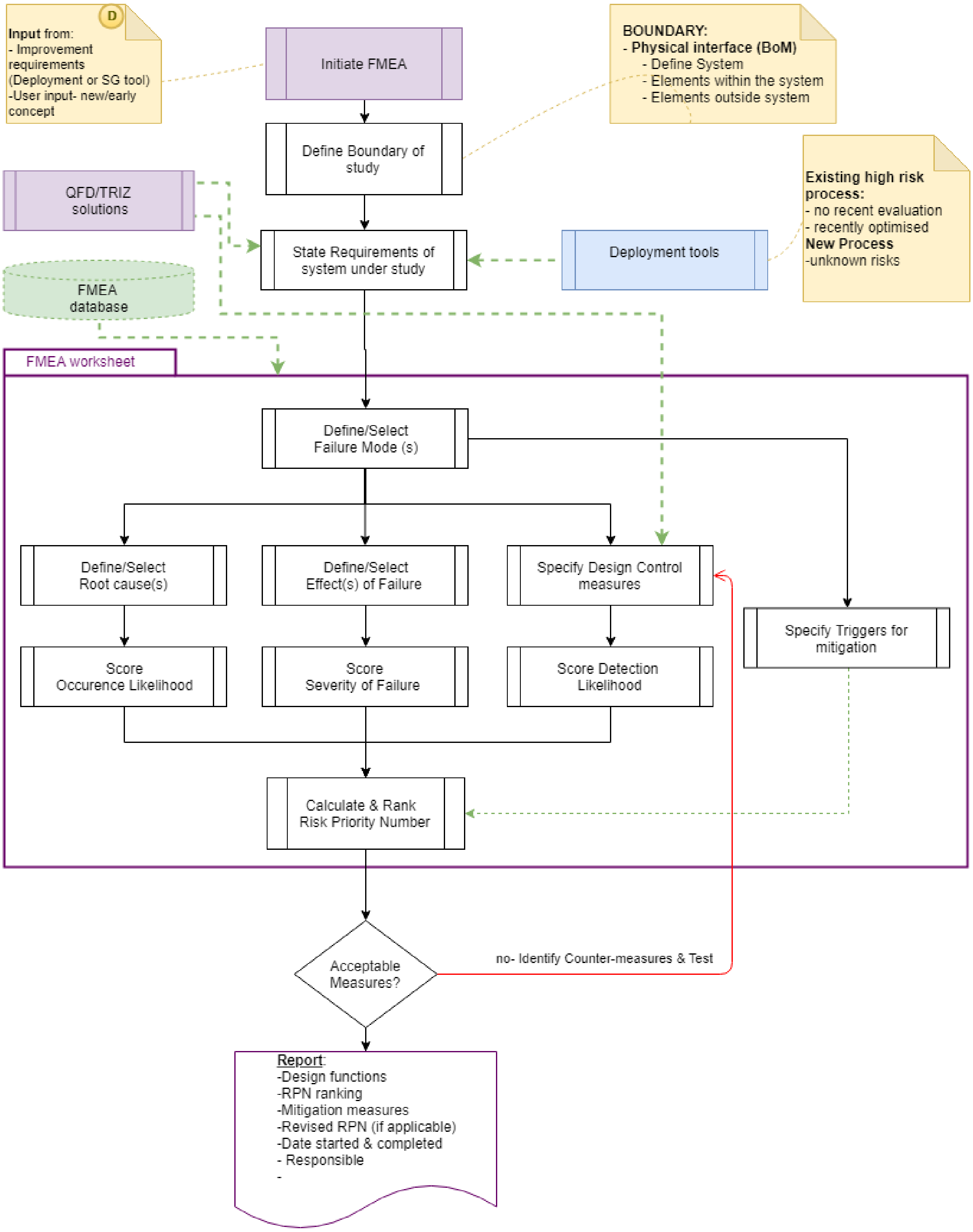


FIGURE 3.8: FMEA PROCESS WITHIN THE STRUCTURED INNOVATION TOOL

3.3.6 REPORTING

All the data provided by the user and calculated by the SI tool are outputted as a standardised report. This report can be downloaded as a PDF file using the Report page of the SI tool's GUI.

The report can be generated after completing any of the main functionalities to output: the objectives and priority assessment, the list of functional requirements, their metrics, conflicts and impacts, the design briefs (includes requirements, specifications and gaps), the ideality assessment, the optimum solutions, and the technical mitigation measures.

The optimum solutions are those with the highest impact, but which consider the organisational effort. Obtaining this ranking also allows the user to understand the impacts between solutions, so one lower-ranked solution might be key to more impactful solutions, and this should be considered in those cases.

The output is a list of solutions, their metrics, conflicts and interrelationships, and impact. This can be in report format or as a set of data files for further analysis and updates in the future. The report allows the designer to actively use and update the tool as the design is reviewed in a consistent manner.

The user then has a wide range of choices as to what to do next with the reported information, including carrying out further activities within the SI tool or embarking on other activities in other tools within the DTOceanPlus suite of tools. Some of these are indicated in the use cases set out at the start of Section 3.

One example of possible further activity within the SI tool would be additional phases of QFD analysis, as described in 2.2.1.2 . Once the phase-1 HoQ analysis is complete, the user may then choose to take this to Phase-2 by starting a new study and transferring only the relevant impactful functional requirements from the Phase-1 analysis into the Phase-2 study. The same process may be implemented for all phases to Phase-4 with the relevant details.

4. THE IMPLEMENTATION

4.1 ARCHITECTURE OF THE TOOL

The Structured Innovation tool is implemented in three parts, which can be called Business Logic, Back End and Front End. The interaction between these parts is shown in the sequence diagram overleaf in Figure 4.1, which shows the creation of a requirement (chosen for this example because requirements exist for both FMEA and QFD analyses). Both the Front End and the other DTOceanPlus modules communicate with the Back End using the HTTP protocol, with data being transferred in JSON. The Business Logic python modules are imported into the backend as libraries.

The responsibilities of the components are shown in Table 4.1.

TABLE 4.1. RESPONSIBILITIES OF COMPONENTS

Component	Responsibilities
Front End	Providing the user with a visual interface. Passing user input to the Back End.
Back End	Passing data between the business logic components and the Front End. Communicating with the other modules of DTOceanPlus. Providing suggested inputs to the user via the Front End.
Business Logic	Persisting data. Ensuring that all data stored is valid. Maintaining the relationship between individual components of analyses. Calculating results of analyses.

The following sections describe in further detail the implementation of the components and the key libraries used in their development.

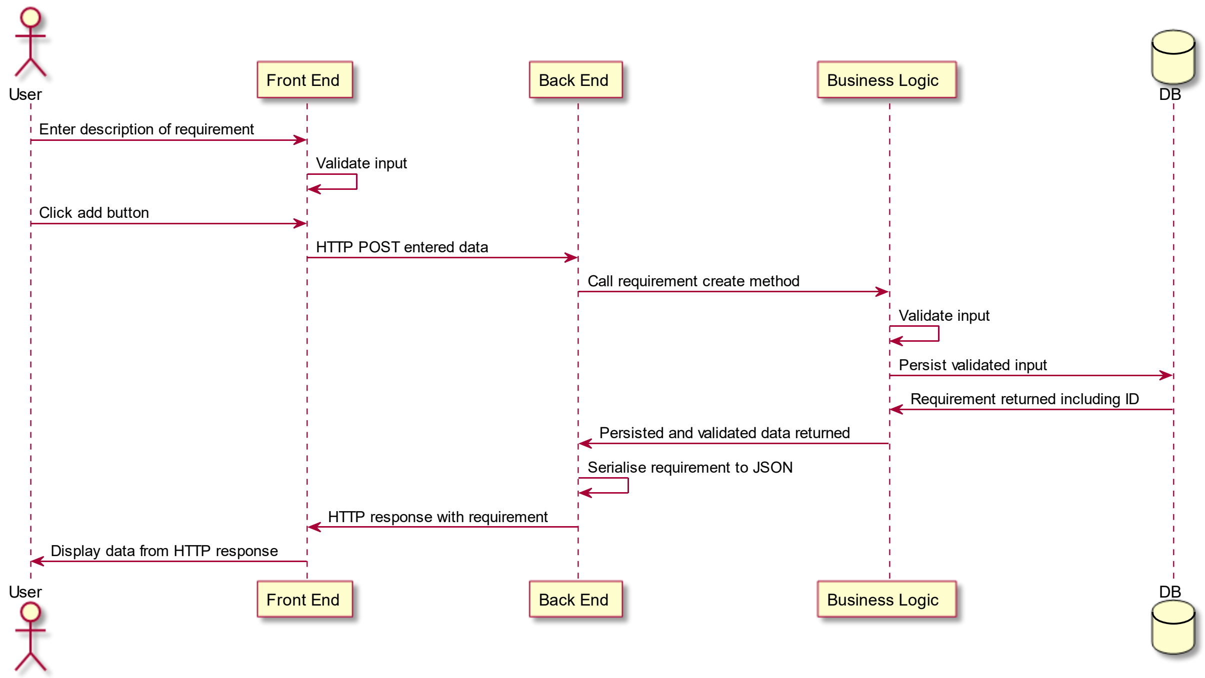


FIGURE 4.1: SEQUENCE DIAGRAM FOR CREATION OF REQUIREMENT

4.1.1 BUSINESS LOGIC

The business logic is implemented as two Python modules: *pyfmea*, for FMEA Analyses, and *pyqfd*, for the integrated QFD/TRIZ. A pydantic schema is used to ensure that inputs and outputs are of the expected Python type, casting them where necessary. The UML diagrams (Figure 4.2 and Figure 4.3) show a simplified representation of these schemas. The actual implementation includes additional inheritance structures to ensure that existing objects always have an *id* field, but new ones do not. Key libraries used:

TABLE 4.2: KEY LIBRARIES

Library	Use case	URL
Pydantic	Validation of input and output data. Partially responsible for serialising (conversion to JSON) and deserialising (conversion from JSON) data.	https://pydantic-docs.helpmanual.io/
SQLAlchemy	ORM for communication with the sqlite database.	http://sqlalchemy.org/

A common core for both pyqfd and pyfmea handles the basic operations: create, retrieve, update, and delete through an instance of the Action class, which associates a database model with a Pydantic schema. The ***create*** and ***update*** methods persist the data through sqlalchemy only if the input data conforms to the schema. A few special cases build upon these where required, for example to ensure the symmetry between functional requirement interactions.

With the exception of ***delete***, the return value of all methods must also conform to the relevant schema.

The data is stored in a sqlite3 database.

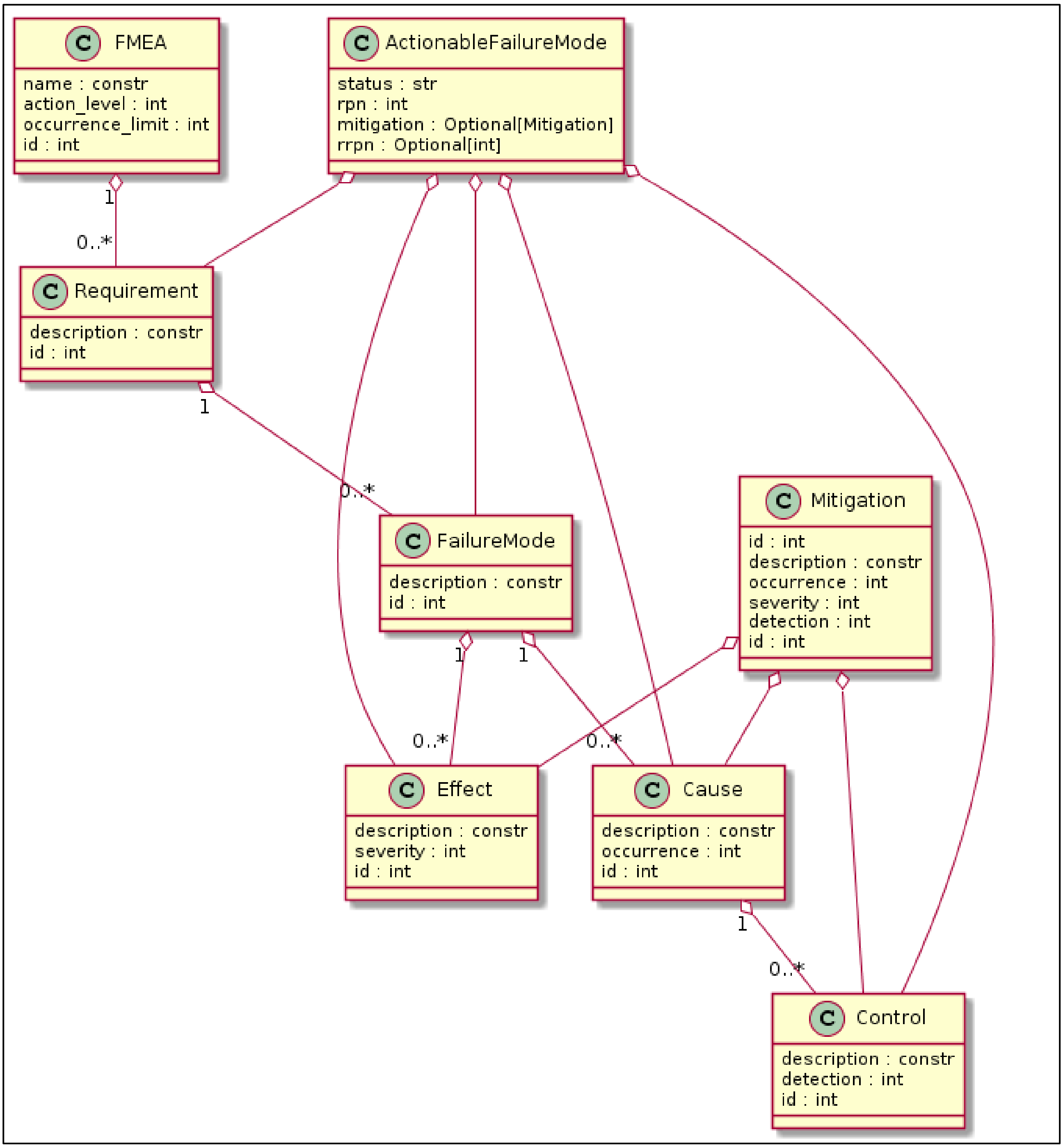


FIGURE 4.2: SIMPLIFIED REPRESENTATION OF FMEA SCHEMA

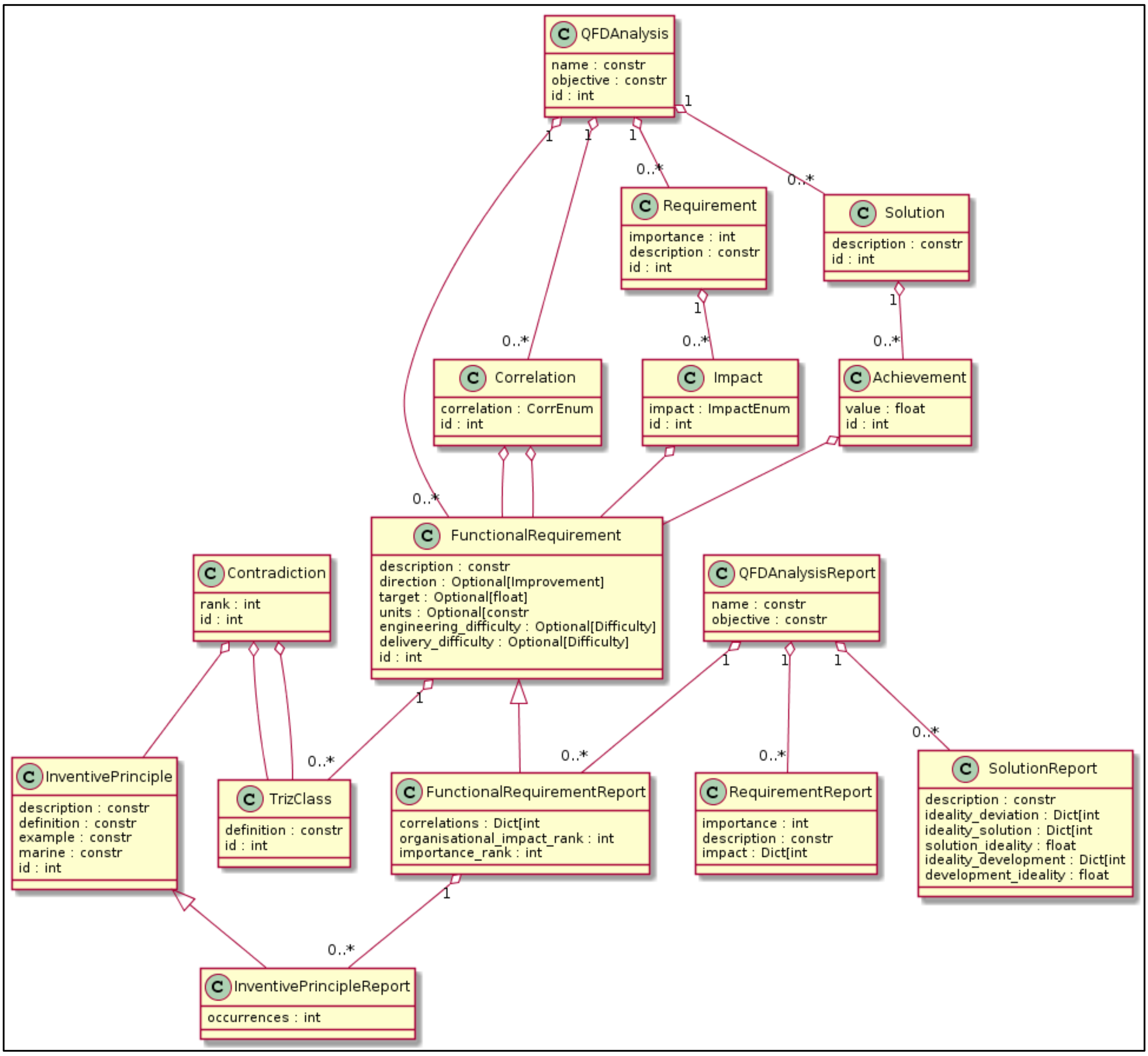


FIGURE 4.3: SIMPLIFIED REPRESENTATION OF QFD/TRIZ SCHEMA

4.1.2 BACK END

The Back End is a web service, implemented using the Flask microframework for Python. The code is organised into multiple Blueprints for FMEA, QFD/TRIZ, external API for other modules, and a suggestions Blueprint, which provides suggested inputs to the user via the Front End.

Library	Description	URL
Flask	'Microframework' for Python. Handles http requests and responses.	http://flask.palletsprojects.com/
Requests	HTTP library. Handles HTTP requests originating *from* the Back End to other services.	https://requests.readthedocs.io/

4.1.3 API

The Back End also provides the API exposed to other DTOceanPlus modules, published to the other modules OpenAPI, and which currently includes two endpoints. The parameter *qfdId* is an integer value representing the ID of the QFD/TRIZ analysis.

Method	Path	Description
GET	/{qfdId}/targets	Returns a list of targets for a QFD analysis
GET	/{qfdId}/solutions	Returns a list of solutions for a QFD analysis

4.1.4 FRONT END

To achieve a consistent look and user experience, all DTOceanPlus modules are using the same JavaScript framework and component library. The Front End is separated into FMEA and QFD/TRIZ, with the ability to move between these in a simple and integrated manner.

Library	Use	URL
Vue.js	JavaScript framework used for Front End	https://vuejs.org/
ElementUI	Ready-made UI components for VueJS	http://element.eleme.io/
Wretch	Wrap the JavaScript Fetch API for making HTTP requests	https://elbywan.github.io/wretch/

This section provides an overview of the Front End of the SI tool, with a short description of the functions and features within each layout.

4.1.4.1 FMEA

The user inputs the name of the analysis they are carrying out on the FMEA *Begin* page, as shown in Figure 4.4, followed by the action level and the occurrence limit. The action level and occurrence limit fields both use number fields which can be inserted by the user, dependent on the threshold values they want to set.

Each page also consists of a next or previous button for guided progression throughout the process.

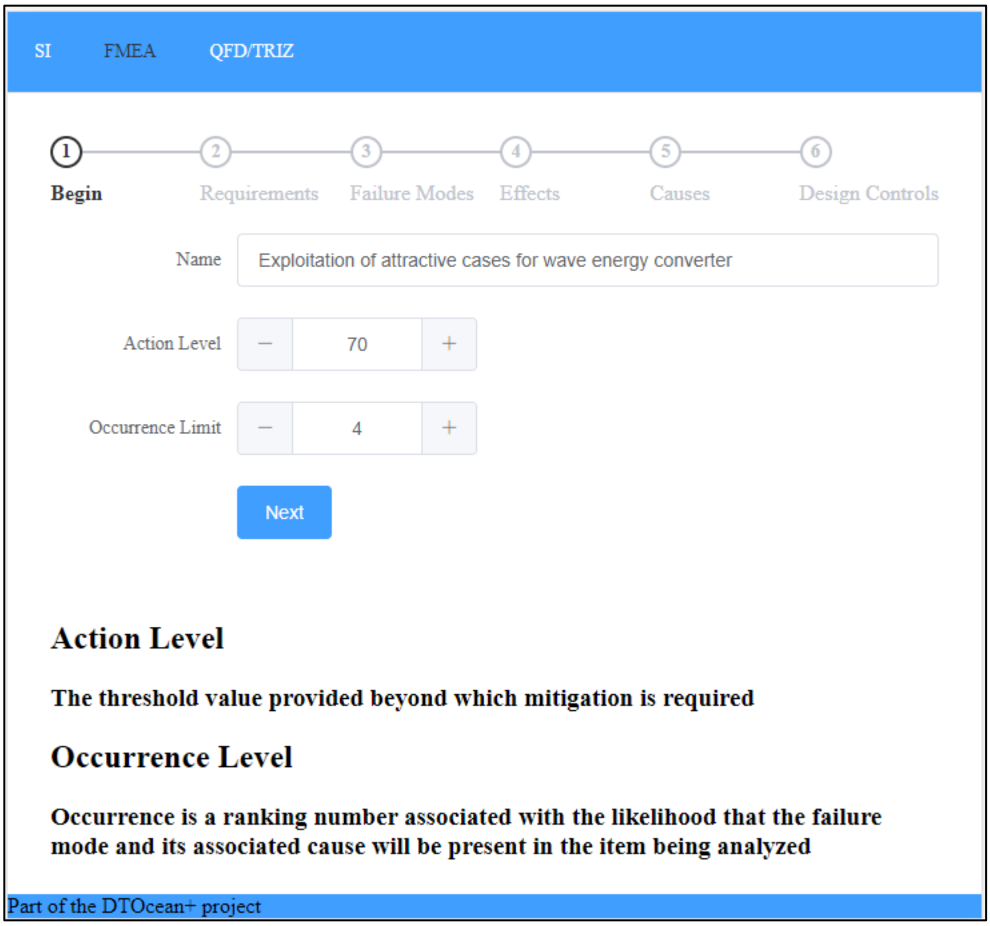


FIGURE 4.4: FMEA BEGIN PAGE

The *Requirements* page, in Figure 4.5, is where the user can input their requirements. The field is made up of a button which allows the user to delete the field and a text field where the requirement would be entered. There is also a Add Requirement button which automatically creates a new field to enable addition of multiple requirements.

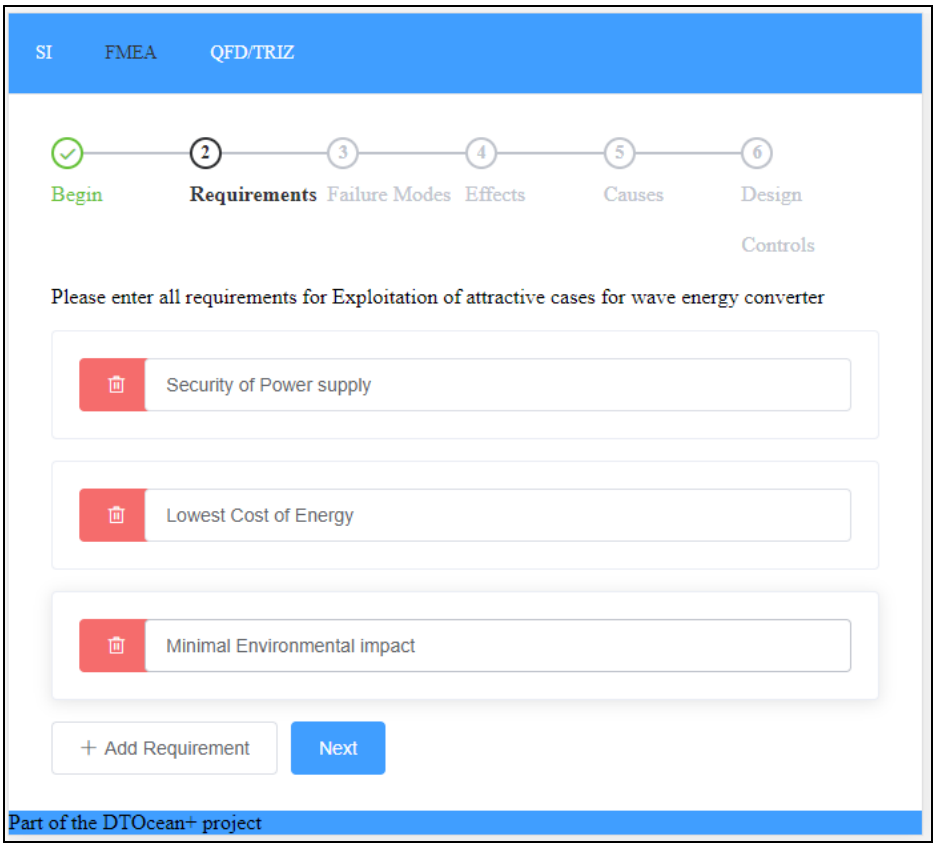


FIGURE 4.5: REQUIREMENTS PAGE

The *Failure Modes* page, in Figure 4.6, allows the user to insert failure modes for the requirements they have entered. The *Failure Modes* page follows the same layout as the *Requirements* page where the user can add new failure modes by clicking on the 'Add Failure Mode' button or delete the field by clicking on the red trash icon.

When the user clicks on the 'Next' button they will be shown the same page, but it will cycle through all the requirements that the user has entered so that they can enter failure modes for each requirement.

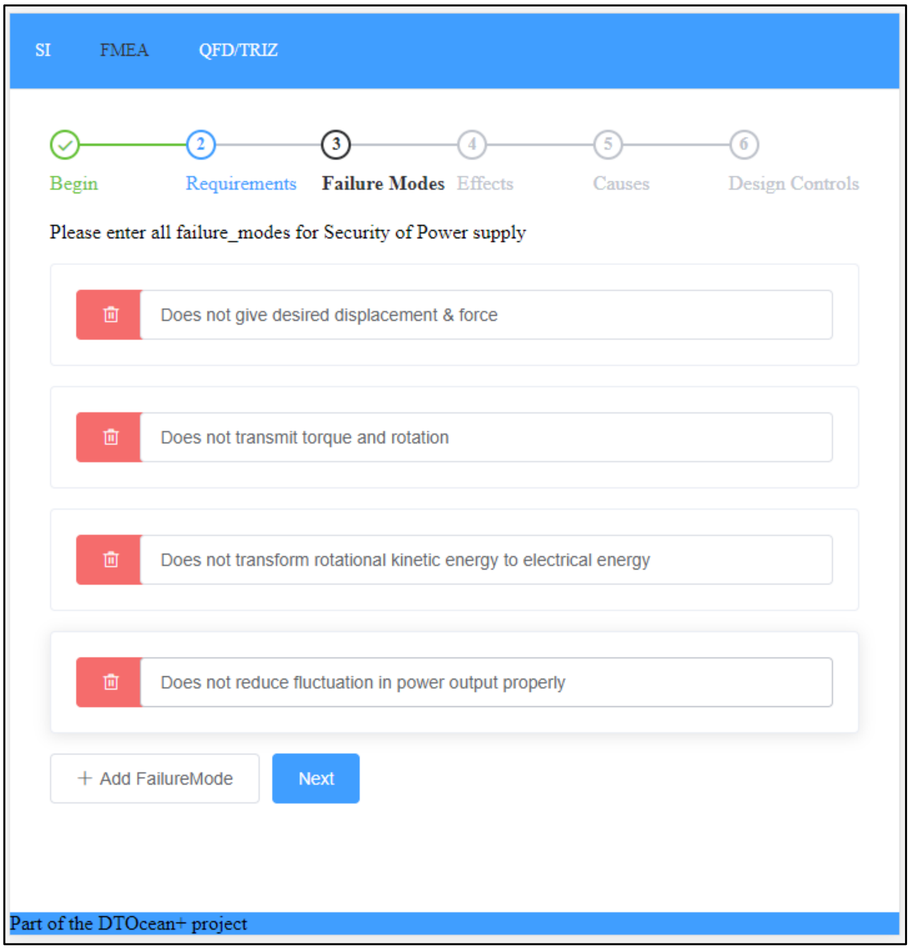


FIGURE 4.6: FAILURE MODES PAGE

The *Effects* page is where the user includes the effect(s) that the failure mode could face. The Page, as shown in Figure 4.7, is made up of two fields which are the name of the effect and the severity option. The severity field is made up of a drop-down list which consists of a number ranging from 1-10 that the user can pick from. This severity ranking was defined in Table 2.3.

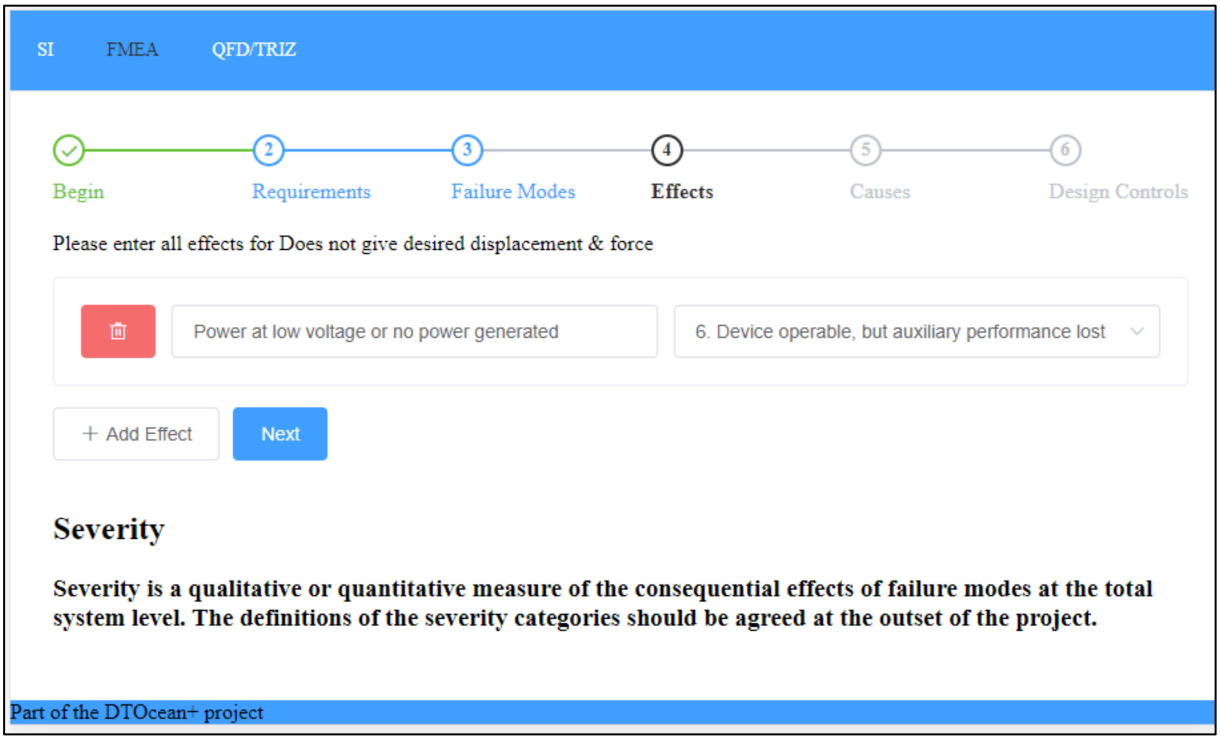


FIGURE 4.7: EFFECTS PAGE

The *Causes* page, shown in Figure 4.8, is where the user identifies causes and problems which are related to the failure modes. The page is made up of 2 fields which include the input field to describe the cause and then a field for the occurrence limit. The occurrence field is made up of a drop-down list of occurrence limits which range from 1-10. The occurrence ranking is defined in Table 2.4. The occurrence limit also has a small description next to the occurrence value to give an understanding of what the user is choosing e.g. 6. Occasional failures (1 in 80).

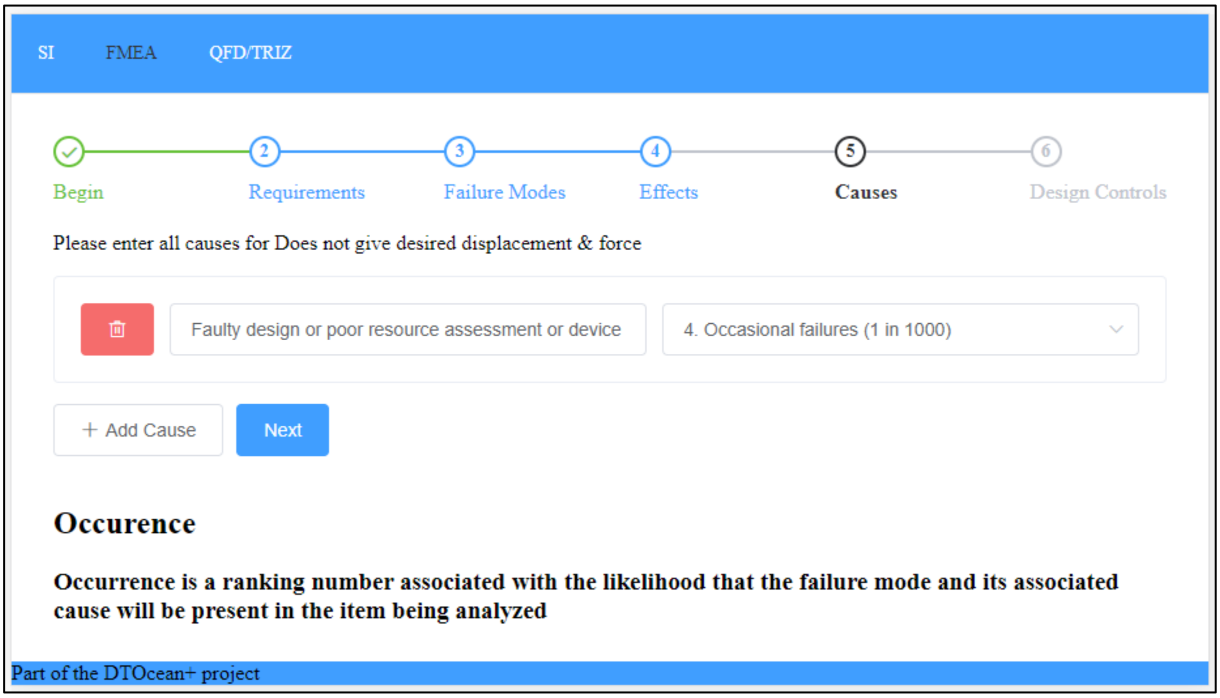


FIGURE 4.8: CAUSES PAGE

The *Design Controls* page, shown in Figure 4.9, is where the user inputs the design controls for the causes which were previously added. The user inputs the name of the design control and then the Detection value. Details about the Detection ranking can be found in Table 2.5. The second field on the page follows the same layout as the previous pages where the Detection field is made up of a drop-down list

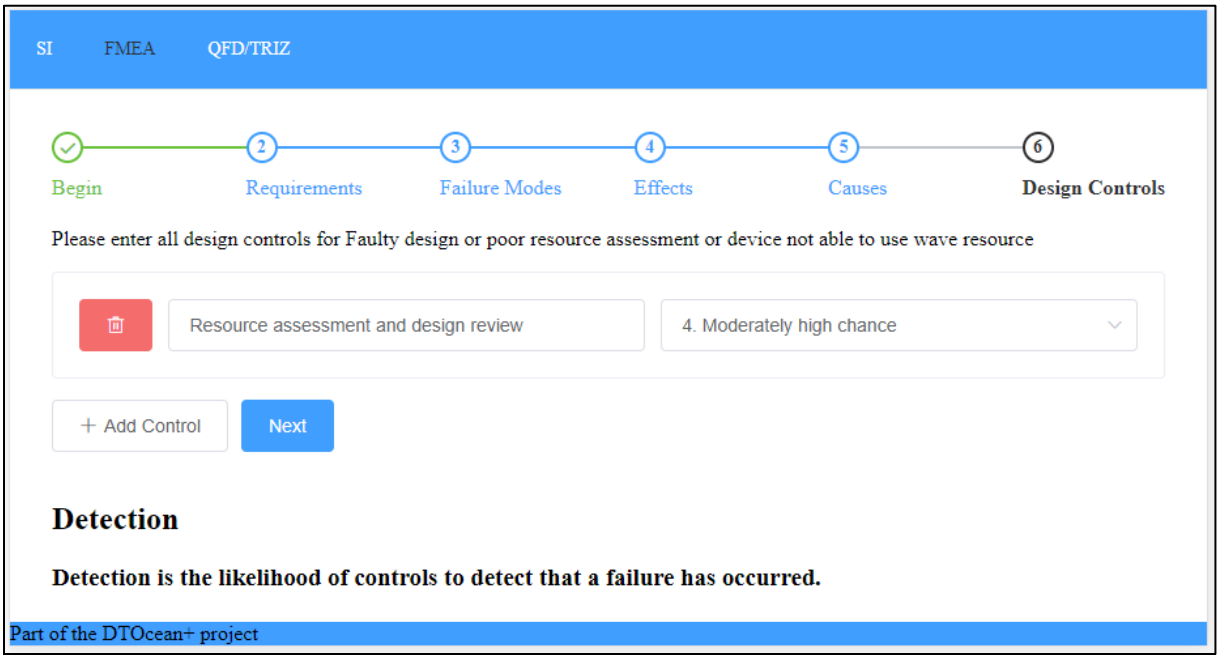


FIGURE 4.9: DESIGN CONTROLS PAGE

The *Results* page, in Figure 4.10, shows all the information that was inputted by the user. It consists of the Requirement that was inputted followed by the failure mode. The effects are also included, with the severity level, causes and the occurrence level, and the design control and detection level. When these are all calculated together the final value is shown in the 'RPN' field.

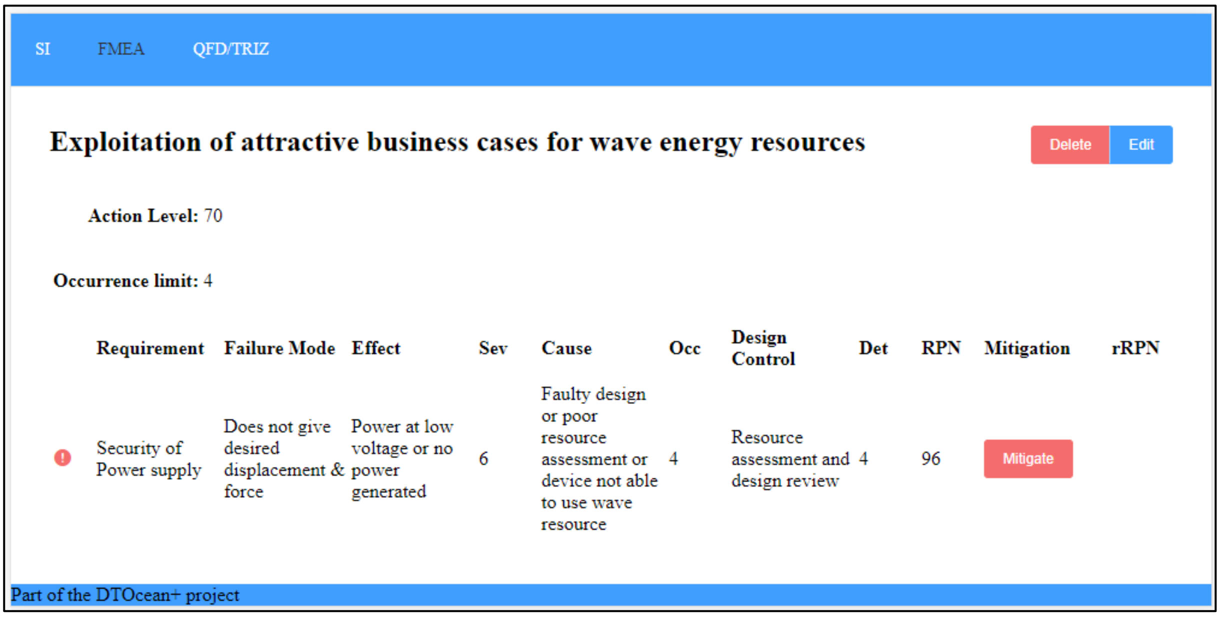


FIGURE 4.10: RESULTS PAGE

There are also Delete and Edit buttons in the top right-hand corner of the page (Figure 4.10) where the user can delete the whole analysis or Edit certain parts if they wish to amend their study.

As can be seen in the first column, there is a red indicator which indicates that the final RPN value is higher than the Action Level which was stated at the start of the analysis. If the RPN value is lower than the action level, then this indicator would be green. If the Indicator is orange that means that the RPN is below the action level, but the Occurrence limit is too high. This can be changed by clicking on the 'Mitigation' button which then allows the user to go through the analysis again and make changes where possible.

Once the user clicks on the mitigation button, the *Mitigation* page, as shown in Figure 4.11 overleaf, will appear. The user can then describe the Mitigations and then change the values of the Severity, Occurrence and Detection levels as shown in Figure 4.12.

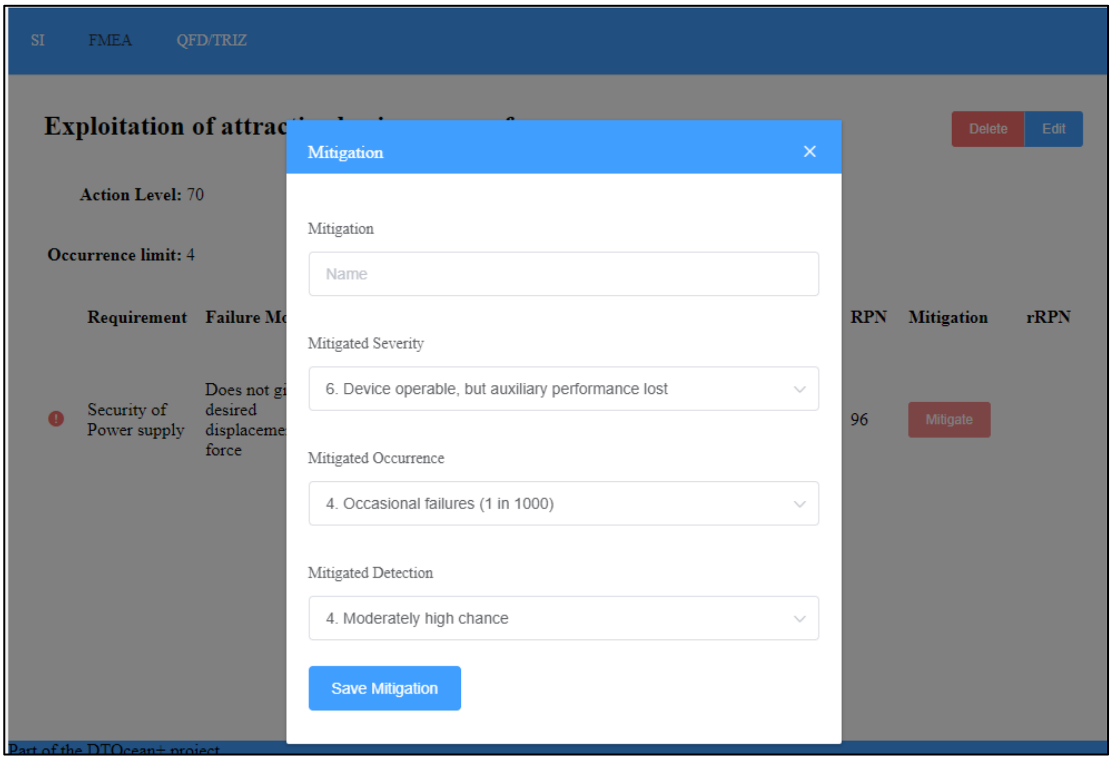


FIGURE 4.11: MITIGATION POP-UP PAGE

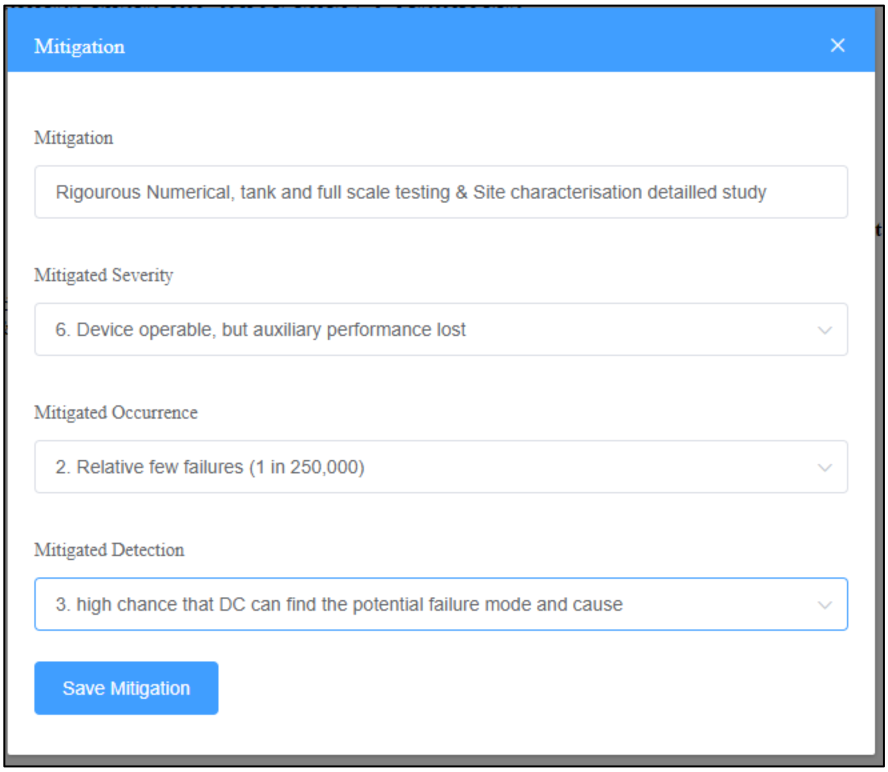
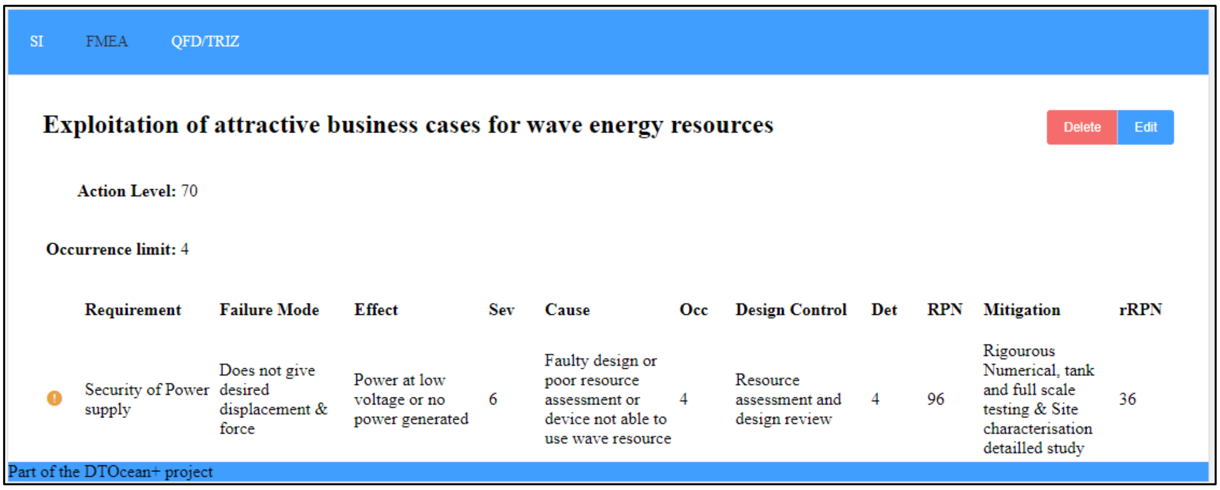


FIGURE 4.12: MITIGATION PAGE COMPLETED

Once the Mitigation is saved, the Mitigation pop-up window will disappear, and on the *Results* page, a new RPN value will be shown in the reviewed 'rRPN' column as seen in Figure 4.13 .



Requirement	Failure Mode	Effect	Sev	Cause	Occ	Design Control	Det	RPN	Mitigation	rRPN
Security of Power supply	Does not give desired displacement & force	Power at low voltage or no power generated	6	Faulty design or poor resource assessment or device not able to use wave resource	4	Resource assessment and design review	4	96	Rigourous Numerical, tank and full scale testing & Site characterisation detailled study	36

FIGURE 4.13: RESULT PAGE WITH GENERATED RRPN

Note here that the orange Indicator next to the requirement means that the RPN is below the action level, but the Occurrence limit is nevertheless beyond the Occurrence threshold given as 4. This can be changed by further mitigation of the design controls and proposed ways to reduce the probability of occurrence of the given failures. The 'Mitigation' button will allow the user to go through the analysis again and make changes where possible.

4.1.4.2 QFD/TRIZ

The Front End of the QFD/TRIZ module guides the user through identifying the stakeholder and technical requirements for the analysis and their interactions and highlighting conflicts. The user is prompted to identify TRIZ classes which apply to each functional requirement. Finally, the user is presented with information about the ideality of the potential solutions, and a list of the TRIZ inventive principles that would have the greatest impact.

The Contents page, as shown in Figure 4.14, is the main screen for the SI tool. There is a similar layout for both the FMEA and the QFD/TRIZ components. The top toolbar is a link to the different components which make up the SI tool.

The 'New' button on each Content page allows the user to start a new analysis. Each Content page includes links to analyses which have already been created. Figure 4.14 shows the QFD/TRIZ content page allowing the user to create a new QFD/TRIZ analysis, import or open an existing analysis.

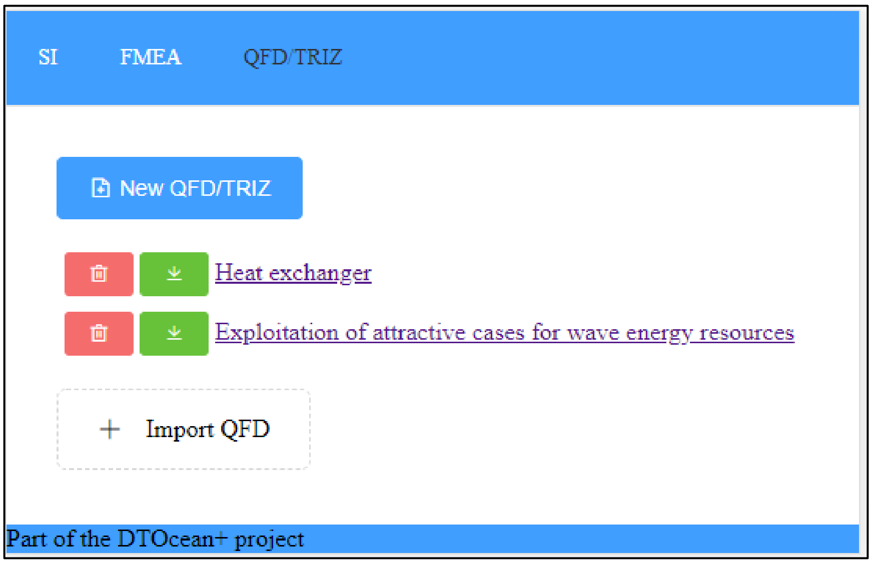


FIGURE 4.14: QFD/TRIZ CONTENT PAGE

Figure 4.15 is the *QFD/TRIZ Starting* page of the SI tool. The user would input the name of the analysis and the objective that they are trying to achieve.

FIGURE 4.15: CREATE QFD/TRIZ PAGE

Figure 4.16 shows the QFD/TRIZ *Requirements* page. The green button allows new requirements to be added and the red button allows the user to delete the requirement. Due to the page needing requirements to be in order of priority, users can insert requirements and then move (drag) them around until they have their desired order.

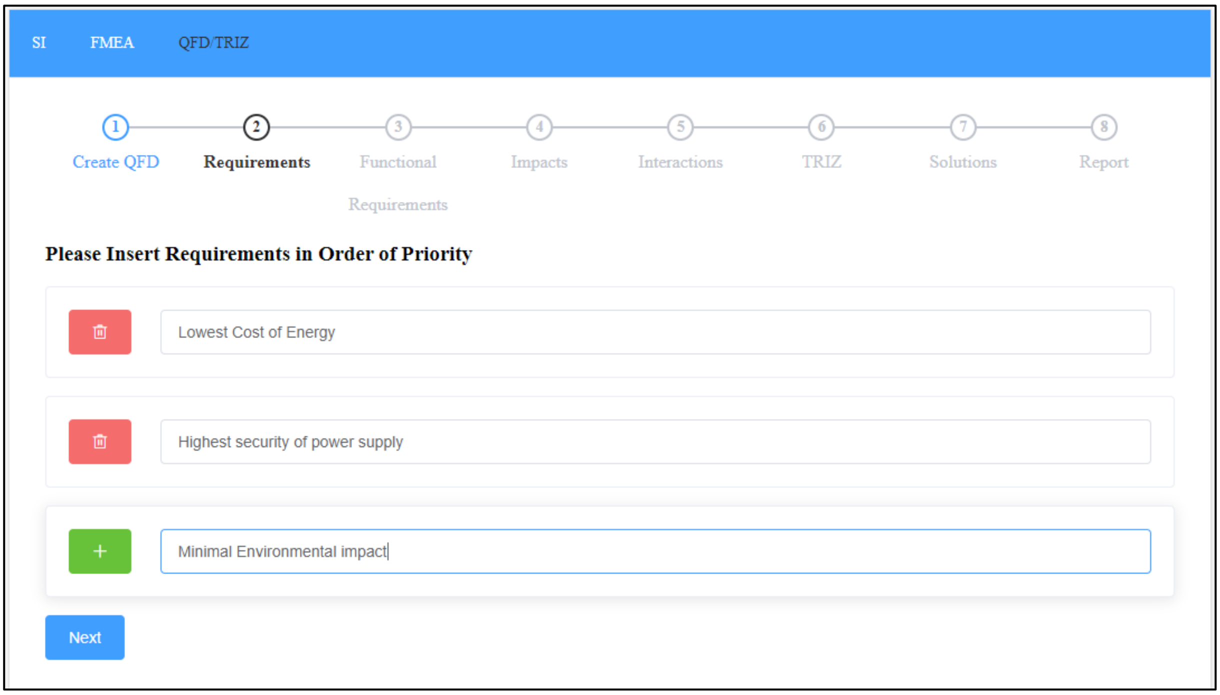


FIGURE 4.16: REQUIREMENTS PAGE

The *Functional Requirements* page, as shown in Figure 4.17, consists of engineering requirements which contribute to achieving requirements set out in step 2 of the process. The fields consist of a description of the functional requirement, the target values, the units, the overall direction of desired improvement, the difficulty to engineer and the difficulty to deliver.

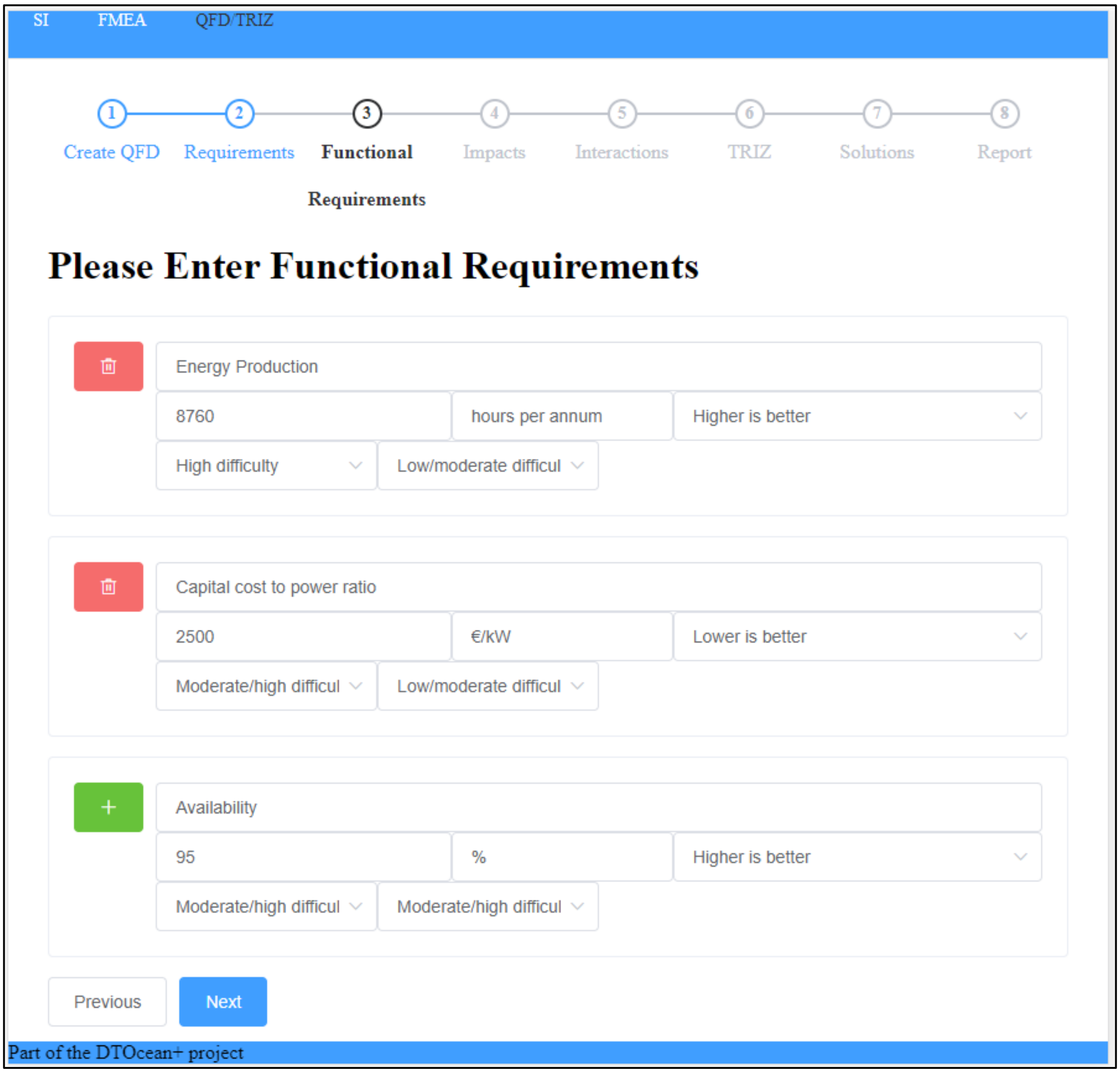


FIGURE 4.17: FUNCTIONAL REQUIREMENTS PAGE

The *Impacts* page, as shown in Figure 4.18, is used to define the level of impact that the functional requirements will have on the customer requirements, using drop-down boxes.

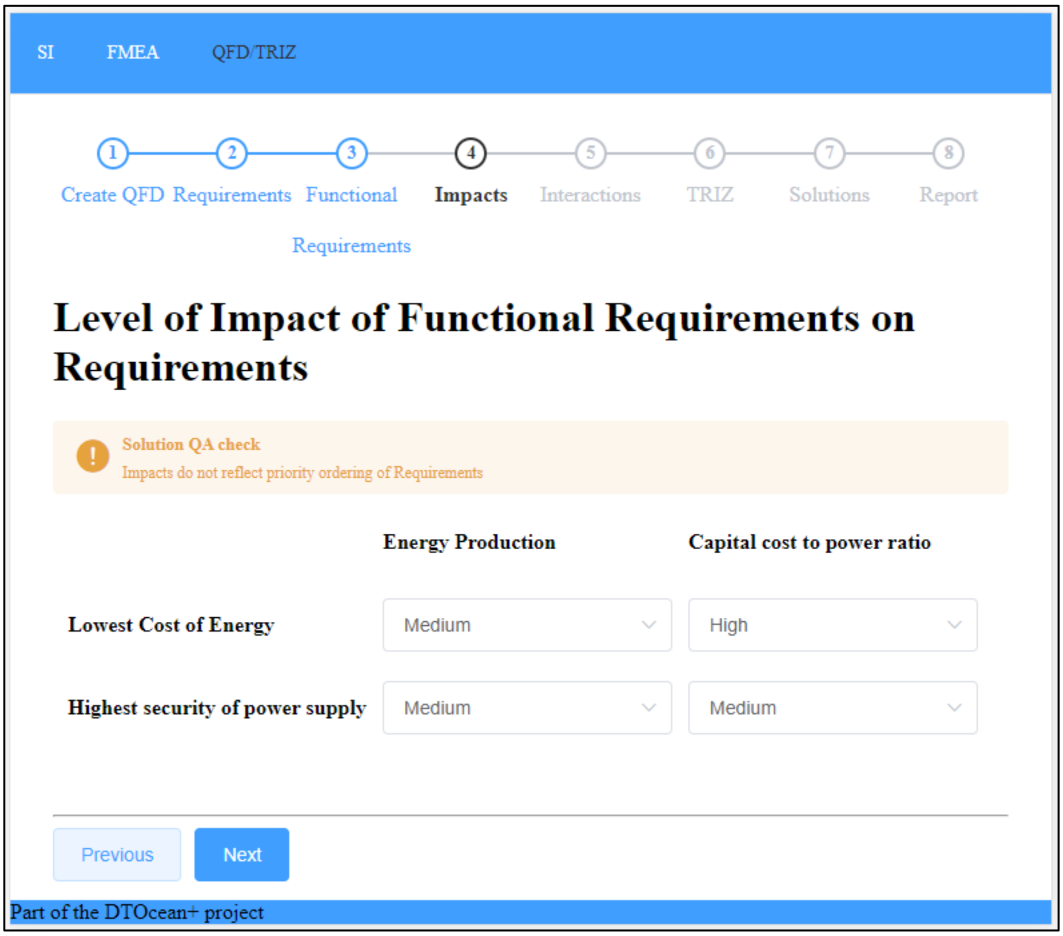


FIGURE 4.18: IMPACTS PAGE

The *Interactions* page, as shown in Figure 4.19 is used to define the interdependencies between the different functional requirements. Each functional requirement has a slider which can be moved by the user. The functional requirements collapse or expand as the user selects a different requirement.

The rankings for the slider are high negative, medium negative, low negative, none, low positive, medium positive and high positive. When the user moves the slider for a particular functional requirement it will also be moved on the corresponding functional requirement.

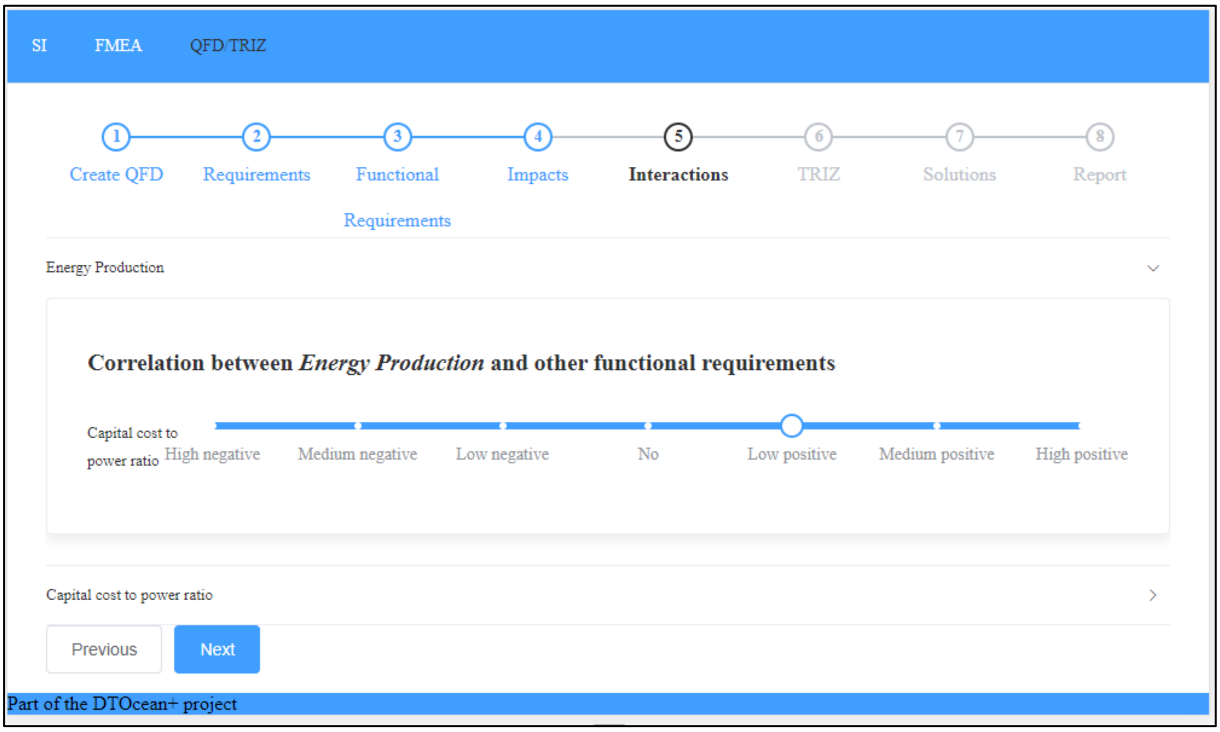


FIGURE 4.19: INTERACTIONS PAGE

The *TRIZ Classes* page (overleaf) consists of all the functional requirements which were inputted by the user. This section, known traditionally as the roof of HoQ, helps the user specify the various engineering features that have to be improved collaterally. Sometimes one targeted feature impacts many others highlighting engineering trade-offs.

There are pre-existing TRIZ classes which are completed automatically, dependent on the requirement which was entered. Figure 4.20 shows a dropdown of predefined TRIZ features from the contradiction matrix (Figure 2.4). The 'multiple select' feature can be included by a touch of the mouse but can also be cancelled by clicking on the cross function as seen in Figure 4.21 .

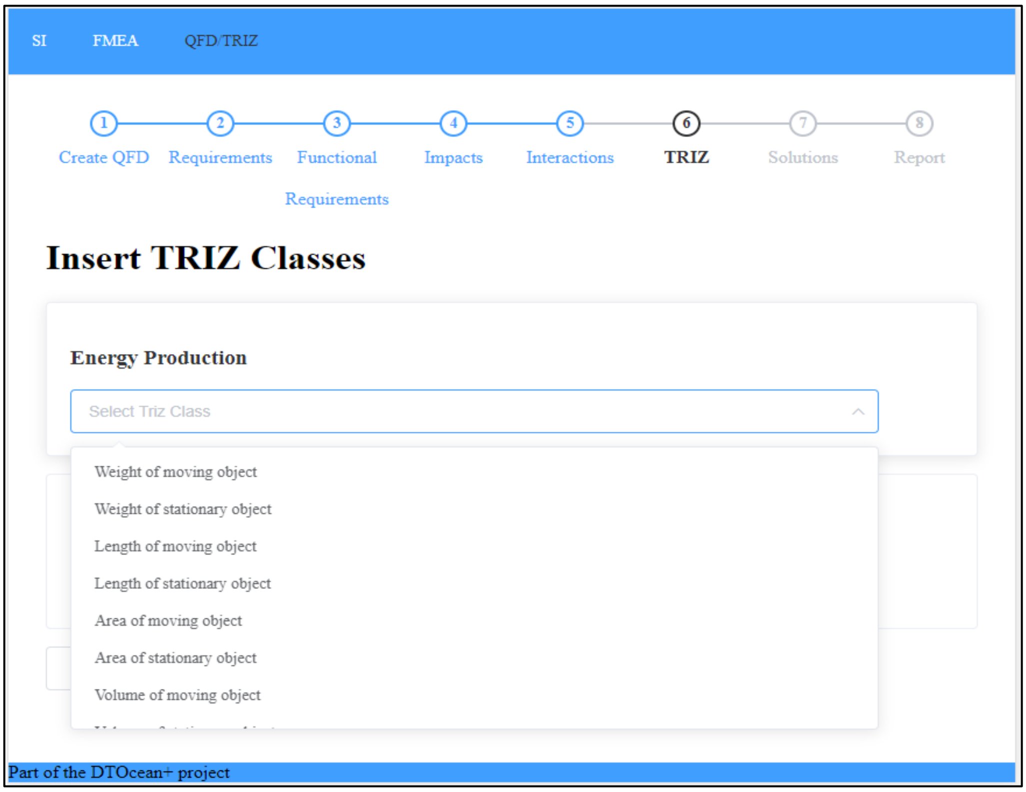


FIGURE 4.20: TRIZ CLASSES PAGE PREDEFINED FEATURES

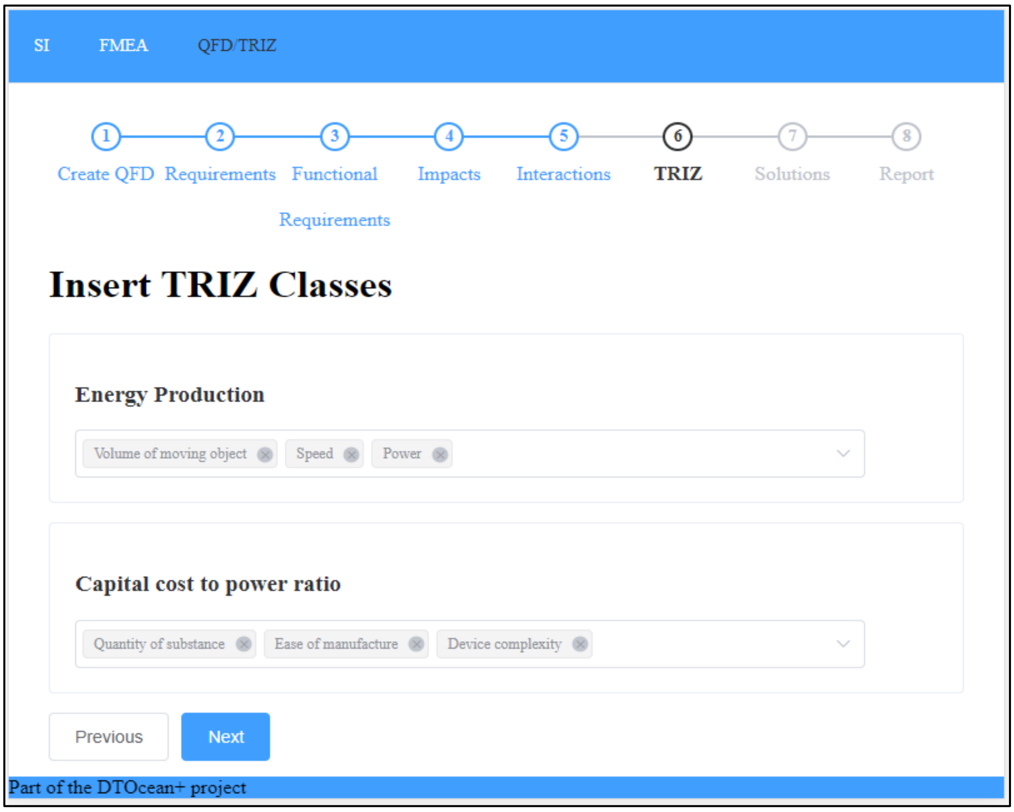


FIGURE 4.21: TRIZ CLASSES PAGE COMPLETED

The *Solutions* page consists of various input fields. Here, the relevant functions of the State-of-the-art or the competitor's technologies are compared to the ideal target values proposed for innovation. The tool will warn the user if an input field is left blank as seen in Figure 4.22.

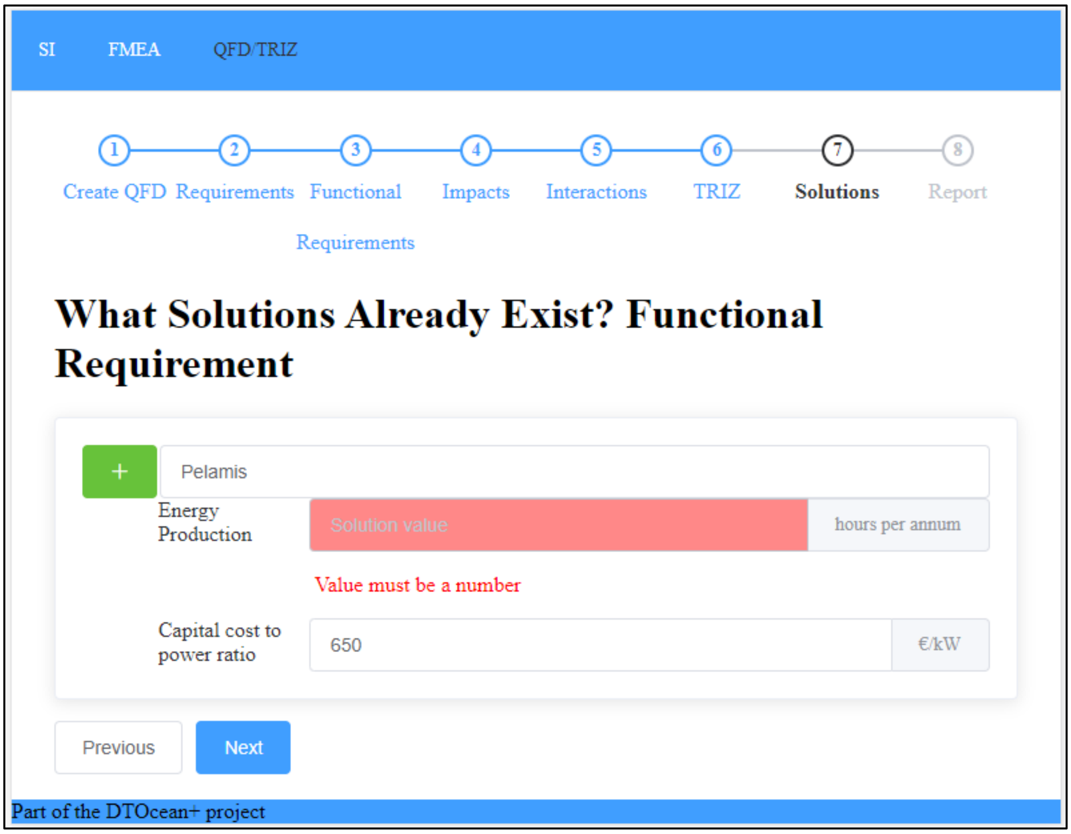


FIGURE 4.22: SOLUTIONS PAGE ERROR IF VALUE IS NOT ENTERED

The units fields at the end of each line are automatically inserted, dependent on the requirements and data which have already been inputted by the user. The input fields can be deleted, and new ones can be added by either clicking on the red trash icon or clicking on the green add button.

A completed Solutions page is shown overleaf in Figure 4.23.

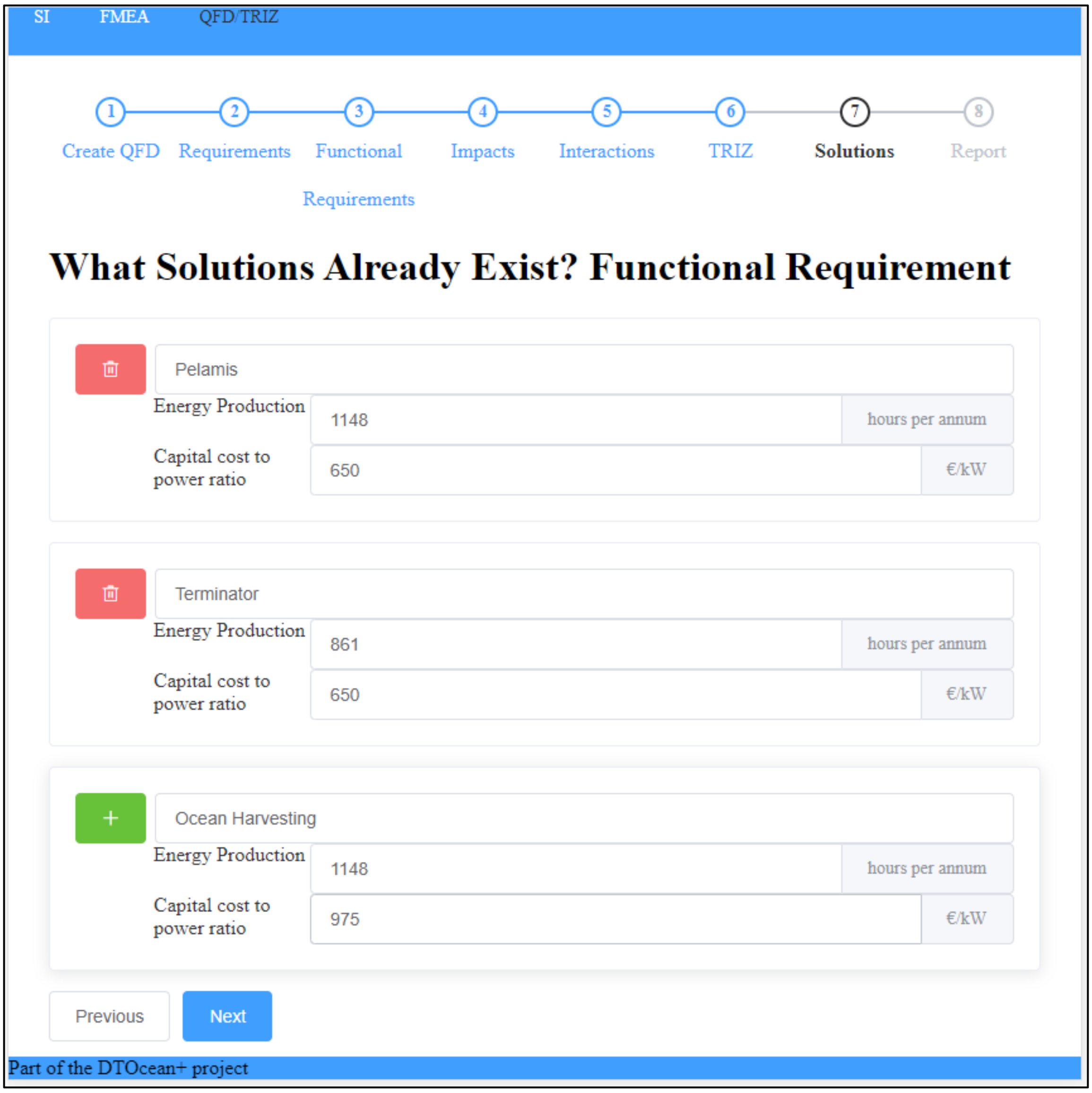


FIGURE 4.23: SOLUTIONS PAGE COMPLETED

The *Report* page summarises three sections: the solution ideality, the development ideality and the TRIZ suggested inventive principles. Figure 4.24 shows the Solution Ideality on the report page, which tells the user whether the competitive solutions meet the target criteria and their compliance. The higher the figure the better it is.

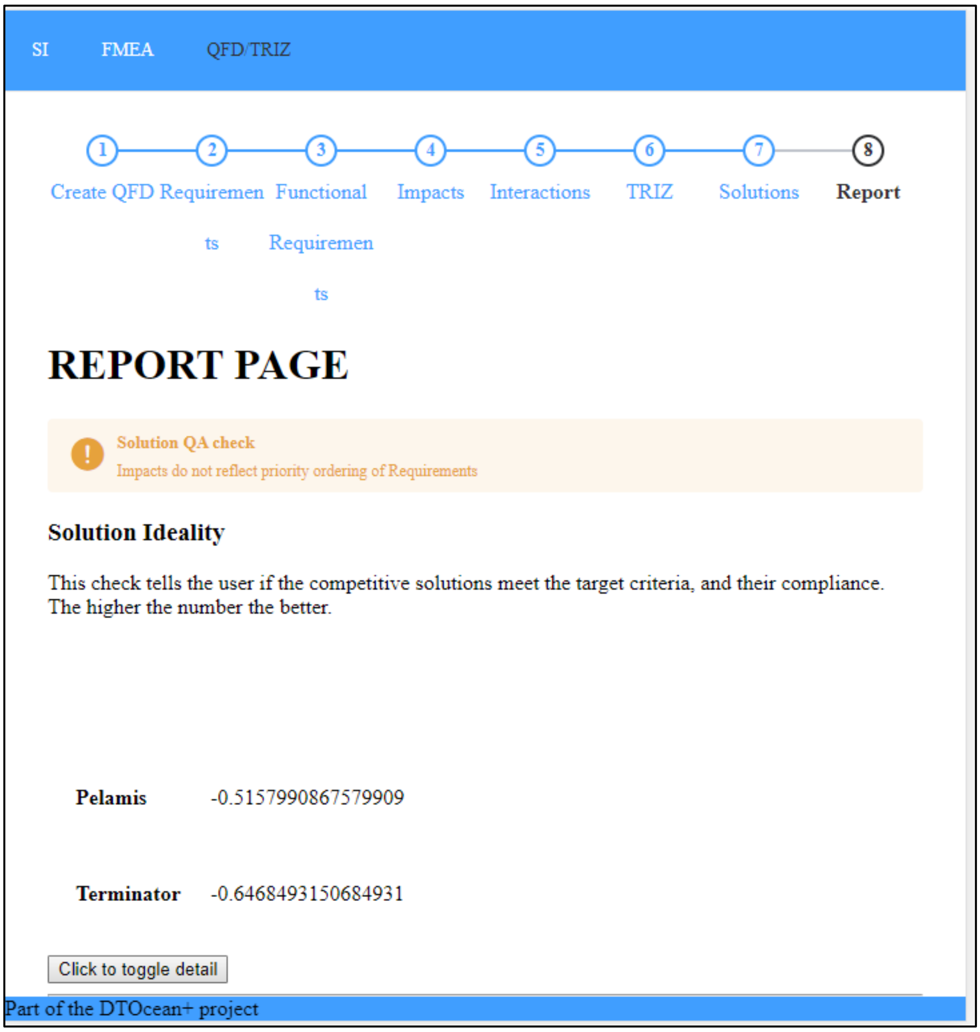


FIGURE 4.24: REPORT PAGE SUMMARISING THE SOLUTION IDEALITY ASSESSMENT

At the bottom of the screen there is a button labelled 'click to toggle detail'. This toggles between the summary shown above and a screen with expanded detail.

Figure 4.25 shows the Development Ideality on the *Report* page. This indicates the likelihood that the competitive solution can meet the target criteria. The Development Ideality follows the same layout as the solution ideality.

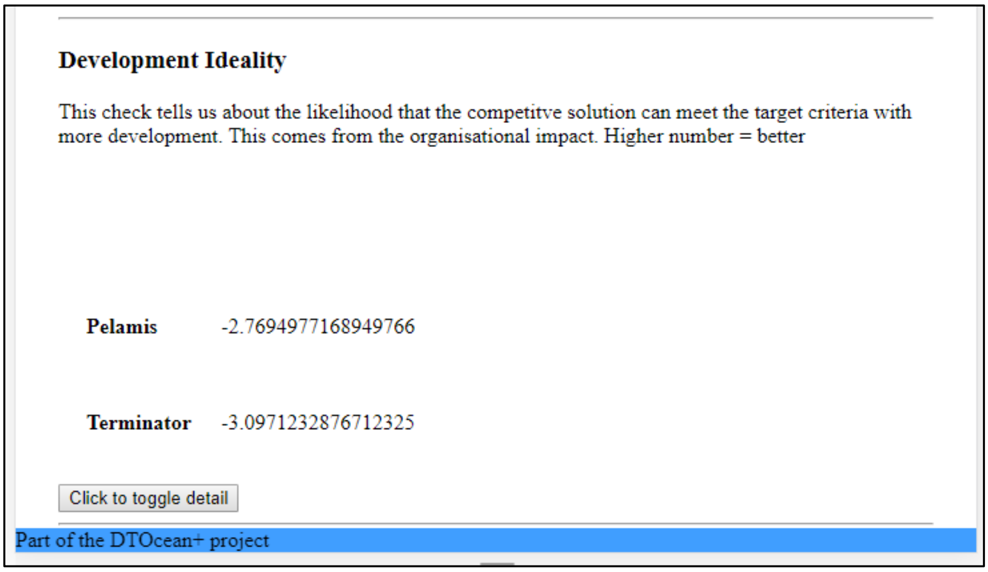


FIGURE 4.25: REPORT PAGE SUMMARISING THE DEVELOPMENT IDEALITY

Figure 4.26 shows the Suggested Inventive principles which are located on the *Report* page. Again, a button on the bottom left of the page allows the user to expand and shrink the information.

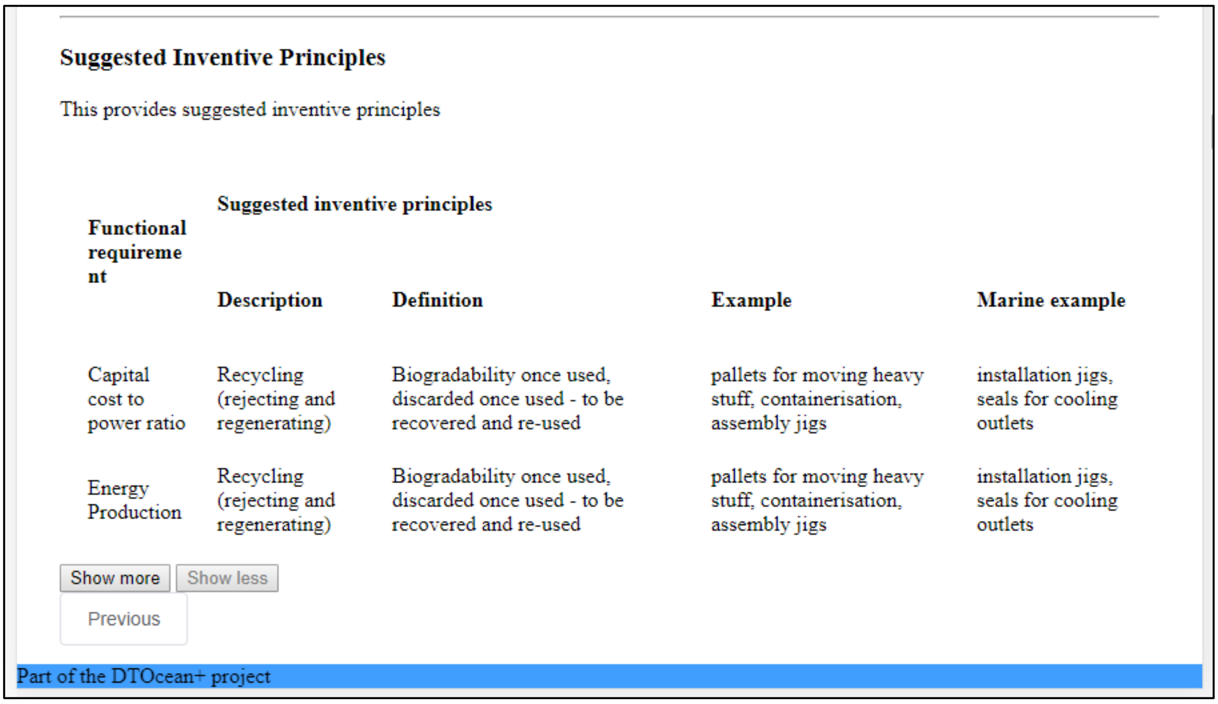


FIGURE 4.26: REPORT PAGE WITH SUGGESTED INVENTIVE PRINCIPLES

4.1.5 THE TECHNOLOGIES

The Business Logic and the API of the SI tool were coded in Python version 3.8, and the GUI of the module was developed in Vue.js, using the library Element-UI.

The installation of the module requires the following non-standard Python packages:

- flask-cors
- Flask-WTF
- pydantic
- SQLAlchemy-Utils

The testing of the module requires the following non-standard Python packages:

- deepdiff
- dredd-hooks
- pytest-cov
- pytest-env
- pytest-flask
- requests

The API will rely on OpenAPI specification v3.0.2.

TESTING AND VERIFICATION

Testing of the Structured Innovation tool is being carried out using multiple testing libraries and several approaches. Unit tests are being used to test the component functions of Back End and Business Logic, with a target of 100% code coverage. The Front End is being tested as part of the End-to-end testing, which ensures user requirements are met. The implementation of services provided to other modules is also being tested against the OpenAPI description.

The libraries currently being used for testing are outlined in the Table 4.3.

Table 4.3: Libraries used for testing

Library	Use Case	URL
Pytest	Unit testing Back End and Business Logic	https://docs.pytest.org/
DREDD	Testing that service implementation matches OpenAPI description	https://dredd.org/
Cypress.io	Testing the user requirements are met (End-to-end testing)	https://www.cypress.io/

The tests performed by Pytest outline the code coverage achieved for each module[1].

[1] https://gitlab.com/energysystemscatapult/dtoceanplus/dtop_structinn/-/jobs/526054406#L102

5. FUTURE WORK

The present deliverable collects the main functional and technical aspects of the Structured Innovation design tool (SI), implemented during tasks T3.1 and T3.2 of the DTOceanPlus project. At the time of writing, the module can be run in a standalone mode. Some progress has been made toward the integration with other DTOceanPlus tools. For instance, a collaborative API was configured in which modules had to link to the schemas and routes they required from other modules. However, in order to fully integrate the SI tool with the remaining modules of the DTOceanPlus suite of design tools, the following steps are required:

- The front-end (FE) unit tests and end-to-end (E2E) integration tests need to be extended to ensure 100% coverage for all the Structured Innovation functionalities.
- Contract testing will be implemented using 'Pact'. This is a tool for testing HTTP integrations using *contract testing*. This is a technique that tests an integration point by checking each application in isolation to ensure the messages it sends or receives conform to a shared understanding that is documented in a 'contract'[2]. Testing using Pact has already been set up for the Structured Innovation tool and one of its provider modules. Tests need to be written for each of the modules that will interact with the SI tool.
- The actual integration of the modules must then take place and *integration tests* must be developed. Integration testing is the phase in software testing in which individual software modules are combined and tested as a group. This task extends the preceding tasks of Dredd validation (which has been completed) and the Pact testing mentioned above.
- Further detailing of solution hierarchy, particularly in the lower levels.
- Further detailing of Fundamental Relationships database.
- Further refinement of some functionalities throughout the SI tool to implement additional details, improve user experience, etc. (These will not impact interfaces with other modules).
- Additional refinements dependent on feedback from the verification testing.

These activities will be developed within task T3.3 - Verification of the Structured Innovation tool (Beta version). These subsequent tasks will extend the functionalities of the Structured Innovation tool from the current standalone version to be fully integrated in the DTOceanPlus suite of tools.

[2] See the Pact documentation for more details; https://docs.pact.io/

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I. ANNEX

This Annex contains lists of the following information:

1. **TRIZ Inventive Principles**
2. **Solution Hierarchy (levels 1 to 3)**
3. **FMEA Library**
    a) Generic Failure Modes
    b) Generic Effects
    c) Generic Causes
    d) Generic Design and Process Controls

TRIZ INVENTIVE PRINCIPLES

The inventive principles are listed overleaf in Table 0.1, Table I.0.2 and Table I.0.3.

TABLE 0.1: TRIZ INVENTIVE PRINCIPLES IN THE SI TOOL (1/3)

40 Inventive Principles			
Principle #	**Description**	**Define**	**Marine Energy Example from existing practice**
1	Segmentation	Divide into independent parts, make objects sectional, increase degree of segmentation	turbine blades in connectable modules
2	Separation or extraction	Extract the problem, extract the needed element or function	
3	Local quality	Different properties rather than homogeneous, segmented parts operate under own rules	turbine blade leading edge protection
4	Asymmetry	Replace symmetry, increase degree of asymmetry	WEC floats, blade sections, sub-frame stringers using prime number spacing
5	Merging or combining	Join similar objects and functions, Bundle multiples, merge dissimilar object to make new object	Bearing cooler acts as a heat sink
6	Multi-functionality	performs additional functions without hindrance	generator acts as a brake
7	Nested	Split structure or function to save space	telescopic turbine blade spoilers
8	Counter-weight	Balance asymmetrical forces and couples	air-lift bags for recovery and installation, balanced blade arrangements
9	Preliminary counter-action	Counter stress in advance, like pre-loading	pre-loading of polymer seals for longer life
10	Preliminary action	In advance of function, do part or whole action or function	install blades before turbine installation
11	Preliminary Compensation	For high occurrence, prepare, provide arrangement to negate problem	slipping clutches for torque overloads
12	Equipotential	Change process for level action, work on flat surfaces, reduce bends and contours	OWC for wave in existing structures
13	Other way around	Reverse usual action, use opposite features, change part or function, go back to front	buoyant nacelles, tensegrity foundations

TABLE I.0.2: TRIZ INVENTIVE PRINCIPLES IN THE SI TOOL (2/3)

40 Inventive Principles			
Principle #	**Description**	**Define**	**Marine Energy Example from existing practice**
14	Curve increase	Change lines to arcs, squares to circles, cubes to spheres	blade curvature to offset deflection due to thrust
15	Dynamism	Add adjustment, movability,	Adjustable blade sections, flow adjustment devices
16	Partial or excessive action	Provide more than needed and remove later, provide less than needed and top up later	rotors machined to size,
17	Moving to another dimension	Move to a higher or lower dimension	WEC floats that act in heave and sway
18	Mechanical vibration	Set structures vibration level or noise	use shaker to remove biofouling, WEC floats in resonance
19	Periodic action	Pulsing or vibration spacing or periods	Periodic cleaning of hulls, blade pitch adjustments to give lower turbulence
20	Continuity of useful action	Operate at max power, remove idling and transitions	rate for max power, and then load shed anything above that
21	Hurry Through	Performa harmful or useless operations quickly	Speed up through resonance
22	Blessing in disguise (harm to benefit)	Turn harm to good	
23	Feedback	Introduce feedback, enhance or change existing feedback	CBM or in-process testing
24	Intermediary	Temporary joints or functions	lift airbags for lowering to sea floor
25	Self-service	Self-operation by aux functions, self-righting lifeboats	Self-repairing systems
26	Copying	Use cheap copy of original,	patterns from original prototype
27	Cheap disposable	Replace robust originals with weaker	sacrificial anodes

TABLE I.0.3: TRIZ INVENTIVE PRINCIPLES IN THE SI TOOL (3/3)

40 Inventive Principles			
Principle #	**Description**	**Define**	**Marine Energy Example from existing practice**
28	Substitution of Mechanical system	Replace mechanical system with electrical, optical or radiation	
29	Pneumatics or hydraulics	Replace solids with gas or liquids	
30	Flexible films or membranes	Use flexibility and fine thickness membranes	Nacelle structures held rigid by auxiliary structures like brake reaction rings
31	Porous materials	Make the structure porous, or fill holes in porous structures with a dissimilar material	Blade structures with holes filled with resin
32	Optical changes	Change of colours, brightness or transparency	surface coatings on floats to aid visibility
33	Homogeneity	introduce conformity of key features when there is strong interaction	Water lubricated bearings need no seals
34	Recycling (rejecting and regenerating)	Biodegradability once used, discarded once used - to be recovered and re-used	installation jigs, seals for cooling outlets
35	Physical or chemical properties	Change from solid to liquid to gas, freeze rather than heat, use intermediary states like bi-phase or elastic states	
36	Use phase changes	use properties that change in phase changes, volume, heat capacity, shape etc.	heat pipes for cooling purposes
37	Thermal expansion	Use expansion and contraction properties of materials	
38	Strong oxidants	Use enriched air, O_2 or Ozone O_3, or even special gasses to aid the function	biofouling removal?
39	Inert environment	Remove O_2 and replace with inert gas, work in a vacuum	prevent fire in remote structures with nitrogen atmosphere
40	Composite materials	combine two or more materials to provide improved characteristics	blades and active structures, dielectric materials

SOLUTION HIERARCHY

The solution hierarchy has been developed in five levels for ocean energy projects. This has been completed in all five levels for most sections of the hierarchy, and a small number of additional sections will be further developed during Task 3.3. The complete list can be accessed on GitLab[3]

Levels 1 to 3 of the hierarchy are shown overleaf, in Table I.4, Table I.5 and Table I.6.

Levels 4 and 5 are omitted for clarity, since the tables become too large and more difficult to read when displayed as a single table on an A4 page. However, the full hierarchy is available for reference and all items from it are usable within the Alpha version. As part of the GUI refinement during Task 3.3, a user-friendly map will be developed to complement the context-sensitive drop-down lists.

[3] https://gitlab.com/energysystemscatapult/dtoceanplus/dtop_structinn/-/blob/master/src/dtop_structinn/pyqfd/SolutionHierarchy.tsv

TABLE I.4: SOLUTION HIERARCHY IMPLEMENTED IN THE SI TOOL (1/3)

Cost functions		
Level1	Level2	Level3
Lowest Cost of Energy	Capital cost	Materials cost
		Material amount
		Machinery complexity
		structural complexity
		Standardisation
		Manufacturing complexity
		Manufacturing standard minutes
		Installation costs
		Decommissioning time & effort
	Operational costs	Reliability
		Accessibility
		Designed for maintenance
		Seabed lease costs
		Cost of Capital
		Insurance
		Energy supply
		Economic service life
	Energy Conversion	Resource Activity
		Hydrodynamics
		Machine efficiency
		Grid connection losses
		Availability

TABLE I.5: SOLUTION HIERARCHY IMPLEMENTED IN THE SI TOOL (2/3)

Environmental (Design functions)		
Minimised Environmental Impact	Material Selection	Corrosion
		Radioactivity
		Abundance
		Recyclable
		Robust
		Toxicity
	Fluid flow	Turbulence
		Erosion
		Blockage
		Deposition
		Wave Turbulence
		Splash losses
	Human interaction	Visibility
		Accessibility
		Lighting
	Degradation	corrosion
		Toxicity
		creep
		ageing
		fatigue
	Noise emissions	
	Material Emissions	

TABLE I.6: SOLUTION HIERARCHY IMPLEMENTED IN THE SI TOOL (3/3)

Security of Supply		
Security / Safety of Power	Survivability	structural complexity
		Fatigue
		Strength
	Grid support	
	Grid strength	

Commercial Risks		
Reduced Commercial Risk	High TRL components	
	System Engineering approach	
	Accelerated life testing	
	Social-economic benefits	Local communities
	Social acceptance	Low GHG emission source
		Low polluting energy source
		Minimal impact on taxpayers
		Contribute to energy security
	Low cost of capital	
	Established working practices	

FMEA LIBRARY IN SI TOOL

TABLE 0.7: GENERIC FAILURE MODES IN THE SI TOOL

Failure Modes	
Premature operation	Electrical
Failure to operate at a prescribed time	Electrical short
Intermittent operation	Connector fault
Failure to cease operation at prescribed time	Generator failure
Loss of output or failure during operation	Electrical Overload
Degraded output	Battery failure
Loss of pre-tension	Instrumentation
Entanglement	Calibration error
Drags from position	Fire Alarm
Structural failure	Software Fault
Incorrect orientation	Intermittent output
Structural failure	Comms, failure
Loss of watertight integrity	Material Failure
Hull Breach	Deformation
Structural failure	Fracture/Separation
Deformation/yielding	Surface distortion/ Damage
Disconnection	Degradation/ Capacity reduction
Hydraulic	Functional Failure
Seal failure	Instability
Hose burst	Loss of support
Water ingress	Loss of position keeping
Oil Leakage	Sinking
Valve jump shut/open	Change in draft/buoyancy
	Change in Hydrodynamic properties

TABLE 0.8: GENERIC EFFECTS OF FAILURE IN THE SI TOOL

Effects of failure	
Local Effect	Thermal conductivity
Effect at next higher level of function/assembly	Component Failure
Effects on the system	Insufficient stability
High static stress	Foundation/ground failure
Creep	Extreme load
Capacity reduction	Component Failure
High static stress	Foundation/ground failure
High Dynamic stress	Component Failure
Capacity reduction	Unintentional Flooding
Corrosion	Component Failure
Surface Fatigue	Marine growth
Wear	Unintentional Flooding
Fusion of foreign Material	Component Failure
Crazing	Marine growth
Mechanical Strength	Unintentional Flooding
Hydrogen Damage	Component Failure
Electrical Conductivity	Marine growth
Magnetic stability	Unintentional Flooding

TABLE 0.9: GENERIC CAUSES OF FAILURE IN SI THE TOOL (1/2)

Cause of Failure		
Anchor Bolt Design - Type / topology	Dimensions wrong	Geotech survey error
Anchor bolts Design - arrangement	Dirt & debris	Incorrect fastener torque
Anchor bolts Design - number	Dynamic heating - stress too high	Incorrect tightening sequence
Anchor bolts Design - pre-load	Dynamic Stress – high	Incorrectly located
Anchor bolts Design - size	Dynamic velocity exceeded	Initial position incorrect
Anchor bolts loose	Electrical Power Loss	Lamination
Assembly Defects	Electrical sensor loss	local structural bending
Assembly forces too high	Environmental Compatibility	Loose Bolts
Assembly process design	Fabrications design error	operating temperature exceeded
Bearing failure - steady	Fabrications dimensional error	Pile Design
Bearing failure - top	Fabrications geometry	Pile Manufacture
Bearing support failure	Fabrications materials error	Porosity
Belt Drive degradation	Fabrications not installed correctly	Power Failure
Belt Drive Failure	Fabrications orientation error	Rotor Assembly
Biodegradation	Fasteners Arrangement error	Rotor Design
Bond Failure	Fasteners not implemented properly	Rotor manufacture
Bond Failure - fatigue	Fasteners not sized	Settlement and creep
Cable Damage	Fasteners pre-load wrong	Shim design
Catalytic material incompatibility	Fasteners quality problem	Shim geometry
Composite Material degradation	Fasteners thread errors	Shim Materials
Composite Material Selection incorrect	Fasteners tightening sequence wrong	Shim placement
Compression set	Fasteners wrong material	Shim Quality
Cracks	Geotech Design	Shims missing

TABLE I.10: GENERIC CAUSES OF FAILURE IN THE SI TOOL (2/2)

Cause of Failure		
Shock dislocation	Structural failure – overload	Weld Failure - Fatigue
Stator Geometry	Surface finish degradation – rough	Weld Failure - lack of penetration
Stator Stiffness	Surface finish erosion	Weld Failure - process error
Stator strength	Surface finish polished	Weld Failure - stress relief
Structural failure - corrosion	Surface finish salt or ice	Weld Failure - too small / design
Structural failure - High Cycle Fatigue	Thermal expansion	Wheel location failure
Structural failure - Low Cycle Fatigue	Vibration - belt drive	Wheel rolling resistance too high
Structural failure - Other	Vibration - out of balance	Wheel support failure
Software error - failure to restart	Vibration - structural failure of foundation	Wheel surface degradation
Software error - I/O	Vibration - structural failure of rotor	Wheel surface failure
Software error - unforeseen condition	Water Absorption	Workmanship error - process adherence
Stator Assembly Error	Water ingress – softening	
Stator distortion	Weld Failure – corrosion	

TABLE I.11: GENERIC DESIGN AND PROCESS CONTROLS IN THE SI TOOL

Design and Process Controls	Notes
Alignment test	in-process or service test
Condition monitoring	service test
Configuration Management	records the issue status of a design
Crack Detection	Crack detection as NDT - various methods, such as dye-pen, acoustic emission etc.
Design History Records	Related to the advancing TRL of design
Design Input Verification	controlled assumptions
Design Review	design review as per BS7000-2
Design Verification Review	review of a verified design
Electrical insulation test	semi-destructive test, in-service or process
Electrical system test	system operation test, in-service or end-of-line
Engineering change control	design change control process and review
Fits and Finished Review	part of a design review, often for critical fits and finishes
Flatness Measurement	in-process test
Force fit monitoring	in-process test
Geometrical check and review	in-process test
Geometry Review	part of a design review, often for critical dimensions and shapes
Interface Review	part of a design review, in context of critical interfaces
Leak Test	in-process test
Material Audit - Environmental	defines environmental conditions and checks material compatibility
Material Tests	verification of materials properties, in-process test and design process
Modal Analysis	first-of-a-kind test, end-of-line test
Power Quality Analysis	End-of-line test
Risk Analysis	part of design review, project focus
Root Cause Investigation	used for analysis of failures and defects discovered during any part of process or design
Stage Gate Review	Project review
Standards Conformance Review	design review as per BS7000-2
Strategy Review	Project review
Tension test	in-process or service test
User Needs Review	part of a design review, checking that the requirements are met
Vibration Test	in-process or service test

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