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

Deliverable D3.1

Technical Requirements for the implementation of Structured Innovation in Ocean Energy Systems

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EXECUTIVE SUMMARY

This document, D3.1 Technical Requirements for the implementation of Structured Innovation in Ocean Energy Systems, is a deliverable of the DTOceanPlus project, which is funded by the European Union's H2020 Programme under Grant Agreement №785921.

The overarching objective of the DTOceanPlus project is to develop and demonstrate an open source, integrated suite of 2nd generation design tools for ocean energy technologies that support the entire technology innovation process. The suite of design tools will be applicable to different levels of technology (from subsystems, to devices and arrays) and across all stages (from concept, to development and deployment). DTOceanPlus will assist users in working towards an optimal solution based on information available at a particular stage. The DTOceanPlus suite of design tools can help accelerate the development of the ocean energy sector and reduce the technical and financial risks of devices and arrays to achieve the deployment of cost-competitive wave and tidal arrays.

A coherent set of functional and technical requirements have been developed for the DTOceanPlus suite of design tools based on analysis of gaps between the current state-of-the-art tools, learning from the original DTOcean project, and the stakeholder expectations identified in the user consultation survey. The technical requirements in this document are translated from the general requirements for the overall suite of tools, and specific requirements (functional, operational, user, interfacing, and data) for the Structured Innovation design tool that will be developed as part of this project. These requirements relate to detailed technical requirements of the technology and environment, for the development, maintenance, support and execution of the software specifications to best meet the needs of the ocean energy industry.

D3.1 includes a review of the current state-of-the-art for structured innovation approaches in mature industries and proposes a Structured Innovation design tool for the DTOceanPlus suite of tools; a detailed description of technical requirements of the Structured Innovation tool to be developed within the DTOceanPlus projects; moreover, a full section is dedicated to the technical requirements for the integration of the Structured Innovation design tool with the other sets of tools (Deployment design tools, Assessment design tools, and Stage Gate design tools, as well as for the integration with the underlying platform and the digital representations and for the interaction with the user.. A detailed description of the technical requirements of the tool is discussed in addition to the integration of the tool with the underlying platform, the other set of tools (Deployment tools, Assessment tools and Stage Gate design tools), and the digital representations.

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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
BIM	Building Information Modelling
BS	British Standards
CAD	Computer Aided Drawing/Design software
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
GIS	Geographical Information Systems
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
MRE	Marine Renewable 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
P-Diagram	Parameter Diagram
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
VOC	Voice of the Customer
WEC	Wave Energy Converter
WES	Wave Energy Scotland
WP	Work Package
UML	Unified Modelling Language

DTOCEANPLUS TERMINOLOGY

The following hierarchy is used to describe DTOceanPlus, illustrated in Figure 0.1:

Suite of Tools Over-arching term for all the tools in DTOceanPlus (shown as a dark blue dashed line in Figure 0.1).

Design Tools The DTOceanPlus suite comprises of four design tools (shown in blue): 'Structured Innovation', 'Stage Gate', 'Deployment', and 'Assessment'.

Modules The design tools (except Stage Gate) are split into modules e.g. 'QFD', 'Site Characterisation', 'Energy Capture', 'System RAMS (Reliability Availability Maintainability and Survivability)' (shown in light blue). This follows the terminology of the original DTOcean software.
These each contain multiple functions/processes/routines etc. that perform the calculation/assessment (not shown for clarity).

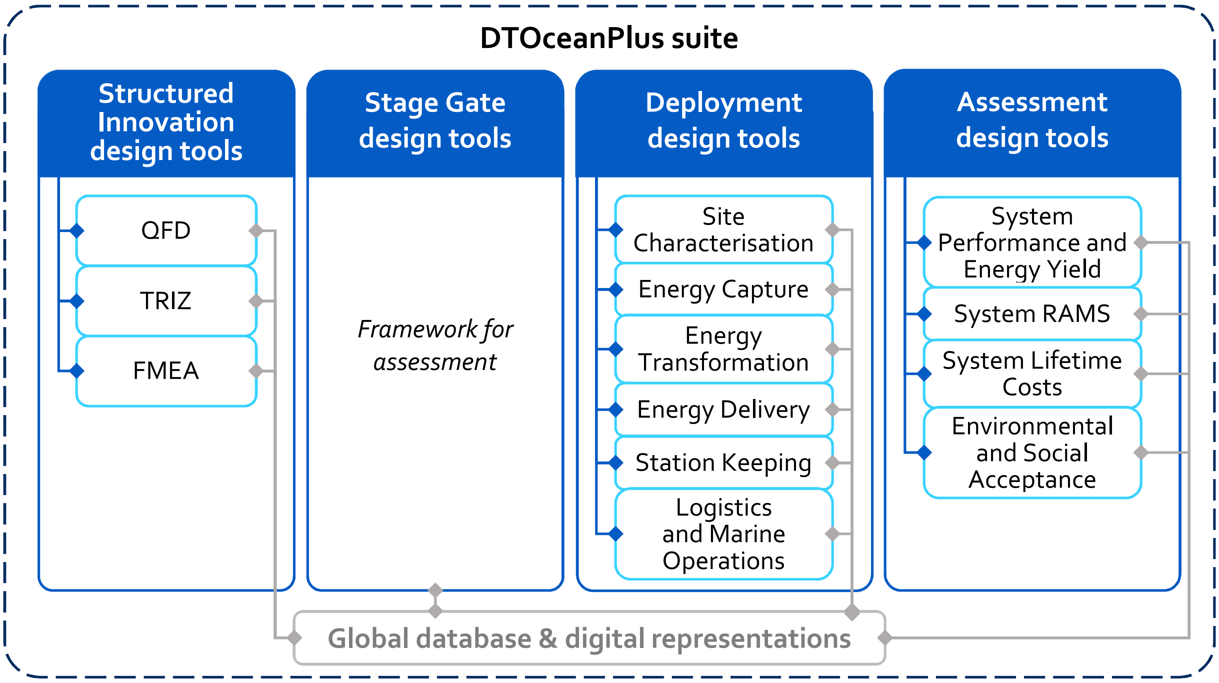

FIGURE 0.1 REPRESENTATION OF THE DTOCEANPLUS TOOLS HIERARCHY

In addition, there are a number of terms with a specific meaning generally or within DTOceanPlus.

Operational Requirements Define the major purpose of a system (i.e. what it fundamentally does; its capability) together with the key overarching constraints. The Operational Requirement(s) is a succinct clear and unambiguous statement as to what the system fundamentally does, including its key constraints.

Functional Requirements Specify what the system must do to achieve the Operational Requirements. A Functional Requirement does not define how it is done or how well it is done and should be implementation independent.

Technical requirements Factors that are required to deliver a desired function or behaviour from a system to satisfy a user's standards and needs. Specify how to implement what the

	system must do in order to get what is required. These include accessibility, adaptability, usability, auditability, maintainability, performance, etc.
Digital Representation	A complete description of the user's project at a given time. It can be seen as a digital version of the real project and therefore it should contain all the needed information to describe the project. It describes all the concepts defined in the DTOceanPlus application (concept creation, contradictions ...). Each of these concepts is handled by one of the tools of the application, so it means that the Digital Representation can be seen as an assembly of the extracted data from each tool, and as an export of the current project. This export will be done in a standard format, such as XML or JSON, with a documented structure so that it can be used by other applications. However, the Digital Representation is not a complete export of a DTOceanPlus project. Indeed, as this format is presented as a standard to represent an ocean energy system, it is important that it remains independent from the DTOceanPlus application. Therefore, not all the concepts that are internal to DTOceanPlus application should be exported in the Digital Representation.
Global database	A shared structured dataset containing input data, the digital representations of components to arrays, and accessed by all the design tools. It contains the Reference Database which is a package that contains a list of catalogues. These catalogues can be described as standard references that can be imported from organisations (e.g. list of devices or vessels) or can come from several databases (local or online), or even files (CSV or any format).
User Interface/ Graphical User Interface	"The user interface (UI), is the space where interactions between an end user and a machine occur to allow effective operation and control in order to achieve desired output(s). The graphical user interface (GUI) is a form of UI that allows users to interact with electronic devices through graphical icons and visual indicators, instead of text-based user interfaces[1]".
Local Storage	A structured dataset containing input data only relevant to the Structured Innovation modules. The DTOceanPlus modules can be developed in a way that they can be run independently in a standalone mode, or with the rest of the modules in the DTOceanPlus application. This can be useful for users who want to use one of the tools, and who won't need to install the full platform but only one tool. A standalone module can work independently with the required data saved in the local storage, but also use data from the database.
Quality Function Deployment (QFD)	A structured method 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)

[1] https://en.wikipedia.org/wiki/Graphical_user_interface

which is a matrix used to describe the most important product or service attributes or qualities [1].

Theory of Inventive Problem (TRIZ) A systematic problem-solving approach based on universal principles of creativity, patents and research. The module 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 module 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 [2].

Stage Gate Metrics The measures of success which define the performance of a technology. These are strongly linked to the Deployment and Assessment tools which calculate the required metrics.

Evaluation Areas These are a list of the topics which are to be assessed. Examples of some of these are: Maintainability, Installability and Energy Capture.

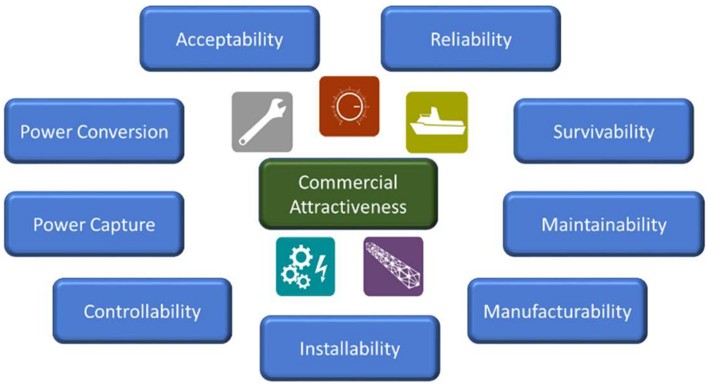

FIGURE 0.2 EXAMPLE OF EVALUATION AREAS IN THE ASSESSMENT OF THE COMMERCIAL ATTRACTIVENESS OF OCEAN ENERGY TECHNOLOGY

Stage gate metric thresholds These are the user defined performance criteria which must have been achieved for a technology to "pass" a particular metric within a topic area. These may be defined by the users of the tool themselves, or they can be selected from a list of default values. For example,

Metric: Mean Time To Failure, MTTF (hours), Threshold: 50000 hours

Stage Activities These are the activities which have taken place in the development of a technology. For example, this includes "Numerical models have been completed and validated against tank test data", "Small scale physical testing is complete in realistic wave conditions".

Stage Gate Metrics Framework The structure which defines what to assess, in what level of detail, and against which benchmarks for success for technologies in a technology development process.

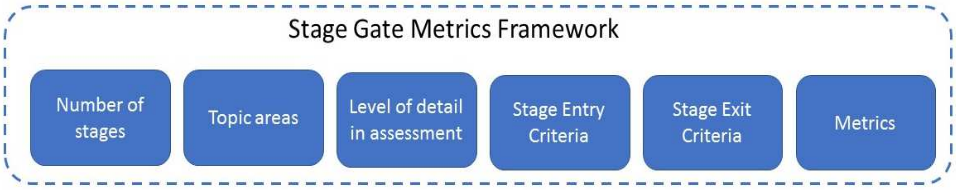

FIGURE 0.3: REPRESENTATION OF A STAGE GATE METRICS FRAMEWORK

Within a stage gate metrics framework, the following is defined:

- Number of stages within the stage gate metrics framework
- Stage entry and stage exit criteria Topic areas: These are a list of the topics which are to be assessed and are linked to the Deployment and Assessment tools. Examples of some of these are: Maintainability, Installability and Energy Capture.
- Level of detail for each stage and topic area: At lower TRL (lower maturity), technologies are likely to have less data supporting their performance and therefore will be assessed at a higher and less detailed level. At higher TRL (higher maturity), there may be more data available and therefore the level of assessment can be more complex and detailed.
- Metrics: The measures of success, these are the measures which define the performance of a technology.

Stage Entry Criteria
Defined activities which have taken place in the development of a technology – but not the results of such activities (i.e. It is not a measure of performance). For example, Entry to Wave Energy Scotland (WES) Stage 2 includes "Numerical models have been completed and validated against tank test data" or "Small scale physical testing is complete in realistic wave conditions".

Stage Exit Criteria
The thresholds of performance which must have been achieved for a technology to "pass" a stage which it is being assessed against. These may be defined by the users of the tool themselves, or they can be selected from a list of default values.

Power Take-Off
Subsystem to convert mechanical energy (from Hydrodynamic subsystem) to useful electrical energy. It is composed of at least of prime mover, an electrical generator and a power converter.

Annual Energy Production (AEP)
Average annual electricity production, in MWh, of a device or array.

Bill of Materials
List of components, sub-assemblies and/or logistical actions that are associated with a project, technology or subsystem under analysis, with associated quantities

Discount Rate
The discount rate is a measure of time-value, which is the price put on the time that an investor waits for a return on an investment. Furthermore, the discount rate is also used to account for the risks and uncertainties of an investment. It is used for present value calculations.

Capital Expenditure (CAPEX)
Initial costs for setting up a project, including project development, site preparation, procurement, construction and installation.

Internal Rate of Return (IRR)	Discount Rate that sets the net present value of all cash flows at zero. It is the rate at which the project will reach the break-even point at end.
Levelised Cost of Energy (LCOE)	Economic assessment of the energy-generating system costs over its lifetime, accounting for the time-value of money and risk.
Net Present Value (NPV)	Sum of the present values of the individual cash flows of the same entity. It is a measure of the profitability of a project.
Operational Expenditure (OPEX)	All the cost incurred during the operational lifetime of the project.
Development Expenditure (DEVEX)	All the cost incurred from initiation to implementation of a project.
Payback time	The payback period is the time needed for the project to break even. It can be simple, i.e. not accounting for time-value, or discounted, i.e., using a discount rate.
Present value	The value of a future quantity at the present time, accounting for time-value and risk.
Weighted Average Cost of Capital (WACC)	The rate obtained by combining the rates on investment and/or interest rates of the different financing options, weighted by the contribution to financing.
Receptor	A receptor is the entity that is potentially sensitive to a stressor (see definition of stressor below) related to an ocean energy project. Receptors can be for instance *marine mammals or birds* (sensitive to stressors such as collision risks with vessels or underwater noise due to operation and maintenance); *seabed habitat and associated communities* that can be degraded due to anchoring systems or; *fish and invertebrates* that can be impacted by chemical pollution such as oil or lubricants used by vessels and marine infrastructures. In DTOceanPlus, social acceptance will also be considered as a receptor. Estimating carbon footprint for manufacturing materials, producing energy or operation and maintenance activities can have an impact on *social acceptability*.
Stressor	A stressor is any physical, chemical, or biological entity that can generate a pressure or an environmental/ social impact. Stressors create a pressure on the environment such as *collision risk* (i.e. interaction between wildlife – e.g. mammals and birds – and vessels that may result in physical injuries); *footprint* (i.e. seabed that can be degraded by operation and maintenance activities - e.g. anchoring systems) or *carbon footprint* for manufacturing materials, producing energy or operation and maintenance activities.
	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,

Structured Innovation Methodology

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 [3]. The methodology is to be developed in accordance with the concept shown in Figure 0.4:

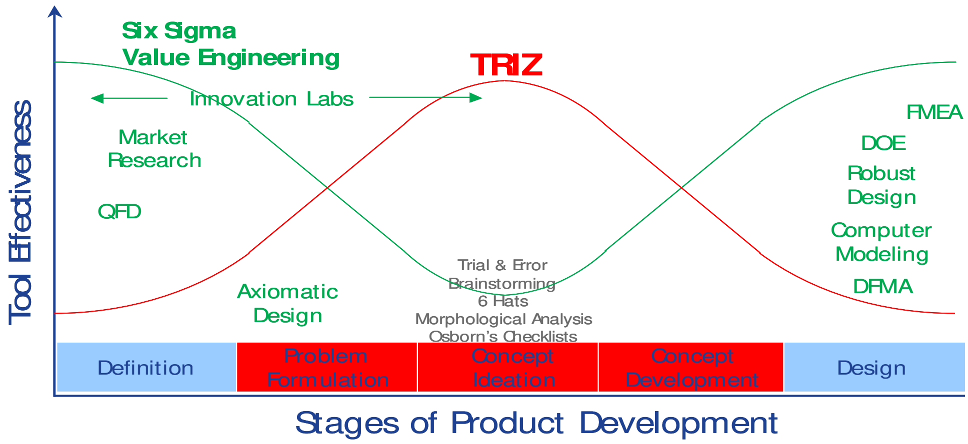

FIGURE 0.4: TOOL EFFECT VS PRODUCT DEVELOPMENT STAGE [4]

1. INTRODUCTION

The DTOceanPlus project will develop an open-source integrated suite of 2nd generation tools for ocean energy technologies [6]. The tools will support the entire technology innovation and advancement process from concept, through development, to deployment, and will be applicable at a range of aggregation levels: subsystem, device, and array.

The proposed tools are covered in more detail in section 1.4. At a high level, these will include:

- **Structured Innovation tool**, for concept creation, selection, and design.
- **Stage Gate tool**, using metrics to measure, assess and guide technology development.
- **Deployment tools**, supporting optimal device and array deployment.
- **Assessment tools**, used by the other tools to quantify key parameters.

1.1 SCOPE OF REPORT

This report is the outcome of Task 3.1 'Technical Requirements for the implementation of Structured Innovation in Ocean Energy Systems'. It is one of four concurrent deliverables to produce detailed specifications for the DTOceanPlus software tool development in conjunction with tasks T4.1, T5.1, T6.1, and T7.1 of work packages 3–7, as shown in **¡Error! No se encuentra el origen de la referencia.**.

These deliverables document the current understanding of the requirements at the time of writing. It is inevitable however that some of the specific details of implementation will change over the course of the software development. The full description of the technical specifications of the tools will be published in the technical manuals to accompany the final software release.

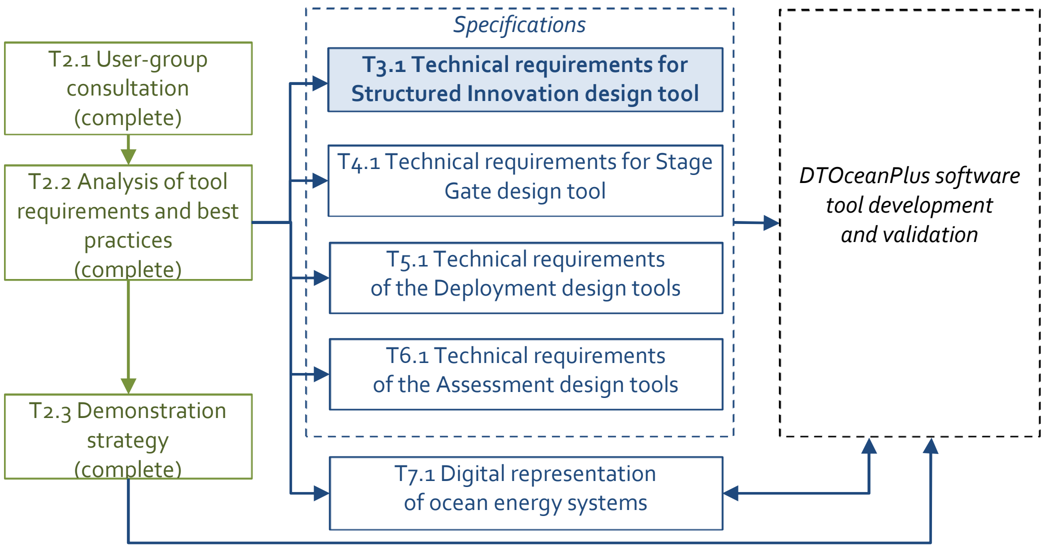

FIGURE 1-1: GRAPHICAL SUMMARY OF SOFTWARE SPECIFICATION TASKS (EXTRACTED FROM GRAPHICAL PRESENTATION OF THE PROJECT [7])

1.2 OUTLINE OF REPORT

This report specifies the detailed requirements (functional, operational, user, interfacing, and data) for the DTOceanPlus suite of tools.

The remainder of the report is laid out as follows:

- Section 2 compiles best practices in the various industries and performs a gap analysis to understand the discrepancies between the structured innovation current state-of-the-art in mature sectors and in emerging industries such as the ocean energy sector. From these, a set of modules is proposed for concept creation and selection in the DTOceanPlus suite of tools
- Section 3 sets out the technical requirements for the development of the Structured Innovation design tool: the data requirements, methodology, and outputs expected from the tool.
- Section 4 sets out the technical specifications for the integration of the Structured Innovation design tool in the DTOceanPlus suite of tools.
- Finally, section 5 gives conclusions and summarises the next steps.

1.3 TECHNICAL SPECIFICATIONS OF DTOCEAN

The original DTOcean Project produced a first generation of freely-available open-source design tools for wave and tidal energy arrays. The project built an integrated suite of tools [8] split into five modules or stages:

- **Hydrodynamics**: designs the layout of converters in a chosen region and calculates their power output.
- **Electrical subsystems**: designs an electrical layout for the given converter locations and calculates the electrical energy exported to shore.
- **Moorings and foundations**: designs the foundations and moorings required to secure the converters at their given locations.
- **Installation**: designs the installation plan for the energy converters and the components required to satisfy the electrical subsystem and moorings and foundations designs.
- **Operations and maintenance**: calculates the required maintenance actions and power losses resulting from the operation of the converters over the lifetime of the array.

These were brought together by a global decision tool containing optimisation routines, as shown in **¡Error! No se encuentra el origen de la referencia.**. These routines evaluate each stage of the design, and the design as a whole, using three thematic assessments:

- **Economics**: produces economic indicators for the design, in particular the Levelised Cost of Energy (LCOE).
- **Reliability**: assesses the reliability of the components in the design over the array lifetime.
- **Environmental**: assesses the environmental impact of each stage of the design.

The original DTOcean suite of tools is currently considered to be at TRL 4, having been validated in a research (laboratory) setting.

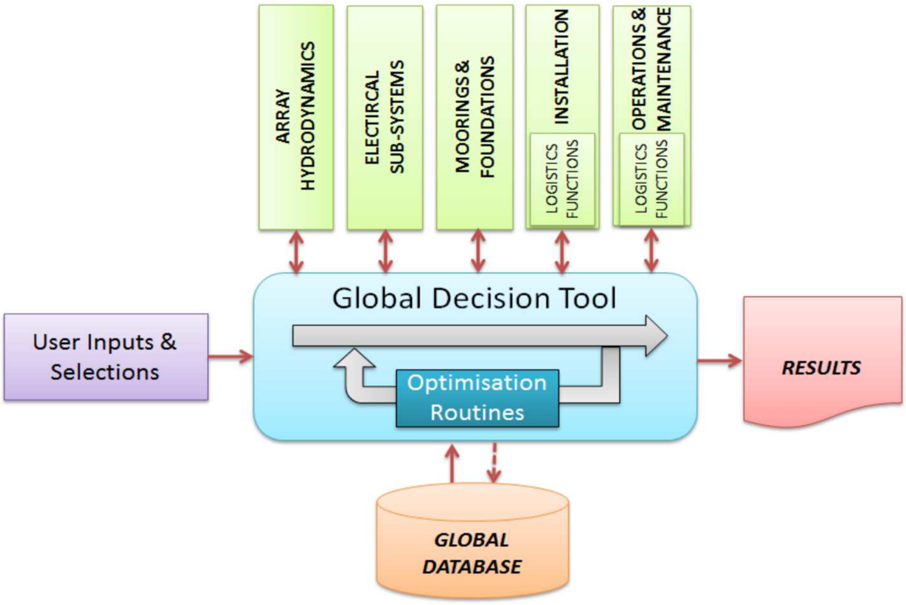

FIGURE 1-2: FUNCTIONAL STRUCTURE OF ORIGINAL DTOCEAN SOFTWARE [8]

1.4 OUTLINE OF THE DTOCEANPLUS SUITE OF TOOLS

The DTOceanPlus software will comprise an integrated suite of 2nd generation design tools, which are summarised below and illustrated at a high level in Figure 1-3. These build upon the tools originally developed in the DTOcean project[2] between 2013 and 2016, and the latest release of DTOcean 2.0[3].

- The Structured Innovation and Stage Gate design tools are new to DTOceanPlus. Based on best practices from the ocean energy and other sectors, they will provide structured methods for concept creation and assessing the progress of technology development through defined stages and stage gates. The Deployment and Assessment Design Tools will be significantly improved from the original DTOcean versions. The whole suite of design tools will be designed to assess various levels of complexity and to be used throughout the project lifecycle.
- **Structured Innovation design tool**, for concept creation, selection, and design, with three modules:
  - Quality Function Deployment (QFD).
  - Theory of Inventive Problem Solving (TRIZ).
  - Failure Modes and Effects Analysis (FMEA).
- **Stage Gate design tool**, using metrics to measure, assess and guide technology development. As part of this, the DTOceanPlus project will develop:
  - A stage-gate structure.
  - Metrics.
  - Tools for measuring success and analysing performance against metrics and thresholds.
  - Stage gates and metrics graded to the relevant stage in through the technology development process.

[2] Funded under EU FP7 framework Grant Agreement № 60859
[3] https://www.dtoceanplus.eu/Tools/DTOcean-Version-2.0

- **Deployment design tools**, supporting optimal device and array deployment. These will improve and expand on the capabilities of the original DTOcean software to consider the main functionalities of ocean energy technologies and systems, split into six modules:
  - Site Characterisation (e.g. metocean, geotechnical, and environmental conditions), a new module within DTOceanPlus.
  - Energy Capture at an array level.
  - Energy Transformation (PTO and control), also a new module within DTOceanPlus.
  - Energy Delivery (electrical and grid issues).
  - Station Keeping (moorings and foundations).
  - Logistics and Marine Operations (installation, operation, maintenance, and decommissioning), with expanded scope beyond just O&M in DTOcean.
- **Assessment design tools**, will provide objective information to the developer or investor on the suitability of a technology and project, and will also support the other DTOceanPlus design tools, split into four modules:
  - System Performance and Energy Yield.
  - System Lifetime Costs.
  - System Reliability, Availability, Maintainability, Survivability (RAMS), with significantly expanded scope beyond just reliability in DTOcean.
  - Environmental and Social Acceptance, with expanded scope from DTOcean to also include social aspects.
- Underlying these will be **common digital models** and a **global database**.
  - A digital representation will be developed to provide a standard framework for the description of sub-systems, devices and arrays. This will be a common digital language for the entire sector.
  - The global database will contain catalogues of reference data from various sources.

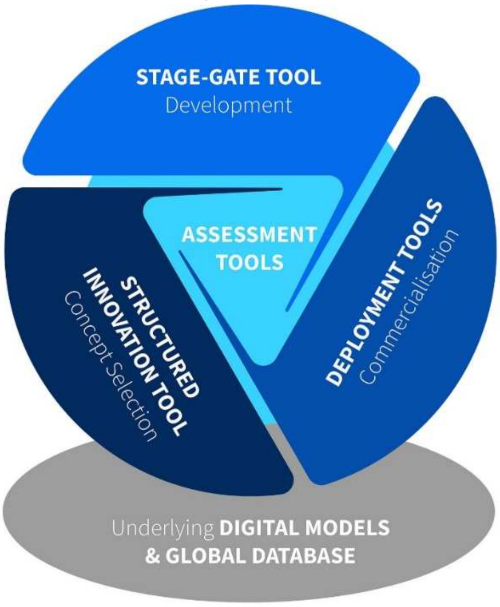

FIGURE 1-3: REPRESENTATION OF DTOCEANPLUS TOOLS.

The technical requirements for the Stage Gate design tool are set out in this document. Accompanying deliverables set out the technical requirements for the other design tools as follows:

D3.1 Structured Innovation, D5.1 Deployment, and D6.1 Assessment. Further details of the common digital models or digital representation will be proposed in D7.1 'Standard data formats for the Ocean Energy Sector' due to be published in autumn 2019.

USE AT DIFFERENT LEVELS OF COMPLEXITY

DTOceanPlus will support the development of ocean energy technologies at all stages of the project lifecycle — from concept creation through design development to commercial deployment — with increasing level of data available and detail required at each. It will also be designed to support users with differing requirements in terms of detail; from investors wishing for a high-level overview of a technology or project, to developers performing more detailed technical assessments, e.g. for project consenting.

The project lifecycle can be seen from two complementary perspectives:

- The chronological phases of a project: namely conception, design, procurement, construction, installation, operation (including maintenance), and decommissioning.
- The project development and/or the technology deployment can be split into three stages for clarity (Early, Mid, and Late), as described in Table 1-1. These can broadly be linked to the widely-used TRL scale [8]. Those three stages address all the phases described above, with different levels of complexity accounted for in the project definition.

TABLE 1-1. INDICATIVE STAGES OF PROJECT DEVELOPMENT LINKED TO TRL AND DEVELOPMENT PROGRESS USED WHEN DEFINING DTOCEANPLUS REQUIREMENTS.

STAGE	APPROX. TRL	DEVELOPMENT PROGRESS	DESCRIPTION
Early	1-3	Concept definition	Early stage analysis of potential device or site. Gives an overview of capabilities and next development steps, but may be based on limited data.
Mid	4-6	Feasibility	Includes an in-depth study of the topics covered in the concept definition. More accurate than previous stage, with additional data requirements.
Late	7-9	Design and deployment	Key project features are planned in this stage, informed by the previous phases. Makes use of detailed information about the project.
Note that while three stages are shown here to guide the functional requirements and ensure the varying level of complexity throughout the project lifecycle is being addressed appropriately, the number and scope of stages used in DTOceanPlus will be configurable by the user as required.			

As well as being used at different stages in the project development lifecycle, DTOceanPlus will also be applicable to three different levels of aggregation, specifically:

- **Sub-system**, e.g. PTO, or moorings and foundations that form part of a device.
- **Device**, i.e. one complete system that can be deployed individually or to make up an array.
- **Array** of multiple devices deployed in a farm.

Where applicable, the design tools will consider details of assemblies and components, however they will not be designed to assess technologies at this level.

The design tools within the DTOceanPlus suite can be summarised as follows:

- The Structured Innovation design tool generates new concepts; including novel concepts for wave and tidal energy devices, or an improvement of a sub-system, device, or array at higher maturity level. The tool also provides the ability to assess technologies at the early concept stages when there is minimal data available and will inform part of the inputs for the Stage Gate design tool.
- The Stage Gate design tool supports the objective assessment of technologies in the development process, ensuring a fair assessment of sub-systems, devices and arrays from early stage concepts up to commercial deployment.
- The Deployment design tools provide optimised solutions and layouts for the deployment of ocean energy technologies, and define all the technical design specification to run the Assessment design tools for the evaluation of metrics.
- Finally, the Assessment design tools execute the key calculations to measure the vital parameters at all stages of the project lifecycle, and ultimately support the Stage Gate design tool by delivering these fundamental computations.

Therefore, an important functionality of DTOceanPlus is the ability to assess the performance of technologies throughout the project lifecycle, as a technology matures; when there is little to no data available about a technology at the concept definition stage, and more data from testing and simulations at the design and deployment stage.

Table 1-2 below outlines how the assessment method changes through these different stages, depending on the data available. This assessment is a key functional requirement of the software, and will have consistency in the approach through integration of the tools provided by the Digital Representation. As a running theme throughout the project lifecycle, assessment of sub-systems, devices and arrays must be flexible to the users' requirements depending on the particular user type, the maturity of the technology and the amount of data available. This is highlighted in the use cases described in section 2.2 of D2.2 Functional requirements and metrics of 2nd generation design tools [9].

TABLE 1-2 INCREASING TOOL COMPLEXITY FOR DIFFERENT DEVELOPMENT STAGES.

Stage & approx.TRL	Data availability	Assessment method
Early stage (TRL 1–3)	Little quantitative data available; overview of capabilities and operating modes	Assessment through the Structured Innovation and Stage Gate design tools by utilising the earliest level assessments of technologies; these may use: ▫ Fundamental physics, engineering and economic relationships. ▫ High-level quantitative assessments from the Assessment and Deployment design tools. ▫ Scoring of a technology by qualitative assessment from an expert assessor.
Mid stage (TRL 4–6)	Low complexity; limited data available	High-level 'basic' quantitative assessments through the Deployment and Assessment design tools. These can be the same as the detailed 'advanced' tools but with simple parameters and/or default values used.
Late stage (TRL 7-9)	Full complexity; makes use of detailed information about the project.	More detailed 'advanced' quantitative assessments through the Deployment and Assessment design tools.

2. STRUCTURED INNOVATION BEST PRACTICE IN INDUSTRY

Across most industries, innovation comes hand in hand with the competitive position of firms. According to H. Chesbrough [11], companies are moving away from the traditional R&D innovation models to more open and structured innovation approaches that use a combination of internal and external ideas in addition to responding to market needs. These models integrate the needs of the people, the process, the market and the technology.

Nowadays, most companies developing new products or services use a form of the structured 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. This is seen across a wide variety of sectors in companies such as ExxonMobil [12], Ford Automotive [13] [14] [15], Rolls-Royce [16], companies in the medical and pharmaceutical industry [17], and many more.

Despite the positive impacts of structured innovation approach, not many companies have adopted it. This section attempts to determine structured innovation best practices to date and how a similar approach can be used in the ocean energy industry.

2.1 CURRENT STATE-OF-THE-ART

2.1.1 AUTOMOTIVE SECTOR

The Ford Motor Company used a structured innovation approach to facilitate new technology introduction for the development of low-cost independent rear-suspension, known as "Control-Blade" that was first used on the original Ford Focus. The initiation was from a corporate strategic decision to consult customers, and this gave a requirement for improved ride quality, but with contradictions of improved cornering, and lower cost. The approach taken developed an intimate understanding of the customer's requirements, with emphasis on the contradictions and their relative impacts. The results of this showed that these contradictions needed to be solved by radical innovation rather than incremental improvements since the existing technologies could not solve all requirements. TRIZ was used to solve these contradictions, using three of the 40 inventive principles to bring a cost-reduced independent rear suspension to medium-size cars that had only been possible in premium cars. The innovations were the modularity, energy conversion, and light-weighting [13].

The company uses the combined QFD and FMEA approach which is fully integrated in some of its tools: EQUIP (Engineering Quality Improvement Programme) and FTEP (training & technical quality skills), the Ford Motor ULEV (ultra-low emission vehicles), the exhaust gas ignition (EGI) system, electrically heated catalyst (EHC) system, etc. [13] [18].

The stakeholder requirements are obtained from their legislative customers (emission control monitoring system), environmental groups, vehicle purchasers and the input from their internal and external suppliers (supply chain). The company Marketing Research Operation team also creates customer satisfaction triangles for the collection of themes from the different markets around the world, from events such as customer information days and/or feedbacks from customer satisfaction and industry experts [13] [14] .

Toyota integrated the QFD analysis in the company's areas of product design to meet the user's needs. According to Sullivan [15], "the company reported a 61% reduction in start-up costs, a one-third reduction of the product development cycle (time to market), and fewer design changes overall. A case study at Eaton Corporation found that the use of QFD to design blend door actuators for automobiles resulted in: 30% reduction in size, 50% reduction in selling price, 50% reduction in engineering expenses, 20% reduction in drafting expenses, a reduction in noise from 50 decibels to 38 decibels, and mounting flexibility allowing it to be used on three additional car lines" [15] [19].

2.1.2 AEROSPACE SECTOR

Like the automotive sector, the aerospace industry has grown significantly and holds an important place in the modern transportation sector; leading the innovation space in development and application of both products and processes. With a duty to deliver high safety, high performance, low tolerance to failure, and competitiveness, innovation is crucial and a primary driver of the sector.

Rolls-Royce introduced a Requirements Capture and Management (RC&M) and Systems Engineering (SE) initiative to improve its design processes — in particular: the lead times and the costs of rework because of poor translation of customer requirements —resulting in the improved robustness of their solutions. The company adopted IBM's Rational DOORS (Dynamic Object-Oriented Requirements System) software as an enhanced customer integration tool. Like the QFD, this tool captures all individual requirements and integrates them in the processes throughout the product life. This tool, however, is a premium-ware (i.e. distributed at a cost to the end-user) client-server application, unlike the QFD tool that is an open source freeware application [20].

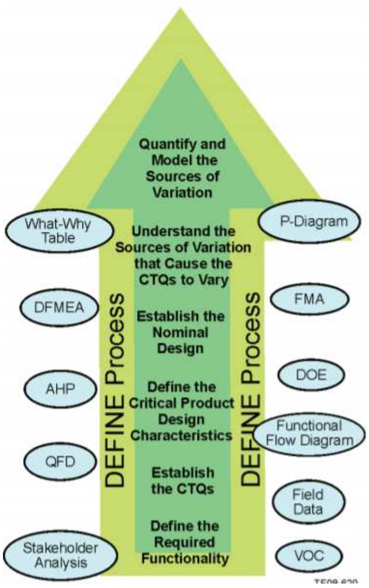

FIGURE 2-1: DEFINE PHASE- COURTESY OF ROLLS-ROYCE [21]

Over the years, the Rolls-Royce engineering teams have also used various Design for 6-sigma tools in combination with their standard design processes "Define, Characterise, Optimise Verify" to implement their products, services and innovation processes in a structured way (Figure 2-1). During the "Define -D Phase", the teams ensure the voice of the customers is captured, validated and modelled into the characterisation of the model. This is achieved using the QFD House of Quality approach. One example was the use of the QFD tool in the Rolls-Royce Power Engine Plant programme to understand and structure their new engine. The customer needs were addressed and translated into the functionalities of their engine's functional requirements from the system to the key subsystem requirements. QFD combined with Pugh Matrices were used to assess the various options against the user requirements before settling on a design solution and moving to the characterisation phase to build a robust design process [21]. With the need to increase automation at the early stages of the process to improve performance attributes such as weight, fuel consumption, cost, noise and turbine entry temperature, Rolls-Royce relies on modelling tools such as QFD and TRIZ to capture their customers' needs and ensure the trade-offs between attributes are resolved without increasing complexity of the design [22].

The **Boeing 787 Dreamliner** project adapted the QFD/TRIZ approach by moving away from the "bigger version of what we've already got" safe strategy to an innovation strategy that strives to meet the stakeholders' requirements. Some of the end-users (passengers) needs are their comfort, economical flights, suitable locations and short time to travel [23]. The Boeing 787 Dreamliner as a result, was designed as a "smaller but still long-range aircraft that would serve point-to-point routes". The customers' needs were translated into technical requirements such as lightweight composite fibres rather than aluminium, aerodynamic shapes and with ultra-efficient engines for long haul flights [16] [23]. The QFD approach was used to design elements of the Boeing 787 interior design (Table-7, [16]).

As a strategy, Boeing's structured innovation approach was radical, moving away from the company's traditional innovation approach (i.e. safe incremental innovation); to use an 'open innovation' approach. This meant that the company gained knowledge from contributions of a wider range of experts and external companies; hence most of the design and manufacturing works for specific parts were contracted to various suppliers (Japanese firms Mitsubishi, Fuji and Kawasaki; Italian firm Alenia; US firm Vought…). The first aeroplane was delivered nearly four years later than its original plan [24]. According to [24] [25], the delays were mainly due to poor planning and management of the supply chain. The radical innovation approach meant a disruptive, out-of-the box approach to innovation, however "the suppliers helped us develop and understand technologies and options for the airplane as we went through the early phases of concept development" [24]. The company however did not investigate the possible conflicts and the potential risks associated with multiple parties involved.

This example highlights some of the issues around adopting disruptive innovation approaches and what is considered poor practice in the company's approach. These are firstly: the ability to identify and mitigate the conflicts that may arise from having multiple supply chains, and secondly: the ability to define and mitigate potentials risks that may arise from the execution of the project at super system and subsystem levels.

2.1.3 CHEMICAL INDUSTRY

ExxonMobil have used a systematic innovative approach to increase the company yield at all stages of production from conceptual phase to commercialisation. The process of innovation in the company is integrated into the business strategy allowing the various ideas and opportunity identification to be analysed and the concepts assessed against the internal stage-gate process and decisions to be made to progress or terminate some of the ideas [26].

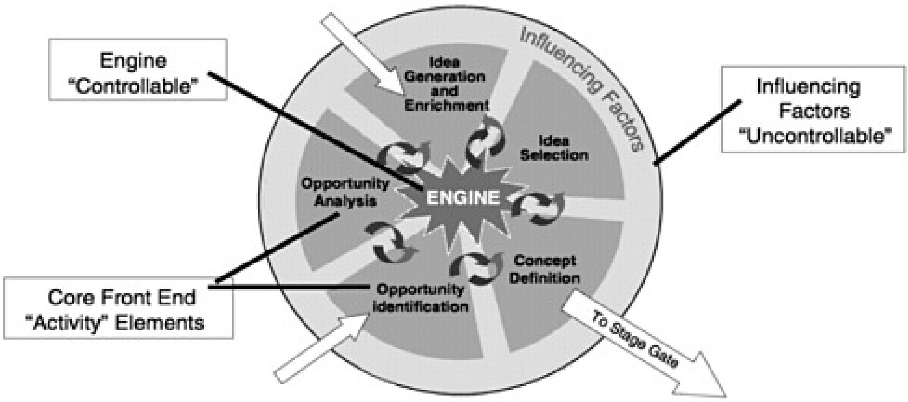

FIGURE 2-2: EXXONMOBIL FUZZY FRONT END CONCEPT DEVELOPMENT MODEL [26] [27]

Within the company's internal tool (like the QFD module), the stakeholders' needs are captured after the preliminary stage gate process to allow more detailed assessment of the values and importance of the idea(s) [26]. The added values to the stakeholders, to the market, to the part of the business and the overall company are then assessed against the company strategic plans, the market, profitability and feasibility in a second stage-gate process before a decision is made to progress or terminate the concept(s). The internal structured innovation & stage gate tool is known as Product Innovation or Capital Investment Management Portfolio. Such a tool relies on expert inputs within the company, and the standard objective criteria (e.g. percentage revenues, competitive edge, patents…) to evaluate project merits as well as the strategic plans of the business [12] [26]. This tool however is only available internally with bespoke entry and exit metrics.

2.1.4 MEDICAL SECTOR

The trend of development in the health sector is also fast paced and very competitive, responding to the numerous needs and added values of products and services. With the advancement in technology reliability, information and communication, the increased demand for sophisticated healthcare services, medical and pharmaceutical companies always investigate ways to design sophisticated, light, accurate and cost-effective healthcare devices. Therefore, creative and innovative thinking is key to stay ahead of the competition and meet the user needs by breaking through the unending limitations of designs [18].

The QFD approach was used in many cases to improve the quality of the services and products in the healthcare system. It was used for the design of a computer network service for occupational therapists [28], for the improvement of the radiation safety management [29]; in [30], the QFD was used to find innovative ways to improve quality-in-service. A combined QFD/ANP (Analytic Network Process) approach was also used by [31] to find ways to improve services for elderly patients.

A study was conducted to improve the design of the Equivital EQ02 LifeMonitor, small detection devices that can detect, record, and transport users' health condition [17]. These devices are designed to capture and analyse data from all the detectors (heartbeat, blood pressure, blood glucose, etc.). In this study [17], the use of QFD was proposed to integrate the various user needs into the improved design of the devices. The QFD approach was used in combination with the Analytical Hierarchical Process (AHP) to rank and prioritise these user needs with respect to their technical specifications. TRIZ was then used to solve the various contradictions arising from the interdependence between the requirements in the systems [32].

Another study looked to combine the use of TRIZ with the SERVQUAL model to improve the quality aspects of services provided for patients in hospitals. SERVQUAL is a database model of collected data from consumers' feedback such as their expectations and perceptions with respect to security, reliability, communication, competency, accessibility. SERVQUAL was used to capture patients' needs and where these needs had to be met. Qualities such as tangible solutions, reliable system, responsiveness and assurance of staff were some of the main feedback. TRIZ was used to improve the strategies needed for the services provided. Of the 40 inventive principles, self-service, parameter change, and others were used to implement improved strategies for hospitals [32] [33].

2.1.5 ENERGY

Siemens Wind Power have used a combination of QFD, TRIZ and FMEA to select technologies and overcome technical and commercial challenges associated with the development of wind turbines suitable for offshore applications, including some of the key components required. In this case, the use of integrated TRIZ, FMEA and their toll-gate processes meant that a highly innovative solution was found allowing them to tackle both design and manufacturing / supply chain issues that could have prevented the rapid time-to-market and preparedness that is essential to building a new business solution in a growing market. The use of TRIZ solutions is apparent in the application of at least six of the 40 inventive principles, as evidenced by the highly modular design, with functions included in each module.

Converteam (now GE) applied the combination of QFD, FMEA and the TRIZ 40 inventive principles for the development of their novel electric drive systems. The drive system would compete against established solutions and would need to be able to provide compelling reasons to use and clear commercial benefits. GE is an enthusiastic user of six-sigma / lean engineering-based tools and decided to use QFD to represent the voice of the customer through the technology decision process. Their approach to QFD was characterised using intense customer engagement to derive the needs and their relative importance by using paired question analysis. This analysis showed that using a robust technology used in the mining industry would provide differentiation, and significant cost benefits. The integration of the QFD and cost analysis was impactful in the extremely competitive cost per unit thrust that their innovation achieved.

The examples above show the adoption and integration of a structured innovation approach into the business and design strategies, enabling the various sectors to ensure creative inventions that have market advantage, and low cost and risk profiles. The DTOceanPlus Project will aim to use a similar approach to ensure creative inventions that have market acceptance and low cost and risk profiles.

2.2 CURRENT STATE-OF-THE ART IN THE OCEAN ENERGY SECTOR

In the ocean energy sector, the adoption of structured innovation methodologies is less evident in the literature. The US-based National Renewable Energy Laboratory (NREL) and Sandia National Laboratories use a structured innovation approach to identify and develop new wave energy converter concepts with high techno-economic performance potentials [34]. Along with a stage-gate assessment tool, NREL and Sandia use their tools for the implementation of the best 'technology-development' trajectory with respect to time, cost and risks and assess the development path of these technologies with respect to their readiness levels and performance levels [35] [36].

Project SEAWEED by Wave Energy Scotland is developing a structured innovation tool to "identify attractive scenarios for exploitation of wave energy resources". As a standalone package, the SEAWEED module facilitates the creation of concepts by scanning the design space and then selecting the most attractive and achievable options. The evaluation could be based on high-level metrics such as internal rate of return of an investment, payback time, commercial risk, and technical risk [37].

The collaborative project TiPTORS between the Offshore Renewable Energy Catapult and Ricardo UK was carried out to develop a design for reliability process for tidal turbines' power take off units [38]. The core design process for this project started by capturing customer requirements using QFD. A fault tree, a route cause and the Failure Modes & Effect and Criticality Analysis (FMECA) were integrated into the core process of the tool to mitigate the impacts of potential failures of the PTO units and define the overall reliability of the concepts proposed. It was highlighted that some trade-offs were likely to be derived from the set of the engineering specifications, however within the literature, it wasn't clear what process was used to eliminate those trade-offs within the QFD matrix. The recommendation from this project was that the design for reliability tool needs to be further tested to align with the industry standards [39].

The Energy Technology Institute (ETI) conducted Tidal Energy Converter (TEC) system demonstrator projects to "identify, develop and obtain the best routes and supply-chain options to commercially viable tidal stream technologies when deployed at array scale". The aim of the ETI through these projects was to demonstrate the importance of the tidal energy sector within the whole energy system, and, to identify and prioritise the key technology and deployment issues faced by the marine sector. Among others, the combined QFD/FMEA tools were used to define the design, innovation and optimisation of an array-scale coordinated collection of turbines [39] [40] .

2.3 GAP ANALYSIS

Various sectors have adopted structured innovation methodologies to innovate their products and services. The adoption of these methodologies is more advanced and matured in some sectors (e.g. automotive) than others (wave or tidal). There are several commercial and internal tools available such as IBM Rational DOORS, that integrate user requirements to stage gate processes to evaluate the various concepts. However, information related to the conceptual design phases tends to be mainly limited to requirement specification documents and system architecture diagram documents [41].

From the above examples in the various sectors, it is seen that most sectors are benefiting from using one or a hybrid of two of the three QFD/TRIZ/FMEA modules to implement a structured innovation approach to their designs. Each module can be applied standalone. However, when applied together, the limitations of one tool are overcome by the strength of the other tools (e.g. the QFD-TRIZ hybrid combination between customer-driven and innovation-driven design) [42].

TABLE 2-1: SUMMARY OF INDUSTRY BEST PRACTICES

Stakeholder requirements
▫ QFD as a step-by-step tool that captures customer requirements ▫ Tool that enables a step-by-step process to implement a series of matrices (HoQ) approach ▫ Tool that includes prioritisation of stakeholders' needs ▫ Tool that evaluates ideas against a set of industry-accepted criteria (e.g. MRL, stage gate criteria, etc.) ▫ Tool that enables the prioritisation of customer requirements against scoring metrics or thresholds ▫ The need for a larger pool of data (interviews, questionnaires, monitoring systems, internal feedback, marketing, competitive approach…) ▫ Simple and comprehensive tool ▫ Visual representation of tool with separated stages (systems, subsystems, components….) ▫ Ability to use tool for concept creation or for implementation of parts of design
Functional Requirements
▫ Ability to understand impacts of interdependency between needs and technical requirements ▫ Measures of success through target values and/or stage-gate process ▫ Ensure trade-offs between attributes are resolved without increasing complexity of the design
Tools
▫ Well-known and developed process ▫ Problem-solving tools ▫ Visual approach ▫ Logical approach to inventive problem solving (Beyond trial-and-error methods) ▫ Information flow from specific problem- to generic problem/solution-to specific solution ▫ Ability to validate tool ▫ Ability to measure innovation performance indicators and to assess the rate of penetration of innovation activities for each aspects of the company ▫ Tools that can be used as standalone tools or integrated to companies' portfolio management tools.

For decades, several methods have been used for product improvement from the traditional reactionary approach, to precautionary research analysis, reactive competition and market research, then to a systematic 'Voice-of-the-customer' integrated approach. The Six-sigma total quality management approach was derived from the need to move away from trial-and-error methods, unstructured brainstorming and market-only research analysis [43] [44]. This was integrated in the various sectors using either standalone innovation tools or a hybrid of tools such as QFD/TRIZ/AD, QFD/AHP/TRIZ, QFD/DOORS, brainstorming/TRIZ/stage gate, etc.

As far as the authors are aware, the Structured Innovation design tool within the DTOceanPlus suite is one of a kind beyond the current state-of-the-art. This will enable the transfer and adaptation of the QFD, TRIZ and FMEA modules to the ocean energy sector. For a sector such as ocean energy where the number of design options is still very high, the proposed open-source Structured Innovation design tool is needed to help deal with the complexity of the engineering challenge – resulting in a more efficient evolution from concept to commercialisation.

Although the Structured Innovation tools used in other sectors can be considered mature technologies (at TRL 9), in transferring and adapting them to the ocean energy sector a reduction in TRL to 4 is appropriate. Therefore, in addition to bringing Structured Innovation tools into the sector, DTOceanPlus will develop these tools from TRL 4 to TRL 6, firstly validating them against relevant scenarios, then demonstrating them in real-world use.

2.4 SUMMARY

This section reviewed the current state-of-the-art for structured innovation approaches in mature industries such as the automotive and the aerospace sectors. Based on this review, best practice methods were selected and proposed for the DTOceanPlus suite of tools: The Quality Function Deployment method to define the innovation problem and to identify trade-offs in the system, and TRIZ as a systematic inventive problem-solving method to generate potential solutions to the contradictions raised from the QFD requirements. The outcome from QFD/TRIZ tools will generate several design requirements along with target engineering metrics; and the FMEA will be used to assess the technical risks associated with the proposed design concepts.

3. TECHNICAL REQUIREMENTS OF THE TOOL

In this section, the technical requirements for all the modules of the Structured Innovation design tool developed in DTOceanPlus will be described.

As part of the Agile Modelling approach [45], the technical requirements include a set of non-functional requirements that the software should be able to satisfy in order to accomplish the specific functions to be carried out. Essentially, these involve performance, reliability, and availability issues. In the following sections, the discussion is focused on non-technical requirements, rather than specific technologies. This prevents requirements from becoming obsolete as technologies change. Indeed, the following sections make reference to the data requirements and the main classes of technologies such as the GUI, the global database, each tool's local storage, etc…

The technical requirements are numbered following a "business rule", i.e. TR-XXX-YY, where YY is the sequential number of the technical requirement of tool XXX indicated by the acronym of the tool.

The following section will be organised in four subsections:

1. FROM FUNCTIONAL TO TECHNICAL REQUIREMENTS: in this subsection, the transition from functional requirements identified in D2.2 Functional Requirements [10] (Appendix II) towards the technical requirements is described as well the connection between them;
2. ARCHITECTURE OF THE TOOL: in this subsection, the main architecture of the tool is described. A diagram will illustrate the flow of the actions that the tool will carry out when running, the functions that are implemented and the interactions with other modules of the tool;
3. MAIN FUNCTIONS AND MODELS: in this subsection, the main functions are described;
4. DATA REQUIREMENTS: in this subsection, a brief overview of the requirements in terms of data and their organisation into classes within the tool.

Following this, subsections 3.5and 3.6 will collect general technical requirements, applicable to all or most of the set of tools, covering:

- INTERFACES/COMPATIBILITY/PORTABILITY: in this section, the possibility of connecting the tool to other software (commercial, open-source, in-house) through the use of interfaces is described, as well as the ability to import inputs and export outputs.
- MAINTENANCE: in this section, the management of extensions and updates in the future is briefly discussed.

The Structured Innovation design tool is intended to provoke innovation and help represent the voice of the customer through the design process, manage risk and therefore produce new concepts. The combined QFD and TRIZ modules will allow the designer to understand the logical "art of the possible" when considering the design targets, which is critical to the success of the design, and to commercial realisation. The art of possible rather than the state-of-the-art considers ideality of devices or processes only limited by physics (e.g. Betz limit, yield strength, etc.) and extreme conditions to provoke new concepts.

The overarching objective of the integrated Structured Innovation tool is to support the entire technology innovation process from concept, through to development and deployment, using QFD/TRIZ/FMEA modules.

As described in Deliverable D2.2 [1], the Structured Innovation design tool will have two main objectives:

- At very early stage: to provoke innovation by scanning the design space, by identifying the potential innovative concepts, and by ensuring every proposed concept is assessed and has objective scrutiny.
- At later stages of product development: to help address emergent challenges, and sometimes to reappraise and redesign components or systems to overcome such challenges.

This section defines the processes and the specifications required to integrate the Structured Innovation design tool into the DTOceanPlus suite. The tool's specifications, the architecture diagrams and the interface with other DTOceanPlus tools are also detailed in this section.

3.1 FROM FUNCTIONAL TO TECHNICAL REQUIREMENTS

Based on the Deliverable 2.2. [1], the functional requirements for the Structured Innovation design tool are presented in Table 3-1. From these, a set of technical requirements has been developed. These are the actions to be carried out by the Structured Innovation modules to meet the functional requirements.

TABLE 3-1: FUNCTIONAL AND TECHNICAL REQUIREMENTS OF THE STRUCTURED INNOVATION DESIGN TOOL

Functional Requirements	
FR-SI-1.	Scan the design space and identify attractive areas of innovation
FR-SI-2.	Create new concepts and identify areas of opportunities
FR-SI-3.	Identify and solve the contradictions arising from the proposed solutions
FR-SI-4.	Mitigate the potential technical risks associated with the attractive concepts to satisfy the user
FR-SI-5.	Improve existing concepts
Technical requirements	
TR-SI-1.	User inputs the stakeholder requirements through the GUI
TR-SI-2.	User inputs priority rankings through the GUI for each stakeholder requirement (SR) to determine, prioritise and rank their relative importance
TR-SI-3.	From the local storage, the user loads and selects from the look-up table, the technical solutions (TS) to meet the SRs
TR-SI-4.	User selects from the dropdown the direction of improvement for each TS
TR-SI-5.	User loads up and selects the relationship scale from the local storage and selects from dropdown scales specifying the relationship between the SRs and TSs
TR-SI-6.	User imports Stage Gate specific thresholds/benchmarks to set engineering target values
TR-SI-7.	User imports Stage Gate benchmark to assess the compliance of existing product options against the target values

TR-SI-8.	User assesses and ranks the organisational importance of meeting the requirements by running the in-built functions within the SI tool to determine the level of difficulty of achieving these technical solutions
TR-SI-9.	The tool displays the outputs of the quality assurance checks, which run using in-built functions (stored in the local storage) to ensure enough 'valid and impactful solutions' are given to meet the SRs and ascertain the proposed TS innovation.
TR-SI-10.	User ranks the strengths of the relationships between the technical solutions, either by selecting from the in-built list of ranking or by inputting a bespoke ranking (potential synergies and contradictions)
TR-SI-11.	User evaluates the conflicting TSs using the in-built Conflict Dashboard with relevant in-built functions and data stored within the local storage. The displayed outcome highlights if/when alternative solutions should be sought (strongly negative impacts) i.e. trigger of TRIZ (library of solutions)
TR-SI-12.	The tool loads and the user selects from the in-built dropdown list of possible TRIZ solutions, the relevant alternative solutions to resolve the design conflicts
TR-SI-13.	Once the user has selected broad generic solutions types, they then select from the look-up table (stored in the local storage), specific solutions relevant to their designs.
TR-SI-14.	Relevant solutions are passed to the Digital Representation to re-evaluate the compliance of the proposed concepts against the target values (steps SI-TR 6-9) and the outcome is displayed
TR-SI-15.	User loads the proposed concepts from QFD or inputs bespoke functions to define the requirements in the FMEA worksheet
TR-SI-16.	User either selects from dropdown lists (stored in the local storage) or inputs the failure modes, effects of failure, causes of failure, and the design and process control measures
TR-SI-17.	User selects from the ISO standard definitions' look-up table (stored in local storage), each failure mode's severity (SEV), occurrence (OCC), and detection (DET) rating
TR-SI-18.	User displays outcomes of the risk priority number (RPN) for each failure mode executed using pre-defined functions within the local storage
TR-SI-19.	User inputs or selects from list of threshold values beyond which mitigation measures MUST be triggered (e.g. occurrence>4, RPN>70…)
TR-SI-20.	User proposes or selects from the recommended look-up table of remedial actions (e.g. inspections, design with more sensors…) and re-evaluates the RPN (SI-TR18-19)
TR-SI-21.	User inputs the details of the person or organisation responsible for each action and the target dates to achieve them

Depending on the needs of the user, the QFD/TRIZ/FMEA modules within the tool can be used separately or in combination to investigate the potential innovations within the system using the above steps.

It should be noted that the QFD involves a sequence of House of Qualities (HoQs) to deploy specific functions forming the design characteristics, and to develop the methods for achieving those designs into the subsystems, component parts and the specific elements of manufacturing processes (as appropriate). There are steps in the Structured Innovation process that will be executed several times and in a number of HoQs depending on the targets and the complexity of the problem to be solved for each stage of product development and production requirements [15] [17]. Each of these results is a technical requirement. The technical requirements together deliver the functional requirements, according to the relationships presented in Table 3-2.

TABLE 3-2: FUNCTIONAL AND TECHNICAL REQUIREMENTS MATRIX FOR THE STRUCTURED INNOVATION DESIGN TOOL (BLUE SECTIONS = TR REQUIRED FOR FR)

FR / TR relation matrix		Functional Requirements				
		FR-SI-1	FR-SI-2	FR-SI-3	FR-SI-4	FR-SI-5
Technical Requirements	TR-SI-1	X				X
	TR-SI-2	X				X
	TR-SI-3	X	X			X
	TR-SI-4	X	X			X
	TR-SI-5	X	X			X
	TR-SI-6	X	X			X
	TR-SI-7	X	X		X	X
	TR-SI-8	X	X		X	X
	TR-SI-9	X	X		X	X
	TR-SI-10		X	X		X
	TR-SI-11		X	X	X	X
	TR-SI-12		X	X	X	X
	TR-SI-13		X	X	X	X
	TR-SI-14		X	X		X
	TR-SI-15	X			X	X
	TR-SI-16				X	X
	TR-SI-17				X	X
	TR-SI-18				X	X
	TR-SI-19				X	X
	TR-SI-20				X	X
	TR-SI-21	X			X	X

All the requirements listed in Table 3-2 will be satisfied by the modules within the Structured Innovation design tool (QFD/TRIZ/FMEA). These are designed to provoke innovation and represent the voice of the customer through the design process, manage risks and therefore produce new or improved concepts. However, in order to assess concepts, the Structured Innovation design tool calls upon the Stage Gate, Deployment, and Assessment tools to enable objective assessment of the overall system (e.g. PTO design, transmission system…).

3.2 ARCHITECTURE OF THE STRUCTURED INNOVATION DESIGN TOOL

The Structured Innovation design tool will be used for concept creation and design improvement. The main functions of the tool as shown in Figure 3-1, highlight how each module will be used to meet the functional requirements and how the Structured Innovation design tool interacts with the other design tools within the DTOceanPlus suite.

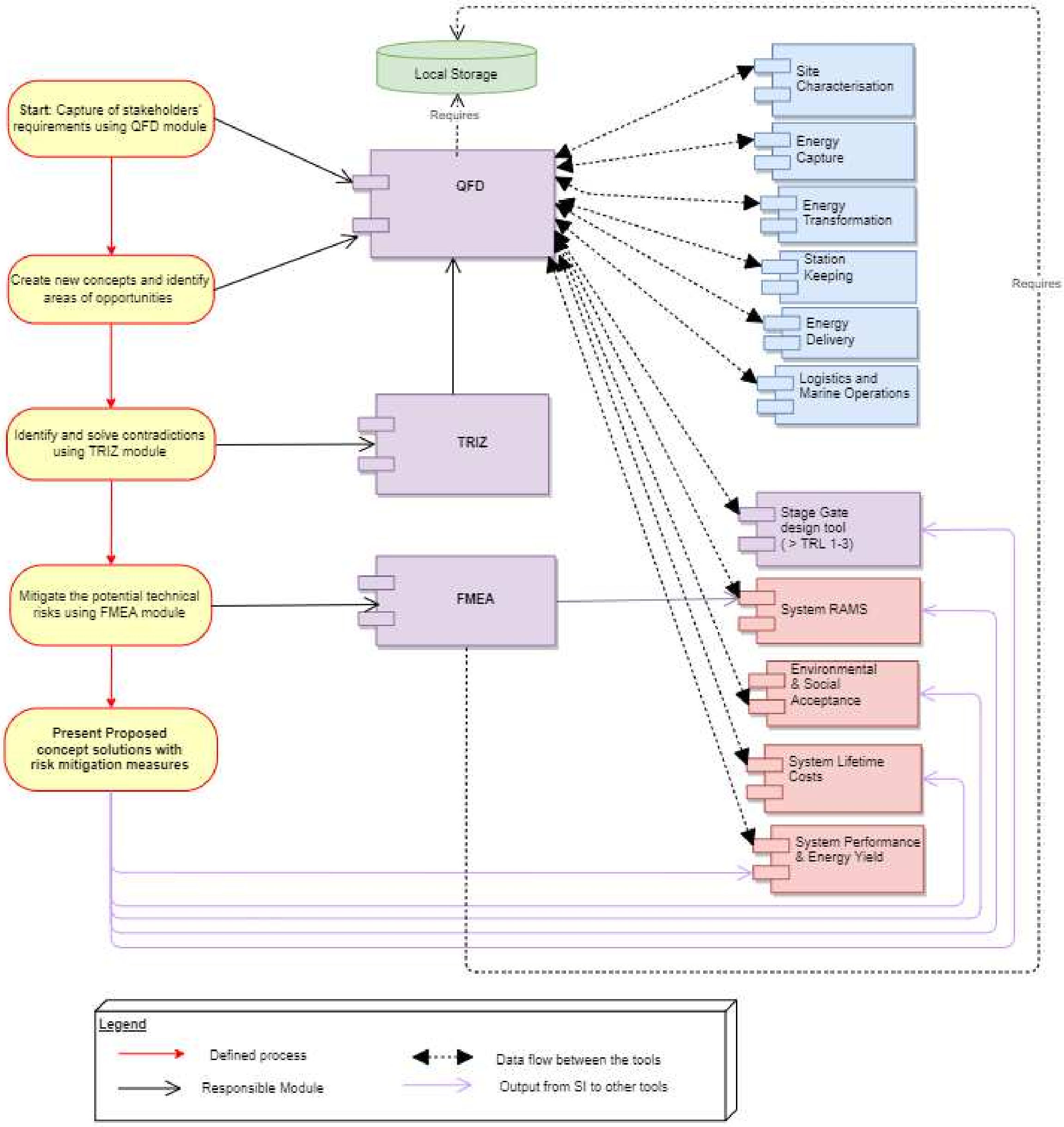

FIGURE 3-1: MAIN FUNCTIONS OF THE STRUCTURED INNOVATION DESIGN TOOL (BLOCKS IN PURPLE REPRESENT STAGE GATE AND STRUCTURED INNOVATION TOOLS, BLUE- DEPLOYMENT TOOLS, RED-ASSESSMENT TOOLS)

3.3 MAIN FUNCTIONS AND MODELS

This section lists out the main functions to be implemented in the Structured Innovation design tool and the models to be adopted. For clarity, UML diagrams are used to describe the set of actions that the users of the tool will have to execute for each module.

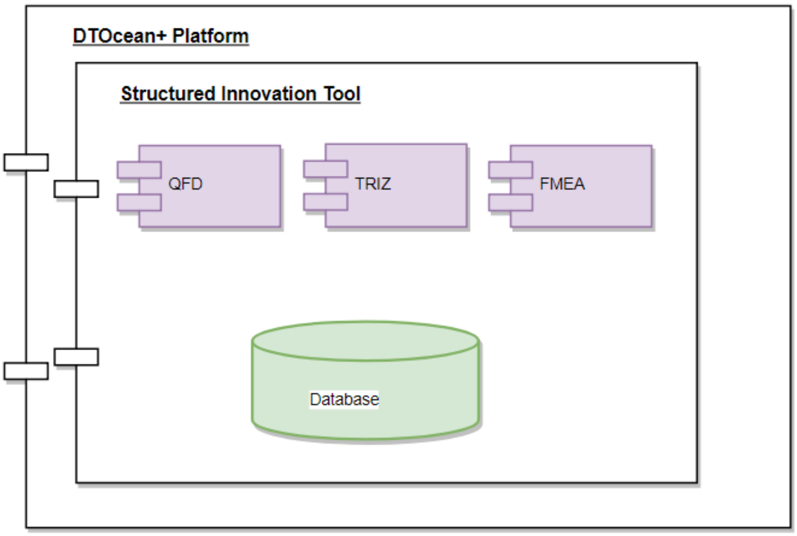

FIGURE 3-2: MAIN ELEMENTS OF THE STRUCTURED INNOVATION DESIGN TOOL

The predominant users of DTOceanPlus can be split into three main categories as identified in the User Consultation D2.1 [46] and Demonstration Strategies D2.3 [47]:

1. Technology Developers – focusing on developing their specific device/technology
2. Project Developers – focusing on deploying devices/arrays commercially
3. Public & Private Investors – with largely overlapping requirements of understanding financial implications in support of the first two users and development of the sector

The Demonstration Strategies in D2.3 [47] highlighted that the Structured Innovation design tool is likely to be used by the technology developers at subsystem level to create new or improved subsystems concepts. However, this study also highlights significant responses from the investors wanting to use the tool to enable them to identify attractive areas of innovation for investment.

The architecture of the Structured Innovation tool remains the same regardless of the user type and what they are looking for. However, the inputs will be different for each stage or mode of development. Some examples of use cases for the Structured Innovation design tool are identified in Table 3-3.

TABLE 3-3: USE CASE EXAMPLES FOR THE STRUCTURED INNOVATION DESIGN TOOL

User Type	Objectives	Stage
Funders & Investors	Assess potential of technology	Early
Funders & Investors	Target funding opportunities in sector	Early
Innovators & Developers	Assess novelty in technology	Early
Innovators & Developers	Look for improvement areas	Mid
Project Developers	Assess subsystem concepts in a device	Mid
Policy makers & Regulators	Assess environmental impact of a specific technology/site	Mid
Innovators & Developers	Assess areas of improvement and technical challenges	Late

These use case examples highlight some of the reasons why the Structured Innovation design tool might be used. The technical requirements identified in Table 3-1 remain the same regardless of the use cases (Table 3-3). 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. These modules can be used separately or in combination depending on the user requirements. The diagrams below (Figure 3-3 to Figure 3-5) show typical process flows through each module for such cases.

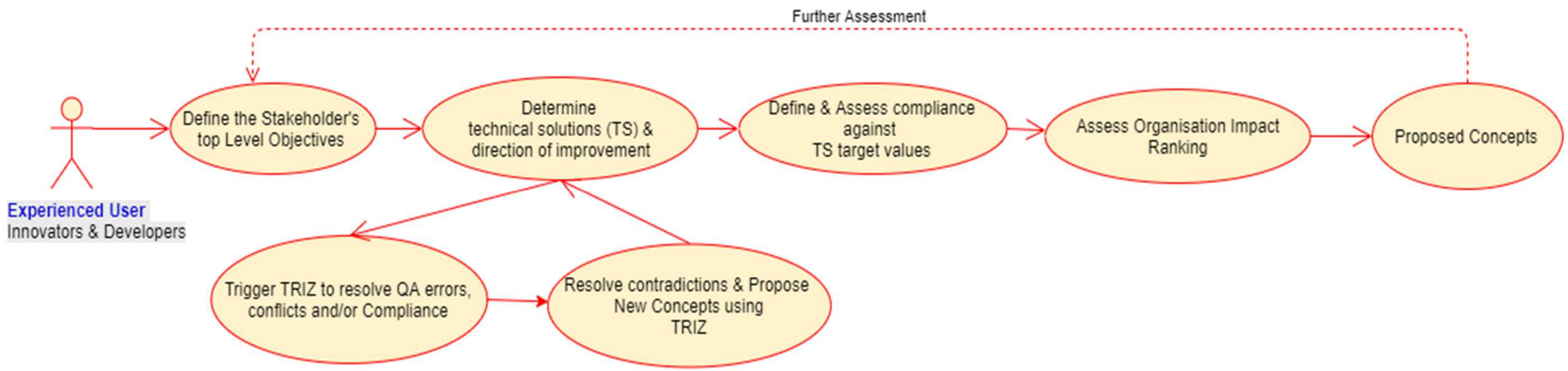

FIGURE 3-3: PROCESS FLOW FOR SCANNING THE DESIGN SPACE AND IDENTIFYING POTENTIAL INNOVATION CONCEPTS (QFD /TRIZ MODULES)

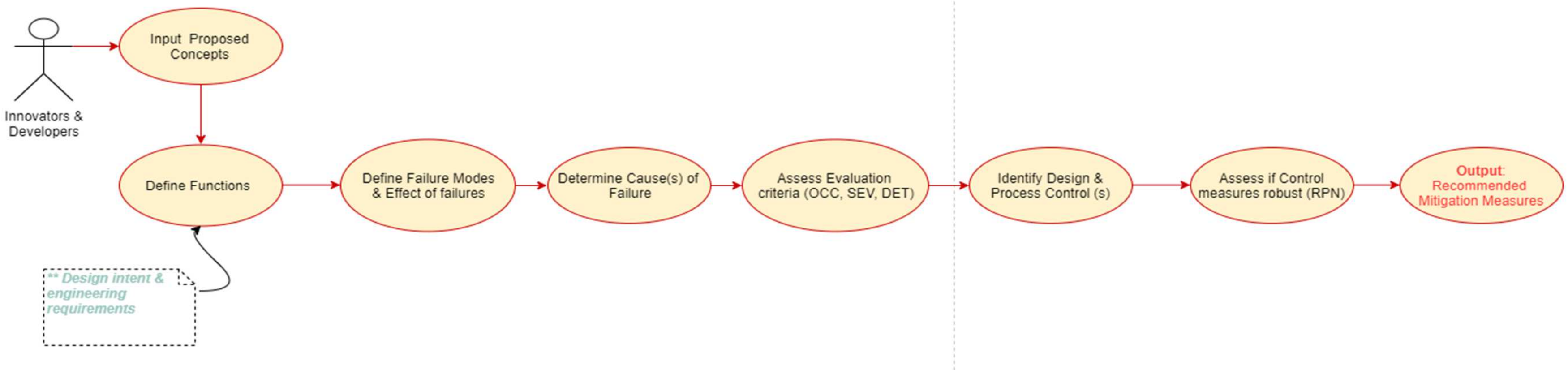

FIGURE 3-4: PROCESS FLOW FOR MITIGATING RISKS OF PROPOSED CONCEPTS (FMEA MODULE)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 785921

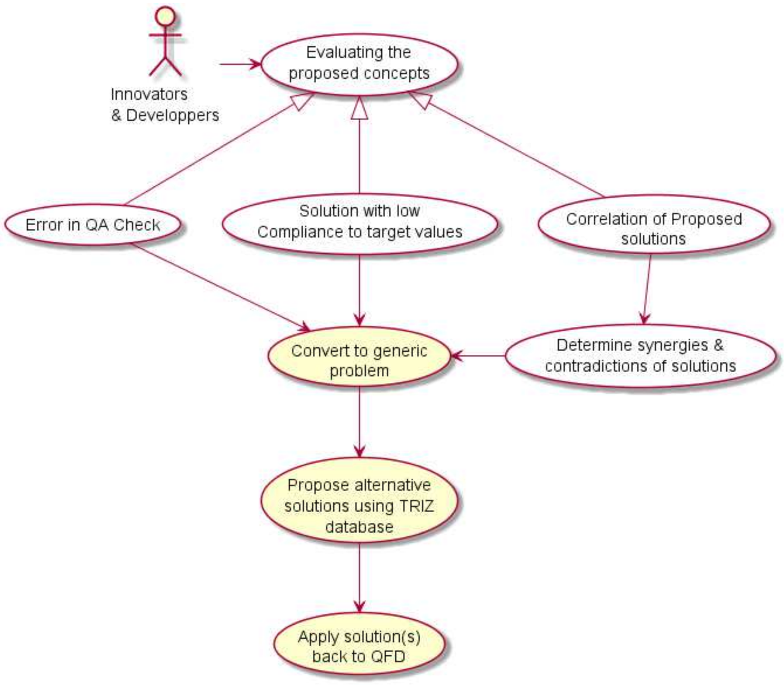

FIGURE 3-5: PROCESS FLOW FOR EVALUATING THE PROPOSED CONCEPTS (QFD/TRIZ MODULES)

3.4 DATA REQUIREMENTS

Inputs for the Structured Innovation tool will come from: the user inputs (project definition, definition of the top objectives of the assessment, etc.) , the other tools (e.g. Stage Gate design tool) , the Database (e.g. vessels, ports, etc.) and the Structured Innovation local storage (e.g. QFD-solution hierarchy, TRIZ library, etc.), and others in the database (e.g. list of components, reference data, catalogues, etc.). Therefore, the data requirements are represented as part of a digital twin with which it interacts, which are represented in Figure 3-6.

Examples of inputs required from other modules include:

- Mean power production per device from the deployment tools
- Accessibility data from the Logistics and O&M module (e.g. weather windows)
- High level assessment of global efficiencies of PTOs from the Energy Transformation module
- Bathymetry and soil properties from the Site Characterisation module
- Basic costs related to operation and maintenance schedules provided by Logistics and O&M module from the System Lifetime Costs public methods

Examples of outputs required from the Structured Innovation design tool include:

- Concept design description
- Engineering specifications of the concepts
- Potential conflicts and risks within the design

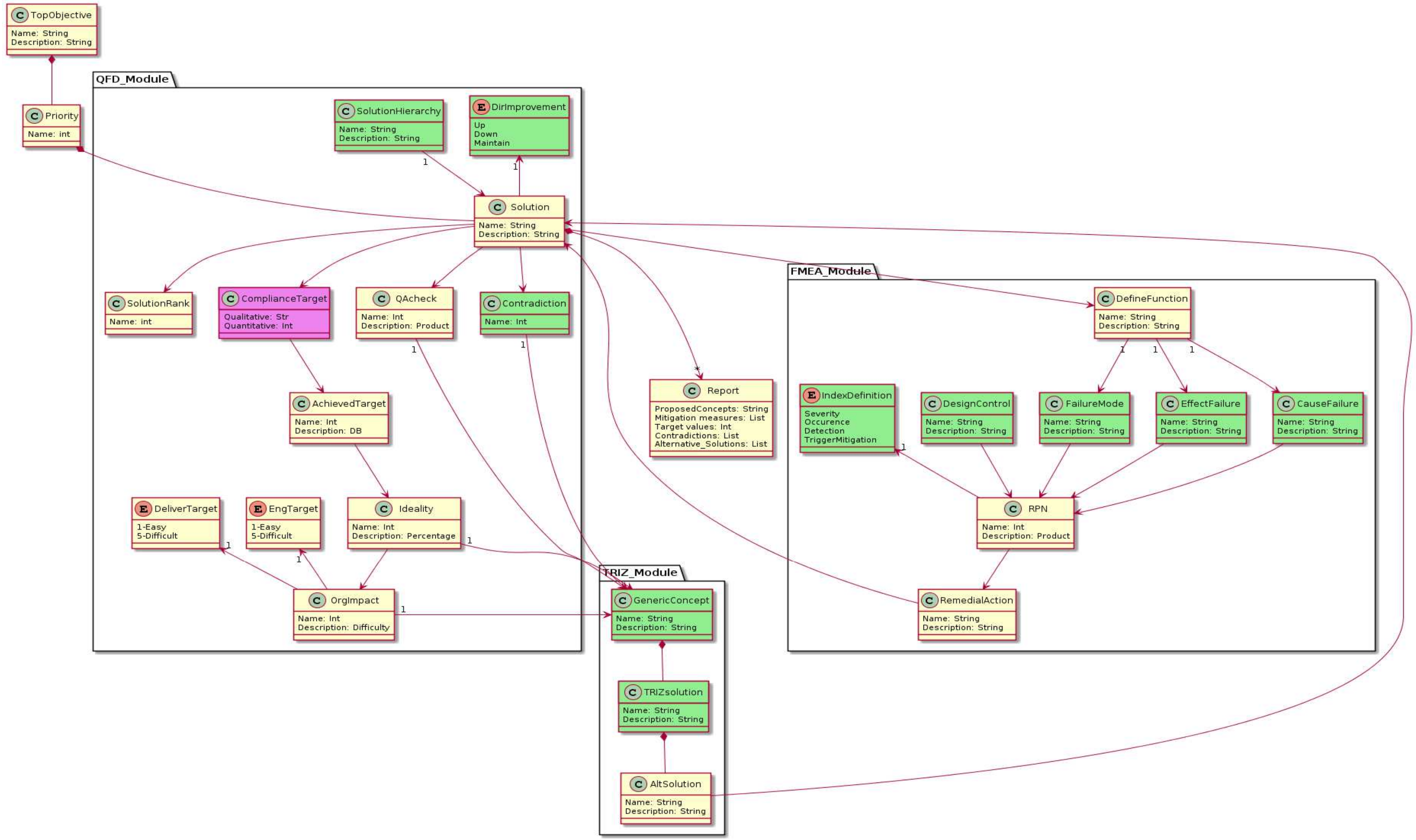

FIGURE 3-6: DATA STRUCTURE OF THE STRUCTURED INNOVATION DESIGN TOOL (CONTEXT DATA-PINK, LOCAL STORAGE DATA-GREEN, CLASSES OF DATA- YELLOW)

3.5 INTERFACES, COMPATIBILITY AND PORTABILITY

3.5.1 EXTERNAL INTERFACES

Several responses from the user consultation D2.1 [46] stressed the importance of linkages between the tools, and with external software. One technology developer suggested having an Application Programming Interface (API) to allow external software and scripts two-way access to the DTOceanPlus tools and data, allowing flexibility to use either DTOceanPlus or another tool as deemed most appropriate [46]. This section lists some external software tools that could complement the Structured Innovation design tool.

The Structured Innovation design tool will enable data to be imported/exported in formats compatible with some of the following tools to enable pre- and post-processing of data to/from other software including exporting in .csv format. However, there is a wide range of other software tools and products that can be used to support the assessment of ocean energy throughout concept creation, selection, and design. Features from a selection of these are summarised below:

TABLE 3-4: OTHER METHODOLOGIES USED FOR CONCEPT CREATION AND SELECTION

Tools	Key Functionality
Morphological Analysis [48]	Well-developed process
	Multi-dimensional approach/ interaction
	Bringing two opposing notions together (contradictions)
	Problem-solving tool – problems are decomposed
	Morphological Matrix
	Visual approach (Morphological chart)
Brainstorming	Well-known and widely used
	Aiming for ideality
	Large pool of experience & teams
	Simplest approach
Biomimetics	Emerging technologies mimicking nature & adoption in design features
	Problem definition
	Collection of biological effects/phenomena
	Well recognised approach [49]
Axiomatic Design (AD)	Systematic deconstruction of function design relationship
	Identification of design conflicts' couplings
	Deconstruction process to identify leaf (lowest) level variables and parameters
	Systematic way of laying out 'in-play' factors for the design

However, presently, there is no foreseen external interface between the Structured Innovation design tool and any such external tools. It should be noted that data can be imported in the database to assess specific requirements of subsystems in DTOceanPlus compatible input formats. As the sector matures, it should be noted that the tool will evolve to address emerging needs in the sector.

3.5.2 COMPATIBILITY AND PORTABILITY

The use of the FMEA module to perform standalone analysis describing any system's or subsystem's failure mitigation measures is anticipated. Similarly, the QFD and the TRIZ modules can be used individually to obtain the characteristics of innovative components/processes to be inputted to the deployment tools to generate all design information for the different subsystems of a project/device/technology. The assessment tools will receive the design information from the deployment tools and will make some further calculations and present results to the user in the form of suitable metrics. It should be noted that the modules will be able to run standalone only in the case where the necessary input parameters are provided by the user.

3.6 MAINTENANCE

Following the development and delivery of the DTOceanPlus suite of tools, the software maintenance requirements expected with respect to the Structured Innovation design tool are:

- QFD database: Updates to solution hierarchy defining the top-level objectives and the possible technical solutions to achieve them.
- TRIZ inventive principles: Although updates of the TRIZ problem-solution database are not anticipated, there might be a need for updates to related solutions with regards to the ocean energy context as the sector evolves.
- FMEA module: The types of data that may need updates in the FMEA module will generally be the library information defining common generic failure modes, effects and the design control measures. The user of the tool will also be able to import look-up tables with definitions and descriptions of potential failure types and details in addition to values of the ratings (Occurrence, Detection, Severity).

As the sector evolves, the data will need updating and this will be done using configuration files most likely in .xml, json and/or .csv formats.

4. TECHNICAL SPECIFICATIONS FOR THE INTEGRATION OF THE STRUCTURED INNOVATION DESIGN TOOL IN THE DTOCEANPLUS SUITE OF TOOLS

A critically important aspect of the DTOceanPlus project is the integration of the suite of tools around a central core, provided by a software platform with a graphical user interface (GUI), digital models for the representation of ocean energy systems, and a global database.

The selection of this core architecture builds on learning from DTOcean and expands on the benefits realised in that project. The following sections present the technical requirements for the integration of the Structured Innovation design tool within the DTOceanPlus suite of tools.

4.1 INTEGRATION WITH THE UNDERLYING PLATFORM AND DIGITAL REPRESENTATION

The DTOceanPlus platform is modular with each module representing a tool or a set of tools. Each module will need to provide a list of services (i.e. Python functions), and the main application will publish these services in the main User-Interface (UI). This architecture will allow modules to be developed independently and to be run in a standalone mode, without the main UI.

The Structured Innovation design tool interacts with all the tools within the DTOceanPlus suite as shown in Figure 4-1. The interaction is summarised as:

- The Structured Innovation tool is triggered when the user looks to identify potential innovation within their technology or to improve their existing products and services.
- The Deployment design tools are used to provide design information based on the technology, aggregation level and context choices made by the user.
- The Assessment tools take the given data and assess the parametric values which are fed back into the Structured Innovation design tool to define potential areas of innovation.
- The Stage Gate design tool is triggered to assess the divergence of the proposed art-of-the possible values against to the state-of-the-art technology thresholds set in the Evaluation Areas of the tool.
- The digital representation stores information about:
    - The user's top objectives and their relative importance rankings
    - The tool's report highlighting the proposed concepts, their target values, the comparative assessments of ideality against competitive solutions and organisational impacts
    - The contradiction dashboard and the suggested alternative solutions
    - The risk mitigation measures of the proposed concepts

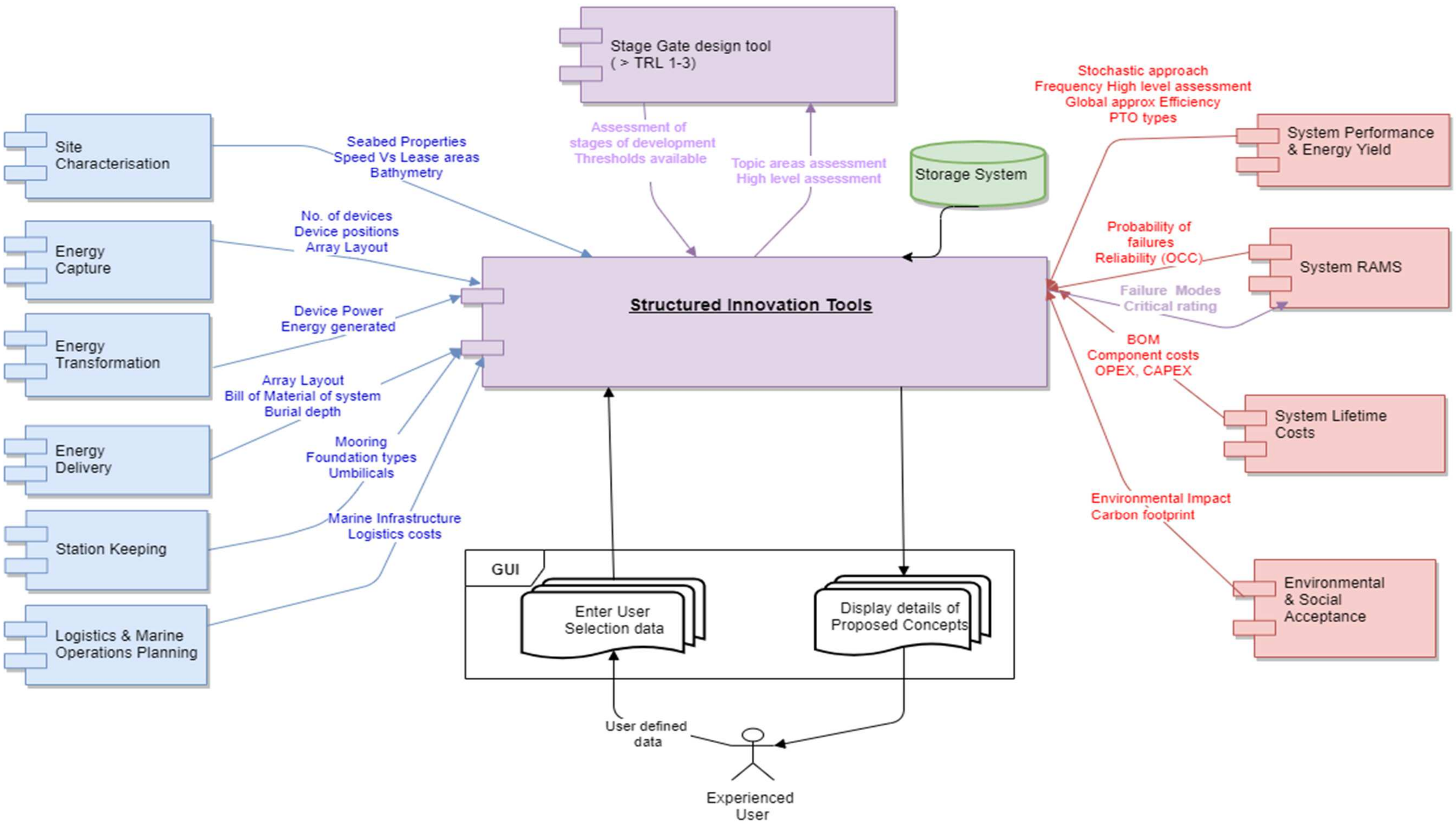

FIGURE 4-1 LINKAGES BETWEEN STRUCTURED INNOVATION, GUI AND OTHER TOOLS WITHIN THE DTOCEANPLUS SUITE

4.2 INTEGRATION WITH THE DATABASE

The Structured Innovation design tool is expected to interact with the global database via the main platform when the project context is defined. This is the place where the known technical specifications are defined. As a centralised storage for common references of the applications, the Database will contain a list of catalogues that will be accessible by any module.

The modules will consult the catalogues through one or several services offered by the main application. In addition, the Structured Innovation tool will require information very specific to its modules within the tool and these data will be stored locally within the local storage of the Structured Innovation tool. Section 4.6 explains in detail the various interactions within the Graphical User Interface including interaction with the local storage.

4.3 INTEGRATION WITH THE STAGE GATE TOOL

As part of DTOceanPlus, the Structured Innovation design tool will interact closely with the Stage Gate tool to assess the proposed concepts against the tool's key metrics and to guide the users of the Structured Innovation design tool in understanding the compliance of their concepts against the Stage Gate framework benchmarks.

The Structured Innovation design tool will require the same assessment processes as the earliest stage assessments of the Stage Gate design tool. However, in the case of new concepts where there is little to no data available, the Structured Innovation design tool will request the specific target values from the relevant assessment tools instead of the Stage Gate design tool key metrics. The Structured Innovation and the Stage Gate design tool are strongly linked in their functionality. The proposed areas of innovation recommended in the Structured Innovation design tool will be fed into the Stage Gate design tool and will utilise the simplest assessment and deployment tools to assess these concepts. These may be based on fundamental engineering, physics and economics relationships. In the case where a result of the stage gate assessment highlights a weakness in a technology or an area of potential improvement, this will trigger the Structured Innovation improvement cycles. At this point it is expected that the Structured Innovation tool will be able to access the relevant design information about the technology from the Digital Representation, the relevant Deployment and Assessment tool, the Stage Gate threshold values and from the Structured Innovation design tool local storage. This will then provide a starting point for the Structured Innovation tool to guide the user in improving their design.

Throughout the development process, technologies may be output from the Stage Gate design tool with areas of improvement and technical challenges highlighted. These can be fed into the Structured Innovation design tool to be reappraised and subsystems or the system redesigned to overcome such challenges with the suggestion of concepts, guidance for concept creation or highlighting areas of promising scenarios.

Where available, the Stage Gate design tool will provide thresholds for metrics to the Structured Innovation tools. These may come from benchmarking the state-of-the-art which will be useful for the users of the tools to create the target values as part of the Structured Innovation design tool.

4.4 INTEGRATION WITH THE DEPLOYMENT TOOLS

The Structured Innovation design tool will interact with the Deployment design tools to obtain design information needed to assess the potential innovative concepts. At the earliest stage, high level design parameters will be passed on to the Assessment tools to measure the potential of the concepts proposed. The design data from the Deployment to the Assessment tools will inform the engineering, physics and economic fundamental relationships which drive the earliest stages of assessing the attractiveness of concepts.

4.4.1 SITE CHARACTERISATION

The information related to the site is critical for the Structured Innovation design tool, since it defines the wave and tidal condition at the selected location, as well as the installation area, the bathymetry and seabed properties, etc. At very early stage where little to no data are available, simplified basic assessment to define fundamental relationships will be used. The resource data can be selected from class of sites lookup tables provided in the tool's database/catalogue.

TABLE 4-1: STRUCTURED INNOVATION AND SITE CHARACTERISATION INTEGRATION

Parameters	Very Early- Early	Mid- Late stage
Resource data	Class of generic site selected (Low/ Medium/ High energy site) provided from the catalogue/ database	User-defined or computed Wave/tidal resource for site specific assessment (e.g. On site Current harmonic field, Current speed 3D fields, Wave spectrum field, scatter diagram
Site information		Site specific assessment to inform availability, accessibility of site and logistics needed

4.4.2 ENERGY CAPTURE

The Energy Capture module will produce required hydrodynamic data for the captured energy. This module will interact with the QFD and the TRIZ modules within the Structured Innovation tool at very early stage to assess the average captured energy for the various high, medium or low energy sites. This information will also feed into the FMEA module to inform the potential risks associated with existing and proposed areas of innovation. This will enable early assessment of potential energy and technologies at different sites. The Structured Innovation design tool will then perform a holistic analysis of the system and propose potential areas of innovation to the tool. The integration between the two tools is shown in Figure 4-1 and in the Summary SUMMARY

Table 4-2.

4.4.3 ENERGY TRANSFORMATION

The Energy Transformation (ET) module will provide optimal design solutions for the Power Take Off (PTO) and all the subsystems and components. The Structured Innovation tool will therefore interact with the Energy Transformation module in order to identify potential innovative designs and:

- Assess potential innovative design concepts by using the tool's reference data for the analysis of suitable PTO and control designs
- Determine the technological barriers and identify the gaps in terms of technological availability or compatibility of the components. When the outcomes generated cannot satisfy the user requirements, the Structured Innovation tool is alerted and receives details on the current configuration
- Measure the uncertainty level depending on the level of complexity and the accuracy of the assessment provided in the ET module

4.4.4 ENERGY DELIVERY

The Energy Delivery module will develop optimal design solutions for the electrical infrastructure by defining and selecting optimal equipment and components for the intra-array and transmission system. At the earliest stage of assessment, the Energy Delivery module will provide design solutions based on minimal parameters such typical transmission cable costs, and energy yield based on rated power. The Structured Innovation tool will support this module by assessing the potential innovative concepts within the energy delivery system, which will include consideration of new topologies (e.g. multiple export cables), intelligent clustering of devices and improved cable routing, etc. The user can re-run the DTOceanPlus tools with the innovative concepts identified by the Structured Innovation tool to assess their impacts on the study overall. These would be input into the Energy Delivery module by the user and would override the optimisation routines used in the module.

4.4.5 STATION KEEPING

At the earliest stage of assessment, the Station Keeping module will assess a range of input values and produce basic designs based on standard components for the various foundations and mooring designs with no expected optimisation. However, the level of detail as the technology matures will increase and enable the Station Keeping module to produce optimised design solutions. These outputs will feed into the Structured Innovation tool to enable the assessment of potential innovation of sub-structures. The characteristics of the proposed innovative concepts from the Structured Innovation tool will feed back into the Station Keeping module to design according to the user requirement.

4.4.6 LOGISTICS AND MARINE OPERATIONS

The Structured Innovation design tool will interact with the Logistics and Marine Operations (LMO) module in identifying attractive areas of innovation to reduce costs related to the required logistical infrastructure of the ocean energy project. The LMO module will provide basic costs related to the operation and maintenance schedules, early logistic requirements (e.g. Costs against basic class of sites), and infrastructure data (lookup tables of existing vessel capacities and costs, ports, equipment, etc.) as shown in Summary Table 4-2.

4.4.7 SUMMARY

TABLE 4-2: INTERACTION OF THE STRUCTURED INNOVATION TOOL WITH THE DEPLOYMENT TOOLS

Module	Parameters	V.Early to Early	Mid- Late stage
Energy Capture	Captured energy for the site(s)	Average absorbed captured energy for specific sites	Quantification of the absorbed energy at farm and device level Captured Mechanical Power per sea state (for wave energy) or current velocity profile (for tidal energy) Array q - factor
Energy Transformation	Cost of PTO & Control systems Energy Yield Efficiencies	Bill of materials from default PTO parts based on catalogue values Assessment of innovative characteristics within PTO and control systems High level assessment of Power production per device, breakdown per conversion step, components efficiency from default values taken from the catalogue	Bill of materials for specific PTO designs Selection of optimised configuration of PTO & control systems Optimised Control strategy Power electronics
Energy Delivery	Electrical infrastructure Bill of Materials	Specific components not identified for energy delivery network. Distances based on proxies, and do not consider installation/protection methods	Typical to specific components for energy delivery network selected from catalogue Distances based on optimal cable routing, including detailed information on installation/protection methods
	Efficiency of Electrical Infrastructure	Network Efficiency - Energy yield based on rated power of device/ array only, (no losses or default percentage losses e.g. 5% for HVAC...)	Annual Energy Production of project is calculated including full Bill of Materials with optimised electrical infrastructure layout and averaged/detailed resource data
Station Keeping	Mooring Lines & interaction Foundation type Dynamic umbilical cables	Basic station keeping design based on list of standard components for WEC/TEC rating (e.g. based on a lookup table of standardised moorings and foundations designs) Generic costs (% of CAPEX....	Modelling of motion solving, foundation... Techno-economic approach
Logistics and Marine Operations Planning	Logistic solutions such as vessels, port, equipment costs and scheduling of costs throughout the project	Typical combination of vessels, equipment, and ports and cost estimated based on fundamental relationships (water depth vs. logistical requirements, logistical requirement vs. vessel types, etc)	Detailed logistic requirements (lifting capacity, towing requirements...) & Optimal logistic solution (vessel combination, equipment, ports) that minimises costs. Maintenance schedules (requirements & optimal costs)

4.5 INTEGRATION WITH THE ASSESSMENT TOOLS

The Structured Innovation design tool will require high level assessments including lifetime costs and reliability to measure the potential of the proposed concepts which are generated, which will be outputs of the Deployment design tools. The output data from each assessment tool will vary in complexity and level of details at the various stages of the project development (i.e. early, mid, and late stage). A high-level summary of the requirements for the Assessment tools are that they will:

- Inform the engineering, physics and economic fundamental relationships which drive the earliest stages of assessing the attractiveness of concepts
- Provide simple tools to support evaluation of requirements and solutions in QFD at early stage – i.e. objective QFD scoring. These may be the full complexity tools with default inputs
- Link to complex tools applied through Stage Gate design tool to guide improvement needs in later stage technologies and prompt use of Structured Innovation design tool

Through the technology or array development process, the level of detail of the design and assessment activity increases, and this is mirrored by the complexity of the tools. At early stages, tool calculation processes could be simplified by using less complicated or proxy parameters, or by using default/example values to substitute those which simply do not exist yet.

4.5.1 SYSTEM PERFORMANCE AND ENERGY YIELD

At the earliest stage of development, the System Performance and Energy Yield (SPEY) will provide estimates of average energy production based on high level assessments. The SPEY module will provide to the Structured Innovation tool, basic energy yield information on the efficiency of all the subsystems, and estimation of mean power production per device or array. Outputs from the SPEY module will be used by the Structured Innovation design tool to inform potential improvements within all the subsystems in terms of energy yield, efficiency, power quality and availability of the system.

TABLE 4-3: OUTPUT VARIABLES FROM THE SPEY TO THE STRUCTURED INNOVATION DESIGN TOOL

Parameters/ Projects deployment stages		Project deployment stages	
		V Early - Early	**Mid-Late**
Parameters	Device AEP (Annual Energy Production)	X	X
	Array AEP (Annual Energy Production)	X	X
	Device Capacity factor	X	X
	Array Capacity factor	X	X
	Captured Energy		X
	Mechanic -Electrical efficiency		X
	Electrical-Electrical efficiency		X
	PTO Efficiency		X
	Transmission efficiency		X
	Total efficiency	X	X
	Planned and unplanned downtime		X
	Cut-in / Cut-off		

4.5.2 RAMS

From its FMEA module, the Structured Innovation design tool will provide to the RAMS module information related to the high-risk subsystems, devices or arrays. Some of these FMEA outputs will be a list of potential failure modes and risk mitigation actions to reduce their rate of occurrence, severity and recommended changes to the design & control measures, etc.

Along with inputs from the other tools, the RAMS module will generate the failure rate/ probability of failure / mean time to failure / mean time to repair of an array/ a device/ a subsystem/ a component needed for the occurrence calculation. At the earliest stages of assessment, the RAMS module will use the failure rates obtained from the Database. The failure rate of the subsystem, device or array can also be calculated based upon the classical reliability theory.

TABLE 4-4: OUTPUT VARIABLES FROM THE RAMS TO THE STRUCTURED INNOVATION TOOL

Parameters/ Projects deployment stages		Project deployment stages	
		V Early - Early	Mid-Late
	Probability of failure of the structural subsystem	X	X
	Failure rate of the electrical subsystem		X
	Failure rate of the mechanical subsystem		X
	Failure rate of the control subsystem		X
	Failure rate of the OES (the device)	X	X
	Availability of OES (the device)		X
	Maintainability of OES (the device)- MTTR		X

4.5.3 LIFECYCLE COSTS

The Structured Innovation design tool will interact with the System Lifetime Cost module by using costing functions (available through public methods) to evaluate possible design choices. These design choices will be fed into the System Lifetime Costs from the bill of materials which will be used to aggregate all the costs incurred in the design under evaluation. The functions to calculate different economic metrics will also be available as public methods for use by the Structured Innovation tool.

For the calculation of economic and financial viability metrics, the relevant design parameters will be retrieved from the deployment tools (e.g. the annual energy production from the SPEY module) to generate costs information such as cost proxies at the earliest stages of assessment that provide qualitative cost rankings, allowing the selection of the less costly solutions.

TABLE 4-5: OUTPUT VARIABLES FROM THE LIFECYCLE TO THE STRUCTURED INNOVATION TOOL

Parameters/ Projects deployment stages		Project deployment stages	
		V Early - Early	Mid-Late
Parameters	**Economic Feasibility**- Total Lifetime Costs	X	X
	Levelised Cost of Energy	X	X
	Financial Feasibility- Internal Rate of Return		X
	Net Present Value		X
	Payback time		X
	Required FiT		X
	Required Grant		X
	Weighted Average Cost of Capital		X

4.5.4 ENVIRONMENTAL AND SOCIAL ACCEPTANCE

The Environmental and Social Acceptance module will interact with the Structured Innovation tool by passing the outputs of the environmental impact assessment (EIA), the estimation of the carbon footprint in terms of CO_2 greenhouse gas emission (CFP) and the estimation of social acceptance index like number of jobs and LCOE (ESA).

Depending on the level of complexity of the assessment, the assessments within the Environmental and Social Acceptance module could be simplified to produce basic estimates or thresholds of the carbon footprints. Some of these parameters could be the carbon dioxide emissions (kg/MW), effect on marine life (collision risk and electric fields) and underwater noise (increase in dB level) for environmental tools, and number of jobs created (jobs/MW) and cost of energy for social tools.

4.6 INTEGRATION WITH THE GUI (PLATFORM AND TOOLS)

4.6.1 QFD AND TRIZ MODULES

As seen in Section 0, the QFD/TRIZ modules are used to assess innovation in product designs, in order to advance the technology and create the optimum social, economic and environmental impacts. The aim of the QFD module is to improve the designs according to the stakeholder requirements. The technical solutions are defined and evaluated to meet these requirements. The contradictions arising from conflicting solutions are resolved using the TRIZ module by proposing innovative solutions that meet the design principles.

The Structured Innovation tool will use reference data to provoke innovation through its QFD, FMEA and TRIZ functions. One example of this is through the concept of ideality which is often used in TRIZ. In DTOceanPlus, the Structured Innovation QFD module 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 three benchmark data types namely the state-of-the-art, commercial acceptance targets or ideal technology values.

Most reference data required for the QFD/TRIZ modules are only related to the Structured Innovation design tool; meaning that the data will be managed locally by the QFD and TRIZ modules using the local storage system. As the DTOceanPlus suite of tools is developed, it will be decided if some of these data will remain in the local storage system or moved to the main database for convenient reasons (e.g. if required by other tools).

Benchmarking, datum parameters and reference data are essential to this, being used in the Structured Innovation tool primarily for ideal solutions, concept initiation, and early stage assessment. The kind of data will be stored within the responsible tool's internal storage system or the Structured Innovation internal storage system.

From the Structured Innovation internal storage system, some of data/information that may be required by **the QFD module** are:

- Catalogue of captured stakeholders' requirements
- Definition of the relative importance of requirements
- Catalogue of possible technical solution paths
- Definition of the interdependence evaluation matrices (e.g. 1-Weak, 4-Medium, 9-Strong, …)
- Look-up table of the current state-of-the-art's target compliance values

And from the Structured Innovation internal storage system, the TRIZ module will require the reference data such as:

- Catalogue of 'Ideal Final Results (IFR)'
- Catalogue of 'Problem-solutions'
- Definition of an impact' scale describing the impact(s) of one technical solution over another (e.g. Beneficial= +9, good=+1, harmful= -4…)
- List of relationships between the interacting functions of proposed solutions (e.g. Good, harmful…)
- Interaction with technical solutions
- Catalogue of TRIZ problem-solutions matrices (39X39 Contradiction matrix)

4.6.2 FMEA MODULE

As defined in BS 60812 [50], a Failure Modes and Effects Analysis (FMEA) is a method of establishing the effect of failure within systems or processes. This analysis can be performed at any level of an individual assembly or subsystem-to-system level to identify and mitigate all failure modes which have a significant effect on the system reliability. At concept level and early stages of design, a concept or design FMEA can be performed to mitigate the potential failure modes associated with the various concepts proposed; when applied to processes it is called a process FMEA.

As an advanced design suite of tools aiming to enable the selection, development and deployment of ocean energy systems, aligning innovation and development processes with those used in mature engineering sectors, the DTOceanPlus software will use both the concept (cFMEA) and design FMEAs (dFMEA)

4.6.2.1 INFORMED USER INPUT

The following data/information will be required from the informed user when performing an FMEA:

1. Defining the design intent or engineering requirements
    a. As a standalone tool, the user will define the system/ subsystem's functions
    b. As part of the Structured Innovation design tool, the stakeholder requirements will be the requirement inputs
2. Recording the functions/ components under analysis
3. Defining and describing the severity, the probability of occurrence and detection

   a. Default values can be used from the local FMEA storage system
   b. User-defined values using free field form
4. Recording the failure modes, causes and likelihood of failure for each function/component
   a. Default lists of failure modes and root causes from the local FMEA storage system
   b. Or user-defined values can be inputted
5. Specifying the potential design control measures in place for each function/ component
6. Rating each failure mode' severity (SEV), occurrence (OCC), and Detection (DET) to obtain the risk priority number (RPN)
7. Specifying critical values beyond which a trigger for corrective actions is required:
   a. limit RPN values (e.g. RPN- 70)
   b. Special characteristics such as occurrence (e.g. OCC>5.)
8. Re-evaluation of the RPN with the revised SEV, OCC, DET
9. Recording all information about:
   a. Who is responsible and the target dates?
   b. Function
   c. Component
   d. Purpose
   e. Creation & Revision dates

4.6.2.2 INTEGRATION WITH THE INTERNAL STORAGE SYSTEM

The FMEA module can be used as standalone and/or as part of the modules within the Structured Innovation design tool. The FMEA catalogue of data can be stored locally within the Structured Innovation design tool. However, if the outputs from the FMEA are to be used in the RAMS module or other tools within the DTOceanPlus suite of tools, the storage system can be managed within the global database for convenient reasons.

4.6.3 MOCK-UP OF THE STRUCTURED INNOVATION DESIGN TOOL GUI

Below are screenshots of the mock-up of the Structured Innovation modules GUI representing the QFD/TRIZ and FMEA modules (Figure 4-2 - Figure 4-4). At this point, the GUI of these modules are still being developed and the alpha version of the tool will be released in Deliverable D3.2.

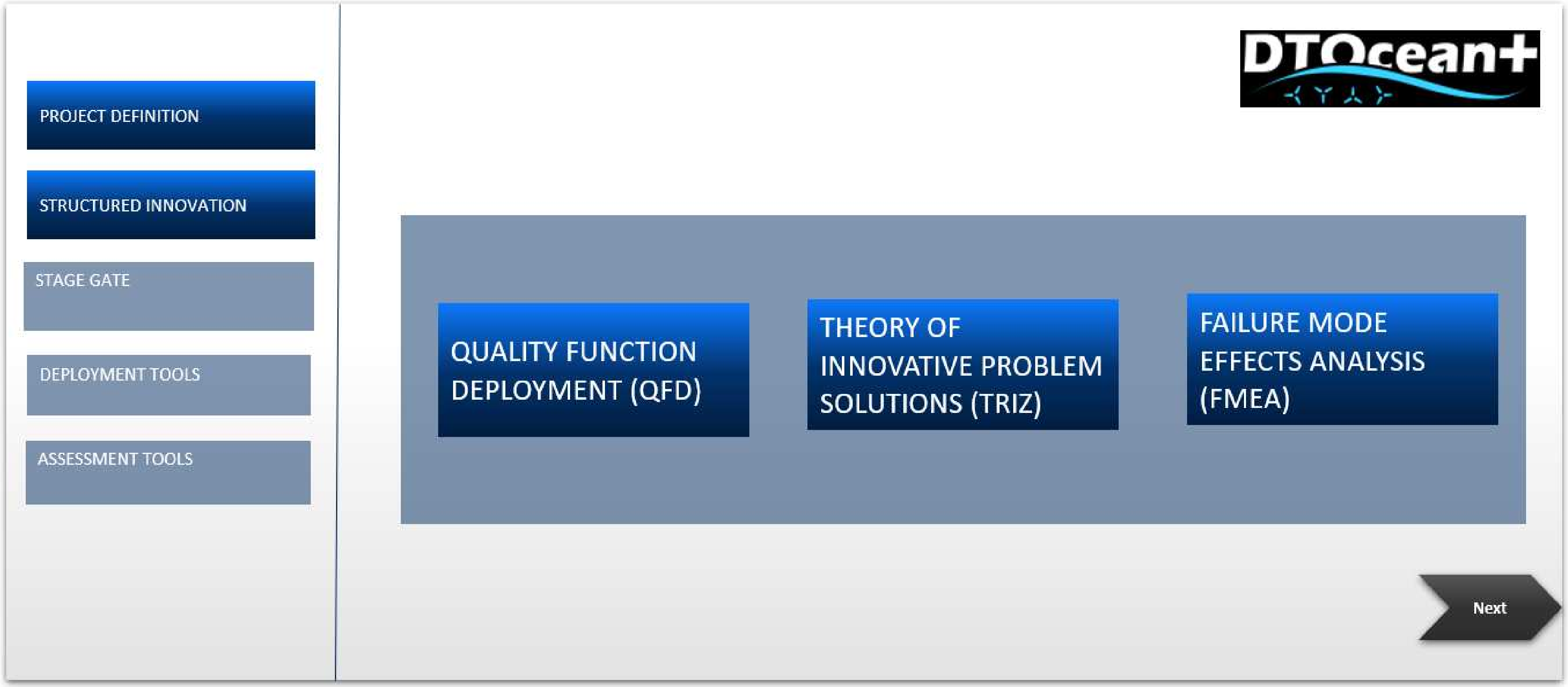

FIGURE 4-2: STRUCTURED INNOVATION DESIGN TOOL GUI MOCK-UP: REPRESENTATION OF THE TOOL

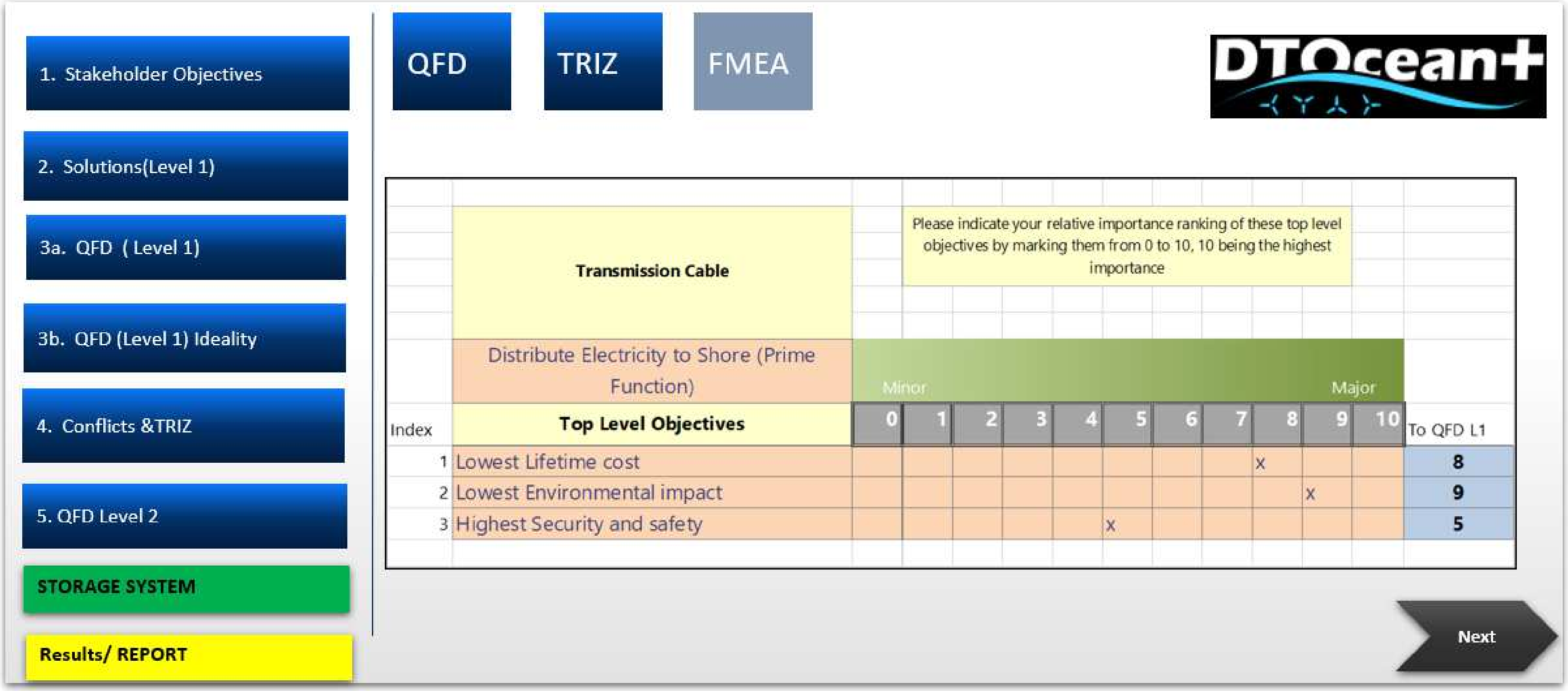

FIGURE 4-3: STRUCTURED INNOVATION DESIGN TOOL GUI MOCK-UP: REPRESENTATION OF THE QFD AND TRIZ MODULES

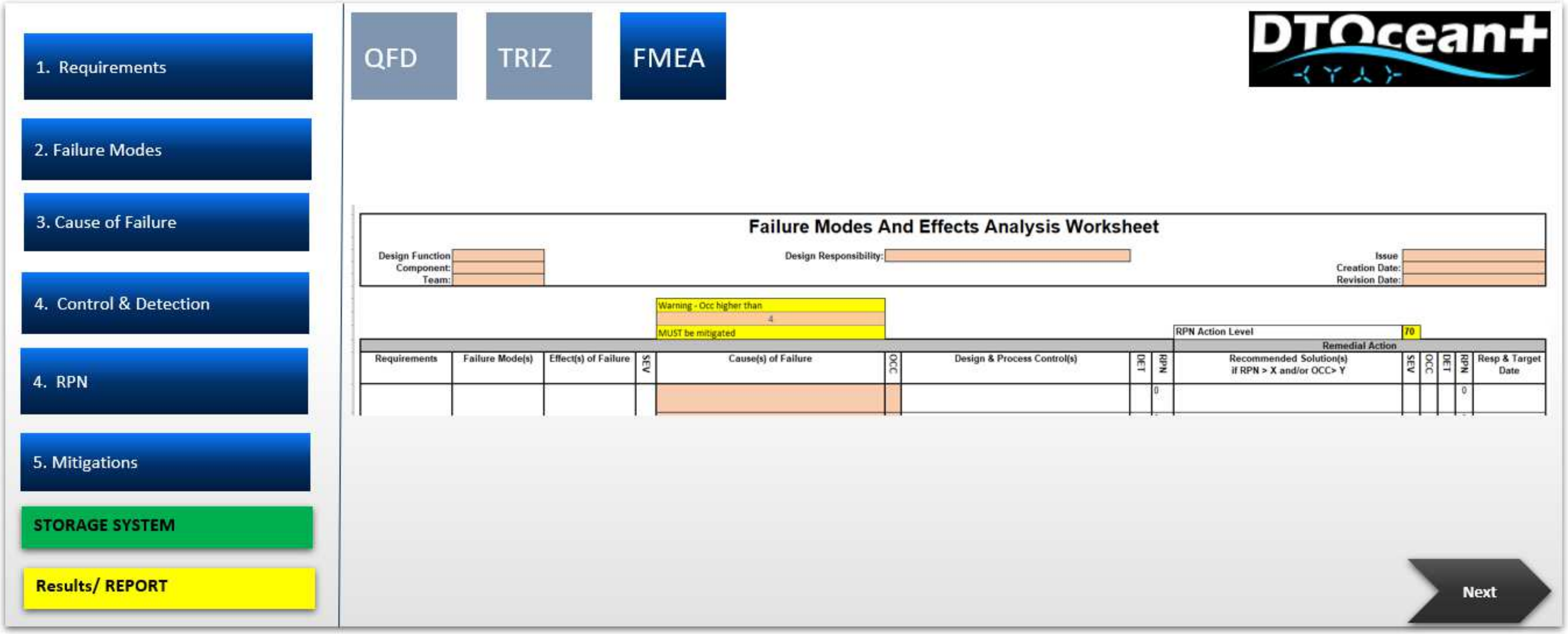

FIGURE 4-4: STRUCTURED INNOVATION DESIGN TOOL GUI-MOCK-UP- REPRESENTATION OF THE FMEA MODULE

5. SUMMARY AND NEXT STAGES

The addition of the Structured Innovation design tool in the DTOceanPlus suite will facilitate concept selection methodologies in the ocean energy in line with those used in mature, commercial sectors.

This report reviewed and analysed structured innovation best practises from standards and other sectors, before adapting the recommended modules suited to the needs of the ocean energy sector. This include the QFD module to define the innovation problem space, TRIZ as a systematic inventive problem-solving module and FMEA for assessing the technical risks

The technical requirements specific to the development of each module within the Structured Innovation tool are defined in this report including the data required, methodologies, interactions with other tools within the DTOceanPlus suite, and outputs expected to meet the functional requirements [1].

The next task (Deliverable D3.2) is to develop the alpha version of the Structured Innovation tool based on these technical requirements. The alpha version will contain all the core functions of the tool in its simplified form with dummy links to the inputs and outputs. This version of the tool will contain the framework of the tool and its functional requirements, but not necessarily with the GUI. The coding of the tool will be done in Python using the PEP8 codes and the developed tool tested to ensure it meets all the requirements.

The beta-version on the other hand will be a complete version of the tool with all the data flow, digital representation, public functions and interaction functions, including the GUI. The beta-version of the tool will be developed to fulfil the Deliverable D3.3 and will carry out validation of the tool in order to verify that it meets the requirements defined both in this report and in Deliverable D2.2 [1].

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7. ANNEX.

I. STATE-OF-THE-ART IN STRUCTURED INNOVATION APPROACHES

Table 7.1: The benefits and limitations of the modules and alternative applications

	BENEFITS	CHALLENGES	ALTERNATIVE APPLICATIONS
QFD (6-SIGMA)	Method of new product or service development	Poor translation of defined customers' needs	QFD & Axiomatic Design AD
	Integration of customer needs into the design process	Non-standardised approach to rating/scoring	QFD & Analytical Hierarchical Process (AHP)
	Database-driven portal	Inability to overcome trade-offs as standalone tool	Concurrent Function Deployment (QFD concepts into concurrent product development
	Identification of dependencies, unacceptable attributes	Need for accuracy in customer needs data collection (bias...)	QFD & Kano model
	Assistance to understand details of competition from design aspect	Need for training to use the tool	Brainstorming
	Enhance teamwork and input	Not widely adopted	Process mapping tools
	Prevent omission of key technical considerations	Customer expectations changes rapidly	TRIZ flowcharting tools
	Standardised tool (ISO 16355, ISO9000)		
MARKET RESEARCH	Competitive product analysis data	Short-term value-added services	QFD & Market Research
	Competitive edge (prices, learning curve)	Timely product development	Market research with Pugh's concept Pugh,1991)
	Precautionary measures approach instead of reactionary short-term fixes	No inclusion of end-user needs	
	Marketing management approach	Hard to integrate in fast-pace environment	
	Internal satisfaction (employees, targets).	Limitations to historical data/ existing information	
TRIZ	Similarities to Biomimetics analysis	Need for training and practice	Brainstorming
	Resolve physical & technical contradictions	Limited as a standalone to determine "success" of new concept	Mind mapping
	Logical approach to inventive problem solving	Lack of standard (Best-practice guide, right tools for specific tasks...)	Lateral thinking
	Beyond identifying problem/root cause, TRIZ finds solution	Organisational structure	Morphological analysis
	Set of solutions (patents, inventive principles, trends of evolution, ideality		TRIZ & QFD (Domb, 1998)

	From specific problems- to generic problem/solution-to specific solution	Lack of visualisation	TRIZ & AD (Ungvari, 1999).
	Fast innovation process (focus & short resolution time)	Complex methodology	TRIZ & Kano model (Slocum & Kermani, 2006)
	Clear language & framework		TRIZ & 6-sigma tools
			TRIZ with management, marketing, psychological tools

II. FUNCTIONAL REQUIREMENTS OF THE STRUCTURED INNOVATION DESIGN TOOL

1. To scan the design space and identify attractive areas of innovation

The Quality Function Deployment (QFD) will be used to firstly scan the design space by mapping options of key parameters which make up ocean energy concepts or projects, then ranking the attractiveness of these scenarios through high level physical and economic assessments as well as the environmental impacts that are potentially induced by the innovation. Secondly, QFD will be used to define the innovation problem space to represent the voice of the customer (stakeholder requirements) and make immediate objective assessment of the best solutions which fit the users' requirements. The standard QFD techniques used in the automotive industry were developed further and adapted 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 (the "whats") and answers them with a set of technical solutions (the "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 method allows these contradictions to be identified, and their impact assessed.

2. To create new concepts and identify areas of opportunity

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

3. To identify and solve the contradictions arising from the proposed solutions

TRIZ is a systematic inventive problem-solving method that will be 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 method 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. These two methods will be linked within the set of tools to allow visualisation of areas of opportunity and risk.

4. To mitigate the potential technical risks associated with the attractive concepts to satisfy the user requirements

Technical risks will be framed by using the concept FMEA module, linked to QFD and the Assessment tools (e.g. RAMS). The FMEA will provide ratings for each defect or failure in terms of severity, occurrence and detection. The FMEA will use 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. The failure modes identified in the FMEA will be passed on to the RAMS tool in readable format for the assessment of failure rates of subsystems.

In the 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 scenarios and in presentation of the QFD requirements (for example, could be cost of energy and reliability, amongst many). The overall result will be an acceptability rating that allows objective assessment of the design. Via the Graphical User Interface (GUI), selections and input data will be presented with both graphical and tabulated outputs.

Modules: The QFD, TRIZ and FMEA toolkits are defined as modules within the Structured Innovation design tool. These modules will be built with their relevant processes and reference data to execute them. They can operate as standalone and/or as part of the Structured Innovation set of modules to propose potential innovative concepts

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