A novel framework for the Digital Representation of physical and functional characteristics of Ocean Energy Systems

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Abstract— [1] **The digitalisation process has already become widespread in several mature engineering sectors, e.g. advanced manufacturing and the building sector. In less mature sectors, such as Ocean Energy Systems (herein limited to tidal and wave energy technologies), building a digital modelling framework becomes even more challenging, as the representation should involve not only well-established technologies, but also innovative and immature components, subsystems and devices. Nevertheless, the digitalisation of this sector is seen as one of the promising paths for accelerating the time-to-market and the deployment of the first commercial projects. The herein proposed novel framework for the Digital Representation of physical and functional characteristics of Ocean Energy Systems is developed within the EU-funded DTOceanPlus project. The transition from the physical reality towards the Digital Representation passes through the establishment of an appropriate data model accounting for the technical characteristics of the subsystems, their mutual coupling and operational requirements. The outcome of this on-going modelling effort is presented herein, concluding with a critical discussion of the subsequent challenges and issues to be solved.**

Keywords—**DTOceanPlus, Digital Representation, Ocean Energy Systems**

I. The Path towards the Digitalisation of Engineering Systems

THE traditional concept of engineering design focused on representing physical components is evolving to account for the whole product lifecycle, which also includes system processes and performance features. This is reflected by the increasing interest of companies in the implementation of Product Service System (PSS) approaches [1], as they are interested not only in delivering products, but also in providing through-life support for these products. This necessitates the integration of different tools for providing the required service. In order to develop an integrated PSS process, it is mandatory to build an "information architecture" through which the integration of different tools can be achieved. The technical implementation of PSS approaches has taken advantage of the digitalisation process [2]. Indeed, digitalisation not only helped in increasing the interactions between clients and provider, supporting the process of capturing the customer needs [3], but also became the infrastructural pathway towards the servitization of engineering sectors, e.g. through the development of internet-of-things [4] and big data treatment [5]. As a matter of fact it can be concluded "the service revolution and the information revolution are two sides of the same coin" [6]. Moreover, the purpose of digitalisation will drive towards innovation and performance by allowing testing of concepts in a virtual environment.

Many sectors, in which servitization can assume an important role, have already taken advantage of digitalisation. For example, advanced manufacturing and Industry 4.0 have benefited from the interaction with digitalisation, adding value to products, to processes and to managerial decisions [7]. However, the construction sector can be considered to be pioneering digitalisation, through the definition of the Building Information Modelling (BIM) framework. The BIM approach provides significant value throughout a project's life cycle [8]. This is supported through the use of digital objects, or digital twins, i.e. the Digital Representation of a physical asset (e.g. a building, a ship), and it can contain various digital models and collections of information and processes related to this object. The building industry shares the opinion that the use of digital twins is becoming a standard practice for construction projects [9].

In the maritime and energy fields, DNV GL [10] has recently stated that achieving data smart asset solutions could lead to improved business performance and better risk management. According to them, the digital twin approach is central to this next-generation offering. Similarly, in the field of renewable energy, and in particular in wind energy, the Digital Representation of the system can help to increase its competitiveness, as it can allow asset condition and performance to be tracked

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dynamically. Therefore, international efforts currently focus on the Digital Representation of wind energy systems. For example, the European Technology and Innovation Platform on Wind Energy (ETIP Wind) identified digitalisation as a key pathway towards cost reduction and system integration [11]. Among the attempts to achieve a holistic representation of wind energy systems suitable for digitalisation, the work developed within Task 37 (Systems Engineering) developed by the International Energy Agency (IEA) Wind is noteworthy. One of the objectives of IEA Wind Task 37 is to fully describe the ontology of a turbine (onshore and offshore) and associated plant. Also Task 33 of IEA Wind, although with a different perspective (reliability and operation and maintenance), has tackled the issue of standardising the taxonomy of a wind plant [12]. It is important to use a common standard for operators and manufacturers of power plants. The German systems in wind energy, as Identification System for Power Plants (KKS, from the German Kraftwerk-Kennzeichensystem) and the Reference Designation System for Power Plants (RDS-PP) [13], for example, are a set of tools integrating the international codes.

Also in the ocean energy sector, therefore, it seems unavoidable to establish an integrated architecture of interacting digital objects representing the various components, subsystems and devices forming an ocean energy array project. Indeed, given the lack of a continuous streaming flux of operational data in the field of Ocean Energy Systems due to the early stage of development of ocean energy project, the static behaviour of the elements in the digital representation is reflected considering digital objects instead of digital twins. Such an integrated architecture is not only aimed at representing the physical features of Ocean Energy Systems, but also facilitates the assessment of economic (e.g. lifetime costs) and technical (e.g. performance, energy yield, reliability and maintainability) impacts, as well as the social and environmental acceptance of such systems. In this way, Digital Representation will allow easier assessment of the readiness level of current technologies and as well as identification of criticalities, focusing on the innovation efforts. The digitalisation process of Ocean Energy Systems can also count on easy expandability and scalability among its features, thus enabling representation of early designs, more mature technologies or commercial projects. There is currently no standard method of describing the key characteristics and attributes of ocean energy technologies. Without such a standard it can be difficult, if not impossible, to objectively analyse innovative technologies and compare competing technologies. This hinders the ability of the ocean energy sector to engage in knowledge sharing activities and focus limited funding and resources on only the most promising technologies. One of the objectives of the Water Power Programme funded by the US Department of Energy [14] was to support the development of a standard taxonomy in order ·to reduce the technical barriers to marine and hydrokinetic device development, to improve device reliability and performance, and to understand and evaluate various technology types". In the case of wave energy, a breakdown of a wave energy system is presented in [15] and [16], for example. In [16], a Wave Energy Converter (WEC) is decomposed in a few common discrete subsystems, based on a functional approach, i.e. identifying a list of functions that the WEC system should perform. Five major subsystems have been identified (namely, hydrodynamic system, PTO subsystem, Instrumentation and Control, Power transmission, and Reaction Subsystem). However, the technological taxonomy focused only on the structural design, neglecting the operations inherent to these operations and the related logistics. On the other side, Bull et al. [17] have presented an effort to apply a Systems Engineering Process approach to wave energy systems in order to identify capabilities and functions of a wave farm. In this work, after identifying a mission statement for a wave energy farm (cit. "*The wave energy farm will convert ocean wave energy to electricity and deliver it to the continental grid market in a competitive and acceptable manner across the lifecycle*"), a hierarchical structure for capabilities and functions has been built, encapsulating the stakeholder perspective and design agnostic elements required to satisfy user's requirements. Even though this approach is not technology related, it comprises the entire lifecycle of a wave energy farm, from engineering design, towards procurement, construction, installation, operations and disposal, i.e. such an approach also allows consideration of the main marine operations through the life of the wave energy project.

The purpose of the present paper is to make a step forward towards the definition of a novel framework for the Digital Representation of Ocean Energy Systems, involving both their physical and functional characteristics. The work is being developed within the EU-funded DTOceanPlus project [18]. The digitalisation process will foster the definition of a standard framework for the description of Ocean Energy Systems of different Technology Readiness Levels (TRLs), significantly enhancing the ability of sector stakeholders to work collaboratively. This will accelerate development of the sector, whilst also further supporting stakeholders who wish to make objective comparisons between various technologies. In this work, an effort is made to reconcile and expand the approaches in [16] and [17]. First, the scope has been extended to cover the two more developed sources of ocean energy, namely tidal and wave energy. After identifying user expectations for the Digital Representation and using an approach comprehensive of the whole lifecycle, the Digital Representation framework has been inferred and translated into a set of digital objects, hierarchically arranged in a rooted tree structure, accounting for all the functionalities to be covered in an ocean energy design. The transition from physical embodiment towards Digital Representation was made through the establishment of a data model defining the objects in the array, i.e. their topology (groupings), design datasets and attributes. Experience of previous projects and the first deployments was valuable in this process. Not only was it necessary to model the physical objects, but also to include the marine processes in the models. This allows continuous follow-up of the project through its entire lifetime as these activities can have a significant impact on the economic viability of ocean energy projects.

Section II describes the approach followed in this paper. After a brief description of the context in which this work is developed (subsection A), the aim and requirements of the Digital Representation are stated (subsection B) and the methodology followed is described (subsection C). In Section III, the hierarchical organisation of the Digital Representation for Ocean Energy Systems is described and an example is proposed. Finally, Section IV presents a critical review of the main achievements obtained so far in DTOceanPlus and discusses the main challenges to come.

II. A Systemic approach for the Digital Representation of Ocean Energy Systems

A. *The DTOceanPlus Project framework*

DTOceanPlus, acronym for the European funded project Advanced Design Tools for Ocean Energy Systems Innovation, Development and Deployment within the framework of the H2020 programme [18] aims at accelerating the commercialisation of the Ocean Energy sector by developing and demonstrating an open source suite of design tools for the selection, development, deployment and assessment of Ocean Energy Systems (including sub-systems, energy capture devices and arrays). At a high level, the suite of tools developed in DTOceanPlus will include:

- Structured Innovation Tools, for concept creation, selection, and design, comprising tools like Quality Function Deployment (QFD), TRIZ and Failure Modes and Effects Analysis (FMEA);
- Stage Gate Tools, building the evaluation framework, applicable to different levels of complexity and providing guidance for further technology development;
- Deployment Tools, supporting optimal device and array deployment, from site characterization to energy transformation, station keeping and marine operations.
- Assessment Tools, to quantify key parameters and metrics, from system performance and energy yield, to lifetime costs, reliability, availability, maintainability, survivability, as well as environmental and social impacts.

The design tools will be supported by underlying common digital models and a global database, as shown graphically in Fig. 1.

The final outcome of DTOceanPlus will be an extensive toolset that will be demonstrated using real case scenarios. This will include a database of reference and project data, and a standard Digital Representation of Ocean Energy Systems which will provide an agile, robust and generalised framework for the description of Ocean Energy Systems at different levels of complexity, from sub-systems to devices and arrays. These models will constitute the "communication method" among various tools and software, and they also ambitiously aim at providing a first implementation of a common language for the entire ocean energy sector.

B. *Aim and requirements of the Digital Representation for Ocean Energy Systems*

The framework for Digital Representation of Ocean Energy Systems responds to the objectives of DTOceanPlus and more generally to the needs of the sector. As in the wind energy case, a digitalisation process in the field of ocean energy would accelerate integration of different subsystems, facilitate communication between various players, and yield data-driven designs and strategies to bring the cost of ocean energy down.

In order to achieve the targets of the Digital Representation, a set of minimum requirements can be identified.

1. The flexibility of the representation should allow capture of the characteristics of Ocean Energy Systems for different levels of project complexity and aggregation. Indeed, the Digital Representation is going to reproduce the characteristics of the system throughout all the project development phases, from the most conceptual ones, when a design is not fully established and several concepts are still under evaluation, to the most detailed phases of the design, when the amount of information is considerable and the technologies to be used have been selected. The information stored at different levels of project maturity must be commensurate with the research, development and demonstration activity carried out at that stage, and vice versa. The DTOceanPlus project will generate a recommended set of stage activities that

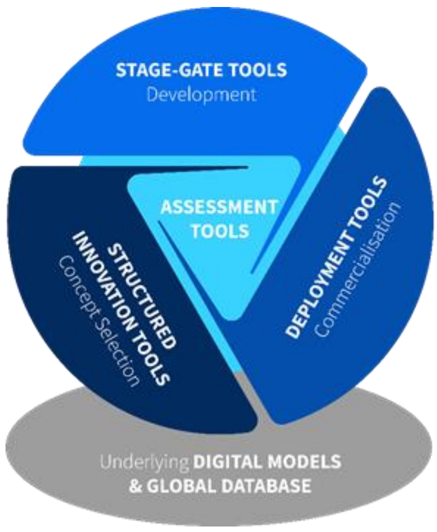

Fig. 1. Schematic view of the tools developed in DTOceanPlus.

are capable of producing the appropriate information, at the appropriate level of detail.

2. The Digital Representation will also keep account of system performance (estimated by the DTOceanPlus toolset or any other software) at different levels of aggregation, thus opening the way to assessing the behaviour of a single device or subsystems and benchmarking them against various technologies, using a common base framework.
3. The third aspect of a Digital Representation framework to be considered is standardisation in order to help the development of the sector. This aspect could be seen from a double perspective. From a more technical point of view, the Digital Representation is going to work as the base interface and "common language" making easier the exchange of data and communication among software. Therefore, the Digital Representation for Ocean Energy Systems is a common framework for transferring information among tools, not only those developed within the DTOceanPlus toolset, but also with other commercial alternatives, or other open sources modules, as well as in-house solutions. From a more semantic perspective, a standardised Digital Representation framework "universally acknowledged" will constitute the base for developing a common understanding among different stakeholders of the ocean energy sector. By doing so, not only will the communication be de-risked and made seamless, but also the decomposition of an ocean energy system could be more easily understood. This requirement of the Digital Representation strongly combines with the requirement of standardisation of the sector. Only standardisation can capitalise on the lessons learnt in a project and ensure the outcomes of improved concepts, designs and operational planning can be further exploited.
4. An important feature of the Digital Representation we wish to implement is expandability. As the ocean energy sector matures, lower levels of representation could be added, following the same "standards". Moreover, such an approach will permit continuous upgrade and maintenance of the digital objects. The introduction of new concepts, indeed, will be much easier in a well-established framework. Finally, the Digital Representation framework herein developed and based on digital objects, should be easily expanded towards the inclusion of fully functional digital twins, fed by operational data if available.

C. *The methodology*

The process of creating a Digital Representation for Ocean Energy Systems can be summarised in two main phases. The first consisted of defining the expectations of the users of such a digital framework in greater detail. This served to identify the context and the structure that such a framework would assume. The second phase consisted of filling such a framework with the elements (digital objects) that complete the full design of the Digital Representation. As mentioned in Section II B, when identifying the requirements, the Digital Representation should also be expandable to consider innovations in the sector.

To understand the user expectations, a user group consultation was undertaken in the early stages of DTOceanPlus project, to establish the operational requirements for the final set of tools. The outcome of this survey can be consulted in [19]. In the survey, proposed to a set of participants selected on a voluntary basis after an illustrative webinar about the project, the respondents were asked about the usefulness of a Digital Representation for the next generation of ocean energy tools. Respondents confirmed the importance of the Digital Representation to keeping track of the project development stages (from conceptual stage, to low TRL technologies, to commercial phase), as well as managing the level of complexity of the project (from the single component to a single device, or an array), and designing or evaluating several types of technologies. Accounting for the outcome of the survey, therefore, it seemed reasonable that the framework for building the Digital Representation could assume the shape of a rooted tree, i.e. similar to the structure achieved in [17] for the capabilities and functions, but with a different scope in the present case. Such a structure leads into a hierarchical set of relationships, representing the level of complexity of the project and the (de-)composition of the system into subsystems at different levels of details. A rooted tree data structure could provide the means for the integration of different software packages. Such a structure could be expandable to a certain extent, supporting work at different levels of data granularity e.g. for lower TRLs with lacking technical information or for more mature technologies. This can be reflected in a flexible description of the object as a function of the TRL, or coarseness of the data. Despite this, each object should have the same categories of attributes, for example, physical attributes, design (technical) attributes, process parameters, metrics, quantities and connectivity.

Moreover, a rooted tree will allow hierarchical and/or topological relationships between object categories to be shown explicitly.

After identifying the structure of the Digital Representation, a holistic approach was used in order to fill such a rooted tree structure with digital objects. It was clear that the representation, in this case, should not consist of functionalities as in [17] or be focused on technologies as in [16]. The need for a complete view of the system was the prime driver for achievement of a standard Digital Representation of Ocean Energy Systems. When analysing an ocean energy project, attention should be focused not only on physical system assets, but also on other important characteristics, such as the deployment site and the operational phases of the project lifecycle, from the subsystem installation to decommissioning. Moreover, the designer should be able to constrain the potential designs space to include some design options which are driven by the users, depending on financial aspects, technology choices or deployment-site related prerogatives that could impact design direction.

III. THE DIGITAL REPRESENTATION OF OCEAN ENERGY SYSTEMS

As result of the process in Section II, digitalisation of the Ocean Energy Systems using a rooted tree to describe the relationships between different elements in an ocean energy project was selected as the most appropriate solution.

The elements in a rooted tree are:

- The root node: this represents the initial node of the tree, or the top of the hierarchy. It acts also as a parent, as the following levels will depart from the root through branches. The root node in the Digital Representation of Ocean Energy Systems is "the project".
- *Parent-child* nodes: depending on the user viewpoint, these are the nodes from which other branches depart (in this case, they act as parents) or connect to an upper level (in this case they act as *children*). The first parent is the root, and so on. The first level *children* are directly connected through branches to the root, and they represent the first level of detail of the system. In DTOceanPlus, the first level nodes are defined as "*families*" and the second level of nodes are "*groups*". Further levels of detail can be expected, according to the requirements and needs of the user.
- Leaf nodes: these are nodes, *children*, from which no other branch will depart. They represent the lowest level of detail in an ocean energy project.

The shape assumed by a rooted tree is like the one in Fig. 2.

It is important to note that each node works like a blueprint for the *class* of elements at that level of complexity, and stores the following information:

- a set of design attributes: describing the specifics of the node or digital object and including physical, technical and process features;
- Performance specifications: including a set of metrics and indicators capturing the performances in terms of reliability, costs, energy yield, environmental and social impacts of the digital object in the framework of the ocean energy project being studied;
- hierarchy: describing the hierarchical and logical connection among objects;
- Connectivity: describing the topological relationships as well as the sequential interactions in the process description and energy transformation chain among specific *instances* of the Digital Representation of the physical system (see Section III-G).

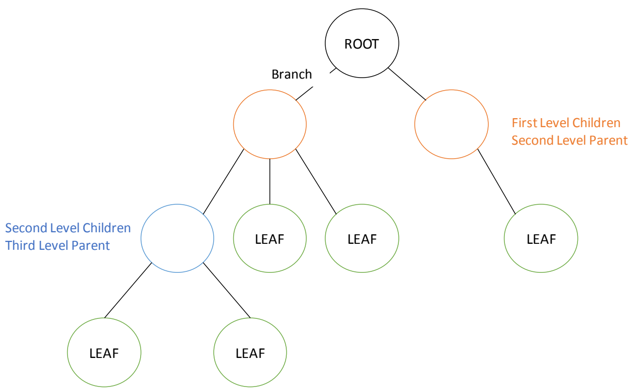

Fig. 2. Schematic view of the rooted tree approach.

The particularisation of the rooted tree for ocean energy system, as obtained from the task in DTOceanPlus, is reported in Fig. 3 and discussed in the following sections.

The major novelty of the Digital Representation developed in DTOceanPlus is that it not only includes elements of the "physical domain" [20] but also elements of the "process domain" and "performance and assessments" as a substantial parts of an ocean energy project. The physical domain elements respond to a "working principle" [21], i.e. a set of geometrical, physical, material related properties for the development of a function. Physical elements and processes are interrelated (connectivity) and both can significantly affect the viability of an ocean energy project.

D. *The Root: the Project*

The root *class* of the Digital Representation is the "Project" (grey box and black circle in Fig. 3). This represents the highest hierarchical level of an ocean energy project, collecting all the major information about the project and outcomes of the assessments. At this level, general information about the project and the technologies, the topology and other major characteristics, as well as the global assessment in terms of energy yield, reliability, economics, and environmental and social impacts will be collected. A project can be either a fully developed array or a single device.

E. *The First Level Branches: the families*

The identified nodes and can be grouped in the following *families* (blue box and circles in Fig. 3):

- Site: this *family* will compile all the data inherent to external factors, such as bathymetry, resource and marine life. The data in this *class* could be structured using a generally accepted format for bathymetry, for example, and provide post-processed data ready for use by the tools in DTOceanPlus as well as external software; For example, time histories of significant wave height Hs as well as scatter diagrams could be stored in this *family* along with some partial and intermediate assessment outputs related to energy yield (e.g. available energy) and environmental and social acceptance.
- Technology Design: this *family* contains particularly varied information. It will contain information on the main subsystems of the Ocean Energy farm: Hydrodynamic system, PTO, Control, Power Transmission and Station Keeping systems [15]. At this level, the information related to each technology adopted

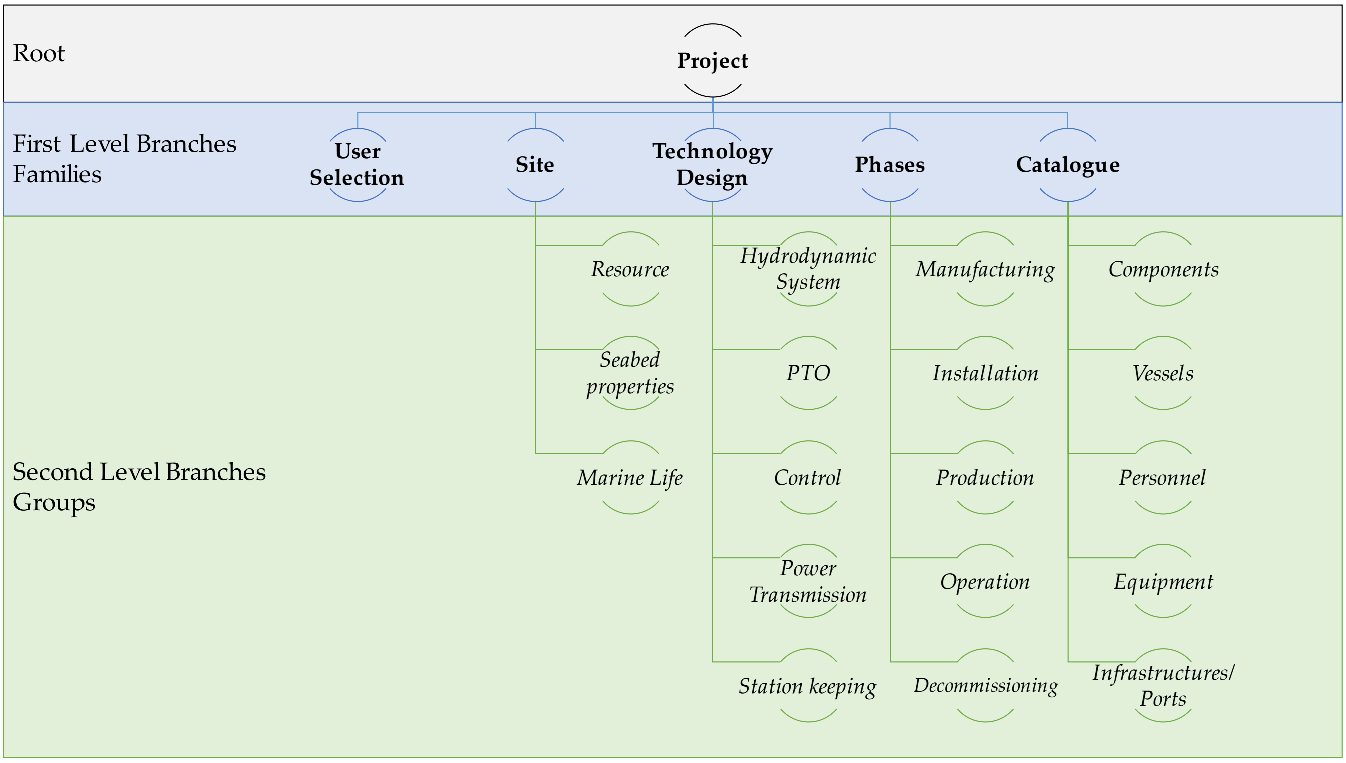

Fig. 3. Digital representation of an Ocean Energy System

in the project is collected, as well as information on their capital cost, efficiency in the power production chain, reliability and maintainability, or environmental impacts of the technologies.

- Phases: This is the *family* in which the information about the processes in the project are represented, from Manufacturing to Decommissioning. Technical information on the logistics (selection of vessels, ports, personnel) as well as the phases of the project are compiled. Moreover, the impacts on operational expenditure are included, as well as environmental impacts during throughout the whole lifecycle of the project.
- Catalogue: this is a static *class*, in which information on vessels, components, personnel equipment and ports is compiled.
- User selection: a set of user options allows the definition of project context, such as financial information and project life, as well as other constraints and options that could drive the design direction (e.g. the choice of a specific topology for the electrical inter-array network, or mooring systems).

These *families* can be flexible, being represented as leaves at an early level of complexity or further expanded to second level branches (*groups*) for more detailed designs.

F. *The Second Level Branches: the groups*

The *families* described in Section E will have several *children classes*, which have been named "*groups*". As any other object in the Digital Representation, each *group* will be characterised by a set of technical or technology related attributes, but also from partial assessments. In Fig. 3 the *groups* are contained in a blue box and blue circles.

The *groups* that are *children* of Site are:

- Resource;
- Seabed properties;
- Marine Life.

The *children* of the Technology Design *family* include all the technology design related subsystems:

- Hydrodynamic System; which will include the hydrodynamics of an array of devices and their interactions, if the project contains more than one device;
- Power Take Off (PTO)
- Control
- Power Transmission, which includes the design of the export cables, substation, dynamic cable and inter-array cabling;
- Station Keeping, including foundations and mooring systems, when applicable.

As it could be seen in Fig. 3, the Phases *family* has several *children*, in order to cover the whole lifecycle of the processes, from the manufacturing *group* to the decommissioning. Similarly, the Catalogue *family* has several *children*, from components, to personnel, vessels, equipment and infrastuctures/ports.

As for the *families*, these *groups* could be treated as leaves, with no *children* departing from them at an early level of complexity, or further expanded for more detailed designs.

G. *Other aspects of the Digital Representation*

An important aspect to tackle when considering a real ocean energy project is inherent to the treatment of the *instances*. In the Digital Representation, an *instance* or item is a specific actual object. As an example, let us suppose that the mooring system of a floating tidal device can be composed of four chain lines. Each line is connected to the seabed by a drag anchor. Each anchor and each line are *instances* of the anchor *class* and mooring line, respectively, belonging to the *group* of the Station keeping in the family of Technologies.

It is extremely important to identify the interactions between *instances* in order to assess array reliability, power performance and other metrics. These interactions can be represented using a topological approach. Methods such as the Design Structured Matrix (DSM) [22] will be used for this purpose, in which case, all the *instances* at the lower level can be considered as a row and a column in the matrix, with the cell in the resulting matrix being filled where a connection exists. Where the inputs are represented in rows, the strength of connectivity could be defined, perhaps using numbers or colours to express the intensity or the level of connectivity. For example, Fig. 4 presents the structured matrix for representation of the example of a floating device with four mooring lines and four anchors, if each anchor is connected to only one mooring line: a value equal to 1 is included in the matrix when it exists connection.

It is important to consider that different matrices can be built in order to reproduce an interface between components which covers different aspects:

- Physical and topological connection: in this case, a symmetric matrix is expected;
- Reliability matrix;
- Load transmission matrix;
- Energy transmission matrix;
- Matrix relating operations with activities;
- Etc…

Similarly, it is important to build connectivity interfaces among elements of the physical domain and the process domain (e.g. among physical components and the operations to be carried out for their maintenance).

Element Name		1	2	3	4	5	6	7	8
Mooring 1	1	1				1			
Mooring 2	2		2				1		
Mooring 3	3			3				1	
Mooring 4	4				4				1
Anchor 1	5	1				5			
Anchor 2	6		1				6		
Anchor 3	7			1				7	
Anchor 4	8				1				8

Fig. 4. Design Structured Matrix for the example (four mooring lines connected to four anchors independently).

IV. Examples of Digital Representation and Future Challenges

Some examples have been developed in order to show the capability of the Digital Representation to capture the main characteristics of the physical assets and processes associated with an ocean energy array, and the corresponding assessment activity.

The first example (see Fig. 5) shows different levels of detail for a physical asset in an ocean energy project; Table I adds further details to the description of the case study. On the upper left side of the figure, an array of wave energy converters is represented. This corresponds to the first hierarchical level of the wave energy project: the project. A set of attributes (see Table I) describe the physical assets of this wave energy project: the deployment site, the rated power of the array, etc… It is noteworthy that the Digital Representation in DTOceanPlus can capture different levels of aggregation

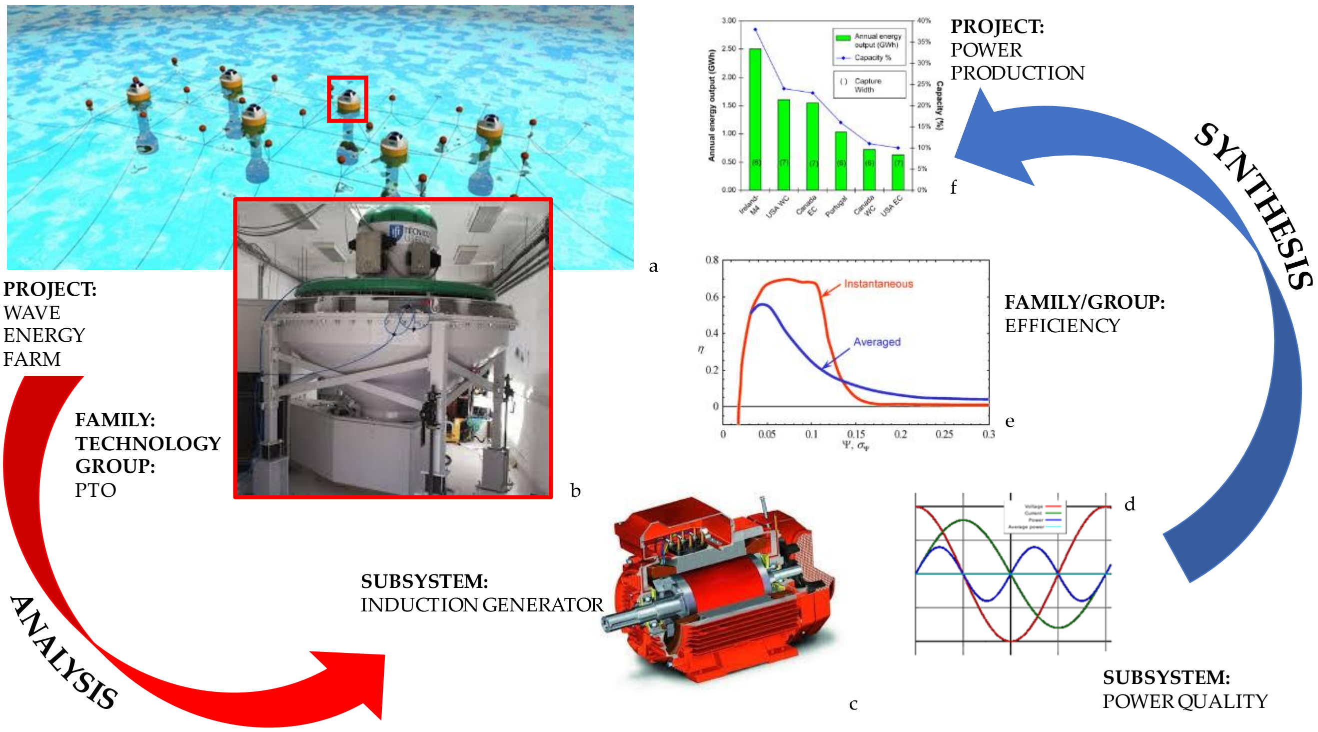

Fig. 5. Example of Digital Representation of a physical asset (designing the induction generator for the PTO of a wave energy converter) and assessments in an ocean energy project. (Images courtesy: a and b of [23]; c of [24]; d of [25]; e of [26]; f of [27]).

(array, device, subsystem). At the next level of the Digital Representation, the PTO system is analysed: in this case, an air turbine. This level of aggregation is also characterised by some attributes, such as the maximum rotational speed of the turbine and the rated power of the PTO. The next level of increased detail describes other subsystems in the PTO, such as an induction generator, characterised by nominal voltage, nominal frequency, inertia and other properties. At any of these hierarchical levels assessment of key metrics can be carried out. These assessments are carried out via using a synthetical approach to translate from assessments at more detailed subsystem level towards higher hierarchical levels for the estimation of global metrics.

In this example, evaluation of system performance (one of the four assessments in DTOceanPlus) at the hierarchy level of the generator, can occur at various levels of detail. At the most detailed level power quality could be assessed; at a higher level, the efficiency of the PTO could be assessed and finally all this information is condensed in the final value of the power production of the array.

Similarly, an example of the Digital Representation applied to a process is reported (see Fig. 6 and Table II). In this case, the installation of the mooring system for a one-device tidal project is considered. At this hierarchical level, the activities to be carried out, the operational limit conditions and some logistical requirements (e.g. port distance, etc.) could be identified. When analysing the description of this process, the mooring systems hook-up is one of the activities to consider. At this level of detail, attributes such as the vessel characteristics, the personnel involved, the weights of the components are relevant for the description of the activity. When these inputs are defined, the duration of the activity and its cost can be assessed. At a higher level, the duration of the whole operation (intended of a set of activities) will be obtained by considering all the activities involved; estimating the weather window occurrence will also allow measurement of the accessibility of the site. Finally, all this information will be used to generate the assessment at project level, for example the estimation of the Levelized Cost of Energy (LCoE).

As could be seen in Table I and II, it is crucial to establish the connectivity between the physical domain and the process domain, to associate each physical element with a set of processes and vice versa.

The Digital Representation can capture the characteristics of the system at different stages of the project (early stage, mid stage or late stage), according to the level of information available, the TRL of the technology and the stage of development of the project (from conceptual stage to detailed engineering). This means that the framework of the Digital Representation can work throughout the project lifecycle and that the functions implemented in the tools, as well as the detail of the data required and the assessment to be computed, could vary accordingly.

Similarly, one of the major advantages of the Digital Representation is to take a picture of the ocean energy array at different levels of detail, according to what is required by the user and the scope of the project

H. *Future challenges*

At the time of writing (February 2019), the construction of the Digital Representation in DTOceanPlus project represents an ongoing activity. Even though at the present stage the implementation phase has not started yet, the need to use a standardised approach for the treatment of

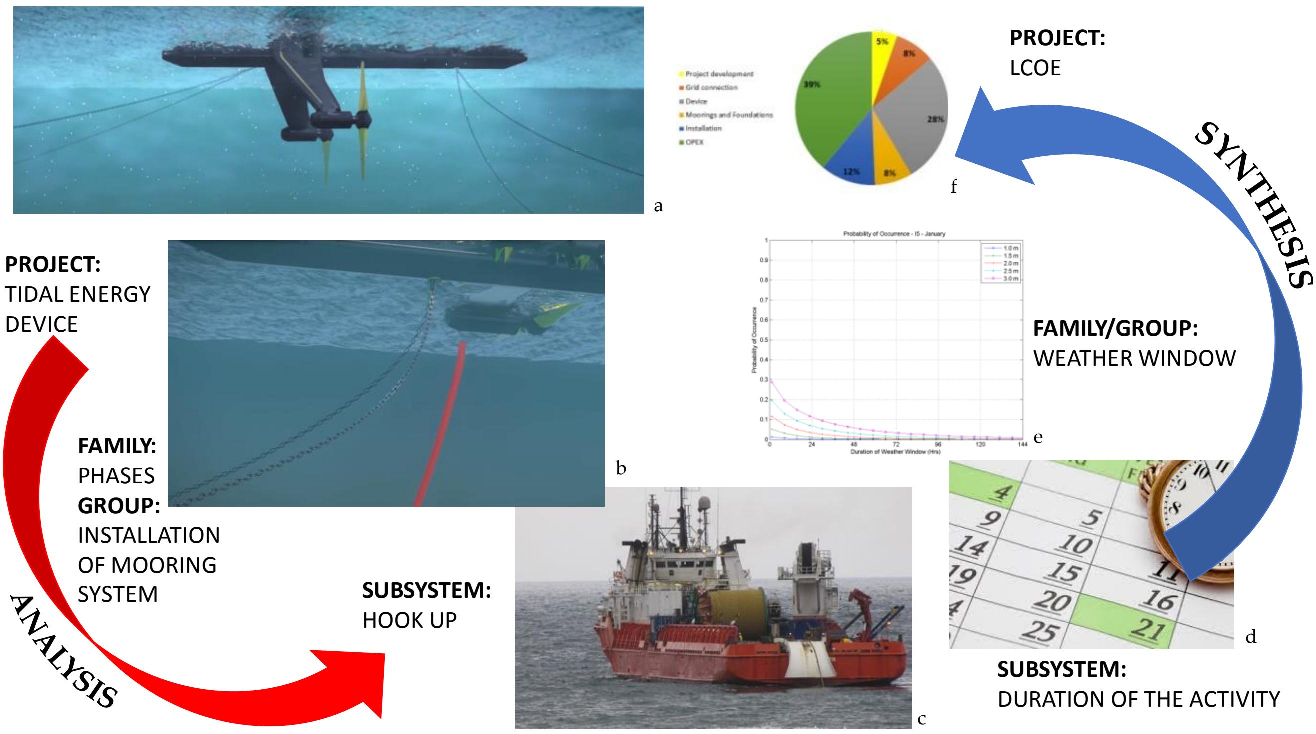

Fig. 6. Example of Digital Representation of a process (installation of a mooring line) and assessments in an ocean energy project. (Images courtesy: a and b of [28]; c of [29]; d of [30]; e of [31]; f of [32]).

TABLE I
EXAMPLE OF DIGITAL REPRESENTATION ATTRIBUTES AND ASSESSMENT IN A WAVE ENERGY PROJECT FOR A PHYSICAL ASSET

Level	DOMAIN	Attribute or Assessment	Connectivity
Project: ***Wave Energy Farm***	Ph.D.	Project Name Technology Type Rated Power Deployment Site Design Life Etc…	
	A.	Power production Environmental Impacts Risk Priority Number Etc…	
Family/ Group: ***PTO***	Ph.D	Air Turbine Diameter Rated Power Maximum Rotational Speed Etc..	
	A.	Efficiency of the Transmission system Cost of the total PTO Mean Time to Failure Noise Level Etc…	
SubSystem: ***Induction Generator***	Ph.D.	Nominal voltage Nominal frequency Stator resistance Inertia Identifier Etc…	P.D. Operation Phase
	A.	Power Quality factor Efficiency Failure Rate Increase of Temperature Etc	

Ph.D stands for Physical Domain; A. for Assessment; PD for Process Domain.

TABLE II
EXAMPLE OF DIGITAL REPRESENTATION ATTRIBUTES AND ASSESSMENT IN A WAVE ENERGY PROJECT FOR A PROCESS ASSET

Level	DOMAIN	Attribute or Assessment	Connectivity
Project: ***Tidal Energy Device***	Ph.D	Project Name Technology Type Rated Power Deployment Site Design Life Etc…	
	A.	LCOE Environmental Impacts Risk Priority Number Etc..	
Family/ Group: ***Installation of a Mooring System***	P.D.	Sequence of Activities Port distances Operating Limit Conditions Vessels Required Etc…	Ph. D. Device position Ph.D. Mooring Line ID
	A.	Weather Window Occurrence Duration of all the Operation Cost of the operation Pollution Levels Etc…	
Subsystem: ***Hook Up***	P.D.	Requirements of the activity Port distance Vessels Requirements Etc…	Ph.D. Fairlead Location
	A.	Personnel Duration of the activity Cost of the activity Etc	

Ph.D stands for Physical Domain; A. for Assessment; PD for Process Domain.

instances and their interactions is under investigation. During the build of a development of a digital representation framework for DTOceanPlus, at least two major "challenges" have been identified.

- IMPLEMENTATION: the Digital Representation for Ocean Energy Systems aims at facilitating communication between different software components and stakeholders. This requires that widely accepted, standardised data formats are used in its implementation. Experience from other sectors, acceptance among potential users, the level of dissemination, flexibility of use, expandability and maintenance constitute some of the main drivers in the selection of the most appropriate solution. Several data formats are commonly used for data sharing, such as text based hierarchical data formats (e.g. HDF5) or mark-up language (e.g. XML), as well as non-mark-up options (e.g. YAML). These are taken under consideration along with other data formatting from BIM experience.
- INTEROPERABILITY of DATA: The need to guarantee a smooth, robust and fast data flow among software developed by different developers represents a challenging benchmark for the Digital Representation and its aim to become a milestone in the definition of a common language and an interface for integrating external commercial tools. Indeed, through a robust and community-acknowledged Digital Representation scheme, the Digital Representation may take on the role

of common interface when more than two tools must interact. More ambitiously, the Digital Representation aims at becoming a common data sharing structure not only among tools, but any kind of actor (i.e. user, software, stakeholder) in general (see Fig. 7).

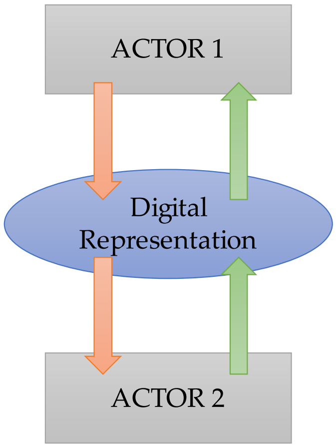

Fig. 7. Digital Representation as a data sharing framework among different actors.

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