A Decision Support System for Decommissioning of Offshore Windfarms: The Data Platform

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***Abstract*—This paper presents a data protocol for storing the information which are required for the planning of windfarms decommissioning. The data protocol is the base of a decision support system software tool which allows its user to define various decommissioning scenarios and to evaluate them against cost, risk, and environmental impact measures. The protocol categorises the data into four categories, namely, windfarm, site, logistics and legislations. It is generic, flexible, expandable and easy to handle by the software and its user. The capabilities of the data protocol have been illustrated through a number of examples.**

Keywords—decommissioning, removal, offshore wind, windfarm, decision support system, data protocol

I. INTRODUCTION

The global installed offshore wind power capacity increased from 2.13 GW in 2009 to 23.36 GW in 2018 [1]. The European union with the total capacity of 18.52 GW in 2018 was the global leader in offshore wind. The European union has set an ambitious plan to increase its offshore wind capacity to 150 GW and 460 GW in 2030 and 2050, respectively [2, 3, 4]. The expected lifespan of offshore windfarms is estimated to be between 20 and 25 years [5], and in some cases the windfarms are decommissioned before the expected lifespan [6,7]. This means that the number of offshore windfarms to be decommissioned will be increased significantly in the coming years. Decommissioning process consists of several stages, including, planning, preparation for removal, removal, recycling/reutilisation/ reuse, and post decommissioning monitoring.

Offshore windfarm decommissioning is still quite new area with limited documented and historical data or experience available, which can lead to many uncertainties, increased assumptions and thus, less accurate estimates. Moreover, layout, number, size and type of wind turbines, site specific characteristics such as water depth and weather profile, available logistics, and regulatory constraints changes from one windfarm to another. It is not feasible to have a single decommissioning execution plan [5]. Recycling and reutilisation of decommissioned windfarms, the environmental impact of the decommissioning process itself, and its relatively high cost have become the centre of focus of the industry, authorities and research community. With the overall aim of reducing the cost, risk, and the environmental impact of the decommissioning of windfarms, our approach in the EU Interreg NSR funded project DecomTools, is to develop a decision support system (DSS), by which one can define different decommissioning scenarios and then evaluate them against CRE (Cost, Risk, and Environmental impact) measures. This paper elaborates on the first phase of the development of the system and is focused on the data required for decision making and optimisation of the process.

II. DECOMMISSIONING DECISION SUPPORT SYSTEM (DECOM DSS) & DATA

The first fundamental question is ‘what do we need to know’ to be able to evaluate a decommissioning scenario against CRE measures. The answer to this question depends on the adopted approach in predicting the CRE measures. In a top-down approach, as reported in [8, 9], the decommissioned costs have been estimated by applying given percentage values to the installation costs. This approach may lead to overpredicted/underpredicted results [10]. Moreover, while applicable to cost, it cannot be applied to risk analysis or environmental impact analysis as a removal process can be completely different from an installation process in terms of the sequence and type of the operational events. Adopting a bottom-up approach, the answer to the question above would be (i) detailed data and (ii) models corelating the data to CRE measures.

The models corelating the data to CRE measures, regardless of their fidelity and complexity, either exist or are adaptable from other industries. Now, the second fundamental question is ‘how to store the data’ in a suitable way that can be used in a DSS for defining and evaluating decommissioning scenarios. There are many players in a decommissioning process, such as windfarm owner, ports, recycling centres, authorities, and many service providers. This implies that besides the data obtainable from the manufacturers/suppliers of a windfarm components (e.g. wind turbine, structures, power equipment, etc), other required data are scattered in different places and in different formats. We need to define a bespoke data protocol which includes all the data we need to feed to the models for evaluating a decommissioning scenario.

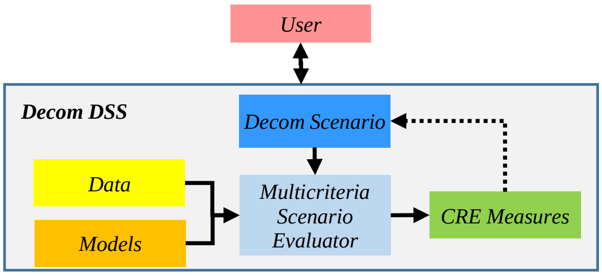


Fig. 1. Windfarm decommissioning decision support system Decom DSS

Besides the fidelity of models implemented in the DSS, the accuracy of the predicted CRE measures depends on the level of details of the data. Two arbitrary models below are used to provide the reader an insight into the depth and the breadth of the data required for estimating the cost of an event and the degradation of a component. As shown in Eq. 1, the cost of an operation can be divided into fixed and variable cost parts, where the variable part can be time-dependant and/or size dependant. For instance, the associated cost to the removal of a single blade includes all three cost parts and, just to name a few, requires data associated to the wind turbine characteristics (e.g. mass and size of the blade, rotor hub height and the number of bolts attaching the blade to the hub), the mobilisation and daily rate of the lifting vessel and its characteristics (e.g. deck area, crane capacity, jacking speed, and transit speed), site characteristics (e.g. weather data, water depth, distance to shore, etc).

$$cost_{oper} = cost_{fixed} + cost_{var}(time) + cost_{var}(size) \quad (1)$$

Degradation models of windfarm components are required for evaluating their status for reuse/reutilisation or operational risk analysis. A general degradation model for predicting the degradation status of a component at a time t, $D_{comp,t}$, is given by Eq. 2.

$$D_{comp,t} = f\left(D_{fat},\, D_{cor},\, S_{t_i}\right) \qquad (2)$$

in which, D_{fat} and D_{cor} , respectively, stand for the degradation due to fatigue and corrosion and S_{t_i} is the status of the component at the initial or a previous state. Expanding one term only in each step, one notices how vast is the breadth of the data we need for predicting the status of a wind turbine foundation: $D_{fat} = f(\vec{F}(t), \{M\})$, where $\vec{F}(t)$ is the force and $\{M\}$ is the set of material properties; $\vec{F}(t) = f(F_{wind}, F_{wave})$, where F_{wind} and F_{wave} are the wind forces on the wind turbine rotor and tower and the wave force on the foundation respectively; $F_{wind} = f(\{WT\}, V(t))$, where $\{WT\} = \left\{A_{WT},\, H_{hub}, C_p(V), C_T(V), pitch(V),\, \Omega(V)\right\}$ are the wind turbine characteristics (respectively, rotor area, hub height, power coefficient, thrust coefficient, pitch response and rotor speed response) and V is the site annual wind speed profile, given in time-domain or in the form of probability density function.

III. DATA PROTOCOL

All required data are classified in four categories as shown in Fig. 2. Our aim is to define a data protocol which can be applied to all four categories with the following key features:

- Expandable, allowing defining the data at different levels of detail to provide the accuracy we require
- Generic, allowing definition and evaluation of different windfarms, different types of wind turbines, foundations, etc
- Flexible, allowing generation of new scenarios, both manually and automatically as well as different known decommissioning scenarios
- Expandable to include new set of data as new technologies emerge
- Easy to handle by the user of DSS, as well as the modules in the DSS

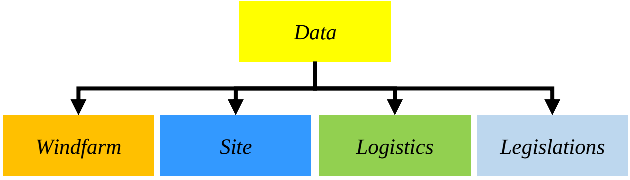


Fig. 2. Four categories of data required for offshore windfarm decommissioning

A. *Windfarm*

Windfarm data are defined in a structure of *component.parent* and *component.attribute.* That is each component in the windfarm is defined by its parent and its attributes.

A *component.parent* structure

- is a simple table with two columns containing the name of the components and their parents;
- is expandable to any level of details that we need;
- is suitable for defining cut and removal, as the removal of a parent implies removal of its children; and
- allows making new type of windfarms easily.

Table I shows part of a flat two-column data file used to define Sheringham Shoal offshore windfarm in the North Sea, England. As shown in this table, there is only one rule: each component must have only one parent. Order is not important. That is, the user can add a new component at the end of the list and assign it to a parent, which already exists in the table. One can see that in this table, we can define the smallest components the same way as we define the top-level components (shown in Fig. 3). This allows us to break a windfarm down to its smallest pieces (for instance, see the gearbox sensors and the tower internal lighting system at the bottom of the table) and analyse the windfarm in details, not only for removal process but for preparation, recycling and reutilisation. For instance, the presence of the fuel tanks on the offshore substation (see OFSS Fuel Tanks in Table I) indicates that in the preparation phase of the decommissioning, these tanks must be emptied safely before the start of the removal process.

Decom DSS software reads the *component.parent* file, finds the level of each component and assigns a unique code to it. Fig.s 4 and 5 show how *component.parent* data structure makes the data protocol expandable with no limitation in the level of details. Fig. 4 shows the offshore windfarm up to 3 levels of components produced by the software.

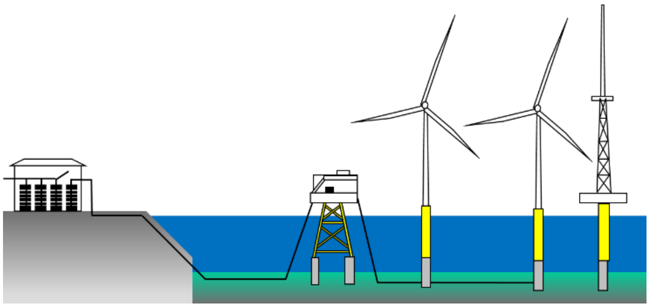


Fig. 3. Top level components of an offshore windfarm: offshore substation, power transmission lines, wind turbines, onshore substation, metrological mast and scour protection.

TABLE I. PART OF THE TABLE DEFINING A WINDFARM BY ITS COMPONENTS

Component	Parent
Windfarm	Root
Wind Turbine	Windfarm
Offshore Sub-Station	Windfarm
Onshore Sub-Station	Windfarm
Power Transmission	Windfarm
Meteorological Mast	Windfarm
Scour Protection	Windfarm
MM Foundation	Meteorological Mast
MM Topside	Meteorological Mast
MM Tower	Meteorological Mast
OFSS Electrical System	OFSS Topside
OFSS Facilities	OFSS Topside
OFSS Fuel tanks	OFSS Facilities
OFSS Topside	Offshore Sub-Station
Export Cable	Power Transmission
EC Cable cleats	EC Accessories
EC Cable trays	EC Accessories
EC Joints	EC Jointing and testing
Cable mattresses	Cable Protection
Rock placement	Cable Protection
Nacelle	Wind Turbine
Tower	Wind Turbine
Transition Piece	Wind Turbine
Foundation	Wind Turbine
Blade1	Wind Turbine
Blade2	Wind Turbine
Blade3	Wind Turbine
Hub	Wind Turbine
Pitch System	Hub
Rotor Spinner	Hub
Rotor Auxiliary Systems	Hub
....	...
Main Shaft	Nacelle
Gearbox	Nacelle
Generator	Nacelle
Power Take-off System	Nacelle
Power Control System	Nacelle
Yaw System	Nacelle
Auxiliary Systems	Nacelle
Nacelle Cover	Nacelle
Condition Monitoring System	Nacelle
GB Bearings	Gearbox
GB Gears	Gearbox
GB Lubricants	Gearbox
GB Sensors	Gearbox
Tower Internal Lighting	Tower Internal Systems

Fig. 5 shows the components of the topside of the offshore substation to 2 sublevels. Offshore substation topside itself is at level 3 making the overall level of details 5.

Fig. 6 shows how *component.parent* data structure allows the user to define new types of wind turbine/foundations by changing the data, here for example only two rows in the table of *component.parent* to change a bottom fixed monopile wind turbine to a floating wind turbine. This feature makes the software tool versatile.

Besides its parent, each component is associated to a set of attributes. A *component.attribute* structure is expandable and can include any attribute that is important in any of the planning, removal and post removal phases. Mass, material, dimensions, connection, functions, and hazard tag are examples of attributes.

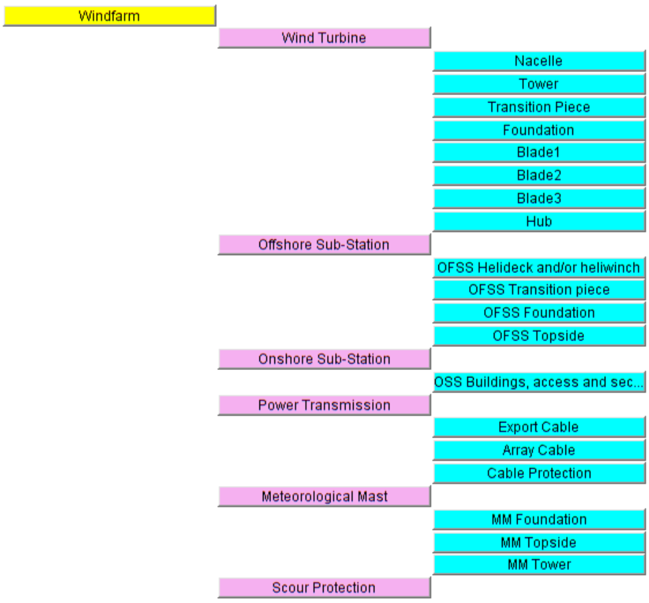


Fig. 4. Windfarm components to three levels produced by Decom DSS based on the data in Table I.

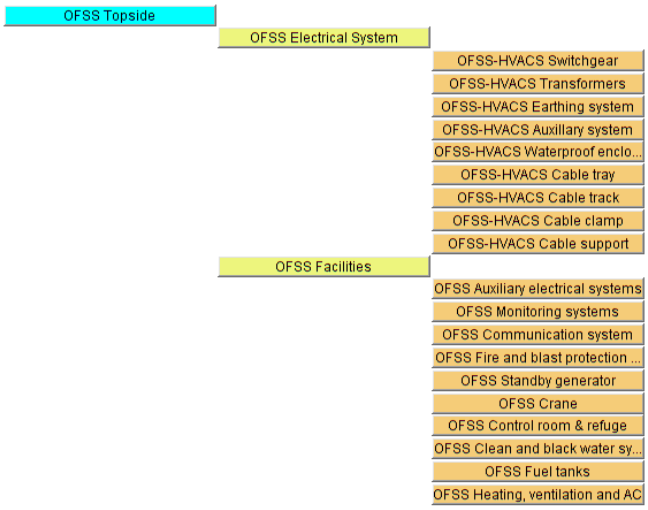
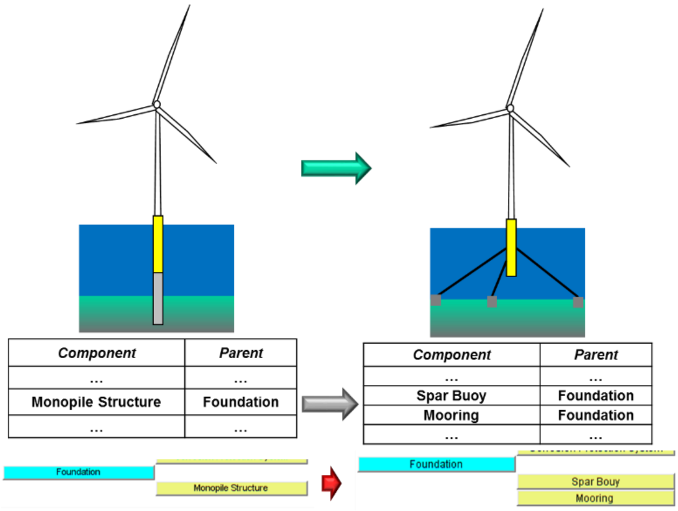


Fig. 5. Offshore substation topside sub components to level 3 produced by Decom DSS based on the data in Table I.



Component	*Parent*
...	...
Monopile Structure	**Foundation**
...	...

Component	*Parent*
...	...
Spar Buoy	**Foundation**
Mooring	**Foundation**
...	...

Fig. 6. Defining new types of wind turbine/foundations by changing two rows in the *component.parent* table. Top: bottom fixed/floating wind turbines; Middle: *component.parent* in the windfarm tables; Bottom the software output.

These attributes can be processed towards producing new information which can be used for making decisions or directly feed into the DSS computational modules. Attributes are sorted in the same file as the parents for a component. Not all attributes apply for all components. For instance, hazard tag applies to components which contain hazardous chemicals. The software retrieves all attributes from the windfarm file, process them, and display them. The mass and dimension attributes for the top-level components are of prime importance when planning the logistics for removal and defining a removal scenario. A combination of the mass and material attributes, on the other hand, is important for recycling purposes. For example, knowing that 95% of the material of a 2000 kg wind turbine blade is glass reinforced epoxy is a crucial piece of information for recycling cost analysis. The attribute dimension includes all important dimensions, including maximum size in x-y-z directions, and, where applicable, thickness (e.g. shell thickness for monopile), diameter (e.g. size of export cables), height (e.g. nacelle) and depth (e.g. burial depth of monopile).

Functions, in the mathematical sense is another attribute. Functions can have different forms, such as inline m-scripts, m-files, or just simply a table of data stored in normal data file formats. These mathematical functions are different from the models, implemented in the DSS. Functions are specific to the components. For instance, the Siemens SWT-3.6-107 wind turbine in the Sheringham Shoal offshore windfarm has its own specific functions $C_p(V)$, $C_T(V)$, $pitch(V)$ and $\Omega(V)$. These functions are the characteristics of the wind turbine irrespective of where it is installed.

The attribute connection identifies how a component is connected to other components. It is a crucial attribute required to be assigned to some of the components to able to define a removal scenario. We can define connection attribute for all components, as all components are connected to each other in a way or another. However, in practice, depending on what we aim to model and analyse, some connections become irrelevant. For example, the connection of the generator to the base plate of the nacelle is a redundant piece of information in a decommissioning scenario in which the nacelle is removed completely, but the same connection is required if the major parts of the nacelle are planned to be shipped directly from the windfarm site to different recycling centres. Each connection attribute contains information such as the type of the connection (e.g. bolted, weld, driven, grouted, etc), available/applicable disconnection method (e.g. plasma cut, unbolt, wire cut, water jet, etc), and where applicable, a value which is important for calculating the cutting/disconnection time (e.g. 64 bolts for unbolting). Once a connection was attributed to a component, there is no need to define the same connection for the counterpart component.

A recent unpublished study by the authors on four recently decommissioned offshore windfarms shows that about 58% of the overall decommissioning cost is associated to the offshore removal process and 17% of the cost is associated to the offshore preparation activities. That is, a total of 75% of the decommissioning cost is associated to the offshore operation. This fact is a good motivation for exploring all possible means of reducing the time offshore operation, amongst them exploring different removal scenarios. Fig. 7.a shows a schematic description of installation steps. Fig. 7.b shows a reverse installation removal scenario. In Fig. 7.c two steps are combined (e.g. removal of the rotor and nacelle in one cut and lift operation). Fig. 7.d shows a case of splitting a component to smaller components and remove it in more than one step (e.g. instead of removing rotor, removing blades one by one). With reference to Fig. 7 one notices that many different removal scenarios can be defined by forming different combinations or splitting components into smaller parts. Different removal scenarios require different logistics and have different removal time and cost, environmental impact and operational risk.

Having connections as an attribute, the software retrieves all connections and the information associated to them. The user (or automated optimiser) selects some of them to form a complete removal and selects one of the available cut/disconnection methods defined for that connection. Fig. 8 shows a removal scenario in which a wind turbine is removed by 8 cut and lift operations (3 cuts for removing the blades from the hub, and then removing the hub from the nacelle, nacelle from tower, tower from transition piece, transition piece from foundation structure, and finally foundation from seabed). The operational time and cost for each one of these cut and lift operations can be calculated using the cost models implemented in the software.

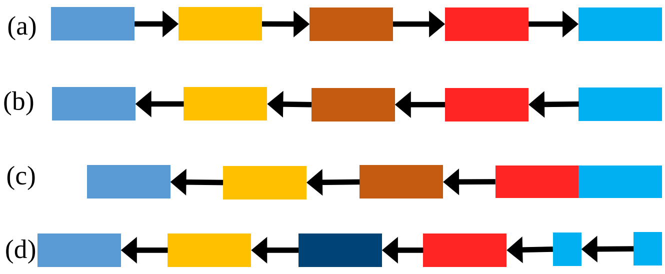


Fig. 7. (a) Installation, (b) reverse installation, (c) combined lift, (d) split and lift

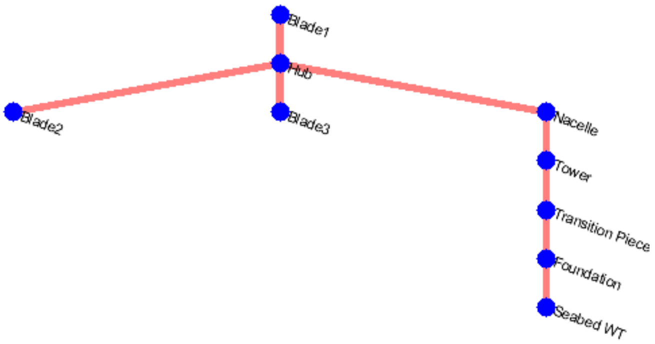


Fig. 8. Wind turbine removal by 8 cut and lift operations

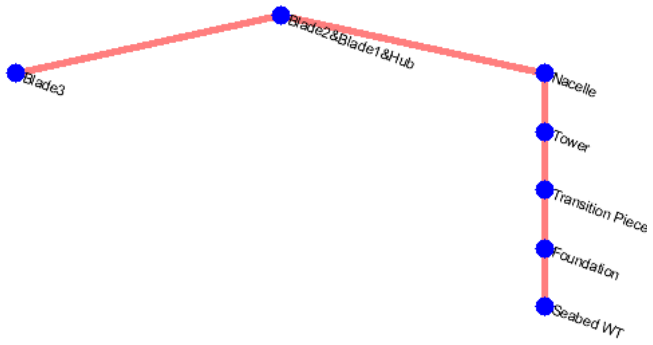


Fig. 9. Wind turbine removal by 6 cut and lift operations by combining two blades and the hub

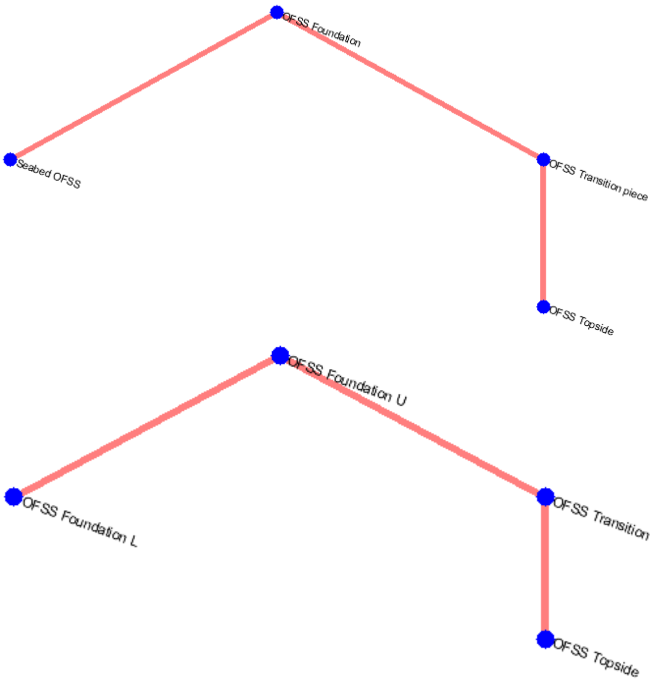


Fig. 10. Top: Complete removal of offshore substation; Bottom: Partial removal of offshore substation by defining a continuous connection in the foundation.

The user can also combine components (similar to the case shown in Fig. 7.c) and evaluate the removal cost. Fig. 9 shows a 6-cut-and-lift removal scenario, in which the hub and two blades are combined.

The flexible data protocol behind the software allows us to define continuous connections and use them to generate new/ undocumented removal scenarios, such as partial removal for reutilisation purposes. Fig. 10 shows a complete removal of offshore substation and a removal case, in which the foundation of the offshore substation has been defined as a two-part component by a continuous connection. The lower part stays in the site to be utilised for another purpose, while the upper part is removed alongside the rest of the offshore substation.

B. Site, Logistics, and Legislations

Site is defined by its attributes. The attributes include all information about the characteristic features of the site which affect different phases of decommissioning. Examples of information stored in *site.attributes* include: site geographical location, distance to shore, water depths in different points of the windfarm, annual weather profile, layout of the windfarm (location of each wind turbine and offshore substation), and the number of wind turbines and substations. These attributes can take different forms such as numbers, strings of text and data files (e.g. isobaths and weather data). The software retrieves all attributes from the windfarm file, process them, and use them as inputs to the CRE models and computational modules.

Logistics data plays an important role in offshore windfarm decommissioning projects. It is necessary to comprehensively define available logistics which are required to carry out a decommissioning project. Besides different vessels and equipment (i.e. lifting vessels, ROVs, tugboats, and cable laying vessels) which are required for removal operation, logistics also include a database of recycling centres and ports. Similar to windfarm data, the logistic is defined by its components, and for each component a list of attributes. For example, the attributes for a lifting vessel consists of the daily rate, crane(s) capacity, jacking speed, transit speed, and mobilisation rate.

Legislations data includes all regulations and standards that are applicable to the decommissioning operation. While some regulations are international regulations, some others may differ from one site to another depending on, for example, the location of the site and the applicable local regulations, the insurers policies, and the internal health and safety regulations of service providers. Legislations data, in practice, are applied as constraints to a decommissioning project and play a key role when planning a decommissioning project and making major decisions. For example, the answers to the questions such as ‘is there any flexibility in the legislation which allows partial decommissioning (e.g. leaving the scour protection or cable protection at the seabed) or all components must be removed’ or ‘is there any constraint applied by the vessel insurance policy or a service provider company health and safety regulations on the weather condition during offshore operation’ change the planning and form of a decommissioning project.

One may argue that regulations are clear and following them results in a specific single decision not multiple choices requiring a decision support system. It should be noted that this is not always the case as Legislations data, in practice, can be interpreted as either hard constraints or soft constraints. Contradicting soft constraints leads to fines and penalties with no further action. One the other hand, hard constraints cannot be legally contradicted. For example, whether to carry out a complete decommissioning, or a partial decommissioning and pay the finer remains an open question, unless a decision support system like Decom DSS is used to go through a comprehensive cost-benefit analysis, in which the fines and penalties are included as a cost component in the overall cost.

C. Data Hierarchy

Like other data protocols, a data hierarchy is applied to the four categories of windfarm, site, logistics, and legislations, as shown in Fig. 11. This data hierarchy is required to allow the interaction between four categories of data and applying constraints, filtering, and discarding contradicting data or infeasible scenarios. The following examples show how the DSS incorporates legislation-windfarm, legislation-logistics and logistics-windfarm hierarchies in different cases.

Legislations-windfarm data hierarchy: Explosive cutting is a cheap, fast and relatively safe cutting technique which has been defined as a potential cutting technique associated to the connection between the foundation and the seabed in ‘windfarm data’. However, depending on the location of the site, this technique might be banned by the legislations. Hence, at the stage of defining the removal scenario, the software checks for the feasibility of this cutting technique and if it is not allowed will be removed from the list of available cutting techniques.

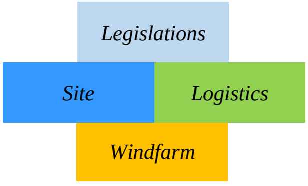


Fig. 11. Data hierarchy in four categories of data

Legislations-windfarm data hierarchy: Since the scour protection is a component in windfarm, the software, by default, assumes that it must be removed. However, if leaving scour protection is allowed with reference to the regulations in the legislations data, the software removes it as a windfarm component.

Logistics-windfarm data hierarchy: When defining a removal scenario by combining components, the software checks the feasibility of operation by the available logistics, more specifically the crane capacity of the lifting vessel and the deck space of the barge, to see whether the total mass and size of the combined components are less than the crane capacity and the deck space.

Legislations-logistics data hierarchy: Legislations may require that recycling of certain materials or components to be/not to be processed locally. The software filters the recycling database accordingly.

IV. SUMMARY AND CONCLUSION

European union has set an ambitious plan to increase its offshore wind capacity from 23 GW in 2018 to 150 GW and 460 GW in 2030 and 2050, respectively. That is, the number of offshore windfarms to be decommissioned will be increased significantly in the coming years. Offshore windfarm decommissioning is still quite new area with limited documented and historical data or experience available, which can lead to many uncertainties, increased assumptions and thus, less accurate estimates. Decommissioning of offshore windfarms is a complex process with many players involved in it. It can be very costly if not planned optimally. Hence, a decision support system is required for optimal planning of the process. A data protocol for storing the required information for the planning of a decommissioning scenario is explained in this paper. The protocol is generic, flexible, expandable and easy to handle by the software and its user. These features allow us to define windfarms with different types of wind turbines, foundations, etc; apply constraints; and generate and evaluate various removal scenarios. The capabilities of the data protocol have been illustrated through a number of examples.

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