Wave Energy Converter hull design for manufacturability and reduced LCOE

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Abstract- Wave Energy Converter structures are associated with the highest percentage share of LCOE costs, however, existing geometry optimization studies just consider maximization of power production and, in some cases, mass as a proxy for structural costs. How to include cost factors related to geometry in the optimization process with a particular focus on design for manufacturing is discussed here. Two different methodologies - depending on the available information and goal of the study - are presented, and example cases for these are given. The results show the potential and suitability of applying these methodologies to wave energy converter hull design for improved manufacturability and reduced LCOE.

Keywords- wave energy converters, geometry, levelised cost of energy, manufacturing process, materials, optimization.

I. INTRODUCTION

Many different types of wave energy systems have been developed in the past years, with the goal of finding an economically competitive design, which at the same time enables maximal power extraction. Various studies show that the biggest cost reduction potential is associated with the device's structure [1], [2]. It is therefore important to include geometry optimization of the device's shape in the early stages of the design process, considering not only power performance, but also its associated costs that contribute to the Levelised Cost Of Energy (LCOE).

Previous techno-economic assessment studies of WECs identify the prime mover structure as the biggest cost centre accounting for example for 28% of the manufacturing costs in [1], and 32% of the LCOE in [2]. In these studies the structural cost is represented by the price per kilogram of material and the volume of the device. A similar approach has been used for shape optimization of devices to minimize their LCOE, where costs of the structure are purely represented by their volume or surface area [3], [4]. Otherwise many shape optimization studies aim just at maximizing the device power performance without accounting for costs [5]–[7]. However, if not using a predefined shape, like a cylinder with variable diameter and draft, but a more flexible geometry definition such as B-spline surfaces as suggested by McCabe [4], resulting shapes might not be adequate for survivability in harsh environments or cost efficient to manufacture. To restrict the possible outcomes within such a geometry optimization process, different constraints, implemented through the choice of materials and manufacturing processes, can be applied.

Manufacturability has been considered for ship hull design for many years, where rolled mild steel sheets are most widely used, and composite materials - and Glass Reinforced Plastics (GRP) in 95% of the cases -, have been used for bulkheads and moulded hulls [8]. In [9] Letcher gives an overview of ways of defining hull geometries, using B-spline surfaces among others, recommending the use of developable surfaces in the hull design for ease of manufacturing (see section III. A). How to use developable surfaces in hull design was first described by Kilgore in [10] and has since been widely used for ship hull fabrication. Methods to ensure the fairness of the surfaces for aesthetic and manufacturing ease purposes have also been developed [11]. Most recent studies further develop these concepts for their use in Computed Aided Design and optimization processes [12], [13], [14].

In the wave energy sector the main potentials and challenges regarding manufacturing and materials were already identified in 1980 by Hudson [15] with corrosion and fatigue as the main design drivers, and anti-corrosion coated steel, reinforced or pre-stressed concrete and GRP as potential materials for the prime mover. In a more recent materials landscaping study from Wave Energy Scotland (WES) [16] potentials for development of certain technologies were identified, such as adhesive bonding of composites and steels, rotational moulding of polymers, Fibre Reinforced Polymer (FRP) reinforced concrete and the use of hybrid material constructions such as polymer or composite and steel hybrids, or concrete and steel hybrids. To develop these promising fields multiple projects are ongoing as part of the WES Structural Materials and Manufacturing Processes Projects: from a feasibility test of a point absorber out of FRP to the development of advanced rotational moulding processes for composites. Project results are, however, not yet available.

Only very few studies on manufacturability of WECs are available, among these: a study done by Pelamis [17], in which an optimized steel design, post-tensioned concrete and GRP were identified as possible alternatives to their initial steel design, with post-tensioned concrete giving the best results; and another study designing for buckling resistance was performed for the SeaWave device in [18], where Carbon Fibre Reinforced Plastic (CFRP) is identified as the most suitable material.

Given the importance of the structure for cost reduction and the ongoing efforts in development and analysis of different manufacturing processes and materials for their application in wave energy converters, it seems fundamental to define a geometry optimization process that considers these. The objective should be to minimize the LCOE by considering not only generated power and device size but including relevant cost factors linked to the structure, such as reliability, survivability or manufacturability. How these can be included in a geometry optimization process, producing meaningful results, within an acceptable time scale is discussed in this study. Initially the inclusion of manufacturability is considered by looking at available and new promising manufacturing processes and materials, and how they constraint device geometry, through structural parameters such as curvature or thickness.

Therefore, the question that we are hereby trying to address is: How can we account for the manufacturability of the device in the concept development stages of the design process so that later increased costs can be avoided?

II. METHODOLOGY: HOW TO INCLUDE MANUFACTURABILITY IN GEOMETRY OPTIMIZATION

A wave energy converter geometry optimization process, as well, as two possible ways to account for manufacturability through constraints, and a manufacturability metric for its inclusion as an objective function are presented here.

A. The Geometry Optimization Process

In an early design stage the geometry of the floating body might not be defined and an optimization process to find the most suitable shape is required. A general optimization process for the shape of a wave energy converter is represented in **Figure 1**. First a geometry is defined through a number of optimization variables - for example, in the case of optimizing a vertical cylindrical shape, these would be radius and draft. The shape can then be analysed with the help of BEM based programs such as NEMOH, WAMIT or ANSYS AQWA to evaluate its hydrodynamic characteristics, such as added mass, added damping and the wave excitation force on the body. With this and the wave climate for a certain location represented by, for example, an occurrence matrix, the annual energy production produced with the hull shape can be calculated by assuming linear theory. An example of such a procedure can be found in [4].

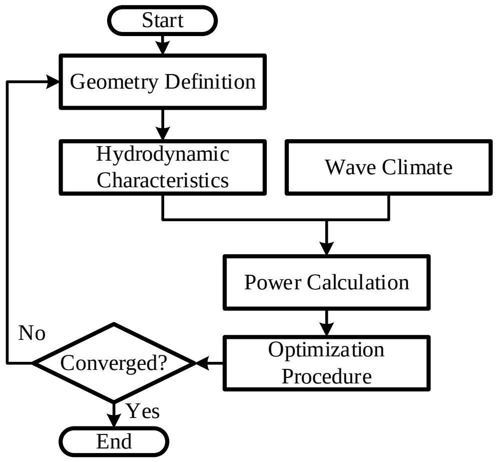
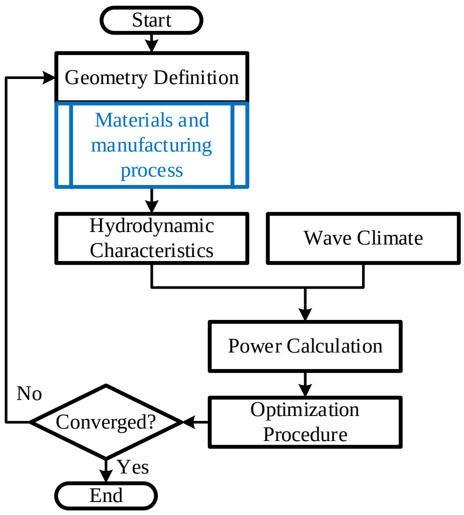
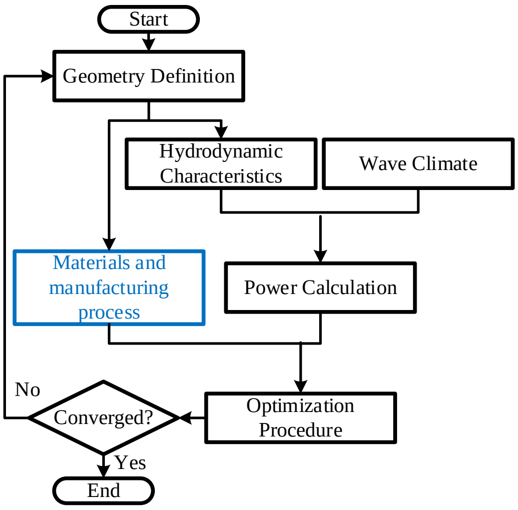


Figure 1 : Flow diagram of general geometry optimization process.

There are different strategies for including manufacturability and materials in the geometry optimization process. On one hand, if a certain manufacturing process and material combination has been chosen, this can change how the geometry is defined or can introduce additional constraints to the optimization variables or to feasible resulting geometries. On the other hand, if the aim is to find an optimal geometry that can be manufactured regardless of the manufacturing process and material choice, the geometry can be checked through similar but less limiting constraints. Both these options are represented in **Figure 2 a**. Another option is to not only constrain the geometry but to include the price or ease of manufacturing as an objective function in the optimization (see **Figure 2 b**). This can be done by scoring the manufacturing processes and materials so that the most suitable manufacturing process aiming at cost reduction can be chosen. Hence, the result is either a multi-objective optimization, where one objective is the manufacturability score and the second objective is the annual energy production, or a single-objective optimization, where these two objectives are combined to represent a meaningful objective, for example as components of the LCOE.



a)



b)

Figure 2: Flow diagrams of general geometry optimization processes which include manufacturability: a) as a constraint in the geometry definition stage, and b) as an objective function of the optimization.

III. METHODOLOGY A: MANUFACTURABILITY AS CONSTRAINT

A. Review on possible manufacturability constraints

As an example of how the geometry can be constrained depending on the choice of material and manufacturing process, a number of materials and processes are chosen, to represent the main options identified in [15] and [16]. The materials listed in **Table 1** include: Mild steel, steel reinforced concrete, High Density PolyEthylene (HDPE), short-fibre Glass Reinforced Plastic (GRP) and long-fibre Fibre Reinforced Plastic (FRP).

Table 1: Selection of materials and manufacturing processes

Material	Material Example	Manufacturing Processes Examples
Steel	Mild	Bending, Rolling, Welding
Concrete	Reinforced	Casting
Polymers	HDPE	Rotational moulding
Composites	GRP	Spray, Adhesive bonding
	FRP	Vacuum bag moulding, Adhesive bonding

Each of these manufacturing processes and material combinations requires different design considerations. For instance, undercuts should be avoided for moulded parts, rotationally moulded parts have constraints on the minimum angles and radii (r), to allow for a correct polymer powder flowability, and the minimum radius allowable for bending of steel sheets is restricted by each sheet's wall thickness (t). The available machine sizes also restrict the structure in its total size, as is the case for rotational moulding, or in the number of required bonding connections, as for moulded composites and rolled and bent metal sheets. Some of these processes also don't allow for so called double or compound curvature of the surface, which is the case for bending and rolling of metal sheets and moulding of long-fibre composites. The curvature of a surface is defined by its Gaussian curvature (κ) along two orthogonal, and so called principal, axes (κ_1, κ_2), according to equation 1.

$$\kappa = \kappa_1 \kappa_2 \quad (1)$$

If a surface has no curvature in one direction, $\kappa = 0$ and the surface is called developable, otherwise for $\kappa \neq 0$ the surface is called compound curved [9]. Cylinders and cones are examples of developable surfaces.

A summary of some relevant design considerations that can be taken into account in the geometry definition for the selected manufacturing processes can be found in **Table 2**. These are to be understood as initial considerations in the shape design that can be included in a flexible optimization process for initial concept choice, but a more detailed study for design for assembly and manufacturing accounting for all required parts and steps should be done once the basic design concept has been chosen.

Table 2: Manufacturing process specific constraints

Process	t[mm] Min	t[mm] Max	r[mm] Min	Size Max	$\kappa \neq 0$
Bending	3 [20], [21]	150 [20]	$0.5 \cdot t$ [19]	2·4 m [20], [21]	✗
Rolling	0.13 [22]	25 [22]	$2 \cdot t$ [22]	2·4 m [20], [21]	✗
Welding [23]	3.175	-		-	✓
Casting	-	$t_{min}/2$ [24]	$1.5 \cdot t$ [24]	-	✓
Rot. Moulding [25]	0.75	50	13	10 m^3	✓
Spray	1.524 [26]	- [26]	6 [27]	100 m^2 [27]	✓
Vacuum bag moulding	2.032 [26]	12.7[a] [26]	1 [27]	20 m^2 [27]	✗
Adhesive Bonding [28]	$2 \cdot t + 0.051$	$2 \cdot t + 0.254$	-	-	✓

[a] This is a limit given by this specific manufacturer but larger wall thicknesses should be possible.

B. Case Study: Use of developable surfaces in the geometry definition

The most limiting factor in the manufacturing of hulls out of rolled and welded steel sheets is the fact that these processes do not allow for double curvatures. It is common practice in ship hull design, that the hull shape is designed to be composed of developable surfaces that can be formed from flat steel sheets. The geometry definition is, therefore, limited here to the use of developable surfaces as a design constraint for manufacturability with steel. The resulting optimized shapes are compared to the unconstrained case.

The hull shape geometries for a point-absorber oscillating in surge only are evaluated for maximal annual energy production production and maximal mean annual production to volume ratio according to the method used in [4]. The maximal stroke is constrained to 5m and the rated power of the Power Take-Off (PTO) constraining the maximum instantaneous power is set to 2.5MW.

In the manufacturability-unconstrained case, the geometry is defined as in [4] through a set of 11 vertices of a polyhedron represented in **Figure 3**, which are approximated by a bi-cubic B-spline surface. Preliminary results for shapes optimized for maximal annual energy production, and annual energy production to volume ratio are shown in **Figure 4** and **Figure 5**, respectively.

The manufacturability-constrained geometry is split into three developable surfaces (P1, P2, P3 in **Figure 6**) defined through cubic-splines in one parametric direction and linear splines in the other. The same definition of the polyhedron vertices is used as in the previous case. Results for shapes optimized for maximal annual energy production, and annual energy production to volume ratio are shown in **Figure 7** and **Figure 8**, respectively.

C. Results discussion

The objective values achieved for the shapes optimised for maximal annual energy production are very similar and tend to simple spherical shapes, with the shape defined for manufacturability achieving 1.2% more power. In case of the shapes optimised for maximal annual energy production to volume ratio a 19.5% lower objective function value is achieved defining the hull with three developable surfaces.

The results show the suitability of this method to obtain hull geometries that are manufacturable out of rolled steel sheets. However, it becomes apparent that the objective function of annual energy production to volume ratio might not be suitable in this context since the volume does not act as a correct proxy for costs and the resulting shape might be more costly to manufacture due to the increased surface area of material required. With this in mind, an optimization to minimize the ratio of annual energy production to surface area would be more suitable for this analysis.

IV. METHODOLOGY B: MANUFACTURABILITY AS OBJETIVE FUNCTION

A. Relation between LCOE and geometry cost factors

The Levelised Cost Of Energy (LCOE) (equation (2)) is broadly used in the energy generation industry as a metric that enables comparison between different generation technologies based on their energy generation costs and is used within the wave energy sector to compare different devices. It describes the ratio of Capital (CapEx) and Operational (OpEx) Expenditures to the Annual Energy Production (AEP), discounted to their Present Values (PV).

$$\mathrm{LCOE} = \frac{\mathrm{PV(CapEx)} + \mathrm{PV(OpEx)}}{\mathrm{PV(AEP)}} \qquad (2)$$

When improving WEC design, the ultimate goal is to reduce the LCOE. This seems like the optimal metric to be used for device comparison. However, given the lack of available costs information and the diversity of the WEC designs, it is difficult to use this metric in terms of absolute values reliably. For instance, evaluating absolute costs for different materials and manufacturing processes is very difficult, given that economies of scale, development of certain industries or production chains and specific geometric requirements can result in one manufacturing technology being more cost-effective than another.

Multiple techno-economic studies try to define the relevance of different cost centres within the LCOE calculation. In [2], where previous techno-economic studies are compared, average figures for the identified cost centres are given as a percentage of the LCOE. CapEx costs include structure (32%), PTO (18%), installation (6%), connection (8%) and foundation and moorings costs (12%). Operation and Maintenance (O&M) costs then represent 24% of the LCOE. These percentages for each cost centre (*i*) will be referred to as α_i.

For this study multiple cost factors with an effect on geometry were identified. The choice of manufacturing process and material can constrain geometric characteristics such as the maximal allowable curvature. The available resource influences the range of operation and with it the total size of the structure. Reliability of the structure can be understood as the capacity to withstand variable loads. Survivability can be characterized by the maximum load that the structure is expected to experience. The two latter cost factors affect wall thickness and reinforcement requirements.

Each of these geometry cost factors will influence different LCOE cost centres in different ways. An overview of these relationships are given in **Table 3**. The choice of material and manufacturing process will, therefore, have an effect on the CapEx for the structure and the installation.

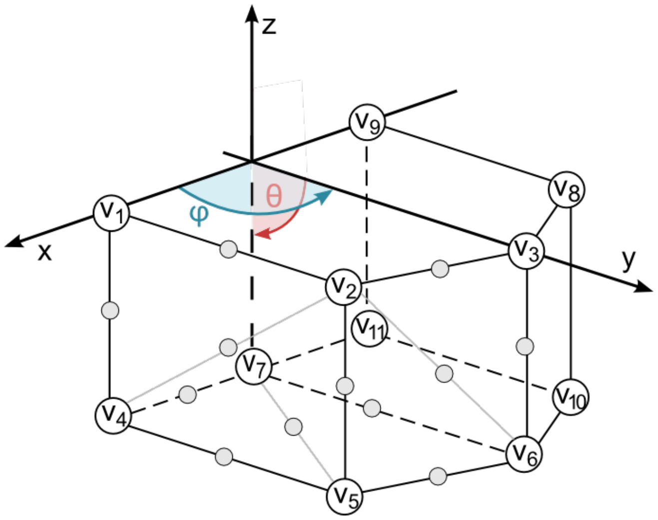


Figure 3: Original geometry definition as bi-cubic B-spline surface as described in [4].

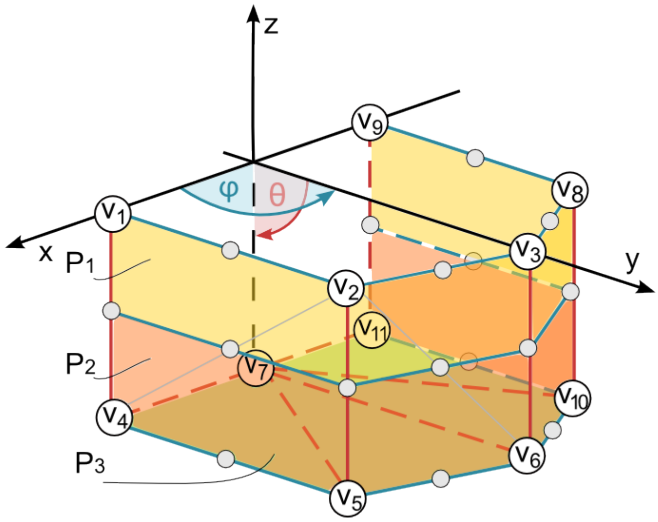


Figure 6: Geometry definition using 3 developable surfaces (P1, P2, P3) defined with cubic splines in one direction (blue) and linear splines in the other (red).

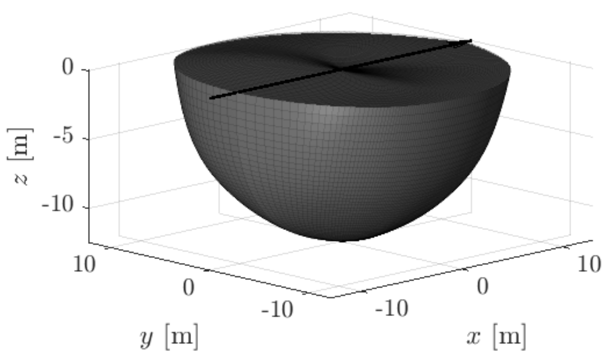


Figure 4: Optimized geometry defined according to [4] for maximal annual energy production (P = 386.39kW). Arrow indicates wave direction.

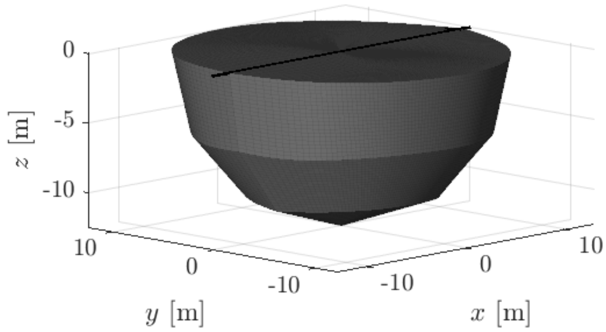


Figure 7: Optimized geometry defined with 3 developable surfaces for maximal annual energy production (P=391.18kW). Arrow indicates wave direction.

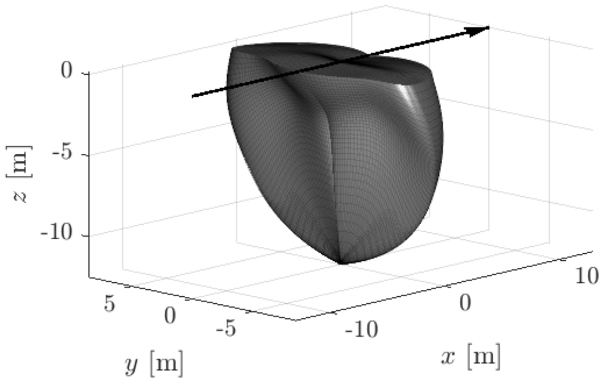


Figure 5: Optimized geometry defined according to [4] for maximal annual energy production to volume ratio (P/V= 705.44 W/m^3). Arrow indicates wave direction.

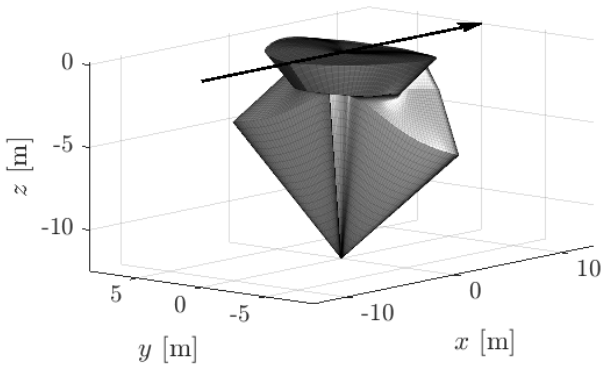


Figure 8: Optimized geometry defined with 3 developable surfaces for maximal annual energy production over volume (P/V=567.97 W/m^3). Arrow indicates wave direction.

Table 3: Relation between identified cost factors with an effect on geometry and LCOE CapEx cost centers.

Cost factor (n)	Structure	PTO	Installation	Connections	Moorings
Manufacturing process	X				
Material	X		X		
Resource	X	X			
Reliability	X				X
Survivability	X				X

Within the OpEx, as in the CapEx, different cost centres have been identified [29], and models exist for their calculation [30]. However, due to many factors that play a role in O&M such as weather windows or availability of vessels, and the amount of information required for its calculation - that is generally not available at very early design stages - only the effects on CapEx are considered for the purpose of this study.

B. Metric for Manufacturability: LCOE percentage change

Given the difficulty in defining absolute LCOE values, to be able to compare the effect of improvements in each of these cost centres with respect to a reference case, the percentage change in LCOE is chosen as an indicator.

If AEP and OpEx are assumed to be unchanged, due to changes in manufacturing process and material, and all CapEx investment happens in year 1; the LCOE with a new manufacturing process and material ($\mathrm{LCOE_{new}}$) with respect to the LCOE for a reference case ($\mathrm{LCOE_{ref}}$) can be described with help of an LCOE change ($\Delta\mathrm{LCOE_{new\text{-}ref}}$) originating only from a CapEx change (ΔCapEx):

$$\begin{aligned}\mathrm{LCOE_{new}} &= \mathrm{LCOE_{ref}} + \Delta\mathrm{LCOE_{new\text{-}ref}}\\ &= \frac{\mathrm{CapEx} + \Delta\mathrm{CapEx} + \mathrm{PV(OpEx)}}{\mathrm{PV(AEP)}}\\ &= \frac{\mathrm{CapEx}(1 + \Delta\mathrm{capex}) + \mathrm{PV(OpEx)}}{\mathrm{PV(AEP)}}\end{aligned} \quad (3)$$

Hence, the change in LCOE due to change in material and manufacturing process is:

$$\Delta\mathrm{LCOE_{new\text{-}ref}} = \Delta\mathrm{capex}\frac{\mathrm{CapEx}}{\mathrm{PV(AEP}} \quad (4)$$

where Δcapex is the percentage change in CapEx. Additionally, as mentioned before, the CapEx for each cost centre can be calculated with the cost centre's percentage contribution of the total LCOE (α_i) as in equation (5).

$$\frac{\mathrm{CapEx}_i}{\mathrm{PV(AEP)}} = \alpha_i\ \mathrm{LCOE} \quad (5)$$

From equations (4) and (5) it becomes clear that the percentage contribution from a specific cost centre ($\Delta\mathrm{capex}_i$) on the change in LCOE ($\Delta\mathrm{LCOE}_{\mathrm{new\text{-}ref},i}$), will follow:

$$\begin{aligned}\Delta\mathrm{LCOE}_{\mathrm{new\text{-}ref},i} &= \Delta\mathrm{capex}_i\frac{\mathrm{CapEx}_i}{\mathrm{PV(AEP}}\\ &= \Delta\mathrm{capex}_i\ \alpha_i\ \mathrm{LCOE}\end{aligned} \quad (6)$$

The indicator for manufacturability chosen here is, therefore, the LCOE percentage change. The cost-centre specific value is defined here as:

$$\Delta\mathrm{capex}_{\mathrm{LCOE},i} \equiv \Delta\mathrm{capex}_i\ \alpha_i \quad (7)$$

The total LCOE percentage change is then:

$$\Delta\mathrm{capex_{LCOE}} = \sum_i \Delta\mathrm{capex}_{\mathrm{LCOE},i} \quad (8)$$

If $\Delta\mathrm{LCOE}_i$ is taken as absolut value of the LCOE change for a specific cost centre, then $\Delta\mathrm{capex}_{\mathrm{LCOE},i}$ can be understood as the percentage change of this absolute value. Analogously, this applies to $\Delta\mathrm{LCOE_{ref\text{-}new}}$ and $\Delta\mathrm{capex_{LCOE}}$. For instance, the change in LCOE from the structural cost centre will be the sum of the changes in capital expenditures from each of the geometry cost factors (n) listed in **Table 3** (see equation (9)). This is defined analogously for the installation cost centre in equation (10).

$$\Delta\mathrm{capex_{LCOE,Str}} = \sum_n \Delta\mathrm{capex}_{\mathrm{LCOE,Str},n} \quad (9)$$

$$\Delta\mathrm{capex_{LCOE,Inst}} = \sum_n \Delta\mathrm{capex}_{\mathrm{LCOE,Inst},n} \quad (10)$$

C. Metric for installation costs variation through material choice

Installation costs include costs of grid connection, vessel hire, time required for deployment, etc. The installation costs influenced by the choice of material will just be limited to the costs of the vessel required. The type of vessel required for installation will be mainly set by its crane lifting weight limitations, apart from the environmental conditions and availability [31].

Although only certain crane lifting limitations exist, as an initial approximation the effect of materials on installation costs can be assumed to vary proportionally with the weight (m) of the device.

$$\mathrm{CapEx_{Inst}} \sim m \quad (11)$$

To compare a new material choice with respect to a reference case, the hull surface area (S) is considered to be unchanged, but the required wall thickness (t) will vary with the material due to structural integrity requirements. The volume is, hence, expressed as $V = S \cdot t$. The percentage difference in CapEx from installation costs can be defined as follows:

$$\Delta \text{capex}_{\text{Inst,Mat}} = \frac{m_{\text{new}}}{m_{\text{ref}}} - 1 = \frac{\rho_{\text{new}} \cdot t_{\text{rel,new}}}{\rho_{\text{ref}} \cdot t_{\text{rel,ref}}} - 1 \qquad (12)$$

The weight can be calculated from the material density (ρ) and the percentage variation of the required wall thickness (t_{rel}). If taking steel as the reference, a steel wall thickness equivalent can be derived (see **Table 4).** The differences in wall thickness stem from structural considerations for a cylinder shaped attenuator WEC [17] .

If steel rolling and welding of a cylinder is taken as the reference case, and an HDPE rotationally moulded cylinder as the new case to be analysed, the difference in CapEx can be calculated as:

$$\begin{aligned}\Delta \text{capex}_{\text{Inst}} &= \frac{m_{\text{HDPE}}}{m_{\text{MildSteel}}} - 1 \\ &= \frac{2300 \left[\frac{\text{kg}}{\text{m}^3}\right] \cdot 2.5}{7800 \left[\frac{\text{kg}}{\text{m}^3}\right] \cdot 1} - 1 \\ &= -0.52\end{aligned}$$

The installation cost centre share of the LCOE change due to material costs, as defined in equation (7), becomes:

$$\Delta \text{capex}_{\text{LCOE,Inst}} = \Delta \text{capex}_{\text{Inst,Mat}} \alpha_{\text{Inst}} = -3.1\%$$

In this case, a reduction of the CapEx by 3% would be achieved by using a rotationally moulded HDPE cylinder instead of a rolled and welded steel sheet based cylinder.

Table 4: Material data to obtain wall thickness (t) dependent weight ratios (t_{rel}) based on structural integrity study of a cylinder shaped WEC by Pelamis [17] and on density values (ρ) from [16].

Material	***t*[mm]** [17]	**t_{rel} [-]**	**ρ[kg/m³]**	**Reference equivalent weight [kg]**
Mild Steel	20	1	7800	7800
Reinforced Concrete	60	3	2300	13800
HDPE	50[b]	2.5	1500	3750
GRP	22	1.1	1900	1650
FRP	22	1.1	1390-2800	1529-3080

[b] This value is not given in [17] but is assumed here just for example purposes.

D. Metric for structural costs variation through manufacturing process and material choice

The choice of manufacturing process and material will have an effect on structural costs that will be a function of material costs (C_{Mat}) and structural weight (m); as well as shape complexity and resulting production costs (C_{Prod}). Resource, reliability and survivability as defined here would also have an effect on structural weight, but these are not considered here. The structure related CapEx ($\text{CapEx}_{\text{Str}}$) can therefore be defined as:

$$\text{CapEx}_{\text{Str}} \sim C_{\text{Mat}} m + C_{\text{Prod}} \qquad (13)$$

The production cost C_{Prod} will depend on the number of devices produced. For instance, the cost for a moulded part will vary highly depending on the number of parts produced, since the costs of the mould can then be split over more manufactured parts. This should be considered in future studies.

Based on equation (13), the percentage change for the LCOE would be:

$$\Delta \text{capex}_{\text{Str, Mat\&Man}} = \frac{C_{\text{Mat,new}} m_{\text{new}} + C_{\text{Prod,new}}}{C_{\text{Mat,ref}} m_{\text{ref}} + C_{\text{Prod,ref}}} - 1 \qquad (14)$$

If the same conditions, reference case and new case are assumed as before, the HDPE cylinder can be rotationally moulded in one piece, and the steel sheet formed version will require dividing the cylinder into three parts and, therefore, two welded connections. An overview of material and fabrication costs is given in **Table 5**, where fabrication costs are given as a percentage of total manufacturing costs, with the rest being materials costs. Percentages are extracted from the literature [16], [32], and in case of rolling and spray-up of GRP percentage assumptions were made based on information in [22] and [27]. The percentage change in CapEx can then be calculated as:

$$\begin{aligned}&\Delta \text{capex}_{\text{Str,Mat\&Man}} \\ &= \frac{\left(1\frac{£}{\text{kg}} + \frac{0.3}{0.7} \cdot 1\frac{£}{\text{kg}}\right) \cdot 3750\text{kg}}{\left(10\frac{£}{\text{kg}} + 3 \cdot \left(\frac{0.2}{0.8} \cdot 10\frac{£}{\text{kg}}\right) + 2 \cdot \left(\frac{0.7}{0.3} \cdot 10\frac{£}{\text{kg}}\right)\right) \cdot 7800\text{kg}} \\ &- 1 \\ &= -0.989\end{aligned}$$

Inserting this into equation (7) results in the structural cost centre share of the LCOE change due to material and manufacturing costs:

$$\begin{aligned}\Delta \text{capex}_{\text{LCOE,Str}} &= \Delta \text{capex}_{\text{Str,Mat\&Man}} \alpha_{\text{Str}} \\ &= -31.6\%\end{aligned}$$

Table 5: Manufacturing costs breakdown

Material	Material costs [£/kg]	Fabrication costs as percentage of total manufacturing costs [%]
Mild Steel	10 [16]	20 for rolling 70 for welding [16]
Reinforced Concrete	0.046 [16]	22 [16]
HDPE	1 [16]	30 [16]
GRP	2.5 [33]	40 for spray-up 50 for bonding [16]
FRP	11 [33]	40 for moulding [32] 50 for bonding [16]

The total LCOE percentage change considering both structural and installation shares of LCOE changes according to equation (8) is then:

$$\begin{aligned}\Delta\text{capex}_{\text{LCOE}} &= \Delta\text{capex}_{\text{LCOE,Inst,Mat}} \\ &\quad + \Delta\text{capex}_{\text{LCOE,Str,Mat\&Man}} \\ &= -34.7\%\end{aligned}$$

This means that by using rotationally moulded HDPE, instead of rolled and welded steel sheets for a cylinder-shaped WEC, an LCOE reduction of approximately 35 % can be achieved.

This method can be used to prioritise manufacturing processes and material combinations regarding manufacturability of a shape, but should not be relied on for quantitative comparisons given the assumptions made. A methodology to include the effects on costs of the structure due to resource, reliability and survivability considerations is not included here. They can be considered in the wall thickness requirements, as done here with the steel wall thickness equivalent for a cylindrical-shaped device, or as extra costs for reinforcement within the material and production costs.

V. CONCLUSIONS

Two methodologies for the inclusion of manufacturability considerations in the optimization process of a wave energy converter hull design were presented.

The first option, to include manufacturability constraints in the geometry definition stage can be helpful to make sure that the geometries generated during the optimization process will be manufacturable with a specific material and manufacturing process. Since volume does not represent a good proxy for costs, the use of annual energy production or annual energy production to surface area ratio as objective function is recommended in this case.

The second option, to define a metric for manufacturability and include this as an objective function in the optimization process, can be used to find a trade-off between high annual energy production and reduced costs. This can be done as exemplified here by considering the percentage change of LCOE achieved through the use of a certain material or manufacturing process with respect to a reference case. Then, the change in LCOE - as a manufacturability indicator – can be used as a second objective function of a multi-objective optimization, with the first objective function being annual energy production. With this method, the cheapest material and manufacturing process combination for each shape would be chosen. However, for this to be integrated within the optimisation process, the definition of geometric conditions is required so that the number of parts and production steps for the different cases can be determined automatically during the optimisation – i.e. if the curvature is too high, split the geometry into two parts.

Future work includes, therefore, applying the described objective function to a geometry optimization process and developing the set of conditions that will account for shape complexity in the manufacturing process choice. Moreover, to allow for a fairer comparison of the manufacturing processes, the change in production costs, depending on the number of produced parts, should be included in the calculation.

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