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Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact

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Consideration of the cost implications for mooring MEC devices

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Summary

Many marine energy devices rely on mooring systems to maintain their position on station. This report summarises the primary design considerations for device mooring systems and identifies several factors that would influence mooring system cost. The implications of employing these mooring systems for station-keeping of arrays of devices are briefly discussed.

CONTENTS

1 INTRODUCTION

To ensure a safe and economical station keeping of a floating marine energy converter (MEC) the following key parameter needs to be addressed though not necessarily in the same way as a traditional offshore mooring application, namely: i) physical body, ii) physical environment, iii) maintenance and installation and iv) costs. The mooring design approach for typical offshore structures are likely to be too expensive and often not appropriate to enable a MEC to convert efficiently power from the wave or current field. The following generic design considerations for the station keeping of a wave energy converter and partly for a tidal energy converter have to be made:

A. Ensure the station keeping (motional about equilibrium position).
    - Withstand the operating site extreme environmental.
    - Restrict the WEC excursions to a reasonable level in order to (i) provide a realistic “footprint” for each device to minimize the use of sea space (ii) ensure the feasibility and integrity of the electrical transmission cable.

B. Minimize the impact on power conversion. For those devices that rely on relative motion between floating structure and the wave field, the moorings will always have some affect in comparison with an “unconstrained” system. This will be dependent on the particular deployment (loadings/ depths)

C. The system should be designed to reflect the safety and risk arising from the deployment.

D. It should require the minimum degree of inspection and maintenance over the service life of the device.

E. The system should be cost effective in:
    - Capital costs
    - Installation costs
    - Operational costs (inspection and maintenance).

From the view of conventional design of offshore structure point A above is by far the most important and to some extent drives the other aspects of deployment and maintenance. Also the number of moorings employed in a particular project and their mode of operation is significantly different for WECs, particularly for large arrays.

Design considerations are at present typically based on three codes of practice for floating MEC:

- DnV-OS-E301 Position Mooring [1]
- API-RP-2SK Design and Analysis of Station keeping Systems for Floating Structures [2]

These codes are standard for the offshore engineering industry and are reviewed for the application for WECs in [3]. There is now a draft guideline from Carbon Trust/DnV, which differs from the above mainly in its acceptance of the lower “consequence of failure” which will allow explanation of lower design safety factors than the two “offshore” codes.

- DnV Guidelines on Design and Operation of Wave Energy Converters [4]

The codes deal with the design requirements of any moored structure in terms of the design life of the structure and the environmental conditions. The API codes requires design in terms of the 100 year return period combined loading events (wind/ wave, wind/current and wave/current). API allows the definition of the return period for a structure with a design life significantly less than 20 years whereas DnV does not. It is assumed that wave energy converters will have design life of 15 to 20 years.

It is important to realise that the deployment of WECs is likely to require a different balance of design analysis from that required for a conventional offshore structure. This is because:

- The relative size of the device to the mooring/ water depth
- The deployment of devices in energetic wave regimes
- The resulting dynamics of the floating body and its moor.

2 COMPONENTS

Primary mooring components are the mooring line and anchor. These are used along with other items such as connecting elements, floats, fairlead, etc. [5]. The choice of primary component must be consideration in respect to the mooring configuration, installation location and the top-end structure to be moored. Additional long term mooring requirements needs to be considered if a floating unit is positioned at the same location for five years or more years [1].

2.1 PRIMARY MOORING COMPONENTS – MOORING LINE

2.1.1 Chain

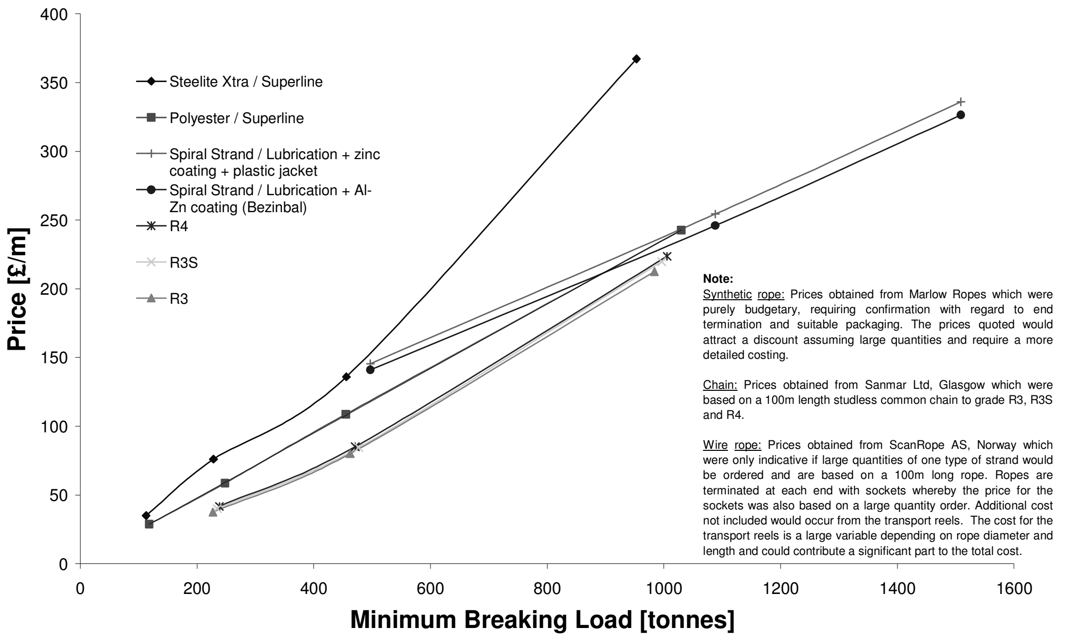
Depending on required proof strength Grade 3, 3S or 4 should be used for offshore moorings. Chains provide a good catenary stiffness effect and have good abrasion and bending properties. Suitable for long term moorings but corrosion allowance or anodes need to be considered, as well as required inspections/maintenance intervals.

2.1.2 Synthetic fibre rope

Typical fibre ropes are Polyester, Aramid, HMPE or Nylon ropes. The weight of the ropes in water are close to neutrally buoyant or buoyant. The weight and elasticity properties make them more common for very deep water tether applications. Previous experience from realistic installation conditions has resulted in the need for high safety factor. Latest R&D has resulted in a better understanding of the behaviour of fibre ropes that consequently reduced uncertainties and hence the required safety factor. Considerable change in axial stiffness after installation requires re-tensioning. Axial compression and hysteretic heating at extreme storm condition needs to be avoided and fish bite can be a problem.

2.1.3 Wire rope

Spiral Strand, Six Strand and Multi-Strand wire ropes are available but only the Spiral Strand is suitable for long term mooring. Due to the elasticity of wire ropes it can be used in tensioned mooring applications. Extreme bending must be avoided. A generic cost comparison for various chain, synthetic fibre and wire ropes was produced in [5] that is shown in figure 2.1.



Note:

Synthetic rope: Prices obtained from Marlow Ropes which were purely budgetary, requiring confirmation with regard to end termination and suitable packaging. The prices quoted would attract a discount assuming large quantities and require a more detailed costing.

Chain: Prices obtained from Sanmar Ltd, Glasgow which were based on a 100m length studless common chain to grade R3, R3S and R4.

Wire rope: Prices obtained from ScanRope AS, Norway which were only indicative if large quantities of one type of strand would be ordered and are based on a 100m long rope. Ropes are terminated at each end with sockets whereby the price for the sockets was also based on a large quantity order. Additional cost not included would occur from the transport reels. The cost for the transport reels is a large variable depending on rope diameter and length and could contribute a significant part to the total cost.

Figure 2.1 Comparison for costs of mooring line materials

2.2 PRIMARY MOORING COMPONENTS – ANCHOR/POSITIONING SYSTEMS

2.2.1 Gravity Anchor

The anchor provides the fixing point at the seabed to which the mooring line is connected. Table 2.1 provides an overview of available generic anchoring methodologies [5]. The choice of the anchor is mainly dependent on the mooring configuration and the geotechnical properties of the seabed. The simplest anchor is the gravity anchor where installation costs are low. This anchor that is typically applied as a horizontal holding anchor provides the holding capacity through its own weight and friction with the seabed. As a result gravity anchors typically have large dimensions, which is a limiting factor. Anchor base structures are also gravity anchors, however these are often additionally supported with drilled and grouted anchors. The installation cost of a gravity anchor is typically low, but the dimension of these anchors can become an issue. If a gravity base is used, that has typically large dimensions, seabed constraints could become an issue and cost can significantly increase for both, the base itself and the installation.

2.2.2 Drag-Embedment Anchor

Drag-Embedment (Fluke) anchors are horizontal load anchors that have their principal holding direction in the direction of installation. Various embedment anchors are available (Table 2.1) that have different holding capacities. Characteristics holding capacities are provided in standards (e.g. [2]) for an installation in soft clay and sand. The installation of the fluke of an embedment anchor should be conducted to recommended procedures [6] that add to additional installation costs. The suitability of drag embedment anchors is dependent on the soil properties.

2.2.3 Vertical Load Anchors

Vertical Load anchors can be categorized into three different methodologies i) Driven Pile/Suction Anchor, ii) Special Vertical Load Anchor and iii) Drilled and Grouted Anchor (Table 2.1). The capital cost of such anchors is relatively low in comparison to the installation costs and, whilst all of these anchor categories provide vertical holding capacity, the major disadvantage is the overall high cost. Specific installation procedures must be followed (e.g. [7]) requiring special offshore equipment and highly trained staff. These anchors are applied for special mooring applications like Tension Leg Platforms (TLPs).

Table 2.1 Anchor characteristics

Anchor	Characteristics	Costs
Gravity Anchor	Horizontal and (vertical) holding capacity is generated by dead weight and friction between seabed and anchor.	Low
Drag-Embedment Anchor	Horizontal holding capacity is generated in the main instalment direction by the embedment of the anchor in the ground. (Bruce, Stevpris, Navmoor, Stato, Moorfast, LWT, Stockless, Danforth, Boss, Hook, Stevdig, Stevmud, Stevfix, Flipper)	Medium
Driven Pile / Suction Anchor	Horizontal and vertical holding capacity is generated by forcing a pile mechanically or from a pressure difference into the ground, providing friction along the pile and the ground.	High
Special Vertical Load Anchor	Horizontal and vertical holding capacity is generated due to a specific embedment anchor allowing loads not only in the main instalment direction.	High
Drilled and Grouted Anchor	Horizontal and vertical holding capacity is generated by grouting a pile in a rock with a pre-drilled hole.	High

2.2.4 Dynamic Positioning System

Dynamic positioning (DP) is a technique of automatically maintaining the position of a floating structure within a specified offset from the equilibrium. Onboard thrusters are used in combination with position mooring (GPS/ wireline/ sonar) along with a sophisticated control system to maintain an accurate position in space. The position of the floating structure is corrected if the offset becomes unacceptable due to wind, wave and current forces. Such a system could be employed to minimize mooring loads but the added complexity makes this option unrealistic.

2.3 SECONDARY MOORING COMPONENTS

2.3.1 Clump Weight

Clump weights can be introduced into a mooring leg to improve performance and reduce costs of mooring lines. The additional clump weight, typically installed at the lower end of a mooring leg, adds a point restoring force to the moor. This load can be applied to reduce the overall length of a chain catenary that results in cost reduction from that component of the mooring. Clump weights can be added to a wire/fibre rope to increase stiffness characteristics.

Advantages: - reduces scope and costs of mooring lines
- increases stiffness characteristics

Disadvantages: - increases complexity of the mooring and cost of installation/ inspection
- increases design/installation complexity
- increases complexity of numerical modeling

2.3.2 *Spring Buoy*

The addition of spring buoys in the form of surface or subsurface buoys can be used to overcome the effect of the weight of the chain, reducing the influence on the device. In effect the buoy includes a second spring effect. It is recommended that a spring buoy is foam filled. If a floating structure is moored horizontally to a surface buoy typically a light synthetic rope is used as a connecting element.

Advantages: - reduces weight of moor that has to be supported by the floating structure
- reduces effects of line dynamics in deep water

Disadvantages: - increases scope of the mooring
- increases complexity of the mooring
- increases complexity of design/ numerical modeling

2.3.3 *Connecting Hardware*

Connecting hardware such as shackles, swivels, fishplates and detachable links are required to connect mooring line sections as well as the mooring leg to the anchor and the floating structure. Inspection and replacement of connecting hardware in a long term mooring configuration is difficult and can be very expensive. According to [1] connecting elements for a long term mooring requires custom designs for the design life of the installation, including purpose made shackles or tri-plates. Swivels, pear links, C-links, Kenter shackles and ordinary D-shackles are not permitted by current offshore regulations for long term moorings. The design of connecting hardware in a long term mooring configuration should include the evaluation of stress concentration, fatigue and corrosion analysis.

2.3.4 *Winching Equipment/Fairlead*

Winching equipment can be required to adjust a mooring leg during initial installation or production cycle, depending on the mooring system and floating structure to be handled. For the mooring design of a WEC a winch system such as a i) windlass, ii) chain jack, iii) drum-type winch, iv) linear winch or v) traction winch might not be cost effective. Dependent on the physical size of the WEC device the mooring may well have a direct connection to a static connection point, providing no adjustment to the mooring leg.

Dependent on the location of these connection points a fairlead might be required. If a fairlead is used a sufficient sheave-to-line diameter ratio needs to be applied. Within the standard [2] the following sheave-to-line ratio are recommended to minimize tension-bending failure for chain and wire; i) chain: 7-pocket wildcat sheaves and ii) wire rope permanent mooring: Sheave to wire rope diameter of 40/60. Recommendation for fibre ropes should be obtained from the manufacturer. Again each of these components increases the complexity of the design, installation and maintenance requirements.

2.3.5 *Anodes*

Mooring standards [1,2] typically applying corrosion allowance to components, which effectively produces a safety factor increase. Cost reduction might be achieved by using anodes to control the corrosion of load bearing components. However, the introduction of anodes would require regular inspection intervals.

3 MOORING OPTIONS

In the following four generic mooring configurations are considered, namely a) configuration 1 – Catenary, b) configuration 2 – Catenary & Spring Buoy, c) configuration 3 – Taut and d) configuration 4 – Taut & Spring Buoy (figures 3.1 – 3.4). In each figure only a single mooring leg is indicated. Realistically three or more legs would be used depending on the load cases. Also variations on these basic configurations could be applied. The configurations 1 and 2 are entirely conventional mooring configurations, applied in various combinations. The taut configuration (configuration 3) has its application in the offshore oil and gas industry (e.g. TLPs) but it has not be applied in the marine energy context, whilst configuration 4 is entirely novel, within the context of marine applications.

3.1 CONVENTIONAL CATENARY MOORING

3.1.1 General comments

A catenary mooring system is the most basic configuration of slack mooring (Figure 3.1). This configuration consists typically of a heavy chain arrangement, falling in a catenary shape to connect the device to the anchor. Wires or synthetic ropes or a combination of both may be included at the upper section of the moor to provide specific mooring properties. The catenary provides the main restoring force through the weight of the chain. A horizontal load anchor is typically used which is not designed to support a significant vertical loading towards the anchor point. Typically, the paid out length (POL) is in the order of hundreds of meter.

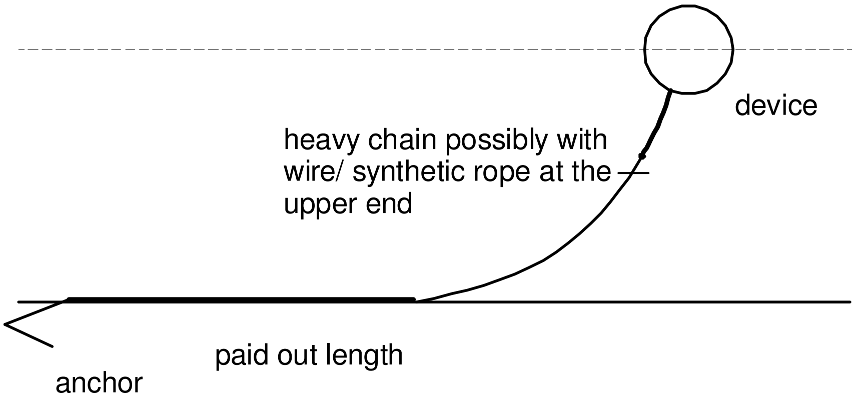


Figure 3.1 Basic catenary with horizontal load anchor

3.1.2 Main characteristics

- Horizontal load anchor
- Simplicity
- Minimal components
- Dependency on device buoyancy to support heavy chain - required to minimise horizontal displacements (and the results footprint).
- Loading is approximately linear at small horizontal scope, but becomes highly non-linear at large horizontal scope.

3.2 CATENARY WITH SURFACE/SUB-SURFACE FLOATER (AND CLUMP WEIGHT)

3.2.1 General comments

A catenary arrangement with spring buoys (Figure 3.2) may be applied to provide greater elasticity in the system. The influence of the mooring system to the coupled system could be reduced in moderate sea conditions, but in extreme seas this could adversely affect both the dynamics and significantly increase the footprint. A clump weight may be added to the mooring line configuration to control the footprint.

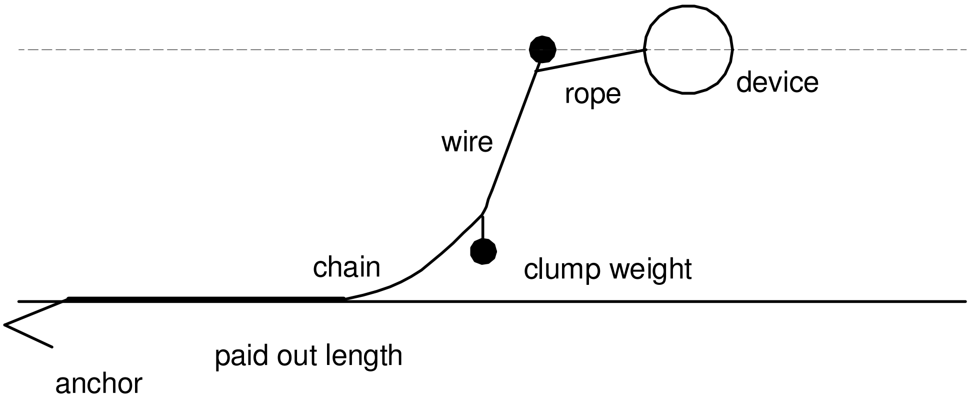


Figure 3.2 Chain catenary with surface buoy and clump weight

3.2.2 Main characteristics

- Horizontal load anchor
- Greater complexity; increase of cost and failure sources
- Chain: - Dependency on device buoyancy to support heavy chain – required to minimise horizontal displacements (and the results footprint).
- Loading is approximately linear at small horizontal scope, but becomes highly non-linear at large horizontal scope
- Potential for increased design loads on mooring lines due to dynamic response of buoy in extreme seas and currents.

3.3 TAUT MOORING

3.3.1 General comments

Tethered moorings (Figure 3.3) are used to restrain structure in the offshore industry in the form of Tension Leg Platforms (TLPs). They rely on tension developed by the buoyancy of the device or some other buoyancy component. The advantage is the small footprint and its stable configuration, whilst the need for large pre-tensions and expensive anchors will increase the cost significantly. In addition the ratio between tidal variation and water depth for most installation locations for WECs would require a component/design for compensation.

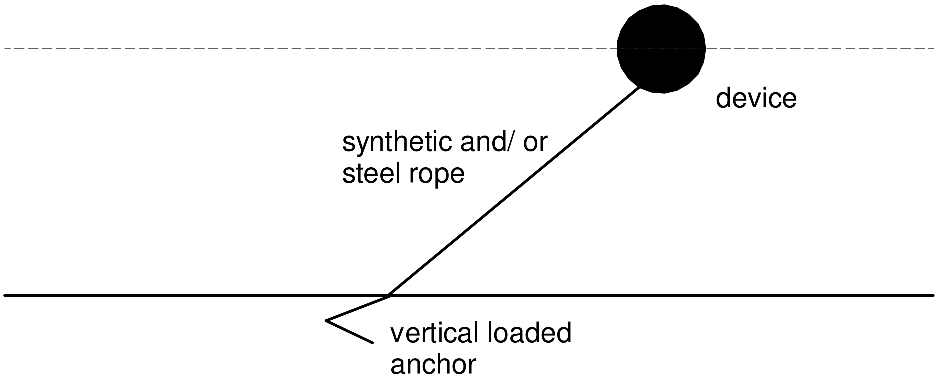


Figure 3.3 Taut mooring system

3.3.2 Main characteristics

- Requirement of an anchor with a high vertical loading capacity
- High pre-tensions
- Smaller footprint
- Loading characteristics predictable
- Arrangement required to compensate for tidal variations

3.4 TAUT MOORING SURFACE BUOY AND HORIZONTAL SURFACE LINE TO DEVICE

3.4.1 General comments

The arrangement of a taut mooring surface buoy that holds the WEC device on station using a horizontal mooring rope (Figure 3.4) reduces the footprint area, in comparison with a similar catenary mooring, whilst additionally the influence of the mooring system to the WEC is also reduced. This arranged is a non-standard arrangement and would need a detailed study. Cost could be large but these might be reduced by a "shared anchor" arrangement.

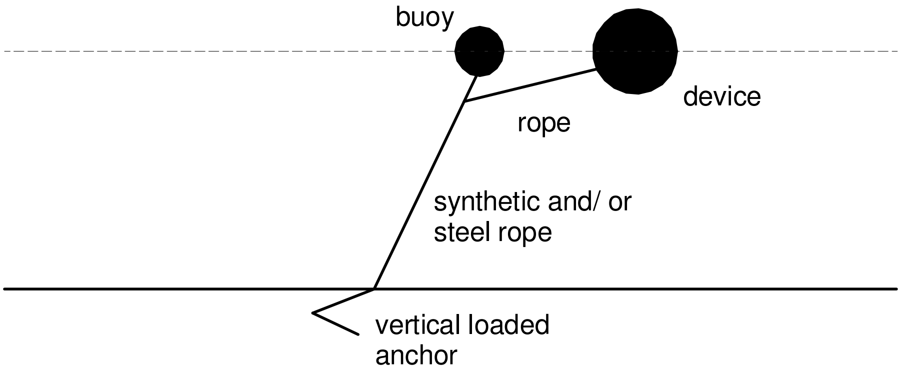


Figure 3.4 Taut mooring system with horizontal surface line

3.4.2 Main characteristics

- requirement of an anchor with a high vertical loading capacity
- small footprint
- 'de-coupling' of mooring system to WEC device possible
- can compensate for tidal variations in mean water level

4 INTER-COMPARISONS

A tabular inter-comparison of the four generic configurations is conducted in section 4.1 and 4.2 considering the implications of i) generic engineering context and ii) costs. In section 4.3 the array installation is examined regarding its design requirements. These comparison are based on 10 different design aspects, namely a) anchor requirements, b) loading/survivability, c) fatigue, d) installation requirements, e) maintenance considerations/intervals, f) footprint area requirements, g) redundancy, h) umbilical aspects, i) complexity of components/system, j) novelty. The individual design aspects are considered in the following context:

a.) Anchor requirements

Anchor requirements are particularly related to a specific mooring configuration. Possible anchors and their characteristics that will be applied here are identified in Table 2.1. Installation procedures are commented in aspect d) and j).

b.) Loading/Survivability

Loading and survivability are considered in the context of an ultimate limit state (ULS), where the design strength has to enable the moor to survive extreme environmental action [1]. The resulting loadings must then be applied to the individual mooring configurations and considered for each variation. Fouling could contribute to additional hydrodynamic and static loading, where the fouling may be considered to be constant with depth.

c.) Fatigue/Corrosion

The fatigue is considered in the context of a fatigue limit state (FLS), where it has to be ensured that individual lines and components have adequate capacity to withstand cyclic loading [1]. Consideration is given to the extent that a mooring configuration and its various components is subject to fatigue concerns.

Corrosion is here understood in the context of a component that is deteriorating over time. Offshore standards require an allowance to be made for this in the design of a long-term mooring. The corrosion allowance increases the safety factor and is dependent on the intended inspection intervals and zone of mooring leg section, such as splash zone, catenary, bottom, etc. Since MECs may be in relatively shallow water the corrosion allowance may be considered to be constant with depth.

d.) Redundancy

Redundancy is here understood in the context of an additional allowance of the mooring configuration to provide adequate capacity to compensate for the failure of a mooring leg. The redundancy within a mooring layout is an important requirement in offshore standards typically demanding the survivability of a device in an accident limit state (ALS), where one line experienced failure in extreme conditions. Redundancy could be achieved with multiple legs that themselves could consist of a multiple line arrangement. The multiple leg/line arrangement would allow i) sharing loads and ii) maintain the structure on station after single leg/line failure.

e.) Installation requirements

The installation of a device will be a main cost source requiring the use of a special installation vessel for the installation of the mooring system and the device itself. Particular mooring configurations require specific anchor and mooring installation procedures that needs to be followed to offshore guidelines/recommendations. A major uncertainty in cost is the hire rate of the installation vessels; offshore anchor handling and installation barge costs can vary by an order of magnitude depending on the activity and demands of the offshore industry.

f.) Maintenance & Inspection

The operation cost will be based on the maintenance/inspection intervals of the mooring system. Particular mooring configuration with specific components requires maintenance and inspection intervals for a safe station keeping. The design of particular configurations should consider, where possible, the use of components with a low maintenance and inspection interval. The likelihood of marine growth (fouling) within a particular installation location will influence the inspection interval and a periodic cleaning of mooring legs might be required.

g.) Footprint area

Footprint requirements could be a major concern for WEC array installations, where multiply devices have to be located in a limited sea space to allow for optimum economics. The footprint area that is required by a device is dominated by its mooring configuration that has a seabed footprint itself and control’s the offset of a device at the surface. Whilst no figures are available to “value” sea area, nor for the most economical spreading of devices, it might be reasonable to argue that a dense installation would improve economic return since more energy can be harvest from an allocated area.

h.) Power Umbilical/Riser

Power umbilical/risers are required to transfer fluids or electricity/data from the WEC to the seabed. The allowable horizontal surge of a device has to be considered in relation to the bending properties of the umbilical/riser and how these contribute to the mooring design requirement. The stiffness characteristic and the dynamic response of an umbilical/riser, resulting from fluid loading and top-end motions, must be considered in the coupled motion of the moored WEC. The construction and material properties of an electrical umbilical are such it would both be prone to damage from large motions and also could contribute an affect to the dynamics of the entire system.

i.) Complexity of system/components

Any complexity introduced into a mooring system as a result of specific components or as a result of a specific configuration is often associated with a substantial cost increase in any marine application. The cost can arise from reduction in performance, an increase in failures and a greater need for inspection and replacement. As a result the complexity of a specific configuration needs to be identified, and consideration needs to be given as to whether a long term benefit would result.

j.) Novelty

The introduction of novel concepts introduces uncertainties to a design. Design uncertainties require typically higher safety factors that would be associated with increasing cost. A higher inspection frequency over a certain period would typically be required to obtain long term information of such novel designs. Novelty could arise from *either* the introduction of a new concept, or more likely the use of a conventional component in an untried function. In the long-term major cost reductions might only be achievable through innovation which often implies short-term increase in costs. Any introduction of novel mooring configurations or components would need to be shown to provide a long term benefit.

4.1 GENERIC ENGINEERING CONTEXT

Table 4.1 reflect the criteria for selection within a generic engineering context. The evaluation is based on the engineering aspects of the particular mooring configuration; the practical and theoretical design procedures, standard components, installation methods, etc. and how they can be implemented efficiently. A valuation scheme is used from 1 to 5, where the value 1 indicates the “worst” situation where engineering conventional design and practice cannot be applied in a simple manner; and the value 5 indicates the “best” situation, where the system can be understood and designed using conventional engineering knowledge implemented in a standard manner.

Table 4.1 inter-comparison of four generic mooring configuration – Generic engineering context

	Configuration 1 Catenary	Configuration 2 Catenary & Buoy	Configuration 3 Taut	Configuration 4 Taut & Buoy	Comment
Anchor requirements	5	5	1	1	A high value is placed on a configuration which can use standard and easily available anchors and installation methods. However, seabed constraints may have a strong influence.
Loading / Survivability	4	3	2	2	A system for which there is good theoretical and practical understanding of the requirements for load analysis is considered better. Added complexity will introduce uncertainties into design and numerical modelling. This also must consider the novelty of the application to MEC.
Fatigue / Corrosion	4	3	2	2	Taut arrangement would result in higher accumulated cyclic loading. Local dynamics due to spring buoy and/or clump weight could increase accumulated loading. Corrosion needs to be considered.
Redundancy	5	3	5	2	For configuration 1 and 3 simple engineering solutions for multiple leg/line arrangement can be implemented, allowing i) share loads and ii) maintain structure on station after single line failure. The complexity of configuration 2 and 4 makes the addition of multiple lines more complex.
Installation requirements	5	4	2	1	A high value is placed on a configuration which can use standard and easily available installation methods.
Maintenance & Inspection	4	2	4	2	Complexity of configuration would add to challenges for maintenance and inspection.
Footprint area requirements	1	2	5	3	The configuration that would provide the smaller overall footprint area is rated more highly.
Power Umbilical/Riser	2	3	5	3	A key aim is to minimise motion of the umbilical. Either through reduction in the top motion of device, or through motion restraining components.
Complexity of system / components	5	4	3	1	Complex configurations are rated less highly as increased complexity results in challenges (uncertainty) in numerical analysis, component choice, installation and maintenance.
Novelty	5	4	2	1	In a short term consideration novelty typically introduces engineering challenges and uncertainties. The valuation is based on the short term consideration ignoring possible long term benefits.
Total value	40	32	31	18	Maximum value for configuration: 50

4.2 COST IMPLICATION

Table 4.2 provides a “generic” rating for the contribution of the different elements to cost. No detailed cost analysis was performed and it should be remembered that certain costs can be subject to large variations depending on the particular project/timing. The valuation scheme is again from 1 to 5, where the value 1 indicates high costs; and the value 5 implies relatively low costs.

Table 4.2 inter-comparison of four generic mooring configuration – Cost implication

	Configuration 1 Catenary	Configuration 2 Catenary & Buoy	Configuration 3 Taut	Configuration 4 Taut & Buoy	Comment
Anchor requirements	5	5	1	1	Configuration 3 and 4 requires vertical load anchor that has cost implication due to specific installation needs.
Loading / Survivability	4	3	2	2	A system providing an efficient horizontal restoring force will have relatively lower costs to cope with peak loadings in extreme conditions.
Fatigue / Corrosion	4	3	2	2	Additional cost implications due to accumulated load aspects.
Redundancy	5	2	4	1	Additional cost implications due to specific redundancy arrangements, that increases design complexity.
Installation requirements	5	4	2	1	Additional cost implications due to specific installation requirements.
Maintenance & Inspection	3	2	4	3	Additional cost implications due to specific maintenance requirements.
Footprint area requirements	1	2	5	3	It is assumed that a smaller footprint area would provide cost benefits.
Power Umbilical/Riser	2	3	4	2	Additional cost implications due to specific umbilical/riser arrangements.
Complexity of system / components	5	3	2	1	Additional cost implications due to complexity of configuration and components.
Novelty	5	4	3	1	Additional costs due to uncertainty aspects in form of increased safety factors or required R&D.
Total value	39	31	29	17	Maximum value for configuration: 50

4.3 ARRAY INSTALLATION

4.3.1 General array installation considerations

(i) The acceptable size of surface and subsea footprint. This is absolutely key in determining the mooring configuration. Given "unlimited" space the choice would be for either a simple catenary or compliant system which will provide the most well understood and load accepting configurations. However the need to produce a particular density of machines will then have a strong influence on mooring requirements which could radically increase costs as higher load capacity is required in the legs for smaller footprints.

(ii) The loading criterion will affect the dimensions and arrangement of a mooring configuration and is fundamentally related to the site conditions (wave, current and wind) AND the device characteristics. For example, PELAMIS is designed to particularly "shed" the higher loads from extreme wave as a principle of operation. The mooring configuration will also be affected by any "directional" properties of the device that will produce particular directional loading states that has to be considered in the mooring design. The degree of redundancy must be considered carefully. Although there is not the same degree of health and safety concerns within a MEC array, the consequence for the array of a single device becoming detached could be serious.

(iii) A key cost reduction philosophy for array deployment would be to reduce the number of components/installation requirements as array number increases. The sharing of each anchor point to connect to several lines could be considered. This has advantages in minimising the number of installation points. It may also provide a reduction in overall loading on the anchor point. This arrangement would require a piled anchor connection and be more complex to install.

A second method of minimising sea bed attachments and anchors points might be to provide compliant (surface) connections between a number of devices in the array. This would have a high degree of novelty. There has been a large amount of analysis on two body, tanker-tanker or tanker-calm mooring analysis but the multi-body dynamics for multiple linked devices would be uncertain.

(iv) The response of the umbilical due to device motions is a key concern when designing the mooring. Methodologies that would allow "de-coupling" of the umbilical or, perhaps, shared umbilical arrangements could result in reduced costs for umbilical/mooring arrangements.

(v) Quick release connection/disconnection systems would reduce maintenance and servicing costs within a large array, but should be weighted against the general survivability/availability criterion.

4.3.2 Array system costs

This will depend on the allowable footprint but indicates the approximate magnitudes. In general as the allowable offset of the device is increased the total cost will decrease.

(i) chain and lines (50 -70% of costs) is the largest cost factor. Note cost of anchors is dependent on required holding power and weight and this is sensitive to subsurface geotechnical conditions. For example – sand is better than clay with cost of anchors being approximately 25% for clay deployment.
The capital cost of a driven pile is considerably less (around 40% of equivalent capability anchors) BUT installation costs for piles are much higher (vessels types time and spreads). For suction piles both the capital cost and installation cost increase.

(ii) connectors (shackles etc)

(iii) buoys and clump weights

4.3.3 Array installation costs

Cost of installation is heavily dependent on two factors:

(i) the need for specialist vessels
and
(ii) the time required to install.

These are both driven by the complexity of the system (e.g. system with wire rope, chain, synthetic fibre, mid line buoy, etc), the water depth and the available installation vessel. Furthermore consideration must be given to the installation of a single or multiple devices.

For single (small number of machines) all of the “standard” mooring methods could be appropriate. It is unlikely that for these numbers the footprint would be of great concern with regards the use of sea space. The prime consideration would be to ensure that the umbilical was adequately protected from undue motion and fatigue loading.

It is likely that the catenary with spring buoy would be most attractive. This is because of the better loading characteristics (though care is needed to consider the effects of the survival conditions of overly compliant systems). The major advantage would be in deployment of the device/maintenance of the device. The inclusion of a surface line has the following benefits, (i) greater ease of connecting during installation and disconnection for removal of the device; and (ii) failure of an individual line is relatively simple to repair (a failure of a simple catenary would imply recovery of the end from the sea bed).

For larger arrays (multiple devices systematically arranged) the use of sea space becomes more important and the footprint of both the device and the seabed spread has to be included in the mooring design that will effects installation methodology.

- Pure catenary would require larger sea space. Installation would well understood and so installation costs might be expected to be least for a pure catenary.
- Catenray & spring buoy would reduce the footprint somewhat but add to the complexity of the mooring. For a large array this could be very expensive in terms of time of installation and maintenance. Note that a decrease in the footprint will generally lead to an increase of costs through the requirement for higher load bearing capacity of the chain/wire. Installation costs would be higher due to the greater complexity requiring more specialist handling and installation equipment. The multiplicative factor of a large array will make this more important.
- It is for this case that the tension leg mooring might have a long-term benefit. It could provide the ability to minimise footprint whilst providing enough compliancy to minimise static loading. The main barrier to this in terms of cost would be the need to provide vertical hold anchors. This would imply specialist (DP) vessels and so installation costs and uncertainty high. This may also provide a design solution for floating tidal turbines for deeper waters. The use of more compliant moorings (and resulting motions) may have highly adverse effects on the efficiency of floating tidal devices.

4.3.4 Overall economic considerations of array installations

For the installation of multiple devices in an array layout the choice of a mooring configuration may not be based necessarily purely on the capital, installation and operation costs to account for the overall economics of the array. Economic factors must consider the wave energy available and the extent to which this can be harvested. A wider spread for the same devices will reduce the number that can be installed in a given area. To achieve an economical arrangement that is profitable, devices may have to be more closely packed, demanding specific mooring configurations. (A devices that generates high power per m^2 of sea surface area may typically have a larger mooring spread. Alternatively a device which produces less power per m^2 must be “packed” more closely.) There may be no straight forward “generic” assumption that can be made as to how closely devices may situated, requiring a detailed understanding of the design capacity of each specific device.

5 DISCUSSION

The generic configurations chosen in this article do not provide a specific solution to any given project, but can be used as an methodology to decide on the “best” solution and to identify the aspects of mooring that contribute to costs of that solution. The evaluation approach introduced in section 4 is therefore a generic tool that may be used for the evaluation of a specific installation. It is also the case that the categories chosen could be different. It might also be useful to apply a weighting to each category to further refine the final scores. For example the requirements for a “tight” footprint may or may not be important on a case by case basis. A proposed weighting for some of the major elements is given below:

Design aspect	value
Loading/Survivability, Installation requirements, Maintenance & Inspection	5
Anchor requirements, Fatigue/Corrosion, Redundancy,	4
Footprint area requirements, Complexity of system/components	3
Power Umbilical/Riser	2
Novelty	1

At this stage it is very difficult to apply the evaluation approach to identify a suitable array arrangement of the generic four configurations. But the design aspects can be used to draw some general conclusions and also raise questions regarding the design concerns of moorings in an array arrangement. Survivability and economical aspects need to be considered carefully and with an equal weighing of their importance.

6 CONCLUSIONS

The fundamental requirement of a mooring configuration is to ensure safe station keeping. However it also forms a key element in the uncertainty of costs for a marine installation. The mooring design has an influence not only towards the capital, installation and operation cost, but has an influence also to the overall economics. In order to perform a realistic evaluation the mooring system has to be considered in its entire complexity, considering not only device, location and the possibility of array arrangement, but also that the generic design considerations (safe station keeping, maximum power conversion, safety and risk to other sea user, low inspection/maintenance and downtime, cost efficiency) are satisfied.

7 REFERENCES

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