

Engineering assessment report

DRAFT: V0.1

THE SEASTEADING INSTITUTE

Author: Eelco Hoogendoorn

Acknowledgement: Miguel Lamas Pardo, Bart Kemper, Alexia Aubault

NOTE: This is a first draft of this report. It is being publically released for community feedback. Due to still being in a state of considerable flux and expected changes due to feedback, polishing is not yet high on the agenda. Please send any feedback you might have regarding content to eng@seasteading.org.

Preface:

This document is a high-level analysis of the engineering challenges involved in homesteading the high seas. The aim is not to provide a detailed design of a specific seastead, but rather to find answers to general questions, such as the cost per unit area of functional real estate.

There are many different ways to enable living on the oceans, from oil platforms to cruise ships, to untried concepts. The goal of this document is to facilitate the identification of a promising candidate concept that best meets TSI's criteria. In a way, living on the water is a solved problem: houseboats offer floating real estate at a cost indistinguishable from that on land, and cruise ships provide luxurious accommodations on the open ocean. However, the former do not function outside of protected waters, and the latter are expensive. Consideration of cost are of paramount importance, and the problem can be stated as identifying the sweet-spot of the relation between cost and functionality.

The main types of ocean going structures can be classified as ships, semi-submersibles and spar platforms. This classification is not perfect: some concepts are best regarded as falling somewhere in between these archetypes. Some concepts fall outside this classification, and will be treated separately.

The problem of selecting a good strategy involves a wide spectrum of considerations, including political, oceanographic and personal preference. Many parameters still contain significant uncertainty, and definite conclusions can not be reached on all fronts. Regardless, the goal is to uncover as much relevant information as is possible. To this end, a wide variety of designs will be evaluated with regard to the key criteria, in the context of a set of likely scenarios.

This paper is split in two parts; a section where the assumptions made and methodology used are described, and a section where specific designs will be analyzed using this framework.

Preface:

Part 1:

1. General
 - 1.1. Innovation
 - 1.2. Scale
 - 1.3. Materials
2. Oceanography:
 - 2.1. Locations
 - 2.1.1. International waters (DP)
 - 2.1.2. EEZ (moored)
 - 2.1.3. Free-floating
 - 2.1.4. Territorial waters / Bay
 - 2.2. Recommended oceanography
3. Mobility
 - 3.1. Introduction
 - 3.2. Degrees of mobility
 - 3.3. Station keeping
 - 3.3.1. Anchoring
 - 3.3.2. Dynamic positioning
 - 3.4. Energy cost
 - 3.5. ClubStead review
 - 3.6. Force calculations
 - 3.6.1. Drag
 - 3.6.2. Wave drift
 - 3.6.3. Interaction effects
4. Waves (under complete revision due to recent feedback)
5. Physical principles
 - 5.1. Size
 - 5.1.1. Ship
 - 5.1.2. Island
 - 5.2. Depth
 - 5.2.1. Sub
 - 5.2.2. Semi-sub
 - 5.2.3. Spar
6. Comfort
 - 6.1. Motion sickness
 - 6.2. Methodology
 - 6.3. ClubStead metocean
 - 6.4. Example
7. Modularity

7.1.

8. Criteria

8.1. Capital costs

8.2. Mobility costs

8.3. Maintenance costs

8.4. Scale

8.5. Safety

8.6. Comfort

8.7. Modularity

Part 2:

9. Candidates

9.1. Spars

9.1.1. Classic spar

9.1.2. Flip

9.1.3. Short spar

9.2. Semi-sub

9.2.1. Classic semi

9.2.2. ClubStead

9.2.3. MiniFloat

9.3. Ship-shaped

9.3.1. Small boats

9.3.2. Mono hull ship

9.3.3. Multi hull ship

9.3.4. Barge (concrete)

9.4. VLFS

9.4.1. PSP/indirect displacement

9.4.2. VersaBuoy

9.4.3. Seadrome

9.5. Misc

9.5.1. Submerged

9.5.2. Breakwater

10. Scenarios

10.1. Boat in international waters

10.2. MiniFloat in EEZ

10.3. Etc

11. Conclusions & recommendations

General:

The purpose of this section is to establish some basic observations, assumptions and common terminology.

This document contains some terminology and names not in common usage; below is a short list of recurring terminology.

- **ClubStead:** A lot of data and information in this document is drawn from TSI's ClubStead design. Clubstead is a floating platform of semi-submersible type, designed with the explicit goal of seasteading in mind. The report of the ClubStead design can be found on TSI's website, and is frequently referred to in this paper.
- **MiniFloat:** MiniFloat is another design by the company that designed ClubStead, MI&T. It is another of semi-submersible type; more information can be found on MI&T's website.

[suggestion welcome]

Innovation:

Existing structures that enable living on the ocean are not built with the explicit purpose of living on the ocean as a goal in itself, with the exception of (The world of) Residensea. Most living on the ocean that happens today is a means to the ends of transportation or resource extraction.

Given the fact that Seasteading presents a specific and novel set of goals, the approach of taking existing conceptual designs and retrofitting them for Seasteading may be missing out on opportunities for achieving a more effective design.

This observation should be balanced against the fact that innovation is expensive, and the resource of TSI are limited. Only if a concept is identified that promises to significantly outperform either an adapted boat or adapted platform should such an innovative strategy be pursued. Additionally, candidates serving different goals may be identified, such as a solution for the long term and a solution for the short term.

Scale:

The overall scale of a seastead concept influences many aspects of Seasteading; among which are financial, engineering and societal aspects.

- **Financial:** The most direct aspect in which scale manifests itself is financial. All proven concepts for living out on the ocean, from oil platforms to cruise ships, are large scale structures. This manifests itself in price tags of a hundred million dollars and upwards. This kind of money clashes quite strongly with the notion of small incremental steps. Ideally, a seastead would be able to scale down all the way to the size of a single autonomous house. Although this seems unlikely to be accomplished, this is not an all or nothing situation, and trying to approach this ideal as close as possible is worthwhile.
- **Engineering:** Big structures with a reasonable price per unit floor area are known to exist, but a smaller version of such a concept would be preferable. However, typically, the size of a concept

is a feature of its design. Scaling down a cruise ship yields a small boat. Small boats are only comfortable in calm seas. Scaling down a spar that extends far into the water undisturbed by waves yields a structure that has the bulk of its presence right in the middle of the wave action. In general, smaller structures are more responsive to wave motion, and big structures are more expensive, both of which are undesirable. The goal is to find a design that best unifies these conflicting demands.

- **Societal:** Dynamic geography (DG) rests on the premise of being able to move real-estate around with little effort. If a house/apartment is locked into a big vessel with many other apartments, its physical location relative to its direct neighbors is fixed. Dynamic geography on the scale of the vessel itself is still possible, but ideally, DG would be enabled on as fine-grained a scale as possible.

Aside from the increased difficulty of funding a large structure, it has societal implications as well. Who will finance the investment, and what will the position of the investor be within this community? This is perfectly compatible with some models of anarcho-capitalism, but essentially rules out bottom-up grassroots community building.

In conclusion, there are compelling reasons to aim for a small scale incremental seastead design; it is more likely to get off the ground, and it enables more socio-political options. On the other hand, it increases the engineering difficulty.

Materials:

As a construction material for the hull, essentially two candidates exist: concrete and steel. These are the materials with a cost per unit strength ratio unrivalled by any other options on the market today. For instance, contrary to popular belief, plastic is not cheap; it is merely cheap to process where small parts are concerned. Especially its cost per unit strength is not at all attractive.

The prevailing construction material in the offshore industry is steel. Concrete is used for some offshore platforms, primarily ones placed on the ocean floor. Some concrete ships have been built in the past, but the practice has not caught on.

The fact that concrete is not in favor with the shipbuilding industry today does not mean it will not be the most appropriate material for seasteading. The additional displacement and associated fuel costs have been found to be prohibitive for shipping in the past, but a concrete ship/barge will still rank next after steel ships, and outperform all other seastead concepts in this regard. The loss of mobility relative to a steel hull may well be outweighed by the advantages offered by concrete, given that shipping and seasteading have very different priorities.

Given the higher yield strength of steel over concrete, supporting a given load requires far more concrete than steel. Even though concrete has a lower density, this translates into heavier components, by about a factor 2-3 for standard concrete. Concepts which are already presenting difficulty due to the magnitude of their total displacement, such as spars, would likely better be built from steel, or may perhaps only be effectively realizable in steel. The estimated cost per unit strength of concrete appears

to be somewhat lower, but not by a large amount. The near absence of maintenance costs for properly constructed concrete, is however a strong argument in its favor.

Tensioned concrete, even though it superficially resembles reinforced concrete, should be regarded as a separate material. It consists of reinforced concrete with tensioned steel tendons. This results in a material with much improved strength in tension. In tensioned concrete, the tensioning steel is effectively carrying all the loads, and the concrete fills the role mainly of corrosion protection and a non-thermal bond between the steel. Due to the fact that the tendons need not be welded, but are embedded in the concrete, a much higher strength steel can be employed: the yield strength of these tendons are a factor 8 higher than that of typical plate steel. All existing concrete floating offshore structures are built using tensioned concrete.

Cylindrical constructions which are loaded by a dominant compression force, such as spars or submarines, could be constructed out of reinforced concrete; elongated structures such as ships/barges, that may experience large net tension forces, can only be effectively realized out of tensioned concrete.

With regard to corrosion control of steel, it should be noted that nearly all marine structures in existence today are either ships, undergoing regular drydocking, or oil&gas platforms, being designed for short (20-25year) service lives [2], which is of questionable compatibility with the expectations people have of real estate. Ships are scheduled for extensive drydocking at least every five years. Maintaining offshore steel beyond 25 years without drydocking seems like experimental territory, for which no cost indications have been found. Betting on these methods being economically available seems imprudent.

The novelty introduced by the use of concrete is minor; projects of various kinds have been realized in concrete before, and they have had neither technical problems, nor problems obtaining approval by a classification society or securing insurance. Nonetheless, working in concrete will be far less convenient than working in steel: there is no continuous fluid offshore concrete industry like there is for steel. The need for large temporary docks, and a large temporary workforce, complicate comparisons with steel construction [7].

Some numerical properties:

Steel:

- Cost: 5000\$ per ton end of yard cost for simple/routine project [ClubStead report], up to 12.000\$ per mt estimate seen used [6].
- Yield strength:
 - 200MPa (typical shipyard steel)
 - 320MPa (high yield shipyard steel)
- Density: 7800kg/m³
- High maintenance costs due to corrosion and fatigue. Typical guaranteed lifespan of non-docking offshore structure is 25 years.

Reinforced Concrete:

- Cost (material+rebar+labor):

- Gravity Dams built in north America: 200-400\$ per m3. Large volume, simple geometry: Low end estimate. [ref]
- Float inc: 361\$ per cu-yrd 1999, 612\$/m3 2009 (claimed, not demonstrated). [ref]
- Concretesubs: 330\$ per ton displacement, or ~1000\$/m3 demonstrated. Low labor cost, but high complexity geometry. [ref]
- Post tensioned concrete bridge construction: 1700\$/m3 [5]
- Summarizing: no clearly interpretable figures for actual offshore concrete have been found, but 1000\$ per cubic meter seems like a reasonable estimate for large scale in-dock construction.
- Yield strength (compression)
 - 20-25MPa typical
 - 50-80MPa high grade [1]
- Density: 2700kg/m3 typical. Alternatively: 1900kg/m3 @70MPa described in [4]. May be a good candidate for concrete spar.
- No maintenance, and very long life if rebar is properly protected (up to 200 years claimed).

Tensioning tendons:

- Yield strength: 1800MPa [1]
- Cost: not dominant relative to other materials and labor [5]

[1] <http://www.abam.com/uploadedfiles/tp-World'sLargestPrestressedLPGVessel.pdf>

[2] <http://www.stoprust.com/7cpforfpsos.htm>

[3] <http://www.logicsphere.com/products/firstmix/hlp/html/stre2i04.htm>

[4] http://books.google.com/books?id=1OwkUrXuhjQC&pg=PT549&lpg=PT549&dq=Elf+Congo's+Nkossa+barge&source=bl&ots=CKsOOarsZz&sig=269anRh72x7yZgLRvE0cQp72tY&hl=en&ei=Bl8bS7WKllaasgPqkMz8BA&sa=X&oi=book_result&ct=result&resnum=5&ved=0CBwQ6AEwBA#v=onepage&q=&f=false

[5] <http://www.dot.state.fl.us/Structures/StructuresManual/CurrentRelease/DesignGuidelines/SDG9.1General.htm>

[6] http://www.isodc.com/1st_ISODC07_TexasA&M_Team_3_SemiSub_for_Malaysia.pdf

[7] Offshore Structures – A new challenge: How can the experience from the marine concrete industry be utilized

Oceanography:

There are still many unknowns to the input of any engineering design, both political and environmental in nature. These options are simplified into several location scenarios, consisting of a set of assumptions and their consequences. The key properties considered here are distance to land, which is very important both in terms of political climate and bootstrapping a community/economy, the peculiarities of station keeping, and the most significant environmental variable, the worst case wave conditions.

International waters (dynamic positioning):

The best option in terms of political independence is residing in international waters. International waters are found 200+ nautical miles away from coastal states.

- Location: 200+ miles from land.
- Water depth: Due to the legal definition of the continental shelf, international shallow waters are likely rare, and thus unlikely to coincide with other criteria for a good location.
- Station keeping: Mooring is not an option (due to anchoring/modularity conflict in deep waters), thus dynamic positioning is a necessity.
- Waves: Waves may get big; 200nm fetch is enough to produce large waves, so even the landward side need not be safe. The metocean data from the ClubStead report describes a 100 year storm with $H_s=8.3\text{m}$. Further searches suggest that these are indeed relatively calm waters in international waters; more benign locations have not been identified.

Distance:

The 200nm limit does not apply to all locations; if the continental shelf extends beyond these 200nm, and the same legal claims are extended there, up to a 350nm limit. However, it is presumed that suitable locations are available where the continental shelf does not extend beyond the EEZ.

The distance from land is a significant obstacle in this scenario. Travel to land will take around ten hours by boat. This presents a barrier to entry for seasteading, as presumably few people would be willing to live in a small community if it were isolated to this degree.

Depth:

The EEZ was originally defined as all waters within 200nm from land. The area known as the continental shelf carries the same claims regarding economic activity and permanent installations. Since the continental shelf is effectively defined as 'all shallow waters adjacent to the EEZ' (the definition is very complex, but this is what it boils down to for seasteading purposes), it seems as if politically free shallow waters are rare. An exception would be seamounts not piercing the water surface, not being within 200nm of any land. NB: A region of shallow international waters near Mauritius has been identified. It is currently being scrutinized more closely; its potential implications are not yet accounted for in this version of the document.

Note that there is a difference between the geological definition of the continental shelf, which includes a 100-200m water depth definition [1] and the legal definition [2]: The latter is more expansive, and allows claims up to 2500m of depth.

[1] http://en.wikipedia.org/wiki/Continental_shelf#Geographical_distribution

2[] http://www.un.org/Depts/los/clcs_new/continental_shelf_description.htm

Mooring:

The water depth encountered in this scenario will be too large to effectively moor. Even though mooring costs are small relative to structural costs even in waters as deep as ~2km [MiniFloat documentation], mooring fails the modularity requirement in this scenario. Catenary lines allow for significant movement within some range of up to hundreds of meters *"The typical, watch circle is 80-200m when FLIP is tri-moored in 4 km water"*. [FLIP documentation]

Further, the footprint of catenary mooring lines has a radius of about twice the water depth. This implies that a reasonably dense formation of seasteads cannot be formed by means of mooring, as crossing mooring lines do not seem feasible given the way they are installed (dropping and/or dragging the anchor with the cable pre-attached).

A connected cluster of seasteads might choose to share a single anchoring point between many seasteads, thus obtaining a significant density. This would however require some nontrivial innovation. Connecting seasteads in a relative-position fixing manner is a hard problem in open waters; if not an unsolvable problem for many concepts, as discussed in the modularity section.

Waves:

ClubStead conditions are measured a hundred miles off the coast of San Diego; because there are no geographic features suggesting otherwise, they are presumed to be comparable 200 miles off the coast.

EEZ (moored)

The basic premise behind this scenario is that residing in the EEZ is acceptable, either due to a favorable legal interpretation, a contract with a host nation, or (temporary) concessions from the side of the seasteader. If a seastead is a positive influence on its surroundings, jurisdictional arbitrage can be leveraged.

- Location: 12 (24)+ miles away from shore
- Depth: Water depths of any choice assumed to be available
- Station keeping: Mooring is both affordable and does not suffer from modularity conflicts; units can be moored close together. Note: by mooring, a professionally deployed (semi)permanent system is meant, as opposed to anchoring. Anchoring systems can not be relied upon to hold vessels in close proximity during storms, and would pose a risk of collision damage. Dynamic positioning may still be preferable in locations with low external forcing.
- Waves can still become big in most parts of the EEZ, but by appropriate choice of location, on the leeward side of the prevailing winds of land masses for instance, locations outside territorial waters can be found having a significant wave height not exceeding $H_s=3-4$.

This scenario both increases and decreases the need for mobility. Due to the possibility of anchoring without any complications, mobility requirements are less of a concern with respect to currents; locations with significant currents would be feasible in terms of operating costs. On the other hand, due to residing in legally troubled waters, having the option to move over long distances if the political climate turns around is a necessity. It is hard to travel large (1000+km) distances without encountering significant currents. Crossing a current of a few knots will require the ability to move with at least this speed; it is not clear that this is feasible for all concepts.

Example EEZ locations:

Mediterranean:

International waters do not exist in the Mediterranean, as there are no points further than 200nm from land. In general, worst case wave conditions in the Mediterranean need not be an improvement over ClubStead conditions, a maximum $H_s=8-9$ can be found in many places.

Favorable exceptions are found on the leeward side of land-masses. An example of such a location might be off the east coast of Malta [1], where a maximum $H_s=3-4$ is found. However, this location is arguably lacking in proximity to a population hub and economic activity.

The Hadrianic sea has more nearby cities, and waves up to $H_s=5.5$ [2] under rare circumstances.

[1] <http://www.capemalta.net/maria/pages/level1/>

[2] <http://www.map.meteoswiss.ch/map-doc/icam2005/pdf/poster-sesion-b/B08.pdf>

Baltic sea:

For the Baltic as a whole, the worst case scenario of $H_s=7$ [1] is again not a large improvement over the ClubStead 100y storm.

The gulf of Finland, offers a combination of moderate waves (max $H_s=5.5$ [3]), nearby cities and a warm political climate. However, the actual climate is less ideal; the northern half of the Baltic can get covered by ice up to half a meter thick [2]. If this ice is moving in any way, as it will, this seems like an unmanageable complication for any moored structure. For a vessel with dynamic positioning, this might however not be a significant technical problem, although perhaps a logistical one.

[1] http://www.coastalwiki.org/coastalwiki/Using_satellite_data_for_global_wave_forecasts

[2] http://www.fimr.fi/en/tietoa/jaa/jaatalvi/en_GB/2003/_print/

[3] http://www.fimr.fi/en/tietoa/veden_liikkeet/en_GB/aaltoennatyksia/

South China Sea:

Conditions as found in [1] are fairly benign, with a hundred year storm of $H_s=6.5$ meter, with insignificant swell. Little else is known about the desirability of this location, and the political climate is questionable, but it stands to reason these island regions offer many relatively sheltered locations.

[1] http://www.isodc.com/1st_ISODC07_TexasA&M_Team_3_SemiSub_for_Malaysia.pdf

Free-floating:

Another scenario that has been considered, is the free-floating scenario, where a seastead is neither anchored, nor makes a (significant) effort to influence its heading. Arbitrarily drifting over the entire globe is not deemed an acceptable strategy. Instead, the idea is to find a geographic location having no net drifting forces.

However, any such gyre scenario will nearly invariably take one far from shore most of the time, which clashes with the desire to operate as close as possible to population centers.

One interesting scenario proposed by Vince Cate is following the Gyre in the Sargasso sea. His research suggests that the period of going once around this gyre is nearly one year, so with only minimal external forcing, a yearly migratory pattern could be established. This migration could be chosen such as to avoid both northern winter storms, and the southern hurricane season. A detailed analysis of the minimum worst case Hs thus attainable has not been performed, but it seems plausible a substantial improvement could be achieved. This specific proposal has come to our attention too late to be incorporated in this document, but it certainly warrants future investigation.

Bay/territorial:

- Location: all the way up to shore
- Depth: severely constrained. For instance, the SF bay might not even offer 20m, excluding shipping lanes. This rules out spar concepts.
- Station keeping: trivial; no significant currents, and easy anchoring.
- Waves: trivial

Inside territorial waters, no amount of political autonomy is expected. In many places, even temporarily residing there will be heavily regulated, even without any political aspirations. Therefore, a design that merely works in these conditions is not a valid candidate. However, if a design does work in these conditions, it is a definite plus, as it would facilitate bootstrapping. For instance, most ships would work inside a bay, whereas a spar would be too deep for any bay which has been investigated.

Recommended oceanography:

This section lists some questions in oceanography that are deemed to have priority as far as their relevance to future engineering decisions are concerned.

- **EEZ wave/metocean data:** Operation inside the EEZ may be politically feasible. Yet finding such locations actually beating ClubStead metocean is not easy. Locations with maximum Hs of 3-4 meters have been identified, but they are not the norm. Can we find locations combining consistent low waves and other desirable criteria? Multiple such locations in relative proximity (f.i, within the Mediterranean) would be ideal, as it would allow for jurisdictional arbitrage.

- **Current strength:** some concepts, most notably spars, are very sensitive to current strength. Publically available data does not give a very good impression of what to expect. The data found is either instantaneous, or a long term average, neither of which carry enough information. Having a time-series for a single location would be most informative. Identifying locations with a minimum average current, and obtaining an impression of what can reasonably be expected would be highly useful. The 1-knot scenario wielded now may be prohibitively conservative. If this could be lowered by a factor two, required fuel consumption would drop by an order of magnitude (there is a limit to this fast decrease however; at this point, other forcings would start to dominate)
- **Gyre scenario:** the free floating gyre scenario has not made it into this version of the document, but if a more detailed study shows significantly improved worst case storm conditions, the disadvantages of residing far from any economic activity most of the time may well be outweighed.
- **Wave directionality:** elongated shapes such as ships and barges, are sensitive in their operation to the amount of spread in the wave directionality. Especially cross-seas, with waves generated in two different wind systems, are noted as a hazard to ships. Such sea-states are likely to interfere with concepts that depend on their orientation towards the waves for operation. For instance, ClubStead metocean indicates a 100deg angle between predominant swell and wind directions. Information of the magnitude of wave and swell components individually would be useful; perhaps one of the components is significantly smaller. Closer to land, such as in the gulf of Finland, unidirectionality is expected. Due to proximity to land, it is expected many EEZ waters will display this characteristic, but identification of international waters having rather consistently unidirectional seas would be very desirable.

Mobility:

Introduction:

This chapter explores various facets of mobility as related to a seastead. Mobility is to be interpreted broadly; the analysis of moving by engine, or station keeping by anchor.

Political importance:

Mobility has an important political aspect. Even though the sovereign powers of a nation technically do not extend beyond their territorial waters, permanent installations in the EEZ are regulated with regard to most aspects. All vessels have right of free passage. What exactly distinguishes free passage and permanent installations is unclear, but a permanently anchored structure probably does not qualify as passage. Whether a non-anchored loitering vessel would, is not clear.

If loitering would provide freedom from EEZ restrictions, this would be a very strong argument against anchoring. If it does not, then two options remain: operation near territorial waters, where anchoring will be cheap, or operation outside the EEZ, where anchoring will be irreconcilable with other requirements, and dynamic positioning will be required.

Engineering importance:

When designing a stationary platform for a given location, the problem is not coping with the everyday conditions, but with the extreme states. This is unfortunate, since there is no such thing as a guaranteed maximum waveheight. The design will have to be dimensioned to accommodate the long tail of worst case possible events.

On the other hand, a seastead with sufficient mobility is capable of moving away from, or outrunning storms. How much mobility is required depends on many factors, such as the extent and speed of the storm, and the proximity of sheltered locations. However, there is a clear division between seastead capable of utilizing this ability, and those unable; only ship-shaped seasteams will be able to attain the required velocity.

Degrees of mobility:

We can distinguish several degrees of mobility:

- Fully migratory: a seastead mobile enough to be able to continuously move at considerable (several knot) speeds, without incurring a prohibitive cost. It is not obvious that any concept meets this criterion: even for ships, the associated costs will be substantial.
- Occasionally migratory: moving over long distances would be affordable once in a while, but not on a permanent basis. This should be affordable to ship-type constructions.
- Station keeping: a seastead that is capable of maintaining a fixed position in spite of environmental forcing.
- Lazy station keeping: a seastead that is capable of maintaining its position in a time averaged sense. Large storms may push it away from its neutral position, but it will be capable of maintaining a constant political/natural climate.

- Free floating: no propulsion at all. This approach is not considered in the present paper due to its limitations, and the legal/practical uncertainties associated with this mode of operation.

Concepts are required to at the very least be capable of lazy station keeping. But beyond this, it is not immediately obvious what degree of mobility is desirable. Seasteads capable of merely lazy station keeping would require a thorough answer to the question of how to avoid collisions between them, as the external forcing need not be uniform among seasteads.

Relative to a ship, mobility is an obvious factor to economize on, since moving around is not the core business of seasteaders. However, designing for a high degree of mobility does offer advantages, even if the possibility is not used often, for the political and engineering reasons mentioned above.

Dynamic geography (DG):

All dynamic geography requires a degree of mobility. We can distinguish two classes of dynamic geography.

- Internal DG: repositioning relative to other Seasteads. This merely requires the ability to move small distances at low velocities. All seastead concepts, with the exception of those whose functioning depends on contact with solid ground (towers, tension leg platforms, which are therefore not considered here) will be capable of this type of movement.
- External DG: repositioning relative to other nations / environmental condition. If the political attitude of the nation whose sphere of influence a seastead resides in becomes hostile, the ability to move over long distances would be desirable. The economics of such an operation are non-trivial; not all concepts are expected to be able to meet this criterion economically.

Station keeping:

As noted above, all seastead concepts should be capable at least lazy station keeping. While one of the attractive features of floating real estate is that moving it is far cheaper than moving real estate on land, the flipside is that most of the time, one does not want real estate to move, yet if kept unchecked on the ocean, it will.

Station keeping can be accomplished in essentially two ways: Mooring or dynamic positioning.

Mooring:

By mooring, (semi)permanent non-retractable anchoring system is meant; retractable systems do not offer the desired reliability: they would not hold during storms.

The only concrete cost data located so far is in the MiniFloat technical documentation. Material costs for mooring a 1600st structure are estimated at 1M\$, 4M\$ for a 5500st structure [4]. This amounts to roughly 1/4th of the cost of materials and construction of the hull, which is a non-dominant cost. This is for a large water depth of ~2km.

However, as argued in the section on modularity, deepwater mooring is considered to conflict with modularity. Hence, anchoring is only considered in shallow waters. When constrained to shallow waters, anchoring is certainly the cheapest option, although this cost advantage will have to be weighed against the advantages offered by a higher degree of mobility.

Dynamic positioning (DP):

Alternatively, a structure can be kept in position by means of a dynamic positioning system, consisting of a multitude of computer coordinated thrusters, capable of holding the seastead in place. This will work regardless of water depth, and will allow for a lazy station keeping option, unlike a mooring system.

However, such a system will demand a continuous energy input, depending on the external forcing

The net current, wind and wave loads will be modeled by a continuous 1 knot equivalent current (modeling the effects of current, wind and waves: time averaged, the effect of currents will dominate). There are definitely locations where this is overly optimistic, such as in the middle of oceanic currents, and some where this is overly pessimistic, such as in the center of a gyre. The former can be avoided, but it is not clear that the latter are situated in any otherwise suitable locations. Given the many constraints on geographical location, it seems imprudent that an optimally still location is available, but less than one knot on average should certainly be possible.

The ClubStead metocean data notes the current speed during the 1-year storm as roughly one knot, so the current will hardly ever exceed one knot. These currents are all assumed to be wind-driven, so during less wind, as is typically experienced, the currents will be proportionally less too. This does not account for any global current, nor other external forcings. For the ClubStead mobility scenario, a 2-knot countercurrent is assumed. No motivation is given.

[1] <http://oceancurrents.rsmas.miami.edu/>

[2] http://seacoos.org/Data%20Access%20and%20Mapping/Currents_product_desc/

[3] <http://sampit.geol.sc.edu/Wera%20maps.html>

[4] MINIFLOAT: A Novel Concept of Minimal Floating Platform for Marginal Field Development, p540

Cost of energy:

In order to estimate the cost of mobility in dollars, in this paragraph, an estimate of the cost of energy on the sea is made.

- The cost of marine diesel is estimated at \$4/gal [2]
- Diesel weights 7.15lb/gal
- One short ton equals 2000 pounds
- Thus, the cost of marine diesel is: $4 * 2000 / 7.15 \approx \$1200/\text{st}$
- One st of diesel equals 5MWh of electric energy, if run through a generator (ClubStead report)

Estimated cost of a diesel generated kwh: \$1200 per st of diesel, equals 5MWh, or \$0.24 per kWh.

The average cost of electricity from the grid: \$0.10/kWh [1]

Therefore, electricity comes at a premium on the sea: accounting for some variability in fuel costs, it is safe to say it is three times as expensive as on land.

Propellers can be very efficient in optimal conditions (~90%), but due to the low velocities under consideration, efficiency will likely suffer. For the Electric-to-fluid conversion, a 60% efficiency is assumed, which is on the low end of non-cavitating propellers, which seems appropriate in this regime.

[1] http://tonto.eia.doe.gov/energyexplained/index.cfm?page=electricity_factors_affecting_prices

[2] <http://www.psmfc.org/efin/data/fuel.html#Data>

ClubStead review:

The ClubStead report contains some calculations with regard to mobility. They will be reviewed here, to provide some clarification, and to establish a reference point to compare other designs with.

- ClubStead mobility scenario: 2 knot movement against a 2 knot current 25% of time, for a 4 knot velocity relative to the water.
- Outcome: propulsion OPEX 1700st of fuel per year, or roughly twice the expected utility OPEX of 750st per year

This level of mobility does not provide much beyond station-keeping ability. Infact, if the 2-knot current acts all the time in roughly the same direction, moving at 4 knots 25% of the time does not even suffice to maintain position. However, the origin of this 2 knot current is unclear, and inconsistent with the one knot maximum current derived in the metocean section of the ClubStead report.

The utility OPEX is derived as the total American national electricity consumption divided by its population. However, this is a much higher number than merely domestic electricity consumption, which is arguably the more relevant number.

Going by the figures in [1], the American *per household* consumption should be slightly *lower* than the American *per person* consumption used in the ClubStead report. At 2.6 people per American household, the relative comparison of the mobility costs and utility costs in the ClubStead report is off by roughly a factor three, if utility OPEX is interpreted as stated above.

The propulsion cost estimate contained some mistakes; after some discussion, these have been corrected. After these corrections, and accounting for propeller inefficiencies, a fuel consumption of some 4500st of fuel per year is arrived at: almost a factor three higher than the original figure. Using the utility consumption estimate lowered by a factor three, and increasing propulsion consumption by a factor three, the gap between the two is suddenly a worrisome factor 20. Given that as established above, off-grid energy is not cheap to begin with, this is reason for concern.

Translated to dollars, a figure of \$1600 per person per month in propulsion cost alone is obtained, assuming full occupancy. This might be acceptable for a high cash flow operation, such as a casino, but for residential applications, this is almost certainly prohibitive.

When subjected to the continuous 1 knot current scenario, the fuel costs per person per month would be \$100. This is an acceptable figure, but not without risk: it assumes full occupancy, and current fuel prices, neither of which are guaranteed. For a household of several people, it is still very conceivable that mere station keeping costs might become prohibitive. On the other hand, the 1-knot current scenario might well be pessimistic; establishing narrower bounds on the current scenario is worthwhile. Further, it should be emphasized that ClubStead is not optimized for mobility; these results need not be representative for semi-subs as a whole, and could conceivably be much improved upon (although not within the ClubStead paradigm of separate columns without a continuous underwater pontoon; a semi-sub with a streamlined underwater pontoon would be required, as is common in semi-subs with propulsion).

Either way, these figures established a reference point to draw comparisons with. The station keeping costs of ClubStead are borderline acceptable in the context of the 1-knot current; an order of magnitude higher would clearly not be, an order of magnitude lower clearly would.

[1]

http://wiki.answers.com/Q/How_much_electricity_does_the_average_American_household_use

[reference scripts with detailed calculations: put in appendix?]

Force calculations:

Exactly predicting the force on a moving or stationary body is very complicated, but a simplified model will suffice for the purpose of performing a feasibility study.

Only low speeds relative to the water will be considered. The external force components are due to current, waves and wind. For the present analysis, only a single seastead will be considered, and possible interaction effects will be ignored.

By wave forces, second order wave drift forces are meant: the net time average force caused by a wave, as this is relevant for station keeping and mobility, whereas the cyclical component is relevant for comfort and structural integrity considerations only.

Wind forces are found to be small relative to these other forcings for high-drag structures such as semi-subs; they can be significant for a more hydrodynamic ship-like design (wind is noted as up to 50% of resistance for big container ships), but their mobility costs are better estimated from available empirical data, if desired, rather than from ab-initio methods.

Drag force:

Drag forces can be calculated by means of a quasi-empirical relation.

$$F = 1/2\rho CAv^2$$

The meaning of A and C, area and drag coefficient respectively, vary by context. For streamlined bodies at low speeds, such as ships, A is the wetted surface area, and C a number far smaller than one. For ships and ship like structures, drag forces are believed not to be limiting, so this is of comparatively little interest.

For blunt bodies such as cylinders, drag is calculated relative to the projected area. The drag coefficient is a function of the velocity and diameter (Reynolds number), and can be looked up in a table. Drag coefficients for cylinders in the region of our interest turn out to be bounded from above by one, and bounded from below by 0.5. generally, they are closer to one, and hard to estimate, so a factor one will be used as a safe guess. In [1], a factor 0.7 is suggested, but this is for an arguably higher Reynolds number. to be on the safe side, a factor one is used: the same conservative approximation is made in the ClubStead report calculations.

This is sufficiently accurate to model the drag on moving spars and semis, although the latter might have significant horizontal area, and interaction effects between the multiple vertical columns that might cause complications. However, these effects are believed to be small enough not to be worthy of more detailed study at this point.

Wind drag can be estimated by similar semi-empirical relations, but has not been found to be a significant contributor.

Wave drift force:

Wave drift forces are forces due to the reflection or absorption of waves. This can be understood in analogy with particles reflecting off the surface, or more directly, by analogy with electromagnetic waves. The waves carry momentum, and a change in their direction will cause a reaction force.

Calculating the magnitude of wave drift forces on general structures is a complicated matter. A worst case estimate can be obtained by assuming pure reflection of all waves along the waterline. This is a good approximation for large floating islands facing the waves perpendicular to their direction of propagation. The force per meter of structure in this scenario can be found from [1]:

$$F = 1/2\rho gA^2$$

This force is quadratic in wave height; thus of little concern in calm seas, but potentially the dominating factor in rough seas. For larger structures and stormy conditions, this force component is dominant [2], exceeding current drag forces by an order of magnitude. Station keeping by mooring is hardly possible for large floating structures as described in [2], and would be impossible or prohibitively expensive in deep waters. Only lazy station keeping would be possible for such a construction; accommodating the worst case wave drift forces would require up to 10mt of force per meter exposed. By comparison, a large, 10m beam tugboat, is capable of delivering 100mt of force. This illustrates quite clearly that

accommodating this worst case scenario is unlikely to be economical in terms of capital costs: a lot of engine power would be required that would under normal circumstances be completely useless.

The force on a cylindrical structure is less than derived from its projected waterline area, or diameter, the force on a cylinder being $F = 1/3\rho g A^2 D$, reflecting the fact that not all of the waves are reflected back, but some are reflected to the side.

Significant reflection only occurs when the wavelength is not big relative to the structure. A cylinder of a meter diameter will hardly be capable of reflecting any waves, and will not experience much wave drift forces. The typical wavelength of energetic waves in the open ocean is in the 50-200m range. Objects an order of magnitude smaller than this will be nearly unaffected. Similarly, a big but slender (ship-like) structure oriented into the waves will experience only modest wave drift forces.

[1] http://www.wikiwaves.org/index.php/Wave_Drift_Forces

[2] <http://www.offshoremoorings.org/moorings/2005/Maas/index.html>

[3]

http://books.google.com/books?id=AVmtOw6bLxgC&pg=PA241&lpg=PA241&dq=Wave+drift+forces+on+OTEC+platforms&source=bl&ots=xHlszANZzg&sig=t65Kq8qa9FIQF2CD0D7jfJz9MyI&hl=en&ei=jj4LS5f4CoqusgOg6-iWAw&sa=X&oi=book_result&ct=result&resnum=5&ved=0CCAQ6AEwBA#v=onepage&q=&f=false

Interaction effects:

Wave drift forces depend on wave transmission, or lack thereof, and since wave transmission is a complicated matter, so are wave drift forces. Even though a single column is nearly entirely transparent, reflecting only a small fraction $1/m$ of wave energy, this does not mean an arrangement of n columns will reflect n/m . [2]

In fact, an array of columns is entirely opaque to some wavelengths, related to the spacing between these columns.

Experimental studies find wave drift forces on a semi-sub VLFS, which presents an array of columns to the waves, to be up to half the force experienced on a similarly sized pontoon system [3], which nearly completely reflects the waves. While this represents some reduction of force, it is still of the same undesirable order of magnitude. In [3], the distribution of force between the individual columns is not measured; it is unlikely all columns experience the same forces; in fact the absorption/reflection will mostly go on in the first ranks of columns. Thus instead of providing a homogenous translating force, these forces will tend to push a spar forest into itself, leading to either high loads on connection systems,

or if considering a forest of individual spars, impossible requirements for the dynamic positioning systems of the first rows of seasteads facing the waves.

A semi-sub, having multiple columns, might be suspected of experiencing significant wave drift, however, with merely four columns wave drift forces are found not to dominate over current and wind loads [1], making up only about 10% of total forces during a storm.

[1] http://www.isodc.com/1st_ISODC07_TexasA&M_Team_3_SemiSub_for_Malaysia.pdf

[2] <http://www.isopec.org/publications/journals/ijope-11-3/ijope-11-3-p176-abst-CH-45-Kashiwagi.pdf>

[3]

http://docs.google.com/viewer?a=v&q=cache:i2iVfWojZxgj:www.journalofoceantechnology.com/getFile.asp%3Ffile%3DAfloat_on_an_angry_sea.pdf%26article%3DTrue%26vol%3D2%26issue%3D3+Afloat+on+an+angry+sea&hl=en&gl=us&pid=bl&srcid=ADGEESjwxMc8wg2mhhVWUE3y-Z9np4OcVp6JsX_050be4XmSJeK2AsrtZc90TwdOhqm5vEl3qv-RQMQ6gflg44qY48fkWmn0gVdRYqbKdoWXYNDfvkx2xD849kDLshfl6n8dApoH4r63&sig=AHIEtbRKpzYtrti0AhxKXctKfjuRzej7zA

Comfort:

Motion sickness:

One often encounters the notion that heave motion is the dominant contributor to motion sickness. Yet considerable disagreement as to the exact causes is found in the literature. Not only as to the magnitude of these effects, but also the relevant metric by which to assess them, and the relative roles of vertical, horizontal and rotational motion.

ISO standards for both vertical and horizontal accelerations exist, but it should thus be noted that this is not an exact science. The horizontal acceleration are derived on the context of the sway of high rise buildings. Some information is reviewed in [1]. Based on that, the following conclusions are drawn:

- Recommended maximum RMS for offshore structures is 0.40m/s^2 .
- Recommended maximum RMS for general purpose buildings is 0.07m/s^2 .
- 0.2m/s^2 is noted as the limit where desk work becomes difficult, nausea starts.

The ISO limit on vertical acceleration is defined as conditions which on long term exposure will result in motion sickness in more than half of passengers on a ship, where 'motion sickness' is defined by the objective physical signal of vomiting (not just subjective discomfort, this may be far higher).

- ISO limit RMS horizontal acceleration: 0.25m/s^2 [2]

It is not clear that this data supports the notion that vertical acceleration is indeed more critical than horizontal acceleration. The 0.25 horizontal limit is defined as provoking strong nausea, involving throwing up, whereas 0.20 vertical acceleration leads to mere mild nausea. In addition, a spar platform (and under some circumstances, a semi-sub) has stronger horizontal response than vertical response, thus for these structures, the horizontal motions may in fact be limiting.

This horizontal exposure limit is based on data for non-mariners. It is frequently remarked that people experience strong adaptation to motion-induced sickness; yet this effect is nowhere quantified. (the only quantitative information found is that 5% of people do not experience any adaptation at all). In absence of quantitative substantiation of these claims, the strongest conclusion is that this is a conservative standard for permanent residents. The large spread between the recommended values for horizontal motion between general purpose and offshore structures might represent an adaptation effect, or a selection effect. Either way, it is a large difference. If such a factor 5-6 difference in comfort could similarly be assumed for vertical motion tolerance, this would greatly reduce any motion sickness concerns. Further investigation of this topic is strongly recommended.

[1] <http://www.cppwind.com/support/papers/papers/structural/PEAKvsRMS.pdf>

[2] ClubStead hydroanalysis report

Methodology:

Detailed prediction of motion performance is a costly and concept-specific process, that is not justified given the level of the present investigation. The present methodology for assessing comfort is based on simplifying all seas to an equivalent monochrome wave of comparable properties. Ocean waves can be regarded as being composed of a multitude of frequencies, yet for a typical sea, these frequencies tend to cluster strongly around a dominant wavelength. Only the effect of the peak frequency in isolation will be considered, and its relation to other key parameters such as natural periods.

In general, floating structures do not perfectly follow the waves; the degree to which their motion matches that of a wave of a given frequency is captured by the notion of a response amplitude operator (RAO), which specifies the ratio of wave-height to motion response for all frequencies. A RAO of 1 in heave at a certain frequency means the structure will exactly ride out waves of that frequency. In elongated structures, such as ships and spars in particular, the linear motion response at an extremity is a function of both the translational and rotational degrees of freedom. For instance, even if a ship has insignificant heave at its center, this does not preclude large vertical motions at its bow.

A particle moving in sinusoidal motion as $A \sin(\omega t)$, as a particle in a monochromatic water wave does, experiences a peak acceleration of $A \omega^2$, which corresponds to a RMS (root mean square) acceleration of $A \omega^2 / \sqrt{2}$. The RMS of acceleration is commonly used as a measure to describe a 'quantity of motion'. By evaluating the RMS acceleration for some worst case scenarios in this way, an adequate impression of overall motion response can be obtained.

The computation of entire RAO's is a complicated process, requiring specialized software that is not easily reproduced. All RAO's considered are drawn from external sources.

The most important characteristic of a RAO are its resonant frequencies. At frequencies far above resonance, response will tend to zero, and at frequencies far below resonance, response will tend to unity. Therefore, low resonant frequencies are generally desirable.

Calculation of resonant frequencies is fairly straightforward for spars and semi-subs, it follows the same logic as the classic harmonic oscillator: frequency in radians per second equals the square-root of restoring force stiffness over inertia; $\omega = \sqrt{\frac{k}{M}}$. For the heave period, we have $\omega = \sqrt{\frac{gA}{V+V_a}}$ with g the gravitational acceleration, A the waterplane area, V the displaced volume, and V_a the added displaced volume (density drops out). Since having low angular frequencies is desirable, this condition translates into a low waterplane area and a high total displacement being desirable. Thus the good heave performance of a spar and semi-sub.

ClubStead metocean:

The most detailed metocean data available is found in the ClubStead report. From the various numbers encountered in reading, it can be concluded that ClubStead metocean conditions are particularly gentle for a (near) international water location. The main bodies of the Mediterranean or Baltic experience similar worst case conditions, of $H_s \sim 8\text{m}$. As far as issues of comfort are concerned, worst case conditions may be considered to be $H_s = 5\text{m}$; these waves occur with a frequency of 3.2% of the time.

Higher waves occur less than one percent of the time (only 3 days per year), which we consider negligible for comfort considerations. For these $H_s=5\text{m}$ waves, a typical tip period is $T_p=14\text{s}$.

Example calculations:

As an example calculation of motion sickness, perfectly following the motion of these ($H_s=5$, $T_p=14\text{s}$) waves, as one would in a small boat for instance, would incur 0.35m/s^2 RMS acceleration both horizontally and vertically, far above the limit for either vertical or horizontal motions. As such, having sub-unitary response at this frequency is important. (Note: H_s equals amplitude/2 for a perfect sinus/swell: for a more irregular sea, this equation is a conservative approximation. Since H_s is defined as the average height of the $1/3^{\text{rd}}$ of highest peaks, the mean acceleration might be overestimated by a theoretical maximum of a factor three, if two out of three waves have zero amplitude; In practice, the difference probably isn't very big)

Looking at the RAO's found in the ClubStead report, we see that heave response at this frequency is minimal. Yet surge response at this frequency is roughly $2/3$, leading to a total acceleration still above the 0.20 limit. That is, not considering compounding rotational/pitch contributions to topside motions.

From looking at model tests and some RAO's found, it seems as if spars have a horizontal response at the topside not far below unity, for a combination of long waves and short spars. Regardless, a spar in ClubStead conditions would rarely break the 0.4 limit, but the nausea limit of 0.2 could be straddled regularly. Exactly how problematic this is, is hard to tell given the vagueness and contradictions in the standards. But one thing to note is that in general, there is not much one can do to counter these effects; the only solution is increasing draft, and as argued in the spar section, spar draft is a variable already severely constrained by mobility considerations.

The longest swell ever experienced in the ClubStead scenario would not break the ISO limit on vertical motion even if occurring at its maximum amplitude and followed exactly with unit response, due to the longer period translating into lower accelerations. ($T_p=20\text{s}$, $H_s=4\text{m}$, $\lambda=270\text{m}$)

This demonstrates that amplitude is far from everything; the waves potentially most dangerous to comfort are the shorter waves, due to their higher frequency. The waves in the ClubStead scenario having the most compromising combination of length and amplitude are roughly ($T_p=8$, $H_s=4$, $\lambda=90$). A swell of these properties, followed exactly, would lead to a RMS acceleration of 0.9m/s^2 , or $\sim 1/10^{\text{th}}$ g. It is imperative the structure has very little response to these kinds of waves. Spars and semisubs of any kind will. As can be inferred from the wavelength, a 200m long hull in head seas would be strongly sub-unit excited by these waves, since it is far larger than the wavelength. As can similarly be inferred from the existence of longer waves of up to 300m in length, achieving such an effect over the entire spectrum requires a rather long structure.

Further, it illustrates just how badly the ISO limits can be exceeded for smaller ships in the open ocean. Any vessel with dimensions not exceeding half this wavelength ($\sim 40\text{m}$) in any direction, will tend towards

unit response to these kind of waves. These shorter waves would compromise comfort for such a structure even when only one meter high.

Modularity:

Intro:

The Seasteading Institute does not aim at enabling the creation of a single isolated seasteed, but rather a city that can grow according to demand. As such, all concepts will need to facilitate the possibility of moving goods and people between them. This is especially true for smaller seasteeds; when living on a hypothetical single family seasteed, moving to other seasteeds will be a daily need. Summarizing, modularity here refers to all issues related to the transfer of goods and people between seasteeds.

Direct vs indirect

Two different ways of accomplishing these goals can be distinguished: direct or indirect transfer. Indirect transfer here means transfer by means of an intermediate vessel, as opposed to direct transfer, which is between two seasteeds. Indirect transfer is also transfer, and thus encounters the same problems; the problem of transfer is dealt with first, and the peculiarities of indirect transfer are treated afterwards.

Bridging:

The problem of modularity can be regarded as consisting of two steps: creating a walkway between them, and in order to achieve this, retaining the vessels in some more or less fixed relative position.

An example of a bridge between vessels is provided by the Offshore Access System (OAS) [1]. Its intended purpose is to facilitate the transfer of people between oil platforms and their support vessels. It allows for some relative motion between its attachment points, compensating for this by means of several degrees of freedom. The range of motions it can handle is limited, and hence its operability is bounded by the sea-state.

Another way of bridging the gap between vessels is by means of a crane. This is primarily used for the transfer of goods. The operability of cranes is quite strongly bound by both wind and waves.

[1] http://www.offshore-solutions.nl/en/products_services/the_offshore_access_system_oas_for_heavy_seas

Relative positioning:

In order for such bridges to be formed, vessels will need to be able to remain in physical proximity without compromising safety. The desired degree of relative position keeping can be attained in three ways: a dynamic positioning system, by mooring or some form of connections between the vessels.

Mooring:

The potential for a mooring system to meet this requirement depends on the water depth. In deep waters, a moored structure will always be capable of significantly deviating from its neutral position; up to hundreds of meters. Besides expensive tension legs, other mooring line systems require a footprint

with a radius equal to or higher than the water depth itself (its 'watch circle'). This severely limits the potential density of deepwater moored seasteads.

Due to the definition of the EEZ, attractive locations in international waters where mooring is possible may not exist. Hence, outside the EEZ, relative positioning will have to proceed by other means than mooring lines. If mooring is an option, it will be capable of providing quite robust relative positioning, and an OAS-type bridge between the seasteads can be employed.

Dynamic positioning:

Dynamic positioning was originally conceived to perform this very task; it is therefore a guaranteed functional solution. The capability of such a system to guarantee no collisions between vessels will depend on sea-state, but a typical DP system will operate up to [look up exact numbers!], so will function most of the time under ClubStead metocean conditions. During strong storms, a more spread out formation will have to be assumed. One disadvantage of this method is the continuous operating cost. this cost is believed to be small relative to station keeping costs.

Connections:

If seastead modules are constrained by some form of (semi)permanent connection, their relative position will be fixed, and adding a bridge/walkway between them will be trivial.

These connections will have to bear the brunt of the relative wave forces between the vessels, and will therefore have to be of considerable strength. This also implies they will have to be of at least semi-permanent nature, as large, multi-ton and typically welded structures are not easily removed.

In general, it will not be possible to implement connections between existing structures not designed with these connections in mind. Attempting to connect two normal ships in any way, for instance, would introduce forces its load-carrying structure would not be prepared to handle.

By connecting modules into a larger structure, their motion characteristics are altered. The bigger structure will in general be less responsive to waves, more stable, and therefore more comfortable. This provides an additional motivation to connect seasteads into a larger agglomerate.

Two subtypes of connections can be distinguished: dense and sparse connections. A dense connection is one where different modules are mated without any spacing, as with ephemeral 'cassettes', and the connected whole presents a single front to the waves. A sparse connection is one where the individual components are connected by means of some truss or similar structure; the separate legs of ClubStead may be regarded as such modules. Waves will be able to pass through the structure, and the modules may experience large differential forces.

Sparse:

ClubStead may be regarded as an example of a sparse modular structure. Some of the difficulties encountered in implementing this solution are discussed in the ClubStead documentation. The core problem is that the individual columns are spatially separated, and thus will experience different wave forces at the same instant. The most problematic component is the horizontal force, which can be found through Morrison's equation. The prying forces thus introduced are hard to constrain; a significant part of the steel budget of ClubStead is taken up by the trusses that link the columns together, precisely for this reason.

Some concepts have been proposed which are essentially even more modular semi-sub (ClubStead is not designed to be extended beyond its 4 columns), but the difficulties encountered in ClubStead would become progressively more prohibitive as the structure would be expanded further. No realistic implementations of such a concept have been found, nor do they seem conceivable. A related but somewhat different concept is discussed in [VLFS reference].

Aside from the fact that as such connections are repeated, it becomes more difficult to ensure their integrity, the resulting array of columns would create other problems. The wave-trapping effects of such a grid would result in amplified wave heights, and a wave-reflectance coefficient approaching that of a similar-sized dense structure. It is questionable what benefits such a structure has over a similarly sized dense structure; the only visible one are reduced hogging and sagging forces, but there are many downsides too.

Dense:

A dense connection is one where the individual components are mated without any spacing in between them. The ephemeris platforms were constructed in such a fashion, the technique has been used for floating docks and it is also proposed for the PSP platform. This technique is rather different as far as the interaction with the water is concerned. The resulting structure can potentially form a somewhat hydrodynamic whole, and differential horizontal forces are of no concern.

The primary challenge in such a connection is resisting the bending moments induced by hogging and sagging forces. If such modules are connected into a large structure, and this large structure happens to be lifted by two wavecrests at its endpoints, a very large bending moment results. This is the dominant concern for longer structures, even for monolithic ones, and connections are typically weak spots. Nonetheless, designing a structure to be able to handle them should be possible.

Flexibility:

Permitting some degrees of freedom in a connection may be beneficial. For both the goals of providing relative positioning and improving motion characteristics, not all degrees of freedom need to be constrained. By unbounded extension of an agglomerate of seasteeds into a rigid whole, the potential worst case hogging and sagging forces will continue to increase. By introducing some flexibility, these wave motions may be permitted rather than fought.

An example of this principle can be found in [VLFS base], where an aircraft carrier consisting of several modules connected into a single airstrip is proposed. Motion between the modules is permitted, as a single rigid mile long structure would experience too large forces. Note that the proposed connection mechanism is large and complex.

I have also considered a flexible connection system for a spar-like concept, but found the outcome unsatisfying. The worst case forces such a system may experience are large, and will require moving parts such as hinges and pistons, which is a bad combination. Designing a system that seems plausible, technically as well as economically, is something I have not succeeded in.

Indirect transfer:

As opposed to moving directly between two adjacent seasteeds, transfer by means of an intermediate vessel might be desirable. These vessel are likely to be small, and have high, and even more importantly, different wave response from the structure they are attempting to interact with. Thus, indirect transfer does not fundamentally ease the problem of modularity; it merely replicates them.

Transfer between vessels in the open ocean is known as a difficult problem. Even in very gentle waters during ephemerisle '09, transfer between boats and platforms was an often time-consuming and demanding process. Indirect transfer by small boats may not be practical under most open ocean scenario's.

If these vessel are relied upon for day to day commutes, they should be able to function under nearly all weather circumstances. Adequate mooring preventing damage may be difficult during a storm; simply tying up to a larger vessel will not be possible due to concerns of damage.

Structures of considerable dimensions in both length and width (island-type seasteeds), will provide a calm leeward side, but few proposed designs meet that property.

It is implied that this discussion deals with surface vessels (boats). Helicopters are unlikely to be economical, nor less weather sensitive. One interesting possibility is using submarines moving between moonpools; it is an elegant way to eliminate concerns about operability and weather, but for all but some concepts this will not be an option, not to mention it would require substantial innovation.

Criteria:

In this section, an attempt is made to break down the question of what makes an effective seastead into a set of quantifiable criteria. All concepts that will be considered are judged against these criteria, so that they can be compared along a standardized measure.

Capital costs:

By capital costs, the application-independent capital costs are meant. That is, the hull and auxiliary/support systems, but not the accommodation units or their furnishing. Many offshore structures, including ClubStead, have luxurious accommodations, but these are not essential to the structure design; the focus here is to be on the costs unique to the ocean, such as to minimize the ocean tax.

Specifically, we are interested in the cost per unit area for real-estate on the given platform. For spars and semis, or structures with an air-gap, the topside tonnage which can be supported is the limiting factor, rather than volume or area; we assume an equivalency between those measures as $1/4^{\text{th}}$ of a metric ton per square meter floor area of furnished real-estate, or 4sqm per metric ton. [sources: ClubStead report, google book link?]. Under this assumption, cost per unit area and cost per ton of topside payload are directly related.

Costs will be expressed in fiscal year 2009 American dollars. Where needed, standard inflation correction will be applied.

The target maximum is 2500\$ per square meter of application independent real estate. This should be achievable based on the analysis of ships and semis done so far, therefore, scoring much worse on this parameter should not be acceptable unless balanced against other large benefits.

Scale:

Most concepts come in various sizes, not all of which may meet our design criteria. In general, smaller is considered to be more attractive. Scale is measured by its relevant metric of total hull CAPEX, in FY2009 American dollars.

Mobility cost:

Different designs will require different levels of energy input to achieve a given degree of mobility, which will translate into operating costs.

Where given, costs are expressed in 2009 American dollars per person per month. However, translating these costs into a dollar figure is complicated, because of the large amount of unknowns involved: depending on fuel prices, uncertainty in forcing scenarios, uncertainty in available space and occupancy rates, the cost per person per unit time can vary wildly. Therefore, a dollar estimate for ClubStead is performed, and for other concepts, comparisons relative to ClubStead are made, these uncertainties between them being equal.

The costs cited under this category are the cost incurred in station keeping, not including any other maneuvers, subject to the external forcing scenario outlined in the mobility section.

Safety:

All structures should meet stringent safety standards. Living on the ocean should be at least as safe as travel on the ocean. Where estimates concerning material requirements are made, a safety factor of at least two is wielded with respect to the worst case loading condition.

Comfort:

Comfort is not a hard requirement. Designing to deal with the long tail of worst case possible events is expensive; a seastead that is uncomfortable a few days a year is to be preferred to one that is comfortable all of the time, yet twice as expensive.

Predicting motion performance in detail is an involved process that is not justified at this stage of analysis, and the mapping between vessel motion and motion sickness is far from completely understood to begin with. Therefore, no attempt at making detailed predictions is made. However, a good deal of information can be obtained from simple estimates of the most relevant parameters, such as natural periods and response amplitude operators, combined with the methodology in the Comfort section. This suffices to separate the plausible from the implausible.

Modularity:

This is measured in terms of the ease of transporting goods and persons between adjacent seasteads.

No quantitative measure of modularity can be devised given our current level of detail, but there are obvious differences between concepts in this regard, and a somewhat subjective estimation of this important parameter is therefore made.

This will mostly entail a judgment of two factors: its motion response and scale. Low motion response means easy boarding and increased capability of connections/walkways of some permanence. A large scale structure (aside from having generally having lower motion response) can more easily amortize the cost of sophisticated cranes or walkways over its budget, lowering the modularity cost per person.

Maintenance costs:

These are the maintenance costs independent of application, or the hull and propulsion maintenance costs. This is a function of material use, draft and mobility.

Steel requires more maintenance than concrete, a deep draft hull is hard to inspect, and only the most mobile structures can afford to move to a dry-dock for maintenance.

Ordering from good to bad is: concrete -> dry-dock maintenance ->shallow draft

It is not obvious that wet steel maintenance is a realistic option at all.