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Article

Identifying Ecosystem-Based Alternatives for the Design of a Seaport's Marine Infrastructure: The Case of Tema Port Expansion in Ghana

Wiebe P. de Boer ^{1,2,*} , Jill H. Slinger ^{3,4} , Arno K. wa Kangeri ⁵, Heleen S.I. Vreugdenhil ^{1,3}, Poonam Taneja ², Kwasi Appeaning Addo ⁶  and Tiedo Vellinga ²

¹ Deltares, Boussinesqweg 1, 2629 HV Delft, The Netherlands; heleen.vreugdenhil@deltares.nl

² Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands; p.taneja@tudelft.nl (P.T.); t.vellinga@tudelft.nl (T.V.)

³ Faculty of Technology Policy and Management, Delft University of Technology, Jaffalaan 5, 2628 BX Delft, The Netherlands; j.h.slinger@tudelft.nl

⁴ Institute for Water Research, Rhodes University, Artillery Road, Grahamstown 6140, South Africa

⁵ Wageningen Marine Research, P.O. Box 57, 1780 AB Den Helder, The Netherlands; arno_kangeri@hotmail.com

⁶ Department of Marine and Fisheries Sciences, University of Ghana, P. O. Box LG 99, Legon-Accra, Ghana; KAppeaningAddo@ug.edu.gh

* Correspondence: wiebe.deboer@deltares.nl; Tel.: +31-6-4691-1209

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Abstract: Long-term sustainable port development requires accounting for the intrinsic values of ecosystems. However, in practice, ecosystem considerations often only enter the planning and design process of ports when required by an Environmental Impact Assessment. At this late stage, most of the design is already fixed and opportunities to minimize and restore ecosystem impacts are limited. In this paper, we adopt a large-scale, ecosystem perspective on port development with the aim to identify ecosystem-based design alternatives earlier and throughout the planning and design of a port's marine infrastructure. We present a framework, termed the 'ecosystem-based port design hierarchy' (EPDH), to identify ecosystem-based alternatives at four hierarchical design levels: 1) alternatives to port developments, 2) port site selection, 3) port layout design, and 4) design of structures and materials. In applying the EPDH framework retrospectively to a case study of port expansion in Tema, Ghana, we establish that ecosystem considerations played only a limited role in identifying and evaluating alternatives at all four design levels in the case study, whereas more eco-friendly alternatives in terms of port layouts, structures, and materials are identified using the EPDH framework. This reveals that opportunities for ecosystem-friendly port designs may have been missed and demonstrates the need for and the potential added value of our framework. The framework can assist practitioners in earlier and wider identification of ecosystem-based alternatives for a port's marine infrastructure in future seaport developments and, hence, represents an important step towards more sustainable port designs.

Keywords: sustainable ports; ecosystem-based management; environmental impacts; port design; nature-based engineering; coastal environment

1. Introduction

Seaports are important transport hubs within a coastal system. These strategic assets [1] are located in complex environments characterized by interactions between physical networks (e.g., infrastructure, transport networks), socio-economic influences (e.g., employment opportunities,

port–city relations), and ecological system processes (e.g., sediment transport, fish migration, coastal habitat dynamics). Whereas most research is focused on the technical and managerial aspects of port developments, awareness is growing that ports can have large and long-term regional effects on communities and ecosystems [1–10]. These impacts or externalities often exceed the scale of the port development itself and can be both positive and negative. For example, ports may lead to positive impacts on local employment opportunities and regional economic growth [1,9,11], but also to environmental degradation and loss of livelihoods [5,9,12–14]. Nevertheless, planning and design of seaport developments is often primarily driven by economic considerations rather than adopting a larger-scale perspective accounting for the regional effects on communities and ecosystems [1]. In contrast, this paper adopts an ecosystem-based perspective on seaport planning and design to place the ecosystem centrally in the design of a port's marine infrastructure.

Such a large-scale perspective, accounting for the intrinsic value of ecosystems, is not only crucial for long-term sustainable development [8,15], but can also benefit the port and its stakeholders. An ecosystem-based approach can prevent the 'green handbrake' on port developments (i.e., where developments are abandoned due to legislative environmental constraints; [16]), and avoid costs and delays in planning and implementation due to fines, lawsuits or clean-up costs [6,8,10,17]. Furthermore, employees, customers, and shareholders are placing increasing pressure on companies in the maritime sector to actively prevent harm to the environment [8]. In addition, negative ecosystem impacts could backfire on the port itself, for example by port-induced coastal erosion and sedimentation [18]. Moreover, an ecosystem-based approach can generate added value in terms of ecosystem services such as flood protection, food production, and recreation [4,6,19,20]. To take such larger-scale effects into account from the onset, several authors have stressed the need for project-superseding Strategic Environmental Assessments (SEA) to incorporate ecosystem values at the higher, strategic levels of decision-making, such as in policies, plans, and programs [21–25].

The potential benefits of an ecosystem-based approach are being recognized, and the concept is increasingly being adopted by the port development community [4,13,26]. However, at present, limited examples and guidelines are available to integrate this concept into the planning and design of a port's marine infrastructure [27,28], whereas these early development stages are often decisive for the final implementation. A recent review of environmental impact assessments (EIAs) for international port development projects by The Netherlands Commission for Environmental Assessment shows that most EIAs lacked well-distinguished alternatives for site selection, port layout, and mitigating measures [24]. This implies that a systematic exploration of more ecosystem-friendly alternatives is often missing and, hence, not included in the decision-making on port planning and design.

In this paper, we aim to address this issue by developing a framework to identify ecosystem-based alternatives throughout the planning and design stages of a seaport's marine infrastructure. By treating ports as an element within a wider coastal (eco)system, we are seeking to move port developments towards retaining and restoring certain ecosystem functionalities, elsewhere referred to as Building (or Working) with Nature [6,26]. More precisely, by placing the ecosystem centrally from the outset, we aim (i) to explicitly include ecosystem considerations in the early stages of the engineering design process, and (ii) to increase the range of potential design alternatives considered at every stage. This a prerequisite for balanced decision making on port development [1] and supports more sustainable coastal management.

2. Methods

We adopt a design science approach [29] to develop and trial an ecosystem-based port design framework. This approach involves iteratively designing a solution or artifact (i.e., a framework), that is both scientifically rigorous and societally relevant [29]. It aims for learning through designing in order to strengthen both the knowledge base (i.e., the rigor) and the applicability (i.e., the relevance) of the framework in its environment (Figure 1). The port environment is characterized by complex interactions between the physical components (e.g., infrastructure, transport networks),

the socio-economic conditions (e.g., employment opportunities, port-city relations), and the ecological systems. This study focuses primarily on the interactions between a port's marine infrastructure and the surrounding ecosystems.

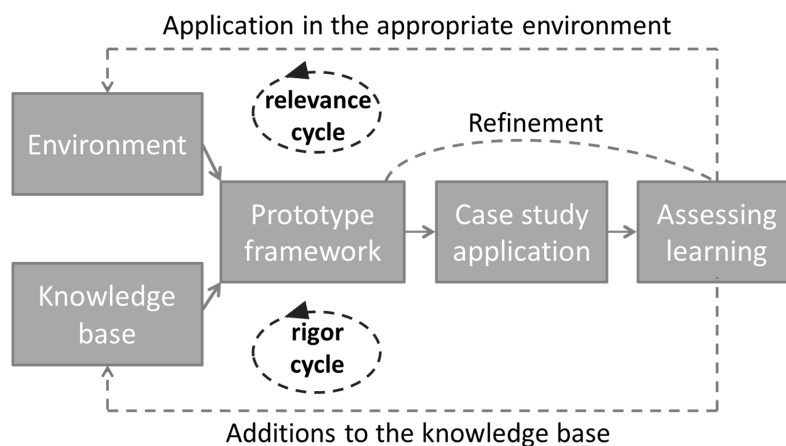


Figure 1. The steps of the design science approach (based on [29]) applied in the development of the ecosystem-based port design framework.

Following the design science approach, we develop a prototype port design framework (step 1), then test it on a case study (step 2), and, finally, draw lessons for further refinement of this framework (step 3; as illustrated in Figure 1). First, we draw from literature review, expert interviews and expert feedback to construct the prototype (Section 3). This initial step comprised two iterations: (1) the construction and presentation of a preliminary framework at the international conference of the World Association for Waterborne Transport Infrastructure (PIANC) in May 2018 [30] and (2) including expert feedback and expanding the theoretical foundations to yield the prototype framework described in Section 3 of this paper. Next, we test and evaluate the utility of the prototype on the case study of the Tema port expansion in Ghana (Section 4). This case study is the focus of the overarching “Sustainable Ports in Africa” research project [31], of which this study forms a component. In Section 5, we derive lessons from the Tema case regarding the application of the framework to future seaport developments (i.e., its relevance) and determine necessary further steps to increase the knowledge base (i.e., its rigor). Finally, Section 6 presents the conclusions of our paper.

3. Developing the Prototype Framework

The prototype framework, termed ‘ecosystem-based port design hierarchy’ (EPDH; see Figure 2), is inspired by the environmental impact mitigation hierarchy that underpins environmental impact assessment (EIA) procedures [27,32]. The environmental impact mitigation hierarchy consists of three levels of impact mitigation in order of priority: (i) avoidance, (ii) reduction, and (iii) offset. The aim of the environmental impact mitigation hierarchy is to attain, at the least, no net loss in ecosystems and biodiversity, and even to generate a net positive effect through restoration or rehabilitation of impacted ecosystems (as illustrated in Figure 3). Similarly to the mitigation hierarchy, the starting point for the EPDH is the human development initiative, or more specifically a seaport development.

In the EPDH framework, we distinguish the following design levels ranging from large to small spatial scales, namely: (1) alternatives to port developments, (2) port site selection, (3) port layout design, and (4) selection of structures and materials (see Figure 2). Moving down the hierarchy from the top to bottom levels, the design space narrows and the mitigation options shift from impact avoidance to offsetting. The higher-level planning and design choices for port developments (i.e., level 1) often require strategic regional or national assessments on the transport capacity needs, transport networks, and transport modalities (i.e., spatial scales of ~100s–1000s of kilometers). The intermediate levels of port site selection and port layout design (i.e., levels 2 and 3) often focus on more local effects of the

port development (i.e., spatial scales of ~1–10s of kilometers). For example, the impacts on local (and regional) economic opportunities, urbanization, ecosystems, or coastal erosion. On a smaller scale (i.e., ~10s–100s of meters, for bigger ports even kilometers) choices can be made on the types of structures and materials to be used in the port’s marine infrastructure. Clearly, for a particular example, these spatial scales will depend on the size of the port development and the case-specific context. The order of the levels is hierarchical, since decisions made at the higher, large-scale levels narrow the choice of options at the lower, smaller-scale levels. Therefore, the earlier that ecosystem-based alternatives can be taken into account and the wider the range of alternatives considered, the greater the potential that ecosystem impacts can be avoided or reduced and restoration options can be taken into account.

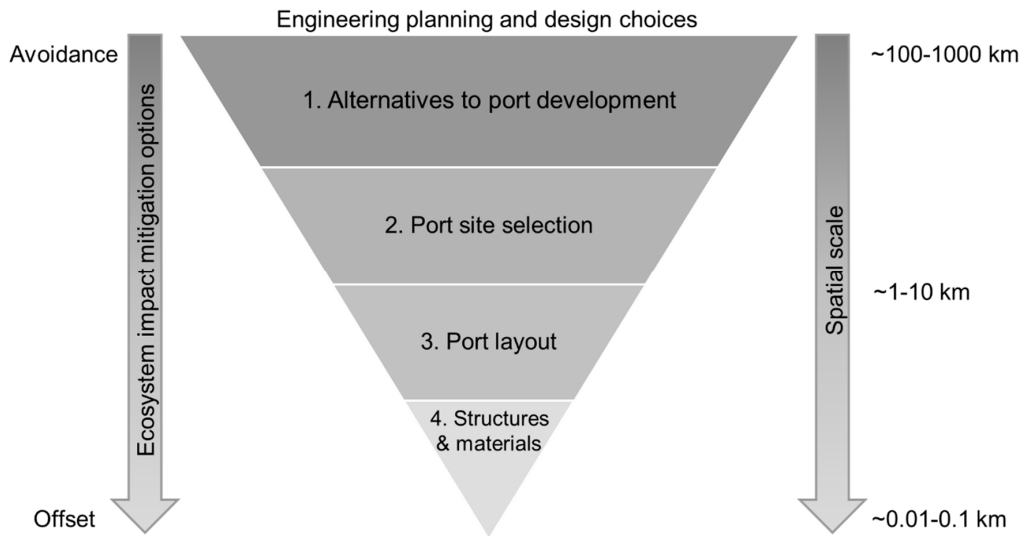


Figure 2. Ecosystem-based port design hierarchy (EPDH), a four-level framework to integrate ecosystems in the planning and design of a seaport’s marine infrastructure (adapted from [25]).

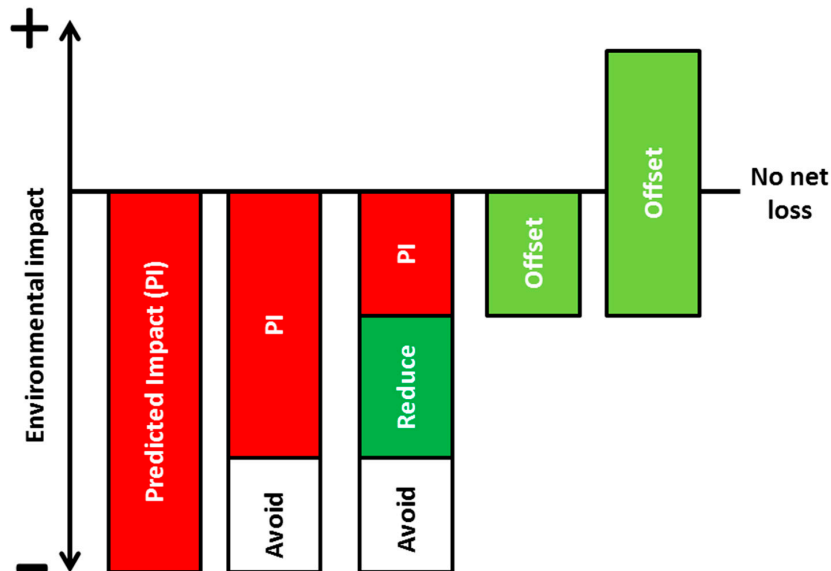


Figure 3. Illustration of the principles of the mitigation hierarchy that places the emphasis first on avoiding, then on reducing, and, ultimately, on offsetting the predicted environmental impacts (PIs) of human developments (adapted from [28]).

Whereas most engineering design starts from the third level (i.e., layout design), we explicitly added the first two levels on alternatives to port developments and site selection, as true ecosystem-based design requires that ecosystems are considered at the earliest stages of decision-making (following [33]).

This larger-scale ‘system-perspective’ often exceeds the project level of an individual port development and requires taking ecosystems into account at higher, strategic levels of decision-making such as in policies, plans, and programs [21]. The lower three levels of the hierarchy align with those suggested in handbooks and guidelines on port design [34–36], although previous studies have indicated that site selection is frequently not part of an EIA and, hence, not part of the public decision-making process [24,37].

Adding to the knowledge base of and current practice in EIAs, we aim to address ecosystem needs earlier in the design process of a port’s marine infrastructure (i.e., at the higher levels) and to widen the solution space with ecosystem-based design alternatives at each level. Accordingly, we identified a variety of examples and concepts for each level of the framework from literature and experts in the domains of port engineering, coastal ecology, and coastal governance (see Appendix A). The subsections that follow provide examples of the ecosystem-based alternatives for each hierarchical level as summarized in Table 1. We note that the range of alternatives should be regarded as a first step and is illustrative rather than definitive or complete.

Table 1. Overview of ecosystem-based examples and concepts for the four levels of the EPDH framework derived from literature and expert interviews.

EPDH Level	Ecosystem-Based Examples and Concepts
1. Alternatives to port development	<ul style="list-style-type: none"> ● Improve efficiency or utilization of existing port infrastructure ● Redistribute or repurpose existing port infrastructure ● Increase cooperation between existing ports ● Improve capacity and efficiency of other modes of transport
2. Site selection	<ul style="list-style-type: none"> ● If possible, extend or requalify established (‘brownfield’) port infrastructure instead of developing a new site ● When a new (‘greenfield’) port is necessary: <ul style="list-style-type: none"> ○ Focus on building or working with nature rather than counteracting it ○ Look for a site with naturally favorable conditions for port functioning (e.g., depth, maneuvering space, mild hydrodynamic conditions) ○ Exclude sites in biogeographically unique areas, regions with a unique function in the local ecosystem, and protected or sensitive ecosystems ○ Explore possibilities to restore or rehabilitate impacted or degraded ecosystems and biodiversity
3. Port layout	<ul style="list-style-type: none"> ● Minimize dredging and civil engineering works ● Explore possibilities for open or unsheltered port layouts ● Consider offshore extensions or jetties at naturally deep(er) water ● Explore synergies between layout designs and natural processes
4. Structures & materials	<ul style="list-style-type: none"> ● Explore concepts of ecological engineering for port structures and materials, such as: <ul style="list-style-type: none"> ○ Breakwaters functioning as artificial reefs ○ Biological concrete for quay walls ○ Artificial habitat creation within the port ○ Novel resurfacing materials or hanging ropes from poles or pontoons to enhance attachment of marine organisms

3.1. Level 1—Alternatives to Port Development

Developing a port by expanding an existing port ('brownfield') or constructing a new one ('greenfield') represents one of a range of potential solutions to a perceived transport capacity problem. Alternative solutions with less ecosystem impacts could be possible. For example, improving the efficiency or utilization of the existing port infrastructure [11,38], redistributing or repurposing such infrastructure [1,39], increasing the cooperation between ports through enhanced networking [7,11,40], or improving other modes of transportation such as railways, roads, and airports and their interconnections [7]. Also, these solutions could have negative ecosystem impacts (and other externalities), which should be compared to those of a port development to determine the most appropriate solution.

So, the highest level of the EPDH includes considering means other than port developments (i.e., expansions or new ones) to meet the need for increased transport capacity. Alternatives for efficiency or utilization improvements, increased cooperation with other ports, or using other transportation modes are available. Ecosystem-based port design requires that the feasibility and effects of these alternative options are considered seriously before selecting a port development as the means to meet the transport capacity need.

3.2. Level 2—Port Site Selection

In many situations, alternatives to port developments are not feasible or are insufficient in resolving the capacity problem. At this point, a port development becomes inevitable and an appropriate site needs to be selected. From an ecosystem point of view, extending and requalifying established ('brownfield') port infrastructure at an existing site is usually preferable to developing a new site [7]. Because the marine and terrestrial infrastructures of existing ports are already in place, the additional impacts of further port development are anticipated to be less severe than for new port developments in pristine or limitedly impacted marine environments. Similarly, the overall costs of a port expansion are generally lower, owing to the presence of physical and supporting socio-economic infrastructure, navigation channels, hinterland connections, and labor.

When constructing a new ('greenfield') port is necessary, appropriate site selection is a crucial step in minimizing the associated ecosystem impacts and exploring restoration opportunities of degraded ecosystems [27,41,42]. Port site selection should then aim to preserve the natural ecosystem functioning as much as possible, considering requirements such as habitat connectivity, endogeneity, trophic web integrity, physical-chemical water quality, and system resilience [43]. This implies working or building with nature rather than counteracting it [4,6,26]. Ideally, the natural conditions at the selected site support port functioning, meaning that little to no human interference is necessary. Such a location for a port would be naturally sufficiently deep, offer sufficient space for maneuvering, and have mild enough hydrodynamic conditions to allow safe and efficient port operations [35,36,38,41,44]. Additionally, such a site would consist of rocky environments similar to those created by port infrastructure and would not be biogeographically unique nor fulfil a unique function in the regional ecosystem, so that the development of the site would not affect the ecological resilience of the local ecosystem or the biogeographic region. Clearly, protected and sensitive ecosystems should be eliminated from the site selection process.

Hence, if port development is inevitable to meet the need for increased transport capacity, ecosystem-based site selection requires preserving the natural ecosystem functioning and, consequently, minimizing negative impacts. In practice, this often means that the expansion of existing ports in already impacted ecosystems is preferred over the development of new ones. For new ports, ideally, sites with favorable natural conditions for port functioning (e.g., sufficiently deep, enough maneuvering space, mild hydrodynamic conditions) are considered to minimize the need for human interference in the ecosystems. Too narrow scoping of potential port sites or too early dismissal of alternative sites may decrease opportunities for ecosystem-friendly port design.

3.3. Level 3—Port Layout Selection

Feasible layout alternatives depend on ambient natural conditions and, therefore, are constrained by the site selection. Except for ‘natural’ ports, human interventions are often required to enable port functioning. For example, dredging to deepen the port basin and access channels or for land reclamations, and civil engineering works such as breakwaters, berths, and quay walls. From an ecosystem viewpoint, these interventions should be avoided if possible, and minimized if not. Port layouts with a minimal need for, and low impacts from, dredging and civil works are therefore preferred.

Traditionally, seaports have breakwaters to provide shelter from ambient wave and current conditions [45]. However, open or unsheltered port concepts have been proposed as alternatives in mild coastal environments. These concepts can reduce the amount of civil works required [45–49] and, hence, can minimize the associated habitat loss and interruption of natural flows. References [45,49] have suggested that innovations in shipping technology and mooring techniques that stabilize ships under more energetic conditions, may open up opportunities for open port concepts at locations that were not considered feasible so far.

Offshore ports and terminals could be another alternative to conventional port layouts. These structures are usually located in deeper water. Therefore, they may require less dredging for the deepening of the port basins and the access channels [50]. At the coast, offshore extensions to existing seaports are potentially more ecosystem-friendly than alongshore port extensions. They may require less dredging works and the generally uniform character of the offshore zone makes it less susceptible to associated ecosystem impacts in comparison with the high habitat richness and biodiversity that characterizes the more heterogeneous coastal zone [51,52]. Even though the feasibility of offshore port layouts remain situation specific and can be costly, the increasingly sophisticated mooring systems, the increasing size of oceangoing vessels, and increasing competition for space in the coastal zone mean that there are now more opportunities for offshore ports than in the past.

Although the opportunities for ecosystem-based layout design are influenced strongly by the natural conditions determined by the site selection, considering the feasibility and effects of nature-based concepts in the early design stages can increase opportunities for more eco-friendly port layouts. Ecosystem-based layouts require minimal interference in the ecosystem with minimal needs for and impacts from dredging and civil works. Open or offshore port concepts and expansions could offer alternatives to conventional ‘port-behind-breakwaters’ layouts.

3.4. Level 4—Selection of Port Structures and Materials

Although the potential to avoid ecosystem impacts is quite limited at the level of structures and materials, choices that minimize impacts, restore ecosystem functioning, or even enrich the ecosystem complexity, can still be made. For a conventional port, breakwaters, quay walls, and a sufficiently deep access channel and basin, are required. Although such infrastructure replaces the naturally occurring habitats [53], it does contribute a significant quantity of hard substrate to which marine organisms can attach. Unfortunately, the high gradients, low structural complexity, and high homogeneity of conventional port infrastructures mean that they do not offer suitable conditions for diverse biological assemblages [54,55]. Instead, port infrastructural habitats are often dominated by underwater nuisance or invasive species [56].

Recent advances in the field of ecological engineering [6,57–59] have delivered innovative concepts for multifunctional, ecosystem-based marine infrastructural design. Some examples from literature are (i) breakwaters that act as artificial reefs [60]; (ii) EConcrete[®], a type of biological concrete that can be used to increase the ecological value of quay walls [55]; (iii) artificial habitat creation to improve the nursery function for juvenile fish [61]; (iv) novel resurfacing materials to enhance surface complexity [62]; and (v) hanging ropes (i.e., hulias) from poles and pontoons so that marine organisms can attach and so increase biological productivity and biodiversity [63]. These and similar ecological engineering options can create alternative habitats or enhance existing habitats and so help to sustain existing ecological functions and even support new ones [61]. Nevertheless, these concepts are rarely

applied as an integral component in the design of port developments, but are sometimes employed as part of ecosystem rehabilitation or restoration efforts undertaken at a later stage [61].

Hence, generally, port structures replace natural habitats with unfavorable conditions for biodiversity due to steep slopes, low structural complexity, and high homogeneity. However, a growing number of ecosystem-based solutions is available to enhance the biological and ecological value of port structures and basins. These alternative solutions may not be sufficient to avoid the ecosystem impacts of ports entirely, but can increase the ecological richness and biological functionality of seaports.

4. Results: Applying the Framework to Tema Port Expansion

In this section, the ecosystem-based port design hierarchy (EPDH) is applied retrospectively to the planning and design of Tema port expansion. The case study serves to demonstrate the need for the framework and its potential added value as well as to learn lessons for further refinement of the framework. First, we introduce the Tema case study (Section 4.1). Then, at each level of the EPDH, we evaluate the extent to which the ecosystem played a role in the choice of design alternatives (Sections 4.2–4.5). Finally, based on the evaluation of the Tema case, the results relating to the need for, and potential added value of, the framework are summarized (Section 4.6).

4.1. Case Study Description of Tema Port Expansion

Situated some 25 km east of Accra, Ghana's capital city, Tema port handles about eighty percent of Ghana's maritime international trade at present, contributing almost 90% to Ghana's total trade throughput [64,65]. The characteristics of Tema port are detailed in Table 2 in terms of port operation, cargo volume and types, ambient environmental conditions as well as the growth perspectives underlying the decision to expand the port (Figure 4). Currently, the first phase of the port expansion is finished.



Figure 4. The location of Tema port with an indication of the realized (in green) and planned (in red) expansion to the west of the existing port and to the east of the Sakumo II lagoon (based on [63]; image source: [64]).

Table 2. Characteristics of the case study of Tema Port Expansion, including the relevant information sources.

Characteristics	Description	Source(s)
Port Operation	Ghana Ports and Harbours Authority (GPHA) Modern container terminal - Meridian Port Services Ltd. (MPS), a joint venture between GPHA, APM Terminals International and the Bollere Group	[64]
Total cargo traffic	Increased from some 7.5 million ton in 2003 to 13.5 million ton in 2016	[68]
Type of cargo	Mainly containers, but also roll-on/roll-off and bulk cargo as well as gas and oil	[65]
Growth perspective	High anticipated growth in cargo traffic, owing to: <ul style="list-style-type: none"> ● Ghana's rapidly growing economy ● increasing demand for transit trade from Ghana to the landlocked countries in the interior ● growth in transshipment activity also anticipated, leading to: expansion of container handling facilities by a joint venture of GPHA and MPS 	[64,65]
Ambient hydrodynamic conditions	Tidal current usually below 0.1 m.s^{-1} Alongshore currents average about 1 m.s^{-1} , mainly wind and wave-driven Waves predominantly swell from Atlantic Ocean with significant wave heights of 1–2 m; SSW angle of incidence and gentle coastal profile lead to eastward littoral drift	[65,66]
Nearby lagoons	Chemu lagoon: east of the port, undergoing infilling by silt and heavy pollution from effluent disposal by industries east of Tema Gao lagoon: 3 km further east of the port, also silting up rapidly and becoming polluted by nearby industries Sakumo II lagoon: 1 km to the west of the port, recognized as a wetland of international importance for migratory and sea birds under the Ramsar convention. Construction of the Accra-Tema coastal road in the 1950s limited water exchange with the sea to a few supra-tidal culverts. Lagoon now consists of a brackish open water area and associated floodplain, freshwater marshes, and coastal savanna. Lagoon holds spiritual value to the indigenous communities living near the lagoon and in Tema, forms a livelihood source for local fishermen, and is a bird watching site.	[64,67,69]

4.2. Level 1—Were Alternatives to a Port Development Considered and Possible?

The (pre-)feasibility studies [64,66] and the ESIA [65] did not explicitly consider alternatives to a port development to accommodate the extra capacity required for container throughput in Ghana. Alternative modes of transport may have been deliberated at higher strategic levels of decision-making, for instance in a strategic environmental assessment. However, in the documents that we reviewed no references to such alternatives were found, nor were the decision makers and advisors interviewed in February 2017 and 2018 aware of any such deliberations [67]. The feasibility study [64] indicated that efficiency and productivity improvements were considered. However, it concluded that “productivity increases alone will not be enough to accommodate the expected long-term increases in cargo volumes and likely increases in vessel sizes” [64]. Increased cooperation with ports in the region as an alternative to port development was not seriously explored. The feasibility study indicated that regional cooperation is hampered by the lack of good coastal roads connecting adjacent ports as well as problems with customs and issues of national pride [64].

This means that a systematic assessment of the alternatives in terms of ecosystem effects is lacking, but does this mean that an ecologically friendly alternative to port development was missed? From the qualitative judgements in the feasibility studies and subsequent expert interviews (see Appendix A), a realistic ecosystem-based alternative to port development in the Tema case study seems unlikely. Although the lack of serious consideration given to Level 1 of the framework is not consequential for Tema, this may be different for other seaports.

4.3. Level 2—Were Different Sites for Port Development Considered and Possible?

Alternative sites were considered in the pre-feasibility study [66]: two existing sites (i.e., Tema and Takoradi) and four new sites (i.e., Ada, Winneba, Apam, and Dago) for port development. As the site selection preceded the ESIA study, the quantitative ecosystem impacts at the sites had not yet been assessed. However, ecosystem aspects were considered qualitatively in the evaluation of the suitability of the new sites. The locations Ada and Dago were dismissed on environmental grounds, because of effects on the littoral drift (i.e., longshore sediment transport rates), nesting grounds for sea turtles, or sensitive natural habitats nearby. Hence, the character and functioning of ecosystems played a role in the process of site selection. However, opportunities to (partly) restore degraded ecosystems were not explicitly considered at this level.

Eventually, the two existing ports were selected as feasible alternatives for expansion, but mainly for functional reasons such as available development space, proximity to deep sea area, hinterland connections, and supporting services. Although not explicitly mentioned in the pre-feasibility study, an existing port is often also preferable from an ecosystems point of view (see also Section 3.2). It is likely that there are more sites than Tema and Takoradi that could be considered feasible for ecosystem-based port development along the coast of Ghana, but that the reduced impacts associated with port expansion predominated over other considerations. Hence, the focus on two sites for further analysis represents sound reasoning in the Tema case study.

4.4. Level 3—Were Different Port Layouts Considered and Possible?

The selection of the port layout for Tema port expansion was addressed in both the pre-feasibility [66] and feasibility [64] studies. The required extent and the geometry of the layout designs were based on two noticeably different development scenarios for Tema port. The first scenario involved a 'gateway port' mainly to serve Ghana and transit traffic with only limited transshipment [64]. The second scenario involved a 'regional hub port' to serve Ghana as well as the neighboring countries by transshipment [64]. Compared to the gateway port scenario, the regional hub port scenario involved a doubling of the traffic volume in Tema and much larger shipping vessels. In the gateway port scenario, several alternative designs were explored to expand the container handling facility and to upgrade the existing port infrastructure within its present layout. Such a scenario would be preferable from an ecosystems' perspective, because of the limited dredging and construction that is required. However, the regional hub port scenario was eventually selected. This required a layout expansion for Tema port.

Within the regional hub port scenario, three alternative port layouts were considered (see Figure 5). Alternative 1 is an expansion to the west with alongshore container berths protected by a shore-attached L-shaped breakwater. Alternative 2 also involves a westward expansion, but the container berths are perpendicular to the shore and are protected by a detached breakwater. Alternative 3 involves a seaward extension with new container berths connected to the present breakwater and protected by an extended breakwater. These alternative designs were developed primarily to satisfy economic and functional requirements, such as minimizing construction costs and creating deep berths. In the reviewed documents ecosystem needs were not considered in the initial design of these layouts.

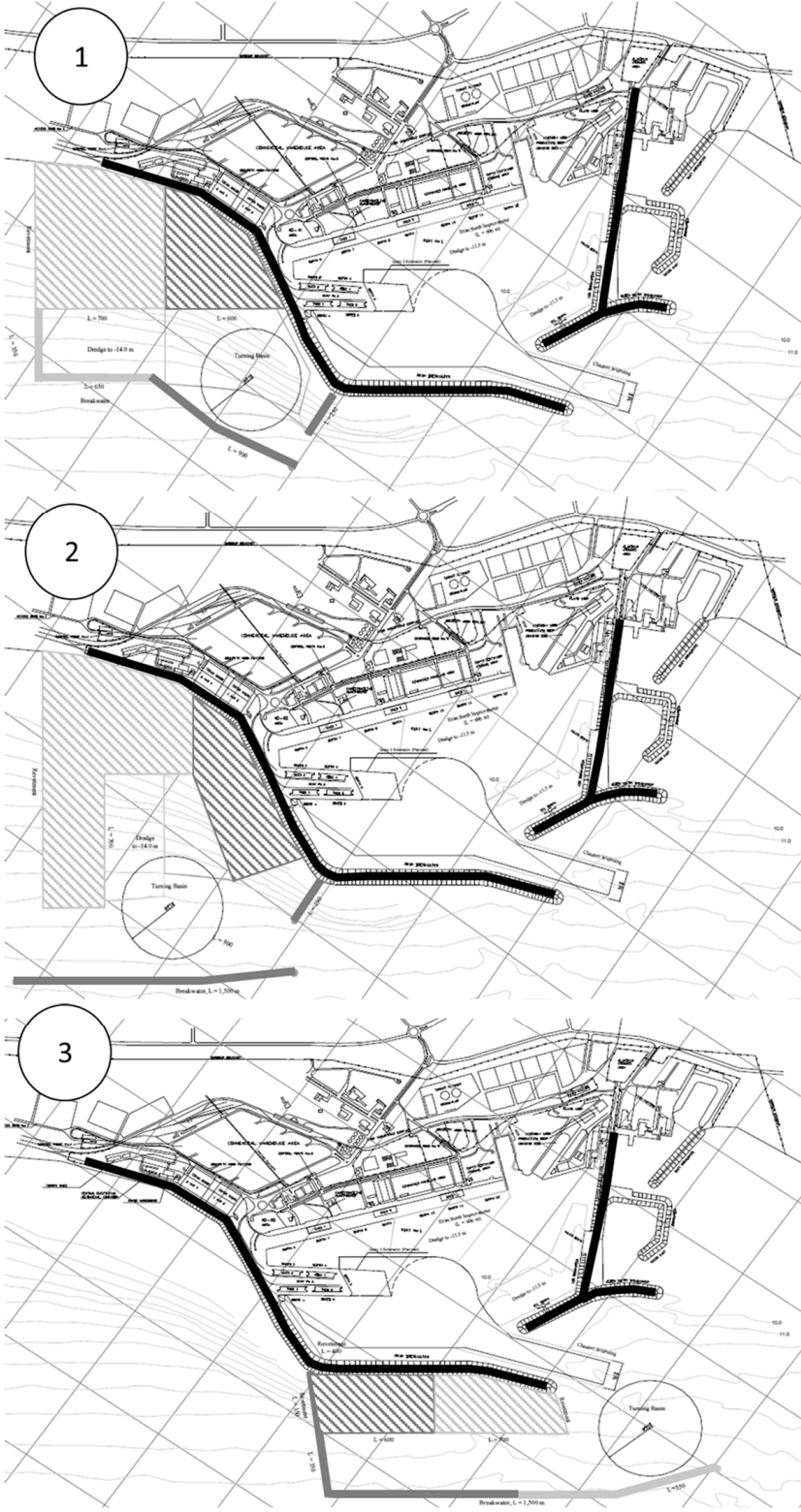


Figure 5. Port layout alternatives considered for Tema port expansion in the pre-feasibility study by JICA and GPHA; Alternative 1, 2, and 3 from top to bottom (adapted from [66]). In black, the breakwater layout before expansion; in dark grey, the first stage construction of the extended breakwaters (lines) and reclamation (diagonally shaded areas); and in light grey, the second stage construction of breakwaters (lines) and land reclamation (diagonally shaded areas).

For the selection of a preferred layout, the alternative designs were compared qualitatively. Although ‘harmonization with environment’ formed one of the criteria, the reviewed documents contained little motivation for the scores assigned to each of the three layouts for this criterion. All alternatives received the highest score of three stars. However, the ecosystem impacts associated with Alternative 3 are in all probability lower than for the other options. First, Alternative 3 requires less dredging to deepen the port basin and access channel than the other alternatives, because the berths are located in naturally deep water. Second, the offshore expansion does not directly affect the coastal zone west of the existing port. This zone has higher heterogeneity and, therefore, is richer in habitats and biodiversity than the offshore zone. The coastal zone is also less affected by the ship traffic that directly impacts offshore ecosystems through noise and pollution. Third, the layout of Alternative 3 leaves the option open to restore the Sakumo II lagoon, the protected Ramsar site adjacent to the port. Although Alternative 3 was also suggested as the preferred option in the feasibility studies [64], an extended version of Alternative 1 was eventually selected for implementation and the ESIA did not consider Alternative 3 at all [65].

A motivation for choosing to exclude Alternative 3 in the ESIA could not be found in the reviewed documents, and was not known to the experts interviewed. In particular, this means that a detailed assessment of the environmental and social impacts of Alternative 3, a potentially more ecosystem-friendly layout design for Tema port than Alternative 1 or 2, was not conducted. Furthermore, restoration options for the Sakumo II lagoon were not addressed, indicating that opportunities for sustainable port development were missed in the Tema case at Level 3 of the EPDH.

4.5. Level 4—Were Ecosystem-Enhancing Options for Port Structures and Materials Considered and Possible?

The feasibility and ESIA studies for the expansion of the port of Tema considered a number of alternatives for the breakwaters and quay walls [64,65], but ecosystem-based alternatives were not included. The feasibility study, based on Alternative 3, considered rubble mound and caissons breakwaters as well as the following quay wall alternatives: concrete block wall, pile-supported platform (pier), and pre-cast concrete caissons [64]. The ESIA considered cellular cofferdams as an additional alternative for the quay walls [65]. However, nature-based solutions for the engineering structures [6,55,58], and other productivity and biodiversity considerations such as the potential to increase the heterogeneity and potential for niche habitats on the hard substrate [60–63] were not included in the identified alternatives. This means that ecosystem-based alternatives for structures with more habitat complexity and the use of eco-friendly materials were possibly missed.

In the evaluation of alternatives, ecosystem considerations were also not mentioned in the reviewed documents. The breakwater options were primarily evaluated on functional, operational, and economic aspects such as structural integrity, ease of construction, material requirements, and the costs of constructing and maintaining the infrastructure [65]. The quay wall alternatives were evaluated qualitatively on buildability, durability, local expertise, availability of equipment locally, adaptability to the local soil conditions, wave reflection, and the costs of construction. This suggests that ecosystem-based considerations had no influence on the selection of the designs for the breakwaters and quay walls.

4.6. Summary of Results at All Four Hierarchical Levels

Table 3 summarizes the results of retrospectively applying the EPDH to the Tema case study. First, the results indicate that ecosystem considerations played a limited role, at best, in identifying potential alternatives at all levels. This highlights the need for a framework to broaden and structure the identification of port development alternatives. Second, in evaluating alternatives, ecosystem-based criteria played a limited role. Only at the level of site selection did ecological aspects contribute to the dismissal of new sites for port development. At each of the other levels, ecosystem considerations were either not included in the evaluation criteria (i.e., level 1 and 4) or weakly motivated in assigning scores to the alternatives (i.e., level 3). Third, our analysis indicates that, although it is unlikely that

ecosystem-based alternatives were possible on the highest levels of planning and design (i.e., levels 1 and 2) in the Tema case study, too early dismissal of alternatives could lead to ecosystem-friendlier alternatives being missed. In terms of the designs for port layout and the structures and materials used (i.e., level 3 and 4), a wider range of alternatives certainly could have been explored. Fourth, because most of the design decisions preceded the ESIA, the environmental effects of potentially more ecosystem friendly design solutions were not assessed in-depth. In consequence, they did not form part of public decision-making on port development in Tema.

Table 3. Summary of the results of retrospectively applying the ecosystem-based port design hierarchy to the Tema case study.

Level of the EPDH	Ecosystem Considered in Identifying Alternatives?	Ecosystem Considered in Evaluating Alternatives?	Ecosystem-Based Alternatives Possible?	Included in ESIA
1. Alternatives to a port	Unknown	Unknown	Unlikely	No
2. Port site selection	Limited	Yes	Unlikely	No
3. Port layout selection	No	Limited	Yes	No
4. Structures and materials	No	No	Yes	Yes

Our analysis suggests that opportunities for ecosystem-based port design were possible missed for Tema, demonstrating the potential added value of our framework in identifying, designing and evaluating a broader range of alternatives. Although a wider variety of alternatives will not guarantee achieving more ecosystem-friendly decisions, the trade-offs made between the technical, economic, and ecological aspects of port development become more explicit and the decision making more balanced and transparent.

5. Discussion of Learning

As the third and final step of the design science approach, we assess the learning from applying the EPDH framework (i.e., the prototype) to the Tema case study (see Section 2 and [29]). We distinguish learning regarding the relevance of the framework to practice (Section 5.1) and learning regarding the rigor of the framework, leading to extending and improving the knowledge base (Section 5.2).

5.1. Relevance of the Framework

The retrospective application of the EPDH framework to the Tema port expansion has demonstrated its potential added value in identifying a wider range of ecosystem-based port alternatives. Our analysis indicated that more ecosystem-based design alternatives and restoration options were possible at the lower levels of port planning and design (i.e., layout, structures, and materials). The ecological effects of these alternatives were not assessed in the EIA, confirming the findings from earlier studies that the number of design alternatives for site selection, layout and structures considered in EIAs is often limited, and that the focus of EIAs is on offsetting rather than on avoiding ecosystem impacts and restoring ecosystems [24,27,32]. These findings are not unique to the Tema case. However, establishing the value of the EPDH framework more generically for port development practice, requires applying it to new case studies of seaport developments particularly *during* the planning and design stages, rather than retrospectively.

The Tema case study proved less suitable for demonstrating the value of incorporating the higher levels of the EPDH (i.e., alternatives to a port development and site selection). Therefore, we turn to the literature. Several studies have stressed the need to incorporate the higher levels in the design and assessment of human developments [21,24,33,37]. If the larger-scale externalities of port developments are not considered at these levels, this could result in long-term negative impacts on both coastal communities and ecosystems [1,9,18]. For example, in the case of Tema, the initial port development (i.e., before the expansion) resulted in rapid urbanization of the area with associated pollution and traffic jams as well as rapid degradation of the ecologically valuable Sakumo II lagoon. Although we

did not have access to the initial design documents of Tema port, it is unlikely that these long-term negative externalities were accounted for in the decision-making process.

5.2. Extending and Improving the Knowledge Base

The focus of the EPDH framework lies on identifying rather than designing and evaluating ecosystem-based alternatives for port developments. Reference [6] provided a framework for designing ecosystem-based design solutions based on: (1) system understanding, (2) identifying realistic alternatives using or providing ecosystem services, (3) evaluating the qualities of each solution, (4) fine-tuning the solution, and (5) preparing the solution for implementation. The EPDH framework precedes this design phase by raising the awareness of port developers that ecosystem-based alternatives do exist and that these need to be accounted for as early as possible in the planning and design process. Once these alternatives are identified the framework of [6] can be used to evaluate the feasibility and optimize the design of these alternatives in the specific project context.

Although the EPDH framework does not explicitly include evaluating design alternatives, the Tema case study demonstrated that inclusion of ecosystem considerations in the evaluation criteria is crucial to achieve ecosystem-friendly port designs. Our analysis demonstrated that ecosystem considerations played a limited role in evaluating alternatives for Tema port expansion. As the higher-level design decisions took place before the EIA (i.e., level 1 to 3), a more comprehensive evaluation of the predicted ecosystem impacts of the alternatives at those levels was not executed. Explicitly including site and layout selection in EIAs (as suggested by [24]) may overcome this problem. Alternatives for structures and materials were considered in the EIA, but ecosystem criteria were not part of the evaluation [65]. This stresses the need to include ecosystem considerations not only in identifying and designing alternatives, but also in the evaluation criteria.

Our study demonstrated that at each level of the framework a wide range of possible ecosystem-based alternatives could be identified from a variety of fields related to seaport development (e.g., ecology, oceanography, engineering, port management, operation technology). The alternatives that we identified should be considered as a first inventory and are only a subset of what is possible in practice. Also, the practical feasibility of the alternatives will be context specific. With the many advances and innovations in all fields related to seaport developments, the number and extent of ecosystem-based alternatives is likely to grow in the near future. Therefore, the contents of the framework and its scientific knowledge base can be further extended and improved by future efforts in science and practice.

Whereas this paper focuses on the ecosystem perspective, also the balance with social and economic perspectives is relevant to achieve sustainable seaport development [1,4,9,13,70]. Reference [1] stressed the importance of more in-depth explorations of the long-term consequences of port developments from economic, social, and environmental perspectives. Considering these other perspectives may result in a diversity of port design alternatives wider than only ecosystem-based alternatives (i.e., the scope of this paper). For example, [9] stressed the need to include and improve the livelihoods of the people in the vicinity of the port development (i.e., the social perspective). Stakeholder inclusion could help to identify an even wider range of design alternatives and mitigating measures [24], addressing the local needs.

Often the requirements from the economic, social, and ecosystem perspectives are interlinked. The concept of 'The Economics of Ecosystems and Biodiversity' (TEEB) [71] can be useful in understanding the links between ecosystems and societal needs as well as in quantifying the value of ecosystems for human beings in the decision-making process [20]. TEEB could potentially aid in demonstrating the economic added value of an ecosystem-based approach to seaport design (e.g., in terms of generated services or prevented loss of existing services), and so support the integration of such economic consequences into the planning and design processes. By recognizing the interdependencies between ecosystems and societal needs in the early stages of port planning and

design, opportunities for long-term mutual value creation for multiple users and user functions (i.e., people, planet, and prosperity) can be increased.

6. Conclusions

In this paper, we presented a framework to identify ecosystem-based alternatives for a port's marine infrastructure earlier and throughout its planning and design process. Placing the ecosystem centrally from the outset increases the opportunities to avoid and restore ecosystem impacts, and to provide ecosystem benefits to stakeholders in and around the port. The framework, termed the ecosystem-based port design hierarchy (EPDH), consists of four hierarchical levels of port planning and design, namely: (1) alternatives to a port development, (2) port site selection, (3) port layout design, and (4) structures and materials. The EPDH framework emphasizes the importance of including ecosystem values in the higher, larger-scale levels, which are often omitted in the environmental impact assessments (EIAs) of port developments.

We tested the EPDH framework by applying it retrospectively to the case study of the expansion of Tema port in Ghana. We found that ecosystem-based considerations played only a limited role in identifying and evaluating alternatives at all four levels of port planning and design. Ecosystem considerations were mostly not taken into account or were only weakly assessed. Applying the EPDH showed that a wider range of ecosystem-friendlier alternatives was possible for Tema, especially in the selection of port layout, structures, and materials. This demonstrates the need for the EPDH and its potential added value in considering a wider range of alternatives in the planning and design process.

The EPDH represents a first step towards sustainable port development by including the ecosystem values throughout the port design process in a structured way. Its added value could be further investigated by applying the framework during the planning and design of seaports instead of retrospectively in other case studies. A relevant future extension of the framework would be to include the social and economic perspectives in the design of a port's marine infrastructure. Furthermore, the concept of ecosystem services could be used to translate the added value of an ecosystem-based approach to port design into economic value to the port and to other stakeholders. Nevertheless, even at this stage, the framework can assist practitioners with earlier and wider scoping of ecosystem-based design alternatives for future seaport developments.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A List of Site Visits, Interviews, Brainstorms, and Feedback Sessions

Date	Activity	Experts Involved
February, 2017	Field trip and open interviews Tema port and surroundings	Prof Kwasi Appeaning Addo and team (University of Ghana), Jacob K. Adorkor (director GPHA), Richard A.Y. Anamo (former director GPHA)
12 May, 2017	Brainstorm port layout design	Martijn de Jong (Deltares), Tiedo Vellinga (Delft University of Technology, Port of Rotterdam), Heleen Vreugdenhil (Deltares, Delft University of Technology), Cor Schipper (Deltares), Arno Kangeri (Wageningen Marine Research), Poonam Taneja (Delft University of Technology), Cornelis van Dorsser (Delft University of Technology), Wiebe de Boer (Deltares, Delft University of Technology)
15 September, 2017	Open interview World Wildlife Fund for Nature (WWF)	Daphne Willems (WWF)
27 September, 2017	Open interview CSIR	Steven Weerts (CSIR)
24 November, 2017	Brainstorm port design hierarchy	Wiebe de Boer, Jill Slinger, Arno Kangeri
08 December, 2017	Research integration meeting	Wiebe de Boer, Jill Slinger, Tiedo Vellinga, Arno Kangeri, Daan Rijks (Royal Boskalis Westminster N.V.), Mark Koetse, Liselotte Hagendoorn, Peter van Beukering (all VU University Amsterdam)
12 January, 2018	Brainstorm ecological engineering designs	Wiebe de Boer, Jill Slinger, Arno Kangeri
February, 2018	Field trip and open interviews Tema port and surroundings	Edward K. Osei (GPHA, director Tema port) and various local stakeholders (for details, see [67])
May, 2018	International feedback on preliminary prototype	International port engineers and scientists attending the 34th PIANC World Congress, 7-12 May 2018, Panama (see [30]), in which the preliminary prototype was presented and feedback was invited.

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