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Comparative financial feasibility analysis of The Vertical Port Concept: A new concept in port expansion.

by

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Abstract

It is well accepted that ports play an important role in the economic development of most of the world nations. Given their importance, mechanisms were established to plan the efficient development of ports. Over the years sophisticated expansion cost evaluation tools were used in an attempt to minimize uncertainties and to support the decision making process, nevertheless, the expansion methods did not change over the time.

This study proposes an alternative port expansion method, the Vertical Port Concept (VPC). The VPC consists on the vertical expansion of the port, by combining several terminals in a vertical structure. This research focus on investigating the feasibility of the VPC as a financially viable port infrastructure expansion alternative, and proposing a methodology that can easily assess the feasibility of the VPC in a purely financial point of view.

This is achieved by compiling the main constraints to port expansions and the variables governing the cost of expanding a port. These variables are then applied in the formulation of a generic port infrastructure expansion cost function that is used to compare the cost of a VPC and a conventional expansion. The outcome of the cost comparison is then compiled into a decision support methodology that intends to provide an easy financial feasibility assessment of expanding by VPC.

The findings of the research suggest that the financial feasibility of the VPC is very dependent on the availability of land. When land is widely available, expansion by conventional methods will result in a much lower investment. When land is not available the site conditions surrounding the expansion will play a major role. The higher the unit costs of the works needed for expanding the port, the higher VPC's feasibility as a potential expansion alternative. The unit cost of the vertical structure, that allows the combination of the terminals vertically, is another key element in the financial feasibility of the VPC. The cost of this structure needs to be at least equal to the savings originated by the VPC when compared to other expansion methods, in order to make the VPC feasible as an expansion alternative.

The methodology proposed focus on the three main aspects mentioned above: The land availability, the site conditions and the savings originated by the VPC. VPC expansion shall only be considered when these three aspects are favourable for a VPC expansion.

Finally, it is imperative that future work investigating other important aspects of the VPC is undertaken, before the final VPC feasibility is achieved.

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1. Introduction

In a globalized world, where prosperity and economic development are influenced by cost-effective transportation systems that link global supply chains, seaborne trade has a major role to play. The United Nations Conference on Trade and Development (UNCTAD) estimates that 80% of global merchandise traded is carried by sea and handled by ports worldwide. These figures reveal the importance of maritime transport for the global economy and how important the sector is to all the countries in the world, developed, developing and even landlocked countries. An effective access to international shipping services and port networks plays a vital role in a country's economic health.

The countries high economic dependence on seaborne trade generates massive cargo volumes that needs to be handled by port infrastructure, bringing pressure on port management strategies. The modern port has to keep up with the latest technological innovations in cargo handling, be able to berth vessels increasingly bigger, compete with neighbour ports for securing trade routes while working to attract new operators. In order to do all this, modern ports must be efficient and competitive.

Frequently, when searching for increasing competitiveness ports need to grow, expanding their areas in order to accommodate new terminals or to expand the existing ones. These expansions represent huge investments and an expansion badly planned could represent the ruin of the port. Common forms of port expansion are either land reclamation, when a port makes use of dredging equipment to create new land from the ocean, river or lake, or the acquisition of new land suitable for port development (Chan & Yip, n.d). In situations of land scarcity, ports have only relied either in land reclamation or in port relocation.

Port expansion developments are extremely costly and complex. Expansion plans must be included in a Masterplan which is used as a guideline for the phased development of the port. Although masterplanning techniques have evolved in recent years, and now are able to account in a more realistic way for the costs and benefits of a certain port development project, the methods of expanding a port have remained the same over the years.

With exception of a very restricted group of terminals, mostly handling vehicle import/export (Williams, 2015), additional capacity was always obtained by relocating the port/terminal in a new area where land is available or by expanding in the original location (Notteboom & Rodrigue, 2005; Chan & Yip, n.d; Hoyle, 1989). With respect to the latter, when land is not available at the original location ports consider land reclamation in order to create land for expansion.

It is the understanding of the author that in cases where land is not available at the original location, or the port expansion is very complex and costly, vertical expansion should be considered. Vertical expansion is a reality in other industries, and the combination of terminals vertically may generate some cost savings when it comes to expanding the port. It is important that this is investigated to know if the vertical expansion of a port can represent an alternative to conventional expansion methods, and if so, under which circumstances can it be considered as an alternative. Taking this into consideration, this research will focus on the Vertical Port Concept (VPC), and study its potential as a financially attractive alternative expansion method.

1.1. The concept

Created to tackle port developments in locations where, for a number of reasons, the expansion of a port is abnormally costly and technically challenging, the VPC consists in combining several port terminals in a multi-storey structure optimizing the land usage. By placing the terminals on top of each other, the expansion area needed for achieving a requested capacity is minimized, given that the area is divided by multiple levels rather than spread horizontally.

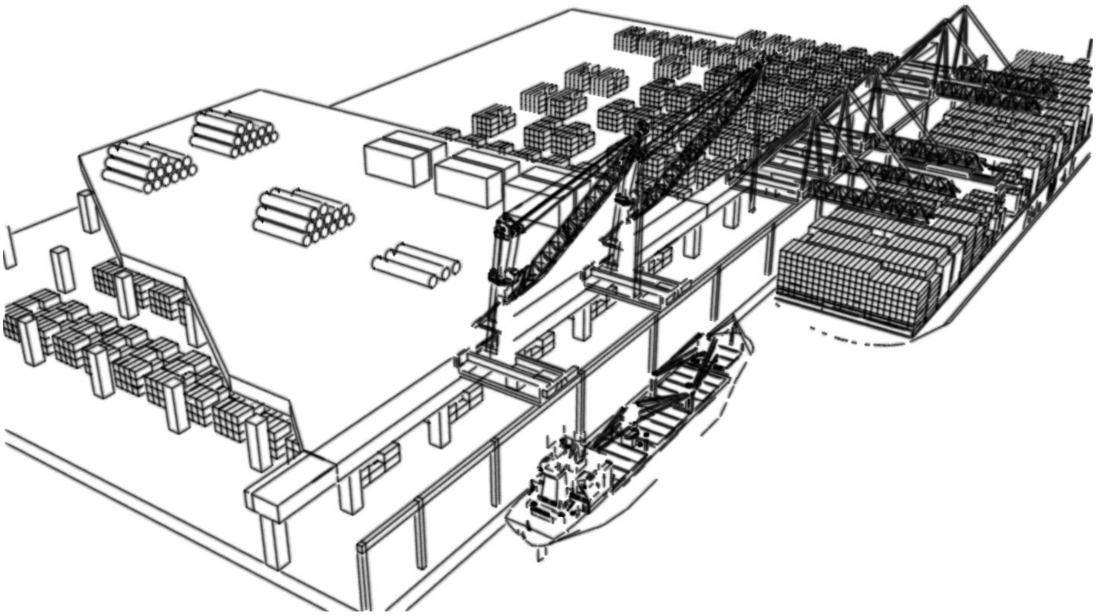

Figure 1 - An artist impression of the combination of two terminals vertically. On the top a general cargo terminal covering half of a container terminal located on the ground floor

It is possible to integrate a wide range of different terminals, and selecting the most suitable combination is a crucial step to ensure a successful implementation. The cargoes that are to be handled must be analysed, ensuring that no inefficiencies or risks are created due to the combination of two non-compatible cargoes. Another field of optimization is the percentage of coverage area. Terminals that are being installed on the top storeys of the structure do not necessarily need to cover the entire ground area, they shall be dimensioned according to the cargo forecasts and capacity requirements. In Figure 1, it is possible to see an artist impression of the vertical combination of a general cargo and a container terminal, on which the top terminal is only covering part of the ground area.

The vertical integration of terminals in many cases does not only optimize the area usage but also creates synergies between the terminals sharing the structure. An example of a potential synergy created by the vertical combination of different terminals is the coverage provided by the top terminal, providing covered storage area for the terminal bellow. This could be beneficial for terminals handling dry cargoes that need covered storage, such as grains or pellets, or help other terminals in meeting the air quality requirements, a very important operational restriction for the bulk terminals specially when installed close to cities or urban areas. One can imagine other synergies such as the concentration of the environmental impact facilitating the implementation of mitigation measures. Nevertheless, this concept is not without challenges, operational and administrative issues may arise when combining terminals vertically and the main uncertainty of them all is the financially viability of building such a vertical structure. These challenges need to be identified and studied in order to investigate the feasibility of the VPC. Additional artist impression drawings can be found in Appendix VI.

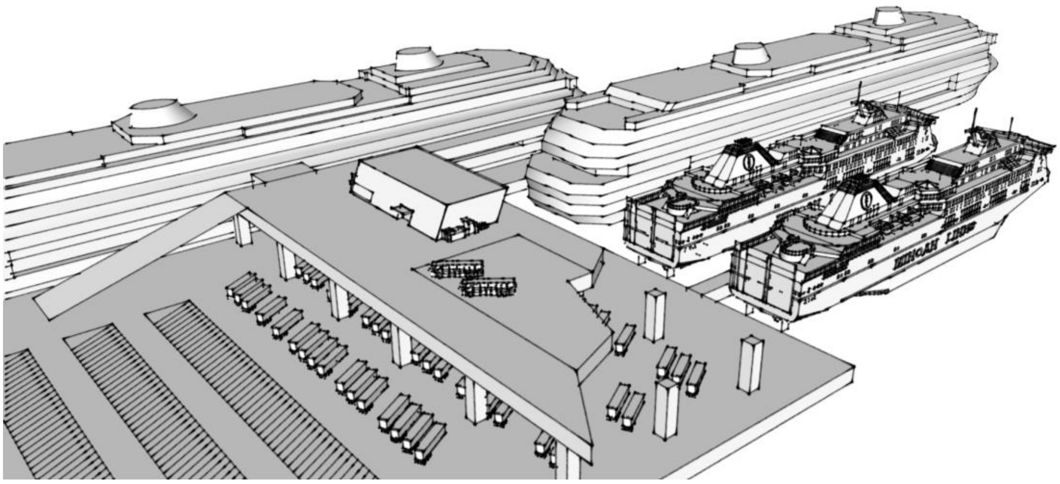

Figure 2 -An artist impression of a cruise terminal combined vertically with a RORO terminal (ground level)

1.2. Objective and research questions

The objective of this research is to investigate and propose a decision making methodology that would allow to easily assess the potential of considering the VPC as an alternative to the traditionally methods applied in a conventional port expansion. By conventional port expansion the author considers expansion by land reclamation at the original site, given that port relocation would be associated with greenfield port developments which lay outside the scope of the present study.

In line with the objective identified, the following main question will steer the direction of this research:

"Under which conditions is the vertical port expansion a financially attractive alternative to a conventional port expansion?"

One can identify two components of the main research question. The first one is with respect to identifying the conditions that will impact a port expansion, and the second one is that a cost comparison between the VPC and a conventional expansion must be performed to assess the financial feasibility of the VPC.

In order to provide a detailed answer to the main research question, the following sub research questions have been formulated and need to be answered:

1) *"Which are the main port expansion constraints?"*

2) *"Which variables are governing the costs of a port expansion project?"*

3) *"How to estimate the cost of a port expansion in a generic mode within an acceptable accuracy that will allow the cost comparison of the VPC and the conventional expansion?"*

Providing an answer to the sub research questions can be grouped under two different approaches. The first approach is to consult available literature that can provide clear and straight forward answers. The second approach will require the development of a cost comparison analysis.

Given the nature of the questions, sub research question 1 and 2 will be answered based in literature review. A considerable amount of literature is available, illustrating the way ports are expanded and the difficulties and challenges encountered by them.

In order to provide an answer to sub research question 3, a cost comparison analysis must be performed. This comes in the formulation of an expansion cost function that will allow the calculation of any given port expansion. The function will be based on the outcomes of sub research questions 1 and 2.

The function will then be validated in order to assess its accuracy and used as an input to the financial comparison of the VPC and conventional port expansion.

The last step of this study will be the preparation of an easy to use VPC financial feasibility assessment methodology, that can be used by the decision maker to easily investigate the feasibility of the VPC as an expansion alternative. Figure 3 presents a schematic view of the research.

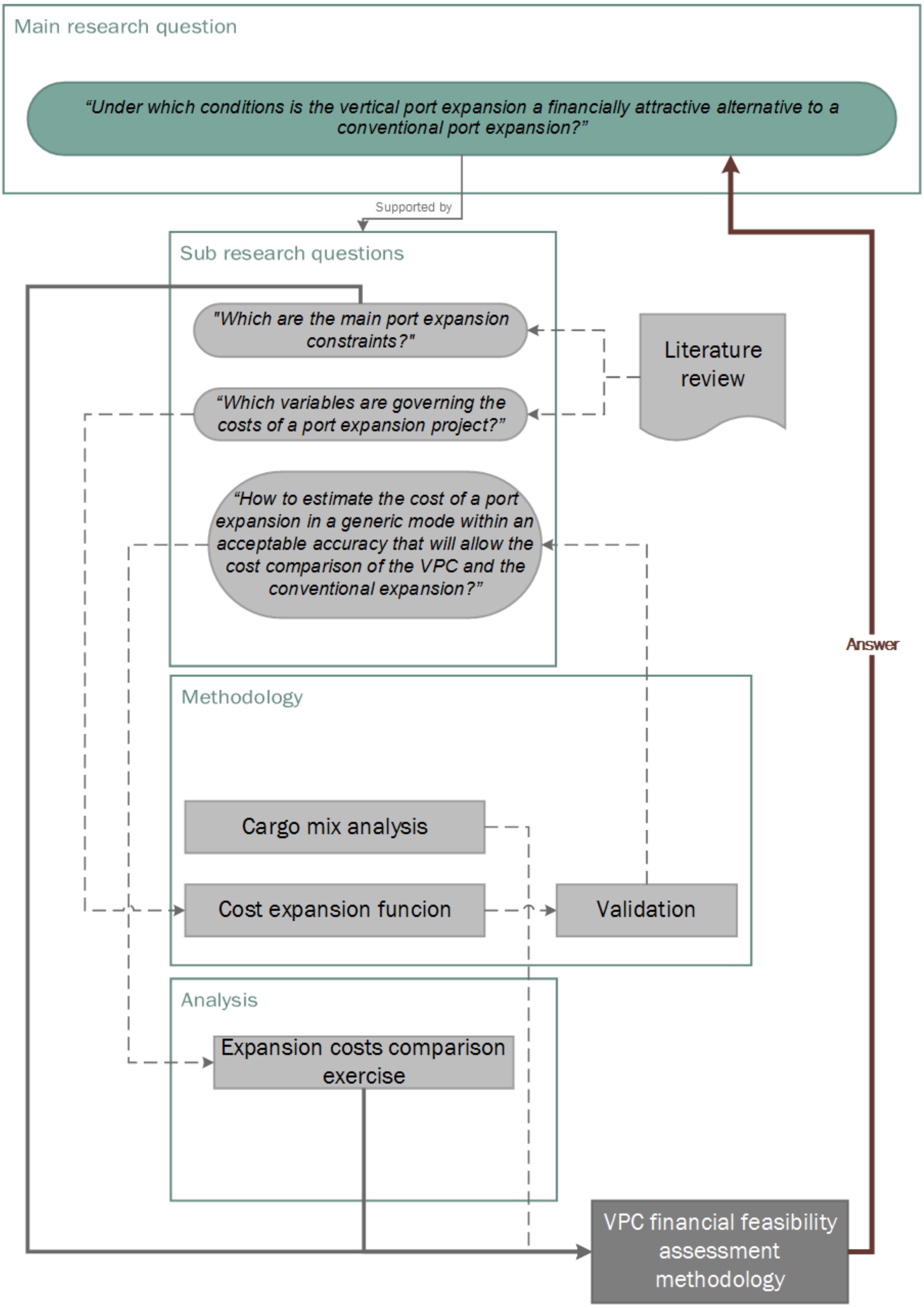

Figure 3 – Schematic view of the research

1.3. Scope of the research

This research focus on the investigation of the condition under which the VPC expansion may be considered as a financially attractive alternative with respect to the conventional port expansion methods.

As mentioned before, for this study the term "*conventional expansion methods"* refer to the expansion by means of land reclamation on the original site of the port. Port relocation is outside the scope of this study.

Although the feasibility of a port expansion is defined to a great extent by the costs of constructing the expansion (Ligteringen & Velsink, 2014), other aspects also play an important role in the decision making process. One of these aspects is the operational feasibility of the alternative. If the proposed expansion will result in an inefficient operational performance, it is likely that the project will not be feasible. Given this, several studies tackling different business areas need to be performed in parallel, to ensure a successful port expansion. Nevertheless, taking into account the size and complexity of these studies, it is not conceivable to investigate all aspects that play a role in the feasibility of a port expansion in this research.

Hence, although the author acknowledges the importance of aspects like the financial structuring of the investment, the institutional set-up (when applicable), operational aspects, socio-economic aspects and environmental impact assessment, in this research only the direct costs of building the infrastructure will be addressed.

With respect to the costs considered in this research, the present study will only focus in the feasibility of the VPC with respect to the construction costs. Other costs, such as congestion costs or externalities are acknowledged by the author but left out of the scope of the investigation. From this point onwards the cost of construction of a port infrastructure expansion will be referred as expansion costs.

Moreover, the scope of the study is limited to the expansion of existent ports with a land lord governance model, where land is not available and port expansion at the original port location can only be achieved by land reclamation. Greenfield port development projects, expansions other than under a land lord port model and ports with available land for expansion are excluded from the scope of this thesis.

Finally, of the port constraints identified further, only the geographical constraints will be taken to account when evaluating the financial feasibility of the VPC. The reasoning behind this is supported by the fact that socio-economic constraints will be somehow independent from the expansion method applied and environmental aspects would need a thorough environmental study, which level of complexity and extension cannot be covered in this research.

1.4. Structure of the document

The present research is structured in 9 chapters. Chapter 2 searches to provide the reader a brief introduction to vertical infrastructure expansion with a special emphasis in port vertical infrastructure, contextualising vertical expansion as a potential way of expanding ports. Examples of what can be considered a vertical expansion in ports as well as vertical integration of services are given in the chapter, working as an introduction to the topic as well as a guide pointing the reader in the direction of the topic of the research.

Chapter 3 aims to provide information acquired from literature review that could answer the sub research question 1. In this chapter, one can find the descriptions of some of the tools and definitions used in port planning and port governance. These definitions are very important for the understanding and identification of the main port expansion constraints.

Chapter 4 will provide a summary of the main techniques existent to evaluate the cost of port expansion and which is the most suitable to apply to the present research. In this chapter the main variables that are considered in a port expansion are also addressed by consultation of the available literature. This step is important given that provides an answer to the sub research question 2 and feeds the variables needed for further chapters.

The formulation of a function that can provide an answer to sub research question 3 is addressed in chapter 5. The formulation of the function will take the output variables resulting from chapter 4.

After the definition of the expansion function, a cost comparison between the conventional expansion method and a VPC expansion is performed in chapter 6. This chapter attempts to identify the main factors that play a role in the VPC financial feasibility with respect to a conventional port expansion method.

In chapter 7, the author proposes a easy to use methodology that allows the decision maker to investigate the potential of VPC as a financial attractive expansion alternative. This chapter is followed by the conclusions of this research compiled under chapter 8.

In chapter 9, some important topics that were not addressed in this research are identified and further work is proposed to allow for an overall VPC feasibility analysis.

2. Vertical expansion

2.1. Introduction

The purpose of this chapter is to provide information of existing structures that allow infrastructure to expand vertically. Although no specific question is answered here, the chapter plays an important role in bringing together information that helps to put into context port expansion and the topic of this research, as well as supporting the motivation behind it.

2.2. Vertical supply

An excellent example of a space consuming expansion is the expansion of cities. Many cities grew from small settlements to modern metropolises fuelled by economic prosperity (Becker & Chen 2015; Glaeser, et al. 1991). Economic prosperity creates new opportunities that attract people and companies from other places to come and settle in the cities, resulting in an increase in the demand for public infrastructure. In order to cope with this increase in demand, authorities need to build new infrastructure to create additional capacity. Faced with land scarcity, cities turn to the sky to grow, and multi-storey structures appeared to satisfy the growth demands. Examples of this were New York City and Chicago, where high rise buildings were constructed to satisfy the demand for quality offices in prime locations (Becker & Chen, 2015) and Singapore where public housing developments include tall and high-density buildings (Wong, 2004).

In the past Singapore managed its land scarcity problems with land reclamation, but this method has limitations and like many other heavily populated cities around the world the solution to accommodate the increasing urban population passes through efficient land usage with super high-rise and high density buildings (Wong, 2004). The majority of modern vertical urban projects consider mixed uses combining commercial and service areas with housing and recreation facilities, all integrated vertically.

Figure 4 - The pinnacle in Singapore. A vertical urban project with high density housing and other services (source: Untourist Singapore)

Vertical expansion is not exclusive to office buildings or housing developments. In the logistic industry the vertical stocking of merchandising and cargo has been around for decades, many warehouses are now stacking vertically. The critical land scarcity in Singapore, resulted in an innovative approach to this issue by a logistics company. The new SH Cogent Logistics PTE one-stop logistics hub combines a warehouse a distribution centre and a container depot in one single building. An interesting characteristic of this integrated structure is that the empty containers are stacked on the roof of the building. This results in a solution to the land scarcity problems of Singapore, according to World Cargo News (2016) Cogent CEO Mr Tan Yeow stated that *“With limitation in land and floor space in Singapore, there is a constant need to be more competitive, efficient and yet cost-efficient”.* This vertical integration of several services shows a constant flow of innovation when it comes to maintaining cost-efficiency when dealing with land scarcity.

Figure 5 - One stop integrated logistic hub with warehouse, distribution and container depot on the rooftop (source: Jack-era.com)

Land scarcity does not necessarily imply there is no land available; in some cases, the land is just not suitable for construction. This is particularly true for mountainous regions and volcanic islands, where steep slopes dominate the landscape. This is the case of Madeira Island, where an airport was build suspended on concrete piles due to the mountainous terrain of the island. See text box 1 in Appendix I. Another example of vertical integration is urban agriculture, see Text box 2 in Appendix I.

Lessons learned from the vertical expansions of other type of infrastructure expansion could represent a solution for ports. By adopting the same high-density vertical expansion, ports struggling with space constraints and increasing demand could reduce the land requirements associated with its expansion.

2.3. Vertical supply in ports

To a certain extent, some terminals have already adopted the vertical expansion philosophy. This is the case of Vehicle import/export terminals. These terminals need parking areas to serve as a buffer between the maritime leg and the land leg of the import/export process. Since cars are a very low-density cargo, large terminal areas are needed to accommodate the vehicles in transit. Faced with land scarcity and increasing distances from the parking areas and the waterfront, some car terminals decided to expand their capacity vertically and installed multi-level car parks. This not only increases the capacity of the terminal, by making optimal use of the available land, but also shortens the distance between the car parks and the waterfront increasing the terminal productivity (Williams, 2015).

Figure 6 - A multi-level car park in a RORO terminal (left), and the cruise terminal at Port of Barcelona. (source: Automotive Logistics Magazine and world Cruiseindustry)

Another example of a type of vertical expansion are the terminal cruises. In order to add value to the terminal operators decided to include other services in the terminal, such as commerce and hotel services. By leasing the commercial areas to prestige hotels and retailers, the terminal operator increases the appeal of the terminal and increase the revenues. This is an example of the potential benefits of combining services vertically, where two different services are delivered in a minimal horizontal port area.

Cruise terminals are not the only port terminals dealing with vertical integration of services. The Kordin grain terminal, located in La Valletta, Malta is also an example of multi-level service integration.

Land is scarce in Malta and the scenario gets even worse if we talk about waterfront land. The Kordin terminal approached this issue in a very interesting way. Installed on a hill near the waterfront the terminal storage silos are located on top of the hill while its handling equipment is installed at the quay wall, located at the foot of the hill, at a considerable vertical distance from the silos. When the grain is unloaded/loaded a conveyor belt makes use of elevators and transports the grain into the silos on the top of the hill. Since the terminal storage is not installed at the same level of the quay wall, it is possible to use the quay to handle other cargo. The terminal also handles Ro-Ro cargo and a small amount of containers. The Kordin terminal is a perfect example of multi-level flexible terminals capable of handling several types of cargo (Kordin Grain Terminal , sd).

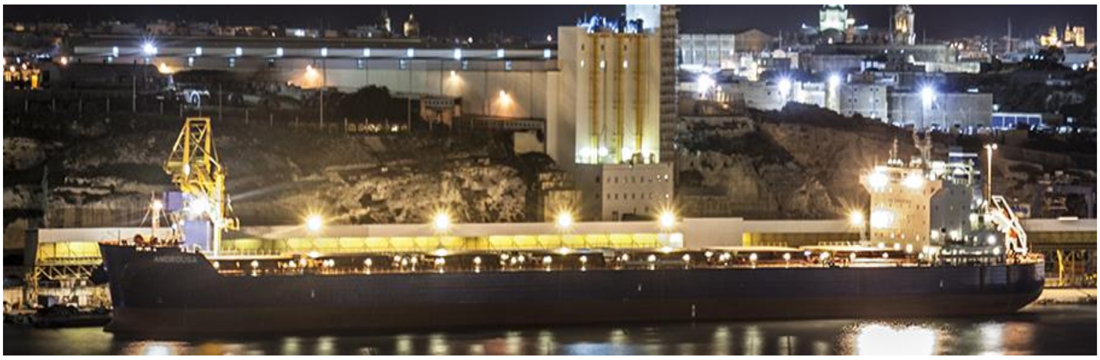

Figure 7 - The Kordin terminal in Malta, with the storage silos on the top of the hill (source: Kordin Grain Terminal)

Another less obvious vertical expansion in ports is the container terminal. Containerization changed the maritime transport forever by allowing the aggregation of break bulk cargoes in a container. Liners are now able to benefit from unprecedented economies of scale and transport costs reduced dramatically.

Figure 8 - Break bulk handling before containerization (left) and a modern container terminal (source: Ship Management International)

Also at the terminal side, there was a revolution, cargo handling efficiency increased rapidly with the introduction of the container.as well as the storage capacity. Terminals were able to accommodate much more cargo on the same amount of stacking area. If we look at this evolution from a different perspective, one can argue that the containerization itself was a sort of vertical expansion of the port. Modern terminals stacking containers with Rail Mounted Gantries (RMG) store on average 5 containers high, in the past the vertical storage of break bulk was very limited, not only because of the shape of the cargo but also due to damages to the cargo given the lack of an exterior hard container. As a result of this, a much larger stacking area was required to accommodate the same amount of throughput.

Another benefit from the container is the weather protection it provides to the cargo replacing the need for covered storage for break bulk. In Figure 8 it is possible to observe the considerable differences between a break bulk terminal before the container era and a modern container terminal. It is clear that the modern container is much more organized, resulting in improved cargo handling efficiency. Another clear difference between the two images is the cargo stacking height, while in the modern terminal containers are stacked on top of each other, in the classic break bulk terminal the stacking density is much lower, with most of the cargo being stocked at the same level.

But perhaps the best example of the vertical expansion in ports is the NYK "Box hangar" installed in Tokyo, described as a "first of its kind" staking solution for containers (World Cargo News, 2008). The hangar consists of a metallic fully automated structure 31 meters high with independent slots for each container compatible with reefers. The hangar will be served by 2 fully automated electric cranes which are able to reach containers stacked at the lower racks without any additional housekeeping moves. By implementing this technology, the yard annual capacity will have an increment of 66% from 36,000 TEU/ha to 60,000 TEU/ha. In Figure 9 it is possible to view an artist impression of the hangar made in 2008 and the actual hangar installed in 2010.

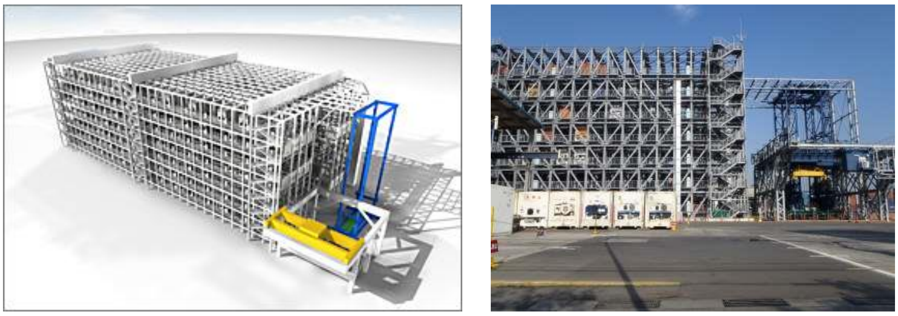

Figure 9 – An artist impression of the NYK Box Hangar (left) and the existing hangar installed in 2010 (source: NYK)

Although some examples can be found of vertical expansion in ports, they tend to handle only one commodity. Terminals with vertical integration of multi-commodity handling, such as the Kordin grain terminal, are very rare and often not built for that purpose. These terminals tend to adapt to its surroundings after being installed and not planning in advance the integration of different commodity handling. Planning ahead is a critical part of any port development project. As a result of the numerous challenges faced by port expansions, there is a need to evaluate the benefits and the costs of expanding a port in the most complete way possible.

2.4. Findings of the chapter

Ports are not the only industry facing expansion constraints, cities, for example, face similar constraints. One of the solutions found in cities to overcome this was to grow vertical. Vertical supply is rare but not new to ports. Some mono-commodity terminals have already made this step, with the clearest example in automobiles import/export terminals multilevel parking lots. The fundamental idea behind growing vertical is to increase the storing density of your land, which will be achieved by storing cargo vertically.

3. Port surroundings and expansion challenges

3.1. Introduction

Ports are historically related to the development of mankind. By connecting major trading hubs and representing the starting point of exploration journeys, ports represent the interface between land and not only water, but with the rest of the world. The economic growth of nations is, to a greater or lesser extent, related to the economic activities of their ports. Ports allow countries to export and import cargo in the most economical way. The economic growth of a country is strongly related to a growth in external trade (Moglia & Sanguineri, 2003) and a growth in external trade often represent an increase in trading volumes, which stimulates the port industry. If more cargo is handled at a port this port will generate more employment and attract more people in search of opportunities, hence more people will establish close to the port, for this reason a number of major cities grew alongside ports. Given their importance, ports need to be as efficient as possible since they represent a vital trade channel and inefficiencies increase the cost of external trade.

In this chapter the author searches to identify the main port constrains that affect many port expansions developments. This is done by understanding the strategy used by ports to evaluate their expansion needs, and the parameters they identify as constraints to their expansion.

By investigating available literature dealing with this topic the author, attempts to provide an answer to sub research question 1

3.2. Port Masterplanning

As a result of their importance to the country's economic health, port strategies must be carefully defined. Masterplanning is the long term planning of the expansion of a given port taking into consideration environmental, urban, physical and eco-social constraints of the port and its surroundings, identifying the objectives of the port and a way to achieve them (Taneja, Walker, Ligteringen, Schuylenburg, & Plas, 2010). In addition, the planning shall not only consider the port expansion by itself but also search for the integration of the port in the in the national and regional strategies and the overall transport network (PIANC, 2014; Moglia & Sanguineri, 2003).

Port expansion strategies can be summarized as two essential questions:

"*When should the port be expanded"* and *"What is the size of the expansion"* (Dekker, Verhaeghe, & Wiemans, 2011).

A very important part of the masterplanning is to be aware of the need of the port users (Thoresen, 2014). This includes the organization of the port itself, or in other words, the port governance.

3.3. Governance model and port expansion

There are 4 generally accepted port governance models: (1) The service port, (2) the tool port, (3) the land lord port, and (4) the private port (Taller, 2009; Langen, 2016; Thoresen, 2014; PIANC, 2014; The World Bank, 2007). There are more variations to these models, such as land lord corporatized model (PIANC , 2014), but we will be focusing on the former 4.

The classification of the port governance model is related with ownership, management, and control of the operations of the port (Taller, 2009; The World Bank, 2007). In a service port all the assets and land are public and owned by the state. The port is managed by a public entity (port authority), and the labour running the ports operations is hired by the port authority.

The tool port is very similar to the service port in the sense that all the assets and land of the port are owned by the government and the port is managed by a port authority, the difference relies on the labour. In a tool port, private cargo-handling companies can be hired to move cargo to and from the vessels.

As for the service and tool ports the land lord port is owned by the government and managed by a port authority. Nevertheless, it leases the land to private operators that will handle the port operations and hire their own labour. The private operators need to build and maintain their own superstructure and acquire the equipment and hire the labour needed to operate the terminal. The private operators pay a lease to the port authority in exchange for a licence to operate in the port for a number of years. The port authority is only responsible for the expansion and maintenance of the basic infrastructure. Given that the port authority owns the port land, the expansion of port land by land reclamation or purchase is also a responsibility of the port authority.

In the case of the private port, the port is owned and operated by a private company. The ownership of the land and assets as well as the equipment belong to the private company that is managing the port.

The services provided by the port can also be outsourced to private companies. Services such as pilotage, towage, mooring services, etc., by private companies with a concession. Typically, service and tool port authorities deliver these services themselves, therefore these are public services performed by labour hired by the port authority. In Private ports the services are performed by private companies, either the private company managing the port delivers the services, or these are outsourced to other private companies. In the case of the land lord port it can be similar to the service and tool ports where the port authority delivers the services or the services can be outsourced to private companies, this will depend on the strategy of the port authority. Table 1 provides a summary of the responsibilities of the port managing authority with respect to the expansion and maintenance of infrastructure, and the provision of port related services.

	ownership	administration	nautical management	Basic infrastructure	superstructure	cargo handling	pilotage	towage	mooring services	dredging
Service port										
Tool port										
Land lord port										
Private port										
		Public responsibility			Private responsibility			Private or public resp.		

Table 1 – Responsibilities of the port managing authority according to the governance model of the port (adapted from The World Bank (2007))

As it was shown, the port governance model of a given port will dictate the responsibility to expand and maintain port infrastructure. In a service port the port authority will be responsible for expanding and maintaining the basic infrastructure and also the handling equipment and superstructure of the terminal. While in a land lord port, the port authority is responsible for the expansion and maintenance of the basic infrastructure but the terminal operator will pay from his own resources the terminal superstructure and equipment expansion and maintenance.

A clear definition of the port governance it is essential given the topic of this thesis. It is important to clarify which infrastructure is to be considered in the expansion cost calculation, and given the scope of this research, only ports with the land lord governance model will be considered. As mentioned above in this case, the port is only responsible for the expansion of the basic infrastructure. The definition of what is generally considered basic infrastructure is provided further in chapter 4.3.1.

All this makes the definition of a long-term strategy plan for a port an extremely complex exercise, where many different areas of expertise need to be combined. Although the expertise applied might differ in nature, they all share an input in common, the location of the port and its constraints.

3.4. Port expansion constraints

Given that the surroundings of the port play a major role in any port strategy, port masterplanning shall always take into account where and how is the port to be expanded. It is of utmost importance that the environmental, socio-economic and geographical constraints are taken into account before the definition of any port expansion strategy (PIANC , 2014; Chan and Yip, n.d.; Hoyle 1989).

Environmental constraints

The environmental awareness in the port industry has gained momentum, mostly because of pressure from stakeholders. Ports are associated with negative environmental impacts, such as, soil contamination, visual impacts, noise, air, water and light pollution. When expanding a port, the environmental impacts must be assessed and the benefits from the expansion must be weighed against the negative externalities of the expansion (Saz-Salazar and Garcia-Menendez 2015; Notteboom & Rodrigue 2005). This is particularly true for ports located in environmentally sensitive areas or surrounded by heavily populated areas.

Socio-economic constraints

Historically many cities evolved together with their ports, resulting in the dense urbanization of adjacent areas of the ports which led to conflicts between the port and the city (Hoyle, 1989). Consequently, the interaction between the port and the city has jumped into the spotlight. This interaction is very important for the efficiency of the services delivered by the ports, an incorrect integration between the port and the cities may cause many unwelcome outcomes, such as congestions in the hinterland links, negative public opinion, land use conflicts, administrative conflicts, among others (Notteboom & Rodrigue, 2005). Parallel to this, expansions in ports surrounded by cities can also be associated with very high opportunity costs (Haralambides, 2002), given that waterfront land is very appealing for real estate developments.

Figure 10 - Urban constraint in ports. To the left the port of Singapore, and the port of Genova (source: Quantum indonesia translogic and The Harbours Review)

Geographical constraints

A port expansion is not only dictated by environmental and socio-economic issues. It is also influenced by its geographical characteristics. Locations surrounded by steep bathymetric slopes or rough terrain might leave few alternatives to port expansion strategies. When surrounded by mountainous terrain or cliffs, the only possibility for port expansion is land reclamation or the relocation of the port.

Figure 11 - The Port of Tenerife and its terrain constraints (source: The Load Star)

Land reclamation can be a very expensive alternative; this is especially true for geographic locations where the continental shelf is very short or inexistent, resulting in high water depths at a short distance from the original coastline. A few hundred meter of quay wall, under such circumstances, might require a very large investment. The same is true for ports surrounded by cities, not only adjacent cities represent a socio-economic constraint, due to the reasons mentioned before, but they also represent a physical barrier that limits the expansion of the port.

3.5. Findings of the chapter

Given the vital role that ports play in global and regional economies, management of the ports is a priority for any maritime nation. Ports need to ensure that they keep up with the demand and adapt to future challenges. The main instrument of ports to do so is called masterplanning. Masterplanning allows ports to plan their activities and their role in the regional or global supply chain. An important part of masterplanning is to derive the functional requirements of the port for the future, and translate that into infrastructure requirements. Often infrastructure needs to be expanded to meet the demand, and to keep a port's market share.

The responsibility of expanding the infrastructure depends on the governance model of a port. For this research the port model that is considered is the land lord port which is only responsible for the expansion and maintenance of the port's basic infrastructure. The basic infrastructure is all the infrastructure that is shared by the port users/operators, this is defined in more detail in chapter 4.3.1.

A smooth port expansion requires the analysis of the port's surroundings that might affect the expansion process. With respect to this, three main expansion constraints were identified: Environmental, Socio-economic and Geographical constraints. This allows the answer of sub research question 1, which asks "*Which are the main port expansion constraints"*.

The environmental constraints are related to the impact of the port expansion in the environment of the areas surrounding the port. The more environmentally sensitive they are, the more significant the environmental constraint will be to a port. Socio-Economic constraints are related to the relation of the port with the community surrounding. In port cities these constraints are very important for ports. Perhaps the most relevant of them all are the geographical constraints, the physical barriers to port expansion are a game changer when it comes to expansion decision making. The geographical constraints can affect the final cost of expansion to a great extent, and will also dictate the type of expansion method to apply.

4. Evaluation of port infrastructure investments

4.1. Introduction

The objective of this chapter is to provide the theoretical background that allows the answer of the sub research question 2. By identifying how are port expansions evaluated and which are the main variables governing their cost, the outcome of this chapter will serve as a valuable input for chapters to come.

A number of evaluation instruments are used in port expansions to ensure the best possible prediction of the outcome of the expansion. Literature regarding the evaluation of port expansion by means of a vertical expansion is rare or non-existent. Nevertheless, there is a considerable amount of literature available on public infrastructure expansion costs, with some of this literature focusing on port conventional expansions. The costs and benefits of expanding a port, being direct or indirect, internal or external, have been researched in detail by the international academic community.

Moreover, given the scope of this thesis, only geographical constraints will be used when investigating the variables governing the expansion of a port. Other variables resulting from other type of constraints will be excluded.

4.2. Typical public infrastructure expansion evaluation tools

A widely used approach to evaluate public infrastructure expansion is by means of a Cost Benefit Analysis (CBA). This methodology is widely used in infrastructure project feasibility evaluation (Saz-Salazar & Garcia-Menendez, 2015) and adopted by administrative bodies such as the European Commission "*Guide to cost-benefit analysis of investment projects"* (Evaluation Unit DG Regional Policy European Commission). Authors like Bristow & Nellthor (2000) studied these strategies and how they apply to transport projects in the European Union, concluding that Multi criteria CBA (MCBA) needs to be applied in order to capture external non-monetary costs more accurately.

In recent years port expansion has become considerably more complex due to the bigger involvement of a larger group of stakeholders (Dekker, et al., 2011; Haralambides, 2002; Moglia & Sanguineri, 2003; Saz-Salazar & Garcia-Menendez, 2015; W.Wiegmans & Louw, 2011). Port expansions need to be able to quantify non-financial impact to the community involving the port, and also to evaluate opportunity costs of expanding elsewhere. Society's higher environmental awareness have made the port expansion more difficult and environmental issues have become a factor of port success (W.Wiegmans & Louw, 2011). Saz-Salazar & Garcia-Menendez (2015) state that CBA alone is a problematic tool for port expansions since it cannot measure multi-dimensional aspects of the project. This results in the representation of a very narrow part of the stakeholders. In order to better quantify the impact of the expansion to a larger group of stakeholders, Multi-Criteria-Analysis (MCA) tools shall be used, in line with the view of Bristow & Nellthorp (2000). Nevertheless, the authors acknowledge the importance of the CBA, by saying that this tool shall still be applied but in a renewed way often called Social Cost-Benefit Analysis (SCBA) running in parallel with some sort of MCA analysis. This will allow having a more complete cover of the impacts of the project, where the CBA covers the monetary part and the MCA covers multiple objectives from the different stakeholders. More advance methods are proposed in order to evaluate external costs and benefits of transport infrastructure expansion, but given the scope of this research they were not addressed.

Having said this, given that the scope of the present research only accounts for capital expenditure related to the expansion of port infrastructure and that environmental and socio-economic constraints will not be considered, a simple cost comparison between different expansion methods will result sufficient to achieve the objectives of this research. At this stage it is assumed that the benefits from the operation of the expanded port area will be very similar regardless of the expansion method applied, hence they are left out of the calculations.

In order to assess the financial feasibility of the VPC as an expansion alternative, it is crucial that the main variables governing the expansion costs are defined. Only after having a clear vision of the variables that will play a role in the expansion of the port, it will be possible to estimate the cost of a given expansion within an acceptable accuracy.

4.3. Variables governing port infrastructure expansion costs

The cost of expanding port infrastructure is directly related with the type and amount of infrastructure that is being constructed. Consequently, the main variables governing the port expansion costs, will be the cost of constructing the port facilities planned in the expansion. Naming the main facilities of the construction of a port expansion is not a straight forward exercise. Port expansions are very case specific, and there is not a standardised approach when classifying the types of port infrastructure. An attempt of naming port infrastructure according to the available literature is done hereafter.

4.3.1. Classification of port infrastructure

Usually in the port industry the port facilities are grouped under more general categories. In widely used port and terminal design literature, such as PIANC (2014), Ligteringen & Velsink (2014) and Thoresen (2014), there is no consensus in how to categorize the infrastructure of a port.

While Ligteringen & Velsink (2014) identify the wet and dry infrastructure and the superstructure, as the main port infrastructure, PIANC (2014) is vaguer, naming a long list of what it classifies of port facilities and infrastructure, but somehow emphasising the infrastructure and the superstructure. The situation gets more complex if we look from the perspective of entity managing the port. As mentioned in 3.3, the port will have different responsibilities depending on the type of governance model. For land lord ports the concept of basic infrastructure is very important, given that it represents the frontier of the ports responsibilities with respect to infrastructure.

Despite a precise definition is not available from the literature, it is possible to identify and classify the following infrastructure in a land lord port point of view:

Dry infrastructure

As the name suggest the dry infrastructure groups all the port infrastructure that is in the dry part of the port that are not specific for a single type of terminal. Given this, the dry infrastructure excludes the structures specific for a given terminal operation, but is rather associated as infrastructure that is shared between the existent terminals of the port or future terminal that may use the port.

Therefore, under dry infrastructure one may find: port access and internal roads, port access rail, general port utilities (e.g. electricity, water, data ducts, etc.) and reclaimed port land

Wet infrastructure
As the dry infrastructure, the wet infrastructure is shared among the users of the port, but in this case it considers only the infrastructure that is on the water side of the port, or the wet side. The wet infrastructure accounts for all the infrastructure that grants safe maritime access to the port, and is composed by: The Navigation channels, the manoeuvring basins, the mooring facilitates, the breakwaters and slope protection installations.

According to Ligteringen & Velsink (2014), the mooring facilities are considered wet infrastructure, even though they establish the interface between the water and the land part of the port. Also, mooring facilities generally have economic lives of 50+ years (PIANC , 2014), given that terminal concessions are usually for 25 to 35 years (Taller, 2009), the same mooring facility can be used by different concessions, making it infrastructure that can be shared between several terminals.

Superstructure
The superstructure is all the infrastructure that is built on the land part of the port that is not shared among the port users, such as: Office buildings, storage yards, pavements and drainage systems, terminal internal roads, terminal utilities installations, crane tracks, covered storage, transfer sheds, workshops, warehouses, etc.

Basic infrastructure
The basic infrastructure contemplate all the infrastructure shared between the terminals, being it dry of wet infrastructure. Thus, the basic infrastructure will include: port access and internal roads, port access rail, general port utilities (e.g. electricity, water, data ducts, etc.), reclaimed port land, navigation channels, the manoeuvring basins, the mooring facilitates, the breakwaters and coastal and slope protection installations.

The concept of basic infrastructure is especially important for land lord ports, given that It will define the limit of the port’s responsibilities regarding the maintenance and expansion of the port.

A summary of the port infrastructure classification is provided in Table 2.

Superstructure	Dry infrastructure	Wet infrastructure	Basic infrastructure
• Buildings • Terminal pavements • Workshops • Terminal internal roads • Drainage system • Workshops • Terminal utilities • Crane and rail tracks • Transfer sheds • Warehouses	• Port access roads • Port access rail • General port utilities • Reclaimed port land • Tunnels • Bridges	• Mooring facilities • Manoeuvring basins • Navigation channels • Breakwaters • Coastal and slope protection • Dams • Dikes • Canals	• Port access roads • Port access rail • General port utilities • Reclaimed port land • Mooring facilities • Manoeuvring basins • Navigation channels • Breakwaters • Coastal and slope protection • Dams • Tunnels • Bridges • Canals • Dikes

Table 2 – Classification of port infrastructure

The design and construction of port infrastructure is influenced by the characteristics surrounding the port (Shneerson, 1981; PIANC, 2014; Ligteringen & Velsink, 2014). Logically the size and the timing of the expansion are an important aspect to take into account (Dekker, Verhaeghe, & Wiemans, 2011), bigger expansions will result in higher capital expenditures. But when holding the size and the timing constant, port surroundings characteristics, or site conditions, ultimately stablish how costly the expansion will be.

4.3.2. Site conditions

Both PIANC (2014) and Ligteringen & Velsink (2014) detail the importance of the characteristics of the surroundings of the port (site conditions) in the design of any port development project. The following site conditions are mentioned in the literature as impacting the design of a port:

Site conditions impacting the design of a port	
Natural site conditions	Man-made site conditions
• Bathymetry • Metocean conditions • Meteorological conditions • Sediment transport • Soil characteristics • Seismic conditions • Topography • Material supply	• Presence of breakwater • Port maintenance policy • Dredging and reclamation needs • Type of quay walls existent • Marine access of the port

Table 3 – Site conditions impacting the design of a port

Different site conditions have different effects on the cost of the infrastructures. Some only impact the construction cost of only one port facility while other may impact a number of facilities. These site conditions are considered as geographical constraints; given that they represent conditions of a specific location. A brief description of the site conditions mentioned before is given further.

Bathymetry
The bathymetry not only affects all the wet infrastructure as one might expect, but also plays a role on the cost of reclaiming land. Essentially, depending on the bathymetric characteristics of the area the land reclamation costs, breakwaters, coastal protection, mooring facilities, manoeuvring basins and navigation channel will vary. Except for the nautical infrastructure (navigation channel and manoeuvring basins), deeper water means higher construction costs.

Metocean conditions
The wet infrastructure is also affected by the metocean conditions of the site. Unfavourable wave climate, for example, will translate in higher vertical motions of the vessels resulting in the need for deeper navigation channels and manoeuvring areas. When berthed the motions of the vessels will transfer higher loads to the quay wall. Consequently, the mooring facilities need to be dimensioned accordingly. The wave climate of the region will also serve as an input to the construction of the breakwaters and coastal defences. More severe extreme waves, will translate in larger more expensive breakwaters.

Meteorological
The meteorological conditions, such as rainfall and wind, will mostly affect the dry infrastructure and the superstructure. On the dry infrastructure side, the rainfall characteristics of the region will influence the drainage system characteristics as well as the roads and pavements. Superstructure will mostly be affected by the site's wind climate. Rougher extreme meteorological conditions will translate in costlier infrastructure.

Sediment transport
The costs of maintaining the wet infrastructure in sites with high volumes of sediment transported by the littoral drift are considerably higher than in places where low or none sediment transport is taking place. The navigation channel is particularly sensitive to this issue, given that a constant draught must be maintained.

Although sedimentation is more related with maintenance dredging, which considered an operational cost of a port, in some occasions costal defence structures must be constructed to account for the effects caused by the port infrastructure in the littoral drift (i.e. accretion or erosion of the coast line). The costs of these mitigation structures are directly related to the amount of sediment transported by the local littoral drift, and must be included in the expansion costs.

Soil characteristics
The soil characteristics of a site are important for the construction of any new port infrastructure. Dry infrastructure and superstructure will use the soil characteristics as a design input, as well as wet infrastructure. Nevertheless, the soil characteristics

assume a higher importance in the case of reclaimed land and wet infrastructure such as navigation channels and manoeuvring basins.

will determine how costly dredging, reclaiming and earthworks in general will be. Poor soils (e.g. composed by soft materials) tend to significantly increase the expansion costs of a port. Dredging is related to the construction of the wet infrastructure such as manoeuvring basins and navigation channels, also when reclaiming land, it may be that the soil has very poor characteristics until a certain depth and needs to be replaced by more suitable material. In these cases, dredging is also needed to create reclaimed land. The amount of earthworks and reclamation will depend on the soil characteristics as well. In the case that extra dredging measures need to be applied to extract soft materials, a larger amount of reclamation material will need to be used. Additionally, there is a high chance that soil consolidation measures will need to be in place before the reclaimed land is suitable to be used.

Seismic conditions
In location exposed to seismic activity it is important that all the port components are designed to deal with earthquakes and tsunamis. Overlooking this aspect could result in a catastrophic outcome.

Topography
The layout of any port expansion is likely to be influenced by the topographic characteristics of the site. Whether an area is relatively flat, mountainous or is below the flooding level, will impact the costs of expanding a port. This is particularly important for reclaimed land, where one must ensure that the final level is above the flood level of the site, and for other dry infrastructure such access roads and rail, where the amount of earthworks necessary will affect the final cost of construction.

Material supply
The availability of natural construction material (e.g. Sand or rocks) will play an important role on the costs of the dry and wet infrastructure. This is particularly important for the creation of port area in cases where land reclamation is needed and for the construction of breakwaters and coastal protection structures. The further away the material is, higher the cost. Also general construction material availability is extremely important. In remote areas, where the construction material needs to be imported over long distances, the construction costs increase significantly.

Man-made site conditions
These site conditions are associated with the evaluation of the existing infrastructure of the port, and analysing if they are in line with the requirements of the expansion.

For example, it can be that an expansion is planned to add more capacity to the port, but that the design vessels remains the same as in the existing situation. This means that the maritime access of the port will, most probably, not require an expansion (granted that no congestion issues would arise).

Given that the man-made existent conditions are constant and their effect in the expansion costs is independent of the expansion method implemented, these site conditions will not be further detailed in this study and will be excluded hereinafter.

The site conditions will impact the design of a port, because they impact the magnitude and complexity of the construction techniques applied in the port expansion. In order to have a better understanding of expansion costs, it is important to focus on the techniques applied in expanding the port. The reason for this is that different construction techniques have different costs. Hence, they affect the total cost of the expansion differently

4.3.3. Construction techniques

The only way to account for the real costs of expanding infrastructure is to consider the amount of works spent on the construction of the expansion. The reason for this is that the infrastructure expansion is achieved by applying several construction techniques, which in some cases, need to be combined. For example, one does not simple construct reclaimed land. Reclaimed land is achieved with a combination of dredging (in the case unsuitable material is in place), reclamation, and earthworks (in the case soil consolidation is needed). Hence, the need of grouping the infrastructure by construction technique.

Most of the superstructure and dry infrastructure is achieved by means of structural and civil techniques. The mooring facilities, breakwaters and coastal defences, although belonging to the wet infrastructure class, are also achieved by means of structural and civil works.

On the water side, the port navigation channels might need to be deepened or expanded, or new channels may need to be dredged, representing a very costly but often unavoidable task.

Certain types of expansion might not only require dredging works but also land reclamation. This is common in cases where ports are left with no other choice than expanding towards the sea, where land reclamation is the only way to provide land for expansion. Dredging and reclamation costs can be very significant for a port expansion.

Earthworks (including soil consolidation) are a vital part of any port development project. Often port development projects are associated with the transportation of massive volumes of soil, either to create or consolidate land. Earthworks are needed across all the main expansion components, but they are especially relevant for the creation of reclaimed land that will be used to install the dry infrastructure and superstructure.

Given the above, in a rather simplistic approach, one may argue that the port expansions can be completed by means of 3 main construction techniques: Structural and civil; Dredging and reclamation and Earthworks.

It is clear that many interactions between the different site conditions are expected. By evaluating the cost of the port expansion by the amount of works (i.e. Structural and civil, Dredging and reclamation and earthworks), that will be required to achieve the desired expansion, one automatically account for the different site conditions and their interactions. For example, one can imagine that land reclamation costs increase for regions with poor soil conditions, where extra earthwork measures need to be implemented, but maybe the material availability is at a very short distance, attenuating soil consolidation cots. By breaking the cost of land reclamation by construction technique, one can have a better description of the reality.

4.4. Findings of the chapter

By describing the existing evaluation methods typically used in evaluating public infrastructure developments, and identifying the main variables governing port infrastructure expansion costs, this chapter searches to answer sub research question 2.

Different tools are available when it comes to evaluated public-infrastructure expansion costs. Depending on the level of detail required and on the aspects taken into account, the decision maker can select from a wide variety of techniques. For this study a simple cost comparison will result sufficient to assess the financial feasibility of the VPC as a port expansion alternative.

By looking from a perspective of a land lord port, the main variables governing the expansion of a port are the basic infrastructure. Basic infrastructure is infrastructure shared by the tenants of the port. The maintenance and expansion of any infrastructure that is specific to a given terminal activity, will be of the responsibility of that terminal and not the port managing entity. Nevertheless, the cost of expanding any port infrastructure, including basic infrastructure, is strongly affected by the site conditions of the expansion area.

The main site conditions identified are: the bathymetry, the metocean conditions, the meteorological conditions, the sediment transport, soil characteristics, seismic conditions, the topography of the site and the material supply conditions. Nevertheless, the cost of expanding a port will be the amount of construction works needed to achieved the given expansion requirements. Furthermore, the site conditions impact on the expansion costs is directly related to the complexity of the construction techniques applied.

Taken this into account, the main variables governing the expansion cost of a port will be the cost of the construction of a port according to the type of construction technique applied. The answer to *"Which variables are governing the costs of a port expansion project?"* is the amount of structural and civil works, dredging and reclamation works and the amount of earthworks required to achieve the expansion.

5. Methodology

5.1. Introduction

In the previous chapters an answer to sub research question 1 and 2 is given. This chapter attempts to answer sub research question 3 by performing by attempting the formulation of a port expansion cost function taking into account the variables identified in 4.3. The function seeks to provide an approximation of the total expansion costs of a given scenario in the most accurate and generic way possible.

Once the function is formulated and validated, it can be applied on an expansion cost comparison analysis between the VPC and the conventional expansion method.

5.2. Port infrastructure expansion costs function

The main variables governing the construction costs of expanding port infrastructure were addressed in chapter 4.3. Three main cost variables were identified as structural and civil costs, dredging and reclamation costs and earthworks costs.

In this chapter, an attempt is made to formulate a generic cost function capable of outputting an estimation of the cost of building a port expansion, by taking into account the main variables governing the expansion cost.

It is important to realize that according to scope of this research (see chapter 1.3), the expansion cost function will focus on ports with a land lord governance model, and will not take into account port expansion in the perspective of the terminal operators.

This means that the port expansion will not consider the expansion of privately operated terminals, but rather the expansion of basic infrastructure that will allow the port to create more capacity by leasing the expanded area to private operators. Consequently, the function that will be proposed further, can only be applied in estimating the expansion costs of basic infrastructure of land lord ports.

The structure that allows the vertical expansion under the VPC method will require special attention. In the VPC concept the vertical structure, which will create extra port surface on which port capacity can be installed, is considered to be basic infrastructure. The reason for this is that once the surface is available it can be shared by several port users/operators, hence consistent with the definition of basic infrastructure provided under chapter 4.3.1. Taking this into account, the cost of building the vertical structure is to be included in the function dealing with the cost estimation of the VPC expansion shown in 5.5.1.

5.2.1. Infrastructure excluded from this research

Dams, dikes, tunnels, bridges and canals need for expansion are associated with the increase in traffic in the port. To avoid congestion, the infrastructure connecting the port with the hinterland needs to be able to absorb a potential increase in traffic due to the port expansion. Thus the need for expansion of the mentioned infrastructure is derived from the existing capacity of the port, and will be the same independent of the type of expansion. Furthermore, expansion of this type of infrastructure is not common to every port, on the contrary, it is only needed in a minority of the port development projects. Taking this into account, this infrastructure will be excluded from this research.

Although the port access roads and rails expansion follow the same principles as the infrastructure mentioned, given their importance for the port and the fact that they are present on almost all port expansion projects, they will not be excluded from this study.

5.2.2. Site conditions excluded from this research

Non-natural conditions are also important to the final cost of a port development project. Still, these conditions are very much related to the existing facilities of the port prior to the expansion. Because of this, the non-natural site conditions will have a similar influence in a conventional and in a vertical expansion. For example, the marine access characteristics of a port will, to a great extent, determine the maximum draught allowed in that port. Independently of having a vertical or a conventional terminal, the draught requirements of the design vessel are the same. Therefore, the depth requirements of the wet infrastructure will be the same. Given this, the non-environmental site conditions will be excluded from this research.

5.2.3. Cost function input variables

Figure 12 provides a summary of the cost variables to be included in the function, the infrastructure under them and which site conditions are affecting them.

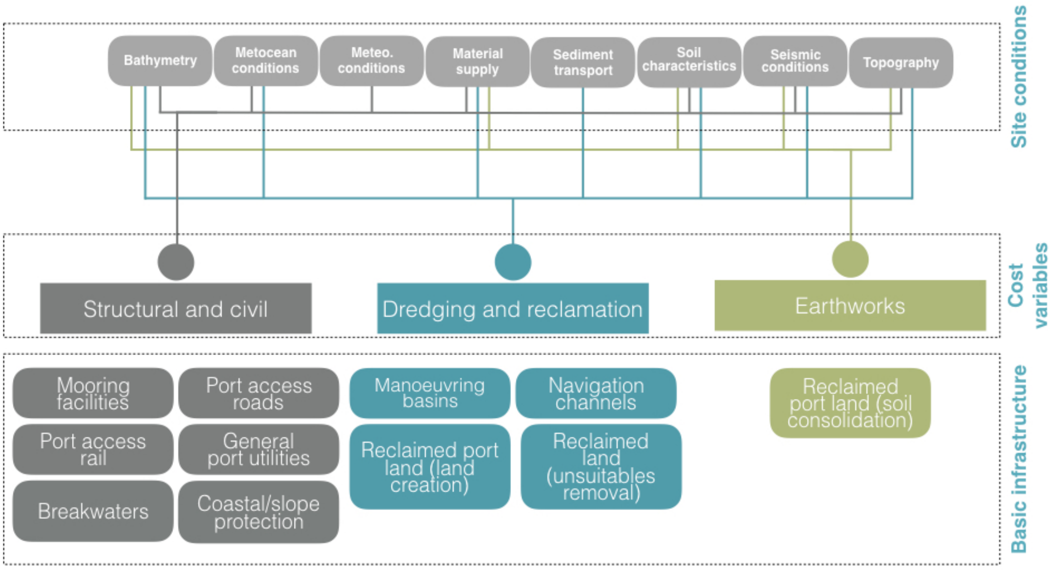

Figure 12 - The construction techniques used to build the main port facilities and the site conditions affecting them (compiled by the author)

5.2.4. General expansion costs function

Taking into account the main cost variables mentioned above, the general port expansion costs function proposed is the following:

$$C_T = C_{SC} + C_{DR} + C_E$$

Equation 1

The expansion total cost (C_T) equals the sum of the structural and civil cost (C_{SC}), the dredging and reclamation costs (C_{DR}) and the earthworks costs (C_E). The main cost variables will reflect the cost of constructing the port expansion infrastructure, which in turn is directly related to the site conditions.

A detailed breakdown of each main cost variable into the infrastructure under it is needed in order to have a better understanding of the interaction between the facilities cost and the site conditions.

5.2.5. Breakdown of the main cost variables

Variables were assigned to the unit cost of constructing a given port infrastructure. This unit cost represents the cost per unit of measure of a given technique used to construct the infrastructure in question.

For example, the mooring facility is constructed by means of structural and civil works and has a certain cost per each meter of quay wall that is constructed. The variables assigned to the basic infrastructure components, the unit of measure for each of the components unit costs and a description of the variable is provided in Table 4.

Port facilities unit cost	Variable	Unit	description
Mooring facilities	C_{mf}	m	The mooring facilities are constructed by means of structural and civil works. The cost of constructing a mooring facility is usually measured by meter of quay wall.
Manoeuvring basins	C_{mb}	m^3	The manoeuvring basins are constructed by means of dredging works. The unit cost of constructing manoeuvring basins is the cost of dredging a cubic meter of material to achieve a given design depth, width and length.
Navigation channels	C_{nv}	m^3	The navigation channels are constructed by means of dredging works. The unit cost of constructing navigation channels is the cost of dredging a cubic meter of material to achieve a given design depth, width and length.
General port utilities	C_u	m^3	The general port utilities are constructed by installing underground utility ducts that allow the supply of water, electricity, data, etc. The unit cost of installation of these ducts is accounted by meter.
Reclaimed port land (land creation)	C_l	m^3	Land creation is done by means of land reclamation works. The cost of land reclamation is measured by the number of cubic meters of material that needs to be transported and deployed to achieve the designed land at the designed level.
Reclaimed port land (removal of unsuitables)	C_{lu}	m^3	In some situations, before reclaiming the area by deploying material, unsuitable material (e.g. soft soils) needs to be removed by means of dredging works. The unit of measure for the dredging of unsuitables in the cubic meter.
Reclaimed port land (land consolidation)	C_{lc}	m^2	The consolidation of the reclaimed land is done by earthworks. The area to consolidate will determine the final cost of the works, therefore the costs are measured in squared meters.

Port facilities unit cost	Variable	Unit	description
Port access roads	C_r	m	The port access roads are achieved by structural and civil works and they are measured in cost per meter of road.
Port access rail	C_{ra}	m	The port access rail is achieved by structural and civil works and it's measured in cost per meter of rail.
Breakwaters	C_{bw}	m	The construction of breakwaters is achieved by means of structural and civil works. The cost of breakwaters is measured in meter of breakwater designed, with an increase on the construction of the head of the breakwater.
Coastal/slope protection	C_{cp}	m	The construction of coastal/slope protection is achieved by means of structural and civil works. The cost is measured in meter of coastal/slope protection designed.

Table 4 – Variables assigned to the port unit cost facilities and site conditions

It is important to stress that in order to calculate the total expansion costs, the infrastructure unit cost needs to be multiplied by the quantity that is actually being constructed. The quantities shall be included in the equations under the term q_i, where *i* stands for the index of the variable in question in line with Table 4.

The purpose of the breaking down of the main variables is to account for the site conditions impact in the final costs of the expansion, since a lower unit cost of a given infrastructure is directly related with how favourable the site conditions are to the construction of that infrastructure. Below the main cost variables are broke down into the infrastructure composing them.

Structural and Civil costs (C_{SC})
Considering *Figure 12*, the structural and civil costs account for the construction costs of the following basic infrastructure facilities:

Basic infrastructure achieved by structural and civil works		
• Mooring facilities • General port utilities	• Port access roads • Port access rail	• Breakwaters • Coastal/slope protection

Table 5 – Basic infrastructure achieved by structural and civil works

The structural and civil costs variable can be decomposed in the facilities mentioned above according to the variables defined in Table 4:

$$C_{SC} = q_{mf}C_{mf} + q_uC_u + q_rC_r + q_{ra}C_{ra} + q_{bw}C_{bw} + q_{cp}C_{cp}$$

Equation 2

Dredging and reclamation (C_{DR})
Following the same approach for the dredging and reclamation costs, the following basic infrastructure facilities will be taken into account:

Basic infrastructure achieved by dredging and reclamation works	
• Manoeuvring basins • Navigation channels	• Reclaimed port land (land creation) • Reclaimed port land (unsuitables removal)

Table 6 - Basic infrastructure achieved by dredging and reclamation works

The dredging and reclamation costs variable can be decomposed in the facilities mentioned above according to the variables defined in Table 4:

$$C_{DR} = q_{mb}C_{mb} + q_{nv}C_{nv} + q_l C_l + q_{lu}C_{lu}$$

Equation 3

Earthworks (C_E)
In the decomposition of the earthworks cost variable the following basic infrastructure facilities were considered:

Basic infrastructure achieved by earthworks
• Reclaimed port land(consolidation)

Table 7 - Basic infrastructure achieved by earthworks

The earthworks costs variable can be decomposed in the facilities mentioned above according to the variables defined in Table 4:

$$C_E = q_{lc}C_{lc}$$

Equation 4

Once the main cost variables have been broken down to the sum of the cost of the facilities under them, it is possible to rewrite the proposed expansion function.

5.2.6. Port infrastructure expansion function

The need of rewriting Equation 1 comes from the fact that the site conditions will have a different effect on the cost of constructing different port infrastructure.

If a break down would not have been made, it would not be possible to accurately account for the interaction between the site conditions and the expansion costs. This interaction needs to be taken into account when investigating the feasibility of the VPC with respect to a conventional expansion.

If we combine Equation 2, 3 and 4 into a single function we obtain the port facilities expansion cost function:

$$C_T = C_{SC} + C_{DR} + C_E \iff$$

$$\iff C_T = \left(q_{mf}C_{mf} + q_u C_u + q_r C_r + q_{ra}C_{ra} + q_{bw}C_{bw} + q_{cp}C_{cp}\right) + \left(q_{mb}C_{mb} + q_{nv}C_{nv} + q_l C_l + q_{lu}C_{lu}\right) + \left(q_{lc}C_{lc}\right)$$

Equation 5

The port expansion cost function presented in Equation 5, can now be used to estimate the cost of expanding basic infrastructure in Ports. Once the unit costs and the quantities necessary have been established, the terms of the expansion can be replaced and the expansion cost estimated. When a given term is not part of the expansion, let's say the port in not expanding the breakwaters, then the term shall be replaced by 0.

Estimating the unit cost of the works is a complex task. These costs are very dependent of the site conditions, and the site conditions can vary within shot distances. Given this, when applying the expansion cost function some simplifications to the unit costs are made.

5.3. Expansion function simplifications

In order to be as generic as possible the port expansion cost function has a simplified approach to some aspects of the cost estimation. This is particularly true for the construction of long structures that cover different types of site conditions (soil, bathymetry, etc.) such as mooring facilities, breakwaters, navigation channels, manoeuvring basins and coastal/slope protection. These long structures can extend for thousands of meters; therefore, the site conditions will have a different impact on a different section of the structure. Consequently, the unit cost of the structure can vary according to the section being analysed.

To tackle this issue, the weighted average unit costs shall be used in the cost function. For example, if the cost per m of quay wall is $20,000/m for the first 200 m and $10,000 for the remaining 100m, the weighted average cost that shall be inputted in the function will be $\frac{2}{3} \times 20000 + \frac{1}{3} \times 10000 \approx \$17{,}000/m$.

Although this simplified approach will decrease the accuracy of the estimation, given that the objective of this research it is assumed that the simplified approach is sufficiently accurate.

5.4. Validation of the expansion function

In order to assess the accuracy of the expansion cost function, Equation 5 was applied to 2 real port expansion cost estimates. These estimations were performed by PCR in the year of 2015 and 2013 for 2 ports located in the West African region. The content of the reports is sensitive, hence not much details can be made public.

Both the ports were greenfield investments, nevertheless the cost estimation is structured in such way that the cost of basic infrastructure is separated from the remaining costs. Hence, it is possible to use these cost estimations to assess the accuracy of the expansion cost function.

It is important that the basic infrastructure costs are available, given that one of the requirements of the expansion function is that only basic infrastructure costs can be estimated.

5.4.1. Control case 1

Since the project is still confidential, some of the information cannot be revealed, such as the name of the project, the client or the location.

Nevertheless, PCR agreed to release the cost estimate to be used in this researched as a control case. The detailed cost estimate, with the quantities, detailed scope items and unit costs can be consulted in Appendix II. Before applying the function, the unit costs need to be simplified according to 5.3. This will allow the use of a single unit cost per variable. Table 8 summarises the amounts per infrastructure, the unit costs of the works and the weighted average unit cost (WAUC).

Scope	unit	quantity	cost scheme	WAUC
Structural and civil				
Breakwaters	m	1 300	96% $31,975/m 4% $35,172/m	$32 103
Slope protection	m	3 300	53% $20,893/m 47% $2233/m	$12 123
contingency	-	20%	-	-
mooring facilities	m	1 850	100% $45,912/m	$45 912
contingency	-	25%	-	
Access roads	m	17500	57% $3,000/m 43% $2000/m	$2 570
Access rail	m	0		
contingency	-	20%	-	
general port utilities	m	8000	100% $1,000/m	$1 000
contingency	-	20%	-	
Dredging and reclamation				
Dredging				
Land reclamation unsuitables	m3	7 908 363	70% $1.93/m3 30% $2.77/m3	$2.18
Manoeuvring basins	m3	15 224 294	20% $1.93/m3 20% $2.77/m3 60% $9.15/m3	$6.43
Navigation channel	m3	5 996 470	10% $1.93/m3 10% $2.77/m3 80% $9.15/m3	$7.79
Reclamation				
Port land reclamation	m3	16 456 012	29% $3.89/m3 29% $6.40/m3 18% $2.23/m3 24% $6.40/m3	$4.92
contingency	-	25%	-	
Earthworks				
Land reclamation soil consolidation	m2	1 085 900	100% $15.07/m3	$15.07
contingency		25%	-	

Table 8 – Control case 1 quantities, unit costs and WAUC summary

Applying Equation 5 to the quantities and WAUC shown in Table 8:

$$C_T = \left(q_{mf}C_{mf} + q_uC_u + q_rC_r + q_{ra}C_{ra} + q_{bw}C_{bw} + q_{cp}C_{cp}\right) + (q_{mb}C_{mb} + q_{nv}C_{nv} + q_{lu}C_{lu} + q_lC_l) + (q_{lc}C_{lc})$$

$$C_T = (1{,}850 \times 45{,}912 + 8{,}000 \times 1{,}000 + 17{,}500 \times 2{,}570 + 0 + 1{,}300 \times 32{,}103 + 3{,}300 \times 12{,}123) + (15{,}224{,}294 \times 6.43 + 5{,}996{,}470 \times 7.79 + 7{,}908{,}363 \times 2.18 + 16{,}456{,}012 \times 4.92) + (1{,}085{,}900 \times 15.07) = \$478{,}825{,}035$$

The estimation of the port expansion for control case 1 is $478,825,035. This value does not include any contingencies. The original estimation calculations returned a total expansion cost for the basic infrastructure of $684,365,166 of which $112,980,512 were contingency costs. Hence, the original cost estimation performed by PCR without the costs of contingency is $571,384,654. If we divide the estimation outputted from the cost expansion function by the original PCR estimation, we can assess the accuracy of the function:

$$accuracy = \frac{478{,}825{,}035}{571{,}384{,}654} \approx 0.84$$

By applying Equation 5 to the unit costs and quantities provided in the control case 1, an accuracy of 84% was achieved with respect to the original estimation performed by PCR. The accuracy of the function is high, even when a simplified approach to the unit price is done.

5.4.2. Control case 2

The control case 2 considers a smaller expansion also located in the West African region. The accuracy of the function was accessed following a similar approach the calculations for the control case 1. The original cost estimation can be found in Appendix II. Table 9 provides the quantities per infrastructure, the unit costs of the works and the weighted average unit cost (WAUC).

Scope	unit	quantity	cost scheme	WAUC
Structural and civil				
Breakwaters	m	1 900	68% $32,479/m 32% $19,487/m	$28 322
Slope protection	m	560	100% $11,760/m	$11 760
contingency	-	0%	0	0
mooring facilities	m	2 500	36% $48,333/m 32% $58,000/m 32% $3,000/m	$36 920
contingency	-	0%	0	0
Access roads	m	0	0	0
Access rail	m	0	0	0
contingency	-	0%	0	0
general port utilities	m	0	0	0
contingency	-	0%	0	0

Scope	unit	quantity	cost scheme	WAUC
Dredging and reclamation				
Dredging				
Land reclamation unsuitables	m3	9 852 000	66% $4.88/m3 33% $2.33/m3	$3.99
Manoeuvring basins	m3	2 289 000	100% $2.33/m3	$2.33
Navigation channel	m3	61 596 550	100% $2.12/m3	$2.12
Reclamation				
Port land reclamation	m3	8 500 000	77% $2.95/m3 12% $3.52/m3 11% $4.73/m3	$3.21
contingency	-			
Earthworks				
Land reclamation soil consolidation	m2	1 320 000	50% $11.73/m2 50% $5.20/m2	$8.47
contingency				$28 322

Table 9 - Control case 2 quantities, unit costs and WAUC summary

Applying Equation 5 to the quantities and WAUC shown in Table 9:

$$C_T = \left(q_{mf}C_{mf} + q_uC_u + q_rC_r + q_{ra}C_{ra} + q_{bw}C_{bw} + q_{cp}C_{cp}\right) + \left(q_{mb}C_{mb} + q_{nv}C_{nv} + q_{lu}C_{lu} + q_lC_l\right) + \left(q_{lc}C_{lc}\right)$$

$$C_T = (2{,}500 \times 36{,}920 + 0 + 0 + 0 + 1{,}900 \times 28{,}322 + 560 \times 11{,}760) + (2{,}289{,}000 \times 2.33 + 61{,}596{,}550 \times 2.12 + 9{,}850{,}000 \times 3.99 + 8{,}500{,}000 \times 3.21) + (1{,}320{,}000 \times 8.47) = \$366{,}382{,}356$$

The estimation of the port expansion for control case 2 is $\$366{,}382{,}356$. This value does not include any contingencies. The original estimation calculations returned a total expansion cost for the basic infrastructure of $\$434{,}093{,}668$, no contingency costs were assumed for this case. If we divide the estimation outputted from the cost expansion function by the original PCR estimation, we can assess the accuracy of the function:

$$accuracy = \frac{366{,}382{,}356}{434{,}093{,}668} \approx 0.84$$

By applying Equation 5 to the unit costs and quantities provided in the control case 2, an accuracy of 84% was achieved with respect to the original estimation performed by PCR. The accuracy of the function is high, even when a simplified approach to the unit price is done.

Accuracy of the expansion function

The accuracy of Equation 5 was checked against two real cases of port development cost estimation performed by a well-known and prestigious port consultancy company. In both cases the accuracy of the expansion function with respect to the basic infrastructure costs original estimations was 84%.

Although the accuracy verification was performed for only 2 cases, it is assumed that the cost expansion function is accurate enough, and can be used to access the feasibility of the VPC.

5.5. The expansion function and the Vertical Port Concept

The objective of this research is to investigate on which cases the VPC could represent a feasible alternative to a port expansion in a financially point of view. In order to do so an attempt to create a generic expansion function that could estimate the cost of expanding a port within an acceptable accuracy was done in 5.2.

The function created can only account for the expansion of basic infrastructure, and it is based in conventional port infrastructure. If the formula is to be applied to estimate the cost of expanding a port vertically, then it must be adapted to deal with the construction of multi-level expansion.

5.5.1. Accounting for the multi-level nature of the expansion

While in a conventional expansion the area needed for the expansion just needs to be acquired or reclaimed and make suitable for construction of the superstructure, in the case of the VPC the acquired land (by purchase of land of land reclamation) will need to accommodate a structure that will sustain the top level of the expansion.

The additional costs of the construction of this structure will need to be taken into account when assessing the feasibility of the VPC. This is done by adding an extra variable to the expansion function, which will attempt to capture the costs of building the structure that will provide the top level of the expansion. The additional variable (C_{VPC}) is added to to Equation 5, resulting in the equation that will be used to estimate the cost of the VPC expansion:

$$C_T = \boxed{(q_{VPC}C_{VPC})} + \left(q_{mf}C_{mf} + q_uC_u + q_rC_r + q_{ra}C_{ra} + q_{bw}C_{bw} + q_{cp}C_{cp}\right) + (q_{mb}C_{mb} + q_{nv}C_{nv} + q_{lu}C_{lu} + q_lC_l) + (q_{lc}C_{lc})$$

Equation 6

Vertical expansion cost variable
The vertical expansion cost variable will account for the extra costs related to the construction of a vertical structure to accommodate the VPC expansion. The structure top floor will create extra surface that will allow the achievement of the required expansion area, with less land requirements.

5.6. Findings of the chapter

The main purpose of this chapter was the formulation of an expansion cost function able to estimate the expansion cost of port basic infrastructure. The function was set up around the variables governing port expansions costs which were addressed previously. Two different types of expansion functions were created, Equation 5 which attempts to estimate the cost of a port expansion by conventional methods and Equation 6 which adds an extra term to account for the vertical structure when expanding with by VPC.

After defining the function, its accuracy was validated by applying Equation 5 to two real cost estimation cases. These cases were provided by PCR and represent the best practices of the industry when it comes to estimating the costs of port expansion. According to the validation tests, the function could estimate the cost of expanding port infrastructure with an 84% accuracy.

The accuracy of the function is high because the infrastructure terms considered in the function usually represent very capital intensive investments, hence accounting for the most of the final costs. Other scope items that were left out of the function, although playing a role in the port expansion, only represent a small part of the final costs.

Having defined the expansion cost function, it is possible to provide an answer to sub research question 3: *"How to estimate the cost of a port expansion in a generic mode within an acceptable accuracy that will allow the cost comparison of the VPC and the conventional expansion?"",* and proceed with the investigation of the VPC as a port expansion alternative.

6. Financial feasibility comparison analysis and results

The financial feasibility comparison searches to support the answer for the main research question by using the outcome of sub research question 3 and applying it to a fictitious expansion case. The comparison will provide valuable information with respect to financial feasibility of the VPC under different scenarios.

In this chapter the cost of the same expansion is calculated for both the expansion methods considered in this study. Equation 5 is applied for the expansion cost calculation by conventional methods and Equation 6 for the VPC. In order to do so, initially the expansion requirements are described and several expansion scenarios are created.

Secondly we focus in the assumptions that were considered for this analysis and attempt to define generic well founded unit costs and quantities for favourable and unfavourable conditions. This step is required granted that we are dealing with a fictitious port expansion, where no information is available. When dealing with a real case, the unit cost estimation will be available as well as the quantities of the works, hence there will be no need for defining the unit cost ranges nor the quantity ranges.

In order to perform the cost comparison between expanding a port by conventional methods and the VPC method, a fictitious port expansion is established. The expansion is carefully designed to allow the best comparison possible between both methods. In other words, both expansions must be submitted to the same functional requirements (i.e. Quay length, approach and berth/de-berth strategy of the vessels, handling of the vessel cargo, etc.).

6.1. General expansion requirements

The initial situation consists of a multi-commodity port with a total area of 120 ha. For a number of reasons, which definition is outside the scope of the present study, the port intends to expand its existing area by 25 ha to increase its capacity.

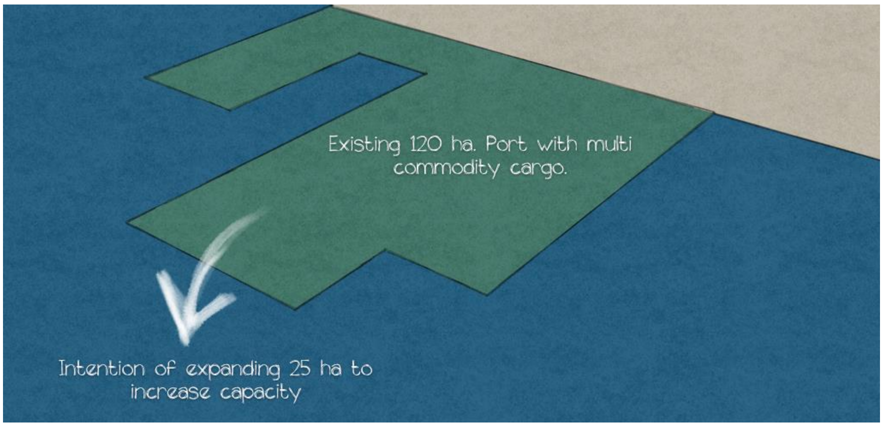

Figure 13 – Expansion requirements.

Additionally, a 500m quay wall will be required. Given that the port is located in a naturally sheltered basin, there is no need for the construction of a breakwater. Additionally, the port access roads and rail will not need further expansion. The same applied to the general port utilities.

As mentioned before port expansions are very case specific, and are affected by many exterior factors. In order to reduce the complexity of the financial feasibility comparison, certain assumptions were considered.

6.2. Assumptions

One of the first steps of any port expansion feasibility study is to assess the site conditions of the area where the port is to be expanded. The reason for this, is that estimating the port expansion costs will be strongly depended on the unit cost and amount of the foreseen works. Site investigations are available or are made available by site visits by experts and surveys, in any port development project. Without the unit costs of the works, estimating the cost of expanding a port would not be possible.

Given that this cost comparison exercise intent to simulate several site realities, and is based in a fictitious expansion case, no unit costs or amounts are available. As a result, the unit costs need to be assumed, granted that this assumption is well founded and reflects the reality to an acceptable extent.

Some of the expansion requirements will be the same independently of the expansion method applied. For example, the fact that additional 500m of quay wall need to be constructed is independent if the expansion is achieved by conventional or VPC method. This will also apply for port utilities, access roads and rails, manoeuvring basins and navigation channels and breakwaters. Thus, it is assumed that these costs will be the same for both methods and they will be left out of the financial feasibility comparison. Therefore, only 4 of the initial 11 variables of the expansion function will be considered, the remaining will be ignored.

It is assumed that no specialized labour or complex techniques are required to achieve the expansion by VPC. The construction of the vertical structure shall be based in existing well known civil structures (e.g. Highway overpasses).

The costs associated with mobilization and demobilization of equipment (i.e. dredging equipment) will not be taken into account, since it is assumed that they will be the same for both of the compared expansion methods.

It is assumed that the site conditions are constant over the expansion area. Therefore, the unit cost of the variables will be constant throughout the entire project implementation site.

Having set the general expansion requirements and the assumptions, several site conditions scenarios were prepared. These scenarios will account for potential site conditions that may occur in a real case port expansion.

6.3. Scenario building

The scenario building will focus in the variation of two main components of the expansion function. The first one is the quantity of works needed to execute the expansion and the second one is the unit cost of the works. For each of the scenarios the cost of expanding the port by a conventional and by a VPC method will be assessed and compared.

The scenarios will try to reproduce variations on the amount and complexity of the works for favourable and unfavourable situations, accounting for situations where the quantity of the works is high but rather simple, as opposed to low quantity of very costly works. By doing so, the author intends to account for the interaction between these two independent variables.

The values to take into account for the low and high unit costs of the works is defined further in this chapter, and are used across the different scenarios. A similar approach is taken in the definition of the low and high quantity of works.

Having said that, four different scenarios were created. In scenario 1, a low quantity of low cost works is estimated. Scenario 4 considers the opposite situation, where a high amount of very costly works is predicted. Scenario 2 and 3 account for the intermediary steps between the two extremes.

The scenarios prepared for the feasibility comparison are summarized in Table 10.

Scenario	Description	Unit cost of works	Quantity of works
1	Favourable unit cost and quantities	Low	Low
2	Favourable unit cost and unfavourable quantities	High	Low
3	Unfavourable unit cost and favourable quantities	Low	High
4	Unfavourable unit cost and quantities	High	High

Table 10 – Scenarios for the expansion comparison

It is important to clarify under which conditions the unit cost will vary and what unit cost is associated to these variations, as well as well as what quantity of works to expect.

6.3.1. Favourable and unfavourable unit costs and quantities

At this point it is clear that the site conditions need to be taken into account when estimating the cost of expanding a port. In this research they are introduced by varying the unit cost of a given facility according to the site conditions. The site conditions are divided into 2 classifications, favourable or unfavourable to the construction of the infrastructure, and they are related to the complexity of the works that will be required.

Another factor that will play a role in the final cost of an expansion is the quantity of the works. As mentioned before, the amount of works will, to a great extent, determine the final cost of the expansion. Also for the quantities, a favourable and unfavourable situation is defined.

The definitions of the favourable and unfavourable conditions for the site conditions and quantities is hereafter provided.

Definition of favourable and unfavourable site conditions

A clear definition must be in place of what are what are the favourable and the unfavourable conditions impacting the unit cost for each port facility. The next step is to create a unit cost range, varying from the unit cost under favourable and unfavourable site conditions to be used as reference in the comparison.

Although establishing a cost range for the infrastructure considered in this comparison is a very complex task, the author resorts to the available literature whenever possible. Some port facilities were studied with much detail, and a considerable amount of literature deals with the costs of expanding them. Whenever the literature search turned insufficient for the definition of a cost range within an acceptable accuracy, the author turned to the empirical knowledge gain by existing port design companies. This resulted in a straight cooperation with the port consultancy company Port Consultants Rotterdam (PCR). A brief description of the company is provided under Appendix III. PCR is specialized in a wide range of port services, among them port expansion studies. It counts with more than 400 successful port development references compiled in a project database. By making the database available for use in this research, it was possible to bridge the gaps in the literature and estimate cost ranges for all the infrastructure variables. The detail procedure in the estimation of the facilities cost ranges is available in Appendix IV. Table 11 summarizes the cost ranges for the variables taken into account and provides a description of the favourable and unfavourable conditions.

Facility	Unit	favourable site conditions ($/unit)	favourable site conditions description	unfavourable site conditions ($/unit)	unfavourable site conditions description
Coastal/slope protection	m	2000	Water depth is ≤ to 2m and filling materials are available locally	20,000	Water depth is ≥5m and filling materials need to be transported over long distances
Reclaimed port land (land creation)	m^3	2	Borrow material is available at a short distance from the filling site, no overburden removal is needed or any extra measures to access the filling material	15	Borrow material is available at long distances from the filling site, considerable amount of overburden removal is needed and extra measures to access the filling material will be needed
Reclaimed port land (removal of unsuitables)	m^3	2	The material dredged is not polluted and the disposal site is at a short distance from the dredging area	20	The material dredged is polluted and cleaning measures need to be undertaken and the disposal site is at a long distance from the dredging area

Facility	Unit	favourable site conditions ($/unit)	favourable site conditions description	unfavourable site conditions ($/unit)	unfavourable site conditions description
Reclaimed port land (land consolidation)	m^2	10	Borrow material is available at a short distance from the filling site	25	Borrow material is available at long distances from the filling site,

Table 11 – Cost ranges of the considered facilities according to the site conditions

The cost ranges estimated are very important to the feasibility study of the VPC. By building scenarios one can replicate certain conditions translated into the facilities unit cost, and evaluate in which cases is the VPC feasible.

The unit costs represent the cost of constructing a given infrastructure by unit of measure. For example the unit cost of the coastal/slope protection under favourable site conditions is $2,000 for each meter of coastal/slope protection built.

Definition of favourable and unfavourable work quantities

As one may expect, the final cost will also be strongly related to the amount of works needed to achieve the desired expansion. In the case of expansions by land reclamation the amount of works will be very much related with the topographic and bathymetric characteristics of the site.

When land is created, it needs to be raised to a certain level to avoid flooding and to allow operations to take place. Land reclamation in deep waters can represent a massive investment even in cases where the unit cost is low, this is because the volume to fill will be very high. Moreover, the volume to fill is also related to the volume of unsuitables that need to be dredged. In the case where soft soil is present at the reclamation site, these unsuitable soils first need to be removed and replaced by suitable material, increasing the required amount of filling material.

Taking the above into consideration, the amount of works in the case of reclaimed port land (land creation) is related to the difference from level at the seabed of the site (after any unsuitables are dredged) until the designed level of the expansion (to avoid flooding and to allow operations to take place). As an example, a port might need the mooring facility to be located at 2m above the mean sea level (MSL), and in that particular site the seabed may be at a depth of -5m with respect to MSL, hence the total volume to fill will be 7m multiplied by the expansion area.

The amount of unsuitables to dredge will be dependent on the thickness of the unsuitable material layer. Nevertheless, for areas where the unsuitable layer is too thick additional measures (i.e. more than 5m deep) different measure will be executed avoiding excessive dredging and posterior filling. Consequently, the maximum height of the unsuitables layer to be taken in this study is 5m, anything higher than that will not be dredged but tackled by other soil consolidation measures.

The amount of works for the land consolidation of the reclaimed land is estimated in a different way of the previous variables. Given the assumption that the site conditions do not vary within the expansion area, the amount to consolidate can vary from 0, in the case where no consolidation is needed, to the entire area, in cases where soil consolidation measures will need to be implemented.

The amount of works does not apply to the coastal/slope protection, given that it will have a pre-defined length and the unit cost variation due to the site conditions already account for cases where more works will be necessary.

Similar to the unit cost estimation, the work quantities estimation was performed by consulting PCR's project database. Table 12 summarizes the quantity ranges for the variables taken into account and provides a description of the favourable and unfavourable conditions.

Facility	Unit	favourable site conditions description	unfavourable site conditions description
Reclaimed port land (land creation)	m^3	The reclamation is done in ≤2m deep waters with a final filling height of 4m.	The reclamation is done in ≥13m deep waters where 5 meters of unsuitables were removed. The final filling height is 18m
Reclaimed port land (removal of unsuitables)	m^3	The material of the site is of appropriate quality and no unsuitables need to be dredged	There is a thick layer of unsuitables located on the expansion site that will need to be dredged. The thick can have a maximum of 5m.
Reclaimed port land (land consolidation)	m^2	The reclaimed land presents adequate soil characteristics for its functional requirements and no soil consolidation is needed	Soil consolidation measures need to be implemented to ensure that the reclaimed land meets its functional requirements. The measures need to be applied throughout the entire area reclaimed.

Table 12 – Favourable and unfavourable conditions for the quantity of the works

The table shows indicative figures for the total in height that will be needed to be filled. Given that one of the assumptions of this research is that there is no variation of the site conditions within the area of the expansion, the total volume to fill can be easily calculated by multiplying the total filling height by the area to reclaim. The same principle applies to the volume of unsuitables to dredge.

The next step is to define the expansion requirements according to the type of expansion method applied. This will allow the financial feasibility comparison.

6.4. Expansion methods

The starting point for any port expansion is the definition of the expansion requirements, these were defined under chapter 6.1. The port wishes to expand its area by 25ha and install a minimum of 500m of quay wall.

With the requirements in mind, it is time to define the final characteristics according to the expansion method that will allow to perform a financial feasibility comparison.

6.4.1. Conventional expansion characteristics

The conventional expansion consists of reclaiming land inside the port area to achieve the expected expansion requirements. This translates in the reclamation of the full 25ha of land, in a 500m by 500m expansion. In this area a 500m quay wall will be installed. The remaining interface between reclaimed land and the port wet area will need to be secured by means of coastal/slope protection. A total of 1000m of slope protection infrastructure is estimated when expanding in a conventional way. An artist impression of the expansion is shown in Figure 14.

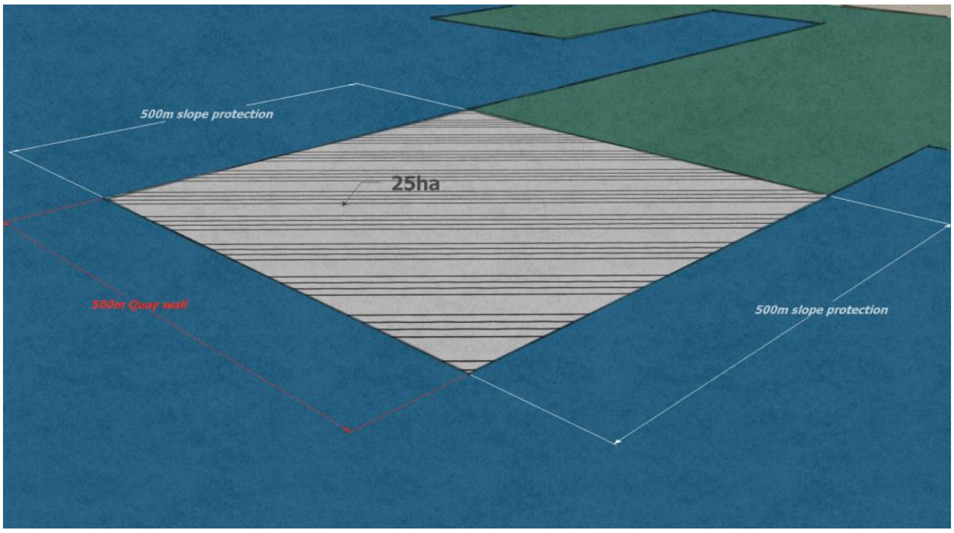

Figure 14 – Artist impression of the conventional expansion

It is possible to understand from the figure above, that the entire 25ha are achieved by land reclamation, and that approximately 1000m of coastal protection will be required.

Expansion function

Equation 5 will be applied as the expansion function in the conventional case. Furthermore, the function will be adapted to the present comparison exercise by taking into account what is stated under chapter 6.2. Therefore, the expansion function to be used for the cost estimation of expanding the port by conventional methods will be the following:

$$C_T = \left(q_{cp}C_{cp}\right) + (q_{lu}C_{lu} + q_lC_l) + (q_{lc}C_{lc})$$

for the purpose of the present cost comparison the total cost of expansion (C_T) will take into account the cost and amount of building coastal/slope protection infrastructure ($q_{cp}C_{cp}$), the costs of reclaiming the land required to accommodate the expansion (q_lC_l), dredging the unsuitables ($q_{lu}C_{lu}$) and any cost associated with soil consolidation measures ($q_{lc}C_{lc}$).

6.4.2. VPC expansion characteristics

The VPC expansion consists on the reclamation of 13.5 ha of land on which a vertical structure is installed providing extra 11.5 ha of surface on top of the reclaimed area.

The extra surface will be sustained by an array of structural piles. The area occupied by the piles needs to be compensated in order to achieve the exact expansion requirements of 25ha. The area reclaimed is larger than the area provided by the vertical structure, the reason for this is that an apron area is to be installed at the lower level of the structure. This apron area will allow operations to take place in a similar fashion as in any modern existing port. The expansion also accommodates 500m of quay wall, and 564m of slope protection infrastructure.

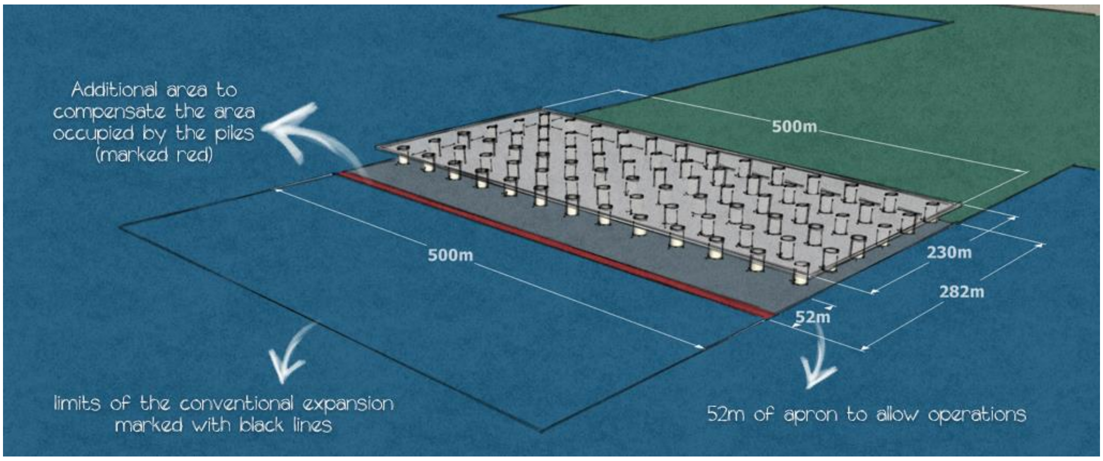

Figure 15 – Artist impression of the VPC expansion

Expansion function

The total cost of the VPC expansion will be calculated with Equation 6. This equation is a modification of Equation 5 considering an extra variable to account for the cost of the vertical structure. The same considerations are taken into account as in the conventional expansion, where only 4 of the 11 variables are to be considered, with the difference that in this case the VPC variable is added. Accordingly, the equation to use in the calculation of the expansion costs by applying the VPC will be the following:

$$C_T = (q_{VPC}C_{VPC}) + \left(q_{cp}C_{cp}\right) + (q_{lu}C_{lu} + q_lC_l) + (q_{lc}C_{lc})$$

The expansion function is very similar to the one proposed for the calculation of the expansion costs of a conventional expansion. The difference lies in the cost of constructing the vertical structure ($q_{VPC}C_{VPC}$).

Deriving the VPC structure unit cost

The cost of constructing the vertical structure will need to be taken into account. Although this type of structure was never applied in a port environment, similar structures are common in other public infrastructure projects. One of these structures are the highway overpasses, where a robust structure sustains the heavy loads of highway traffic. Highway overpasses or viaducts, hold the same basic characteristics needed for the VPC vertical structure. They are constructed over piles, are capable of withstanding very heavy loads, and allow the inferior level to function independently. Given this, the starting point of the VPC variable will be based on the cost of building viaducts.

According to Bouwkosten Kompas (2016), in the Netherlands, the cost of constructing a viaduct is \$1,300 per m^2 (price for 2016). This value will be taken as starting point for the financial feasibility calculations. This variable will represent the core of the financial feasibility comparison, given that by varying the unit cost of the VPC variable, one can compare the feasibility of both expansion techniques proposed under the proposed scenarios.

6.5. Financial feasibility comparison

The comparison will focus on the costs of achieving the port expansion requirements by the expansion methods proposed, the conventional and the VPC method. By considering the different scenarios proposed it will be possible to identify in which situation the expansion is achieved with the least capital requirements.

Table 13, provides a summary of the scenario independent characteristics of each method to achieve the expansion requirements.

Expansion method	Area achieved by land reclamation	Area achieved by other means	Usable area	Quay wall length	Slope protection requirements
Conventional	25ha	0ha	25ha	500m	1,000m
VPC	14.1ha	11.5ha (VPC)	25ha	500m	564m

Table 13 – Expansion characteristics independent of the scenario

The characteristics summarized in Table 13 will serve as input in to the expansion functions of the expansion method, allowing the calculation of the final expansion cost. Nevertheless, some of the characteristics need to be translated into the variables of the expansion function. This is done by taking into account the site conditions and amount of works for each of the proposed scenarios.

The calculations of the quantities to be used in each scenario, according to the expansion method implemented, is shown in Appendix V. The tables presented make the link between the amount of works of the scenario and the characteristics of the expansion method. Additionally, the expansion cost will be calculated for the conventional and VPC expansion methods using the equations shown in Table 14.

	Expansion method	
	Conventional	VPC
Equation	$C_T = \left(q_{cp}C_{cp}\right) + \left(q_{lu}C_{lu} + q_l C_l\right) + \left(q_{lc}C_{lc}\right)$	$C_T = \left(q_{VPC}C_{VPC}\right) + \left(q_{cp}C_{cp}\right) + \left(q_{lu}C_{lu} + q_l C_l\right) + \left(q_{lc}C_{lc}\right)$

Table 14 – Equations to be used according to the expansion method

It is important to stress that in all the scenarios the unit cost of the vertical structure is held constant at \$1,300/m^2, for all the other items the unit cost will vary according to the scenario.

6.5.1. Scenario 1

In scenario one the amount of works is considered to be low for all the variables and the site conditions very favourable to the construction of the expansion. Favourable site conditions will translate in low unit costs of the variables considered.

Table 15 provides a summary of the characteristics of both expansion methods with respect to scenario 1. These characteristics are then used as input in the expansion functions allowing the comparison between a conventional port expansion and a VPC expansion under the conditions set in scenario 1.

	Unit	Unit cost	Quantity conventional	Quantity VPC	Sub-total Convent.	Sub-total VPC	VPC savings (%)	VPC savings (value)
Slope protection	m	$2 000	1 000	564	$2 000 000	$1 128 000	44%	$872 000
reclaiming land	m^3	$2	1 000 000	564 000	$2 000 000	$1 128 000	44%	$872 000
dredging usuitables	m^3	$2	0	0	$-	$-	NA	$-
Land consolidation	m^2	$10	0	0	$-	$-	NA	$-
Vertical structure	m^2	$1 300	0	115 000	$-	$149 500 000	NA	$-149 500 000
				TOTAL	$4 000 000	$151 756 000	-3694%	$-147 756 000

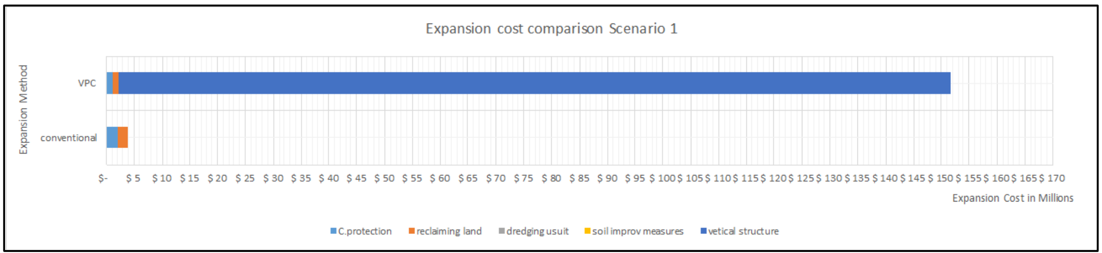

Table 15 - Expansion characteristics and cost calculation for scenario 1

Table 15 shows that under the conditions of scenario 1, with low unit costs and low work quantities, the VPC expansion method will result much costlier than the conventional expansion. In other words, the conventional method would cost much less to achieve the same expansion requirements than the VPC.

The difference between both methods is enormous, with the VPC costing an additional $147,756,000, which represents a 3694% higher investment. Although the VPC allows a 44% saving in the slope protection and reclamation costs, the cost of the vertical structure excludes the VPC as an expansion alternative.

The unit cost of the vertical structure is $1,300/m^2, this value was taken as a starting point and is based in the construction of a similar existing structures. In order to investigate at what unit cost of the vertical structure the VPC becomes feasible a modified breakeven cost analysis will be executed

Breakeven analysis

Two breakeven points will be investigated. The first will represent at which value of the unit cost of the vertical structure alone the VPC will become and alternative, and the second at which unit cost of the remaining infrastructures the VPC will become an alternative, or getting land available.

In the first case it is possible to calculate the exact value of the vertical structure unit cost at which the VPC becomes competitive with respect to the capital investment needed for expanding the port's infrastructure.

For scenario one the breakeven point for both expansion methods is achieved when the unit cost of the vertical structure is reduced to $15.165/m^2. At this value the cost of expanding by VPC and by conventional methods is the same, $4,000,000. This value represents a drop of approx. 99% with respect to the initially unit cost of $1,300/m^2

On the other hand, given that the VPC allows for considerable saves in the construction of the remaining infrastructure (44% for both the costal slope and the land reclamation), it is worthy to investigate how much the unit costs of the infrastructure (with exception of the vertical structure) would have to increase in order to consider the VPC as an alternative. In Figure 16, it is possible to observe the feasibility of the VPC (the point where it comes cheaper to expand by VPC rather than by conventional means) when increasing all unit costs, except for the VPC vertical structure, by a percentage. It is important to stress that increasing the unit costs of the infrastructure will also increase the final cost of the VPC expansion, nevertheless, the conventional expansion cost will grow at a higher rate than the VPC.

In the case of scenario 1 it is clear that not even after increasing the unit costs by 500% the VPC concept represents an economical alternative to the conventional expansion.

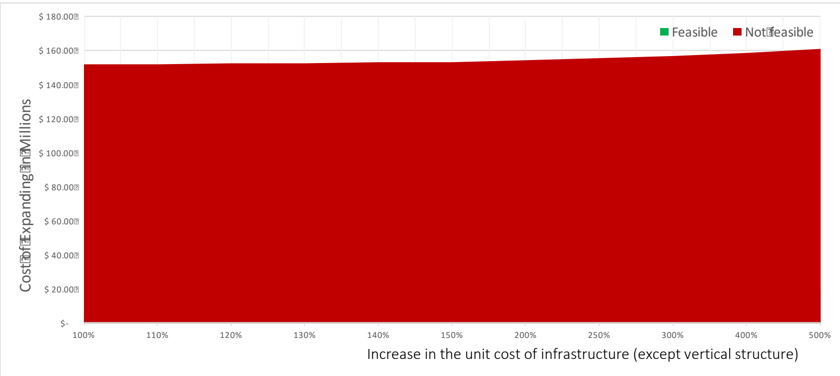

Figure 16 – VPC financial feasibility for scenario 1 when increasing the infrastructure unit costs (except the vertical structure)

6.5.2. Scenario 2

In scenario two the amount of works is considered to be low for all the variables and the site conditions unfavourable to the construction of the expansion, translating into high unit costs.

Table 16 provides a summary of the characteristics of both expansion methods with respect to scenario 2. These characteristics are then used as input in the expansion functions allowing the comparison between a conventional port expansion and a VPC expansion under the conditions set in scenario 2.

	Unit	Unit cost	Quantity conventional	Quantity VPC	Sub-total Convent.	Sub-total VPC	VPC savings (%)	VPC savings (value)
Slope protection	m	\$20 000	1 000	564	\$20 000 000	\$11 280 000	44%	\$8 720 000
reclaiming land	m^3	\$15	1 000 000	564 000	\$15 000 000	\$8 460 000	44%	\$6 540 000
dredging usuitables	m^3	\$20	0	0	\$-	\$-	NA	\$-
Land consolidation	m^2	\$25	0	0	\$-	\$-	NA	\$-
Vertical structure	m^2	\$1 300	0	115 000	\$-	\$149 500 000	NA	\$-149 500 000
				TOTAL	\$35 000 000	\$169 240 000	-384%	\$-134 240 000

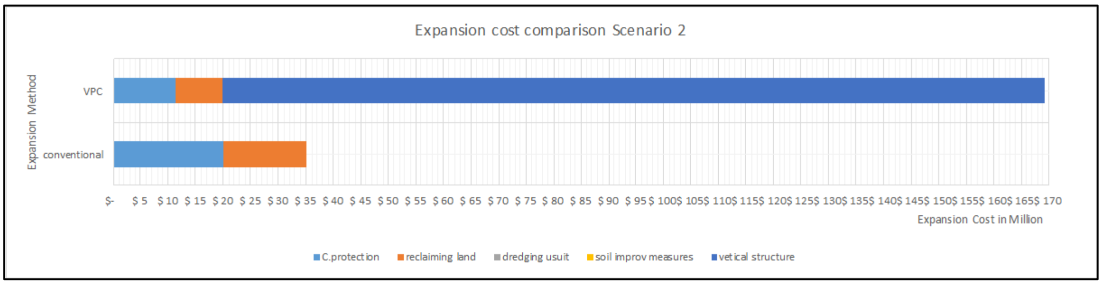

Table 16 - Expansion characteristics and cost calculation for scenario 2

Table 16 shows that under the conditions of scenario 2, with high unit costs and low work quantities, the VPC expansion method will again result in much higher costs than the conventional one.

The difference between both methods is very substantial, with the VPC costing an additional \$134,240,000, which represents a 384% higher investment, considering a vertical structure unit cost of \$1,300/m^2. Although the VPC allows a 44% saving in the slope protection and reclamation costs, the cost of the vertical structure excludes the VPC as an expansion alternative. Although the VPC expansion cost is much higher than the conventional method, the increase in the unit costs of Scenario 2 reduces the difference between the two expansion methods by \$13,516,000.

Breakeven analysis

The breakeven analysis for scenario 2 will follow the same principles as what was presented un scenario 1. In fact, the approach will remain the same for all the scenarios considered in this research.

For scenario two the first breakeven point for both expansion methods is achieved when the unit cost of the vertical structure is reduced to $132.694/m². At this value the cost of expanding by VPC and by conventional methods is the same, $35,000,000. This value represents a drop of approx. 90% with respect to the initially unit cost of $1,300/m². When compared to scenario 1 it is clear that increasing the unit cost plays a major role in the feasibility of the VPC, reducing the cost difference between methods from 3694% to 384%.

In the case of scenario 2 it is clear that not even after increasing the unit costs by 500% the VPC concept represents an economical alternative to the conventional expansion, as shown Figure 17. Nevertheless, the cost difference between the expansion methods was reduced.

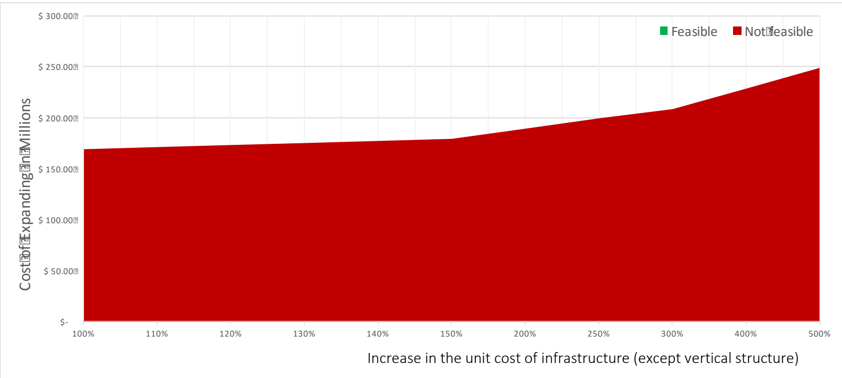

Figure 17 – VPC financial feasibility for scenario 2 when increasing the infrastructure unit costs (except the vertical structure)

6.5.3. Scenario 3

In scenario three the amount of works is considered to be high for all the variables and the site conditions favourable to the construction of the expansion.

Table 17 provides a summary of the characteristics of both expansion methods with respect to scenario 3. These characteristics are then used as input in the expansion functions allowing the comparison between a conventional port expansion and a VPC expansion under the conditions set in scenario 3.

	Unit	Unit cost	Quantity conventional	Quantity VPC	Sub-total Convent.	Sub-total VPC	VPC savings (%)	VPC savings (value)
Slope protection	m	$2 000	1 000	564	$2 000 000	$1 128 000	44%	$872 000
reclaiming land	m^3	$2	4 500 000	2 538 000	$9 000 000	$5 076 000	44%	$3 924 000
dredging usuitables	m^3	$2	1 250 000	705 000	$2 500 000	$1 410 000	44%	$1 090 000
Land consolidation	m^2	$10	250 000	141 000	$2 500 000	$1 410 000	44%	$1 090 000
Vertical structure	m^2	$1 300	0	115 000	$-	$149 500 000	NA	$- 149 500 000
				TOTAL	$16 000 000	$158 524 000	-891%	$- 142 524 000

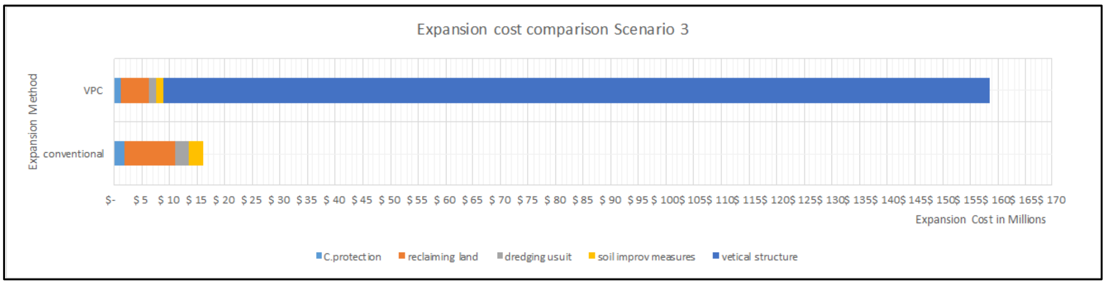

Table 17 - Expansion characteristics and cost calculation for scenario 3

Table 17 shows that under the conditions of scenario 3, with low unit costs and high work quantities, the VPC expansion method will result in a much higher capital investment than the conventional one.

The difference between both methods is high, with the VPC costing an additional $142,524,000, which represents an 891% higher investment, considering a vertical structure unit cost of $1,300/m^2$. Although the VPC allows a 44% saving in all the remaining infrastructure costs, the cost of the vertical structure excludes the VPC as an expansion alternative. Scenario 3 represents an aggravation of the difference between the expansion methods with respect to scenario 2.

Breakeven analysis

The breakeven analysis for scenario 3 will follow the same principles as what was presented in previous scenarios.

For scenario three the first breakeven point for both expansion methods is achieved when the unit cost of the vertical structure is reduced to $60.661/m^2$. At this value the cost of expanding by VPC and by conventional methods is the same, $16,000,000. This value represents a drop of approx. 95% with respect to the initially unit cost of

$1,300/m^2$. The fact that the difference between the methods increased form scenario 2 to scenario 3, from 384% to 891%, shows that high unit costs play a more important role in the feasibility than the volume of the works needed for the expansion.

Again for scenario 3, it is clear that not even after increasing the unit costs by 500% the VPC concept represents an economical alternative to the conventional expansion, as shown in Figure 18.

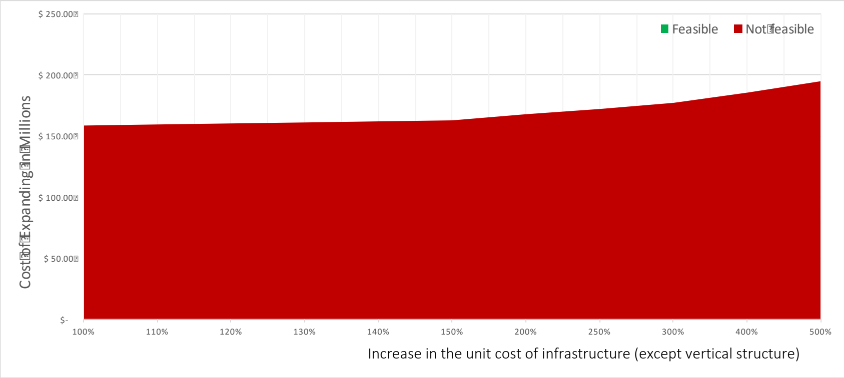

Figure 18 – VPC financial feasibility for scenario 3 when increasing the infrastructure unit costs (except the vertical structure)

6.5.4. Scenario 4

In scenario Four the amount of works is considered to be high for all the variables and the site conditions unfavourable to the construction of the expansion, translating into high unit costs.

Table 18 provides a summary of the characteristics of both expansion methods with respect to scenario 4. These characteristics are then used as input in the expansion functions allowing the comparison between a conventional port expansion and a VPC expansion under the conditions set in scenario 4.

	Unit	Unit cost	Quantity conventional	Quantity VPC	Sub-total Convent.	Sub-total VPC	VPC savings (%)	VPC savings (value)
Slope protection	m	$20 000	1 000	564	$20 000 000	$11 280 000	44%	$8 720 000
reclaiming land	m^3	$15	4 500 000	2 538 000	$67 500 000	$38 070 000	44%	$29 430 000
dredging usuitables	m^3	$20	1 250 000	705 000	$25 000 000	$14 100 000	44%	$10 900 000
Land consolidation	m^2	$25	250 000	141 000	$6 250 000	$3 525 000	44%	$2 725 000
Vertical structure	m^2	$1 300	0	115 000	$-	$149 500 000	NA	$-149 500 000
				TOTAL	$118 750 000	$216 475 000	-82%	$-97 725 000

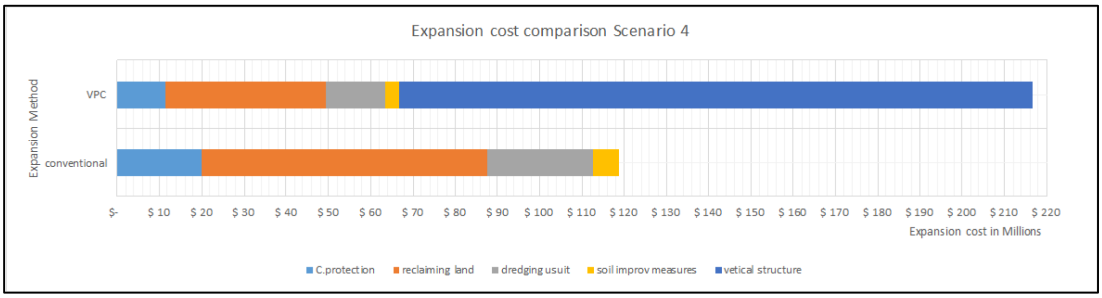

Table 18 - Expansion characteristics and cost calculation for scenario 4

Table 18 shows that under the conditions of scenario 4, with high unit costs and high work quantities, the VPC expansion method will still result in higher costs than the conventional one.

The difference between both methods is considerable, with the VPC costing an additional $97,725,000, which represents an 82% higher investment, considering a vertical structure unit cost of $1,300/m^2. Although the VPC allows a 44% saving in all the remaining infrastructure costs, the cost of the vertical structure excludes the VPC as an expansion alternative. Scenario 4 represents the most favourable scenario for the VPC feasibility. The high unit costs and the high volume of works reduced the cost difference between both methods. The reason for this is that the increase in the quantity of the works increases the benefits of the VPC savings on all infrastructures that are not the vertical structure.

Breakeven analysis

The breakeven analysis for scenario 4 will follow the same principles as what was presented in previous scenarios.

For scenario four, the first breakeven point for both expansion methods is achieved when the unit cost of the vertical structure is reduced to $450.216/m^2$. At this value the cost of expanding by VPC and by conventional methods is the same, $118,750,000. This value represents a drop of approx. 65% with respect to the initially unit cost of $1,300/m^2$. Scenario 4 represents the most favourable scenario for the consideration of VPC as an expansion alternative of all the scenarios considered in this exercise.

In scenario 4, the VPC concept becomes an alternative to the conventional method when the unit costs of the infrastructure (that is not VPC's vertical structure) are raised by approx. 300% (see Figure 19) and holding the unit cost of the vertical structure at $1,300/m^2$.

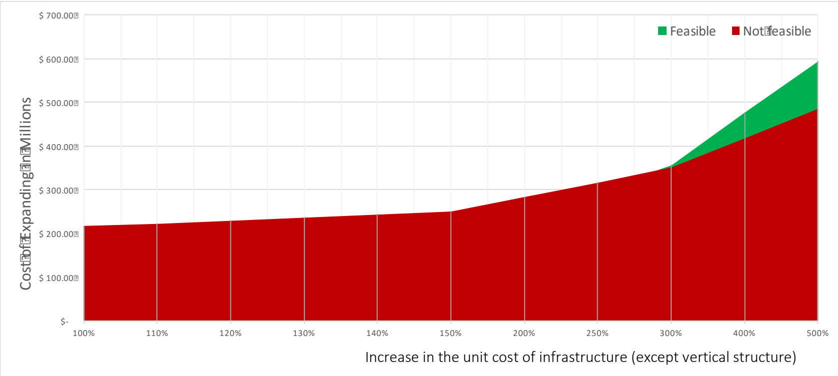

Figure 19 - VPC financial feasibility for scenario 4 when increasing the infrastructure unit costs (except the vertical structure)

6.6. *Findings of the chapter*

The financial feasibility comparison provides useful information in the search for answering the main research question of the present study. By using information provided by PCR, it was possible to extract infrastructure's unit costs and work volumes under favourable and unfavourable situations.

Unfavourable conditions represent sites where the complexity of the works materializes in a higher unit cost, for example constructing coastal/slope protection in deep waters can cost approximately $20,000 per meter, while in shallow waters (favourable conditions) it can drop down to $2,000 per meter, consequently the coastal/slope protection unit cost will mostly be affected by the water depth of the site. The other variables are affected by a combination of different site conditions.

The same principle applies to the favourable an unfavourable amount of works. For example, in deep water land reclamation works higher volumes of material need to be allocated. Nevertheless, the amount of material that needs to be displaced is independent of the cost of displacing it, hence the separation of the unit cost and amount of works.

These were essential to investigate the variation of the expansion costs. This variation was assessed by building scenarios that combined different site conditions and amount of works situation, and comparing the cost of achieving the same expansion requirements by the conventional and VPC methods.

The comparison counts with a number of important assumptions; which objective is to reduce the complexity of this exercise without compromising its relevance. One of these assumptions is that some of the infrastructure will have exactly the same cost regardless of the expansion method applied. Therefore, the estimation is simplified by focusing only in the infrastructure that will have a difference in cost depending on the expansion method selected.

An important aspect of this exercise is that the unit costs and the amount of works for unfavourable and favourable conditions, were derived from PCR database. Although PCR has an extensive project database, these values shall be considered as an indication, and their only purpose is to serve as a starting point in the investigation of the VPC financial feasibility. The same applies to the unit cost of the vertical structure, which is based in the construction of similar structures such as highway overpasses.

One of the immediate findings of the chapter is that scenario 4, with unfavourable site conditions and unfavourable amount of works represents the best financially feasibility situation for the VPC. Nevertheless, if the evaluation of the VPC as an alternative is sonly based on the capital investment of the expansion, then, with a vertical structure costing $1,300/m^2, only in cases where the remaining unit costs are 300% higher than what was assumed for unfavourable site conditions, would the VPC may be considered as an alternative.

If one maintains the unit costs as shown in scenario 4, the only situation where the VPC appears to be financially feasible is if the unit cost of the vertical structure Is reduced to $450.216/m^2, which is a 65% reduction from the assumed cost.

Furthermore, the comparison showed that the unit costs will probably play a more important role than the amount of work. The reason for this, is that when comparing the cost difference between the expansion methods in scenario 2 and 3, the gap is much smaller in scenario 2. Scenario 3 assumed low work quantities and high unit costs as opposed to high work quantities and low unit costs of scenario 3. Table 19 summarises the main outcome of each scenario.

	VPC unit cost ($/m^2)	Cost GAP % between methods (VPC/conv.)	Gap value
Scenario 1	$15.17	3694%	$147 756 000
Scenario 2	$132.69	384%	$134 240 000
Scenario 3	$60.66	891%	$142 524 000
Scenario 4	$450.22	82%	$97 725 000

Table 19 – Scenarios main outcomes

The table above shows the unit cost of the vertical structure (initially set at $1,300/m^2) needed to achieve the same expansion costs between the conventional and VPC method (breaking point). Furthermore, the absolute difference between the expansion methods cost (in form of absolute % and absolute value) is provided when holding the vertical structure unit cost constant (at $1,300/m^2).

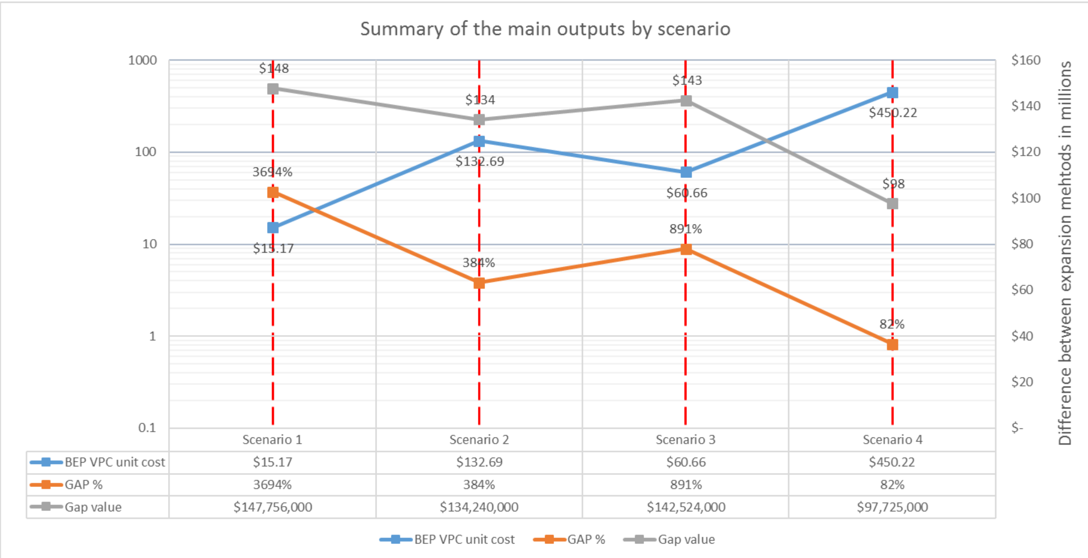

Figure 20 - Summary of the main outputs by scenario

Figure 20, provides a more visual approach to the outcomes of the model summarized in Table 19. It is possible to observe that the breakeven point (BEP) of the VPC vertical structure has a negative relation with the cost difference between the expansion methods compared. A high BEP, and a low GAP % or GAP value indicate a favourable condition for the financial feasibility of the VPC.

Although the above provide valuable information, it is important that more generic information is extracted from the comparison results. One important indicator is the weight of the vertical structure on the total cost. In all the scenarios the breakeven point (BEP) is achieved when the weight of the vertical structure is equal or less to

44% of the total expansion costs. This is because the when compared to the conventional expansion method the VPC allows for costs savings of 44% on all the other variable. Consequently, the VPC becomes feasible when the weight of the vertical structure in the final expansion cost equal the savings allowed by the VPC in the remaining infrastructures.

It is important to mention that in the comparison exercise done in this research, the VPC allowed constant savings across all the scope items, 44%. In the case where the savings of VPC are not homogeneous, the decision maker should make use of the average of the different savings percentages in order to define a general VPC savings percentage.

7. Vertical Port Concept financial feasibility assessment methodology

In line with the objective of this research the author proposes a VPC financial feasibility assessment methodology that will allow the decision maker to easily investigate the potential of the VPC as an expansion alternative.

The methodology proposed, analyses the three core aspects affecting the VPC financial feasibility: the availability of land to expand, the site conditions and the savings originated by the VPC. The methodology is composed by three knot-out decision stages.

The decision maker shall firstly consider the availability of land at the site of expansion. Given the high cost of the vertical structure of the VPC, in a purely financial point of view, the costs of expanding with VPC will be much higher than expanding with conventional methods when land is widely available. Taking this into account the first step of the methodology shall be checking the land availability at the expansion site. In cases where land is available for expansion, the VPC shall not be considered as an alternative to expand.

In cases where land is not available and relocating the port is not an option, then the decision maker shall focus on the analysis of the site conditions. It was shown in the cost comparison analysis that the costs involved in expanding the port using the VPC will only represent an interest investment when the site conditions represent complex and large construction works. When under favourable site conditions, the cost of expanding the port by VPC will result much higher than expanding by conventional land reclamation, hence VPC shall not be considered as a financially feasible expansion alternative.

Lastly, if the site conditions are unfavourable for marine works, the decision maker shall analyse the savings of the VPC against the conventional expansion, and compare them with the cost of the vertical structure. If, the VPC allows for savings equal or superior to the cost of building the vertical structure characteristic of a vertical expansion, then the VPC shall be considered as an alternative for the expansion of a port.

By following this methodology, the decision maker can easily analyse the feasibility of the VPC in a financial point of view. The three-knot out stages, ensure that the VPC is only considered as an alternative in sites where it’s construction will not represent a much higher investment when compared with an expansion by conventional methods. The VPC feasibility check process is summarized in Figure 21.

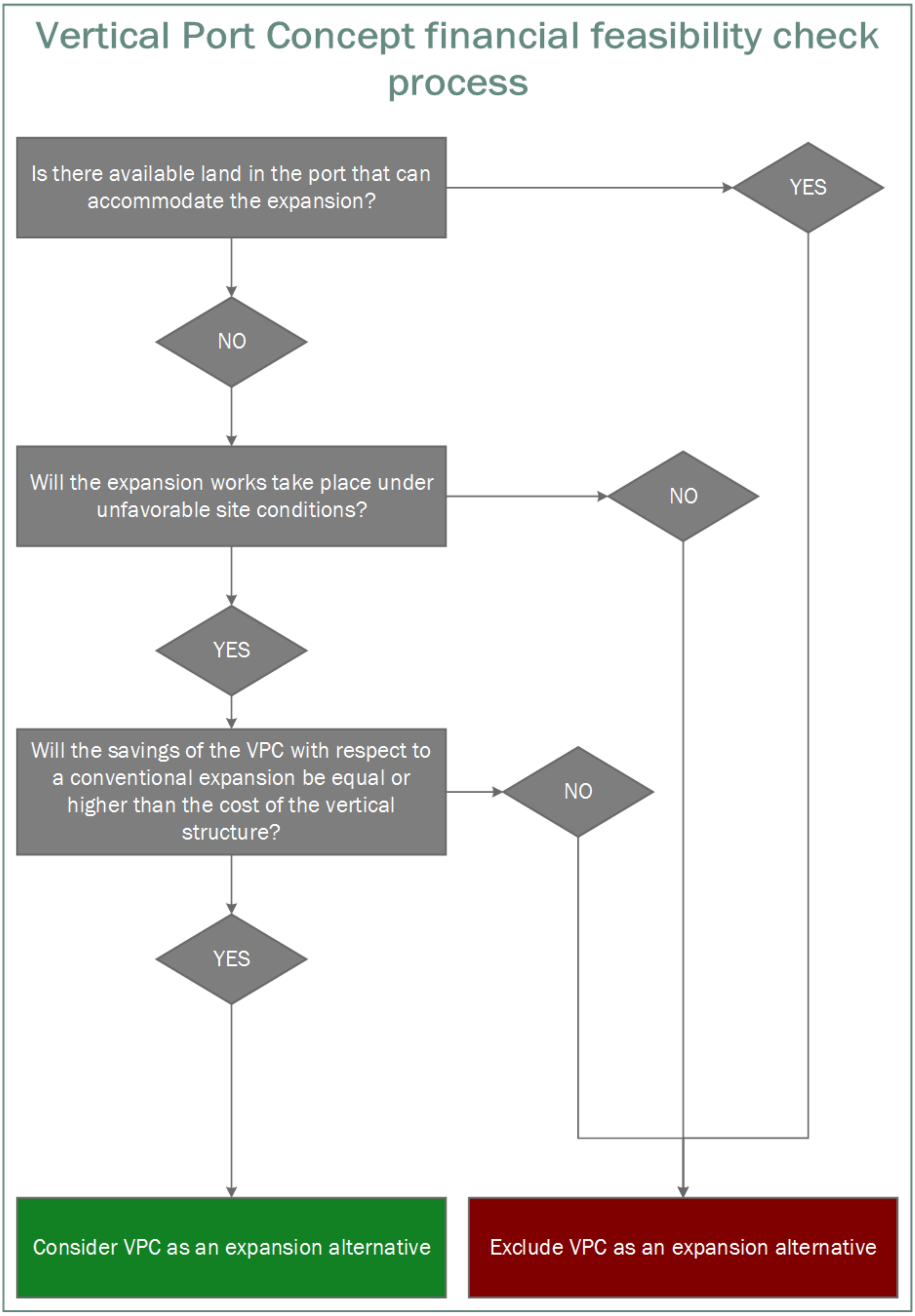

Figure 21 - VPC financial feasibility check process

8. Conclusions

Ports all over the world are constantly expanded to add capacity as a response to an increase in the demand for their services. Over the years sophisticated expansion cost evaluation tools were used in an attempt to minimize uncertainties and to support the decision making process, nevertheless, the expansion methods did not change over the time. According to Notteboom & Rodrigue (2005), Chan & Yip (n.d) and Hoyle (1989), the ports either expand in the original location (by occupying available land or reclaiming land) or relocated to areas where land is available. The objective of this study is to assess the financial feasibility of an innovative expansion concept that could provide an expansion alternative to existing ports expanding at their original location, the Vertical Port Concept (VPC). This investigation is guided by the research question *"Under which conditions is the vertical port expansion a financially attractive alternative to a conventional port expansion?"*.

By restricting the scope of the study to ports where land is not available one already assumed that the feasibility of the VPC is highly dependent on the land availability. The construction of the vertical structure is very costly; thus it will only represent a feasible investment in situations where conventional expansions methods will also result in costly investments, which is the case in ports where land is not available.

When land is not available, and port expansion takes place on the original site of the port, expansion is usually achieved by land reclamation. Under these circumstances, significant cost savings can be achieved by the VPC with respect to land reclamation. The savings in land reclamation represent the core advantage of the VPC expansion method when compared with conventional expansion methods, the reason for this being that the VPC creates port area vertically rather than horizontally. Other savings can also occur, like in coastal protection costs.

Nevertheless, even when port expansion is achieved by land reclamation due to land scarcity, the site conditions will play a major role on the financial feasibility of the VPC. This is in line with what is acknowledged by several authors, where it is mentioned that the expansion of the port will be influenced to a great extent by the site conditions of the expansion location (PIANC , 2014; Chan and Yip, n.d.; Hoyle 1989). After the cost comparison performed in the chapter 6, it is possible to conclude that VPC expansions will only be feasible as an expansion alternative under unfavourable site conditions.

Supporting this, we have that the scenario under which the cost of expanding with VPC is closer to the cost of expanding by conventional methods is the scenario 4. Here, a combination of high unit costs and high amount of works due to unfavourable site conditions, makes the VPC expansion 82% more expensive that the conventional expansion. The cost difference of 82% comes after the calculation of the VPC expansion with a unit cost of the vertical structure of \$1,300/m^2. In this scenario the cost of expanding by VPC becomes the same as expanding by conventional methods when the unit cost of the vertical structure is reduced to \$450/m^2 (also referred to as break-even VPC unit cost). The latter value is more realistic than the break-even VPC unit-cost obtained in the other scenarios, and in some parts of the world it may be possible to achieve such unit cost. Nevertheless, the construction of such structure will need further detailed investigation to have a better understanding of this unit cost.

Furthermore, it was possible to observe that the VPC only becomes feasible when the savings potentiated by the vertical expansion, mostly related to less land reclamation requirements, are equal to the cost of the vertical structure. For example, if the construction of the vertical structure represents 44% of the total expansion costs, then the VPC expansion becomes feasible when it allows for 44% savings when compared to a conventional expansion.

Taking the above into consideration, the author proposes a 3 knot-out stages financial feasibility assessment for the VPC. This methodology considers the 3 core aspects of the VPC feasibility, the availability of land to expand the port at the original location, the site conditions and the savings originated by the VPC.

With respect to the land availability, the high cost of the vertical structure characteristic of the VPC will only represent a feasible investment in cases where land is not available. Expansion by conventional methods in sites where land is widely available will represent a much lower investment that expanding by VPC. Given this, the first knot-out stage will focus in the land availability at the expansion site, and only in sites where land is not available, shall VPC expansion be considered.

The second knot-out stage focus in the site conditions. As mentioned before, the VPC is only feasible where the site conditions represent complex and large construction works. When under favourable site conditions, expanding with the conventional methods will represent a much lower investment than with the VPC. Taking this into account, the second knock-out stage ensures that the VPC is considered as an alternative only in sites where the site conditions are unfavourable for port expansion developments.

The last knot-out stage focus on the savings originated by the VPC. As shown in the cost comparison exercise, the VPC savings in the creation of land need to compensate for the extra cost of the vertical structure. If, by a number of reasons, the cost of constructing the vertical structure is higher than the savings originated by the VPC, then expanding by VPC shall not be considered.

Only in cases where these 3 aspects are present the VPC shall be considered as an expansion alternative in a purely financial point of view.

Furthermore, the author acknowledges that a number of important investigations need to be performed before a final conclusion on the overall feasibility of the VPC as a port expansion alternative is reached. In the following chapter, several studies that could play a role in the overall feasibility and further actions are proposed.

9. Potential benefits and short comes of the VPC and future work

The present research only accounts for the financial feasibility of the VPC, and does so by investigating the capital expenditure (CAPEX) expected in a VPC expansion. During this research the author encountered other fields that will need to be investigated before an overall feasibility is achieved.

Given that the scope of the study was reduced, considering only geographical constraints, the socio-economic and the environmental constraints will need to be addressed as well. Another important field that requires special attention is the operational aspects of the port, will a VPC expansion cause a significant impact of the operations of the port? And if so would this be a positive or a negative impact. Finally, other issues that are not grouped in any particular classification, will also need to be addressed.

These topics are considered to be very important for guiding future investigations of the VPC, hence they are addressed in this chapter.

9.1. Environmental constraints

In chapter 3.4 the main port expansion constraints are identified, among them the Environmental constraints. Several authors address the importance of correctly evaluating the environmental impacts of a port expansion, and that these impacts should be weighed against the benefits of the expansion when evaluating a port expansion feasibility.

A deep environmental investigation is required to analyse the impacts of the VPC expansion on the surrounding areas, given the special characteristics of the concept. The fact that the expansion is achieved vertically rather than horizontally, may result in some environmental benefits to the expansion.

One of the potential benefits is the reduction of the water impacted area. The vertical expansion will translate in less land requirements, which consequently reduces the water area impacted by the expansion. In most of the cases, water areas have stronger environmental regulations than land areas, even though they are classified as a part of the port wet area. VPC may be particularly advantageous in the cases where no land is available and port expansion can only be achieved by land reclamation.

Another related benefit, is the reduction of the mitigation area. Often ports need to apply mitigation measures to compensate or attenuated the impact of the expansion. By concentrating the expansion on a smaller area, the area requiring mitigation measures will be significantly smaller.

With respect to air pollution, the covered area provided by the ground level of the vertical structure, could represent an environmental benefit by containing particles that are airborne when certain cargoes are handled. This is particularly true for dry bulks, which are sensitive to air quality standards, especially when installed close to cities. The same applies to light pollution, given that part of the expansion is covered by the top level, the light pollution will be reduced in a VPC expansion.

Some negative environmental impacts of the VPC expansion are also to be expected. Although the air pollution, the light pollution and the water area affected would be reduced, the visual pollution of such structure would definitely represent a disadvantageous aspect of a VPC expansion with respect to a conventional expansion. Extra visual pollution mitigation measures would be required. Further investigation is required to support these assumptions.

9.2. Socio-economic constraints

The socio-economic constraints are perhaps the most difficult aspects to investigate. The impacts on society of a vertical or conventional expansion are not expected to be very different. Nevertheless, the vertical expansion of a port might increase the prestige of the port, given that it is a new technology that is not widely applied. Also given that the expansion area requirements are lower, the relation between the port and the city might improve.

Other important aspects, such as employment and economic effects of the expansion will probably remain equal independently of the expansion method.

9.3. Operational aspects

Perhaps the biggest differences between the two expansion methods, will be the operational differences arising from operating a vertical terminal. These differences are expected to be as important as the financial aspect considered in this research.

On the forefront of those differences, one can find the handling of the material. Vertical expansion, means that the terminals will be placed on top of each other. Some commodities require cranes that allow the unloading and loading of the vessels calling the terminal, in the case that both the terminals that are combined vertically require cranes in the cargo handling operations, some issues may emerge. These aspects need to be studied in great detailed before a final conclusion is made regarding the VPC feasibility. The VPC can also represent an opportunity for innovation, with new outside the box handling systems developed to tackle land scarcity scenarios. The example made in 2.2, where a Singapore logistic operator uses overhead cranes to handle empty containers stored at the roof of the building, is a very good example of innovation in cargo handling equipment inspired by land scarcity.

Another very important issue is the vessel scheduling. The planner of the expansion must ensure that if the same quay wall is serving both terminals, then enough length must be provided to cope with the existing demand. If the quay length is to short then congestion issues will appear, and berth priorities conflicts may appear between the terminal operators. When faced with this scenario, the terminal planners may choose alternative berthing solutions, placing the berth away from the terminal in the form of jetties, similar to what is already done in some dry and liquid bulk terminals. This situation is illustrated in example 3 in Appendix VI. Nevertheless, in cases where low quay occupancy is an issue, the VPC might represent a solution to quay underutilization.

In order to avoid conflict between the operators of the different terminals, administrative aspects of the VPC must be tackled. Before embracing a VPC expansion the planner must deal with potential conflicts resulting from the combination of two different terminals on top of each other. How would these terminals cooperate? Would the VPC only be feasible in the case where the same operator operates both the terminals? Or is it viable for two independent operators? Further investigation is needed to tackle this issues, and also to ensure a smooth integration on the existing port governance models. The terminal planner dealing with a VPC expansion, shall always keep in mind that the expansion should not bring any undesired inefficiencies to the terminal operators.

9.4. Other aspects

Other relevant aspects were identified during the research. By increasing the terminal density due to the vertical integration, the VPC may be beneficial in cases where infrastructure to provide shelter is required. This is the case of breakwaters; they are essentially used to provide calm waters at the terminals in order to allow operations to take place, decoupling the waters inside the port with the climate outside the port. In the case of greenfield ports, it very common that the construction of a new port will require the construction of a new breakwater. If the shadow zone required (the zone that need to be sheltered from the incoming waves) Is reduced, so the cost of the breakwater. Breakwaters can be very costly, especially in high water depths (higher than 15m), hence this may represent an extra cost saving from applying VPC. This situation is illustrated in Figure 22.

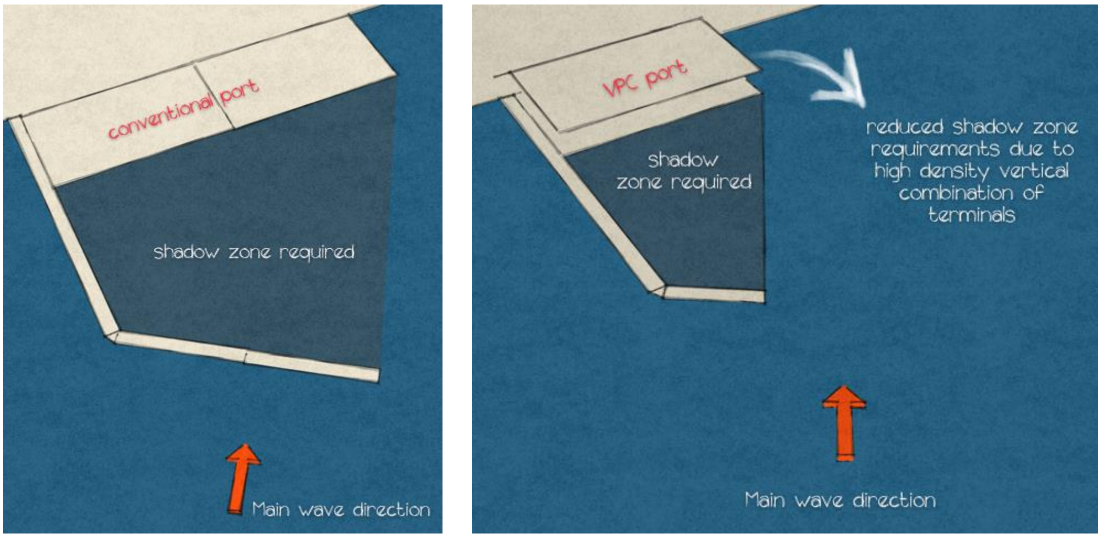

Figure 22 – Artist impression illustrating potential savings in infrastructure (breakwater) due to the VPC

Other potential cost saver is the fact that the top floors of the vertical structure will not require any pavement installation by the terminal operator. Depending on the port governance model the terminal operator might be responsible for the construction of the terminal superstructure. This is the case in land lord ports, where the port provides the basic infrastructure and the operator of the terminal needs to provide the equipment and the superstructure of the terminal. In a conventional expansion, the land is usually provided without pavement, and the operator leasing it must install the pavement required for the terminal operations.

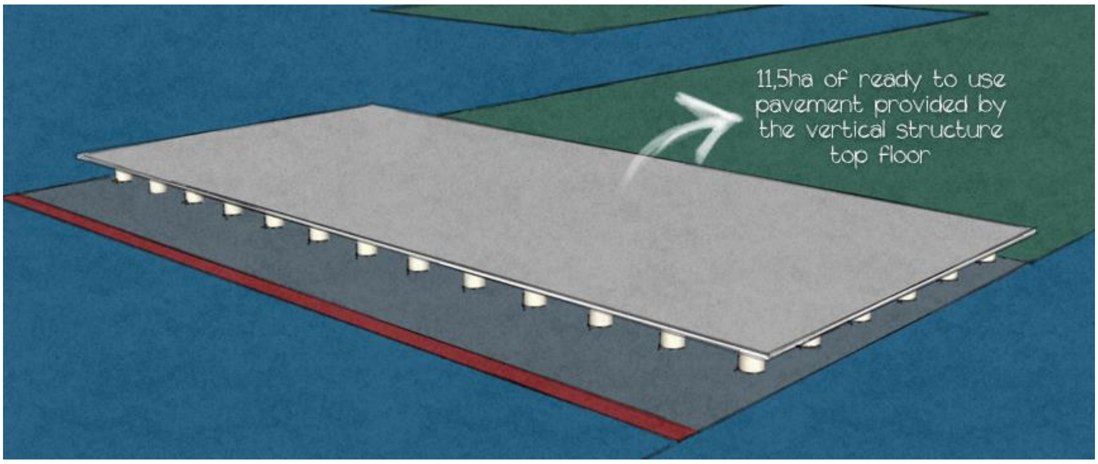

Figure 23 – Artist impression of the VPC top level ready to use concrete pavement

When installing a terminal on the top level of the VPC vertical structure, the terminal operator does not need to install any pavement, given that the structure itself will provide a surface of concrete that can be used as pavement. In some cases, pavements can reach up to $100/m^2, especially for container terminals. Given this, in the case used for the expansion cost comparison, the top level can represent savings for the terminal operator up to $100*115,000m^2= $11,500,000, which is a considerable amount of capital. Further investigations are needed to support this, furthermore who would benefit from the savings is not yet clear given that it would be dependent on the negotiations between the land lord and the operator. Figure 23, provides an artist impression illustrating the above.

In line with the above, it is also necessary that the VPC expansion method feasibility is also researched with respect to greenfield port constructions. Benefits from concentrating the port activities in a smaller area may arise when the port is completely planned to be a vertical expansion port. The breakwater situation illustrated before is an example of a potential benefit. One can think of others, such as less impact on the coastline and, when applicable, opportunity for the development of real-estate or industrial projects next to the port.

Finally, it is strongly recommended that construction economies of scale of the vertical structure are investigated. Haralambides (2002), recognizes that construction economies of scale can play a role in port expansions. Given the size of the vertical structure, and the importance of achieving it at the lowest possible unit price, it is strongly recommended that construction economies of scale are investigated. The present study concluded that the feasibility of the VPC is strongly dependent on the unit cost of the vertical structure, consequently if economies of scale allow for a lower vertical structure unit cost, the VPC feasibility will increase.

9.5. Recommendations for future work

Although the financial feasibility of the VPC expansion is crucial, the author recommends that the aspects that were identified before in this chapter are researched further. Only then, a complete VPC feasibility as a port expansion alternative can be achieved.

In order to reach this ambitious goal, the author proposes that the works are divided in two categories. The first category will consist of major studies that do not intent to increase the accuracy of the financial feasibility study but rather complement it allowing the achievement of a complete VPC feasibility as an alternative expansion method. And the second category is composed by studies that due to its complexity or extension were not included in the present research and may play a role in the accuracy of the financial feasibility of the VPC expansion.

In the first category the author proposes to include the operational feasibility study of the VPC as a port expansion alternative and the environmental impact assessment of a VPC expansion and its benefits or disadvantages when compared with a conventional expansion. These studies are expected to be very complex and extensive and will probably require a higher amount of resources than the studies proposed under the second category.

Under the second category, the focus shall be in the optimization of the financial feasibility study, by providing extra elements that were left out of the present research. In the first place the impact of environmental and socio economics constraints in the financial feasibility of the VPC must be assessed. Secondly issues related with the VPC feasibility under other port governance models, besides the land lord model investigated here, and its feasibility in greenfield ports. Furthermore, the issues under chapter 9.4 must also be further investigated. Potential savings in the breakwaters and navigation channels and the return on the vertical structure investment due to its ready to use pavement, might play a role in the financial feasibility of the VPC as a port expansion alternative. Finally, detailed studies tackling potential construction economies of scale in VPC as well as a clear definition of the unit cost of the vertical structure, are important to increase the accuracy of this research. The future work recommended by the author is summarized in Figure 24.

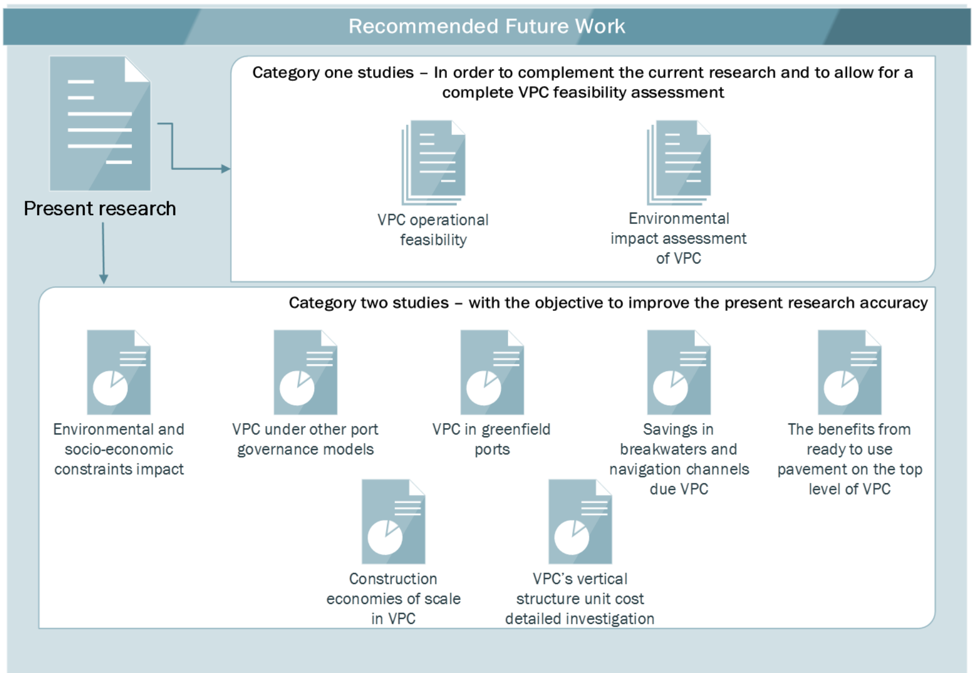

Figure 24 – Recommended future work

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Appendices

Appendix I – Text Boxes

Text box 1 – Vertical integration of services

The island has always been a popular destination for tourists and the main gateway in and out the island, for non-cruise passengers, is the airport. The first airport of Madeira was built on a cliff and was inaugurated in 1964 with 1600m of runway extended to 1800 in 1986. Faced with an increasing demand and an airport close to its maximum capacity the authorities decided to adopt a bold expansion plan. The plan consisted on extending the runway over piles increasing the capacity of the airport to 3.5 million passengers per year (Diario de Noticias da Madeira, 2014). Bellow the runway new services and recreation areas flourish, taking advantage of the newly created space, making this a good example of vertical integration of services.

Figure 25 - An overview of the existing airport (top) and a variety of services installed under the runway. (source: Miguel Nobrega(top) and Tecnovia)

Text box 2 – Urban Agriculture

The expansion of cities and subsequent concentration of population in urban environments creates an increase on demand for all kind of products, among them an increase on the demand for fresh food. Growing food requires land that is not available in the cities, therefore food is usually grown away from the cities. The concept of urban agriculture searches to answer the increasing demand for fresh vegetables while tackling the environmental costs of agriculture by growing the products directly in the consumption centre (Martellozzo, et al., 2014). A part of urban agriculture is to make use of vertical expansion of cities by growing crops in rooftops, an ingenious way of tackling the land scarcity observed in many cities.

Figure 26 - Example of rooftop agriculture in New York City, USA. (source: Do it on the Roof)

Appendix II – Control cases port expansion detailed cost estimate

CAPEX estimate for Control case 1							
		%	**quantity used**	**unit**	**unit cost**	**costs**	**costs**
					[USD/unit]	[million USD]	[million USD]
100	**Dredging and Reclamation**						
100	***Initial works incl mob/demob***						***12.3***
101	Contractor Yard with temporary offloading facility		1	item	1,500,000	1.5	
102	Floatel facilities for accomodation		1	item	1,000,000	1.0	
103	Mob/demob various aux eq by float-in heavy load vessel		1	item	3,000,000	3.0	
103	Mob&Demob TSHD		3	nr	1,000,000	3.0	
103	Mob&Demob XL CSD		1	item	2,000,000	2.0	
105	Provision for wreck removal		1	item	1,750,000	1.8	
110	***Dredge within port boundary***						***75.0***
111	Removal of unsuitables from reclamation areas		7,908,363	m3			
111	Soft clay; TSHD5600; to marine disposal	70 %	5,535,854	m3	1.93	10.7	
111	Stiff clay; TSHD11500; to marine disposal	30 %	2,372,509	m3	2.77	6.6	
112	**Dredge Harbour basin**		15,224,294	m3			
112	Soft clay; TSHD5600; to marine disposal	20 %	3,044,859	m3	1.93	5.9	
112	Stiff clay; TSHD11500; to marine disposal	20 %	3,044,859	m3	2.77	8.4	
113	Corners and precision		10	wk	160,000	1.6	

CAPEX estimate for Control case 1							
	dredging for quaywalls						
114	Sand & siltstone; CSD; re-use in reclamation	60 %	9,134,577	m3			
114	Dredge and re-use sand&siltstone 1-10 MPa by csd	80 %	7,307,661	m3	5.40	39.4	
114	Dredge and re-use siltstone 10-20 MPa by csd	15 %	1,370,186	m3	15.12	20.7	
114	Dredge and re-use siltstone 20-30 MPa by csd	5%	456,729	m3	51.32	23.4	
115	50% of costs for siltstone re-direct to reclamation (item 140)		-50%	item	83,600,146	-41.8	
120	***Dredge access channel***						***24.8***
121	Volume to be dredged		5,996,470	m3			
122	Soft clay; TSHD5600; to marine disposal	10 %	599,647	m3	1.93	1.2	
123	Stiff clay; TSHD11500; to marine disposal	10 %	599,647	m3	2.77	1.7	
125	Sand & siltstone; CSD; re-use in reclamation	80 %	4,797,176	m3			
125	Dredge and re-use sand&siltstone 1-10 MPa by csd	80 %	3,837,741	m3	5.40	20.7	
125	Dredge and re-use siltstone 10-20 MPa by csd	15 %	719,576	m3	15.12	10.9	
125	Dredge and re-use siltstone 20-30 MPa by csd	5%	239,859	m3	51.32	12.3	
126	50% of costs for siltstone re-direct to reclamation (item 140)		-50%	item	43,904,016	-22.0	

CAPEX estimate for Control case 1							
130	***Remove unsuitable from marine borrow***						***6.7***
131	Dredge by TSHD11500, dispose nearby at 50 m water depth		4,375,000	m3	1.53	6.7	
140	***Reclamation terminals***						***144.8***
141	Rainbow up to MSL+1m		14,560,188	m3			
141	Reclamation up to final level (pumpashore)		3,510,375	m3			
141	Settlement compensation (pumpashore)		1,342,947	m3			
141	Volume to be reclaimed		19,413,510	m3			
142	Dredge and re-use sand&siltstone from harbour basin		9,134,577	m3			
142	Dredge and re-use sand&siltstone from access channel		4,797,176	m3			
142	Losses from csd material (assumed)	30 %	4,179,526	m3			
142	Volume to be reclaimed by TSHD (dredged in marine borrow)		9,661,283	m3			
143	50% of costs for siltstone from dredge harbour (item 116)		50%	item	83,600,146	41.8	
144	50% of costs for siltstone from dredge access channel (item 126)		50%	item	43,904,016	22.0	
145	Rainbow tshd (from access channel or borrow area)	50 %	4,830,642	m3	3.89	18.8	

CAPEX estimate for Control case 1							
146	Pumpashore tshd (from access channel or borrow area)	50 %	4,830,642	m3	6.40	30.9	
147	Provision for rehandling costs (volume in front of quay)	15 %	2,912,026	m3	2.23	6.5	
148	Phasing Volume (preceding next phase)	20 %	3,882,702	m3	6.40	24.8	
150	***Geotechnical measures***						***16.4***
151	Surcharge (removal/re-application costs)		1,085,900	m2	15.07	16.4	
190	***Estimate contingency***						***70.0***
191	Estimate contingency dredging	25 %	37%	item	69,962,005	26.1	
192	Estimate contingency reclamation	25 %	63%	item	69,962,005	43.9	
100	**Dredging and Reclamation**					**total**	**349.8**
200	**Breakwater and slope protection**						
200	***Initial works incl mob/demob***						***8.3***
201	Special purpose driving&handling equipment		0.5	item	4,000,000	2.0	
202	MOF with storage area		0.5	item	3,000,000	1.5	
203	Mob & demob of equipment		0.5	item	4,000,000	2.0	
204	Construction site & precasting yard		0.5	item	1,500,000	0.8	
205	Survey/setting out		50.0	wks	40,000	2.0	
210	***Breakwater***						***41.7***
211	Breakwater type 1		1,250	m1	31,975	40.0	

CAPEX estimate for Control case 1							
212	Breakwater type 1 (head, 10% extra costs)		50	m1	35,172	1.8	
220	***Slope protection***						***40.0***
221	Slope protection type 2		1,750	m1	20,893	36.6	
223	Slope protection type 4		1,550	m1	2,233	3.5	
290	***Estimate contingency***						***18.0***
291	Estimate contingency	20 %	1	ite m	18,000,38 9	18.0	
20 0	**Breakwater and slope protection**						**108.0**
30 0	**Quaywalls, Jetties, Civil engineering works**						
300	***Initial works incl mob/demob***						***7.3***
301	Special purpose driving&handlin g equipment		0.5	ite m	4,000,000	2.0	
302	MOF with storage area		0.5	ite m	3,000,000	1.5	
303	Mob & demob of equipment		0.5	ite m	4,000,000	2.0	
304	Construction site & precasting yard		0.5	ite m	1,500,000	0.8	
305	Survey/setting out		100.0	wks	10,000	1.0	
310	***Quaywalls Container Terminal***						***36.7***
312	Quaywall berth 2		350	m	45,912	16.1	
313	Quaywall berth 3		350	m	45,912	16.1	
319	Quaywall - phasing length		100	m	45,912	4.6	
320	***Quaywalls General Cargo Terminal***						***16.1***
321	Quaywall berth 7		250	m	45,912	11.5	

CAPEX estimate for Control case 1							
324	Quaywall - phasing length		100	m	45,912	4.6	
330	***Quaywalls Multi-Purpose Terminal***						***16.1***
331	Quaywall berth 4		350	m	45,912	16.1	
350	***Quaywalls Steel Terminal***						***16.1***
351	Quaywall berth 5		350	m	45,912	16.1	
380	***Jetties & civil engineering works***						***18.1***
381	Jetty 23a dolphins incl loading platform		1	unit	12,975,000	13.0	
383	threstle/land connection/pipe rack		300	m	17,000	5.1	
390	***Estimate contingency***						***27.6***
391	Estimate contingency	25 %	1	item	27,565,441	27.6	
300	**Quaywalls, Jetties, Civil engineering works**						**137.8**
400	**Infrastructure (road, rail)**						
410	***Onshore Infrastructure***						***57.1***
411	Access Road 2*2 incl foundation (outside port perimeter)		10000	m	3,000	30.0	
412	Port road system 2*2 (within port perimeter)		7500	m	2,000	15.0	
431	Pavement (area 6 and 11)		38000	m2	65	2.5	
432	Fencing general port areas		10000	m	300	3.0	
433	Port Gate entrance		1	unit	2,000,000	2.0	
434	Lighting port areas		1	unit	1,400,000	1.4	

CAPEX estimate for Control case 1							
435	Parking area/ pre-check and gates area		50000	m2	65	3.3	
490	***Estimate contingency***						***11.4***
491	Estimate contingency	20 %	1	item	11,424,000	11.4	
400	**Infrastructure (road, rail)**						**68.5**
500	**Utilities and port facilities**						
510	***Port/marine facilities***						***4.4***
511	Port Offices		700	m2	1,000	0.7	
511	Gate control building		20	m2	400	0.0	
511	visitors reporting office		80	m2	500	0.0	
511	Emergency Services		1	item	1,000,000	1.0	
511	Security systems		1	item	1,000,000	1.0	
512	Control Tower		200	m2	1,200	0.2	
514	Radar system		1	item	500,000	0.5	
515	Aids to Navigation - Leading lights & harbour lights		1	item	500,000	0.5	
516	Aids to Navigation - Fairway buoys		1	item	250,000	0.3	
517	Measuring devices		6	nr	30,000	0.2	
520	***Vessels***						***3.0***
523	Port Security Vessels		2	item	1,000,000	2.0	
524	Oil spill equipment		1	item	1,000,000	1.0	
530	***Utilities***						***9.4***
561	Ductbank for data infrastructure		8000	m	175	1.4	
562	Electricity, Water, data infrastructure in port areas		8000	m	1,000	8.0	
590	***Estimate contingency***						***3.4***

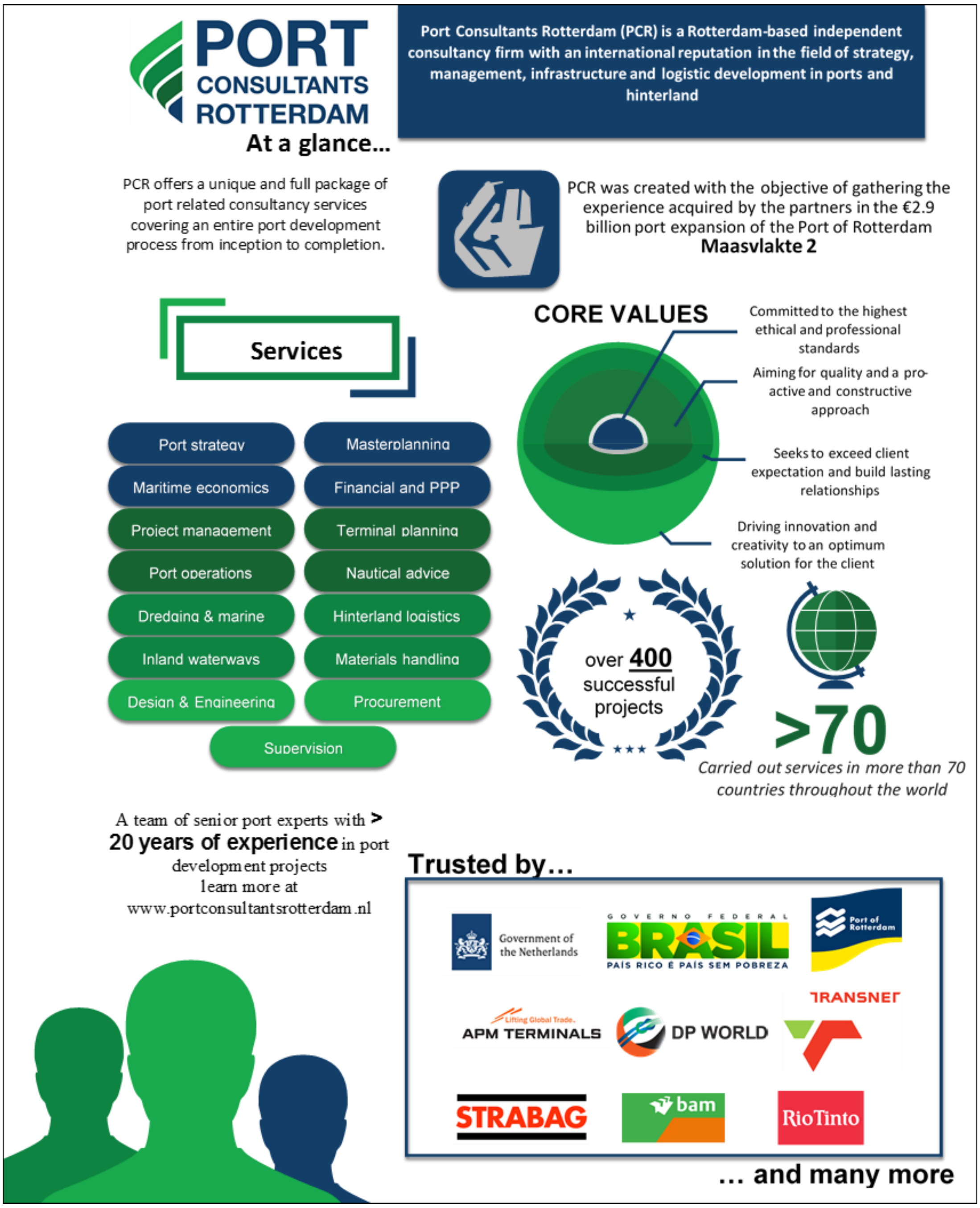
CAPEX estimate for Control case 1							
591	Estimate contingency	20 %	1	item	3,363,600	3.4	
500	**Utilities and port facilities**						**20.2**
					Grand total		684.4

CAPEX estimate for Control case 2					
	%	quantity used	unit	unit cost [USD] *direct construction costs*	costs [million USD] *direct construction costs*
Dredging and Reclamation					
Bushclearing (50% of total area for harbour and reclamation)		3,125,000	m2	3.33	10.4
Remove unsuitable from reclamation area)		2,200,000	m3	4.88	10.7
Dredge Harbour basin - CD -14.3 dredge level		16,420,000	m3	0.00	0.0
Unsuitable, dredge by csd + rehandle by tshd	40 %	6,568,000	m3	4.88	32.1
Unsuitable - direct dredging with tshd	20 %	3,284,000	m3	2.33	7.7
sand re-used, dredge by csd *)	40 %	6,568,000	m3	0.00	0.0
**) no costs here, calculated at reclamation*					
Reclaim to +5 m incl settlement allowance - total		5,500,000	m3	0.00	0.0
Phasing volume		3,000,000	m3	0.00	0.0
Re-use harbour sand dredged by csd		6,568,000	m3	2.95	19.4
Rainbow tshd (from access channel)		1,000,000	m3	3.52	3.5
Pumpashore tshd (from access channel)		932,000	m3	4.73	4.4
Provision for rehandle volume (quay m3)	15 %	825,000	m3	2.95	2.4
Surcharge (removal/re-application costs)	60 %	660,000	m2	11.73	7.7
Vertical drains	60 %	660,000	m2	5.20	3.4
Dredge Harbour basin - CD -17.1 dredge level					
Unsuitable - direct dredging with tshd		2,289,000	m3	2.33	5.3
Dredge access channel - 300 m wide, CD -16.1 m dredge level					0.0
Volume dredged		43,194,990	m3	0.00	0.0

CAPEX estimate for Control case 2					
tshd unsuitable (to marine disposal)	60 %	25,916,994	m3	2.12	54.9
tshd re-use material (available)	40 %	17,277,996	m3	2.12	36.6
tshd actual re-use sand in reclamation*)		-2,386,000	m3	2.12	-5.1
**) volume correction for costs calculated at reclamation and breakwater (tshd rainbow and pumpashore)*					
Dredge access channel - deepening to CD -18.6 m dredge level					
tshd unsuitable (to marine disposal)		18,401,560	m3	2.12	39.0
Total Dredging and Reclamation		**85,876,550**	**m3**		**233**
Breakwater & Sea defence					
Construct sand bund for protection and base of breakwater, tshd pumpashore		2,976,000	m3	4.73	14.1
Shore protection Southwest		560	m	11,760	6.6
Breakwater South		1300	m	32,479	42.2
Breakwater NorthEast		600	m	19,487	11.7
Temporary constructions and special equipment		1	no	5,000,000	5.0
Beach / soft sea defence - total volume		2,500,000	m3	0.00	0.0
Beach/soft sea defence, csd re-use from berm in front of breakwater northeast		2,046,000	m3	4.03	8.2
Beach/soft sea defence, tshd pumpashore		454,000	m3	4.73	2.1
Total Breakwater					**90**
Quaywall & Jetties					
OSB terminal		400	m	48,333	19.3
Idem, phasing length		100	m	48,333	4.8
Dry Bulk terminal		300	m	48,333	14.5
Idem, phasing length		100	m	48,333	4.8
Container terminal		350	m	58,000	20.3

CAPEX estimate for Control case 2					
Idem, phasing length		100	m	58,000	5.8
Idem, slope protection		450	m	3,000	1.4
General Cargo terminal		250	m	58,000	14.5
Idem, phasing length		100	m	58,000	5.8
Idem, slope protection		350	m	3,000	1.1
Service port with mooring facilities for tugs pilots etc		1	unit	1,200,000	1.2
Shore protection for service port		400	m	3,000	1.2
Oil Jetty incl loading platform		1	units	13,500,000	13.5
Treste to jetty, for piperack and car access		300	m	11,000	3.3
Total Quaywall & Jetties					**112**
TOTAL MARINE AND CONSTRUCTION WORKS					**434**

Appendix III – PCR company profile



Appendix IV – Estimation of the infrastructure cost ranges

All figures presented in this appendix are to serve as an indicative cost of the construction of the mentioned infrastructure. The definition of the unit cost range was defined in close consultation with PCR staff and PCR database. The result of this consultation will serve as an input in the comparison analysis and should be taken as an approximation, these values may vary for different regions but it is assumed that the variation will not compromise the analysis.

Furthermore, the figures shown below are based in real cost estimations for successful projects, hence it is assumed that they reflect the industry best practices.

Coastal/ slope protection
Slope protection is needed to ensure the integrity of the slopes connecting the bottom of manoeuvring basins to the land area of the port. These structures main function is to protect the slopes from erosive actions caused by waves or ship propulsion/thruster systems (Thoresen, 2014). Figure 27 illustrates an example of a slope protection installed at a maritime terminal.

Figure 27 - Construction of slope protection in a port (source: The maritime Journal)

For the purpose of the cost comparison, unit costs for favourable and unfavourable conditions needed to be estimated. The cost of coastal/slope protection will mainly depend of two factors, the height difference between the top and the bottom of the slope (depending of the water depth of the basin) and the material availability (from how far are the materials being transported). Therefore, unfavourable site conditions for the coastal/slope protection are associated with deep waters and distant material borrow sites (rocks and gravel of which the structure is made of).

The unit cost range for the construction of coastal/slope protection to be used in the financial feasibility comparison is summarized in Table 20.

Coastal/ slope protection	Unit	Under fav. Site conditions	Description	Under unfav. site conditions	Description
Unit cost ($)	m	2,000	Water depth is ≤ to 2m and filling materials are available locally	20,000	Water depth is ≥5m and filling materials need to be transported over long distances

Table 20 – Unit cost range for the construction of coastal/slope protection under favourable and unfavourable site conditions.

Reclaimed port land (land creation)

A modern land reclamation is performed with dredging equipment. Although the type of dredging equipment used will differ according to the stage of the reclamation process and the volume to reclaim, the main factor affecting the unit cost of land reclamation is the distance between the filling site and the borrow site. Once again the material availability plays an important role in the definition of the unit cost. If the material to borrow (by dredging equipment) is far away from the place of filling (reclamation of land) the unit cost of land reclamation will increase dramatically. This is logical since the cost of transporting the filling material increase very rapidly over large distances. Additionally, in certain cases the material cannot be directly dredged without the previous removal of the overburden (the layer of biomass and unsuitables topping the suitable material), these operations are costly and will impact the final unit cost.

The unit cost range for the creation of reclaimed land to be used in the financial feasibility comparison is summarized in Table 21.

Reclaimed port land (land creation)	Unit	Under fav. Site conditions	Description	Under unfav. site conditions	Description
Unit cost ($)	m^3	2	Borrow material is available at a short distance from the filling site, no overburden removal is needed or any extra measures to access the filling material	15	Borrow material is available at long distances from the filling site, considerable amount of overburden removal is needed and extra measures to access the filling material will be needed

Table 21 - Unit cost range for land creation by land reclamation protection under favourable and unfavourable site conditions

Reclaimed port land (removal of unsuitables)

In certain situations, it is not possible to start filling the area with material to reclaim land before removing the unsuitable material that is underneath. Failing to detect and remove the unsuitable material would result in severe settlement issues for the reclaimed land, and slow and costly soil consolidation measures would be required. In order to avoid this the unsuitable material is dredged before the filling process starts, affecting the filling volume. Higher volumes of unsuitables dredged result in higher volumes to fill.

The unit cost range of dredging unsuitables is mostly affected by the distance where these materials need to be disposed. The reason for this, is that the fraction of the unit cost accounting for the dredging of the material will not experience high fluctuations, given that unsuitable materials are the same, or of similar characteristics, in all parts of the world. Another important factor affecting the final unit cost will be the conditions of the unsuitables. Often these materials are polluted and need additional treatment before behind disposed, the process of cleaning the contaminated material will increase the final unit cost.

The unit cost range for the creation of reclaimed land to be used in the financial feasibility comparison is summarized in Table 22.

Reclaimed port land (removal of unsuitables)	Unit	Under fav. Site conditions	Description	Under unfav. site conditions	Description
Unit cost ($)	m^3	2	The material dredged is not polluted and the disposal site is at a short distance from the dredging area	20	The material dredged is polluted and cleaning measures need to be undertaken and the disposal site is at a long distance from the dredging area

Table 22 - Unit cost range for the removal of unsuitable material before reclaiming land under favourable and unfavourable site conditions

Reclaimed port land (soil consolidation)

It is common that after land is reclaimed soil consolidation measures will be applied to accelerate the settlement of the soil. In nature land settlement would takes years, perhaps decades, before the soil is compacted enough for construction. Given that it would be unacceptable to wait years after land reclamation before starting construction, soil consolidation measures are applied to speed up the process. The most common measure is to surcharge the area with extra loads, accelerating the compacting of the soil.

The costs of soil surcharge measures is mostly related to the transport and handling costs of the material that will be piled up to exert the load (e.g. Sand or dirt). The further away this material needs to be transported from/to the most expensive the soil consolidation will be.

The unit cost range for the creation of reclaimed land to be used in the financial feasibility comparison is summarized in Table 23.

Reclaimed port land (soil consolidation)	Unit	Under fav. Site conditions	Description	Under unfav. site conditions	Description
Unit cost ($)	m^2	10	Borrow material is available at a short distance from the filling site	25	Borrow material is available at long distances from the filling site,

Table 23 - Unit cost range for the land consolidation measures under favourable and unfavourable site conditions

Appendix V – Amount of works according to expansion scenario

	Scenario 1 – Favourable site conditions and favourable amount of work							
	Conventional expansion				VPC expansion			
Variable	Unit cost	Description	Amount of works	Description	Unit cost	Description	Amount of works	Description
Coastal/slope protection	$\$2,000/m$	Shallow water depth and construction material available at short distances	1,000m	2x500m of slope protection	$\$2,000/m$	Shallow water depth and construction material available at short distances	564m	2x282m of slope protection
Reclaimed port land (land creation)	$\$2/m^3$	Borrow material at short distances no overburden removal needed	250,000x4m= 1,000,000m^3	25ha multiplied by the height of filling (from -2m until +2m = 4m of filling height)	$\$2/m^3$	Borrow material at short distances no overburden removal needed	141,000x4m = 564,000m^3	14.1ha multiplied by the height of filling (from -2m until +2m = 4m of filling height)
Reclaimed port land (removal of unsuitables)	$\$2/m^3$	Disposal site at short distance, material free of pollution	0m^3	No unsuitable materials found in the expansion site	$\$2/m^3$	Disposal site at short distance, material free of pollution	0m^3	No unsuitable materials found in the expansion site
Reclaimed port land (land consolidation)	$\$10/m^2$	Borrow material available at a short distance	0m^2	No land consolidation measures required	$\$10/m^2$	Borrow material available at a short distance	0m^2	No land consolidation measures required
Vertical port variable	NA	NA	NA	NA	$\$1,300/m^2$	Value of reference taken from similar structure	115,000m^2	vertical structure providing the missing 11.5 ha

Table 24 – Calculation of the amount of works for the variables taken into account for scenario 1

	Scenario 2 – Unfavourable site conditions and favourable amount of work							
	Conventional expansion				VPC expansion			
Variable	Unit cost	Description	Amount of works	Description	Unit cost	Description	Amount of works	Description
Coastal/slope protection	$\$20,000/m$	Deep waters and construction material available at long distances	1,000m	2x500m of slope protection	$\$20,000/m$	Deep waters and construction material available at long distances	564m	2x282m of slope protection
Reclaimed port land (land creation)	$\$15/m^3$	Borrow material at long distances, overburden removal needed	250,000x4m= 1,000,000m^3	25ha multiplied by the height of filling (from -2m until +2m = 4m of filling height)	$\$15/m^3$	Borrow material at long distances, overburden removal needed	141,000x4m = 564,000m^3	14.1ha multiplied by the height of filling (from -2m until +2m = 4m of filling height)
Reclaimed port land (removal of unsuitables)	$\$20/m^3$	Disposal site at long distance, material is polluted	0m^3	No unsuitable materials found in the expansion site	$\$20/m^3$	Disposal site at long distance, material is polluted	0m^3	No unsuitable materials found in the expansion site
Reclaimed port land (land consolidation)	$\$25/m^2$	Borrow material available at a long distance	0m^2	No land consolidation measures required	$\$25/m^2$	Borrow material available at a long distance	0m^2	No land consolidation measures required
Vertical port variable	NA	NA	NA	NA	$\$1,300/m^2$	Value of reference taken from similar structure	115,000m^2	vertical structure providing the missing 11.5 ha

Table 25 - Calculation of the amount of works for the variables taken into account for scenario 2

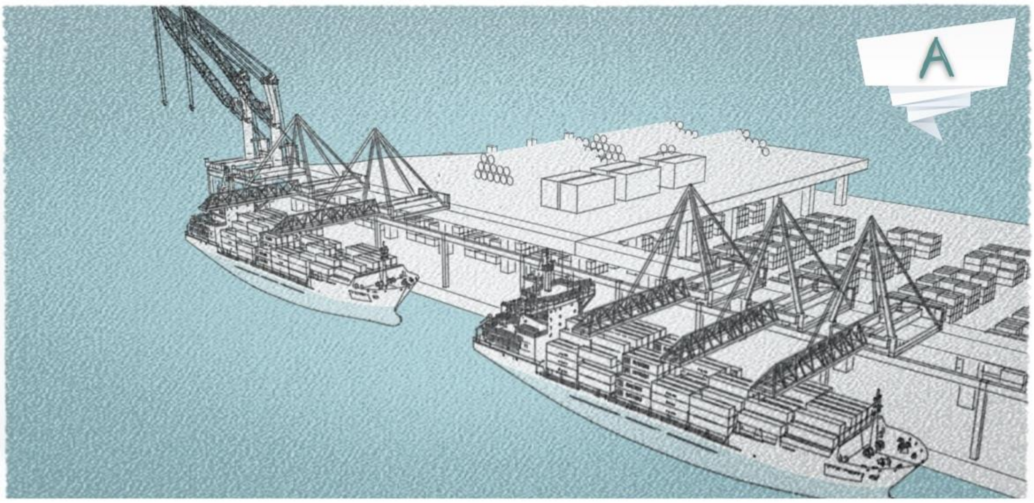
Variable	Scenario 3 – Favourable site conditions and unfavourable amount of work							
	Conventional expansion				VPC expansion			
	Unit cost	Description	Amount of works	Description	Unit cost	Description	Amount of works	Description
Coastal/slope protection	$2,000/m	Shallow water depth and construction material available at short distances	1,000m	2x500m of slope protection	$2,000/m	Shallow water depth and construction material available at short distances	564m	2x282m of slope protection
Reclaimed port land (land creation)	$\$2/m^3$	Borrow material at short distances no overburden removal needed	250,000x18m = $4,500,000m^3$	25ha multiplied by the height of filling (from -13m until +2m + 5m of unsuitables= 18m of filling height)	$\$2/m^3$	Borrow material at short distances no overburden removal needed	141,000x18 m= $2,538,000m^3$	14.1ha multiplied by the height of filling (from -13m until +2m + 5m of unsuitables= 18m of filling height)
Reclaimed port land (removal of unsuitables)	$\$2/m^3$	Disposal site at short distance, material free of pollution	$1,250,000m^3$	Unsuitable layer of 5m will need dredging	$\$2/m^3$	Disposal site at short distance, material free of pollution	$705,000m^3$	Unsuitable layer of 5m will need dredging
Reclaimed port land (land consolidation)	$\$10/m^2$	Borrow material available at a short distance	$250,000m^2$	Soil consolidation measures needed	$\$10/m^2$	Borrow material available at a short distance	$141,000m^2$	Soil consolidation measures needed
Vertical port variable	NA	NA	NA	NA	$\$1,300/m^2$	Value of reference taken from similar structure	$115,000m^2$	vertical structure providing the missing 11.5 ha

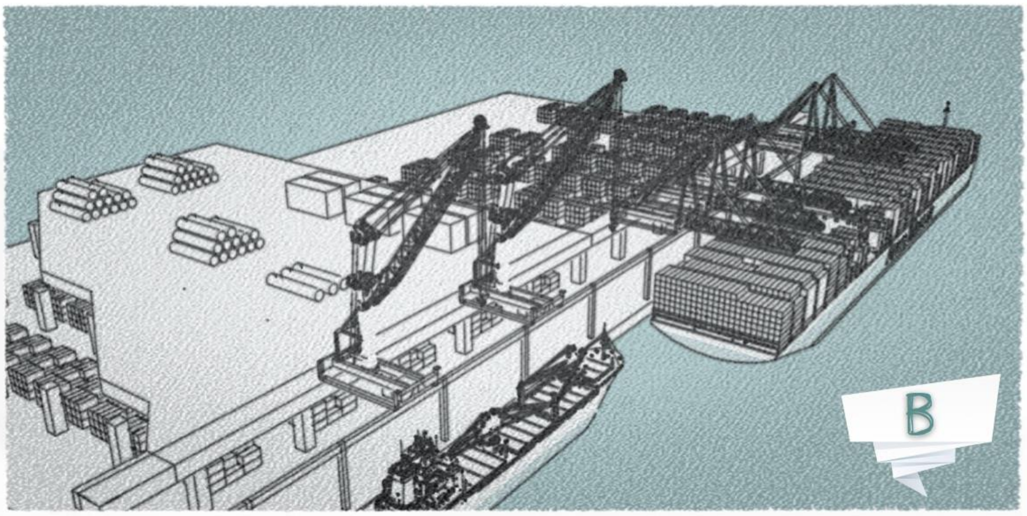
Table 26 - Calculation of the amount of works for the variables taken into account for scenario 3

Variable	Scenario 4 – Unfavourable site conditions and unfavourable amount of work							
	Conventional expansion				VPC expansion			
	Unit cost	Description	Amount of works	Description	Unit cost	Description	Amount of works	Description
Coastal/slope protection	$20,000/m	Deep waters and construction material available at long distances	1,000m	2x500m of slope protection	$20,000/m	Deep waters and construction material available at long distances	564m	2x282m of slope protection
Reclaimed port land (land creation)	$\$15/m^3$	Borrow material at long distances, overburden removal needed	250,000x18m = $4,500,000m^3$	25ha multiplied by the height of filling (from -13m until +2m + 5m of unsuitables= 18m of filling height)	$\$15/m^3$	Borrow material at long distances, overburden removal needed	141,000x18 m= $2,538,000m^3$	14.1ha multiplied by the height of filling (from -13m until +2m + 5m of unsuitables= 18m of filling height)
Reclaimed port land (removal of unsuitables)	$\$20/m^3$	Disposal site at long distance, material is polluted	$1,250,000m^3$	Unsuitable layer of 5m will need dredging	$\$20/m^3$	Disposal site at long distance, material is polluted	$705,000m^3$	Unsuitable layer of 5m will need dredging
Reclaimed port land (land consolidation)	$\$25/m^2$	Borrow material available at a long distance	$250,000m^2$	Soil consolidation measures needed	$\$25/m^2$	Borrow material available at a long distance	$141,000m^2$	Soil consolidation measures needed
Vertical port variable	NA	NA	NA	NA	$\$1,300/m^2$	Value of reference taken from similar structure	$115,000m^2$	vertical structure providing the missing 11.5 ha

Table 27 - Calculation of the amount of works for the variables taken into account for scenario 4

Appendix VI – VPC artist impressions

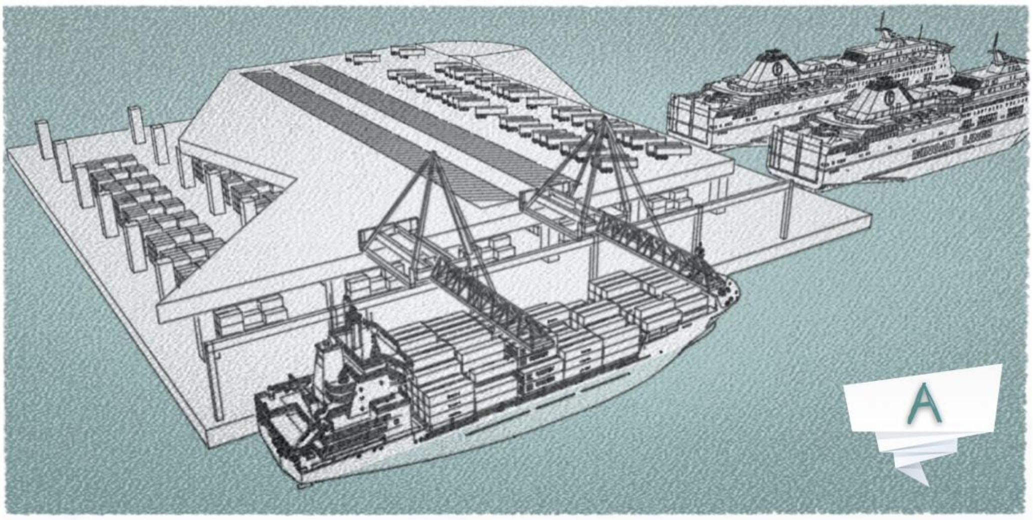


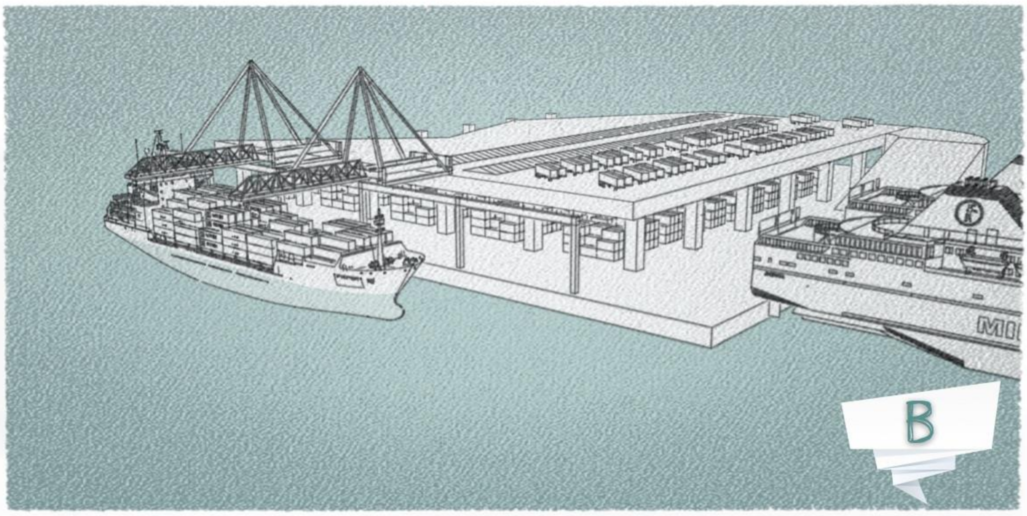


Title: Container terminal and general cargo **Author**: Rodrigo Gonçalves **Date**: 01/09/2016	**DRAWING REFERENCE:** EXAMPLE 1

DESCRIPTION

In this artist impression the vertical integration of a large container terminal and a small general cargo terminal is illustrated. Given the difference in size the general cargo terminal (placed on the top level) only covers half of the area of the container terminal, showing that the VPC is flexible and do not need to cover the entire ground level. Further more, specialised cranes can serve both berths of the terminals. In drawing A the 5 container cranes are serving two smaller container feeders, while the general cargo cranes are idle. In drawing B a larger container vessel is being served by all the 5 container SPS cranes while a small general cargo vessel is using the cranes of the general cargo terminal. A cut is done on the top level showing the reader the arrangement of the containers underneath it.



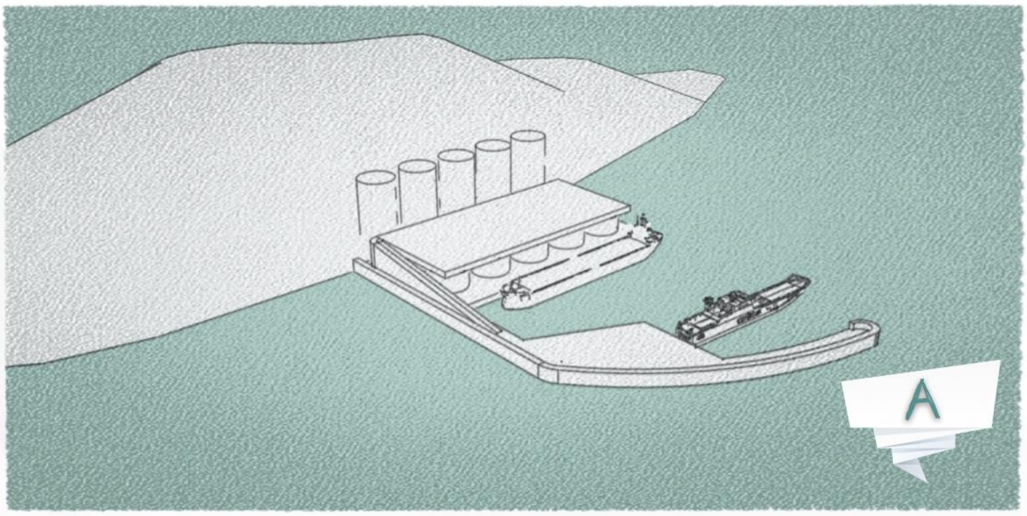


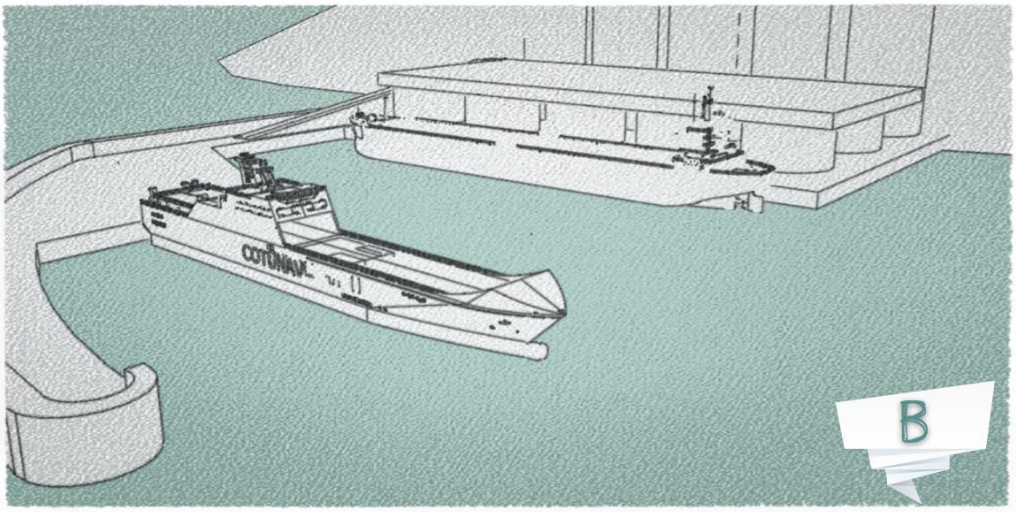
Title: Small container termina and RORO
Author: Rodrigo Gonçalves
Date: 01/09/2016

DRAWING REFERENCE:
EXAMPLE 2

DESCRIPTION

This artist impression depicts the vertical combination of a small container terminal and a RORO terminal. The containers are handled by cranes fixed in the top floor and stored on the ground floor. All the mobile units resulting from the RORO terminal operations are handled at the higher level. In this case the container terminal, due to it higher cargo density shall be placed on the ground floor, given that the loads resulting from the storing of the cargo will be higher. A cut of the top level is shown in drawing A, in order to show the reader the arrangement of the containers on the ground level. In this case overhead cranes could do the housekeeping tasks and stack movements.

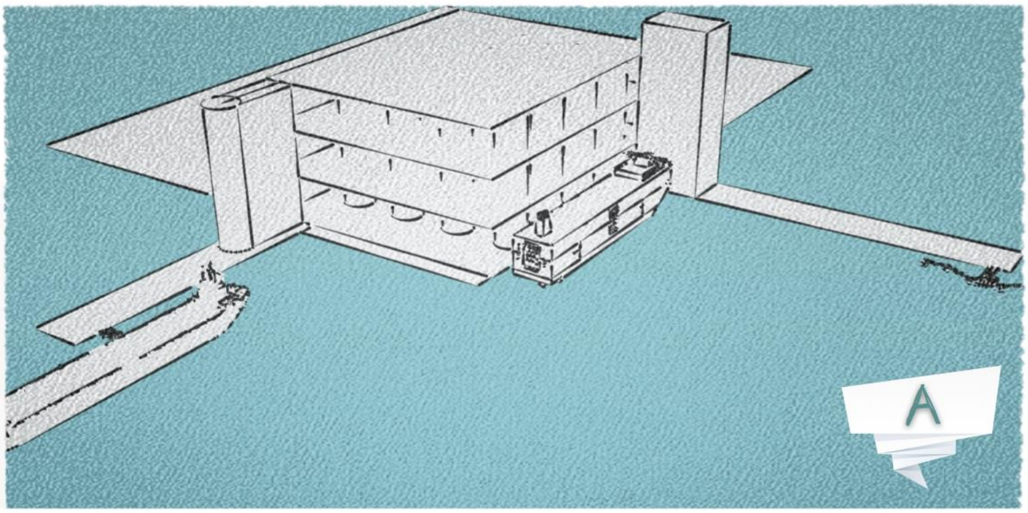


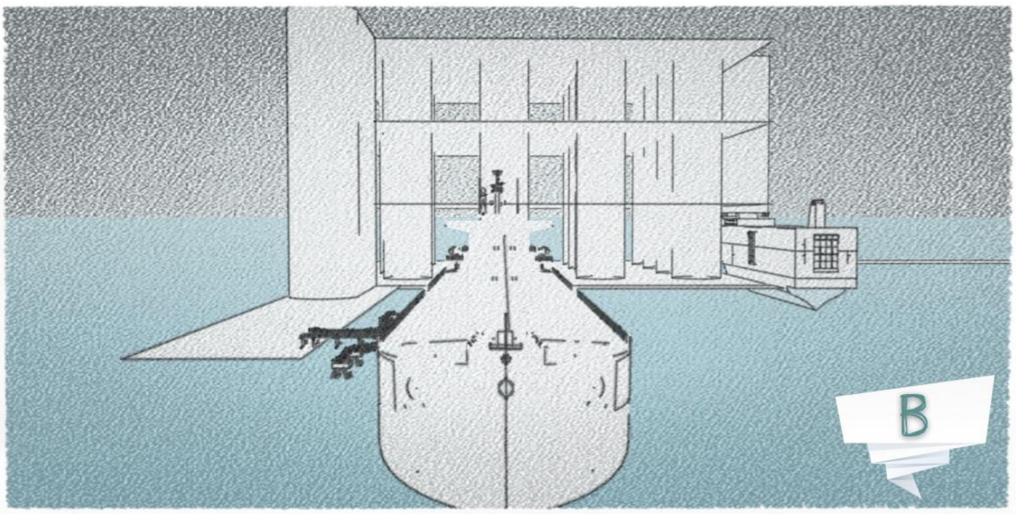


Title: Mountainous terrain agri and RORO
Author: Rodrigo Gonçalves
Date: 01/09/2016

DRAWING REFERENCE:
EXAMPLE 3

DESCRIPTION
The objective of this artist impression is to show the reader a vertical combination of a RORO and a agri-bulk terminal in a mountainous region. The VPC reduces the land reclamation requirements, which in sites with high depths close to shore is considerable expensive. It is possible to see in the drawings that the silos of the agri bulk terminal provide the support for the low density car terminal placed on the top level. Given the flexibility of the mobile units they can be loaded/unloaded at greater distances from the stacking area located on the surface provided by the vertical structure. Extra silo capacity is placed on the back of the VPC.





Title: Multi level integration
Author: Rodrigo Gonçalves
Date: 01/09/2016

DRAWING REFERENCE:
EXAMPLE 4

DESCRIPTION

This illustration provides a futuristic view of what the VPC might be like. In the drawing it is possible to observe 4 terminals combined in 3 levels of a vertical VPC structure. The berths of terminals are distributed around the site, more flexible cargoes are unloaded/loaded in jetties and transported to the higher levels of the structure. The lower level make use on the quay walls installed next to the structure. Although these drawings illustrate a completely new approach to port planning, given the advantages of increasing the cargo density in ports, it could represent an alternative in the future.