Measuring the Capacity of a Port System: A Case Study on a Southeast Asian Port

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Abstract

As economies develop and trade routes change, investment in port infrastructure is essential to maintain the necessary capacity for an efficiently functioning port system and to meet expected demand for all types of cargo. However, these large-scale, expensive investments in long-term infrastructure assets must be made despite a variety of future uncertainties that may potentially influence a port's performance. By using a Southeast Asian multi-purpose port as a case study, this thesis paper enhances the investment decision-making process for port infrastructure through the successful application and modification of two existing methodologies and the development of both an investment tool and a framework for selecting an optimal investment strategy to address capacity constraints within a port system.

Applied at the case study port, the research evaluates a modification of an existing methodology for the measurement of port capacity, developed by Lagoudis and Rice, to identify bottlenecks within the port system. The research then examines a modification of an existing methodology, developed by de Neufville and Scholtes, for the evaluation of potential investment strategies under uncertainty. A simulation screening model is developed to forecast expected profitability under uncertainty for potential investment strategies, including strategies with flexible options, and to determine the optimal strategy. The thesis concludes with the presentation of a decision-making process for port infrastructure investment and recommended refinements to the existing methodologies.

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1. Introduction

The global maritime network, consisting of tens of thousands of ships circumnavigating the world by sea and of strategically located ports across the globe, is an essential part of international trade, as "90% of all trade travels by water" (*U.S. Port and Inland Waterways Modernization*, 2012, p. III). Ocean-bound cargo of all kinds – containerized cargo from apparel to electronics, liquid cargo such as petroleum and vegetable oils, dry bulk cargo from iron ore to cereals, and break bulk cargo such as heavy, oddly-shaped scrap metal – originates from a nation for export and must pass through ports prior to reaching its destination. A port system is a collection of components bridging land and sea that work together to handle the cargo, which arrives sea-side by vessel at anchorage, is transferred land-side to the port terminal at the port's berths, and is eventually transported by intermodal links (e.g. road or rail networks) to the population located in the hinterland demanding the goods. As economies develop and trade routes change, a port system's capacity may need to expand to accommodate future cargo volume demand. However, investment in port infrastructure requires large amounts of capital (sometimes USD billions) and these investment decisions must be made when facing various uncertainties over the long life of these assets (ranging from 20-40 years). This thesis attempts to enhance the investment decision-making process for port infrastructure through the application and modification of existing methodologies and the development of a financial tool.

1.1 Motivation

The motivation for this thesis is threefold. First, the thesis research is an opportunity to extend and enhance an existing methodology for the measurement of a port system's capacity across terminal types (e.g., container terminal, dry bulk terminal, etc.), not just at container terminals as in previous studies. Second, as port capacity expansion projects are highly capital-intensive, existing port capacity must be measured thoroughly prior to committing to an investment decision. The thesis research allows for the application of an existing methodology to evaluate several investment strategies for an infrastructure project while accounting for various uncertainties over the project's useful life. As a result, an investment decision-making process is developed and proposed for future port infrastructure investments. Third, the thesis research assists the case study port in assessing potential investments to improve profitability and increase the port's capacity in order to meet regional demand growth and to compete with nearby ports.

1.2 Scope of Research

The main scope of this project is to assist the management team at the case study port in answering the following question: Can the capacity of a port system be measured using a robust methodological framework in order to develop a decision-making tool for port infrastructure development? The aim of the research is to develop a process for prioritizing investment decisions by evaluating and advancing an existing methodology for port capacity measurement, as well as applying and modifying an existing methodology for assessing investment strategies under uncertainty. The existing methodology for measuring a port system's capacity, developed by Dr. Ioannis Lagoudis of the Malaysia Institute for Supply Chain Innovation and James Rice Jr. of the Massachusetts Institute of Technology ("MIT") in 2011 and which serves as the foundation for this research, focuses on measuring port capacity using static (e.g., point-in-time capacity as illustrated by land availability) and dynamic (e.g., period-of-time capacity as illustrated by equipment technology) criteria. Due to past research primarily focusing on the measurement of capacity for only container terminals, the research in this thesis tests the existing methodology for the measurement of capacity across the varying infrastructure layouts at a multi-purpose port used as a case study. Based on the findings, the existing methodology is refined to include revised criteria and parameters for evaluating capacity, such as redefining the measurement calculations for bulk cargo to account for both volume and mass, and enhancing the presentation of the capacity measurement results to quickly assess the timing for addressing near-term capacity constraints.

Following the identification of bottlenecks in the port system during the capacity measurement stage, various investment strategies are then evaluated under multiple scenarios using an existing methodology described in the 2011 book *Flexibility in Engineering Design* by Dr. Richard de Neufville and Dr. Stefan Scholtes and modified by Dr. Jijun Lin in his application to offshore petroleum projects (Lin, 2008). This screening model and simulation framework allows for the development of a set of investment decision-making steps prioritizing and improving the visibility of port infrastructure investment requirements.

1.3 Description of the Case Study Port

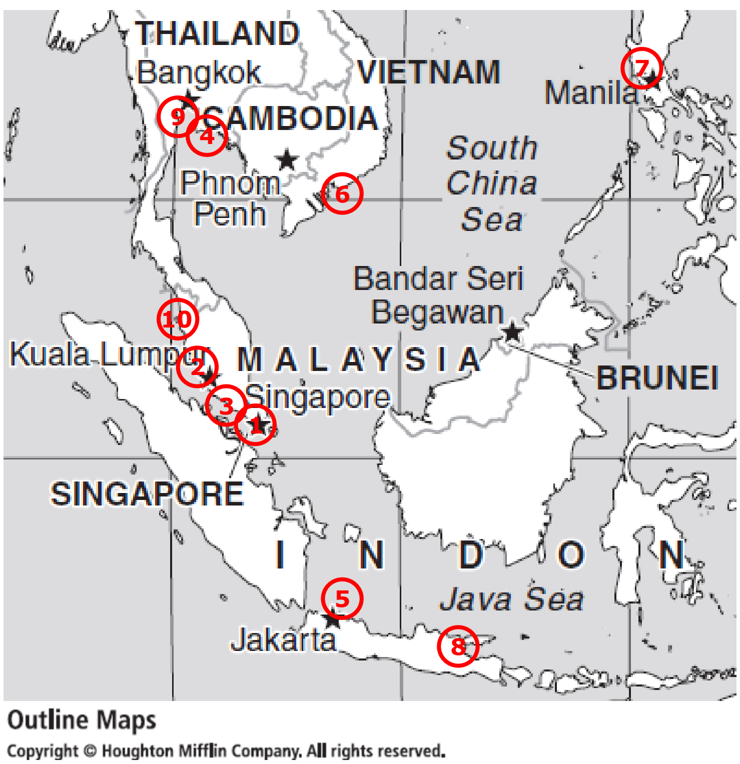
The case study port is a port strategically located in Southeast Asia, which is a critical intersection for international shipping traffic. The port serves a range of industries by maintaining highly diverse operations through various types of terminals supported by landside intermodal links. The layout of the port comprises a container terminal, a liquid bulk terminal, a dry bulk terminal, a break bulk terminal, and capacity to provide both oil and gas maintenance services and warehousing. National rail and road connectivity provide the port with essential access to serve the hinterland. The rail network has just undergone improvements resulting in an upgraded national network, however road remains the dominant means of cargo transport. The port primarily handles origin-destination cargo, but faces competition from both domestic ports and Southeast Asian regional ports. Proposed capacity investments and improvements must focus on productivity, as the port does not have any available land for further expansion.

1.4 The Regional and Economic Landscape

This section presents some of the main forces impacting the case study port. The section, first, describes the ports and projects located in Southeast Asia and, second, describes Country X's economic environment with a comparison to the environment in nearby countries.

1.4.1 Southeast Asia Maritime Landscape

The Southeast Asian maritime landscape is characterized by several of the world's largest ports in terms of throughput and the country in which the case study port is located ("Country X") has ongoing projects intended to transform the nation into a regional hub of products and services. The region's ports (as per Figure 1-1) are located centrally amidst both global and intra-Asia shipping routes. Ten of the top 100 container ports (in terms of 2011 throughput) are located in Southeast Asia. Further, many of these ports handle various non-containerized cargoes and are undergoing substantial expansionary development (*Containerisation International: Top 100 Container Ports*, 2012). The critical shipping conduit for Asia-Europe shipping traffic, the Strait of Malacca, is to the west and the South China Sea and Java Sea are in the east. The long-established global shipping and trading hub of Singapore is just south of peninsular Malaysia.



Key Ports in SE Asia

1. Singapore & Jurong Island
2. Port Klang
3. Port Tanjung Pelepas
4. Laem Chabang
5. Tanjung Priok
6. Ho Chi Minh City
7. Manila
8. Tanjung Perak
9. Bangkok
10. Penang Port

Figure 1-1: Map of Southeast Asia highlighting key ports (ranked in order of highest container throughput in 2011)

1.4.2 Regional and Domestic Economic Trends

The current economic environment and trends, both domestically and regionally, that impact the case study port are presented. Country X is a middle-income nation (Avris, Mustra, Ojala, Shepard, & Saslavsky, 2012) in the process of moving from developing country status toward becoming a developed country (Schwab & Sala-i-Martin, 2013), benefiting from rapidly-growing intra-Asia trade. Seaborne cargo volumes for Southeast Asia are forecasted to increase, with average port terminal utilization increasing from 70.9% in 2011 to 86.1% by 2017, according to Drewry Maritime Research (*Global Container Terminal Operators*, 2012). Moreover, the volume growth is supported by recent government policy and economic developments in Country X. Federal government spending plans support major infrastructure developments with the aim of developing a regional hub of products and services with emphasis on key economic areas such as the oil, gas and energy sector. However, full implementation of the proposed economic and infrastructure development plans may be contingent upon the outcome of periodic national political events. In addition, China will remain one of Country X's most significant trading partners for the foreseeable future, while the country's population and GDP per head are forecasted to rise under current government policy (Economic Intelligence Unit, 2012). As such, it is imperative that Country X's government continue to promote the development of its ports to meet expected demand and increase efficiency, while further challenging Singapore's dominant position for handling regional cargo (Low, 2010).

Singapore is at or near the top of the international business environment rankings (Table 1-2) established by the World Bank and World Economic Forum, due to the nation-state's market efficiency and infrastructure, to name a few factors (Schwab & Sala-i-Martin, 2013, p.11), but Country X may be able to learn from the region's foremost logistics cluster. In the early 19th century, Singapore managed to stand out from the other Southeast Asian ports and develop into the region's premier logistics cluster by attracting volumes through the non-assessment of port fees (Sheffi, 2012, p.187-188). As MIT's Dr. Yossi Sheffi describes in his 2012 book *Logistics Clusters*, Singapore maintains its current status as the region's logistics hub primarily due to its competitive advantage in innovation supported by quality infrastructure, government investment and education (Sheffi, 2012, p. 289). However, the region's neighboring ports, such as those in Country X, also offer similar geographic benefits (strategic location, benign weather) in addition to cheap, available land, low labor costs and an increasingly trade-oriented culture (Sheffi, 2012, p. 64-67, 289). Although it faces tough competition from Singapore, Country X stands to benefit if it can leverage its strengths and catch up in other areas.

Table 1-1: Global rankings comparing select Southeast Asian countries

World Bank Logistics Performance Index 2012

Country	Overall Ranking (out of 155 nations)	Customs	Infrastructure	International Shipments	Logistics Quality & Competence	Tracking & Tracing	Timeliness
Singapore	1	1	2	2	6	6	1
Malaysia	29	29	27	26	30	28	26
Thailand	38	42	44	35	49	45	39
Philippines	52	67	62	56	39	39	69
Vietnam	53	63	72	39	82	47	38
Indonesia	59	75	85	57	62	52	42

World Economic Forum Global Competitiveness Rankings 2012-13

Country	Overall Global Ranking (out of 144 nations)	Institutions	Infrastructure	Macroeconomic Development	Health & Primary Education	Higher Education & Training	Goods Market Efficiency
Singapore	2	1	2	17	3	2	1
Malaysia	25	29	32	35	33	39	11
Thailand	38	77	46	27	78	60	37
Indonesia	50	72	78	25	70	73	63
Philippines	65	94	98	36	98	64	86
Vietnam	75	89	95	106	64	96	91

Country	Overall Global Ranking	Labor Market Efficiency	Financial Market Development	Technological Readiness	Market Size	Business Sophistication	Innovation
Singapore	2	2	2	5	37	14	8
Malaysia	25	24	6	51	28	20	25
Thailand	38	76	43	84	22	46	68
Indonesia	50	120	70	85	16	42	39
Philippines	65	103	58	79	35	49	94
Vietnam	75	51	88	98	32	100	81

World Bank Ease of Doing Business 2013

Country	Overall Global Ranking (out of 185 nations)	Tax Rate (% of profit)	Trading Across Borders	Documents to Export (number)	Days to Export	Cost to Export (USD per container)	Documents to Import (number)	Days to Import	Cost to Import (USD per container)
Singapore	1	27.6%	1	4	5	456	4	4	439
Malaysia	12	24.5%	11	5	11	435	6	8	420
Thailand	18	37.6%	20	5	14	585	5	13	750
Vietnam	99	34.5%	74	6	21	610	8	21	600
Indonesia	128	34.5%	37	4	17	644	7	23	660
Philippines	138	46.6%	53	7	15	585	8	14	660

Sources: Avris et al., 2012; Schwab & Sala-i-Martin, 2013; *Doing Business*, 2013

1.5 Contributions

The results of this research directly enhance the case study port's decision-making capability for investing in its port infrastructure. Better capacity measurement should help alleviate port congestion issues due to underinvestment, while avoiding investments which would lead to unnecessary excess capacity. A straight-forward framework can be applied to measure capacity across all components of a port system to identify capacity constraints. Then, a robust tool can be utilized in a timely manner to assess and rank various investment strategies to address the capacity constraints under multiple scenarios when deciding on port infrastructure investments. Using the tools developed for the Southeast Asian port as the case study, the improved methodological framework may potentially be applied by other terminal operators and port authorities throughout the maritime industry when considering port infrastructure development for various terminal types.

1.6 Thesis Outline

Chapter 2 presents the literature review, which provides an overview of the recent research pertaining to capacity measurement of a port system and its components as well as to port infrastructure investment. Chapter 3 describes the methodology applied in the research, highlighted by the methodology for measuring port capacity developed by Lagoudis and Rice (Lagoudis & Rice, 2011) and the methodology for evaluating investment strategies under uncertainty developed by de Neufville and Scholtes (de Neufville & Scholtes, 2011). Chapter 4 examines the results of the data analysis. Chapter 5 presents the recommendations based on the findings, including the proposed investment process and observations. Chapter 6 concludes the paper with a summary and suggestions for further research.

2. Literature Review

This chapter provides an overview of the academic and institutional research related to this thesis, prior to presenting the methods used for measuring port capacity and evaluating investment decisions under uncertainty, respectively, in Chapter 3. This literature review will, first, summarize past approaches for measuring port capacity generally, followed by a review of approaches for measuring capacity across the individual components (anchorage, waterway, terminal quay, terminal yard, and intermodal links) that comprise a port system. Second, the literature review will present previous methods utilized to evaluate port infrastructure investments. To reiterate, please note that the primary methodologies – Lagoudis & Rice's methodology for port capacity measurement and de Neufville & Scholtes's methodology for evaluating investment strategies under uncertainty – developed from past research and applied in this thesis, are introduced and described in Chapter 3.

2.1 Port System Capacity

Research exists that addresses general performance and capacity measurement across a port system; however, much of the research is focused on container terminals. A recent study on the state of the U.S. port system and its preparedness for the effects of the Panama Canal expansion describes the components of a port system, the factors influencing capacity, and the measurement of port utilization (*U.S. Ports and Inland Waterways Modernization*, 2012). Other maritime experts describe a port system and its operations (Stopford, 1997), as well as the measurement of port performance (Fourgeaud, 2000). One study applies a supply chain management approach identifying a port system's flows (physical cargo, payment, information, and capital) as well as factors related to measuring port capacity (Bichou & Gray, 2004). More specifically, previous studies have addressed capacity measurement across a port system's components: anchorage, waterway, terminal quay/berth, terminal yard, and intermodal links to rail and road. The following summarizes select studies for each of these components, in the direction of inbound cargo.

2.1.1 Anchorage

Past studies have investigated anchorage capacity from different perspectives. Berg-Andreassen examined the economic impact of anchorage capacity using both a mathematical model based on queuing theory and scenario planning, and applying them to anchorage data for the Mississippi River (Berg-Andreassen & Prokopowicz, 1992). Mathematical models based on queuing theory were also used to study efficient loading/unloading at the anchorage-ship-berth link of a port system (Zrnić, Dragović, & Radmilović, 1999). More recently, anchorage capacity and utilization was measured on the basis of anchorage location through the development of two computer-based simulation models – Maximum Hole Degree First (MHDF) and Wallpack MHDF – that suggest a method for improving utilization at the anchorage component (Huang, Hsu, & He, 2011).

2.1.2 Waterway

Research related to the waterway component (i.e., river or canal serving the port) has primarily been focused on Europe, where inland waterways are a widely-used conduit for transporting cargo to and from the continent's hinterland. One study evaluated waterway capacity using numerical models based on both queuing theory and statistical forecasts to estimate delays caused by locks along inland waterways (Dai & Schonfeld, 1998). Another study examined waterway congestion caused by interruptions along the Strait of Istanbul with the use of a queuing model (Ulusçu & Altiok, 2009). The economic impact of vessel delays related to waterway depth was investigated for the waterway serving the Port of Antwerp (Veldman, Bückmann, & Saitua). Two additional studies focused on government policy of inland waterway transport for continental European nations (Seindenfus, 1994), with one study arguing that the UK government should align its waterway policy with that of continental Europe (Burn, 1984).

2.1.3 Terminal Quay

A port system's sea-side and land-side activities meet at the terminal quay/berth, where cargo is loaded/unloaded from the vessel to the terminal yard. A number of studies measured the efficient use of quay cranes and berth utilization at the terminal quays of container terminals. One study investigated cost and time inefficiencies through the use of a simulation model, with the Pusan container terminal in Korea as a case study (Dragović, Park, & Radmilović, 2006). A second study analyzed the scheduling of berths and quay cranes concurrently using a two-phase integer programming model (Park & Kim, 2003). A third study developed heuristics based on a genetic algorithm to determine optimal berth schedules and quay crane allocations (Imai, Chen, Nishimura, & Papadimitriou, 2008). Finally, a fourth study evaluated the delays resulting from quay crane breakdowns using Markov theory and cost analysis (Mennis, Lagoudis, Platis, & Nikitakos, 2008).

2.1.4 Terminal Yard

A large body of research exists describing the layout and operations of a port's terminal yard, specifically of a container terminal yard. However, basic port layout and operations can vary by geographic region (Günther & Kim, 2006). Taiwanese container terminals are the basis for one study that describes the measurement of static capacity at a terminal yard as well as the capacity for dynamic components, such as equipment (Chu & Huang, 2005). Terminal yard layout and operations may also differ depending on purpose – whether the terminal is handling origin-destination cargo or transshipment cargo (Petering, 2011). Other research focuses on the economic impacts of port capacity when deciding on port infrastructure investment. Bassan (2007) states that port capacity and performance should be subject to economic analysis. One recent study argues that an economic approach, as opposed to a widely-used traditional engineering approach, should be utilized when measuring terminal yard capacity for investment decisions, to take into account the benefits to national and regional economies (Chang, Tongzon, Luo, & Lee, 2012).

2.1.5 Intermodal Links (Rail & Road)

As outlined by Lagoudis and Rice, a segment of a port system relates to intermodal links to the hinterland, comprising components related to railway and road. Limited research exists on the intermodal links within a port system. One study of Spanish railway capacity suggests using simpler, less time-consuming analytical methods to identify network bottlenecks and addressing capacity issues with efficiency improvements, instead of expansionary investment (Abril et al., 2008). Research related to trucking puts forward a dynamic, but complex, approach to yard trailer utilization to increase capacity within a container terminal yard (Nishimura, Imai, & Papadimitriou, 2005).

2.2 Port Infrastructure Investment

Much of the research on port infrastructure investment relates to risk management and benefits to society. A port's ownership can be structured in different manners, which may influence investment choices as stakeholders have unaligned goals (Xiao, Ng, Yang, & Fu, 2012). However, one study suggests that the role of local investors, in general, will increase following the 2008 financial crisis, during which a disconnect developed between risk management and investment (Rodrigue, Notteboom, & Pallis, 2010). When public funds are involved, it becomes particularly important for a government to justify the use of large capital outlays. Dekker and Verhaeghe (2008) evaluate port capacity expansion on three dimensions (timing, relief interval, and size) using a system of equations. M. W. Ho and K. H. Ho (2006) propose various risk management techniques for evaluating infrastructure investments, including financial and sensitivity analyses, scenario planning, and optimization with the use of simulations.

3. Methods

This chapter highlights the existing methodology for measuring capacity across a port system and the existing methodology for evaluating investment strategies under uncertainty, as these are the methodologies that form the basis for the research presented in this paper. The modifications of these methodologies for this thesis are also described. The development of the overarching methodology for this thesis was an iterative process focused initially on the methodology of port capacity measurement and then the methodology for evaluating and presenting the results of the investment strategies. Each methodology began with the development and application of a functioning model to evaluate a single port component and/or single investment strategy under a single uncertainty, which was then expanded to include all port components, uncertainties, and investment strategies.

3.1 Methodology for Port Capacity Measurement

The research project aims to extend and improve upon an existing methodology to measure port capacity from a supply chain management perspective. The existing methodology was developed by Dr. Ioannis Lagoudis and James Rice Jr. in their 2011 white paper "Revisiting Port Capacity: A Practical Method for Investment and Policy Decisions" and measures a port's capacity as a system, from sea-side beginning with anchorage to land-side ending with intermodal links connected to the hinterland (see Figure 3-1). A uniform approach for measuring capacity is applied at each component throughout the port system using two dimensions: static capacity, referring to the use of available land at a point in time, and dynamic capacity, referring to the technology of equipment and skill level of labor over a period of time. After applying the demand data to determine utilization levels, this approach allows for the identification of cargo flow bottlenecks at the port and for the implementation of efficiency improvements, potentially through additional investment. The methodology had only been tested on a container terminal. The current research is to extend its application to a multi-purpose port across various terminal types, such as container, liquid bulk, dry bulk, and break bulk.

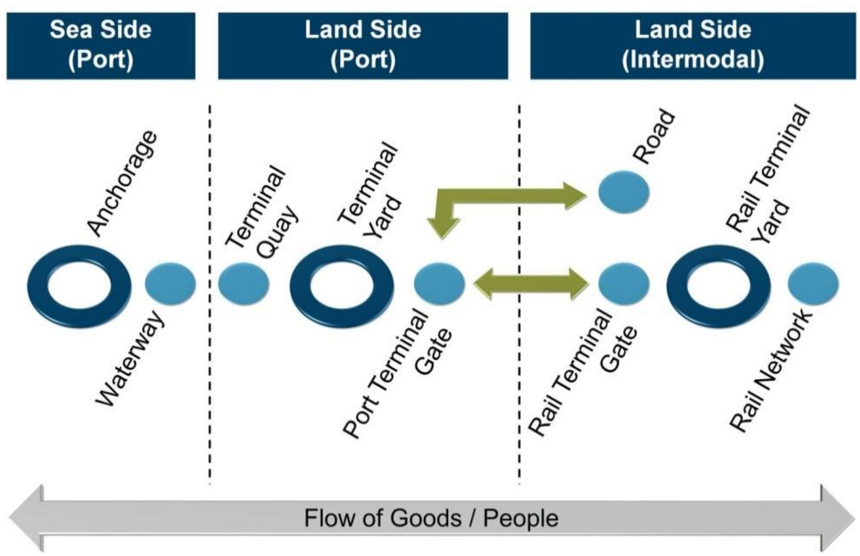


Figure 3-1: A diagram of a port system's components from anchorage to intermodal links (Lagoudis & Rice, 2011)

3.1.1 Static Capacity & Dynamic Capacity

Static capacity is defined by the land availability at a point in time (Lagoudis & Rice, 2011). For example, the static capacity of a container yard's slots is equal to the number of ground slots for twenty-foot equivalent unit (TEU) containers multiplied by the stacking height of the TEU containers (1,000 ground slots * 5 container stacking height = static capacity of 5,000 TEU containers for the container yard). Static capacity is maximized when the port component no longer has additional land to expand.

Dynamic capacity is defined by the technology of the equipment and skill level of the labor force over a period of time (Lagoudis & Rice, 2011). For example, the dynamic capacity of one container crane is equal to the number of moves per hour performed by the crane (25 TEU moves / 1 hour = dynamic capacity of 25 TEU moves per hour for the container crane). Dynamic capacity is maximized when "the full capabilities of technology and labor are exploited" (Lagoudis & Rice, 2011).

By examining both the static and dynamic dimensions of the capacity for a port system's component, one can determine the use of resources and whether efficiency improvements and/or investments should be made to address capacity constraints. Figure 3-2 illustrates the relationship between the static capacity and dynamic capacity dimensions.

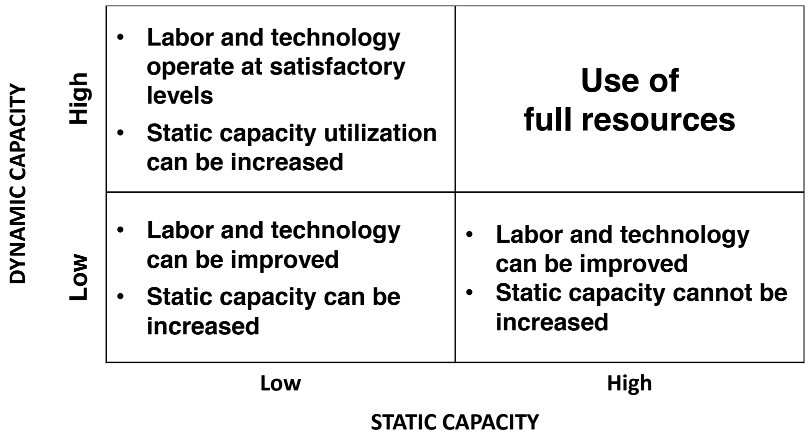


Figure 3-2: The relationship between the dimensions of static capacity and dynamic capacity (Lagoudis & Rice, 2011)

Table 3-1 below presents the calculations for measuring static capacity and dynamic capacity in this thesis. An initial version of the formulas were determined by Lagoudis & Rice and then modified by the thesis author while testing the existing methodology on the case study port. Note that the calculations for select port components (container warehouse, car terminal yard/area, ferry terminal yard/area, cruise terminal yard/area, port terminal gate, rail terminal gate, rail terminal yard and road network) are excluded as these calculations are either not relevant for the case study port or data was unavailable.

Table 3-1: Modified Capacity Calculations based on Lagoudis & Rice Methodology

Port Component	**Capacity Calculations for Static & Dynamic Dimensions** ST = Static Theoretical Capacity DT = Dynamic Theoretical Capacity SA = Static Actual Capacity DA = Dynamic Actual Capacity
Anchorage	$ST_A = d_A / a_A$, where $a_A = \Pi * (0.5 * z_A * s_W)^2$ $DT_A = d_A / (a_A * t_A)$

	where: a_A = Area needed by average vessel size d_A = Designated area for anchorage t_A = Average waiting time z_A = Minimum safety clearance between vessels at anchorage Note that $ST_A = SA_A$ and $DT_A = DA_A$ for anchorage
Waterway	$ST_W = (l_W * n_W) / (s_W + z_W)$ $SA_W = ST_W * (1 - c_W)$ $DT_W = (l_W * n_W) / [(s_W + z_W) * t_W]$ $DA_W = DT_W * (1 - c_W)$ where: l_W = Length of waterway n_W = Number of lanes on waterway r_W = Capacity reduction due to sharing of waterway with other parties s_W = Average vessel size t_W = Average cruising time z_W = Minimum safety clearance between vessels on waterway
Terminal Quay/Berth	$ST_Q = l_Q / (s_W + z_Q)$ $DT_Q = l_Q / [(s_W + z_Q) * t_Q]$ For berths at liquid bulk terminals: $SA_Q = n_Q$, $DA_Q = n_Q * t_Q$ where: l_Q = Length of quay n_Q = Number of berths t_Q = Turnaround time z_Q = Minimum safety clearance between vessels at berth Note that $ST_Q = SA_Q$ and $DT_Q = DA_Q$ for container, dry & break bulk berths

Terminal Yard/Area	
Container	Yard: $ST_{CY} = d_{CY} / s_{CY} = n_{CY} * h_{CY}$ $SA_{CY} = ST_{CY} * u_{CY}$ $DT_{CY} = (n_{CY} * h_{CY}) / [t_{CY} / (o_{CY} - m_{CY})]$ $DA_{CY} = DT_{CY} * u_{CY}$ where: d_{CY} = Designated area for container terminal yard h_{CY} = TEU stacking policy m_{CY} = Average annual downtime days for container terminal yard n_{CY} = Number of ground slots o_{CY} = Annual operating days for container terminal yard s_{CY} = TEU Size t_{CY} = TEU average idle time u_{CY} = Utilization threshold (e.g., congestion at 70% utilization) Equipment: $DT_{CE} = n_{CE} * d_{CE} * (o_{CE} - m_{CE}) * h_{CE}$ $DA_{CE} = n_{CE} * p_{CE} * (o_{CE} - m_{CE}) * (1 - r_{CE}) * h_{CE}$ where: d_{CE} = Number of designed moves per hour h_{CE} = Daily operating hours m_{CE} = Average annual downtime days for container equipment n_{CE} = Number of container equipment (e.g., cranes & RTGs) o_{CE} = Annual operating days for container equipment p_{CE} = Number of designed moves per hour r_{CE} = Maintenance reduction for equipment

Liquid Bulk	ST_{LB} (mass) = $(n_{LB} * s_{LB}) / d_{LB}$ ST_{LB} (volume) = ST_{LB} (mass) $* (1 / c_{LB})$ $SA_{LB} = ST_{LB} * (1 - r_{LB})$ DT_{LB} (mass) = $(n_{LB} * s_{LB}) + (t_{LB} * n_Q * o_{LB} * h_{LB}) / d_{LB}$ DT_{LB} (volume) = $(n_{LB} * v_{LB}) + (t_{LB} * n_Q * o_{LB} * h_{LB}) / d_{LB}$ $DA_{LB} = DT_{LB} * (1 - r_{LB})$ where: c_{LB} = Density of cargo d_{LB} = Designated area for liquid bulk terminal yard h_{LB} = Daily operating hours n_{LB} = Number of tanks o_{LB} = Annual operating days r_{LB} = Maintenance downtime for tanks, as a percentage (i.e., 1 – utilization %) s_{LB} = Average tank capacity (mass) t_{LB} = Average pumping rate (mt / hr) per berth v_{LB} = Average tank capacity (volume)
Dry Bulk	<u>Yard:</u> ST_{DBY} (mass) = s_{DBY} / d_{DBY}, where $s_{DBY} = r_{DBY} / [t_{DBY} / (o_{DBY} - m_{DBY})]$ ST_{DBY} (volume) = $d_{DBY} * h_{DBY}$ $SA_{DBY} = ST_{DBY} * u_{DBY}$ DT_{DBY} (mass) = $[s_{DBY} * ((o_{DBY} - m_{DBY}) / t_{DBY})] / d_{DBY}$ DT_{DBY} (volume) = $ST_{DBY} * (t_{DBY} / (o_{DBY} - m_{DBY}))$ $DA_{DBY} = DT_{DBY} * u_{DBY}$ where: d_{DBY} = Designated area for dry bulk terminal yard

	h_{DBY} = Stacking policy for dry bulk terminal yard o_{DBY} = Annual operating days for dry bulk terminal yard m_{DBY} = Annual downtime days for dry bulk terminal yard r_{DBY} = Annual throughput for dry bulk terminal yard s_{DBY} = Commodity size for dry bulk t_{DBY} = Commodity average idle time for dry bulk <u>Equipment:</u> $DT_{DBE} = n_{DBE} * d_{DBE} * (o_{DBE} - m_{DBE}) * h_{DBE}$ $DA_{DBE} = n_{DBE} * p_{DBE} * (o_{DBE} - m_{DBE}) * (1 - r_{DBE}) * h_{DBE}$ where: d_{DBE} = Number of designed moves per hour h_{DBE} = Daily operating hours m_{DBE} = Average annual downtime days for dry bulk equipment n_{DBE} = Number of dry bulk equipment (e.g., cranes & conveyors) o_{DBE} = Annual operating days for dry bulk equipment p_{DBE} = Number of designed moves per hour r_{DBE} = Maintenance reduction for equipment, as a percentage <u>Warehouse:</u> ST_{DBWH} (mass) = c_{DBWH} / d_{DBWH}, can also just be equal to c_{DBWH} ST_{DBWH} (volume) = $d_{DBWH} * s_{DBWH}$ $SA_{DBWH} = ST_{DBWH} * u_{DBWH}$ DT_{DBWH} (mass) = $ST_{DBWH} * o_{DBWH} / t_{DBWH}$ DT_{DBWH} (volume) = $ST_{DBWH} / t_{DBWH} / o_{DBWH}$ DA_{DBWH} (mass) = $SA_{DBWH} * o_{DBWH} / t_{DBWH}$ DA_{DBWH} (volume) = $DT_{DBWH} * u_{DBWH}$ where:

	c_{DBWH} = Commodity size for dry bulk warehouse (i.e., maximum allowable mass that warehouse is designed to support) d_{DBWH} = Designated area for dry bulk warehouse o_{DBWH} = Annual operating days s_{DBWH} = Stacking policy (i.e., height allowed for dry bulk cargo) t_{DBWH} = Commodity average marshaling time at dry bulk terminal u_{DBWH} = Utilization threshold (% of warehouse for temporary storage)
Break Bulk	<u>Yard:</u> ST_{BBY} (mass) = s_{BBY} / d_{BBY}, where $s_{BBY} = r_{BBY} / [t_{BBY} / (o_{BBY} - m_{BBY})]$ ST_{BBY} (volume) = $d_{BBY} * h_{BBY}$ $SA_{BBY} = ST_{BBY} * u_{BBY}$ DT_{BBY} (mass) = $[s_{BBY} * ((o_{BBY} - m_{BBY}) / t_{BBY})] / d_{BBY}$ DT_{BBY} (volume) = $ST_{BBY} * (t_{BBY} / (o_{BBY} - m_{BBY}))$ $DA_{BBY} = DT_{BBY} * u_{BBY}$ where: d_{BBY} = Designated area for break bulk terminal yard h_{BBY} = Stacking policy for break bulk terminal yard o_{BBY} = Annual operating days for break bulk terminal yard m_{BBY} = Annual downtime days for break bulk terminal yard r_{BBY} = Annual throughput for break bulk terminal yard s_{BBY} = Commodity size for break bulk t_{BBY} = Commodity average idle time for break bulk <u>Equipment:</u> $DT_{BBE} = n_{BBE} * d_{BBE} * (o_{BBE} – m_{BBE}) * h_{BBE}$ $DA_{BBE} = n_{BBE} * p_{BBE} * (o_{BBE} – m_{BBE}) * (1 – r_{BBE}) * h_{BBE}$ where:

	d_{BBE} = Number of designed moves per hour h_{BBE} = Daily operating hours m_{BBE} = Average annual downtime days for break bulk equipment n_{BBE} = Number of break bulk equipment (e.g., cranes) o_{BBE} = Annual operating days for break bulk equipment p_{BBE} = Number of designed moves per hour r_{BBE} = Maintenance reduction for equipment, as a percentage <u>Warehouse:</u> ST_{BBWH} (mass) = c_{BBWH} / d_{BBWH}, can also just be equal to c_{BBWH} ST_{BBWH} (volume) = d_{BBWH} * s_{BBWH} SA_{BBWH} = ST_{BBWH} * u_{BBWH} DT_{BBWH} (mass) = ST_{BBWH} * o_{BBWH} / t_{BBWH} DT_{BBWH} (volume) = ST_{BBWH} / t_{BBWH} / o_{BBWH} DA_{BBWH} (mass) = SA_{BBWH} * o_{BBWH} / t_{BBWH} DA_{BBWH} (volume) = DT_{BBWH} * u_{BBWH} where: c_{BBWH} = Commodity size for break bulk warehouse (i.e., maximum allowable mass that warehouse is designed to support) d_{BBWH} = Designated area for break bulk warehouse o_{BBWH} = Annual operating days s_{BBWH} = Stacking policy (i.e., height allowed for break bulk cargo) t_{BBWH} = Commodity average marshaling time at break bulk terminal u_{BBWH} = Utilization threshold (% of warehouse for temporary storage)
Rail Network	$ST_{RN} = n_{RN} * c_{RN}$, where $c_{RN} = v_{RN} * w_{RN} * s_{RN}$ $n_{RN} = k_{RN} / l_{RN} * t_{RN}$ $l_{RN} = w_{RN} * (x_{RN} + z_{RN}) + y_{RN}$

	$SA_{RN} = u_{RN} * c_{RN}$ $DT_{RN} = [h_{RN} / (2 * k_{RN} / a_{RN})] * o_{RN} * t_{RN}$ $DA_{RN} = [h_{RN} / (2 * k_{RN} / a_{RN} + i_{RN})] * o_{RN} * t_{RN}$ where: a_{RN} = Average cruising speed of train c_{RN} = Number of containers per train h_{RN} = Daily operating hours i_{RN} = Loading/unloading hours per train trip k_{RN} = Length of lane from port to nearest rail interchange l_{RN} = Length of train n_{RN} = Number of trains per lane length o_{RN} = Annual operating days s_{RN} = Stacking policy (i.e., containers high per car) t_{RN} = Number of tracks per lane u_{RN} = Number of trains per lane v_{RN} = Number of containers per car w_{RN} = Number of cars per train x_{RN} = Length of car y_{RN} = Number of locomotives per train * Length of locomotive z_{RN} = Minimum safety clearance between cars / locomotive

Source: Author

3.1.2 Theoretical & Actual Capacity

Along the static and dynamic dimensions, capacity is defined in terms of theoretical capacity and actual capacity. Theoretical capacity is defined as the maximum designed capacity of the port component.

- In the previous static capacity example, the theoretical capacity of a container yard's slots is 5,000 TEU at a single point in time, assuming 100% utilization of all ground slots in combination with 100% utilization of the 5 container high stacking policy.
- In the previous dynamic capacity example, a container crane's capacity is 25 TEU moves/hour. If the 25 TEU moves/hour is the designed capacity of that crane in new condition, then the theoretical capacity of the container crane has been determined.

Actual capacity is defined as the maximum operational capacity of the port component without experiencing congestion.

- For a container yard, it is commonly understood that a port operating at slot utilization levels below 70% of its theoretical capacity will normally operate without experiencing congestion. However, at slot utilization levels between 70% and 80%, the yard is considered to be congested and experiencing delays. Further, at slot utilization levels above 80%, the yard is considered to be highly congested and experiencing significant delays. Thus, the actual capacity of the container slots is determined to be in the range of 70-80% of its theoretical capacity (equivalent to 3,500-4,000 TEU containers).
- For a container crane, in our example the theoretical capacity was previously determined to be 25 TEU moves/hour. However, due to natural wear-and-tear over the course of its useful life, a crane will no longer be able to operate at its designed capacity, even with regular preventive maintenance. For this example, it will be assumed that the container crane is 10 years old

and therefore can now only operate at a maximum of 20 TEU moves/hour, meaning its actual capacity is equal to 80% of its theoretical capacity.

3.1.3 An Example of Capacity Measurement

As demonstrated in Section 3.1.2, both static and dynamic dimensions can be measured in terms of theoretical and actual capacity (as shown in Figure 3-3). In Section 3.1.3, a hypothetical example continues to be used to demonstrate an analysis of capacity measurement, in which the capacity dimensions and the utilization data are used in tandem to determine the capacity constraints of a port component – the container terminal yard – and then to determine the capacity of the container terminal as a whole through a comparison of the container terminal yard and the container equipment along the dynamic dimension.

This example begins with the capacity measurement of the container terminal yard. Static capacity is calculated as a point-in-time figure, which at the container terminal yard is equal to the total number of total containers the terminal yard can handle at a given point in time. Dynamic capacity is equal to the number of containers the terminal yard can handle over a period of time, which considers the average dwell time of the container. Dwell time is the amount of time a container is stored at the yard between the time of delivery and shipment. In this example, we assume a dwell time of 5 days for all containers (import, export, and transshipment). The following calculation states container capacity in terms of land use on an annual basis:

(Number of Ground Slots * Stacking Height * Annual Operating Days) / Avg. Dwell Time

Theoretical Capacity: (1,000 * 5 * 365) / 5 = 365,000 TEU containers annually

Actual Capacity: (1,000 * 0.7 * 5 * 365) / 5 = 255,500 TEU annually

Figure 3-3, a chart format developed by Lagoudis & Rice, presents the theoretical and actual capacity measurements for the terminal yard along the static and dynamic dimensions, and overlays the utilization data (assumed to be 3,100 TEU per day or 226,500 TEU annually in this example) to determine whether a capacity constraint (i.e., bottleneck) exists.

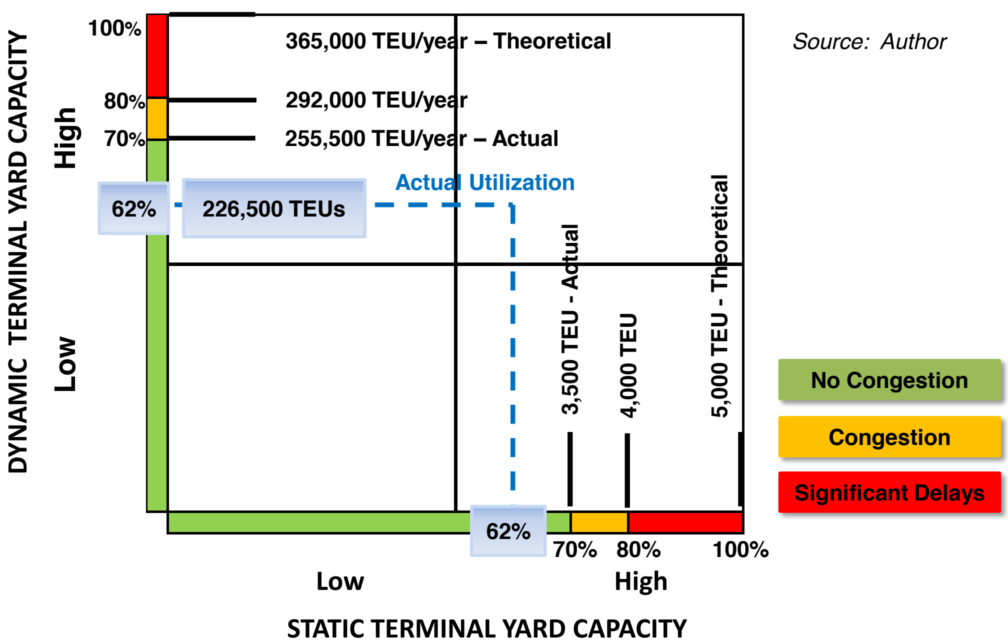


Figure 3-3: An example of capacity measurement for the container terminal yard along the static and dynamic dimensions

Now that the capacity of the container terminal yard is determined, focus turns to measuring the capacity of the container terminal equipment, in order to calculate the capacity of the container terminal as a whole. Equipment is measured along the dynamic dimension. Dynamic capacity must consider the capacity of all relevant equipment. In Section 3.1.2, the dynamic theoretical capacity of a container crane is stated as 25 TEU moves/hour. It is assumed that the container yard has 10 cranes and operates 24 hours per day, 365 days per year. Thus, the theoretical capacity on an annual basis is calculated as follows:

(Number of Cranes * Moves per Hour per Crane * Operating Hours per Day * Operating Days per Year)

Theoretical Capacity: (10 * 25 * 24 * 365) = 2,190,000 TEU containers / year

In addition, Section 3.1.2 states that these cranes currently operate at a maximum capacity of 20 TEU moves/hour due to their age. However, the cranes also operate in combination with the rubber-tyred gantry cranes (RTGs, whose purpose is to stack the containers at the yard), which - due to a limited number of RTGs in operation in this example - restrict the cranes feasible capacity to 18 TEU moves/hour. Accordingly, actual capacity of the equipment on an annual basis is calculated as follows:

(Number of Cranes * Feasible Moves per Hour per Crane * Operating Hours per Day * Operating Days per Year)

Actual Capacity: (10 * 18 * 24 * 365) = 1,576,800 TEU containers / year

Figure 3-4 presents the theoretical and actual capacity measurements for the terminal equipment along the dynamic dimension, and overlays the utilization data (assumed to be 3,300 moves per day or 1,204,500 moves annually in this example) to determine whether a capacity constraint (i.e., bottleneck) exists.

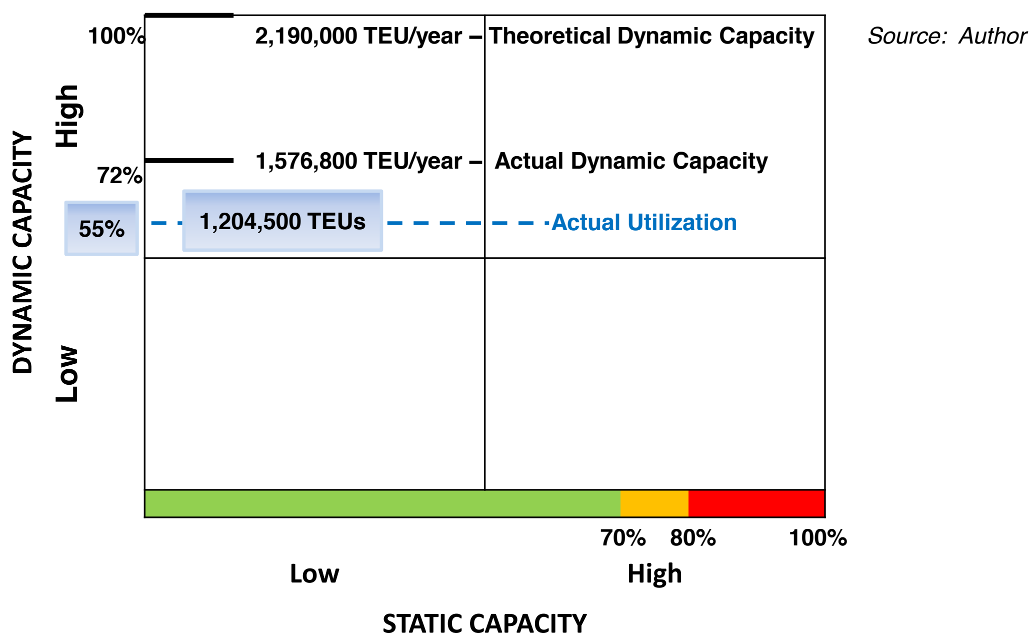


Figure 3-4: An example of capacity measurement for the container equipment along the dynamic dimension

At a container terminal, the capacity may be constrained by either the terminal yard or the terminal equipment, as these two port components work together at the terminal. As such, a comparison must be made between the port components to determine the overall capacity measurement of the container terminal. This comparison should always be made along the dynamic dimension when possible to account for factors impacting capacity over time. In addition, the same time period should always be selected to measure both port components to allow for a fair comparison. Figure 3-5, below, presents the overall capacity measurement of the container terminal by comparing the dynamic capacity of the terminal yard vs. the terminal equipment over a one year period.

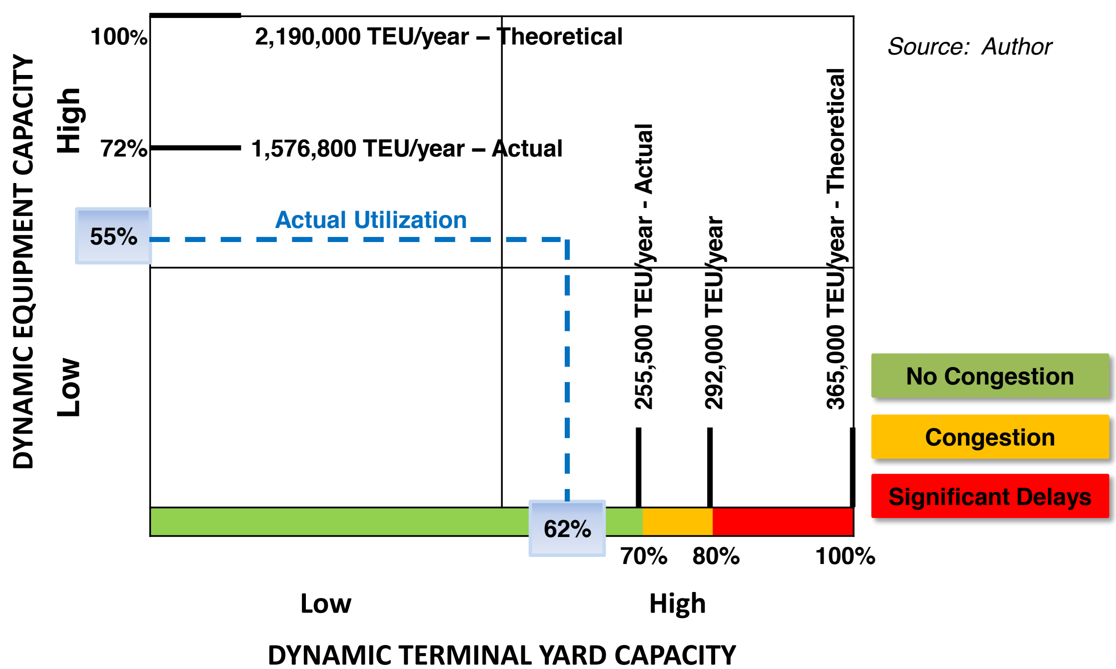


Figure 3-5: An example of capacity measurement for the overall container terminal along the dynamic dimension

The results show that terminal yard's utilization is 62% of its theoretical capacity and below the 70% actual capacity threshold, while the terminal equipment's utilization is 55% of its theoretical capacity and below the 72% actual capacity threshold. Therefore, resources are highly utilized, but investment is not required presently as there still exists sufficient resources before actual capacity is fully utilized. However, the results reveal that there exists room for efficiency improvements for the cranes, which have an actual capacity of only 72% of the theoretical capacity. Additional investment could increase the cranes' actual capacity threshold.

3.2 Methodology for Evaluating Investment Strategies Under Uncertainty

Following the identification of capacity constraints at components within the port system using a methodology for measuring capacity, strategies were evaluated to potentially alleviate the recognized bottlenecks by adding further capacity with consideration for efficiency and profitability. A strategy may involve efficiency improvements (e.g., training of labor force or higher frequency for equipment maintenance) or additional investment in infrastructure or equipment (e.g., purchase of additional cranes). This thesis focuses on the financial impact of additional port infrastructure investment using an existing methodology developed by Dr. Richard de Neufville at MIT and Dr. Stefan Scholtes at the University of Cambridge, as highlighted in their book *Flexibility in Engineering Design,* published in 2011. The practical application of the methodology is demonstrated in 2006's "Real Options by Spreadsheet: Parking Garage Case Example," by Dr. de Neufville, Dr. Scholtes, and Dr. Tao Wang, as well as Dr. Jijun Lin's 2008 thesis paper "Exploring Flexible Strategies to Engineering Systems Using Screening Models: Applications to Offshore Petroleum Projects". The spreadsheet used in the parking garage case example is an Excel spreadsheet that provides the basis for the model used in this thesis.

The existing methodology by de Neufville and Scholtes is useful in three key ways when comparing the profitability of the case study port's terminal types and evaluating potential investment strategies. The methodology provides a framework to evaluate infrastructure investment decisions, which require large capital outlays for long-lived assets while facing various uncertainties that may have both short-term and long-term impacts on the return of the investment (Lin, 2008, p. 22). Due to the various uncertainties an investment may face, the methodology argues that an investment should be designed for a range of potential demand, instead of an average demand (de Neufville & Scholtes, 2011, p. 16). Second, the methodology highlights how investment with design flexibility provides greater value than an investment designed without flexibility (e.g., building a structure with the later option(s) to add additional levels vs. building a structure without flexibility for expansion) (de Neufville & Scholtes, 2011, p. 39-40). Finally, the methodology uses cumulative distribution curves and value-at-risk probabilities to clearly present the expected net present value ("ENPV", or NPV based on an expected range of NPVs) of an investment strategy faced with numerous uncertainties. In this thesis, the ENPV is of the earnings before interest, tax, depreciation and amortization ("EBITDA").

This thesis evaluates the future profitability of the terminals and warehouse and the potential investment strategies by utilizing the first three of the four phases of de Neufville and Scholtes's existing methodology. Accordingly, the process (de Neufville & Scholtes, 2011, p. 13) involves 1) an assessment of future uncertainties, 2) the identification of potential investment strategies, 3) and the evaluation of these selected investment strategies. The remainder of this section will describe the application and modification of the existing methodology for the research in this thesis.

3.2.1 An Assessment of Future Uncertainties

The first step of the methodology is to determine the future uncertainties that will impact the performance of the port components. By establishing the important factors that may impact performance, such as relevant trends and "trend-breakers" (de Neufville & Scholtes, 2011, p. 77), an appropriate range of a port's future performance can be forecasted for the analysis of the investment strategies. Trends refer to the historical pattern of performance that may shape future results. Trend-breakers are sudden, unexpected changes that may drastically influence future performance. Based on trends and trend-breakers, the most likely scenarios to impact the future performance of the port were determined for the analysis. The determination of the historical trend is first described, followed by an examination of the most likely trend-breakers. Then a summary is provided of the three main uncertainties used in the data analysis. The section concludes with an overview of the model used in the analysis.

3.2.1.1 Trends

A port's performance is driven by demand, manifested at the port as cargo throughput, which can by attributed to the general performance of the macroeconomy. As renowned maritime expert Dr. Martin Stopford states in his book *Maritime Economics*, a country's ocean-bound trade is most closely correlated by a wide-margin to its gross national product and imports (Stopford, 1997, p. 228). Based on the thesis author's experience in the ship finance industry, a general rule of thumb prior to the 2008-2009 collapse of the global shipping markets was that the growth of container throughput at a terminal could be approximated at 2-3x that of the growth of gross domestic product. However, a good fit between GDP and port throughput could not be found. Figure 3-6 highlights the non-correlation between Country X's GDP and the throughput at the case study port during a select 10-year time frame.

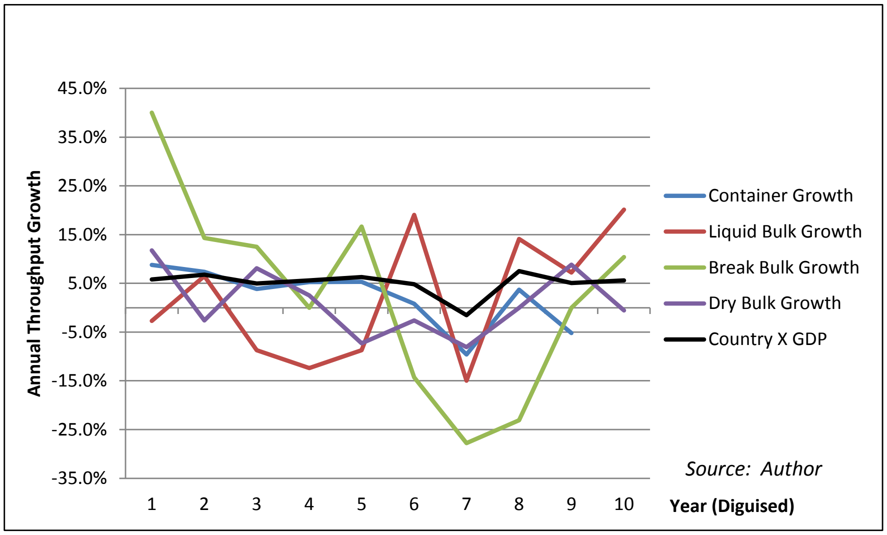


Figure 3-6: Various cargo throughput growth at the case study port does not move closely in line with Country X GDP growth (in black).

The historical throughput data contains annual data points covering approximately a 10-year period, which includes both the historic shipping boom of the early/mid 2000s and the historic shipping crash of the late 2000s. Due to the volatility in the historical data set, regression analysis was applied to trends over various time periods. Note that as only annual data points make up the historical data set, seasonality is not explored in this thesis, despite types of throughput such as containerized cargo peaking during specific times of the year. Based on regression analysis of the limited historical throughput data available for the case study port, a representative trend could not be determined for forecasting future throughput of the different cargo types. Table 3-2 indicates that the strongest adjusted R-squared was 0.62 for the 5-year historical trend of container throughput at the case study port, but not statistically valid.

Table 3-2: Regression analysis results for trends of various cargo throughput at the case study port

Trend	R-Squared	Adj. R-Squared	GDP	t-stat	p-value	Intercept	t-stat	p-value
Container 5-Yr (2007-2011)	0.71	0.62	-25,165	-2.73	0.07	958,274	31.38	0.00
Container 9-Yr (2003-2011)	0.43	0.35	16,274	2.43	0.04	748,215	18.03	0.00
Liquid Bulk 5-Yr (2008-2012)	0.56	0.41	748,609	1.95	0.15	8,861,478	6.97	0.01
Liquid Bulk 10-Yr (2003-2012)	0.01	0.10	-31,937	-0.23	0.82	11,317,470	12.24	0.00
Break Bulk 3-Yr (2010-2012)	0.75	0.50	56,522	1.73	0.33	1,011,594	14.35	0.04
Break Bulk 5-Yr (2008-2012)	0.63	0.51	-183,913	-2.28	0.11	1,900,435	7.12	0.01
Break Bulk 10-Yr (2003-2012)	0.09	0.01	-38,340	-0.93	0.38	78,519,763	0.95	0.37
Dry Bulk 5-Yr (2008-2012)	0.07	0.25	28,261	0.46	0.68	3,802,174	18.57	0.00
Dry Bulk 10-Yr (2003-2012)	0.04	0.07	-14,822	-0.60	0.57	4,108,696	24.32	0.00

Source: Author

Since regression analysis is not sufficient to determine a statistically validated trend for throughput based on Country X's GDP, the thesis determines the forecasted distribution of future cargo throughput by three different methods based on a random selection from a normal distribution using an average historical growth rate and standard deviation of the historical throughput data: 1) a mean reversion to an underlying projected trend based on an average growth rate of the historical throughput data ("Mean Reversion Average Growth method"), 2) a stochastic path (i.e., random walk) around an underlying projected trend based on an average growth rate of the historical throughput data ("Random Walk method"), and 3) a mean reversion to an underlying projected trend based on Dr. Charles Holt's simple exponential smoothing (Silver, Pyke, & Peterson, 1998, p. 93) of the historical throughput data using the initial year for initialization ("Mean Reversion Exponential Smoothing method"). A normal distribution is selected to represent the dispersion of cargo growth rates over the forecasted period (an explanation of the distribution selection is described in Appendix 1). Mean reversion refers to the tendency for the forecasted throughput demand in each period to revert back to the underlying trend. The mean reversion dampening factor ranges from 0 to 1, where 0 equates to no mean reversion (i.e., demand in period t+1 is based on the demand level of period t) and where 1 means that forecasted demand resets at the underlying trend (i.e., demand in period t+1 is based on the underlying trend). Each method is described as follows:

1) Mean Reversion Average Growth method: This method is the preferred method for forecasting the range of cargo throughput in the analysis. The mean reversion dampening factor used in this thesis research is 0.4, where 0 results in no mean reversion and 1 results in complete mean reversion annually. The underlying trend is based on the average historical throughput growth. For determining uncertainty around the trend, a normal distribution of throughput growth is selected, as opposed to a uniform distribution, due to a lower probability of a repeat of the extremes recorded in the historical data set and a greater probability that future results may be near the historical average. The Excel function chosen for representing the normal distribution is

   = NORM.INV (RAND(), Average, Standard Deviation) where the RAND() function generates a random number between 0 and 1. The averages and standard deviations of the throughput growth rates at each of the case study port's terminals are as per Table 3-3, below. Unlike the NORM.DIST function, the NORM.INV function chooses a growth rate based on a given probability. The figures in Table 3-3 are based on the terminals' historical data sets and are used in the Excel formula representing normal distribution.

Table 3-3: Averages and Standard Deviations for the Annual Throughput Growth at Each of the Case Study Port's Terminals

Terminal Type	Average	Standard Deviation
Container Terminal	2.3%	5.7%
Liquid Bulk Terminal	2.0%	12.5%
Break Bulk Terminal	2.9%	19.4%
Dry Bulk Terminal	1.0%	6.4%

Historical data time period (2003-2012), except for the container terminal data (2003-2011)

Source: Author

2) Random Walk method: The stochastical analysis assumes no mean reversion, allowing for each year's forecasted growth to begin from the previous year's throughput level without any influence from the underlying trend, other than the normal distribution parameters. The ineffectual underlying trend is based on the average throughput growth of the historical data set. The average and standard deviations stated in Table 3-3 above are used in same Excel inverse normal distribution formula as in the previous method.

3) Mean Reversion Exponential Smoothing method: Due to the limited number of data points in the historical data set, the thesis examines the use of Holt's simple exponential smoothing technique for establishing the smoothing constants for a level (a) and trend (c) to forecast the underlying throughput trend (ε is the error term), as described in *Inventory Management and Production Planning and Scheduling* (Silver, et al., 1998, p. 93). The underlying model is based on the following equation:

$X_t = a + c_t + \varepsilon_t$, where

X_t is the current year's throughput

The first year in historical data set is used for initialization. A variable (α), ranging from 0 to 1, controls the influence the previous year's throughput figure has on the next year's forecasted throughput figure. A variable (β), ranging from 0 to 1, controls the steepness of the trend.

$X_{t,t+\tau} = \hat{a}_t + \tau\hat{c}_t$, where

$\hat{a}_t = \alpha X_t + (1 - \alpha)(\hat{a}t\text{-}1 + \hat{c}_{t-1})$; and,

$\hat{c}_t = \beta(\hat{a}_t - \hat{a}_{t-1}) + (1 - \beta)\hat{c}_{t-1}$

In the above equations, â represents next year's level, and ĉ represents next year's trend. The α and β listed in Table 3-4 for the smoothing calculations to forecast each terminal's throughput is determined by the thesis author to provide a reasonable forecast, characterized by an acceptable mean absolute percentage error ("MAPE" and ~30% or less), mean deviation ("MD") to mean absolute deviation ("MAD") ratio (close to 1), and coefficient of variation ("CoV" and below or near 1).

Table 3-4: Inputs and Statistical Metrics for Holt's Simple Exponential Smoothing of Port Components' Historical Data

	Container	Liquid Bulk	Break Bulk	Dry Bulk	Warehouse
α	0.10	0.50	0.10	0.10	0.10
β	0.15	0.10	0.05	0.10	0.10
MD	304,640	683,400	713,129	304,640	13,605
MAD	311,192	4,123,116	1,581,615	311,192	35,825
RMSE	125,981	1,539,902	574,478	125,981	12,744
MPE	12%	1%	6%	12%	5%
MAPE	12%	13%	32%	12%	22%
MD/MAD	98%	17%	45%	98%	38%
CoV	41%	225%	81%	41%	94%

Note that RMSE stands for Root Mean Squared Error and MPE stands for Mean Percentage Error

Source: Author

Reasons for not selecting Holt's simple exponential smoothing as the preferred method for forecasting throughput are 1) the subjectivity of selecting influential variables α and β, 2) some terminals have errors with alternating signs (+/-) prior to establishing the level (a) and trend (c) for the forecast, and 3) the fit of the forecast is judged not to be reasonable; for example, the liquid bulk storage terminal that has an acceptable MAPE of 13%, but a low MD/MAD ratio of 17% and a high CoV of 225%.

With a trend established using Holt's simple exponential smoothing technique, macroeconomic uncertainty can be represented using a normal distribution based on the historical throughput data set's average and standard deviation and applying a mean reversion dampening factor of 0.4 to the projected trend.

The macroeconomy trend is described using a linear relationship between throughput demand and time, as opposed to the logarithmic relationship used in de Neufville et al.'s parking garage case example. An argument can made that over the time horizon of a long-lived asset, particularly one that has already been in operation for some time such as the case study port, that demand may be expected to level off as the market matures. Conversely, an argument could be made that a long-lived asset located in a developing country may experience exponential demand growth as the population grows and economic activity increases. However, a linear relationship was chosen to represent demand at the case study port due to three factors: 1) Country X is a developing middle income country (Arvis et al., 2012) in the process of moving toward an innovation-driven market (Schwab & Sala-i-Martin, 2013), meaning the country may be closer to developed status than developing status, 2) Country X's GDP is expected to continue to grow positively and consistently in the mid single-digits for the foreseeable future according to the national government and the International Monetary Fund (World Economic Outlook Database, 2013), and 3) forces exist that could place Country X's economy on either a higher or lower trajectory, but these forces are difficult to predict over the long-term.

3.2.1.2 Trend-Breakers

In addition to focusing on macroeconomic growth as the key trend, identifying the primary potential "trend-breakers" is required. Two main trend-breakers are selected for the thesis analysis: 1) the development of Country X into a regional hub of products and services over the next decade, and 2) the outcome of a recurring political event every five years. A description of each of these trend-breakers follows:

1) Development of Country X into a regional hub of products and services: Major industrial development projects are either underway or planned for the near-future in Country X to achieve the current government's objective of transforming the region into a regional hub. These developments have the potential to generate increased throughput for the country's ports, as construction of the hub's infrastructure results in higher demand for dry and break bulk goods initially and increased economic activity from the hub results in higher demand for liquid bulk storage, containerized goods, and potentially oil & gas services over time. Simultaneously, there may be pressure on ports' liquid bulk storage rates as these ports compete with these developments to provide liquid bulk storage services to clients, which may be more than compensated for in the longer-term as additional prospective clients are drawn to the region as it transforms into a regional hub.

In regard to the regional hub trend-breaker, the following assumptions are used in the analysis:

- A 2.5% rise in container volume over 2015-17 applied pro-rata;
  A 2.5% rise in container volume over 2018-20 applied pro-rata;
- A 10.0% rise in liquid bulk volume over 2014-17 applied pro-rata;
  A 10.0% rise in liquid bulk volume over 2018-20 applied pro-rata;
- A 5.0% rise in dry and break bulk volume over 2014-17 applied pro-rata;
  A 5.0% rise in dry and break bulk volume over 2018-20 applied pro-rata.

All growth rates mentioned above are in addition to the underlying growth from the macroeconomic trend. Note that an assumption is made for a national political event to take place in 2018, which is the reason for having two periods of growth for each terminal type.

2) The outcome of a recurring political event every five years: On the national stage, there is a regular political event that takes places approximately every five years beginning with 2013 in the model. The outcome of the political event may have an impact on the nation's business environment and the completion success of planned development projects, such as the initiative to transform Country X into a regional hub. Due to the influence of these periodic political events on the country's economy and development, the outcome – either A or B – is considered to be a trend-breaker. Outcome A assumes that Country X's economy performs along the projected trend and

developments proceed as scheduled. Outcome B assumes the national economy underperforms and that development plans are repealed.

In regard to the recurring political event trend-breaker, the following assumptions are used in the analysis:

- 75% probability that Outcome A occurs in the 2013 political event;
- 50% probability that Outcome A occurs in any political events thereafter;
- A 33% reduction in annual volume growth following Outcome B;
- A 100% reduction in growth from hub following Outcome B in 2013;
- A 100% reduction in growth from hub following Outcome B in 2018; and,
- A 3% fall in liquid bulk rates for 2013-17 following Outcome A in 2013.

To summarize, the three key uncertainties related to throughput at the case study port that are identified and used for the analysis are 1) macroeconomic uncertainty, which can be represented using mean reversion on a normal distribution, a random walk on a normal distribution, or mean reversion of a trend using a simple exponentional smoothing technique and a normal distribution, 2) the transformation of Country X into a regional hub that may result in an abnormal increase in various cargo throughput, and 3) the outcome of recurring national political events, which may curb Country X’s economic growth.

Finally, the existing methodology stresses the development of a dynamic model to conduct the evaluation of the investment strategies. An Excel spreadsheet model was utilized for this thesis and described in the following section.

3.2.1.3 The Simulation Model

An Excel spreadsheet model was used in this thesis and is a modification of the previously mentioned spreadsheet model for the parking garage case example (de Neufville et al., 2006). The purpose of the model is to generate forecasted throughput based on future uncertainties and then provide a range of profitability for both investment strategies and port components for comparison and ranking against one another. The model utilized a Monte Carlo simulation, running 2,000 simulations in approximately 15 seconds. Each port component was analyzed separately and the results were then aggregated for the port. The profitability of the port was then compared under various investment strategies focused on the vertical construction of the warehouse in this thesis. The investment strategies evaluated in this thesis are the port in its current state (i.e, as is), the port with a new warehouse built without flexibility, and the port with a new warehouse built with flexibility.

The model consists of several tabs divided into six categories: 1) an assumption page for entering inputs and selecting the method for determining the underlying trend (Mean Reversion Average Growth, Random Walk, or Mean Reversion Exponential Smoothing), 2) trend tabs to determine the inputs (average, standard deviation, α, β, $\hat{a}$, and $\hat{c}$) for establishing the underlying trend, 3) static NPV tabs to calculate the underlying trend, 4) a randomized NPV tab to aggregate the uncertainty inputs and both calculate and graphically present the forecasted demand under uncertainty at an individual port component level (Figure 3-7) and at an overall port level, 5) the randomized NPV simulation tabs that provide a table and cumulative distribution curve for each port component (including those components with flexible options), and 6) a summary tab to present the results in graphs and tables.

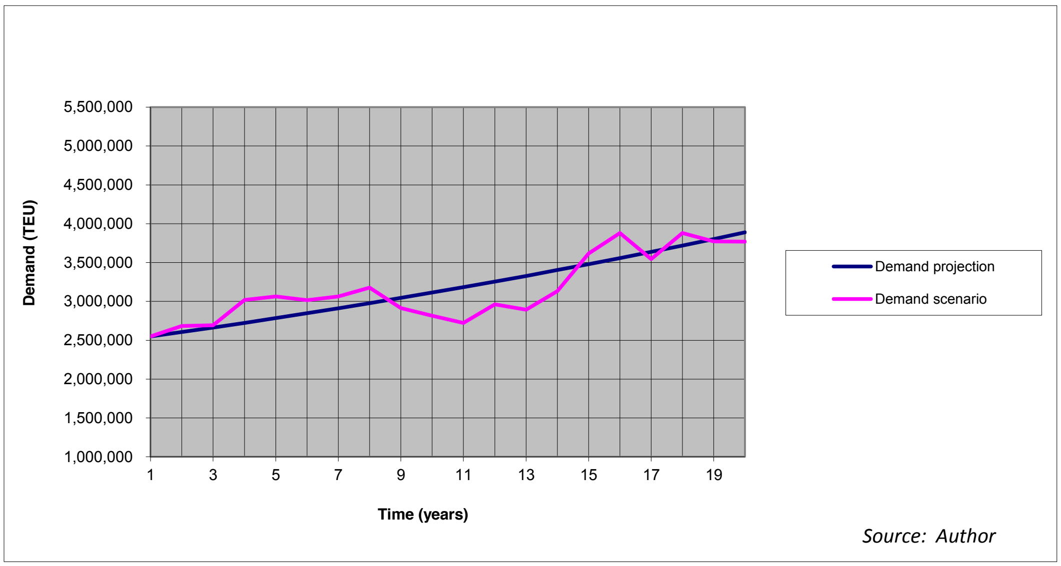


Figure 3-7: An example of a graph for a container terminal from the randomized NPV tab, plotting projected trend vs. demand from a Monte Carlo simulation

3.2.2 Identification of Potential Investment Strategies

Having defined the universe of uncertainties as step one, the existing methodology's next step was to identify potential investment strategies, including those strategies that may have flexible options. According to *Flexibility in Engineering Design*, potential investment strategies should be developed in a timely manner through the use of screening models. A screening model is defined as a "simple, understandable representation of the performance of the system or project under development" (de Neufville & Scholtes, 2011, p. 100) to choose the best strategies from numerous potential investment strategies. Screening models may take the form of top-down models (such as causal loop diagrams) representing the interactions between parts of a system, bottom-up models comprised of basic representations of each part within a system, and simulation models that aim to replicate the workings of a system (de Neufville & Scholtes, 2011, p. 105).

Although this thesis used a top-down approach via causal loop diagrams to better understand the variables impacting the case study port's throughput, the identification of potential investment strategies was conducted through a bottom-up approach using the capacity measurement methodology described in Section 3.1., which was applied at each port component to determine where bottlenecks exist within the port system. A simulator was then used, via the Excel spreadsheet model described in Section 3.2.1.3, to confirm these bottlenecks and identify the investment strategies that may be the most profitable for the port. This research identifies and analyzes the vertical expansion of the port's warehouse facilities as the primary investment strategy, as detailed in Section 4.2. However, a variety of other potential investment strategies exist that could address less profitable terminals and possible opportunities, such as the following:

- As regional demand for oil & gas services may increase with the development of a hub in Country X's geography, a strategy may be examined that replaces berths at less profitable terminals (e.g., break bulk or container) with potentially more profitable berths that provide oil & gas services. Cargo at these less profitable terminals could be rerouted to other ports, which specialize in handling a particular cargo type.

- With Country X soon to be connected by a modern nationwide rail network, the port may explore the development of an inland dry port for its container cargo to be shared with neighboring ports. The development could include flexible options. The strategy would add container capacity, while freeing up land at the port to be used for potentially more profitable activities (e.g., oil & gas services) or addressing other bottleneck issues (e.g. liquid bulk storage).

3.2.3 Evaluation of Selected Investment Strategies

The existing methodology put forward by de Neufville and Scholtes uses a visual presentation that clearly displays a range of profitability for each of the selected investment strategies. The recommended visual presentation is used in this thesis. The visual presentation utilizes cumulative distribution curves to display the Expected NPV ("ENPV") of an investment strategy's EBITDA (along the x-axis) and the probability of missing the target (i.e., the median ENPV) (along the y-axis) in graphical form. The cumulative distribution curves can be thought in similar terms as value-at-risk curves found in the finance industry. The graph is accompanied by a table that includes figures describing the range of values for the investment strategy. When investment strategies are displayed on the same graph, the visual presentation allows for quick comparison and rankings between the investment strategies on the sole basis of profitability. The more profitable the investment strategy, the further to the right the cumulative distribution curve is shifted on the graph.

As an example, a 49-bin histogram (Figure 3-8) for 2,000 Monte Carlo simulations is the basis for the probability distribution curve of a container terminal in Figure 3-9. For clarity, Table 3-5 highlights the metrics used to evaluate the range of profitability. The cumulative distribution curve in Figure 3-10 states that the container terminal has a 20% probability of generating an ENPV of EBITDA between USD 1,532 mill. – the minimum – and USD 1,800 mill. Note that the ENPV, or median, is USD 1,869 mill. with a range of NPV EBITDA between USD 1,577 mill. and USD 2,061 mill. meaning that all outcomes are profitable. In value-at-risk terms, there is a 10% chance that the ENPV of the terminal's EBITDA will be USD 1,748 mill. or below and a 10% chance that the ENPV of the terminal's EBITDA will be USD 1,964 mill. or above. As per Table 3-5, the USD 8 mill. difference between the median and ENPV indicates that the average profitability is below the median profitability.

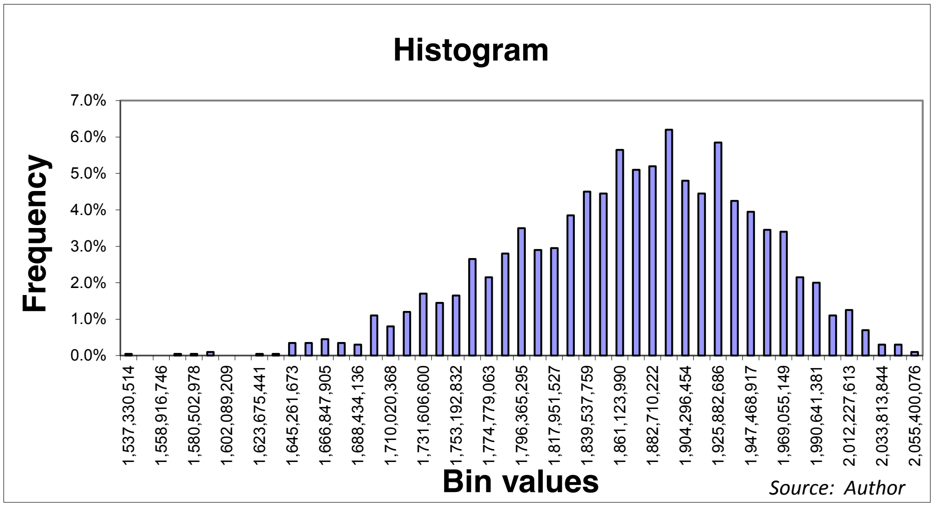


Figure 3-8: Histogram of 2,000 Monte Carlo simulations as basis for cumulative distribution curve of a container terminal

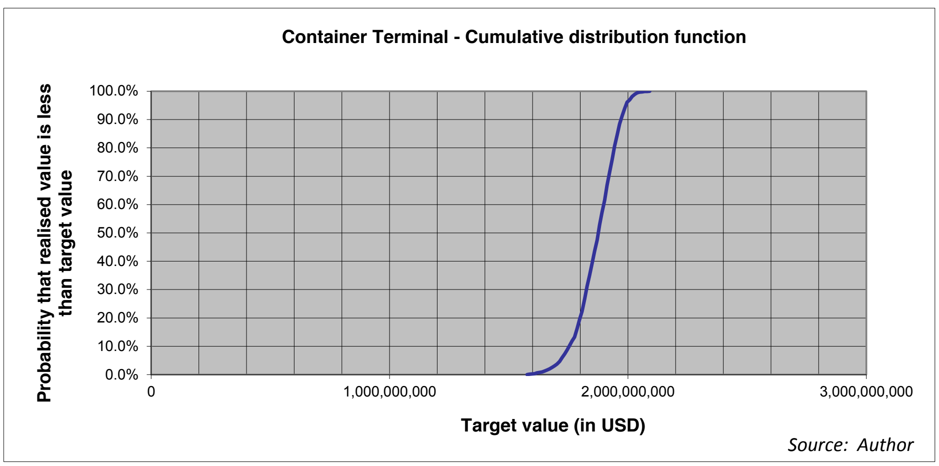


Figure 3-9: Cumulative distribution curve for a container terminal

Table 3-5: Metrics for cumulative distribution curve of a container terminal

Container Terminal Metrics	PV (in USD mill.)
ENPV	1,869
10 percent value at risk	1,748
90 percent value at risk	1,964
Minimum result	1,532
Maximum result	2,061
Range of results	529
Standard deviation	81
Difference between median and ENPV	8

Further, some the investment strategies may include flexible options. A flexible option allows for an investment to expand further at a later time to meet additional demand (e.g., a building may initially be constructed to be 4 levels high, but the base is built more robustly to allow for additional levels to be constructed at a later date if needed). When compared with traditional design strategies based on an average projection, flexibility in design can both "reduce downside consequences, and increase upside opportunities" (de Neufville & Scholtes, 2011, p. 158). A flexible investment strategy may require lower capital expenditure to begin with than a comparable traditional investment strategy, as the the flexible investment may be built on a smaller scale (de Neufville & Scholtes, 2011, p. 58). In the analysis, the savings generated from building one level smaller under a flexible design (for example, 5 levels) vs. a non-flexible design (6 levels) is 10%. The new warehouse with flexibility at the case study port will require a stronger base to support added levels potentially, so there is an additional cost: the cost of the flexible option, which is equal to a percentage of the initial capital expenditure (de Neufville & Scholtes, 2011, p. 58).

Section 3 has described the two main methodologies used to conduct the research in this thesis – the refined methodology developed by Lagoudis & Rice in 2011 for measuring a port system's capacity and the modified methodology published by de Neufville & Scholtes in 2011 for evaluating investment strategies (some with flexible options) under various uncertainties. Chapter 4 will present the results of the thesis research, which analyzes the capacity and potential investment strategies at the case study port.

4. Data Analysis

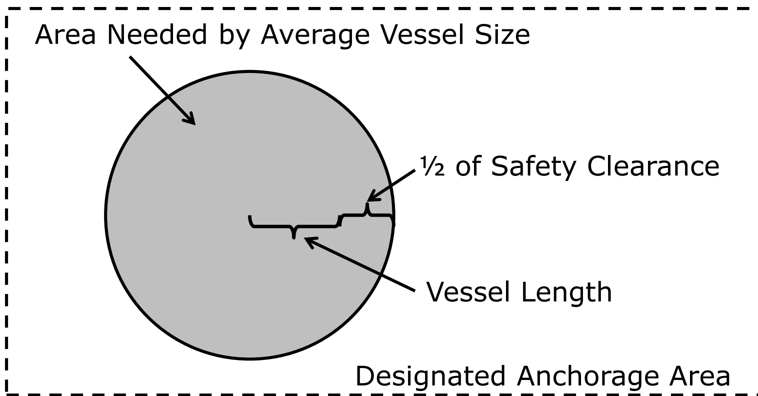
The data analysis begins with a calculation of the capacity measurements at each port component to identify capacity constraints within the port system. Following measurement of capacity, the port components are analyzed based on profitability and strategies to improve efficiency and profitability within the port system are identified and evaluated using the simulation screening model described in Section 3.2. Note that the figures relating to the case study port have been disguised.

4.1 Capacity Analysis of Each Port Component

This section presents the results of the port component capacity measurements. Measurements are stated for both static capacity and dynamic capacity, including theoretical capacity, actual capacity, and utilization. The results are presented in the order of in-bound cargo traveling through the components of a port system, beginning with anchorage. All calculations are based on figures related to the case study port. The key capacity measurement chart is presented for each port component, while supplementary capacity measurement charts for the port components can be found in Appendix 2.

4.1.1 Anchorage

Anchorage is the first component of a port system, where cargo arrives sea-side by vessel into the port system. The arriving vessel waits in a designated anchorage area until a berth at the terminal is ready for its docking, at which time the vessel proceeds along the waterway to the terminal. As highlighted in Figure 4-1, the idle vessel drops anchor in the designated area occupying a circular area with a radius equal to the vessel's length plus half the minimum safety clearance (Huang et al., 2011). A minimum safety clearance for large vessels is conservatively estimated at 7 times the depth of waters in the designated anchorage area (water depth estimated at 11 m for the case study port).



Source: Author

Figure 4-1: Diagram of the area needed by an average ship in anchorage

This section continues with the presentation of the capacity measurement calculations, beginning with the static dimension and followed by the dynamic dimension. The key capacity measurement chart will visually summarize the port component's capacity. This format will be repeated for each of the respective port component's sections.

Static capacity: $ST_A = d_A / a_A$, where $a_A = \Pi * (0.5 * z_A * s_W)^2$

= Designated area / Area needed by avg ship size

Estimated designated area for anchorage = 32.91 sq. km or 32,910,000 sq. m

Area needed by average ship size =

Π * (avg. length of ship + ½ minimum safety clearance)^2

$$\Pi * [172.9 \text{ m} + ((7 * 11 \text{ m}) / 2)]^2 = 140{,}364 \text{ sq. m} \quad \text{(see Table 4-1)}$$

Therefore, static capacity is equal to

$$32{,}910{,}000 \text{ sq. m} / 140{,}364 \text{ sq. m} = 234 \text{ ships}$$

Table 4-1: Average vessel sizes for each cargo type calling the case study port

Vessel Type	% of Total Ships	Avg Length (m)
Liquid	29%	170.0
Bulk	14%	170.0
Container	57%	175.0
		172.9

Source: Author

The static capacity for anchorage means that the designated area has the capacity to serve 234 average-size vessels at a given point in time.

The dynamic capacity for anchorage takes into account the average waiting time of each vessel while in anchorage, as arriving vessels may not dock immediately when berths are fully utilized. At the case study port, vessel calls are prioritized based on scheduled berth windows, then first-come first-serve. No prioritization is given for berth access based on the size of the vessel. Consequently, each ship calling the case study port, on average, should experience a similar anchorage dwell time depending on its cargo type.

Dynamic capacity: $DT_A = d_A / (a_A * t_A)$

= Designated area / (Area needed by avg ship size * Avg waiting time)

$$32{,}910{,}000 \text{ sq. m} / (140{,}364 \text{ sq. m} * 9.5 \text{ hrs} / 24 \text{ hrs}) = 592 \text{ ships / day} \quad \text{(see Table 4-2)}$$

$$32{,}910{,}000 \text{ sq. m} / (140{,}364 \text{ sq. m} * 9.5 \text{ hrs} / 24 \text{ hrs} * 365 \text{ days}) = 215{,}905 \text{ ships / yr}$$

Table 4-2: Average waiting time for each vessel type calling the case study port

Vessel Type	% of Total Ships	Avg Waiting Time (hrs)
Liquid	29%	9.9
Bulk	14%	14.1
Container	57%	8.2
		9.5

Source: Author

The dynamic capacity calculations for anchorage indicate that the designated area for anchorage can handle 592 ships daily, equal to 215,905 vessels annually assuming 365 operating days. The reason dynamic capacity is higher than static capacity is each of the 234 anchorage slots can accommodate 2.5 vessels daily based on an average waiting time of 9.5 hours. Note the theoretical capacity and actual capacity are equivalent when evaluating either the static or dynamic dimensions of anchorage.

Based on historical utilization data (which includes estimates), anchorage capacity is ample, even during peak periods, so there exist no bottlenecks at this component of the port system, as illustrated in Figure 4-2.

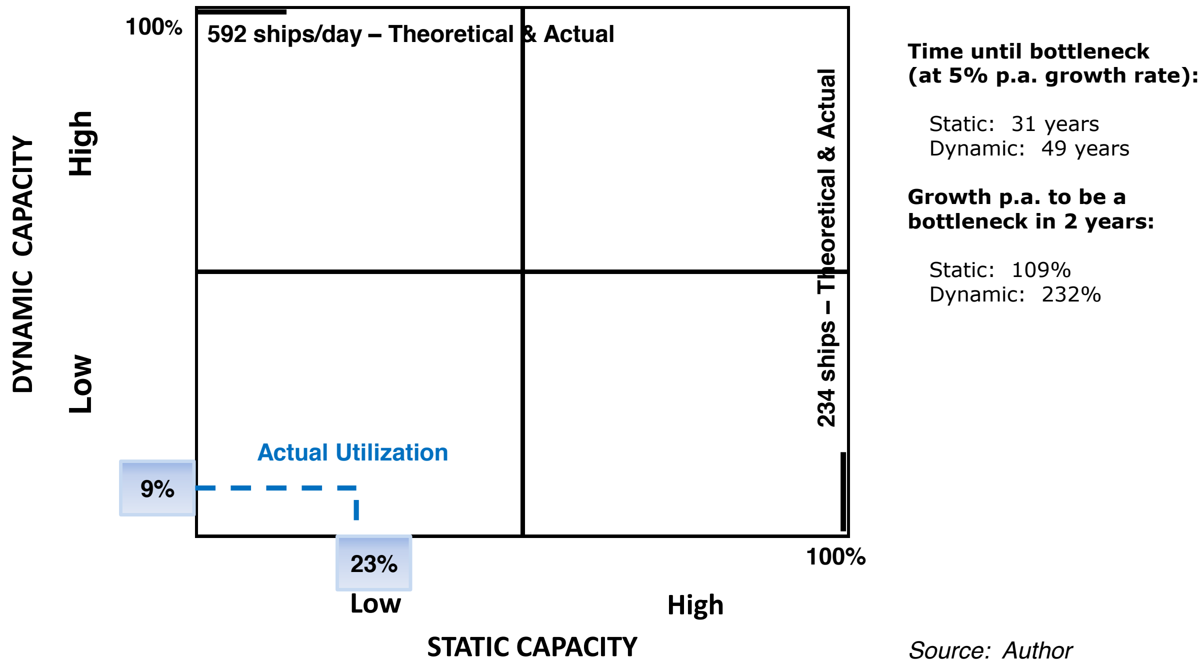
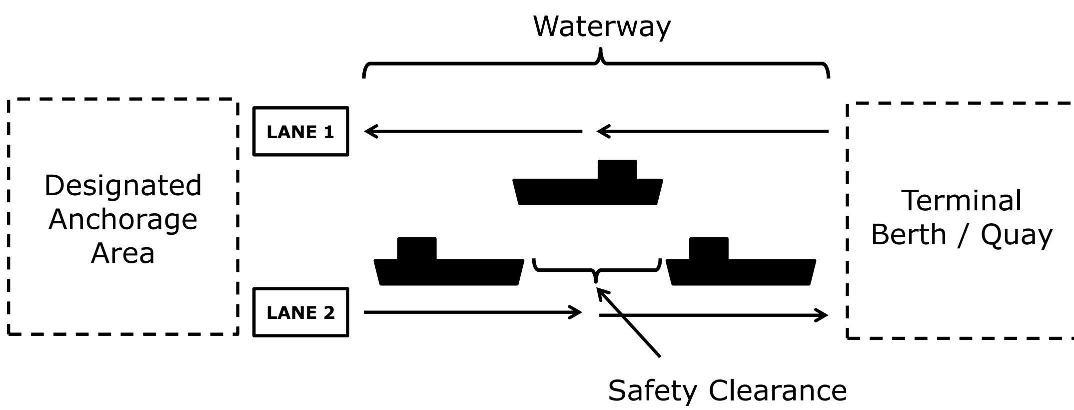


Figure 4-2: Capacity measurement for anchorage along the static and dynamic dimensions

Static capacity analysis shows, on average, up to 23% of anchorage slots can be occupied at a given time. Dynamic capacity analysis indicates that only 9% of the theoretical/actual anchorage capacity is utilized on average during a year. During peak periods, anchorage slot utilization remains stable with an increase to 24% under the static analysis, and up to 10% of theoretical/actual capacity under the dynamic analysis. Note that the analysis does not take into account unexpected, abnormal vessel arrivals (i.e., large number of unexpected vessels arriving at a similar time) that could cause higher utilization rates; however scheduled berth windows should mitigate this risk. Nor does the analysis consider other users of the designated anchorage area, which may reduce capacity.

4.1.2 Waterway

From the designated anchorage area, the vessel travels to the open berth at the terminal for docking and loading/unloading of cargo. The waterway (illustrated in Figure 4-3) may consist of one or multiple lanes for vessel travel within a cruising speed range dictated by the port authority. The waterway depth may restrict the size of vessels able to travel through the channel. The case study port has a waterway length of 45 nautical miles with a cruising speed of approximately 6 knots on its 2 lanes that are open 24 hours daily year-round. A minimum safety clearance of one vessel length between vessels traveling in a series is estimated.



Source: Author

Figure 4-3: Diagram of the waterway component of the port system

Theoretical static capacity: $ST_W = (l_W * n_W) / (s_W + z_W)$

= (Length of waterway * Number of lanes) / (Avg ship size + Safety clearance)

(83,340 m * 2 lanes) / (172.9 m + 172.9 m) = 482 ships

The waterway is shared with several private jetties along the channel, which reduces the actual capacity of the waterway for the case study port. In addition, the waterway is reduced to one lane when large oil tankers use the conduit. Therefore, an estimated 35% reduction in the waterway's actual capacity is assumed.

Actual static capacity: $SA_W = ST_W * (1 - c_W)$

= Theoretical static capacity * (1 – capacity reduction)

[(83,340 m * 2 lanes) / 172.9 m / 2] * (1 – 35%) = 313 ships

The static capacity for the waterway means that the the channel has a theoretical capacity of 482 average-size vessels and an actual capacity of 313 average-size vessels (or 65% of the theoretical capacity) at a given point in time. The theoretical and actual static capacity are based on the current vessel mix calling at the port (as stated in Section 4.1.1).

The measurement of dynamic capacity considers the cruising speed of the vessels on the waterway.

Theoretical dynamic capacity: $DT_W = (l_W * n_W) / [(s_W + z_W) * t_W]$

= (Length of waterway * Number of lanes) / (Avg ship size * Avg cruising time)

(83,340 m * 2 lanes) / [172.9 m * (83,340 m / 1,000 m / 11.1 km / hr)

/ 24 hrs] / 2 = 1,543 ships / day or 563,119 ships / year

Actual dynamic capacity: $DA_W = DT_W * (1 - c_W)$

= Theoretical dynamic capacity * (1 – capacity reduction)

1,543 ships * (1 – 35%) = 1,003 ships / day

563,119 ships * (1 – 35%) = 366,027 ships / year

The calculation for dynamic capacity indicates that the waterway can theoretically handle 1,543 ships daily, equal to 563,119 ships annually. The actual dynamic capacity is 65% of the theoretical dynamic capacity, as shown in Figure 4-4.

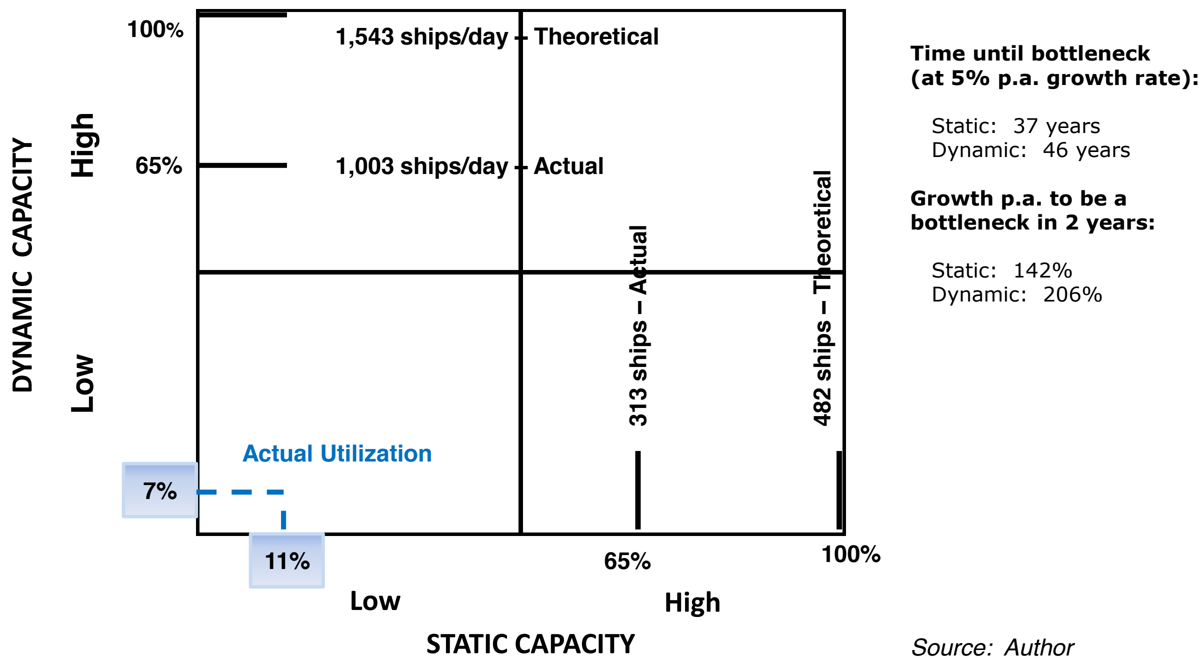


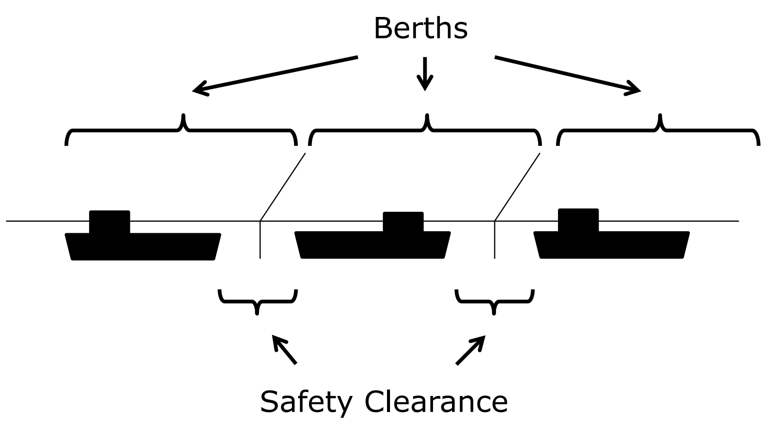
Figure 4-4: Capacity measurement for the waterway along the static and dynamic dimensions

Waterway capacity serving the port is sufficient, as the historical one-year demand data indicates utilization of 11% and 17% of theoretical and actual static capacity, respectively, and only 7% and 11% of theoretical and actual dynamic capacity, respectively. Thus, there are no current capacity constraints on the waterway component of the port system as depicted in Figure 4-4.

4.1.3 Terminal Quay / Berth

The terminal berth, or quay, is the location at the terminal where the vessel docks for unloading/loading. A terminal has a set number of berths, but multiple vessels may dock at the same berth concurrently if size permits. The terminal berth is the final port component where cargo is sea-side, before moving through land-side components. This section presents the capacity measurements of the terminal berths for each cargo type at the case study port.

Note that in the analysis of the terminal quay/berth, theoretical and actual capacity are calculated the same way, with the exception of the liquid bulk terminal quay (as there is one pump per berth). A safety clearance between vessels is estimated at 15 meters between docked vessels at the berths, as per Figure 4-5. Further, the draft (i.e. water depth) at the berths is not a factor in these capacity calculations, as focus of the analysis is on the utilization of the berths by vessels that are able to call at the port. Finally, the case study port's berths operate 365 days annually and 24 hours daily.



Source: Author

Figure 4-5: Diagram of vessels at berths with safety clearance between vessels

4.1.3.1 Container Terminal Quay / Berth

At the case study port, the container terminal has 10.5 berths totaling 2,130 m where container vessels with an average size of 175 m dock. On average, a vessel has a turnaround time of 14 hours, where turnaround time refers to the duration of time between the arrival and departure of a vessel at the berth.

Static capacity: $ST_Q = l_Q / (s_W + z_Q)$

= Length of quay / (Avg vessel size + Safety clearance)

2,130 m / (175 m + 15 m) = 11.2 vessels

Dynamic capacity: $DT_Q = l_Q / [(s_W + z_Q) * t_Q]$

= Length of quay / [(Avg vessel size + Safety clearance) * Turnaround time]

2,130 m / [(175 m + 15 m) * 14 hrs / 24 hrs] = 19.2 vessels daily

2,130 m / [(175 m + 15 m) * 14 hrs / 24 hrs] * 365 days = 7,015 vessels annually

Based on extrapolated historical utilization data, the container berths present a capacity constraint as illustrated in Figure 4-6. The static capacity is utilized 275% and the dynamic capacity is utilized 160%.

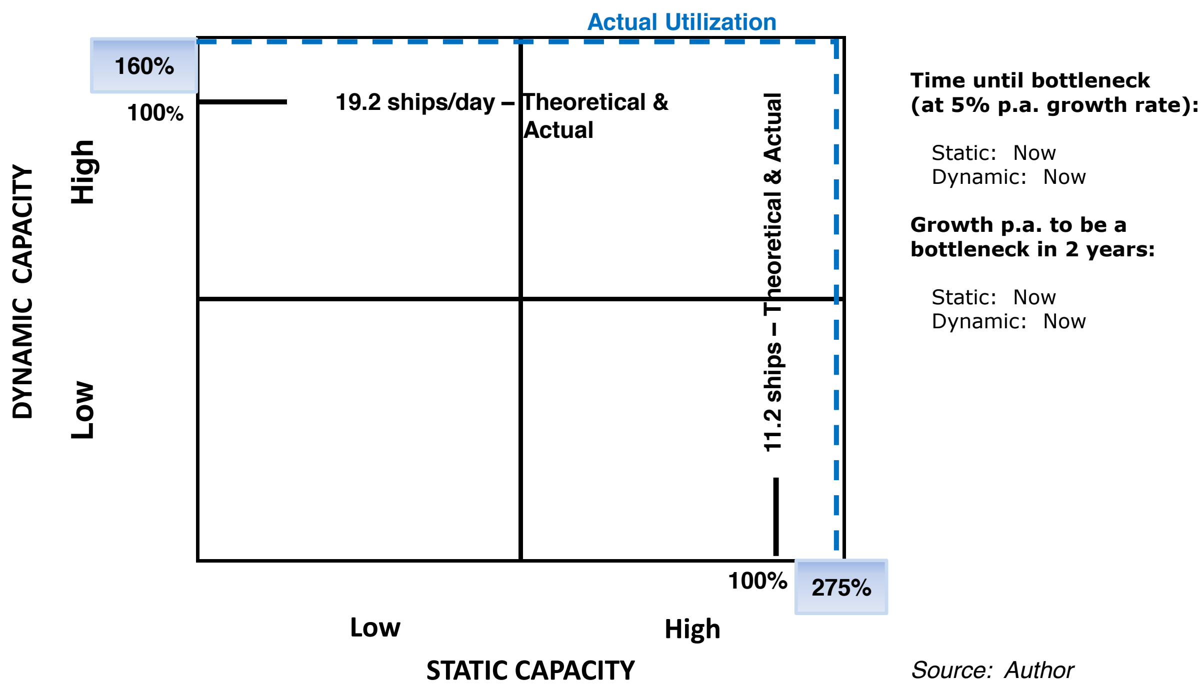


Figure 4-6: Capacity measurement for the container berth along the static and dynamic dimensions

4.1.3.2 Liquid Bulk Terminal Quay / Berth

At the case study port, the liquid bulk terminal has two sets of berths – one set dedicated to non-edible liquid bulk cargo and the other set dedicated to edible liquid bulk cargo. There are 18 berths totaling 3,549 m for non-edible cargo and 21 berths totaling 3,327 m for edible cargo. Both sets of berths handle tanker vessels with an average length of 170 m. On average, a vessel has a turnaround time of 15 hours.

4.1.3.2.1 Non-edible Liquid Bulk Quay / Berth

Theoretical static capacity: $ST_Q = l_Q / (s_W + z_Q)$

= Length of quay / (Avg vessel size + Safety clearance)

3,549 m / (170 m + 15 m) = 19.2 vessels

Actual static capacity: $SA_Q = n_Q$

= Number of berths = 18.0 vessels

Theoretical dynamic capacity: $DT_Q = l_Q / [(s_W + z_Q) * t_Q]$

= Length of quay / [(Avg vessel size + Safety clearance) * Turnaround time)

3,549 m / [(170 m + 15 m) * 15 hrs / 24 hrs] = 30.7 vessels daily

3,549 m / [(170 m + 15 m) * 15 hrs / 24 hrs] * 365 days = 11,203 vessels annually

Actual dynamic capacity: $DA_Q = n_Q * t_Q$

= Number of berths * Turnaround time

18.0 berths * (24 hrs / 15 hrs) = 28.8 vessels daily

18.0 berths * (24 hrs / 15 hrs) * 365 days = 10,512 vessels annually

4.1.3.2.2 Edible Liquid Bulk Quay / Berth

Theoretical static capacity: $ST_Q = l_Q / (s_W + z_Q)$

= Length of quay / (Avg vessel size + Safety clearance)

3,327 m / (170 m + 15 m) = 18.0 vessels

Actual static capacity: $SA_Q = n_Q$

= Number of berths = 21.0 vessels

Theoretical dynamic capacity: $DT_Q = l_Q / [(s_W + z_Q) * t_Q]$

= Length of quay / [(Avg vessel size + Safety clearance) * Turnaround time]

3,327 m / [(170 m + 15 m) * 15 hrs / 24 hrs] = 28.8 vessels daily

3,327 m / [(170 m + 15 m) * 15 hrs / 24 hrs] * 365 days = 10,503 vessels annually

Actual dynamic capacity: $DA_Q = n_Q * t_Q$

= Number of berths * Turnaround time

21.0 berths * (24 hrs / 15 hrs) = 33.6 vessels daily

21.0 berths * (24 hrs / 15 hrs) * 365 days = 12,264 vessels annually

Based on historical utilization data, the liquid bulk berths do not present a capacity constraint. The aggregate (both edible and non-edible) theoretical static capacity and aggregate actual static capacity are utilized 41% and 40%, respectively. The aggregate theoretical dynamic capacity and actual dynamic capacity are utilized 26% and 25%, respectively.

4.1.3.3 Dry Bulk Terminal Quay / Berth

At the case study port, the dry bulk terminal has 12 berths totaling 2,454 m where bulkers with an average size of 170 m dock. On average, a vessel has a turnaround time of 30 hours, where turnaround time refers to the duration of time between the arrival and departure of a vessel at the berth.

Static capacity: $ST_Q = l_Q / (s_W + z_Q)$

= Length of Quay / (Avg vessel size + Safety clearance)

2,454 m / (170 m + 15 m) = 13.3 vessels

Dynamic capacity: $DT_Q = l_Q / [(s_W + z_Q) * t_Q]$

= Length of Quay / [(Avg vessel size + Safety clearance) * Turnaround time]

2,454 m / [(170 m + 15 m) * 30 hrs / 24 hrs] = 10.6 vessels daily

2,454 m / [(170 m + 15 m) * 30 hrs / 24 hrs] * 365 days = 3,873 vessels annually

Based on historical utilization data, the dry bulk berths do not present a capacity constraint. The static capacity is utilized 25% and the dynamic capacity is utilized 31%.

4.1.3.4 Break Bulk Terminal Quay / Berth

At the case study port, the break bulk terminal has 12 berths totaling 2,805 m where bulkers with an average size of 170 m dock. On average, a vessel has a turnaround time of 30 hours, where turnaround time refers to the duration of time between the arrival and departure of a vessel at the berth.

Static capacity: $ST_Q = l_Q / (s_W + z_Q)$

= Length of Quay / (Avg vessel size + Safety clearance)

2,805 m / (170 m + 15 m) = 15.2 vessels

Dynamic capacity: $DT_Q = l_Q / [(s_W + z_Q) * t_Q]$

= Length of Quay / [(Avg vessel size + Safety clearance) * Turnaround time]

2,805 m / [(170 m + 15 m) * 30 hrs / 24 hrs] = 12.1 vessels daily

2,805 m / [(170 m + 15 m) * 30 hrs / 24 hrs] * 365 days = 4,427 vessels annually

Based on historical utilization data, the break bulk berths do not present a capacity constraint. The static capacity is utilized 29% and the dynamic capacity is utilized 36%.

4.1.4 Terminal Yard / Area

The terminal yard is the port component in which cargo is moved land-side via cranes or pipeline from the docked vessel at the berth. At the terminal yard, cargo is either immediately transported away from the yard using intermodal links serving the hinterland or temporarily stored at the yard. Depending on the cargo type (container, liquid, etc.), storage may be in the form of ground slots, tanks, warehouses, or designated areas outside. Cargo stored temporarily on-site is either origin-destination cargo that awaits land-side transport to the hinterland and is stored furthest away from the berths or transshipment cargo that is re-loaded onto another vessel for further delivery to its ultimate destination and is stored nearby the berths. The vast majority of the cargo handled at the cast study port is origin-destination cargo. In addition, it is important to note the case study port is bound by its current land availability; the port does not have the flexibility to expand through acquisition of additional land. This section presents the capacity measurement of the terminal yard for each cargo type at the case study port.

4.1.4.1 Container Terminal Yard

Capacity measurement at a container terminal yard must analyze not only the static and dynamic capacity of land availabilty, but also the dynamic capacity of the equipment (i.e., ship-to-shore cranes and RTGs). Note the case study port does not have a warehouse at the container terminal.

Beginning with the measurement of land availability, the static theoretical capacity of the terminal yard's land is based on the number of ground slots and the stacking policy of containers (i.e., how many containers can be stacked per ground slot). Stacking policy may vary depending on the type of container (import laden, export laden, or empty). According to the case study port management, stacking policy is influenced by three factors: 1) the predictability of the container pick-up schedule, 2) the yard foundation's weight limit, and 3) the strength of the container box. The case study port maintains a stacking policy of 3 high for laden containers and 6 high for empty, resulting in an average stacking policy of 3.84 high based on the volume mix of containers.

Theoretical static capacity: $ST_{CY} = d_{CY} / s_{CY} = n_{CY} * h_{CY}$

= Number of ground slots * TEU stacking policy

15,000 slots * 3.84 TEU high = 57,600 TEU

Actual static capacity must consider the thresholds when the container yard begins to experience congestion (70% utilization) and significant delays (80% utilization).

Actual static capacity: $SA_{CY} = ST_{CY} * u_{CY}$

= Number of ground slots * TEU stacking policy * Threshold

Congestion: 15,000 slots * 3.84 TEU high * 70% = 40,320 TEU

Significant delays: 15,000 slots * 3.84 TEU high * 80% = 46,080 TEU

The static capacity calculations show that the container yard has the theoretical capacity to handle 57,600 TEU at a given point in time. Further, the container yard has the actual capacity to handle 46,080 TEU without experiencing significant delays and 40,320 TEU without experiencing congestion.

Dynamic capacity accounts for average TEU idle time (i.e., the average time a container is stored at the yard) and average downtime due to poor weather conditions, both over the period of one year. The case study port has an average TEU idle time of 5.0 days and average annual downtime due to poor weather of 8.5 days. Dynamic capacity is calculated for a one-year period.

Theoretical dynamic capacity: $DT_{CY} = (n_{CY} * h_{CY}) / [t_{CY} / (o_{CY} - m_{CY})]$

= Theoretical static capacity / [Avg TEU idle time / (Annual operating days – Avg annual downtime days)]

57,600 TEU / [5.0 days / (365.0 – 8.5 days)] = 4,106,880 TEU/year

Actual dynamic capacity: $DA_{CY} = DT_{CY} * u_{CY}$

= Actual static capacity / [Avg TEU idle time / (Annual operating days – Avg annual downtime days)]

Congestion: 40,320 TEU / [5.0 days / (365.0 – 8.5 days)] = 2,874,816 TEU/yr

Significant delays: 46,080 TEU / [5.0 days / (365.0 – 8.5 days)] = 3,285,504 TEU/yr

Based on the case study port's historical throughput figures, the terminal yard makes high use of its land availability without suffering congestion. Recent annual thoughput utilization equals 61% of theoretical capacity and 87% of actual capacity, on average. However, during peak periods of the year, it is estimated that utilization reached 63% of theoretical capacity and 90% of actual capacity. Should annual throughput reach levels experienced at its height in 2008, the terminal yard would experience average utilization levels of 68% of theoretical capacity and 98%

of actual capacity, but suffer congestion during peak periods of the year, with utilization equaling 102% of actual capacity.

Regarding equipment, both ship-to-shore cranes and RTGs work together to maximize capacity at the terminal yard. Static capacity is excluded from this study, as the analysis assumes the terminal is unconstrained by the land use of the equipment. Dynamic capacity is measured by analyzing the performance of the ship-to-shore cranes and the RTGs separately over a one-year period and then comparing the results. Performance may be impacted by the age of the equipment resulting in increased maintenance downtime and poor weather conditions resulting in additional downtime. The case study port operates 18 ship-to-shore cranes well into their useful lives, generally, with average maximum operational capacity of 25 moves/hour, despite designed operational capacity of 40 moves/hour. In addition, the cranes' operational capacity is reduced 20% for maintenance downtime. The average maximum operational capacity of the 57 RTGs is 8 moves/hour. The case study port experiences average annual downtime at the terminal of 8.5 days.

Theoretical dynamic capacity: $DT_{CE} = n_{CE} * d_{CE} * (o_{CE} - m_{CE}) * h_{CE}$

= Number of cranes * Number of designed moves / hr *

(Annual operating days – Avg annual downtime days) * Daily operating hrs

18 cranes * 40 moves / hr * (365.0 – 8.5 days) * 24 hrs = 6,160,320 moves

57 RTGs * 8 moves / hr * (365.0 – 8.5 days) * 24 hrs = 3,901,536 moves

Actual dynamic capacity: $DA_{CE} = n_{CE} * p_{CE} * (o_{CE} - m_{CE}) * (1 - r_{CE}) * h_{CE}$

= Number of cranes * Number of operational moves / hr *

(1 – Maintenance reduction) * (Annual operating days – Avg annual downtime days) * Daily operating hrs

18 cranes * 25 moves / hr * (1 – 20%) * (365.0 – 8.5 days) * 24 hrs

= 3,080,160 moves

57 RTGs * 8 moves / hr * (1 – 20%) * (365.0 – 8.5 days) * 24 hrs

= 3,121,229 moves

Despite the cranes having an actual capacity equal to 50% of the theoretical capacity (primarily due to the age of the cranes), capacity of the container equipment – both cranes and RTGs – is sufficient based on the case study port's historical throughput figures. Based on the above analysis, the theoretical capacity of the container equipment is limited by the RTGs. The actual capacity of the terminal's equipment is impeded slightly by the cranes relative to the RTGs, but operate with only an ~1 percent difference in actual capacity of one another. Recent annual throughput utilization equals 40% and 64% of the theoretical capacity of the cranes and RTGs, respectively, and 81% and 80% of the actual capacity of the cranes and RTGs, respectively.

As illustrated in Figure 4-7, both land and equipment resources are highly utilized at the terminal yard.

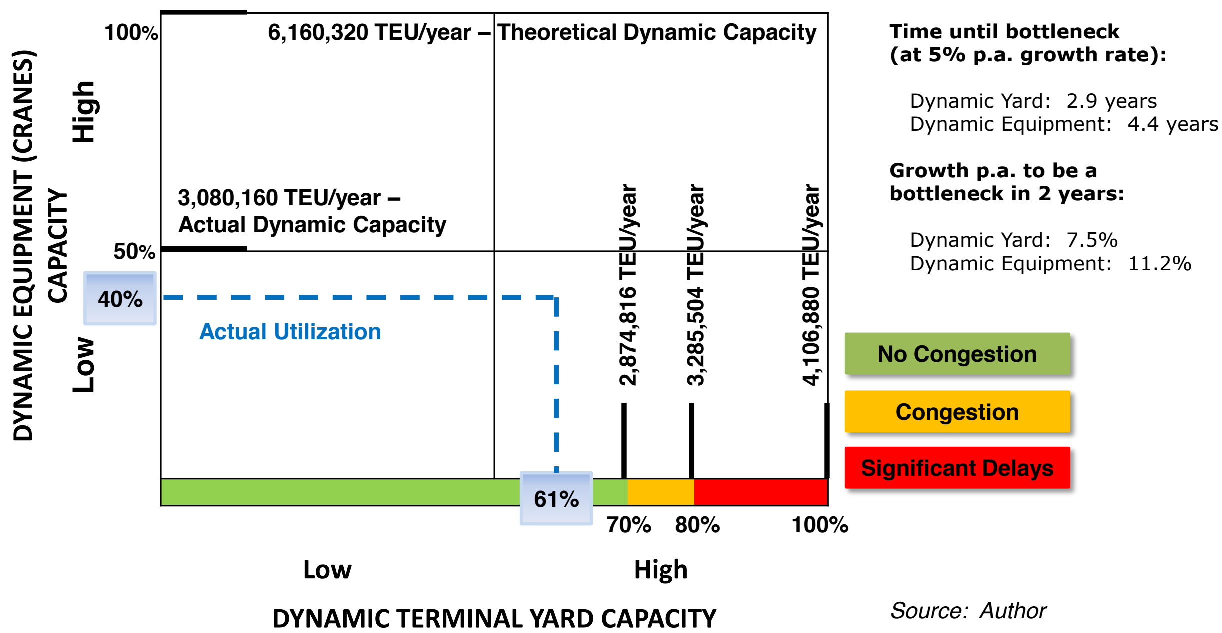


Figure 4-7: Capacity measurement of the container terminal along the dynamic dimension for the terminal yard and the equipment

Increased volumes will result in capacity constraints occurring (in the form of congestion) due to lack of available land before capacity constraints occur due to equipment. However, equipment bottlenecks will occur prior to significant delays resulting from lack of land availability. Any investment in new, more productive cranes to increase capacity would require simultaneous investment in either more productive or greater quantities of RTGs.

4.1.4.2 Liquid Bulk Terminal Area

The capacity analysis of the liquid bulk terminal consists of the static capacity and dynamic capacity of the land on which there is a tank farm to store edibile and non-edible cargo, as well as the dynamic capacity of the pipeline that pumps the liquid bulk cargo from the vessel to the storage tanks land-side. Dedicated tanks store edible (e.g., vegetable oils) and non-edible (e.g., petroleum) cargo separately. The density of the liquid cargo must be considered when conducting a capacity analysis of liquid bulk cargo. Although the case study port stores a variety of liquid bulk cargo with varying densities (edible liquids such as palm oil and coconut oil, and non-edible liquids such as fuel oil and gasoline), the analysis categorizes the cargoes into 3 main groups: edible liquids, non-edible liquids (petroleum) and non-edible liquids (chemical).

Liquid bulk capacity measument is evaluated by mass, and then by volume for edible and non-edible liquid bulk cargo separately.

4.1.4.2.1 Mass

The liquid bulk storage terminal at the case study port covers an area of 180 hectares, comprised of 345 storage tanks for edible cargo with an average storage capacity of 4,000 mt (metric tons) per tank and 957 storage tanks for non-edible with an average storage capacity of 1,622 mt per tank. On average, 3% of tanks (equal to 10.95 days) are out of service for regularly scheduled preventive maintenance.

Theoretical static capacity: ST_{LB} (mass) = $(n_{LB} * s_{LB}) / d_{LB}$

= (Number of tanks * Avg tank capacity) / Designated area

(345 tanks * 4,000 mt + 957 tanks * 1,622 mt) / 1,800,000 sq. m

= 1.629 mt / sq. m

- 1.629 mt / sq. m is equivalent to 2,932,353 mt

Actual static capacity: $SA_{LB} = ST_{LB} * (1 - r_{LB})$

= Theoretical static capacity * (1 – Maintenance downtime)

[2,932,353 mt * (1 – 3%)] / 1,800,000 sq. m = 1.580 mt / sq. m

- 1.580 mt / sq. m is equivalent to 2,844,382 mt

Dynamic capacity accounts for the equipment (the pump) at the terminal yard for which performance is measured by the average pumping time per berth. The case study port has 39 berths for liquid bulk cargo and an average pumping time of 300 mt/hr per berth capable of working 365 days per year and 24 hour per day.

Theoretical dynamic capacity: DT_{LB} (mass) = $(n_{LB} * s_{LB}) + (t_{LB} * n_Q * o_{LB} * h_{LB}) / d_{LB}$

= (Number of tanks * Avg tank capacity) + (Avg pumping time per berth * Number of berths * Annual operating days * Daily operating hrs) / Designated area

(345 tanks * 4,000 mt + 957 tanks * 1,622 mt) + (300 mt / hr * 39 berths * 365 days * 24 hrs) / 1,800,000 sq. m = 58.57 mt / sq. m

- 58.57 mt / sq. m is equivalent to 105,424,353 mt annually
- 105,424,353 mt annually implies 37.1 inventory turns

105,424,353 mt / 2,932,353 mt * (1 – 3%) = 37.1 inventory turns

Actual dynamic capacity: $DA_{LB} = DT_{LB} * (1 - r_{LB})$

= Theoretical dynamic capacity * (1 – Maintenance downtime)

(2,932,353 mt * 300 mt / hr * 39 berths * 365 days * 24 hrs * (1 – 3%) / 1,800,000 sq. m = 56.86 mt / sq. m

- 56.86 mt / sq. m is equivalent to 102,349,593 mt annually
- 102,349,593 mt / 2,932,353 mt * (1- 3%) = 36.0 inventory turns

Based on historical annual throughput data measure by mass, the liquid bulk terminal's capacity is constrained by its land availability, but has substantial surplus dynamic capacity, as shown in Figure 4-8.

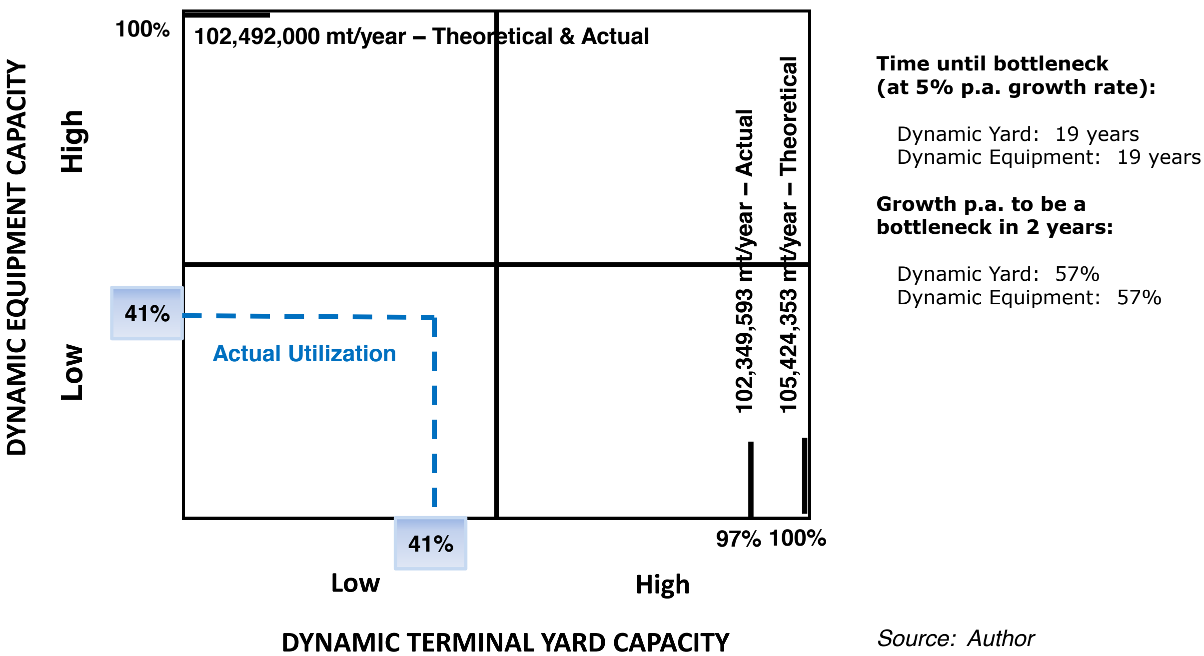


Figure 4-8: Capacity measurement for the liquid bulk terminal along the dynamic dimension for the terminal yard and the equipment

At a given point in time, the terminal utilizes 97% of theoretical static capacity and 100% of actual static capacity, as all available tanks are full and there is no room to expand to add more tanks. The terminal utilizes, on average, 40% of theoretical dynamic capacity and 41% of actual dynamic capacity over a one-year period. These results indicate that if the pumps at each berth were to operate constantly at their maximum rate of 300 mt/hour for the entire year, the terminal would have an inventory turn rate of 36.0x or 10.1 days. However, the most recent annual throughput data implies an inventory turn rate of approximately 14.8x or 24.7

days. If inventory turns were to remain at their current level, the equipment could accommodate a 243% increase in tank storage (in mt) assuming all else (e.g., tank utilization, pump downtime) remains constant in the current state.

4.1.4.2.2 Volume

Based on the current product mix, the density of the edible liquid bulk cargo is estimated at 900 kg/m^3 and the non-edible liquid bulk cargo is estimated at 800 kg/m^3. At the case study port, liquid bulk throughput is split 50/50 between edible and non-edible cargo. The terminal has 21 berths designated for edible cargo and 18 berths designated for non-edible cargo.

<u>Edible tank storage volume capacity:</u>

Theoretical static capacity: ST_{LB} (volume) = ST_{LB} (mass) * (1 / c_{LB})

= Theoretical static mass capacity * (1 / cargo density)

1,380,000 mt * 1,000 kg / mt * (1 / 900 kg / m^3) = 1,533,333 m^3

- Based on 345 tanks, average static volume capacity per tank is 4,444 m^3

Actual static capacity: SA_{LB} = ST_{LB} * (1 - r_{LB})

= Theoretical static volume capacity * (1 – Maintenance downtime)

1,533,333 m^3 * (1 – 3%) = 1,487,333 m^3

- Average static volume capacity per tank is 4,311 m^3

Theoretical dynamic volume capacity: DT_{LB} (vol.) = (n_{LB} * v_{LB}) + (t_{LB} * n_Q * o_{LB} * h_{LB}) / d_{LB}

= (Number of tanks * Avg tank capacity) + (Avg pumping rate per berth * Number of berths * Annual operating days * Daily operating hrs)

(345 tanks * 4,444 m^3 / tank) + [(300 mt / hr * 1000 kg / mt * (1 /

900 kg / m^3)) * 21 berths * 365 days * 24 hrs = 62,853,333 m^3 annually

- 62,853,333 m^3 / 1,533,333 m^3 * (1 – 3%) = 42.3 inventory turns
- Theoretical pumping capacity per berth is 333 m^3 / hr

Actual dynamic volume capacity: $DA_{LB} = DT_{LB} * (1 - r_{LB})$

= Theoretical dynamic capacity * (1 – Maintenance downtime)

62,853,333 m^3 * (1 – 3%) = 60,967,733 m^3

- 62,853,333 m^3 / [1,533,333 m^3 * (1- 3%)] = 41.0 inventory turns

Non-edible tank storage volume capacity:

Theoretical static volume capacity: ST_{LB} (volume) = ST_{LB} (mass) * (1 / c_{LB})

= Theoretical static mass capacity * (1 / cargo density)

1,552,353 mt * 1,000 kg / mt * (1 / 800 kg / m^3) = 1,940,441 m^3

- Based on 957 tanks, average static volume capacity per tank is 2,028 m^3

Actual static volume capacity: $SA_{LB} = ST_{LB} * (1 - r_{LB})$

= Theoretical static volume capacity * (1 – Maintenance downtime)

1,940,441 m^3 * (1 – 3%) = 1,882,228 m^3

- Average static volume capacity per tank is 1,967 m^3

Theoretical dynamic volume capacity: DT_{LB} (vol.) = $(n_{LB} * v_{LB}) + (t_{LB} * n_Q * o_{LB} * h_{LB}) / d_{LB}$

= (Number of tanks * Avg tank capacity) + (Avg pumping rate per berth * Number of berths * Annual operating days * Daily operating hrs)

(957 tanks * 2,028 m^3 / tank) + [(300 mt / hr * 1000 kg / mt * (1 / 800 kg / m^3)) * 18 berths * 365 days * 24 hrs = 61,070,441 m^3 annually

- 61,070,441 m^3 / 1,940,441 m^3 * (1 – 3%) = 32.4 inventory turns
- Theoretical pumping capacity per berth is 375 m^3 / hr

Actual dynamic volume capacity: $DA_{LB} = DT_{LB} * (1 - r_{LB})$

= Theoretical dynamic capacity * (1 – Maintenance downtime)

61,070,441 m^3 * (1 – 3%) = 59,238,328 m^3

- 59,238,328 m^3 / [1,940,441 m^3 * (1- 3%)] = 31.5 inventory turns

Based on historical annual throughput data measured by volume, the results are similar to those in the mass capacity measurements - the liquid bulk terminal's capacity is constrained by its land availability with significant excess dynamic capacity. Further, as cargo density is near 1,000 kg/m^3, the volume analysis should result in minimal variation from the mass analysis. Static volume capacity is consistent with the static mass capacity in terms of utilization. For dynamic volume capacity, the average terminal utilization for edible cargo is 37% of theoretical capacity and 38% of actual capacity over a one-year period. The pump operating at a maximum rate of 333 m^3/hour would result in 41.0 annual inventory turns, or every 8.9 days. The average terminal utilization for non-edible cargo is 43% of theoretical capacity and 44% of actual capacity over a one-year period. The pump operating at a maximum rate of 375 m^3/hour would generate 31.5 annual inventory turns, or every 11.6 days. Most recent annual throughput data indicates 14.8 inventory turns, or every 24.7 days, for the the liquid bulk terminal as a whole.

4.1.4.3 Dry Bulk Terminal Area

The dry bulk terminal area consists of a terminal yard and warehouses. The terminal yard is the location where dry bulk cargo is unloaded from the vessel to the terminal either by cranes or conveyors. Once land-side, the cargo is either immediately transported by intermodal links to the hinterland or is temporarily stored at either the terminal yard or the warehouse.

4.1.4.3.1 Dry Bulk Terminal Yard

The analysis of the dry bulk area first examines capacity of the dry bulk terminal in terms of both mass and volume, as the terminal's throughput charges are based on the higher of mass and volume. The static capacity and dynamic capacity of the dry bulk terminal's equipment is then calculated. The results are then compared with the utilization data.

At the case study port, the dry bulk and break bulk activities share a common 420 hectare terminal yard, which for the purpose of these calculations is assumed to be shared 50/50. Therefore, the area of the dry bulk terminal yard is 210 hectares. The terminal's 12 berths are served by 15 cranes and 12 conveyors. The yard operates 365 days annually and 24 hours daily, but experiences 2.4 days of downtime per year due to poor weather. The yard suffers from congestion once it reaches the 80% utilization threshold.

4.1.4.3.1.1 Mass

Beginning with the capacity measurement of land availability in terms of mass, the dry bulk terminal yard has a designated area of 210 hectacres able to handle 15 mill. tons annually, which is assumed to be the maximum throughput the yard's foundation can sufficiently support. The average idle time for dry bulk cargo is 5.0 days and average downtime due to poor weather is 2.4 days.

Designated area: d_{DBY} = 210 hectares * 10,000 sq. m / hectare = 2,100,000 sq. m

Maximum daily commodity mass (i.e, commodity size): $s_{DBY} = r_{DBY} / [t_{DBY} / (o_{DBY} - m_{DBY})]$

15,000,000 tons / [5 idle days / (365 operating days - 2.4 downtime days)]

= 206,838 tons

Theoretical static mass capacity: ST_{DBY} (mass) = s_{DBY} / d_{DBY},

where $s_{DBY} = r_{DBY} / [t_{DBY} / (o_{DBY} - m_{DBY})]$

= Commodity size / Designated area

206,838 tons / 2,100,000 sq. m = 0.10 tons / sq. m

Actual static mass capacity: $SA_{DBY} = ST_{DBY} * u_{DBY}$

= Theoretical static mass capacity * Threshold

206,838 tons / 2,100,000 sq. m * 80% utilization = 0.08 tons / sq. m

The analysis above indicates that the dry bulk terminal yard can theoretically handle 206,838 tons (or 0.10 tons / sq. m) of cargo at a given point in time, but the yard can actually handle up to 165,471 tons (or 0.08 tons / sq. m) without experiencing congestion.

Theoretical dynamic mass capacity: DT_{DBY} (mass) = $[s_{DBY} * ((o_{DBY} - m_{DBY}) / t_{DBY})] / d_{DBY}$

= (Commodity size * Commodity avg idle time) / Designated area

[206,838 tons * ((365 operating days – 2.4 downtime days) / 5 idle days)] /

2,100,000 sq. m = 7.2 tons / sq. m annually or 15,099,202 tons/year

Actual dynamic mass capacity: $DA_{DBY} = DT_{DBY} * u_{DBY}$

= Theoretical dynamic mass capacity * Threshold

[206,838 tons * ((365 operating days – 2.4 downtime days) / 5 idle days)] /

2,100,000 sq. m * 80% = 5.8 tons / sq. m annually or 12,079,361 tons /year

Based on the historical mass utilization data, the dry bulk terminal makes the maximum use of its land availability by operating at full capacity without experiencing congestion. Theoretical capacity is 80% utilized – the limit for smooth operations – and the actual capacity is 100% utilized for both the static and dynamic dimenisons.

Capacity of the equipment is measured in terms of mass; static capacity is excluded from this study, as the analysis assumes the terminal is unconstrained by the land use of the equipment. Dynamic capacity is measured by analyzing the performance of the cranes and the conveyors over a one-year period. Performance may be impacted by the age of the equipment resulting in increased maintenance downtime and poor weather conditions resulting in additional downtime. The case study port operates 15 cranes and 12 conveyors well into their useful lives, generally, with average maximum operational capacity of 250 tons/hour and 200 tons/hour, respectively. For comparison, the designed operational capacity of the average crane and the average conveyor is 490 tons/hour and 467 tons/hour, respectively. The equipment's operational capacity is reduced 8.55 days annually for maintenance downtime and 2.40 days annually for poor weather.

Theoretical dynamic capacity: $DT_{DBE} = n_{DBE} * d_{DBE} * (o_{DBE} – m_{DBE}) * h_{DBE}$

= Number of cranes & conveyors * Number of designed moves/ hr *

(Annual operating days – Avg annual downtime days) * Daily operating hrs

(15 cranes * 490 tons / hr + 12 conveyors * 467 tons / hr) * (365.0 – 8.55 days – 2.40 days) * 24 hrs = 110,027,705 tons/year

Actual dynamic capacity: $DA_{DBE} = n_{DBE} * p_{DBE} * (o_{DBE} - m_{DBE}) * (1 - r_{DBE}) * h_{DBE}$

= Number of cranes & conveyors * Number of operational moves / hr * (1 – Maintenance reduction) * (Annual operating days – Avg annual downtime days) * Daily operating hrs

(15 cranes * 490 tons / hr + 12 conveyors * 467 tons / hr) * (1 – 20%) * (365.0 – 8.55 days – 2.40 days) * 24 hrs = 52,257,780 tons/year

Based on the historical utilization data, the equipment does not present a capacity constraint, as illustrated along the y-axis in Figure 4-9.

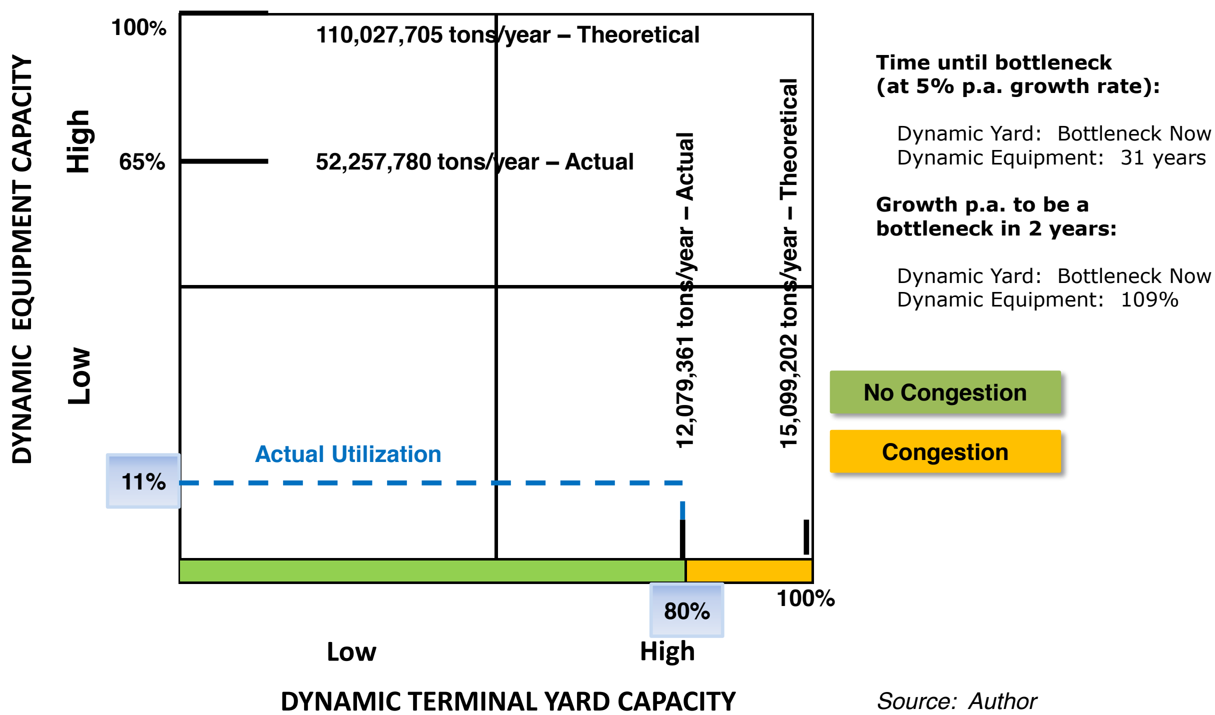


Figure 4-9: Capacity measurement of the dry bulk terminal along the dynamic dimension for the terminal yard and the equipment (based on mass)

Current utilization of the equipment is 11% of the theoretical dynamic capacity and 23% of the actual dynamic capacity. Even at a more detailed level (the conveyors handle specific cargo), the most utilized conveyor – handling cereal – utilizes 29% of theoretical dynamic capacity and 57% of the dynamic capacity.

4.1.4.3.1.2 Volume

The terminal yard has an area of 2,100,000 sq. m and an assumed stacking policy of 3 m high. Based on the current cargo mix, this analysis assumes an estimated average density of 1,200 kg/m^3 for bulk cargo.

Theoretical static volume capacity: ST_{DBY} (volume) = $d_{DBY} * h_{DBY}$

= Designated area * stacking policy

2,100,000 sq. m * 3 m = 6,300,000 m^3

Actual static volume capacity: $SA_{DBY} = ST_{DBY} * u_{DBY}$

= Designated area * Stacking policy * Threshold

2,100,000 sq. m * 3 m * 80% = 5,040,000 m^3

The analysis above indicates that the dry bulk terminal yard has a theoretical capacity of 6,300,000 m^3 at a given point in time, while the actual capacity is limited to 5,040,000 m^3 before the yard begins to suffer congestion.

Theoretical dynamic volume capacity: DT_{DBY} (volume) = $ST_{DBY} * (t_{DBY} / (o_{DBY} - m_{DBY}))$

= Theoretical static volume capacity / Commodity avg marshaling time

6,300,000 m^3 / (5 idle days / 365 operating days – 2.4 downtime days)

= 456,878,457 m^3 annually

Actual dynamic volume capacity: $DA_{DBY} = DT_{DBY} * u_{DBY}$

= Theoretical dynamic mass capacity * Threshold

[6,300,000 m^3 / (5 idle days / (365 operating days – 2.4 downtime days))]

* 80% = 365,502,766 m^3 annually

Based on the historical volume utilization data, the dry bulk terminal has significant surplus capacity due to the high density of the cargo handled. Theoretical capacity is 2% utilized and the actual capacity is 3% utilized for both static and dynamic dimensions.

In conclusion, the analysis reveals that the dry bulk terminal has sufficient capacity with its handling equipment, but is constrained by its yard's land availability in terms of mass, not volume. Any increase in throughput will result in the terminal becoming congested. The yard can handle up to a 25% increase in throughput before land availability is exhausted, while the equipment can handle a 335% increase.

4.1.4.3.2 Dry Bulk Terminal Warehouse

The analysis measures the capacity of the warehouses in terms of mass and volume.

At the case study port, the dry bulk terminal shares its warehouses 50/50 with the break bulk terminal. There are 9 warehouses on-site with an aggregate area of 690,000 sq. m, meaning the dry bulk area equals 345,000 sq. m. Of the 9 warehouses (assumed to be of equal size), typically 8 of the warehouses are used for medium-term (2-3 years) specialized storage – fully utilized with 1,290,000 mt of cargo. Approximately 1 of the warehouses is used for the temporary storage (less than one week) of cargo, which is the focus of this analysis. It is assumed that temporary storage of cargo results in an average of 4 days idle time. The dry bulk warehouses operate 365 days annually and 24 hours daily. The analysis assumes that 50% of dry bulk cargo requires short-term storage at the warehouse.

4.1.4.3.2.1 Mass

The measurement of the dry bulk terminal warehouse capacity, in terms of mass, is as follows:

Theoretical static mass capacity: ST_{DBWH} (mass) = c_{DBWH} / d_{DBWH}, can just be equal to c_{DBWH}

= Commodity size / Designated area

645,000 mt * (9 / 8 warehouses) / 345,000 sq. m: 2.10 tons / sq. m

- 645,000 mt * (9 / 8 warehouses) = 725,625 tons

Actual static mass capacity: $SA_{DBWH} = ST_{DBWH} * u_{DBWH}$

= Theoretical static mass capacity * Threshold

Actual mass capacity consistent with theoretical capacity: 2.10 tons / sq. m

- 725,625 tons * (1 / 9 warehouses) = 80,625 tons

The analysis above indicates that the dry bulk terminal warehouse can theoretically handle 725,625 tons (or 2.10 tons / sq. m) of cargo at a given point in time, but the terminal can actually handle up to 80,625 tons (or 2.10 tons / sq. m) of short-term cargo due to only 11% of the warehouse space being allocated to temporary storage.

Theoretical dynamic mass capacity: DT_{DBWH} (mass) = $ST_{DBWH} * o_{DBWH} / t_{DBWH}$

= Theoretical static mass capacity * Operating days / Avg marshaling days

725,625 tons * (365 operating days / 4 marshaling days) = 66,213,281 tons

Actual dynamic mass capacity: DA_{DBWH} (mass) = $SA_{DBWH} * o_{DBWH} / t_{DBWH}$

= Actual static mass capacity * Operating days / Avg marshaling days

80,625 tons * (365 operating days / 4 marshaling days) = 7,357,031 tons

Based on historical mass utilization data (and estimates), the dry bulk terminal warehouse is nearly a bottleneck as shown in Figure 4-10.

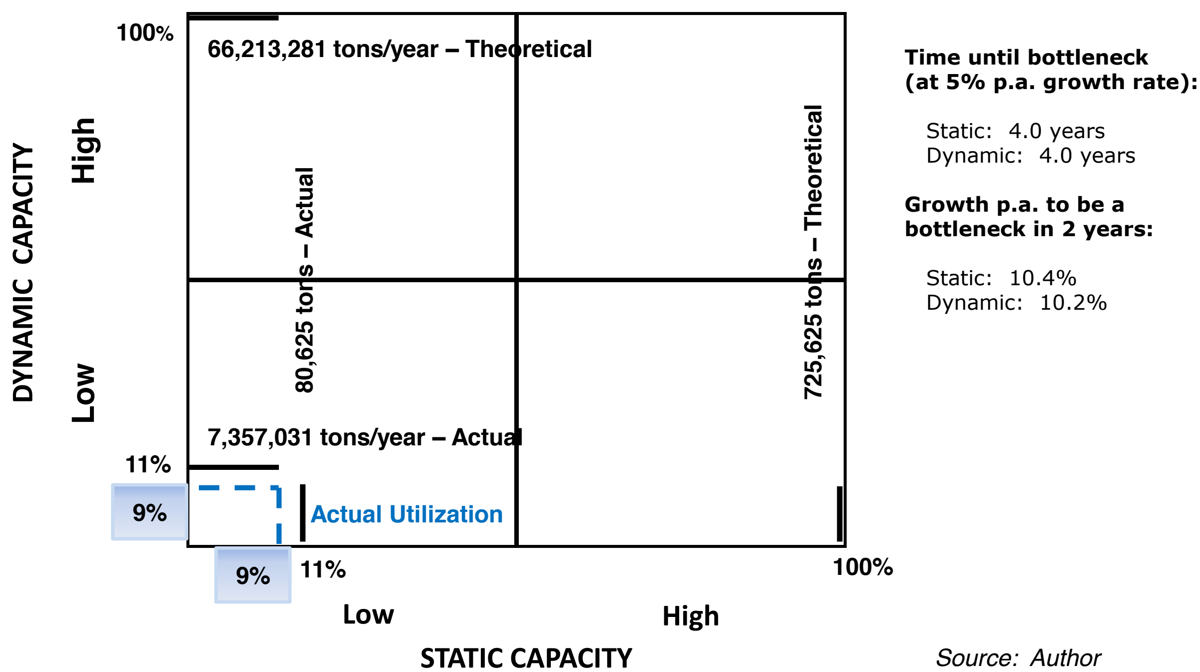


Figure 4-10: Capacity measurement of the dry bulk warehouse along the static and dynamic dimensions (based on mass)

By focusing on the space allocated for short-term storage of cargo, the analysis shows that throughput utilizes 9% of static capacity and 82% of dynamic actual capacity.

4.1.4.3.2.2 Volume

The measurement of the dry bulk terminal warehouse capacity, in terms of volume, is as follows:

Theoretical static volume capacity: ST_{DBWH} (volume) = $d_{DBWH} * s_{DBWH}$

= Designated area * stacking policy

345,000 sq. m * 3 m = 1,035,000 m^3

Actual static volume capacity: $SA_{DBWH} = ST_{DBWH} * u_{DBWH}$

= Designated area * Stacking policy * % of warehouses for temporary storage

345,000 sq. m * 3 m * (1 / 9 warehouses) = 115,000 m^3

The analysis above indicates that the dry bulk terminal yard has a theoretical capacity of 1,035,000 m^3 at a given point in time. However, due to the assignment of 89% of the warehouse space to specialized medium-term storage, only 115,000 m^3 of warehouse space remains available for temporary storage.

Theoretical dynamic volume capacity: DT_{DBWH} (volume) = $ST_{DBWH} / t_{DBWH} / o_{DBWH}$

= Designated area / Commodity avg marshaling time

1,035,000 m^3 / (4 idle days / 365 operating days) = 94,443,750 m^3 annually

Actual dynamic volume capacity: DA_{DBWH} (volume) = $DT_{DBWH} * u_{DBWH}$

= Theoretical dynamic mass capacity * % of warehouses for temporary storage

[1,035,000 m^3 / (4 idle days / 365 operating days)] * (1 / 9 warehouses)

= 10,493,750 m^3 annually

Based on historical volume utilization data (and estimates), the dry bulk terminal warehouse has sufficient capacity. By focusing on the space allocated for short-term storage of cargo, the analysis shows that throughput utilizes 5% of static actual capacity and 48% of dynamic actual capacity.

4.1.4.4 Break Bulk Terminal Area

The break bulk terminal area consists of a terminal yard and warehouses. The terminal yard is the location where break bulk cargo is unloaded from the vessel to the terminal by the vessels own cranes. Once land-side, the cargo is either immediately transported by intermodal links to the hinterland or is temporarily stored at either the terminal yard or the warehouse.

4.1.4.4.1 Break Bulk Terminal Yard

The analysis of the dry bulk area first examines capacity of the break bulk terminal in terms of both mass and volume, as the terminal’s throughput charges are based on the higher of mass and volume. The capacity of the vessel equipment calling at the break bulk terminal is not calculated, as the vessels themselves load/unload the cargo using their own cranes. The results are then compared with the utilization data.

At the case study port, the dry bulk and break bulk activities share a common 420 hectare terminal yard, which for the purpose of our calculations is assumed to be shared 50/50. Therefore, the area of the break bulk terminal yard is 210 hectares. In addition, the terminal has 12 berths. The yard operates 365 days annually and 24 hours daily, but experiences 2.4 days of downtime per year due to poor weather. The yard suffers from congestion once it reaches the 80% utilization threshold.

4.1.4.4.1.1 Mass

Beginning with the capacity measurement of land availability in terms of mass, the break bulk terminal yard has a designated area of 210 hectacres able to handle 18 mill. tons annually, which is assumed to be the maximum throughput the yard's foundation can sufficiently support. The average idle time for dry bulk cargo is 5.0 days and average downtime due to poor weather is 2.4 days.

Designated area: d_{BBY} = 210 hectares * 10,000 sq. m / hectare = 2,100,000 sq. m

Maximum daily commodity mass (i.e., commodity size): $s_{BBY} = r_{BBY} / [t_{BBY} / (o_{BBY} - m_{BBY})]$

= 18,000,000 tons / [5 idle days / (365 operating days - 2.4 downtime days)]

= 248,206 tons

Theoretical static mass capacity: ST_{BBY} (mass) = s_{BBY} / d_{BBY},

where $s_{BBY} = r_{BBY} / [t_{BBY} / (o_{BBY} - m_{BBY})]$

= Commodity size / Designated area

248,206 tons / 2,100,000 sq. m = 0.12 tons / sq. m

Actual static mass capacity: $SA_{BBY} = ST_{BBY} * u_{BBY}$

= Theoretical static mass capacity * Threshold

248,206 tons / 2,100,000 sq. m * 80% utilization = 0.09 tons / sq. m

The analysis above indicates that the dry bulk terminal yard can theoretically handle 248,206 tons (or 0.12 tons / sq. m) of cargo at a given point in time, but the yard can actually handle up to 198,565 tons (or 0.09 tons / sq. m) without experiencing congestion.

Theoretical dynamic mass capacity: DT_{BBY} (mass) = $[s_{BBY} * ((o_{BBY} - m_{BBY}) / t_{BBY})] / d_{BBY}$

= (Commodity size * Commodity avg idle time) / Designated area

[248,206 tons * ((365 operating days – 2.4 downtime days) / 5 idle days)] /

2,100,000 sq. m = 8.6 tons / sq. m annually or 18,000,000 tons / yr

Actual dynamic mass capacity: $DA_{BBY} = DT_{BBY} * u_{BBY}$

= Theoretical dynamic mass capacity * Threshold

[248,206 tons * ((365 operating days – 2.4 downtime days / 5 idle days)] /

2,100,000 sq. m * 80% = 6.9 tons / sq. m annually or 15,000,000 tons / yr

Based on the historical mass utilization data, the break bulk terminal makes low use of its land availability as illustrated in Figure 4-11. Theoretical capacity is 20% utilized and actual capacity is 25% utilized for both the static and dynamic dimensions.

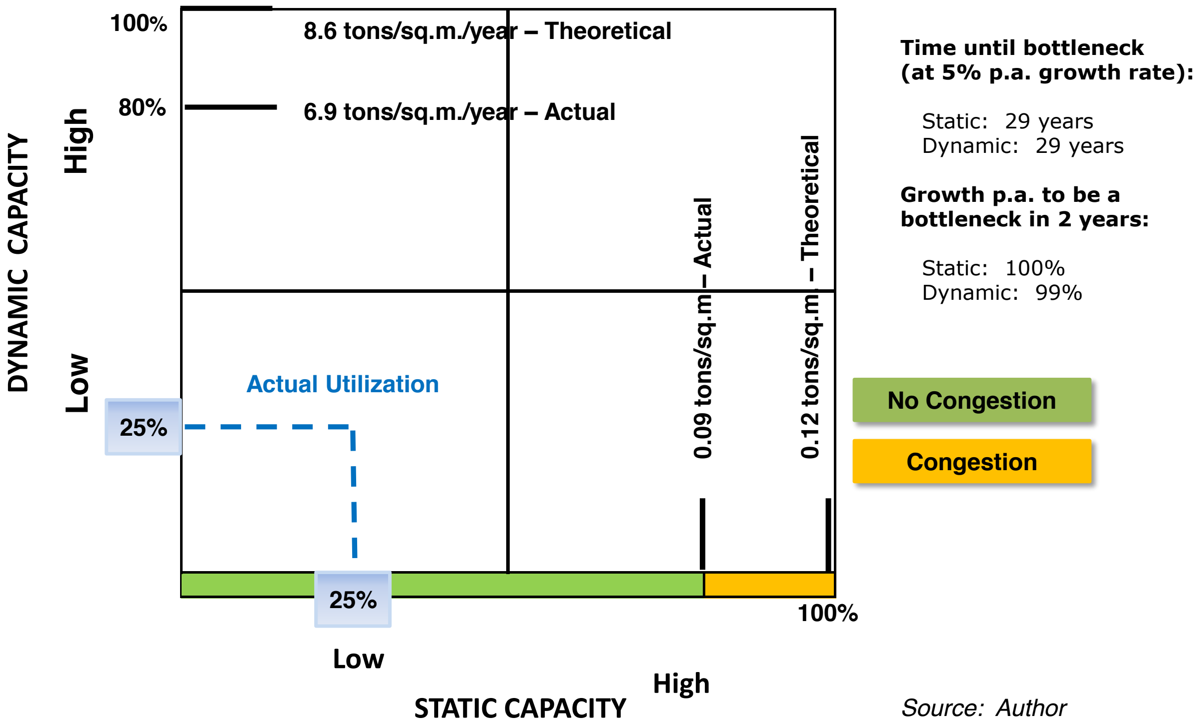


Figure 4-11: Capacity measurement of the break bulk terminal yard along the static and dynamic dimensions (based on mass)

4.1.4.4.1.2 Volume

The terminal yard has an area of 2,100,000 sq. m and an assumed stacking policy of 3 m high. Based on the current cargo mix, this analysis assumes an estimated average density of 5,600 kg/m^3 for bulk cargo.

Theoretical static volume capacity: ST_{BBY} (volume) = d_{BBY} * h_{BBY}

= Designated area * stacking policy

2,100,000 sq. m * 3 m = 6,300,000 m^3

Actual static volume capacity: $SA_{BBY} = ST_{BBY} * u_{BBY}$

= Designated area * Stacking policy * Threshold

$2,100,000$ sq. m * 3 m * 80% = $5,040,000\ m^3$

The analysis above indicates that the dry bulk terminal yard has a theoretical capacity of $6,300,000\ m^3$ at a given point in time, while the actual capacity is limited to $5,040,000\ m^3$ before the yard begins to suffer congestion.

Theoretical dynamic volume capacity: DT_{BBY} (volume) = ST_{BBY} * (t_{BBY} / (o_{BBY} - m_{BBY})

= Designated area / Commodity avg marshaling time)

$6,300,000\ m^3$ / (5 idle days / (365 operating days – 2.4 downtime days)

= $456,878,457\ m^3$ annually

Actual dynamic volume capacity: $DA_{BBY} = DT_{BBY} * u_{BBY}$

= Theoretical dynamic mass capacity * Threshold

[$6,300,000\ m^3$ / (5 idle days / (365 operating days – 2.4 downtime days)]

* 80% = $365,502,766\ m^3$ annually

Based on the historical volume utilization data, the break bulk terminal has nearly no utilization of its resources due to the high density of the cargo handled. Theoretical static and dynamic capacity are both 0.1% utilized and the actual static and dynamic capacity are both 0.2% utilized.

In conclusion of the break bulk terminal, the analysis reveals that the break bulk yard has sufficient capacity and is not constrained by its land availability in terms of mass or volume.

4.1.4.4.2 Break Bulk Terminal Warehouse

The analysis measures the capacity of the warehouses in terms of mass and volume.

At the case study port, the break bulk terminal shares its warehouses 50/50 with the dry bulk terminal. There are 9 warehouses on-site with an aggregate area of 690,000 sq. m, meaning the dry bulk area equals 345,000 sq. m. Of the 9 warehouses (assumed to be of equal size), typically 8 of the warehouses are used for medium-term (2-3 years) storage – fully utilized with 1,290,000 mt of cargo. Approximately 1 of the warehouses is used for the temporary storage (less than one week) of cargo, which is the focus of this analysis. It is assumed that temporary storage of cargo results in an average of 4 days idle time. The break bulk warehouses operate 365 days annually and 24 hours daily. The analysis assumes that 50% of break bulk cargo requires short-term storage at the warehouse.

4.1.4.4.2.1 Mass

The measurement of the break bulk terminal warehouse capacity, in terms of mass, is as follows:

Theoretical static mass capacity: ST_{BBWH} (mass) = c_{BBWH} / d_{BBWH}, can just be equal to c_{BBWH}

= Commodity size / Designated area

645,000 mt * (9 / 8 warehouses) / 345,000 sq. m: 2.10 tons / sq. m

- 645,000 mt * (9 / 8 warehouses) = 725,625 tons

Actual static mass capacity: $SA_{BBWH} = ST_{BBWH} * u_{BBWH}$

= Theoretical static mass capacity * Threshold

Actual mass capacity consistent with theoretical capacity: 2.10 tons / sq. m

- 725,625 tons * (1 / 9 warehouses) = 80,625 tons

The analysis above indicates that the break bulk terminal warehouse can theoretically handle 725,625 tons (or 2.10 tons / sq. m) of cargo at a given point in time, but the terminal can actually handle up to 80,625 tons (or 2.10 tons / sq. m) of cargo due to only 11% of the warehouse space allocated to temporary storage.

Theoretical dynamic mass capacity: DT_{BBWH} (mass) = $ST_{BBWH} * o_{BBWH} / t_{BBWH}$

= Theoretical static mass capacity * Operating days / Avg marshaling days

725,625 tons * (365 operating days / 14 marshaling days) = 18,918,080 tons

Actual dynamic mass capacity: DA_{BBWH} (mass) = $SA_{BBWH} * o_{BBWH} / t_{BBWH}$

= Actual static mass capacity * Operating days / Avg marshaling days

80,625 tons * (365 operating days / 14 marshaling days) = 2,102,009 tons

Based on historical mass utilization data, the break bulk terminal warehouse has sufficient capacity as shown in Figure 4-12. By focusing on the space allocated for short-term storage of cargo, the analysis shows that throughput utilizes 10% of static actual capacity and 89% of dynamic actual capacity.

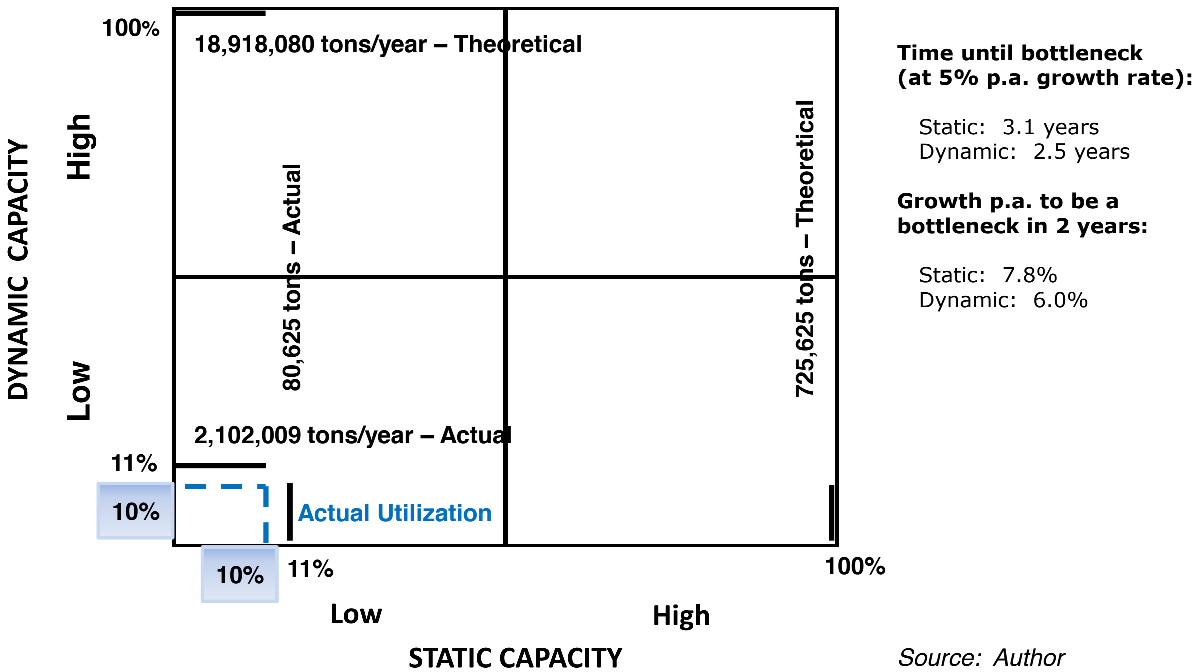


Figure 4-12: Capacity measurement of the break bulk warehouse along the static and dynamic dimensions (based on mass)

4.1.4.4.2.2 Volume

The measurement of the break bulk terminal warehouse, in terms of volume, is as follows:

Theoretical static volume capacity: ST_{BBWH} (volume) = d_{BBWH} * s_{BBWH}

= Designated area * stacking policy

345,000 sq. m * 3 m = 1,035,000 m^3

Actual static volume capacity: $SA_{BBWH} = ST_{BBWH} * u_{BBWH}$

= Designated area * Stacking policy * % of warehouses for temporary storage

345,000 sq. m * 3 m * (1 / 9 warehouses) = 115,000 m^3

The analysis above indicates that the break bulk terminal yard has a theoretical capacity of 1,035,000 m^3 at a given point in time. However, due to the assignment of 89% of the warehouse space to specialized medium-term storage, only 115,000 m^3 of warehouse space remains available for temporary storage.

Theoretical dynamic volume capacity: DT_{BBWH} (volume) = ST_{BBWH} / t_{BBWH} / o_{BBWH}

= Designated area / Commodity avg marshaling time

1,035,000 m^3 / (14 idle days / 365 operating days) = 26,983,929 m^3 annually

Actual dynamic volume capacity: DA_{BBWH} (volume) = DT_{BBWH} * u_{BBWH}

= Theoretical dynamic mass capacity * % of warehouses for temporary storage

[1,035,000 m^3 / (14 idle days / 365 operating days)] * (1 / 9 warehouses)

= 2,998,214 m^3 annually

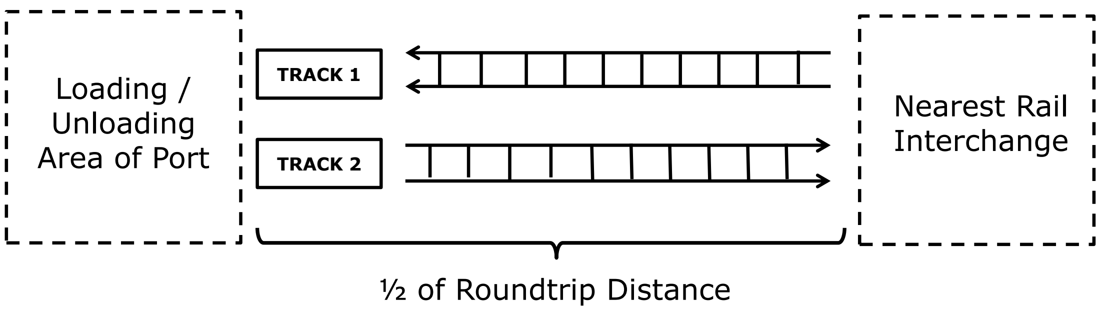
Based on historical volume utilization data, the break bulk terminal warehouse is not a capacity constraint. By focusing on the space allocated for short-term storage of cargo, the analysis shows that throughput utilizes 1% of static actual capacity and 11% of dynamic actual capacity. The warehouse space would be sufficient to handle the throughput at the terminal, but as previously mentioned, the majority of the theoretical capacity is leased for medium-term specialized storage.

4.1.5 Intermodal Links

The intermodal links are the road and rail connections at the port that transport cargo to and from the hinterland. This section analyzes the rail network.

Rail Network

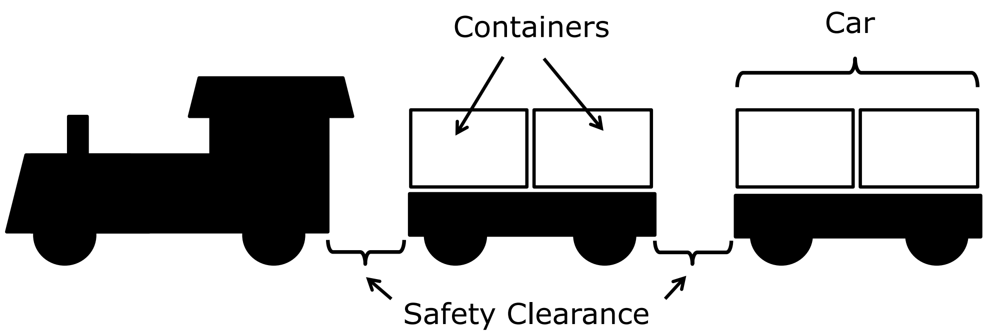
The rail system at port typically consists of a rail terminal gate (through which trucks carrying rail-transported cargo enter/exit the rail terminal yard), the rail terminal yard (where rail-transported cargo is temporarily stored), and the rail network (i.e., the trains and track that transport the cargo to and from the hinterland). The trains transport both containerized and non-containerized cargo in TEU containers. In this analysis, only the capacity of the rail network (illustrated in Figure 4-13) is studied, as the case study port does not have a rail terminal yard and insufficient data was available to measure the rail terminal gate.



Source: Author

Figure 4-13: Diagram of a rail network

The case study port's rail network consists of 2 tracks on which single-stacked trains of 45 wagons (1 x 22 m long locomotive and 44 x 13 m long cars carrying 2 TEU containers each) transport the cargo at an average speed of 27.5 km/hour. A 1 meter safety clearance exists between each train car, as shown in Figure 4-14. The trains operate 365 days annually and 24 hours daily.



Source: Author

Figure 4-14: Diagram of a 3 wagon single-stacked train (1 locomotive and 2 cars)

The static capacity analysis determines the number of TEU containers transported by train per km.

- Train length: $l_{RN} = w_{RN} * (x_{RN} + z_{RN}) + y_{RN}$

  = 44 cars * (13 m length + 1 m safety clearance) + 1 locomotive * 22 m = 638 m
- Containers per train: $c_{RN} = v_{RN} * w_{RN} * s_{RN}$

  = 2 TEU containers * 44 cars * 1 stacked high = 88 TEU containers per train
- Number of trains per lane length: $n_{RN} = k_{RN} / l_{RN} * t_{RN}$

  = Lane length / Train length * Number of tracks

  1 km / 638 meters * 2 tracks = 3.1 trains / km

Theoretical static capacity: $ST_{RN} = n_{RN} * c_{RN}$, where $c_{RN} = v_{RN} * w_{RN} * s_{RN}$

$n_{RN} = k_{RN} / l_{RN} * t_{RN}$

$l_{RN} = w_{RN} * (x_{RN} + z_{RN}) + y_{RN}$

= Number of trains per lane length * Number of TEU containers per train

3.1 trains / km * 88 TEU containers / train = 276 TEU containers / km

Actual static capacity: $SA_{RN} = u_{RN} * c_{RN}$

= Number of trains per lane * Number of TEU containers per train

2 trains / km * 88 TEU containers / train = 176 TEU containers / km

The dynamic capacity measures the number of containers transported to/from the port during a 1 year period, by accounting for the speed of the train, the roundtrip distance to the nearest interchange, and the loading/unloading time for each train. At the case study port, the maximum speed of a train is 40 km/hour, while the average speed of a train is 27.5 km/hour. The analysis assumes 6 hours to unload/load a train.

Theoretical dynamic capacity: $DT_{RN} = [h_{RN} / (2 * k_{RN} / a_{RN})] * o_{RN} * t_{RN}$

= [Daily operating hrs / (Roundtrip distance to nearest interchange / Avg cruising speed of the train)] * Operating days annually * Number of tracks

[24 hrs / (62 km / 40.0 km / hr)] * 365 operating days * 2 tracks

= 994,684 TEU containers annually

Actual dynamic capacity: $DA_{RN} = [h_{RN} / (2 * k_{RN} / a_{RN} + i_{RN})] * o_{RN} * t_{RN}$

= [Daily operating hrs / (Roundtrip distance to nearest interchange / Avg cruising speed of the train + Loading/Unloading hours per train)] * Operating days annually * Number of tracks

- Note: Daily operating hrs / (Roundtrip distance to nearest interchange / Avg cruising speed of the train + Loading/Unloading hours per train) = Number of train trips per day per track

[24 hrs / (62 km / 27.5 km / hr + 6 hours)] * 365 operating days * 2 tracks

= 186,777 TEU containers annually

Based on the historical utilization data, the railway network does not present a capacity constraint and has substantial surplus dynamic capacity (as per Figure 4-15).

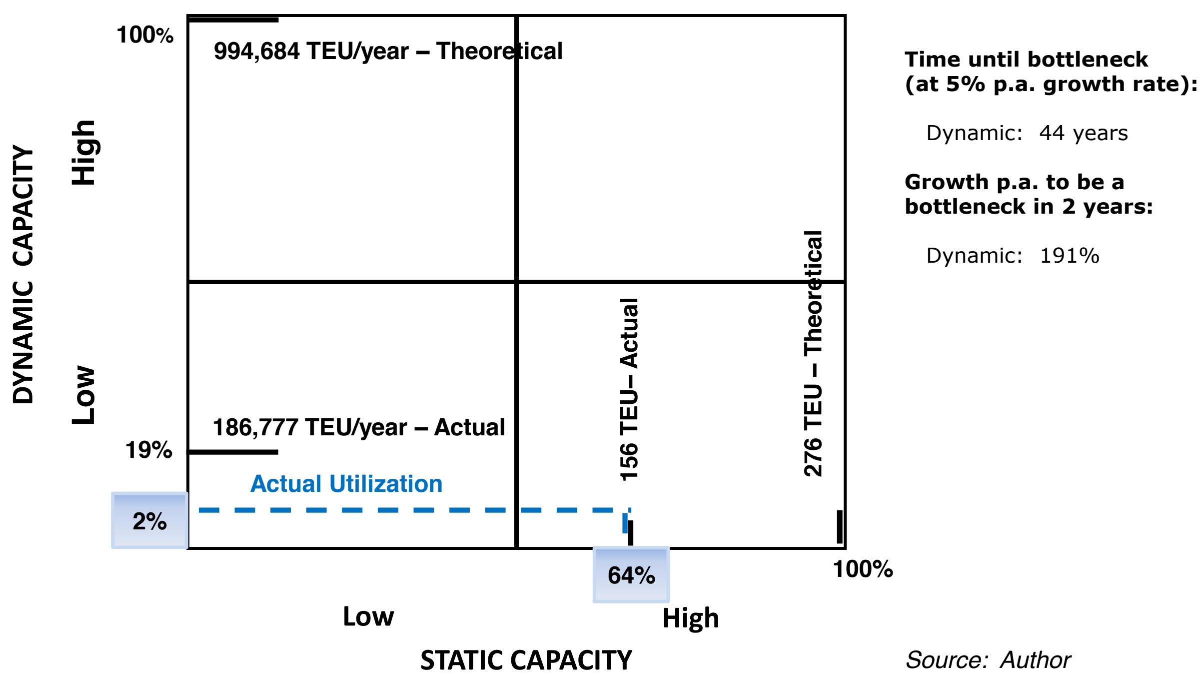


Figure 4-15: Capacity measurement of the rail network along the static and dynamic dimensions

The theoretical and actual static capacity are utilized 64% and 100%, respectively, meaning that the trains arriving at and departing from the port are fully laden. A more relevant measure of the entire rail network's capacity – by considering the factors impacting capacity over time – is the theoretical and actual dynamic capacity, which are utilized 2% and 12%, respectively.

4.1.6 Summary of Capacity Measurement and Identification of Bottlenecks

At this stage of the analysis, the capacity constraints and utilization of all port components have been assessed. Table 4-3 summarizes the results of the capacity measurement analysis.

Table 4-3: Summary of Capacity Measurement and Utilization at Each Port Component of the Case Study Port

	Bottleneck Status	Static Capacity & Utilization Theoretical	Actual	Dynamic Capacity & Utilization Theoretical	Actual	Time until Bottleneck (5% volume growth p.a.)	Growth p.a. to be a bottleneck in 2 years
Anchorage (ships)	No	234 23%	234 23%	215,905 9%	215,905 9%	Static - 31 yrs Dynamic - 49 yrs	Static - 109% Dynamic - 232%
Waterway (ships)	No	482 11%	313 17%	563,119 7%	366,027 11%	Static - 37 yrs Dynamic - 46 yrs	Static -142% Dynamic - 206%
Container Berth (ships/time)	Yes	11.2 275%	11.2 275%	7,015 160%	7,015 160%	Static - Now Dynamic - Now	Static - Now Dynamic - Now
Container Terminal Yard (TEU)	Approaching	57,600 61%	40,320 87%	4,106,880 61%	2,874,816 87%	Static - 2.9 yrs Dynamic - 2.9 yrs	Static - 7.5% Dynamic - 7.5%
Container Equipment (TEU) Ship-to-Shore Cranes	No			6,160,320 40%	3,080,160 81%	Dynamic - 4.4 yrs	Dynamic - 11.2%
Container Equipment (TEU/time) RTGs	No			3,901,536 64%	3,121,229 80%	Dynamic - 4.7 yrs	Dynamic - 12.0%
Liquid Bulk Berth (ships/time)	No	37.2 41%	39.0 40%	21,706 26%	22,776 25%	Static - 20 yrs Dynamic - 29 yrs	Static - 59% Dynamic - 102%
Liquid Bulk Terminal Yard (mt/sqm) Mass	Static - Yes Dynamic - No	1.63 97%	1.58 100%	58.57 40%	56.86 41%	Static - Now Dynamic - 19 yrs	Static - Now Dynamic - 57%
Liquid Bulk Terminal Yard (cbm) Volume	Static - Yes Dynamic - No	3,473,775 97%	3,369,561 100%	123,923,775 40%	120,206,061 41%	Static - Now Dynamic - 19 yrs	Static - Now Dynamic - 56%
Liquid Bulk Equipment (mt/time) Pumps	No			102,492,000 41%	102,492,000 41%	Dynamic - 19 yrs	Dynamic - 57%
Break Bulk Berth (ships/time)	No	15.2 29%	15.2 29%	4,427 36%	4,427 36%	Static - 26 yrs Dynamic - 22 yrs	Static - 88% Dynamic - 68%
Break Bulk Terminal Yard (mt/sqm) Mass	No	0.12 20%	0.09 25%	8.57 20%	6.86 25%	Static - 29 yrs Dynamic - 29 yrs	Static - 100% Dynamic - 99%
Break Bulk Terminal Yard (cbm) Volume	No	6,300,000 0.1%	5,040,000 0.2%	456,878,457 0.1%	365,502,766 0.2%	Static - 131 yrs Dynamic - 130 yrs	Static - 2,285% Dynamic - 2,236%
Break Bulk Warehouse (mt) Mass	Approaching	725,625 10%	80,625 86%	18,918,080 10%	2,102,009 89%	Static - 3.1 yrs Dynamic - 2.5 yrs	Static - 7.8% Dynamic - 6.0%
Break Bulk Warehouse (cbm) Volume	No	1,035,000 1%	115,000 11%	26,983,929 1%	2,998,214 11%	Static - 46 yrs Dynamic - 45 yrs	Static - 205% Dynamic - 200%
Dry Bulk Berth (ships/time)	No	13.3 25%	13.3 25%	3,873 31%	3,873 31%	Static - 29 yrs Dynamic - 24 yrs	Static - 101% Dynamic - 80%
Dry Bulk Terminal Yard (mt/sqm) Mass	Yes	0.10 80%	0.08 100%	7.19 81%	5.75 101%	Static - Now Dynamic - Now	Static - Now Dynamic - Now
Dry Bulk Terminal Yard (cbm) Volume	No	6,300,000 2%	5,040,000 3%	456,878,457 2%	365,502,766 3%	Static - 74 yrs Dynamic - 74 yrs	Static - 505% Dynamic - 501%
Dry Bulk Equipment (mt/time)	No			110,027,705 11%	52,257,780 23%	Dynamic - 31 yrs	Dynamic - 109%
Dry Bulk Warehouse (mt) Mass	Approaching	725,625 9%	80,625 82%	66,213,281 9%	7,357,031 82%	Static - 4.0 yrs Dynamic - 4.0 yrs	Static - 10.4% Dynamic - 10.2%
Dry Bulk Warehouse (cbm) Volume	No	1,035,000 5%	115,000 48%	94,443,750 5%	10,493,750 48%	Static - 16 yrs Dynamic - 15 yrs	Static - 45% Dynamic - 45%
Rail Network (TEU)	No	276 64%	176 100%	994,684 2%	186,777 12%	Dynamic - 44 yrs	Dynamic - 191%

For each port component, capacity is listed in the first row and utilization is listed in the second row.
Static capacity is a point-in-time measurement. Where there is a unit/time measurement, time is equal to one day.
Dynamic capacity is period-over-time measurement. Measurements are given for a time period of one year.
Equipment capacity is measured based on mass.

Source: Author

As highlighted in Table 4-3, capacity is sufficient at 15 of the 22 port components. However, bottlenecks exist at the container berths and the dry bulk terminal yard (in terms of volume). In addition, capacity is constrained for the static dimensions of the liquid bulk terminal yard (in terms of both mass and volume) due to the full utilization of the existing storage tanks without land availability to expand. Dynamic capacity for the liquid bulk terminal yard is sufficient as capacity exists should inventory turns increase. Port components where capacity is not currently constrained, but that are in danger of becoming bottlenecks, are the container terminal yard and the warehouse (in term of mass) handling both dry bulk and break bulk cargo. Based on a 5% per annum growth rate for throughput demand, the container yard has approximately 2.9 years until a bottleneck exists, the dry bulk warehouse (in terms of mass) has approximately 4.0 years until a bottleneck exists, and the break bulk warehouse (in terms of mass) has approximately 2.5 years until a bottleneck. From another perspective, these same port components would require the following per annum growth rates for throughput demand to become a bottleneck in just 2 years: 7.5%, 10.2%, and 6.0%, respectively. Note the large discrepancy between the utilization of theoretical capacity (9-10%) and the utilization of actual capacity (82-89%) for the dry bulk and break bulk warehouses. The reason for the difference in utilization between the capacity measurements is that the designated area for theoretical capacity is based on all 9 warehouses hypothetically having full capacity to handle temporary storage, while the designated area for actual capacity is based on just 1 warehouse in reality having full capacity to handle temporary storage (as previously mentioned, the other 8 warehouses are used for specialized medium-term storage of cargo). Having identified the port components that require attention, the analysis will now determine which investment strategies should be pursued in Section 4.2.

4.2 Evaluation of Investment Strategies Under Uncertainty

This section begins with the screening models described in Chapter 3, providing a brief recap of the future uncertainties identified for the analysis and an overview of the assumptions used in the simulation for determining, and then evaluating, the investment strategies to address the bottlenecks within the port system.

Unless otherwise noted, the graphs and tables used to present the data within the subsections of Section 4.2 originate from the simulation model, which is a modification of the model developed for the 2006 paper "Real Options by Spreadsheet: Parking Garage Case Example" by de Neufville, Scholtes, and Wang.

4.2.1 Screening Models to Develop Uncertainty Scenarios & Investment Strategies

As stated in Section 3.2.1, three types of uncertainty were identified in this analysis. By thinking about the most likely trends and trend-breakers that may potentially impact the financial performance of the case study port, the three uncertainties were identified as the development of future macroeconomic activity, the development of a regional hub for products and services in Country X, and the outcomes of future national political events. Through the use of a combination of a bottom-up screening model (the capacity measurement methodology applied at each port component in Section 4.1) and a simulator screening model (the Excel spreadsheet model detailed in this section), the most attractive potential investment strategies were selected.

4.2.1.1 Assumptions in the Simulation Model

As mentioned in Section 3.2.1.3, the simulator screening model is an Excel spreadsheet model for the purpose of generating forecasted throughput based on future uncertainties and then providing a range of profitability for both investment strategies and port components for comparison and ranking against one another. The model is an investment decision-making tool for those parties interested in determining where port infrastructure investment should be made within the port system and which of these strategies has the most potential for profit.

The simulation model is based on a variety of assumptions, which can be simply input into the speadsheet. The key assumptions are detailed below:

- Mean reversion dampening factor (r): 0.4
- Time horizon for discounted cash flow ("DCF"): 15 years
- Discount rate: 10.5%
    - The discount rate is based on publicly available information for an industrial conglomerate with operations located primarily in Country X.
- Average annual EBITDA per unit of throughput:
    - Container Terminal: USD 90.00 per TEU
    - Liquid Bulk Terminal: USD 5.70 per mt
    - Break Bulk Terminal: USD 11.25 per mt
    - Dry Bulk Terminal: USD 11.25 per mt
    - Current Warehouse:

        - Temporary storage of bulk cargo: USD 11.25 per mt per day
        - Specialized storage of bulk cargo: USD 1.35 per mt per day

    These rates are based on publicly available information from government publications and recent financial reports of leading terminal operators with operations in the Asia Pacific region, and then increased by a multiple.

- Uncertainty scenario assumptions:
    - Macroeconomic development: Refer to Section 3.2.1.1
    - Regional hub development: Refer to Section 3.2.1.2
    - Outcome of national political events: Refer to Section 3.2.1.2
- Flexibility assumptions for a new vertical warehouse:
    - Capex cost growth per level for every level above 2: 10%
    - Capacity capex: USD 150 per mt
    - Initial capacity: 4 levels
    - Capacity limit: 250,000 mt per level
        - Note that a parking garage is typically designed to support loads of 150 lbs per square inch (equal to 105.6 mt per square meter), but may be reinforced to support higher loads if necessary (*Parking Structure Design Guide*, 2009, p. 14).
    - Maximum number of levels for warehouse: 8 levels
    - Expand by 1 level if past 2 years were at full capacity

4.2.1.2 Comparison of 3 Forecasting Methods in Simulation Model

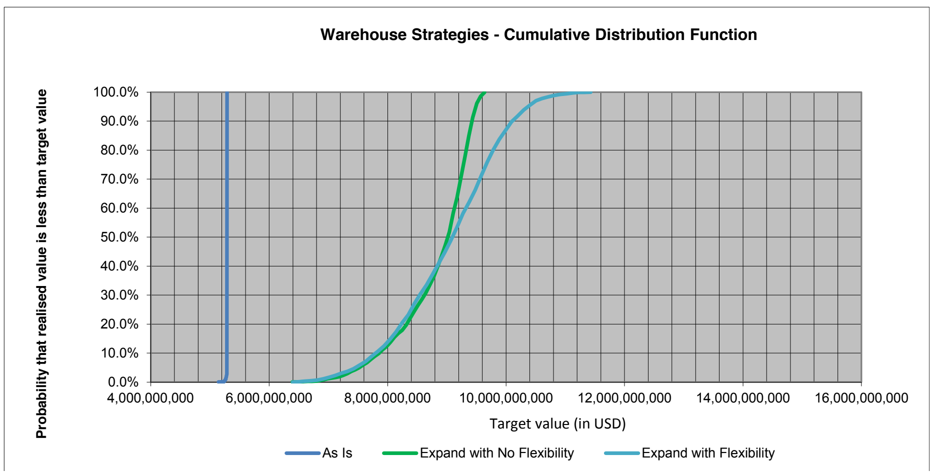
This section highlights the primary method of forecasting demand: random selection from a normal distribution with a mean reversion to an underlying projected trend based on an average growth rate of the historical throughput data ("Mean Reversion Average Growth method") as detailed in Section 3.2.1.1. The Mean Reversion Average Growth method should more closely follow the underlying forecasted demand than the Random Walk method (which would amplify both the upside gains under an investment strategy with flexibility and the downside losses under an investment strategy without flexibility), meaning less variability and less skewness when evaluating the profitability of the investment strategies and port components.

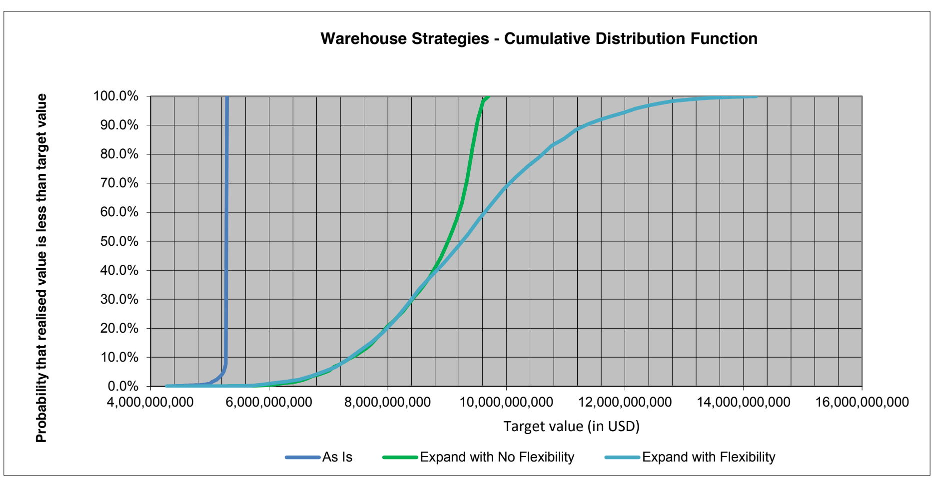
Table 4-4: A comparion of profitability metrics for the warehouse investment strategies between the Mean Reversion Average Growth method and the Random Walk method

	Each Strategy's Warehouse Present Value		
Metric	As Is	Non-Flexible Expansion	Flexible Expansion
ENPV	-0.2%	-1.2%	3.3%
10 percent value at risk	0.0%	-6.2%	-5.4%
90 percent value at risk	0.0%	0.6%	10.7%
Minimum result	-15.5%	-17.1%	-33.2%
Maximum result	0.0%	0.6%	24.4%
Range of results	551.1%	35.6%	97.6%
Standard deviation	1029.9%	36.3%	73.8%
Difference between median and ENPV	1733.8%	51.8%	-188.1%

Source: Author

As shown in Table 4-4, the minimal change of ENPV coupled with the increases in range and standard deviation indicates that the Random Walk method leads to higher variability of profitability than when using the Mean Reversion Average Growth method. As illustrated in Figure 4-16 below, the larger positive difference between the median result and the ENPV for two strategies that did not involve flexibility means that the cumulative distribution curve is more skewed toward downside losses (i.e., the increase in the lower 50% tail exceeds the increase in the upper 50% tail), while the opposite occurred for the flexible option. These findings underscore that a flexible option is more valuable in investment decisions where the future performance is more uncertain (i.e., more volatile).





Source: Author

Figure 4-16: A comparison of cumulative distribution curves for the warehouse investment strategies between the preferred Mean Reversion Average Growth method (top) and the Random Walk method (bottom)

The comparison of the Mean Reversion Average Growth method and the Mean Reversion Exponential Smoothing method reveal few conclusive findings, despite some consistency for certain metrics across investment strategies shown in Table 4-5, below. One result is that the standard deviation increased in all cases when switching to the Mean Reversion Exponential Smoothing method, while the range of results increased in all investment strategies and port components, with the exception of the container terminal. Another finding is that for the port components and the warehouse investment strategies at the port system level (as shown in Appendix 3), ENPV, 10 percent value-at-risk, and 90 percent value-at-risk all move in the same direction, which highlights a shifting of the cumulative distribution curves when switching between methods. A final insight, as shown in Appendix 3, is that in comparisons across investment strategies at the port system level, change in ENPV remained within a range of -1.3% and -1.0% (Table A3-6), while across port components change in ENPV fluctuated within a range of -7.5% and 11.6% (Table A3-2).

Table 4-5: A comparison of profitability metrics for the warehouse investment strategies between the Mean Reversion Average Growth method and the Exponential Smoothing method

	Each Strategy's Warehouse Present Value		
Metric	As Is	Non-Flexible Expansion	Flexible Expansion
ENPV	0.0%	-0.3%	-0.2%
10 percent value at risk	0.0%	-0.2%	-0.7%
90 percent value at risk	0.0%	0.5%	0.3%
Minimum result	-1.3%	-1.3%	0.1%
Maximum result	0.0%	0.6%	1.6%
Range of results	46.0%	4.3%	3.6%
Standard deviation	60.3%	0.5%	2.0%
Difference between median and ENPV	27.0%	-12.0%	-24.2%

Source: Author

Appendix 3 contains the data tables highlighting the results under each of the three data methods for evaluating the current state of the port components, warehouse investment strategies at the warehouse level, and warehouse investment strategies at the overall port system level. In addition, Appendix 3 contains graphs of the cumulative distribution curves data tables, as well as data tables showing the comparison between results under each of the three data methods for evaluating the current state of the port components, warehouses investment strategies at the warehouse level, and warehouse investment strategies at the overall port system level.

4.2.2 Simulation Results of the Port Components & Investment Strategies

The simulation model will be first utilized to confirm the bottlenecks identified in the capacity measurement analysis and rank the port components in terms of future long-term profitability potential, as per Section 4.2.2.1. Investment strategies will then be selected based on the analysis of the port components. In Section 4.2.2.2, these investment strategies will be analyzed using the simulation model and sensitivity analysis. Finally, Section 4.2.2.3, presents a comparison of the investment strategies in terms of profitability at the port system level.

4.2.2.1 Port System in its Current State

The port system is evaluated at each port component based on its future long-term profitability potential. The port system is assumed to remain in its current state; in other words, the analysis assumes no changes to the port layout and rates, and no expansion is to occur for the foreseeable future. The analysis provides a ranking of the port components in terms of ENPV of EBITDA over the next 15 years at a discount rate of 10.5%. Results of the analysis are presented in Figure 4-17 and Table 4-6, which are based on the Mean Reversion Average Growth method.

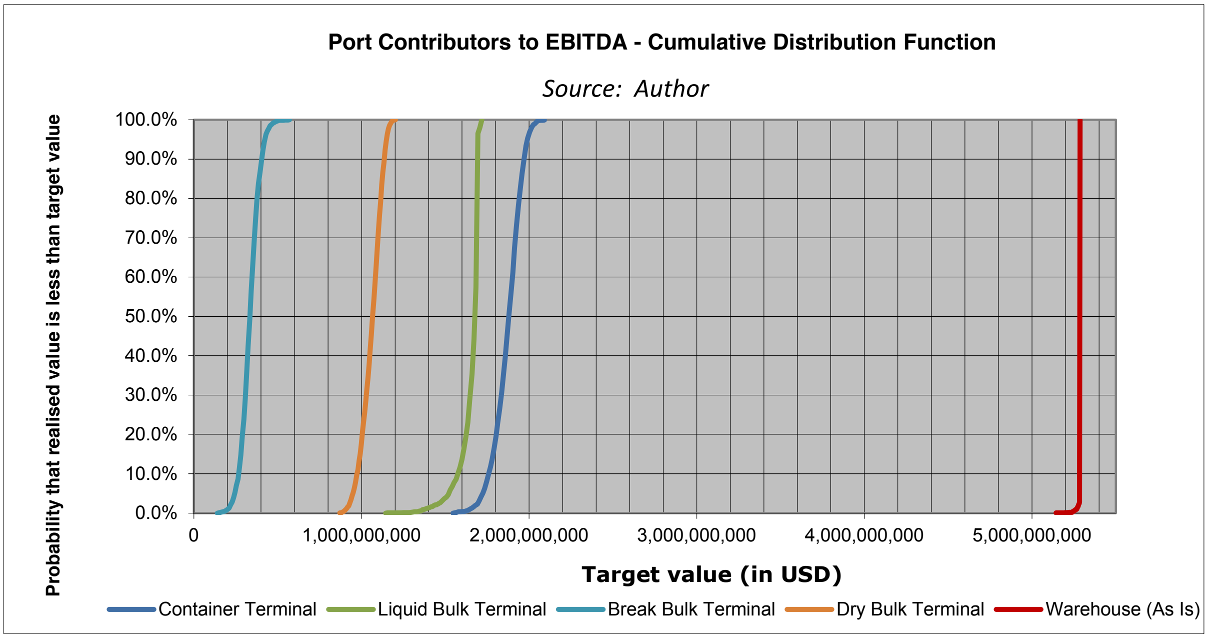


Figure 4-17: The cumulative distribution curves of NPV EBITDA for each of the port components, in their current state, contributing to the port system's EBITDA under the Mean Reversion Average Growth method

Table 4-6: The metrics for evaluating the profitability of each of the port components, in their current state, contributing to the port system's EBITDA under the Mean Reversion Average Growth method

	Each Port Contributor's Present Value (in USD mill.)				
Metric	Container	Liquid Bulk	Break Bulk	Dry Bulk	Warehouse
ENPV	1,871	1,651	334	1,060	5,287
10 percent value at risk	1,757	1,565	263	971	5,287
90 percent value at risk	1,969	1,682	403	1,134	5,287
Minimum result	1,546	1,144	140	870	5,143
Maximum result	2,092	1,717	570	1,202	5,287
Range of results	547	573	430	332	144
Standard deviation	82	63	54	61	6
Difference between median and ENPV	8	25	0	7	1

Source: Author

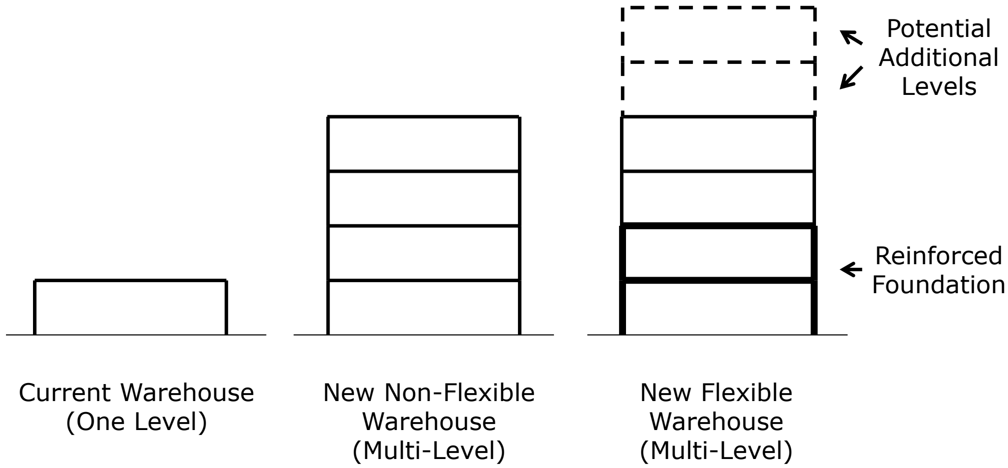
The analysis reveals that all the port components are expected to be profitable over the forecast period, with a minimum profit of USD 140 mill. generated by the break bulk terminal. Based on the ENPV shown in Table 4-6, the warehouse is the port component that is forecasted, by a wide-margin, to provide the greatest profit, followed by the container terminal, liquid terminal, dry bulk terminal, and lastly the break bulk terminal. As the cumulative profitability curves overlap for the container terminal, liquid terminal, and dry bulk terminal, only the ranking of the container terminal as most profitable and the break bulk terminal as least profitable can be conclusively stated based on the analysis.

The steepness of the curves indicates that the forecasted profitability for each of the port components is clustered around the ENPV. Of the terminals, the liquid bulk terminal has the least dispersed results with a standard deviation to ENPV ratio of 3.8% and the break bulk terminal has the highest variability with a standard deviation to ENPV ratio of 16.3%. In addition, the vertical cumulative distribution curve for the warehouse in Figure 4-17 specifies that the capacity constraint is met with a probability of over 95%.

Based on the analysis of the port system in its current state, the results confirm that profitability is constrained at both the warehouse and the liquid bulk terminal. These two port components should be the focus of potential investment strategies. One approach would be to invest at the liquid bulk terminal; however the capacity measurement analysis in Section 4.1 showed that capacity is constrained along the static dimension, meaning there exists no available land for expansion. Capacity improvements can only be made through efficiency improvements via higher turns of inventory, but turns are likely under the control of the clients leasing the tanks or governed by existing contracts. In addition, the simulation model shows that a bottleneck will occur at the liquid bulk terminal with an approximate likelihood of 40%. The other approach is to invest in the warehouse. Although the capacity measurement analysis determined that the warehouse is only approaching a capacity constraint, the simulation model highlights that a bottleneck will occur with over a 95% likelihood due to an expected increase in the demand for specialized storage of certain bulk cargo. Also taking into consideration that the warehouse is the most profitable component of the port (more than 3x more profitable than the liquid bulk terminal, based on ENPV), the warehouse is the most suitable candidate for investment. The investment strategies for the warehouse are explored in the next section.

4.2.2.2 Comparison of Warehouse Investment Strategies

Having identified the warehouse as the most suitable port component for investment, the various investment strategies for the warehouse are studied. Three investment strategies for the warehouse are compared, as illustrated in Figure 4-18: leave the current single-level warehouse as is, construct a new multi-level warehouse – without flexibility to expand by adding more levels at a future time – on the land currently occupied by the existing warehouse, and construct a new multi-level warehouse – with flexibility to expand by adding more levels at a future time – on the land currently occupied by the existing warehouse.



Source: Author

Figure 4-18: Diagram of the 3 investment strategies for the warehouse

The analysis indicates that of the three investment strategies for the warehouse, the strategy of constructing a new multi-level warehouse with flexibility to expand at a later time is the best option, followed by the strategy of constructing a new multi-level warehouse without flexibility. This ranking of strategies is based on a comparison of ENPV, P_{10} and P_{90} value-at-risk, and minimum/maximum results in Table 4-7 for strategies initially built on the same scale (i.e, 4 levels).

Table 4-7: The metrics for evaluating the profitability of the warehouse investment strategies under the Mean Reversion Average Growth method

	Each Strategy's Warehouse Present Value (in USD mill.)		
Metric	As Is	Non-Flexible Expansion	Flexible Expansion
ENPV	5,287	8,810	9,015
10 percent value at risk	5,287	7,849	7,732
90 percent value at risk	5,287	9,372	10,094
Minimum result	5,143	6,392	6,397
Maximum result	5,287	9,637	11,428
Range of results	144	3,245	5,032
Standard deviation	6	622	888
Difference between median and ENPV	1	203	79

Source: Author

The difference between the ENPV of the flexible expansion strategy (not accounting for the cost of the flexible option) and the ENPV of the non-flexible expansion strategy is USD 205 mill., which is the value of the flexible option. Since the cost of the flexible option is equal to USD 24 mill., equivalent to 5% of the initial capital expenditure, it makes sense to acquire the flexible option as the option's value exceeds the option's cost. Note that the range of profitability increases under the flexible expansion strategy compared with the non-flexible expansion strategy, but the vast majority of the increase in range is due to greater upside with the flexible option (as per the maximum result and minimum result). As highlighted in Figure 4-19, a 55% probability exists that the flexible expansion strategy will provide higher profitability than the non-expansion strategy, and a 45% probability that the two strategies will provide roughly the same profitability.

Figure 4-19: The cumulative distribution curves of NPV EBITDA for the warehouse investment strategies under the Mean Reversion Average Growth method

This analysis also examines sensitivity around the cost of the flexible option, as per Lin's 2008 thesis, which applies de Neufville & Scholtes's methodology to offshore petroleum projects (Lin, 2008, p. 220). Note that a new set of simulations are run for the sensitivity analysis, the comparison is between strategies initially built on the same scale, and the forecast method used is Mean Reversion Average Growth. As shown in Table 4-8, the sensitivity analysis finds that the flexible option could cost up to 45% of the initial capital expenditure of the new warehouse and the flexible expansion strategy would still outperform the non-flexible expansion strategy, in terms of ENPV. Also notable, once the option cost exceeds 5% of the initial capital expenditure, the minimum result for the flexible expansion strategy underperforms the non-flexible expansion strategy. Further, the upside potential profitability for the flexible expansion strategy is substantially higher than for the non-flexible expansion strategy, as per the minimum result. Therefore, although ENPV for the flexible expansion strategy will outperform the non-flexible expansion strategy up to an option cost of 45% and will have greater upside profit potential, after the option cost rises above 5% the strategy also comes with greater downside risk.

Table 4-8: Sensitivity analysis around the cost of the flexible option (under the Mean Reversion Average Growth method)

Cost of Option	New Warehouse with Flexibility							New Warehouse	Current
(% of Initial Capex)	0%	5%	10%	20%	30%	40%	50%	without Flexibility	Warehouse
ENPV	9,040	9,016	8,992	8,943	8,895	8,846	8,798	8,810	5,287
Min result	6,051	6,027	6,003	5,954	5,906	5,857	5,809	6,019	5,151
Max result	11,340	11,316	11,292	11,243	11,195	11,146	11,098	9,666	5,287

All figures in USD mill.
Adapted from Lin (2008)

Analysis up to this point has compared investment strategies built on the same scale, however, a comparison should also be made between "best alternatives" (de Neufville & Scholtes, 2011, p. 56). Best alternatives for a 3 level flexible warehouse may not only be a 3 level non-flexible warehouse, but it may also be a 4 level non-flexible warehouse depending on future demand expectations. Table 4-9 summarizes the scale and profitability of competing investment strategies. Contrary to previous results, Table 4-9 indicates that a non-flexible 5 level warehouse is the most suitable investment strategy based on ENPV and value-at-risk metrics, outperforming a comparable 4 level flexible warehouse. However, the investor may consider the higher upfront capital expenditure, the useful life time horizon of the asset, and the lack of flexibility with the 5 level warehouse strategy before making a final investment-decision. The methodology, which explores the distribution of expected profitability under various uncertainties, allows the investor to consider metrics beyond just ENPV – such as value-at-risk or initial capital expenditure – that may be more relevant for a specific investor or situation.

Table 4-9: A Comparison of Flexible Expansion Strategies and Non-Flexible Expansion Strategies for the Warehouse

Number of Levels	Initial Capex*	ENPV	10% VaR	90% VaR
4	485	8,791	7,774	9,399
5	635	**9,120**	**7,742**	**10,238**
6	799	9,033	7,529	10,210
7	981	8,826	7,216	10,163
3, Flexible	366	8,836	7,477	9,879
4, Flexible	509	9,030	7,711	10,033
5, Flexible	666	9,026	7,777	10,034

All figures in USD mill. VaR = Value at Risk
* Initial Capex includes the cost of the flexible option, when applicable
Adapted from de Neufville & Scholtes (2011)

4.2.2.3 Comparison of Warehouse Investment Strategies at an Aggregate Port System Level

This section aggregates the above comparison of the investment strategies for the warehouse with the rest of the port components. The results, in Figure 4-20 and Table 4-10, provide a view of the overall port system's future profitability under each of the three investment strategies. Unsurprisingly, the results reflect the findings of Section 4.2.2.2 that show the comparision of the investment strategies at just the warehouse level. In the event that investment strategies for other port components are explored, this presentation provides the user with the most suitable manner to compare the impact on the port system's profitability under specific investment strategies and combinations of investment strategies.

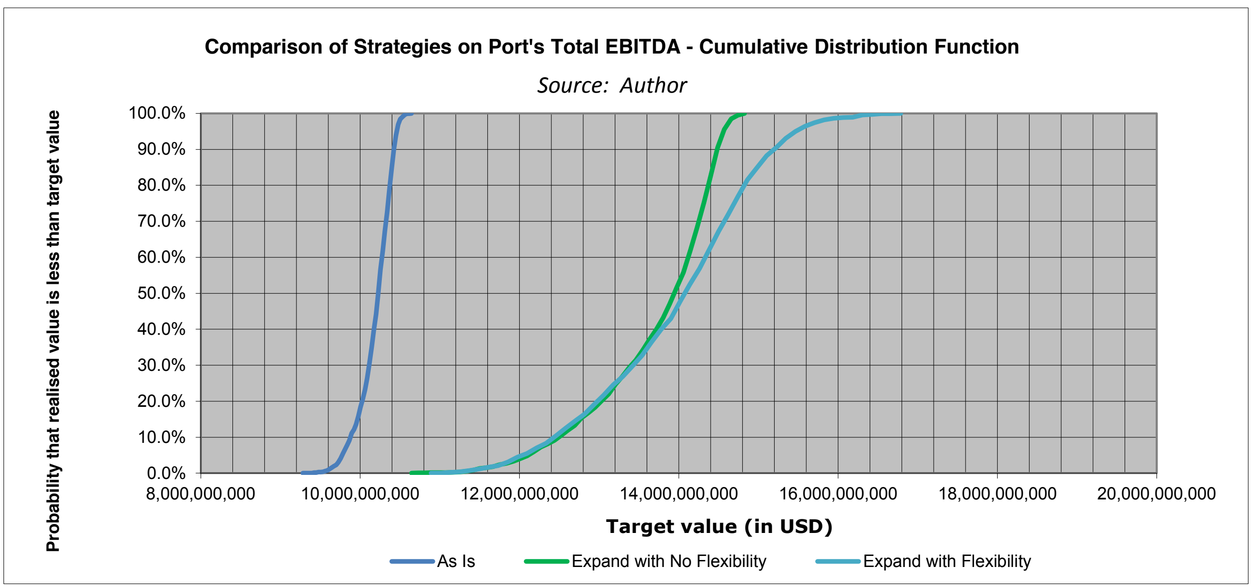


Figure 4-20: The cumulative distribution curves of NPV EBITDA for the overall port system under each of the warehouse investment strategies, using the Mean Reversion Average Growth method

Table 4-10: The metrics for evaluating the profitability of the overall port system under each of the warehouse investment strategies, using the Mean Reversion Average Growth method

	Each Strategy's Aggregate Present Value (in USD mill.)		
Metric	As Is	Non-Flexible Expansion	Flexible Expansion
ENPV	10,189	13,694	13,938
10 percent value at risk	9,865	12,437	12,334
90 percent value at risk	10,421	14,400	15,102
Minimum result	9,281	10,644	10,891
Maximum result	10,643	14,827	16,786
Range of results	1,362	4,183	5,896
Standard deviation	210	789	1,049
Difference between median and ENPV	38	248	137

Source: Author

5. Discussion

The data analysis in Chapter 4 provides the supporting evidence for the key findings and recommendations provided in this section. Based on the application of the methodologies and the research results in this thesis, key findings are first presented, followed by suggested refinements to Lagoudis and Rice's existing methodology for port capacity measurement and to de Neufville and Scholtes's existing methodology for evaluating investment strategies under uncertainty. The chapter closes with a presentation of steps as part of an investment decision-making process developed based on the research.

5.1 Key Findings from the Research

The key findings from the data analysis, which involved the application and modification of existing methodologies, are detailed below.

5.1.1 Key Findings from Methodology for Measuring Port Capacity

The existing methodology for the measurement of a port system's capacity is the foundation for the research in this thesis. The methodology, modified in this thesis, provides a standard, straight-forward approach to measure capacity across port components and terminal types and to identify capacity constraints throughout the port system. Key findings through the application of this methodology are as follows:

- The methodology tested at the case study port confirms that the existing methodology developed by Lagoudis & Rice, as modified, can be extended beyond the container terminal to measure the capacity of other components and terminal types within a port system. The methodology provides a uniform, robust approach for measuring both theoretical and actual capacity along the static and dynamic dimensions. The application of this methodology allows for the identification of bottlenecks across a port system and supports the objective of this thesis by laying the groundwork for the development of an investment decision-making tool.
- Using the methodology for port capacity measurement, three port components at the case study port were identified as current bottlenecks, as follows:
  - The container terminal berths with a utilization equal to 275% of the static capacity and 160% of the dynamic capacity. The container berths may be able to handle more vessels than the calculated capacity due to lower turnaround times than the estimated average

and/or shorter vessel lengths than the estimated average (considering that the container berths are capable of handling more than one ship at a time).

    - The dry bulk terminal yard (in terms of mass) with a utilization equal to approximately 80% and 100% of the theoretical and actual capacity, respectively, along both the static and dynamic dimensions. The results indicate that the dry bulk terminal is operating at the threshold where the yard becomes congested.
    - The liquid bulk terminal yard (in terms of both mass and volume) along the static dimension with a utilization equal to 97% of theoretical capacity and 100% of actual capacity. The results highlight that all available storage tanks are fully utilized.

- By applying the methodology, the analysis revealed 3 port components that were approaching bottleneck status, as follows (beginning with the earliest likely bottleneck):
    - The break bulk terminal's warehouse (in terms of mass) with a utilization of 86% of actual static capacity and 89% of actual dynamic capacity. The break bulk terminal's warehouse is projected to become a bottleneck in 2.5 years along the dynamic dimension (assuming a 5.0% annual growth rate) or in 2.0 years if assuming a 6.0% annual growth rate.
    - The dry bulk terminal's warehouse (in terms of mass) with a utilization of 82% of actual capacity along both the static and dynamic dimensions. The dry bulk terminal's warehouse is forecasted to be a

bottleneck in 4.0 years (assuming a 5.0% annual growth rate) or in 2.0 years if assuming a 10.2% annual growth rate.

- The container terminal yard with a utilization equal to 61% of theoretical capacity and 81% of actual capacity along both the static and dynamic dimensions. The container terminal yard is projected to be constrained in 2.9 years (assuming a 5.0% annual growth rate) or in 2.0 years if assuming a 7.5% annual growth rate. The container equipment – ship-to-shore cranes and RTGs – are also approaching their capacity constraints, however the container yard will become the bottleneck first at the container terminal.

- During adverse weather conditions, various port operations are temporarily shutdown. The impact of this compulsory downtime results in the loss of port capacity, which was accounted for in the port capacity calculations. The annual downtime at the case study port related to adverse weather conditions was as follows:
  - 8.5 days at the container terminal yard, which reduces the theoretical dynamic capacity by 97,920 TEU annually, or 2.4%, and reduces the actual dynamic capacity by 68,544 TEU annually, or 2.3%.
  - 2.4 days for the dry bulk terminal yard, which reduces the theoretical dynamic capacity by 99,208 mt or 3,021,543 m^3 annually (0.7%) and reduces the actual dynamic capacity by 79,361 mt or 2,417,234 m^3 annually (~0.7%).
  - 2.4 days for the break bulk terminal yard, which reduces the theoretical dynamic capacity by 119,042 mt or 3,021,543 m^3 annually

(0.7%) and reduces the actual dynamic capacity by 95,234 mt or 2,417,234 m^3 annually (0.7%).

5.1.2 Key Findings from Methodology for Evaluating Investment Strategies

The existing methodology for the evaluation of potential investment strategies under uncertainty provides the framework for the investment decision-making process in this thesis. The methodology, modified in this thesis, confirms the presence of potential bottlenecks in the port system, assists in selecting potential investment strategies for investigation, and provides a clear approach for comparing and ranking port infrastructure investment strategies under multiple uncertain futures. Flexible options are of value among investment strategies with similar initial scale and may continue to be of value even when the cost is equal to a substantial portion of the initial capital expenditure. However, the investor must carefully consider best alternative investments (such as larger, but comparable, non-flexible strategies) as well as the investment parameters prior to selecting a definitive investment strategy. Key findings through the use of this methodology are as follows:

- The successful application of the methodology for evaluating investment strategies under uncertainty at the case study port achieved the remaining two objectives of this thesis: 1) to thoroughly investigate potential investment strategies, characterized by large capital expenditures, under various scenarios of uncertainty, and 2) to develop an investment decision-making tool for the identification and selection of potential investment strategies that enhance the port's overall profitability and increase the port's capacity.

- A simulation screening model confirmed the presence of future bottlenecks within the case study port's system – bottlenecks first identified through the bottom-up screening model for port capacity measurement – as the liquid bulk terminal and the warehouse. The vertical cumulative distribution curves, which described the range of a port component's future profitability (in terms of ENPV of EBITDA), highlighted whether a port component's capacity was constrained. Based on the results of the analysis, a bottleneck occurred at the liquid bulk terminal with a probability of roughly 40%, while a bottleneck occurred at the warehouse with a probability of over 95%.
- Following the identification of the bottlenecks at the case study port, the comparison of the port components' profitability assisted with the selection of potential investment strategies for further investigation. Based on the projection that the warehouse is to be 3x more profitable than the liquid bulk terminal, in combination with the warehouse's higher likelihood (95%) of a bottleneck occurring under future forecasted demand than the liquid bulk terminal's likelihood (40%), a decision was made to further examine the potential investment strategies related to the warehouse. The potential investment strategies for the warehouse selected for further evaluation were the following: the current warehouse, a new multi-level warehouse without flexibility to add more levels in the future, and a new multi-level warehouse with flexibility to add more levels in the future.

- Future forecasted demand was determined through the use of three forecasting methods (described in Section 3.2.1.1): the Mean Reversion Average Growth method, the Random Walk method, and the Mean Reversion Exponential Smoothing method. In comparing the methods, the analysis revealed that the profitability results under the Mean Reversion Average Growth method and the Mean Reversion Exponential Smoothing method followed a more similar cumulative distribution curve than the profitability results under the Random Walk method, which amplified the variability of the profitability results. The study of the Random Walk method also revealed that a flexible option (i.e., an option to expand further at a later date) is more valuable for investment decisions where the future performance is more uncertain.
- Based on the analysis, the optimal investment strategy was the 5 level non-flexible warehouse, outperforming a comparable 4 level flexible warehouse by an ENPV of USD 90 mill. and with better 10% and 90% value-at-risk results. However, the investor should also consider other factors, such as the higher upfront costs, the useful life of the asset, and the lack of flexibility with the 5 level warehouse strategy, before making a final investment decision.
    - Based on an analysis of investment strategies built to the same scale initially (i.e., same number of levels), the investment strategy with the flexible option was preferable to the investment strategy without flexibility. The flexible option was valued at USD 205 mill. with a cost of just USD 24 mill., equal to 5% of the initial capital expenditure.

There was a 55% probability that the flexible warehouse strategy would be more profitable than the non-flexible warehouse strategy and a 45% probability that the the two strategies would result in similar profitability (i.e., greater upside and no additional downside risk).

- A sensitivity analysis around the cost of the flexible option highlighted that the flexible option cost could rise to 45% of initial capital expenditure and still provide more upside potential for profitability than the non-flexible investment strategy, however with greater downside risk once the option cost exceeded 5% of initial capital expenditure.

5.2 Recommended Refinements to Existing Methodologies

As described previously, the existing methodologies have been modified to conduct the analysis in this thesis. Recommended refinements to these existing methodologies are decribed below.

5.2.1 Refinements to Existing Methodology for Measuring Port Capacity

Through the thesis research, the methodology is enhanced to provide more accurate results, additional information and clarity. As such, the following revisions are proposed:

- Where applicable, capacity measurements should be compared ideally along the dynamic dimension – as opposed to a static vs. dynamic comparison – to capture the factors (e.g. cargo dwell time, equipment efficiency) that impact capacity over a period of time. In addition, the period of time for the comparison of components should be uniform. For example when measuring the capacity of a terminal, the terminal yard and the equipment should be compared along the dynamic dimension over the same period of time.

- Based on the extended application of the existing methodology at the case study port, specific capacity measurement formulas developed for the existing methodology (as stated in Appendix 4) should be revised as per Table 3-1, and as detailed below:
    - Anchorage: The calculation of the area needed by average ship size to be revised to include the safety clearance between anchored vessels. The capacity measurement should consider that the designated anchorage area may be shared with vessels that do not call at the port system being evaluated.
    - Waterway: The formula for waterway capacity to be revised to include the safety clearance between vessels traveling along the waterway. The actual capacity measurement to be revised to account for a capacity reduction should the waterway be shared with ports that have vessels that do not call the port system being evaluated.
    - Berth / Quay: The calculation of the average vessel size to be revised to include the safety clearance between the vessels docked at the berths.
    - Terminal: The capacity of the terminal should be determined by comparing the terminal yard and equipment along the dynamic dimension, as mentioned above. The individual port components in

this comparison (i.e., yard and equipment) can first be assessed on a standalone basis along the static and dynamic dimensions.

  - Liquid bulk terminal: The calculation is to be flipped to express capacity in terms of mt per square meter (sq. m), instead of sq. m per mt. This revised presentation of capacity more clearly expresses the efficient use of the available land. A mt of liquid bulk storage does not require a specific number of square meters; rather the volume of the tanks, the density of the cargo stored, and the number of inventory turns over a period of time determine the cargo stored per available land area (mt per sq. m).
  - Dry bulk & break bulk terminals and warehouses: Calculations to be made in terms of both mass and volume, as bottlenecks will emerge at different times depending on the density of the cargo. Note that contracts for handling this type of cargo at the port may likely be based on the lower of mass and volume.

- Equipment: The theoretical capacity should be based on the designed capacity – not the operational capacity – of the equipment at replacement. For simplicity, the data analysis assumes the designed capacity at replacement is equal to the designed capacity of the current equipment, as opposed to the designed capacity of the newest version of the equipment, with latest technology, that could replace the current equipment.

    - Rail network: The calculations for the rail network to be revised to include factors such as safety clearance between cars when determining train length, stacking policy of train (i.e, single-stacked vs. double-stacked), unloading/loading time per train, and the roundtrip distance traveled by the train from the port to the nearest rail interchange.

- The methodology should also include calculations that provide a reference as to how long until a bottleneck may be expected to emerge at a port component, as shown in the capacity measurement figures in Section 4.1 and Table 4-3 in Section 4.1.6. The existing methodology identifies the capacity at the port component with a comparison to the current utilization to determine if a bottleneck currently exists. However, the results lead to the question: how long until the bottleneck will be reached, in other words, when does the port need to address the capacity constraint – either by efficiency improvements or investment? In this thesis, two reference calculations are provided: 1) the amount of time until a bottleneck is reached given an annual growth rate (5% in this thesis), and 2) the average annual growth rate required for the port component to become a bottleneck within a defined time period (two years in this thesis). The rate and time period used for these reference calculations can be adjusted to fit the port's situation.

5.2.2 Refinements to Existing Methodology for Evaluating Investment Strategies

Through the thesis research, the methodology is enhanced to provide more accurate results, additional information and clarity. As such, the following revisions are proposed:

- The simulation screening model for a port system should include an evaluation of each port component contributing to profitability, as well as the evaluation of these port components at an aggregated port system level. The aggregation of the port components on a port system level allows for comparison and ranking of investment strategies on both a standalone basis and in combination with one another.
- ENPV should be equal to the discounted cash flow of the long-lived asset (for the defined time horizon and which does not include the perpetuity value) minus the initial capital expenditures and the real option cost of flexibility. In the simulation screening model, the real option cost of flexibility is to be deducted, along with initial capital expenditures, from ENPV as shown in the histogram and cumulative distribution curve on the 'Expand Option Sim' tab.

  Although the value of the flexible option is based on ENPV calculations that do not account for the cost of the flexible option (NPV of EBITDA minus initial capital expenditures), when evaluating the flexible investment strategy's ENPV, the cost of the flexible option should be deducted as well (NPV of EBITDA minus initial capital expenditures minus flexible option cost). The reason for the deduction of the flexible option cost from ENPV when evaluating the investment strategy is that the cash flows cannot be generated in this strategy without the flexible option being exercised (i.e., the structure must be built with a reinforced foundation in order to have the ability to expand vertically later). The spreadsheet model for the parking garage case example (de Neufville et al., 2006), which is the basis for the model used in this thesis, did not appear to deduct the real option cost of flexibility from ENPV.

5.3 Presentation of Investment Decision-Making Process

The research has provided a framework for the investment decision-making process for port infrastructure, as highlighted by Table 5-1, below. The steps followed in order lead to the selection of optimal investment strategies to address capacity constraints within a port system.

Table 5-1: Proposed Investment Decision-Making Process for Port Infrastructure

Step No.	**Investment Decision-Making Process**
1)	Identify the port components that make up the port system.
2)	Identify the universe of current and potential bottlenecks within the port system by applying the proposed methodology for measuring port capacity (Section 3.1). Theoretical and actual capacity along the static and dynamic dimensions should be calculated using the formulas in Table 3-1, and compared to utilization.
3)	Identify the primary trends and trend-breakers that may potentially impact throughput demand over the forecast period. Use a top-down screening model for assistance, if necessary.
4)	Input assumptions and uncertainties into the simulation screening model and run the Monte Carlo simulations to generate profitability results.

5)	Select the key port components requiring examination of potential investment strategies, based on these steps: a) Simulation screening model confirms the results of the port capacity measurement methodology that the port component will be a bottleneck during the forecasted period. b) The bottleneck at the port component can be feasibly addressed through additional investment. c) Two factors should be considered simultaneously: • The forecasted profitability of the key port components clearly rank higher than other constrained port components being considered for investment. • The cumulative probability curve indicates that there is a reasonable probability of the bottleneck of the key port components occurring over the forecasted period. Should there be ambiguity in choosing one key port component for evaluation of potential investment strategies over another key port component, all relevant choices should proceed for further investigation.
6)	Determine the potential investment strategies for evaluation in the simulation screening model. Investment strategies may include the port component in its current state, non-flexible expansionary investment, and flexible expansionary investment. Further, the potential investment strategies may be evaluated on a standalone basis or in combination with one another.
7)	Input assumptions for potential investment strategies into the simulation screening model and generate a new set of profitability results.
8)	Compare the generated results across the profitability metrics for the potential investment strategies and select the optimal solution based on these steps: a) An optimal strategy for similar scale investment strategies may be determined by comparing the ENPV and relevant profitability metrics of the potential investment strategies and ranking the investment strategies. b) Compare the optimal strategy selected in the previous step with best alternative investment strategies (i.e., similar, but different scale investment strategies) along relevant profitability metrics, as shown in Table 4-9. A change of assumptions and additional simulation runs may be necessary to represent the best alternative investment strategies in the simulation model. c) Select the optimal investment strategy, while considering factors such as initial capital expenditure, useful life of asset, and future flexibility needs.

Source: Author

6. Conclusion

This final chapter provides an overview of the work covered in this thesis paper. A summary is provided, followed by suggestions for further research.

6.1 Summary

The investment in port infrastructure is critical to maintain the necessary capacity for an efficiently functioning port system and to meet expected demand growth for all types of cargo. However, these large-scale, expensive investments in long-term infrastructure assets must be made despite a variety of future uncertainties that may potentially influence a port's throughput demand. The objective of this thesis was to enhance the investment decision-making process for port infrastructure through the application and modification of existing methodologies and the development of an investment tool or an investment decision-making process. The motivation for this thesis was to 1) extend and refine the two main existing methodologies used in the research, 2) evaluate potential investment strategies under uncertainty, and 3) both improve the profitability and increase the capacity of the case study port, which is located in Southeast Asia.

Following a summary of past research as it pertained to the respective port components, the existing methodologies that form the basis for this thesis were introduced and described. The first methodology used in the data analysis was a modification of the existing methodology for the measurement of port capacity, recently developed by Lagoudis and Rice (Lagoudis & Rice, 2011). The theoretical and actual capacity of the case study port system's components were measured along the static and dynamic dimensions for the purpose of identifying current and potential capacity constraints within the port system. As highlighted in Table 4-3, the application of the methodology revealed 7 current or potential bottlenecks among the 22 port components at the case study port, using this bottom-up screening model.

The second methodology used in the data analysis was a modification of the existing methodology for the evaluation of investment strategies under uncertainty developed by de Neufville and Scholtes (de Neufville and Scholtes, 2011), and earlier applied to a parking garage (de Neufville et al., 2006) and an offshore petroleum project (Lin, 2008). The methodology identified three scenarios of uncertainty possibly impacting future performance of the case study port. A modified version of the Excel speadsheet model used in the aforementioned parking garage example (de Neufville et al., 2006) was developed as the simulation screening model. The simulator used Monte Carlo simulations to forecast the profitability of each port component (the warehouse being the most profitable and the break bulk terminal being the least profitable), displaying the results graphically as cumulative distribution curves.

Based on the simulation results, which also confirmed the findings under the port capacity measurement methodology, the warehouse was selected as the constrained port component for which potential investment strategies would be evaluated under uncertainty. Three potential investment strategies were selected: the warehouse in its current state, a new multi-level warehouse without flexibility for future expansion, and a new multi-level warehouse with flexibility for future expansion. The profitability metrics highlighted that the investment strategy for a new 4 level warehouse with a flexible option was the optimal choice when compared with strategies of similar scale (i.e., number of levels). However, when the investment strategy for a 4 level warehouse with a flexible option was compared with its best alternatives (i.e., comparable strategies, but not on the same scale) in Table 4-9, the optimal investment strategy was actually for a non-flexible 5 level warehouse (although other factors should also be considered prior to reaching a final investment decision).

Based on the research, both existing methodologies were successfully modified and applied to determine the optimal investment strategy. The finding that a non-flexible investment strategy was the best choice does not contradict de Neufville and Scholtes's assertion for flexibility in engineering design, as de Neufville and Scholtes indicate that investment strategies with flexible options can often – not always – increase value compared with non-flexible strategies under uncertainty (de Neufville & Scholtes, 2011, p. 39). In addition, the results of the data analysis in this thesis are in line with the statement that "flexible designs often cost less than inflexible designs" (de Neufville & Scholtes, 2011, p. 57).

Finally, based on the successful application of the methodology put forward in this thesis – the combination of two modified existing methodologies to select the optimal investment strategy for addressing a port system's capacity constraints – a set of investment decision-making steps for port infrastructure were developed.

Moreover, recommended refinements to the existing methodologies were proposed. Ultimately, the research in this thesis paper meets the goals set out in the introduction of this paper and achieves the objective: to enhance the investment decision-making process for port infrastructure through the application and modification of existing methodologies and the development of an investment tool and an investment decision-making process.

6.2 Further Research

This thesis applies, for the first time, the capacity measurement methodology developed by Lagoudis and Rice across terminal types, as well as a modified model based on the investment decision-making under uncertainty methodology developed by de Neufville and Scholtes. Further opportunities exist to test, extend and improve the methodology applied in this thesis, as follows:

- Further evaluate and refine the methodology put forward in this thesis through its application to several other multi-purpose ports by both academic and industry professionals.
- Extend the capacity measurement methodology to those port components and terminal types that were not tested in this thesis. Port components for examination include port terminal gates, rail connectivity such as rail terminal gates and rail yards (in addition to the rail network), and the road network; terminal types include ro-ro (rolling-on, rolling-off cargo, such as vehicles), cruise, and passenger ferry terminals.

- Test the methodology for the impact of addressing bottlenecks through efficiency improvements, such as additional training to increase the skill level of the labor force. The research in this thesis focuses on the impact of large investments to address the port system's capacity constraints.
- Test the investment decision-making model based on de Neufville and Scholtes's methodology for other types of investment strategies, with and without flexible options. As it relate to this thesis, exploration of investment strategies such as the construction of a dry container port with flexible options (considering the recent improvements to the national rail network) or switching focus toward gaining a larger share of the region's oil & gas services market – primarily served by Singapore currently – may be of value.
- Incorporate other types of uncertainty for investigation under the investment decision-making methodology. For example, the methodology may be tested for the impact of various financial uncertainties such as interest rates, inflation rates, and types and timing of available financing (e.g., available credit during economic cycles or a comparison of traditional Western bank financing vs. risk sharing (i.e., Islamic financing) that may also differ in terms of region). In regard to this thesis, the latter financial uncertainty may be of particular interest considering the region's large Muslim population and centers of expertise for Islamic finance.

Appendices

Appendix 1	Distribution Selection used in Forecasting Methods
Appendix 2	Capacity Measurement Charts for the Port Components
Appendix 3	Results and Comparisons of the 3 Forecasting Methods
Appendix 4	Capacity Calculations from Rice & Lagoudis's Existing Methodology

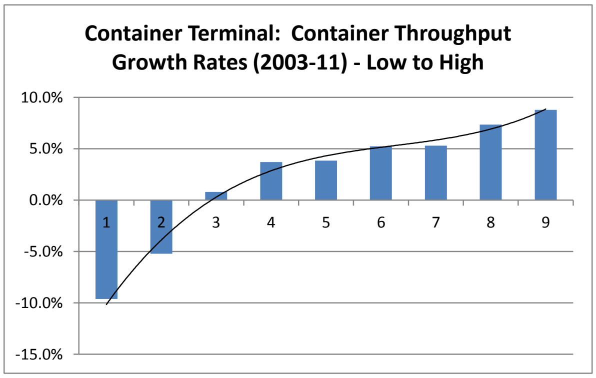
Appendix 1: Distribution Selection used in Forecasting Methods

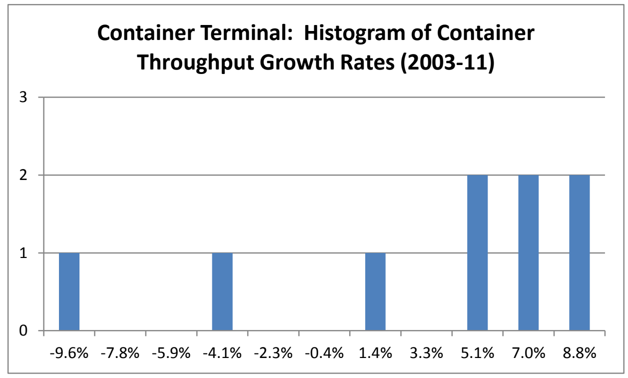
As mentioned in Section 3.2.1.1, a normal distribution was selected for use in the three forecasting methods to represent the dispersion of cargo growth rates in the forecasting methods. The selection of a distribution is subjective. Demand for cargo at the case study port may also be represented by a lognormal distribution or triangular distribution (or other distributions) using @Risk software. A 2009 academic paper by Ding & Teo argues that containerized cargo throughput follows a lognormal distribution based on an analysis of the 300 top global container ports (Ding & Teo, 2009).

According to DeGroot and Schervish's book, *Probability and Statistics,* a lognormal distribution is defined as "if log(X) has the normal distribution with mean μ and variance σ^2, we say that X has the lognormal distribution with parameters μ and σ^2" (DeGroot & Schervish, 2012, p.312). While a normal distribution is characterized by a probability distribution function that resembles a bell-curve where the mean (i.e. the average) and mode (i.e., the 50th percentile) are centered at the peak probability and the curve is "symmetric about the mean" (Bertsimas & Freund, 2004, p. 120), a lognormal distribution is also a continuous distribution, but characterized by a probability distribution function with a positive skew that has the majority of the distribution, or peak probability, shifted to the left; in other words, the mode is to the left of the mean.

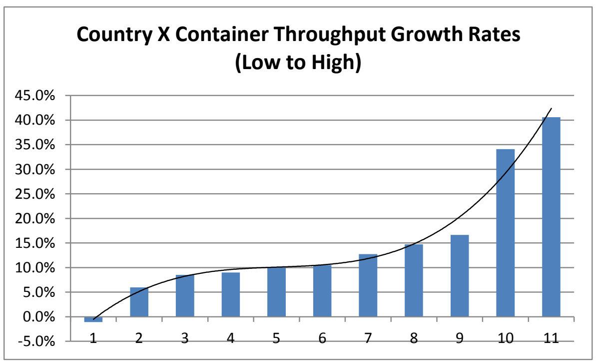
The lack of available historical throughput data for the case study port presents a challenge for accurately representing the distribution of the demand growth driving cargo throughput. In addition, each cargo type may have its own distribution. The thesis author acknowledges there may be other distributions that may be a more suitable fit for the cargo throughput.

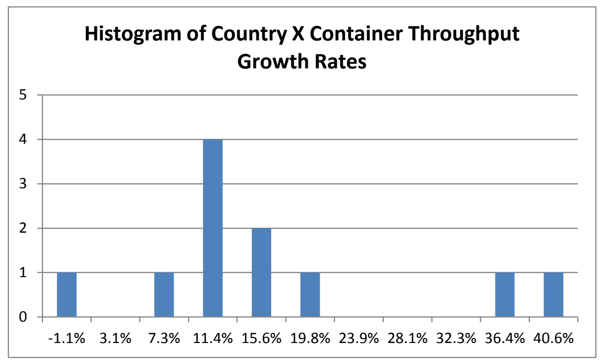
Based on an analysis of an approximate 10-year historical data set of throughput for the case study port's various terminals and a long-term throughput historical data set for certain cargoes globally (Figures A1-1 to A1-5), the thesis selects a normal distribution to represent (along with mean reversion to an underlying projected trend) the variability of demand for cargo throughput in the simulation model. A case for a normal distribution of cargo throughput at four of the five port components (with the exception of the liquid bulk terminal) can be made based on the historical data. For consistency with the distribution at the other terminals, a normal distribution is used in the analysis of the liquid bulk terminal.





Source: Case study port management (based on disguised figures)

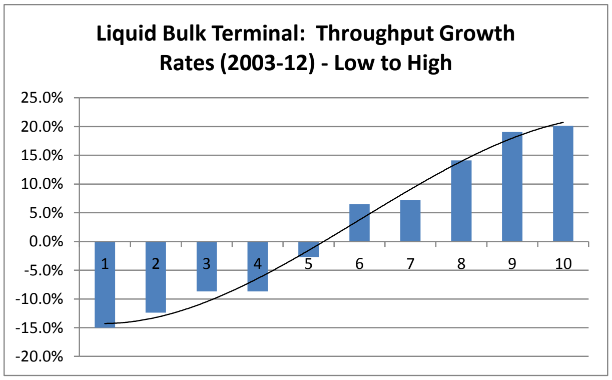


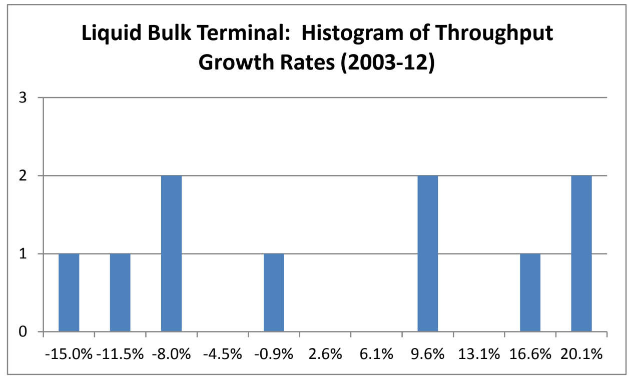


Source: Disguised

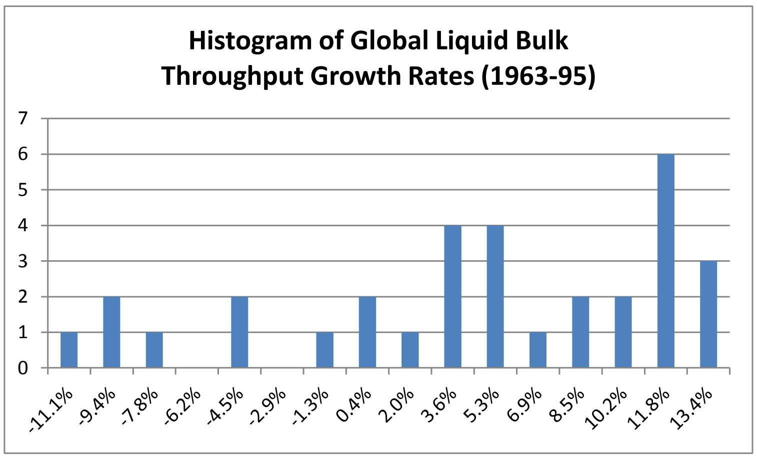
Figure A1-1: Container throughput historical data sets and histograms

The container terminal throughput data for the case study port has an average of 2.3%, a standard deviation of 5.7%, and does not appear to follow a normal distribution. The Country X container throughput data has an average of 14.7%, a standard deviation of 11.6%, and appears to represent a normal distribution. No outliers are removed from the data. Trendlines are polynomial of the 3rd order.





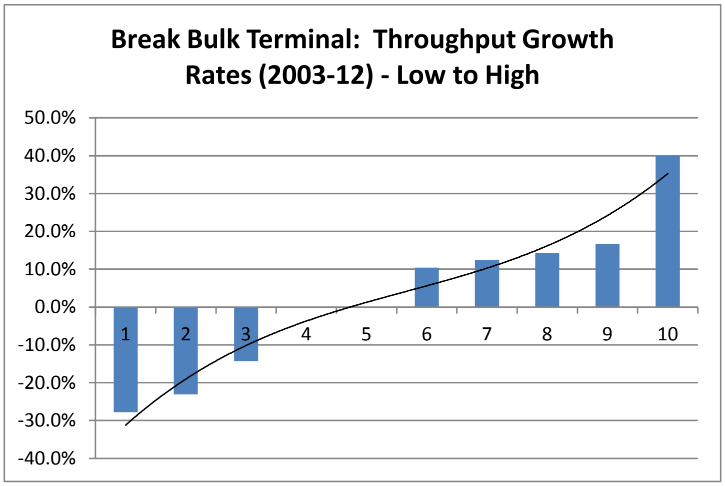
Data Source: Case study port management (based on disguised figures)

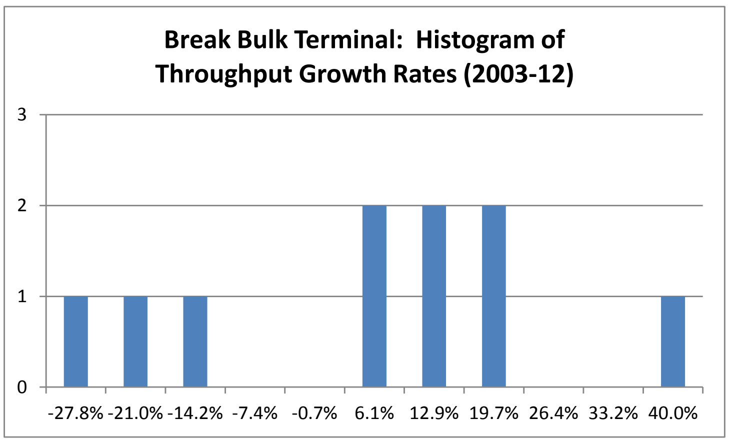


Data Source: Fearnleys Review, Table 1 – Oil + Oil Products, cited in Maritime Economics (Stopford, 1997, p. 520)

Figure A1-2: Liquid bulk throughput historical data sets and histograms

The liquid bulk terminal throughput data for the case study port has an average of 2.0%, a standard deviation of 12.5%, and does not appear to follow a normal distribution. The global liquid bulk throughput data has an average of 3.9%, a standard deviation of 7.1%, and does not appear to follow a normal distribution. No outliers are removed from the data. Trendlines are polynomial of the 3rd order.

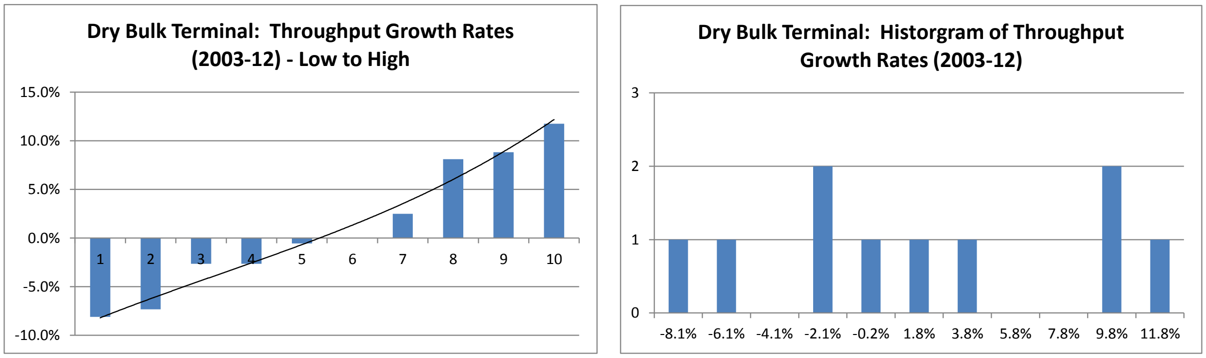




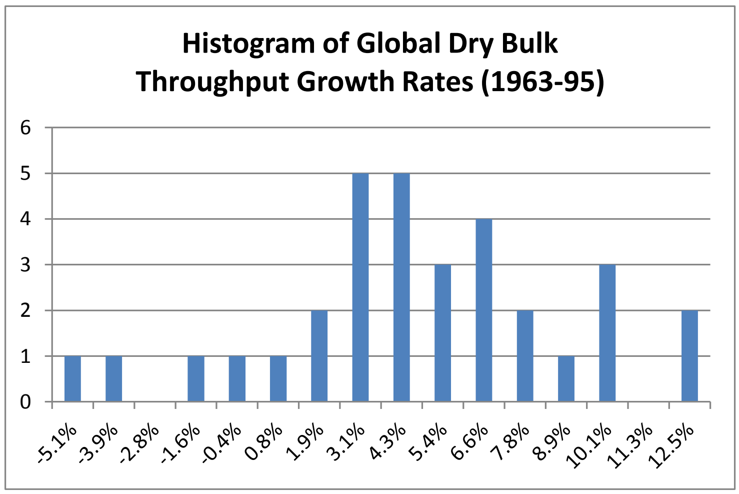
Data Source: Case study port management (based on disguised figures)

Figure A1-3: Break bulk throughput historical data sets and histograms

The break bulk terminal throughput data for the case study port has an average of 2.9%, a standard deviation of 19.4%, and may appear to follow a normal distribution. No outliers are removed from the data. Trendlines are polynomial of the 3rd order.



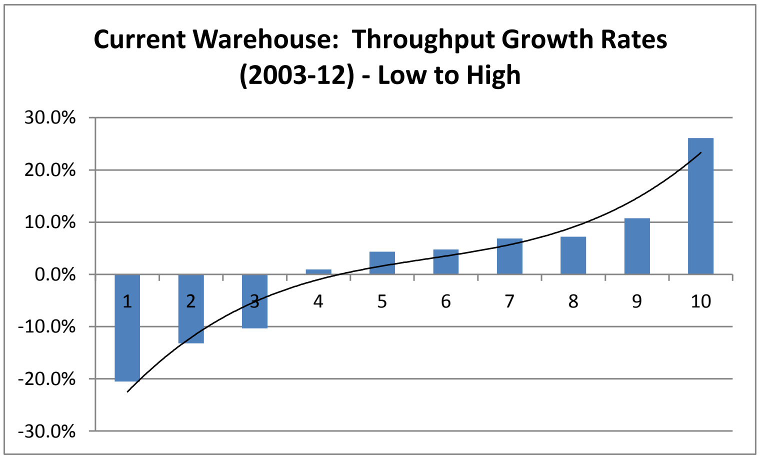
Data Source: Case study port management (based on disguised figures)

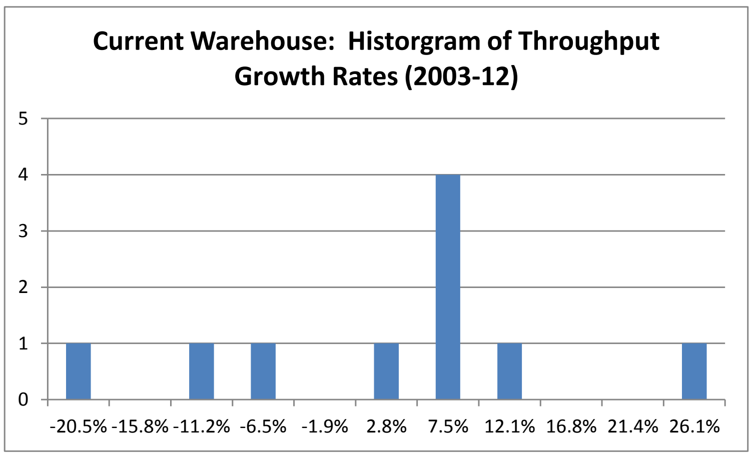


Data Source: Fearnleys Review, Table 1 – Total Dry Cargo, cited in Maritime Economics (Stopford, 1997, p. 521)

Figure A1-4: Dry bulk throughput historical data sets and histograms

The dry bulk terminal throughput data for the case study port has an average of 1.0%, a standard deviation of 6.4%, and does not appear to follow a normal distribution. The global liquid bulk throughput data has an average of 4.3%, a standard deviation of 4.1%, and appears to represent a normal distribution or lognormal distribution. No outliers are removed from the data. Trendlines are polynomial of the 3rd order.





Data Source: Case study port management (based on disguised figures)

Figure A1-5: Current warehouse throughput historical data sets and histograms

The current warehouse throughput (i.e., cargo for temporary storage) data for the case study port has an average of 1.7%, a standard deviation of 12.7%, and appears to represent a normal distribution. The global dry bulk throughput data, which appears to represent a normal distribution or lognormal distribution, provides further support. No outliers are removed from the data. Trendlines are polynomial of the 3rd order.

Appendix 2: Capacity Measurement Charts for the Port Components

The thesis paper provided the key capacity measurement for each of the port components. This appendix presents the additional capacity measurements for the port components.

<u>Liquid Bulk Berth:</u>

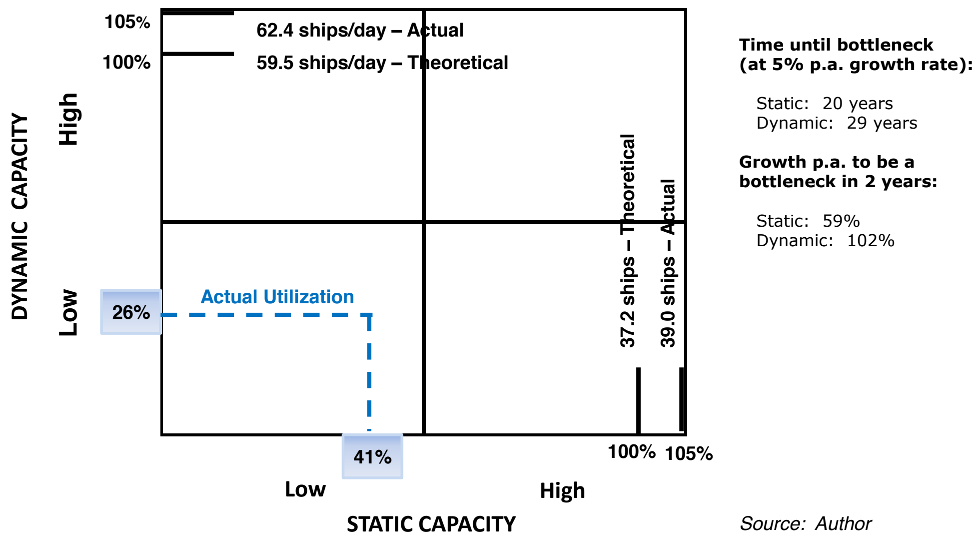


Figure A2-1: Capacity measurement of the liquid bulk berth along the static and dynamic dimensions

<u>Dry Bulk Berth:</u>

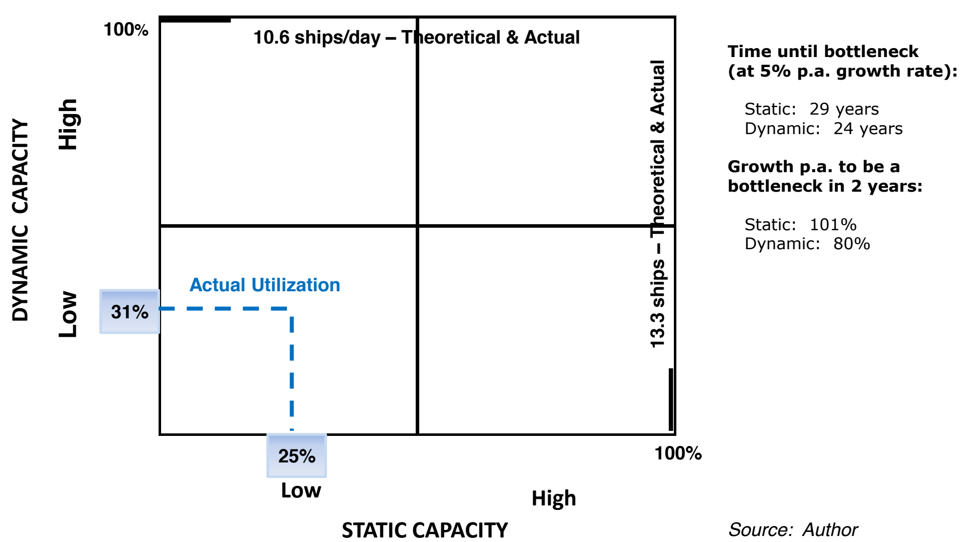
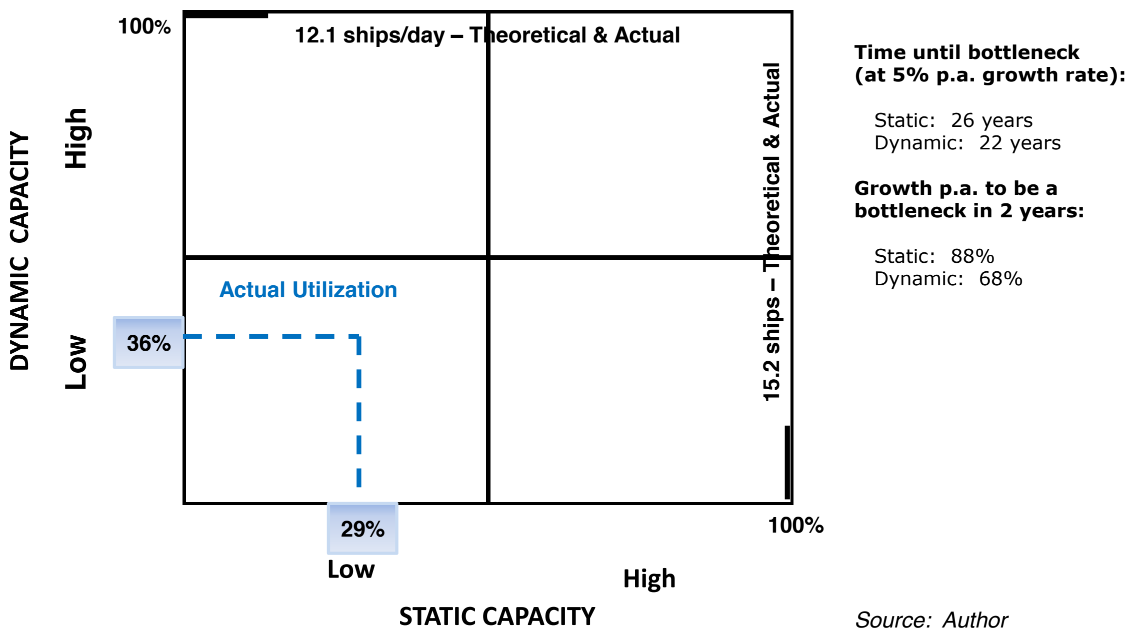


Figure A2-2: Capacity measurement of the dry bulk berth along the static and dynamic dimensions

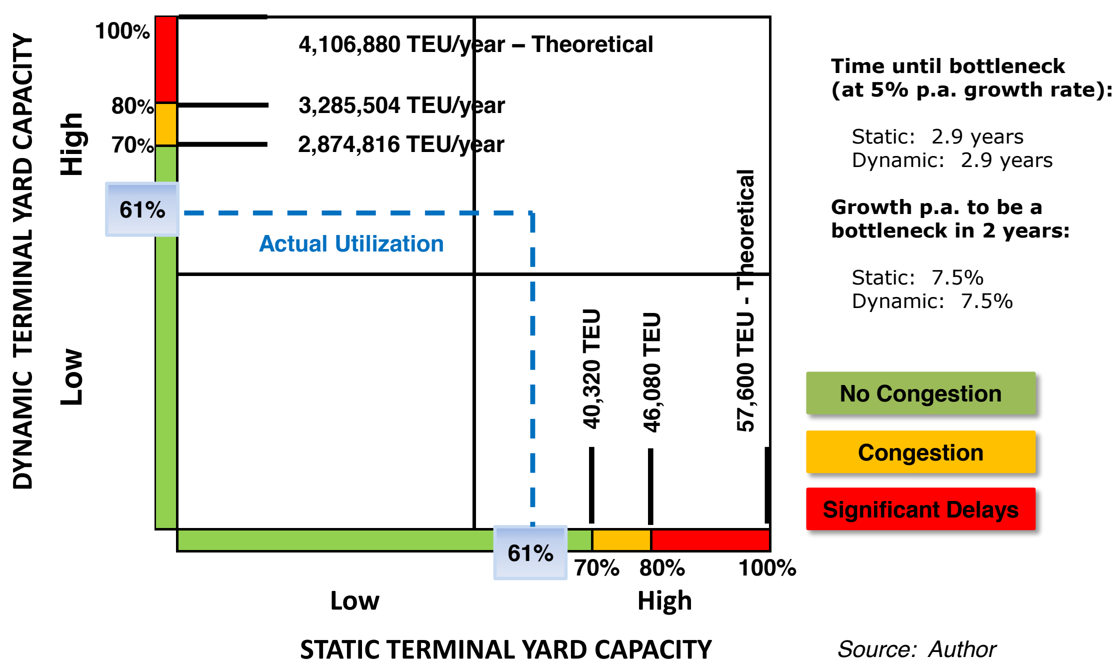
Break Bulk Berth:



Source: Author

Figure A2-3: Capacity measurement of the break bulk berth along the static and dynamic dimensions

Container Terminal Yard & Equipment:



Source: Author

Figure A2-4: Capacity measurement of the container terminal yard along the static and dynamic dimensions

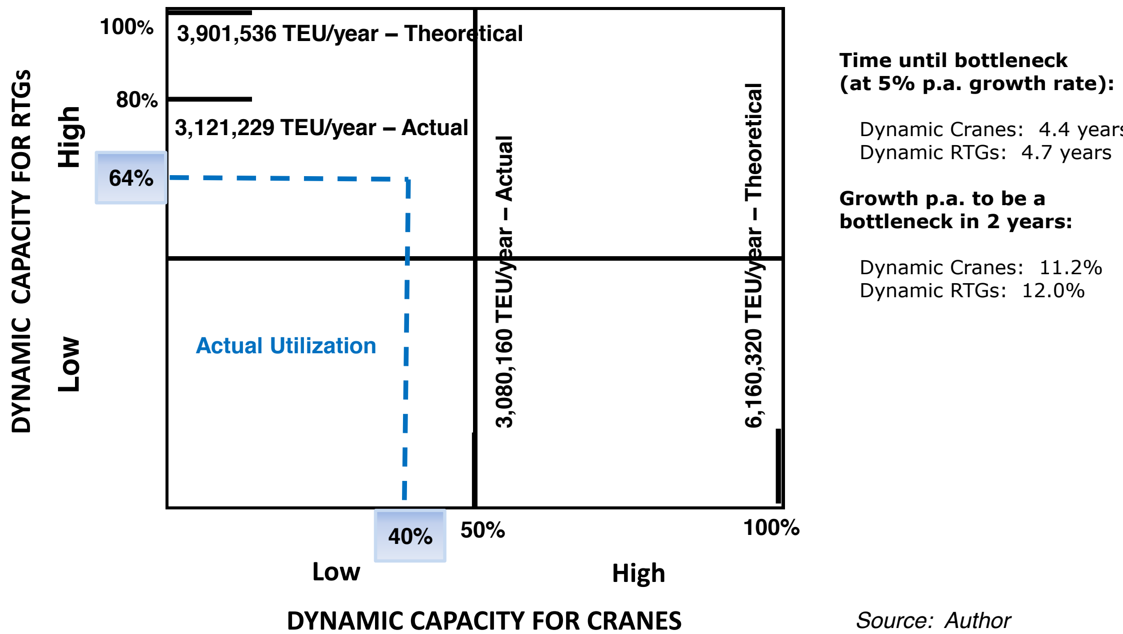


Figure A2-5: Capacity measurement of the container equipment along the dynamic dimension for ship-to-shore cranes and RTGs. Based on the actual dynamic capacity, the cranes will become a bottleneck just before the RTGs do.

Liquid Bulk Terminal:

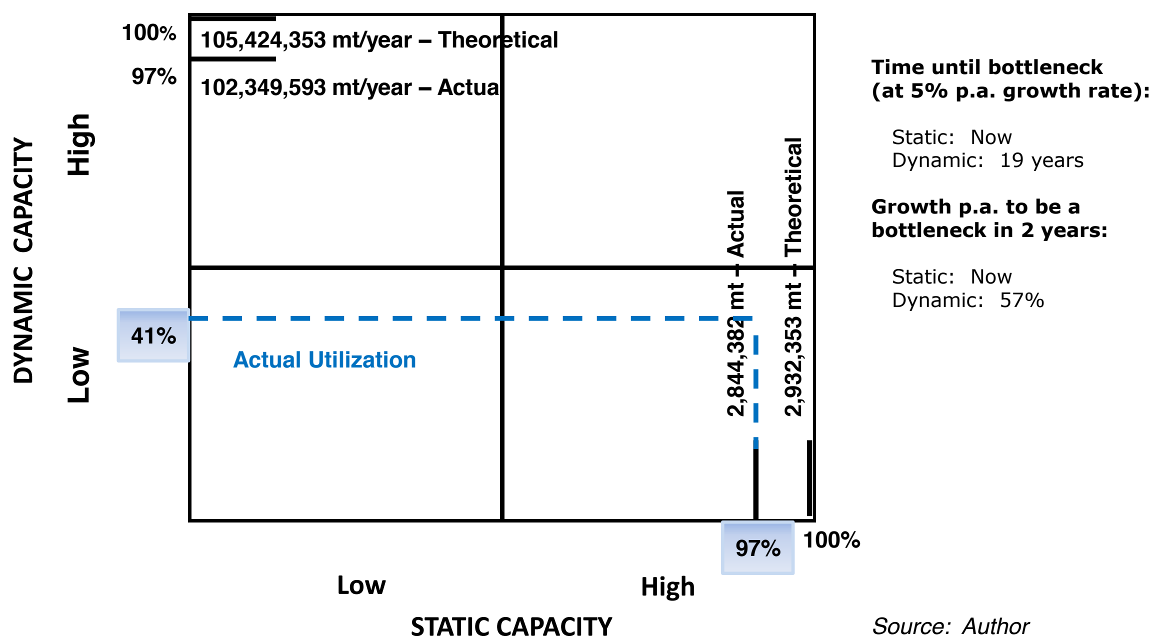


Figure A2-6: Capacity measurement of the liquid bulk terminal yard along the static and dynamic dimensions (based on mass)

Dry Bulk Terminal & Warehouse:

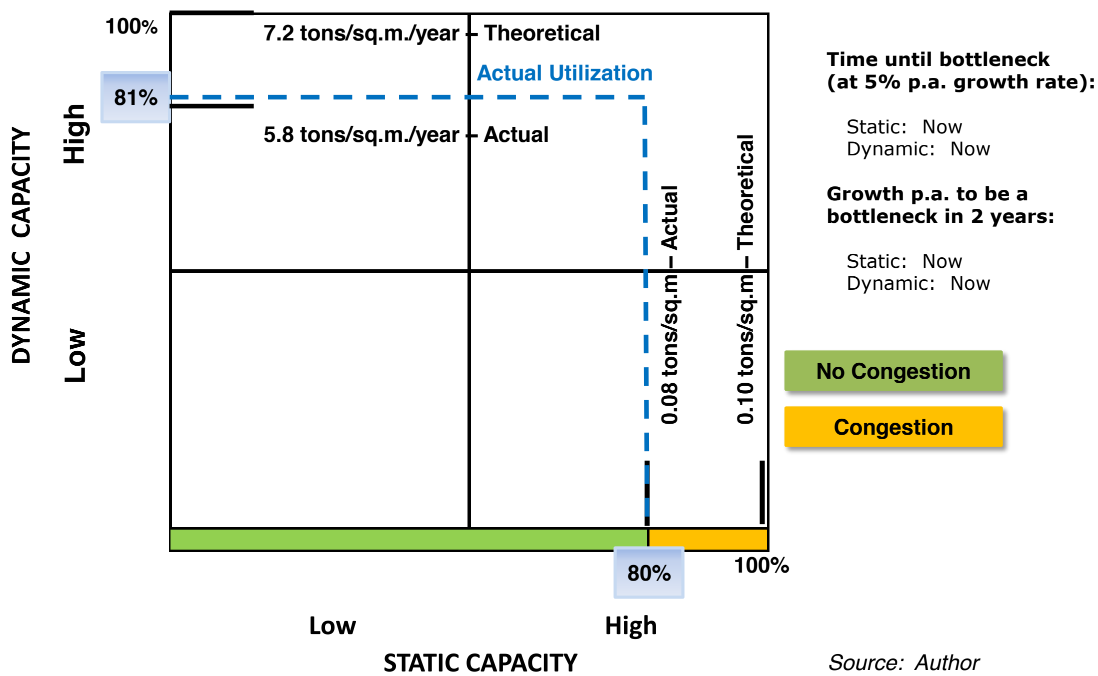


Figure A2-7: Capacity measurement for the dry bulk terminal yard along the static and dynamic dimensions (based on mass)

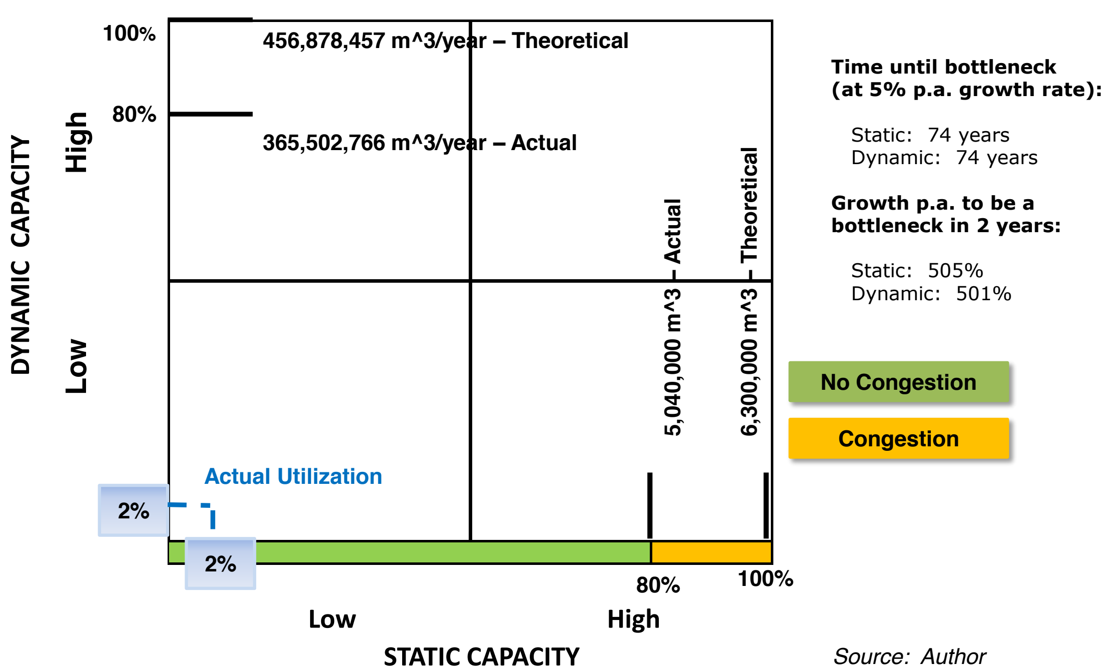


Figure A2-8: Capacity measurement for the dry bulk terminal yard along the static and dynamic dimensions (based on volume)

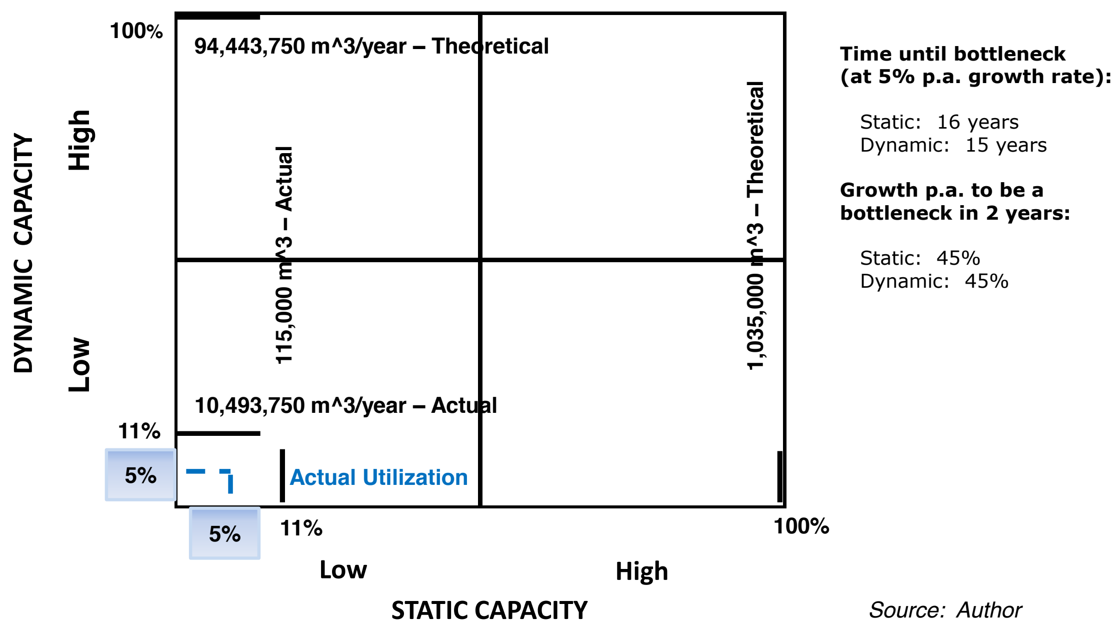


Figure A2-9: Capacity measurement for the dry bulk warehouse along the static and dynamic dimensions (based on volume)

Break Bulk Terminal & Warehouse:

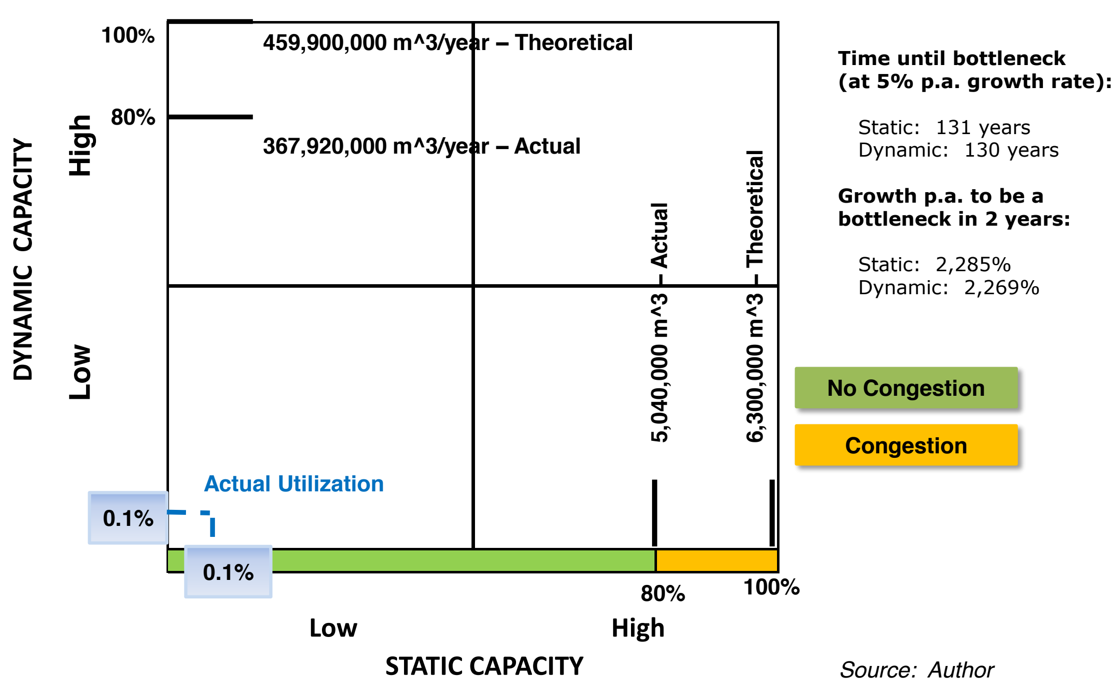
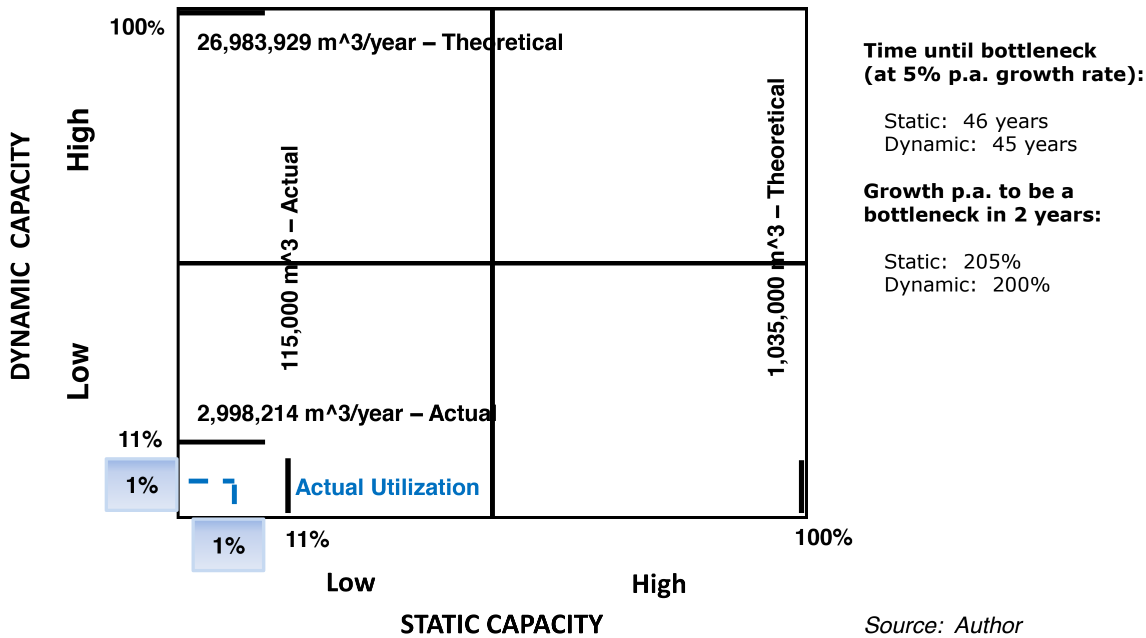


Figure A2-10: Capacity measurement for the break bulk terminal yard along the static and dynamic dimensions (based on volume)



Source: Author

Figure A2-11: Capacity measurement of the break bulk warehouse along the static and dynamic dimensions (based on volume)

Appendix 3: Results and Comparisons of the 3 Forecasting Methods

This appendix contains the results, cumulative distribution curves and the comparisons of the 3 forecasting methods (Mean Reversion Average Growth, Random Walk, and Mean Reversion Exponential Smoothing) used in this thesis to evaluate the profitability of the current state of the port components, the warehouse investment strategies at the warehouse level, and the warehouse investment strategies at the overall port system level.

Table A3-1: Analysis metrics for the current state of the port components

Mean Reversion Average Growth

	Each Port Contributor's Present Value (in USD mill.)				
Metric	Container	Liquid Bulk	Break Bulk	Dry Bulk	Warehouse
ENPV	1,871	1,651	334	1,060	5,287
10 percent value at risk	1,757	1,565	263	971	5,287
90 percent value at risk	1,969	1,682	403	1,134	5,287
Minimum result	1,546	1,144	140	870	5,143
Maximum result	2,092	1,717	570	1,202	5,287
Range of results	547	573	430	332	144
Standard deviation	82	63	54	61	6
Difference between median and ENPV	8	25	0	7	1

Random Walk

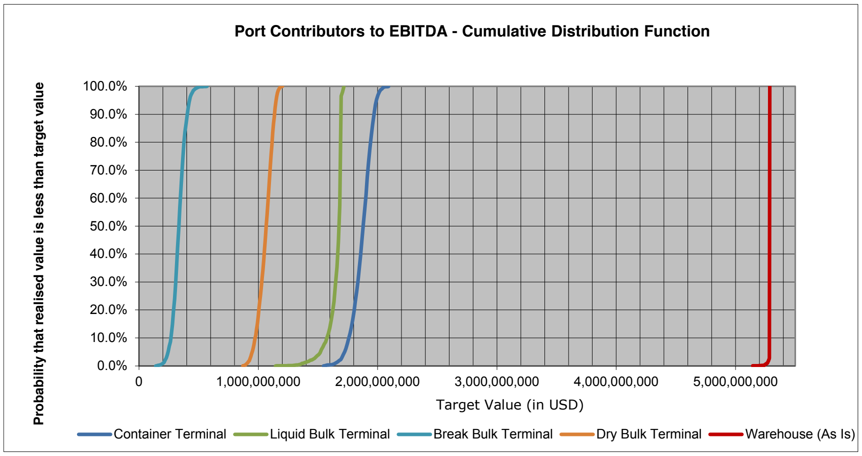
	Each Port Contributor's Present Value (in USD mill.)				
Metric	Container	Liquid Bulk	Break Bulk	Dry Bulk	Warehouse
ENPV	1,849	1,596	334	1,046	5,275
10 percent value at risk	1,641	1,374	188	897	5,287
90 percent value at risk	2,014	1,684	490	1,159	5,287
Minimum result	1,268	916	76	698	4,348
Maximum result	2,099	1,717	856	1,212	5,287
Range of results	831	801	780	514	939
Standard deviation	143	141	119	100	63
Difference between median and ENPV	17	68	-17	13	12

Mean Reversion Exponential Smoothing

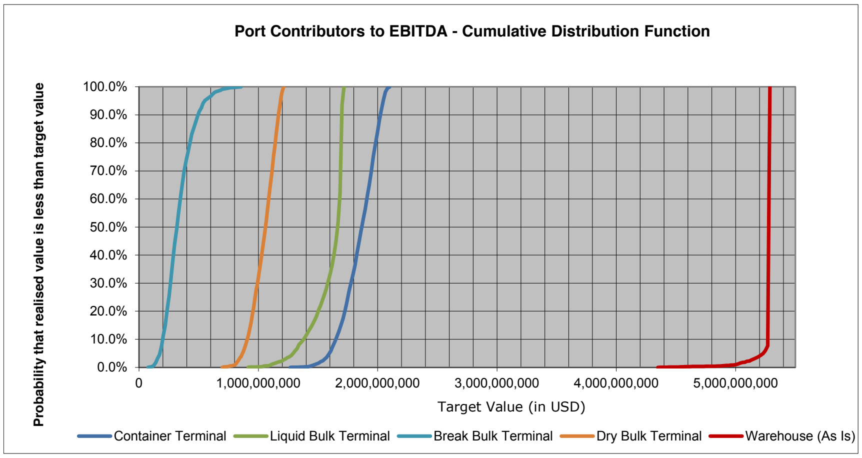
	Each Port Contributor's Present Value (in USD mill.)				
Metric	Container	Liquid Bulk	Break Bulk	Dry Bulk	Warehouse
ENPV	1,829	1,528	373	1,033	5,287
10 percent value at risk	1,714	1,365	291	944	5,287
90 percent value at risk	1,939	1,639	444	1,110	5,287
Minimum result	1,510	924	138	801	5,077
Maximum result	2,036	1,669	607	1,189	5,287
Range of results	526	745	469	388	211
Standard deviation	85	115	62	64	9
Difference between median and ENPV	4	24	0	6	1

Source: Author Adapted from de Neufville & Scholtes (2011)

Mean Reversion Average Growth



Random Walk



Mean Reversion Exponential Smoothing

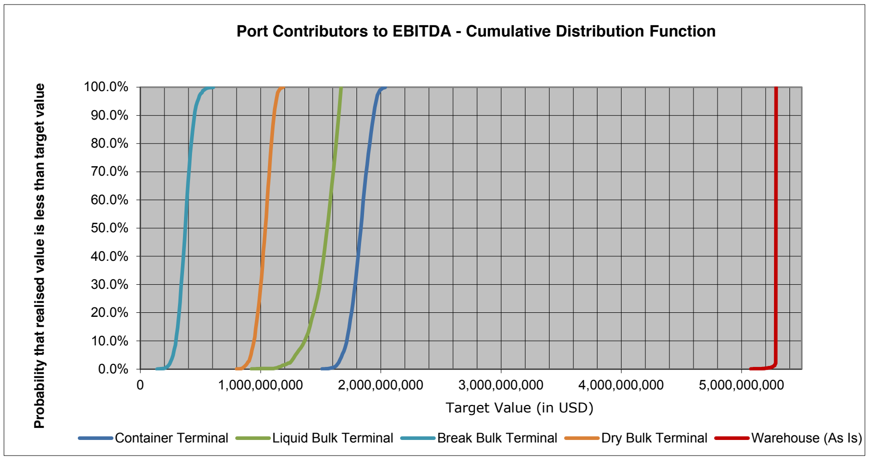


Figure A3-1: Cumulative distribution curves for port components under the 3 forecasting methods

Table A3-2: Comparison of results for current state of the port components

Mean Reversion Average Growth vs. Random Walk

	Each Port Contributor's Present Value				
Metric	Container	Liquid Bulk	Break Bulk	Dry Bulk	Warehouse
ENPV	-1.1%	-3.4%	0.0%	-1.3%	-0.2%
10 percent value at risk	-6.6%	-12.2%	-28.6%	-7.7%	0.0%
90 percent value at risk	2.3%	0.1%	21.5%	2.2%	0.0%
Minimum result	-18.0%	-19.9%	-45.6%	-19.8%	-15.5%
Maximum result	0.3%	0.0%	50.2%	0.8%	0.0%
Range of results	52.1%	39.8%	81.3%	54.8%	551.1%
Standard deviation	73.5%	121.6%	118.7%	63.1%	1029.9%
Difference between median and ENPV	107.1%	176.2%	-3216.6%	87.0%	1733.8%

Mean Reversion Average Growth vs. Mean Reversion Exponential Smoothing

	Each Port Contributor's Present Value				
Metric	Container	Liquid Bulk	Break Bulk	Dry Bulk	Warehouse
ENPV	-2.2%	-7.5%	11.6%	-2.5%	0.0%
10 percent value at risk	-2.5%	-12.8%	10.8%	-2.8%	0.0%
90 percent value at risk	-1.5%	-2.6%	10.2%	-2.1%	0.0%
Minimum result	-2.3%	-19.2%	-1.5%	-7.9%	-1.3%
Maximum result	-2.7%	-2.8%	6.5%	-1.0%	0.0%
Range of results	-3.8%	30.0%	9.1%	16.8%	46.0%
Standard deviation	3.8%	81.0%	13.7%	4.5%	60.3%
Difference between median and ENPV	-48.3%	-1.2%	189.4%	-12.1%	27.0%

Random Walk vs. Mean Reversion Exponential Smoothing

	Each Port Contributor's Present Value				
Metric	Container	Liquid Bulk	Break Bulk	Dry Bulk	Warehouse
ENPV	-1.1%	-4.3%	11.6%	-1.2%	0.2%
10 percent value at risk	4.4%	-0.6%	55.2%	5.2%	0.0%
90 percent value at risk	-3.7%	-2.7%	-9.3%	-4.2%	0.0%
Minimum result	19.1%	0.9%	81.0%	14.9%	16.7%
Maximum result	-3.0%	-2.8%	-29.1%	-1.9%	0.0%
Range of results	-36.7%	-7.0%	-39.8%	-24.5%	-77.6%
Standard deviation	-40.2%	-18.3%	-48.0%	-35.9%	-85.8%
Difference between median and ENPV	-75.0%	-64.2%	-102.7%	-53.0%	-93.1%

Source: Author Adapted from de Neufville & Scholtes (2011)

Table A3-3: Analysis metrics for the warehouse investment strategies (warehouse level)

Mean Reversion Average Growth

	Each Strategy's Warehouse Present Value (in USD mill.)		
Metric	As Is	Non-Flexible Expansion	Flexible Expansion
ENPV	5,287	8,810	9,015
10 percent value at risk	5,287	7,849	7,732
90 percent value at risk	5,287	9,372	10,094
Minimum result	5,143	6,392	6,397
Maximum result	5,287	9,637	11,428
Range of results	144	3,245	5,032
Standard deviation	6	622	888
Difference between median and ENPV	1	203	79

Random Walk

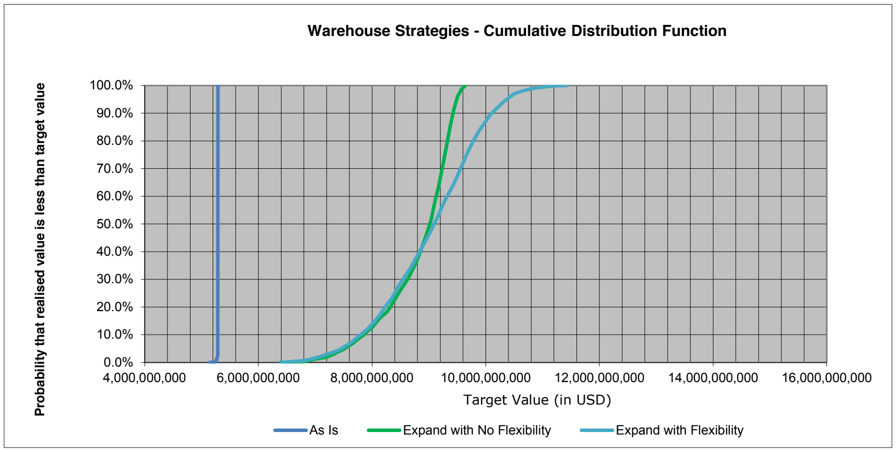
	Each Strategy's Warehouse Present Value (in USD mill.)		
Metric	As Is	Non-Flexible Expansion	Flexible Expansion
ENPV	5,275	8,705	9,308
10 percent value at risk	5,287	7,364	7,316
90 percent value at risk	5,287	9,429	11,171
Minimum result	4,348	5,299	4,273
Maximum result	5,287	9,699	14,214
Range of results	939	4,399	9,942
Standard deviation	63	848	1,544
Difference between median and ENPV	12	308	-70

Mean Reversion Exponential Smoothing

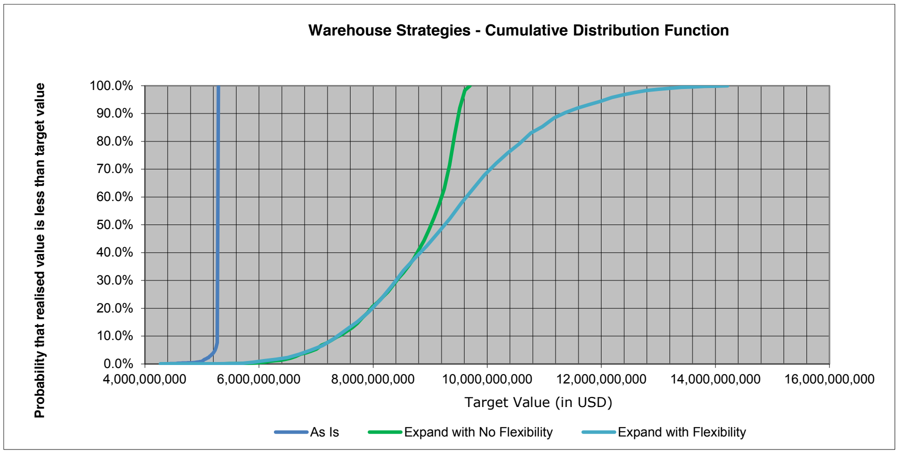
	Each Strategy's Warehouse Present Value (in USD mill.)		
Metric	As Is	Non-Flexible Expansion	Flexible Expansion
ENPV	5,287	8,786	8,993
10 percent value at risk	5,287	7,831	7,679
90 percent value at risk	5,287	9,421	10,126
Minimum result	5,077	6,311	6,402
Maximum result	5,287	9,697	11,616
Range of results	211	3,386	5,214
Standard deviation	9	625	906
Difference between median and ENPV	1	179	60

Source: Author Adapted from de Neufville & Scholtes (2011)

Mean Reversion Average Growth



Random Walk



Mean Reversion Exponential Smoothing

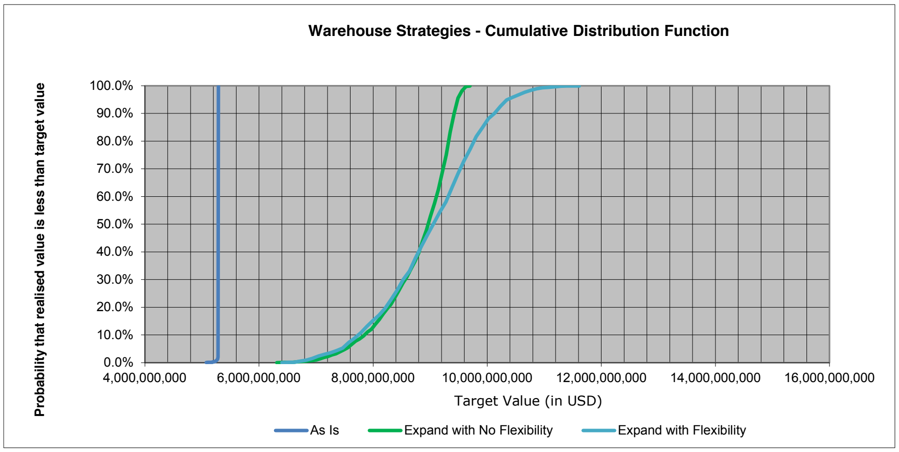


Figure A3-2: Cumulative distribution curves for warehouse investment strategies (warehouse level) under the 3 forecasting methods

Table A3-4: Comparison of results for warehouse investment strategies (warehouse level)

Mean Reversion Average Growth vs. Random Walk

	Each Strategy's Warehouse Present Value		
Metric	As Is	Non-Flexible Expansion	Flexible Expansion
ENPV	-0.2%	-1.2%	3.3%
10 percent value at risk	0.0%	-6.2%	-5.4%
90 percent value at risk	0.0%	0.6%	10.7%
Minimum result	-15.5%	-17.1%	-33.2%
Maximum result	0.0%	0.6%	24.4%
Range of results	551.1%	35.6%	97.6%
Standard deviation	1029.9%	36.3%	73.8%
Difference between median and ENPV	1733.8%	51.8%	-188.1%

Mean Reversion Average Growth vs. Mean Reversion Exponential Smoothing

	Each Strategy's Warehouse Present Value		
Metric	As Is	Non-Flexible Expansion	Flexible Expansion
ENPV	0.0%	-0.3%	-0.2%
10 percent value at risk	0.0%	-0.2%	-0.7%
90 percent value at risk	0.0%	0.5%	0.3%
Minimum result	-1.3%	-1.3%	0.1%
Maximum result	0.0%	0.6%	1.6%
Range of results	46.0%	4.3%	3.6%
Standard deviation	60.3%	0.5%	2.0%
Difference between median and ENPV	27.0%	-12.0%	-24.2%

Random Walk vs. Mean Reversion Exponential Smoothing

	Each Strategy's Warehouse Present Value		
Metric	As Is	Non-Flexible Expansion	Flexible Expansion
ENPV	0.2%	0.9%	-3.4%
10 percent value at risk	0.0%	6.3%	5.0%
90 percent value at risk	0.0%	-0.1%	-9.4%
Minimum result	16.7%	19.1%	49.8%
Maximum result	0.0%	0.0%	-18.3%
Range of results	-77.6%	-23.0%	-47.6%
Standard deviation	-85.8%	-26.3%	-41.3%
Difference between median and ENPV	-93.1%	-42.0%	-186.0%

Source: Author Adapted from de Neufville & Scholtes (2011)

Table A3-5: Analysis metrics for the warehouse investment strategies (port system level)

Mean Reversion Average Growth

	Each Strategy's Aggregate Present Value (in USD mill.)		
Metric	As Is	Non-Flexible Expansion	Flexible Expansion
ENPV	10,189	13,694	13,938
10 percent value at risk	9,865	12,437	12,334
90 percent value at risk	10,421	14,400	15,102
Minimum result	9,281	10,644	10,891
Maximum result	10,643	14,827	16,786
Range of results	1,362	4,183	5,896
Standard deviation	210	789	1,049
Difference between median and ENPV	38	248	137

Random Walk

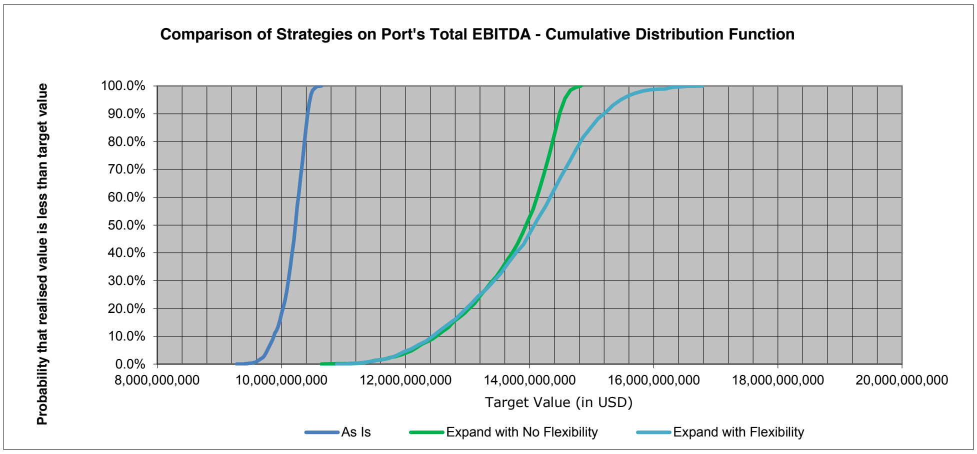
	Each Strategy's Aggregate Present Value (in USD mill.)		
Metric	As Is	Non-Flexible Expansion	Flexible Expansion
ENPV	10,106	13,597	14,184
10 percent value at risk	9,726	12,230	11,946
90 percent value at risk	10,441	14,480	16,313
Minimum result	8,678	9,389	9,035
Maximum result	11,013	15,190	19,225
Range of results	2,335	5,802	10,190
Standard deviation	302	921	1,678
Difference between median and ENPV	22	251	-93

Mean Reversion Exponential Smoothing

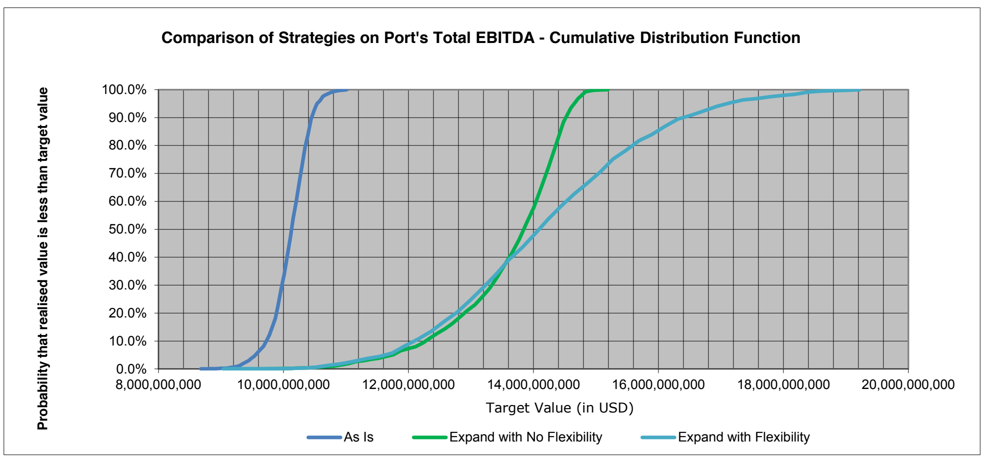
	Each Strategy's Aggregate Present Value (in USD mill.)		
Metric	As Is	Non-Flexible Expansion	Flexible Expansion
ENPV	10,055	13,557	13,754
10 percent value at risk	9,631	12,229	12,218
90 percent value at risk	10,338	14,388	15,062
Minimum result	9,159	10,429	10,538
Maximum result	10,603	14,838	16,872
Range of results	1,444	4,409	6,334
Standard deviation	270	854	1,099
Difference between median and ENPV	45	284	124

Source: Author Adapted from de Neufville & Scholtes

Mean Reversion Average Growth



Random Walk



Mean Reversion Exponential Smoothing

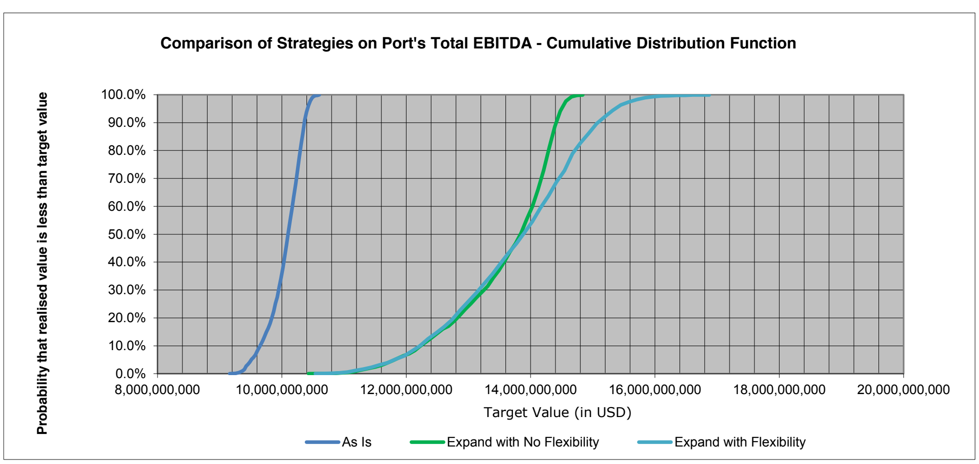


Figure A3-3: Cumulative distribution curves for the warehouse investment strategies (port system level) under the 3 forecasting methods

Table A3-6: Comparison of results for warehouse investment strategies (port system level)

Mean Reversion Average Growth vs. Random Walk

	Each Strategy's Aggregate Present Value		
Metric	As Is	Non-Flexible Expansion	Flexible Expansion
ENPV	-0.8%	-0.7%	1.8%
10 percent value at risk	-1.4%	-1.7%	-3.1%
90 percent value at risk	0.2%	0.6%	8.0%
Minimum result	-6.5%	-11.8%	-17.0%
Maximum result	3.5%	2.5%	14.5%
Range of results	71.5%	38.7%	72.8%
Standard deviation	44.0%	16.7%	60.0%
Difference between median and ENPV	-41.3%	1.0%	-167.6%

Mean Reversion Average Growth vs. Mean Reversion Exponential Smoothing

	Each Strategy's Aggregate Present Value		
Metric	As Is	Non-Flexible Expansion	Flexible Expansion
ENPV	-1.3%	-1.0%	-1.3%
10 percent value at risk	-2.4%	-1.7%	-0.9%
90 percent value at risk	-0.8%	-0.1%	-0.3%
Minimum result	-1.3%	-2.0%	-3.2%
Maximum result	-0.4%	0.1%	0.5%
Range of results	6.1%	5.4%	7.4%
Standard deviation	28.9%	8.2%	4.8%
Difference between median and ENPV	18.2%	14.5%	-9.6%

Random Walk vs. Mean Reversion Exponential Smoothing

	Each Strategy's Aggregate Present Value		
Metric	As Is	Non-Flexible Expansion	Flexible Expansion
ENPV	-0.5%	-0.3%	-3.0%
10 percent value at risk	-1.0%	0.0%	2.3%
90 percent value at risk	-1.0%	-0.6%	-7.7%
Minimum result	5.6%	11.1%	16.6%
Maximum result	-3.7%	-2.3%	-12.2%
Range of results	-38.2%	-24.0%	-37.8%
Standard deviation	-10.5%	-7.3%	-34.5%
Difference between median and ENPV	101.5%	13.3%	-233.7%

Source: Author *Adapted from de Neufville & Scholtes (2011)*

Appendix 4: Capacity Calculations from Rice & Lagoudis's Existing Methodology

This appendix presents the capacity calculations from the 2011 white paper by Lagoudis and Rice.

Table A4-1: Capacity calculations in the existing methodology for port capacity measurement, as developed by Lagoudis & Rice (2011)

Port Component	**Static**	**Dynamic**
Anchorage	Designated Area / Area needed by average ship size	Designated area / (Area needed by average ship size * Average Waiting time)
Waterway	(Length * Number of lanes) / Average ship size	(Length * Number of lanes) / (Average ship size * Average cruising time)
Terminal Quay/Berth	Length of quay / Average vessel size	Length of quay / (Average vessel size * Turnaround time)
Terminal Yard/Area		
Container	Yard Capacity = Designated area / TEU size = Number of ground slots * TEU stacking policy Warehouse Capacity = Designated area / TEU size = Number of ground slots	Yard Capacity = (Number of ground slots * TEU stacking policy) / TEU average idle time Warehouse Capacity = Number of ground slots / TEU average marshaling time
General Cargo	Yard Capacity = Designated area / Commodity size Warehouse Capacity = Designated area / Commodity size	Yard Capacity = Designated area / (Commodity size * Commodity average idle time) Warehouse Capacity = Designated area / Commodity average marshaling time
Liquid	Designated area / (Number of tanks * Average tank capacity)	Designated area / (Number of tanks * Average tank capacity * Average pumping time)
Car	Designated area / Average vehicle size = Number of slots	Designated area / Average vehicle size = Number of slots / Vehicle average idle time
Ferry	Ferry Passenger Capacity = Designated area / Average space per passenger	Ferry Passenger Capacity = Designated area / (Average space per passenger * Average waiting time)

	Ferry Vehicle Capacity = Designated area / Average vehicle size	Ferry Vehicle Capacity = Designated area / (Average vehicle size * Average idle time)
Cruise	Designated area / Average space per passenger	Designated area / (Average space per passenger * Average waiting time)
Port Terminal Gate	Gate length / Gate size = Number of gates	Gate length / Gate size = Number of gates / Average unit process time
Rail Terminal Gate	Gate length / Gate size = Number of gates	Gate length / Gate size = Number of gates / Average unit process time
Rail Terminal Yard	For Container = Designated area / TEU size = Number of ground slots * TEU stacking policy For Bulk = Designated area / Commodity size	For Container = (Number of ground slots * TEU stacking policy) / TEU average idle time For Bulk = Designated area / (Commodity size * Commodity average idle time)
Rail Network	(Truck length * Number of trucks) / Average car size	(Truck length * Number of trucks) / (Average car size * Average cruising speed)
Road Network	(Lane length * Number of lanes) / Average vehicle size	(Lane length * Number of lanes) / (Average vehicle size * Average cruising time)

Source: Lagoudis & Rice (2011)

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