Critical Infrastructure Management: Ports

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Abstract: All societies rely on infrastructure, which are essential to their health, safety, security, and economic well-being. Governments define critical infrastructure as those assets, which provide the essential services and any disruption would impact the economy, security, and health of nations. The transportation system as a critical sector has been vulnerable to natural disaster, attack, performance disruption, damage and destruction for many years and is divided into Air, Rail, Surface, and Marine, which is one of the most important sub-sectors. Every year the goods loaded and off-loaded at Canadian Port authorities, private ports, and smaller regional ports across Canada exceed million tons by volume. For upcoming years, ports should be designed, managed and maintained while addressing novel issues such as sustainability. This study proposes a basic framework for developing an asset management model for ports. This study could be applied to under operation and extension sites such as Montreal Port, which is going to launch a new container terminal.

1. Introduction

All societies rely on infrastructure, which are essential to their health, safety, security, economic, and well-being. Governments define critical infrastructure as those assets, which provide the essential services and any disruption would impact the economy, security, and health of nations. Transportation systems including air, rail, marine, and surface is one the most fundamental sector in any society while maritime transportation systems allow the various modes of transportation to move people and goods to, from, and on the water (Homeland security, 2018; and Government of Canada, 2004).

Aging and budget limitation bring an obvious need for implementing infrastructure asset management platforms in developed and developing nations. Recently, in many countries protection of critical infrastructure is classified as a high interest topic. CRN (2008) identified three common policy trends by monitoring 25 countries, which have different concerns from attention to the concepts of resilience to concentrating on the cyber-dimension of the issue.

Two thirds of the earth's surface is covered by waters, and a significant portion of the world's trade by volume is carried by ship. For instance, more than $700 billion in merchandise annually is transferred by U.S. ports as economic engines (GAO, 2012) or 90% of Canadian imports are travelling by ship while Canada's ports are at the heart of the global supply chain and economic opportunity (ACPA, 2016). For economic expansion, access to the sea is fundamental while ports are essential to prepare this link (Watts, 2005).

Several aspects should be considered in port management in order to protect operation performance, reliability, safety, and security. There is a strong linkage between the various elements of the organizational and spatial structure of the ports. Thus, any disturbance in the work of one port facility effects immediately the operation of the whole port and consequently disturbances the functioning transport chain. Meantime, increasing the size and number of ships while many carry hazardous cargo changes risk levels. Also, ports are open centers and are vulnerable to the natural and human-caused Disasters (Tubielewicz et al., 2010).

Critical infrastructure protection has been studied in several types of research mostly from a security point of view (Náda, 2016 and Homeland security, 2008). Chiappetta and Cuozzo (2017) and GAO (2012) specifically studied the port protection.

Infrastructure service comes from all aspects of performance, resilience and as well as security. Therefore, infrastructure asset management plays a critical role in maintaining assets reliability and quality. However, from asset management point of view and facilities resilience, a few studies focused on ports. ASEAN (2011) published a guideline for strategic maintenance of port structures. In this study general steps are defined for port asset assessment and repair while different countries policies are compared. Ghalibafian et al. (2016) present a risk-based structural assessment approach for port metro Vancouver's asset management. However, these studies only focused on structural elements such as concrete and steel slabs. Paulsen et al. (2013) present an ongoing process of developing an asset management system for the port of Tacoma. Recently more advanced research conducted by Mendes et al. (2015) was applied to Fremantle Port jetties. While the model is not developed in port level, decision-making framework, which compares the life-cycle cost of scenarios, is not elaborated well and uses simple averaging approach for assessment. The model only calculates the optimal replacement time ignoring other preventive maintenance, minor or major replacement actions.

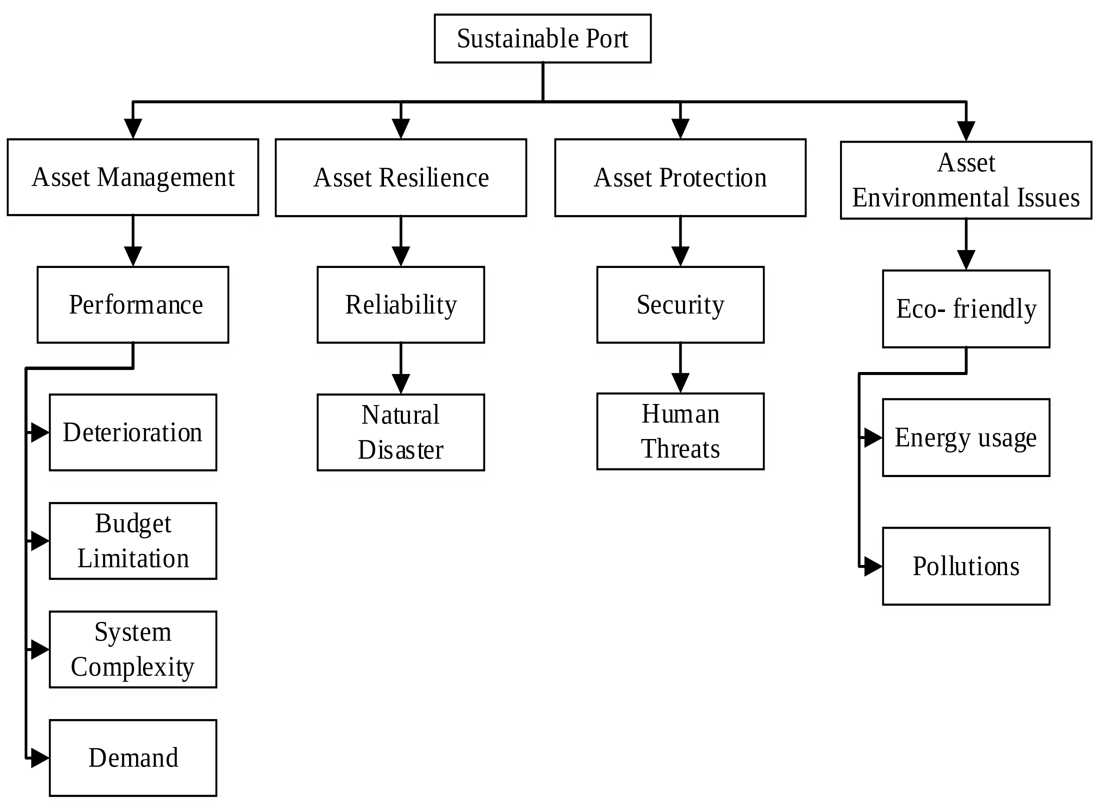
Although, asset management is advanced in some infrastructure such as pavement, bridge and water network; however, the state of art shows few studies in the domain of port asset management probably due to complexity and data availability. Ports are multi-discipline systems including different assets with significantly various natures and deterioration such as breakwaters, berths, cranes and navigation systems. A port asset manager needs a comprehensive decision-making framework to respect performance, safety, security and sustainability issues distributing available budget among several maintenance and rehabilitation alternatives.

The main objective of this research is to investigate port as critical infrastructure addressing key elements of sustainable management view. This research focused on asset management framework to elaborate main phases for developing an applicable and comprehensive decision-making model for port facilities.

2.Methodology

Future generations need sustainable infrastructure, which is more important for critical assets such as ports. Figure 1 shows four main bases to have sustainable ports including asset management, resilience, protection and addressing environmental concerns. There is an interdependency among these factors, in which having mature asset management plan, improves resilience or dropping security, reduces performance and reliability.

Figure 1: Sustainable ports factors and



Asset management and maintenance planning is not the sole factor in sustainable ports. Ports are a big energy consumer in different types and could have significant impacts on gas emission by decreasing usage and replacing more eco-friendly sources. Although, ships bring significant environmental benefits by a highly energy efficient and safe transportation (ACPA, 2016), at the same time, could cause several pollution categories, particularly in the harbor zone, which indicates the level of risk. Automation and mechanization have been more common in port operation and this brings more risks in cyber-attacks while shows the protection needs. Meantime, as an open area, a port is faced natural disasters and resilience is a leading concern. Any disruption could result in transportation chains disconnection. Thus, asset management, resilience, protection and environmental issues should be part of any operation plan for ports. Each factor could be presented by one or more attributes as it can be seen in Figure 1 (e.g. performance for asset management). Meanwhile, several parameters may impact these attributes.
This study focuses on developing an asset management framework and corresponding steps in marine ports. Four key issues should be considered in developing port asset management models:
Deterioration:
Ports structures and facilities are faced natural condition as well as aging (ASEAN, 2011). Salt water leads high rates of corrosion in steel and concrete elements while sediment is always a big challenge. Thus, degradation could not be ignored in maintenance planning.
Budget limitation:
Restricted budget is always an issue in infrastructure management and this situation brings a need to apply an optimized decision-making. The federal Harbor Maintenance Trust Fund (HMTF) in the U.S. assigned $8.41 billion for dredging in harbors; however, despite the significant dredging needs at most U.S. ports, the fund's balance has often been used for other purposes (ASCE, 2017).
System Complexity:
The management of port is a complex process as there are several types of facilities including different berths (container; bulk; liquid; oil and gas, and general cargo), breakwaters, cranes, roads, and railways with many sub-components geographically located across the port. These assets have various natures and life-cycles, which are mostly 24 hours 7 days a week under the operation.
Demand:
The size and number of ships have been changed increasingly during past years. Container ships size has been grown from 10,000 TEU (twenty-foot equivalent units) in 2005 to 22,000 TEU in 2018. It results in the requirement of adjustment in equipment, berth depths, and terminal layout in the ports (ASCE, 2017).
While operation phase is the main phase to address mentioned issues, port design process could also facilitate implementing the ideas.

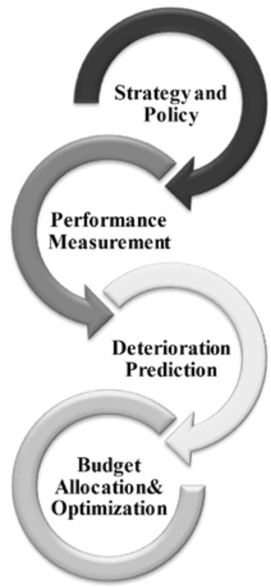
2.1. Port Design

Many new ports are under constructions or expansion in the following years and all mentioned bases could be addressed in the design and construction phase. Location, distance to main city and energy resources, designed layout, mapping facilities, flexibility for maintenance are samples of aspects, which could be considered respecting long-term suitability and asset management view. For this purpose, port and harbor design codes and standards could be modified in order to direct designs to a life-cycle point of views. For instance, Montreal Port Authority (MPA) is building a new terminal with capacity of 1.15 million TEU (20-foot equivalent unit) containers annually to be fifth-largest container port on the American northeastern coast and those mentioned elements could be considered (MPA, 2018).

2.2. Port Operation

Ports and harbors are expensive infrastructure and mostly designed for long life-cycle (e.g. 50 years); therefore, it would be critical to apply maintenance and rehabilitation plan to avoid service disruptions and costly replacements. Implementation of asset management is a primary requirement for this purpose. Figure 2 indicates the main steps for developing an asset management plan. Defining short and long-term strategies, thresholds such as minimum acceptable performances, targets, and other constraints and goals is followed in the first step.

Figure 2: Asset management steps



In the second step, a comprehensive hierarchy of components and sub-components are needed to investigate dependency and relations among components and sub-components. Figure 2, presents the hierarchy of port facilities and components. Each facility should be assessed for evaluating current performance. Performance attributes and grading system could be defined for each component separately; however, final scores should be normalized for integrating results. Table 1, shows one simple qualitative scoring system, which is more popular. However, this system could be extended to more details respecting data; inspection teams and equipment; and budget availability.

Figure 2: Hierarchy network for port facilities

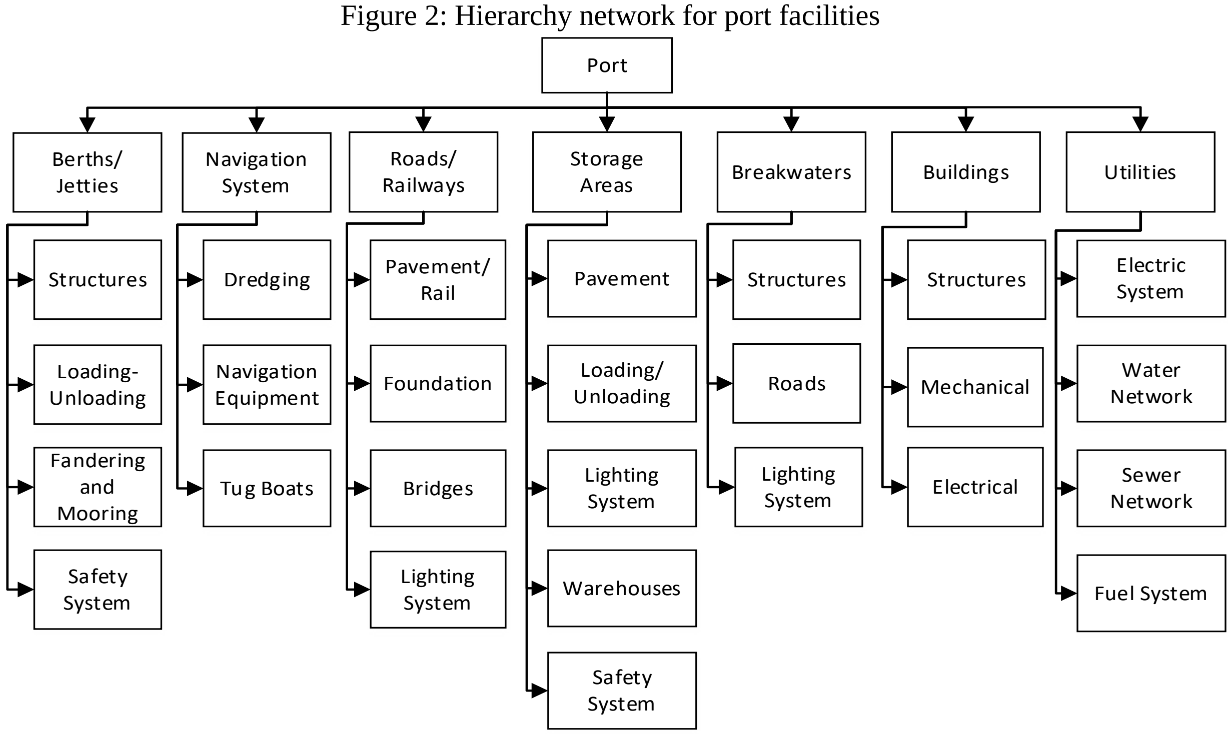


Table 1: One simple scoring system

Qualitative level	Exceptional	Good	Fail	Poor	Critical
Quantitative level	0.9	0.7	0.5	0.3	0.1

Equation (1) and (2) mathematically show port overall performance measurement. In the sub-component level, a weighted geometric average is used to minimize the limitation of simple additive weighting approach.

$$p_i = \left[\prod_{j=1}^{J} (x_j)^{\alpha_j}\right]^{1/\sum_{j=1}^{J} \alpha_j} \quad (1)$$

$$P = \sum_{i=1}^{I} W_i \times p_i \quad (2)$$

Where P is overall performance of port, which could reflect different attributes such as reliability and level of service. x_i and α_i are performance and importance weight of each sub-component while W_i is a corresponding weight for each component (facility) performance (p_i). To estimate importance weight of each component and sub-component different decision-making methods such as AHP (Saaty, 1980) or ANP (Saaty, 2001) could be used.

In the next step, based on historical data, deterioration trend should be modeled and predicted. As it can be seen, decision-makers are faced to basically different nature and degradation rate in facilities, which should be addressed in the maintenance framework. Historical data limitation is a common obstacle and alternative approaches such as developing Weibull distribution based on expert judgments and assumptions could be used as a starting point and further deterioration model should be updated.

Finally, decision-making system should be developed to help asset managers to answer these tactical question: which component or sub-component, when and how to be extended, replaced and renovated first to improve overall performance in the whole of the port within the given budget? Optimization approaches should be applied rather than using worst-first or ranking methods, which cannot guarantee achieving optimum solutions. Equations (3 to 5) present mathematical approach for distribution budgets among alternatives in component level; however, this formulation could be extended to sub-component level. Dynamic binary linear programming with a decision variable $X_{i,t}$ is used in this study to find the optimum options. The model tries to increase overall performance, which is subjected to the available budget. Each year the decision binary variable ($X_{i,t}$) could assign to each component either one, which means considering treatment actions and improvement in performance ($pi_{i,t}$) or zero, which reflects do noting and results in decay ($pd_{i,t}$).

$$MAX(P_t) = \sum_{i=1}^{I} W_i \times p_{i,t} \quad (3)$$

With

$$\boldsymbol{p_{i,t} = X_{i,t}(p_{i,t-1} + pi_{i,t}) + (1 - X_{i,t})(p_{i,t-1} - pd_{i,t})} \quad \mathbf{(4)}$$

Subject to:

$$\boldsymbol{0 < \sum_{i=1}^{I} C_{i,t} X_{i,t} \leq B_t} \quad \mathbf{(5)}$$

Where:

$$X_{i,t} = \begin{cases} 1 & \text{if action is taken on componet } i, \text{in year } t \\ 0 & \text{if no action taken on componet } i, \text{in year } t \end{cases}$$

P_t *= Overall performance on year t on a 0 to 1 scale*

$p_{i,t}$ *= performance of component i on year t on a 0 to 1 scale*

$C_{i,t}$ = *Unitary cost ($) of rehabilitation action of component i on year t*
$Pi_{i,t}$ = *performance improvement from year (t-1) to year t for component i*
$Pd_{i,t}$ =*Dropped portion of performance from year (t-1) to year t for non-selected component i*
B_t = *Available budget in year t*

3.Conclusion

Ports are critical infrastructure and play a significant role in economic growth in societies. To have a sustainable port for future generations, key factors of asset management, resilience, protection and environmental concerns should be considered. Asset management plan, which is faced several issues, is an essential tool for port managers. Although, infrastructure management models are common topics in recent studies especially for pavements, bridges and water networks, there is a lack of a comprehensive model for port facilities maintenance and rehabilitation decision-making. This study investigated ports as critical infrastructure and developed an applicable decision-making model for ports. The framework was elaborated in four phases proposing main bases including performance measurement, prediction and budget allocation. In future research, the model could be extended to more details and could be applied to a case study.

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