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Optimal Sustainable Life Cycle Maintenance Strategies for Port Infrastructures

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Abstract

Port operations are highly important in the central economic and industrial regions which rely heavily on the use of port infrastructures. An economic and efficient maintenance strategy is essential to govern the normal running of port infrastructures and thus seaborne transportation. Many agencies worldwide have managed to develop maintenance strategies to ensure optimal levels of serviceability and safety for port infrastructures. However, there is not much information about how sustainable issues can be implemented in the maintenance planning. This paper proposes a methodology for evaluating, comparing and improving sustainability of maintenance strategies for port infrastructures. The method is developed based on a proposed randomized structural deterioration model. The costs due to retrofitting, operating loss and environmental loss are considered in the total life cycle cost estimation. The concept of utility function is utilized to serve as a criterion for finding the optimal strategy among the alternative maintenance strategies. An investigation is performed on a Tokyo wharf to demonstrate the proposed approach. The maintenance strategies for different structural elements in the port infrastructures are discussed. The results show that the proposed approach can provide more reliable information on the maintenance timing. The predicted cost bounds allow owners/risk managers to understand the current condition of the structure in several ways, which include both safe-side prediction and average prediction.

Keywords: sustainability, life cycle analysis, maintenance, port infrastructure, Markov chain

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1. Introduction

Seaport, being a linkage between land and seaborne transport, plays an essential role in facilitating global trade and economic development. Ports handle 80% of trade and provide many strategic areas for fishing and cruise activities all over the world (Boéro et al., 2009). Therefore, port stability needs to be fully analyzed in the context of risk management since it has a crucial role in providing various kinds of services. The performance of infrastructure is especially a key concern in retaining the stability of port operations. However, a lot of port infrastructures are highly deteriorated. It was reported that the majority of ports (60%) were built before 1955 and many significant damages have been noticed by the port surveyors (Rosquoët et al., 2006). Structural safety is of paramount importance for the port infrastructure during its entire lifetime. As aggressive environment conditions such as hurricane and corrosion can cause a reduction in the port structural functionality, the timely maintenance of port infrastructure performance is necessary to ensure the normal operation of port (Strogen, 2016).

Generally, the importance of port infrastructure maintenance can be viewed in three aspects. First, most port infrastructures need to be utilized for a very long period of time. During the whole service time of a port, structural deteriorations can always exist. For this reason, maintenance work is a long term job which aims to keep the lifetime risk below a target level. Second, port infrastructures are normally built along the coastal areas which demands frequent repair and retrofit works. As most port infrastructures are directly exposed to a harsh environment, a fast deterioration mechanism is usually expected in the constructed facilities. For example, the chloride-induced corrosion is a primary cause of most reinforced concrete structures in onshore marine environment (Zhang, 2015a). There is a need for effective and economic maintenance planning for these fast deteriorated structures. Third, the consequences associated with port infrastructure failure due to insufficient maintenance can be enormous which may bring adverse impacts on the society. It should be realized that a disruption at ports is not only a loss on the ports, but also a possible stoppage of the whole supply chain (Zhang and Lam, 2016). In other words, the condition of infrastructural performance affects the efficiency of port operations and associated sectors. It is therefore essential to provide accurate consideration during the initial design of the port infrastructures, as well as to conduct appropriate maintenance since their services start.

In general, many studies have been conducted on infrastructure maintenance planning and strategy development. Most of these former works focus on the minimization of structural risks due to constrained maintenance budget (Frangopol and Soliman, 2016; Khan and Tee, 2016). To arrive at an appropriate solution, the economic evaluation is usually integrated with structural performance measures such as reliability, redundancy and risks (Zabalza Bribian et al., 2009; Tee et al., 2014). However, very little work can be found in maintenance strategies specifically focusing on sustainable development. Recent studies show that ports can be a contributor to global anthropogenic emissions (Lam and Lai, 2015; Khan and Tee, 2015). Ports face many increasing challenges from social, economic and environmental factors which create significant impacts on port performance and management (Zhang and Lam, 2015a;b). Furthermore, environmental considerations have raised many regulatory control and social responsibility that port planners and operators have to fulfill (Chau et al., 2015). Attaining the economic performance alone is no longer sufficient for the long term maintenance development. However, there is very little research addressing the sustainable issues in infrastructure planning and development. Literature in sustainable maintenance strategies for port infrastructures is even more limited, or almost non-existent.

When assessing the safety of an existing port infrastructure, the uncertainties associated with the structural deterioration process are quite troublesome. The Markov chain model is a widely applied technique in the performance assessment for deteriorating structures (Straub and Faber, 2005). It has such a feature that the structural deterioration process can be characterized by the transition probabilities from one condition state to another. In this respect, many engineering industries tend to implement this technology in their maintenance management, for example geotechnical analysis (Bommer et al., 2010), wind engineering (Sorensen, 2009), bridge engineering (Frangopol et al. 2008) and coastal management (Yang et al., 2013). However, the Markov chain model requires a large amount of inspected data to formulate its transition probability matrix. If only limited amount of data is provided, the obtained Markov chain model could generate large errors in the structural condition predictions. Moreover, the probability transition matrix in the Markov chain model can hardly be modeled as deterministic as most deterioration process is stochastic. The use of single transition probability matrix in Markov chain model might not be accurate and misleading. This study aims to develop a reliable structural deterioration model that can predict the long term performance of port infrastructures. This is achieved by formulating a randomized Markov chain model and its associated simulation approach for characterizing the port infrastructure deterioration process. A theoretical and empirical study is conducted to illustrate and validate the proposed approach.

The paper is organized as follows. After the introduction, Section 2 will provide an overview of the existing research works and techniques regarding port maintenance. Section 3 then presents the framework about how sustainability is incorporated in the port infrastructure maintenance planning. The steps of conducting the structural inspections and measurement are introduced in Section 4. A randomized Markov chain model in characterizing the structural deterioration mechanism for the port structural elements is elaborated in Section 5. The model includes the random variability of the deterioration process and environmental conditions. Sections 6 and 7 detail the cost evaluation methods and decision making criteria for the port infrastructure maintenance strategies. Section 8 presents the results with the demonstration of a case study as example. The comparison of different maintenance scenarios is also discussed. Finally, Section 9 provides the concluding remarks of this study.

2. Literature review

Research on port maintenance is generally rather limited. Some have incorporated port maintenance as one of the factors for considerations in their study especially in the area of terminal operation optimization, for example, Hess and Hess (2010) and Ee et al. (2014). Among others, structural engineering and maintenance is one of the key research focuses. Tsinker (2004) provided a comprehensive discussion on deterioration of waterfront structure due to both external natural environment and human activities. It has also included a detailed guideline on the procedures of maintaining such structures. Boero et al. (2012) provided a reliability analysis for steel sheet-pile seawalls as preliminary requirements on maintenance optimisation. A stochastic (spatial-temporal) model of steel corrosion was proposed in the time-dependent reliability analysis of corroded harbour structures. Sulaiman et al. (2011) studied maintenance requirement of navigational channel under the impact of increasing ship size. It presented the result of the application of best practice simplified method for channel maintenance against vessel design and reception requirement using Port of Tanjung Pelepas as the case study. In recent years, more attention has been paid to the issue of dredging. Mitchell et al. (2013) proposed mathematical integer programming models and heuristic solution algorithms for selection of suitable dredging projects to be awarded with US annual harbour maintenance fund. Scheffler et al. (2014) studied the dredged material management in the port of Lübeck, Germany. By employing a modified computer-aided stochastic multi-criteria acceptability analysis (SMAA)-TRI method, their study identified suitable dredging options for the port of Lübeck.

Besides structural engineering and maintenance, some researchers have dedicated their efforts to the study of port maintenance funding especially in the context of the US. Talley (2007) addressed the issue of financing port dredging cost by taxes or user fees. McIntosh and Skalberg (2010) conducted a statistical analysis on the US harbour maintenance tax rates and replacement user fees in order to gain understanding as to which variables have a strong statistical relationship with maintenance costs and ascertain how they are related quantitatively. More recently, Frittelli (2013) discussed the usage of harbour maintenance trust fund (HMTF) in the US. Several key policy questions have been raised in relation to this area such as the extent to which HMTF be used for improvements that do not benefit commercial shipping and extension of covering scope of HMTF. Simkins and Stewart (2015) also focused on funding for harbour maintenance in the US, and they developed three port financing indicators based on a real value of cargo and illustrated their calculations using the U.S. Port of Duluth-Superior as a case study. McIntosh et al. (2015) further extended the study in which they suggested the current Harbor Maintenance Tax as being not appropriate enough and evaluated three other maintenance payment alternatives.

Another research interest related to port maintenance is the study of environmental management of port structures. Walker et al. (2015) discussed the implications of divestiture on environmental management of port and harbour operations. They proposed that policies to implement education and training and adhering to established management protocols are essential for effective management of associated environmental liabilities (Zhang, 2015b). In Fettweis et al. (2011), the impact of disposal of fine sediments from maintenance dredging works on the suspended particulate matter concentration in a shallow nearshore turbidity maximum was investigated. The paper showed that suspended particulate matter (SPM) concentration can be used as an indicator for environmental changes. Sarma (2015) also studied the siltation problems faced by the shoreline harbors along east coast of India by estimating empirically the sediment transport rates using maintenance dredging records.

To summarize the literature review, very few of these studies provided a comprehensive way to assess the port infrastructure maintenance problem from the sustainable point of view. With the aim of advancing the field of sustainable engineering development, there is a strong need for establishing a detailed framework to highlight all steps that is needed in the maintenance planning. It is found that little attention has been devoted to the research on modeling of deterioration process for port infrastructures. Much more efforts are demanded to further understand this research topic.

3. Framework of developing sustainable maintenance strategies for port infrastructures

In order to derive optimal sustainable maintenance strategies for port infrastructures, it is important to know how sustainable issues can be incorporated in the structural maintenance planning. Normally, the structural maintenance planning is based on a complete structural performance assessment with a full evaluation of all the economic costs. A rational and efficient maintenance procedure needs to be developed based on the life-cycle management concept (Ortiz et al., 2009; Tsai and Chang, 2012). Referring to the fundamental knowledge of life-cycle management (PIANC, 1998), the framework of developing sustainable maintenance strategies for port infrastructures is proposed herein.

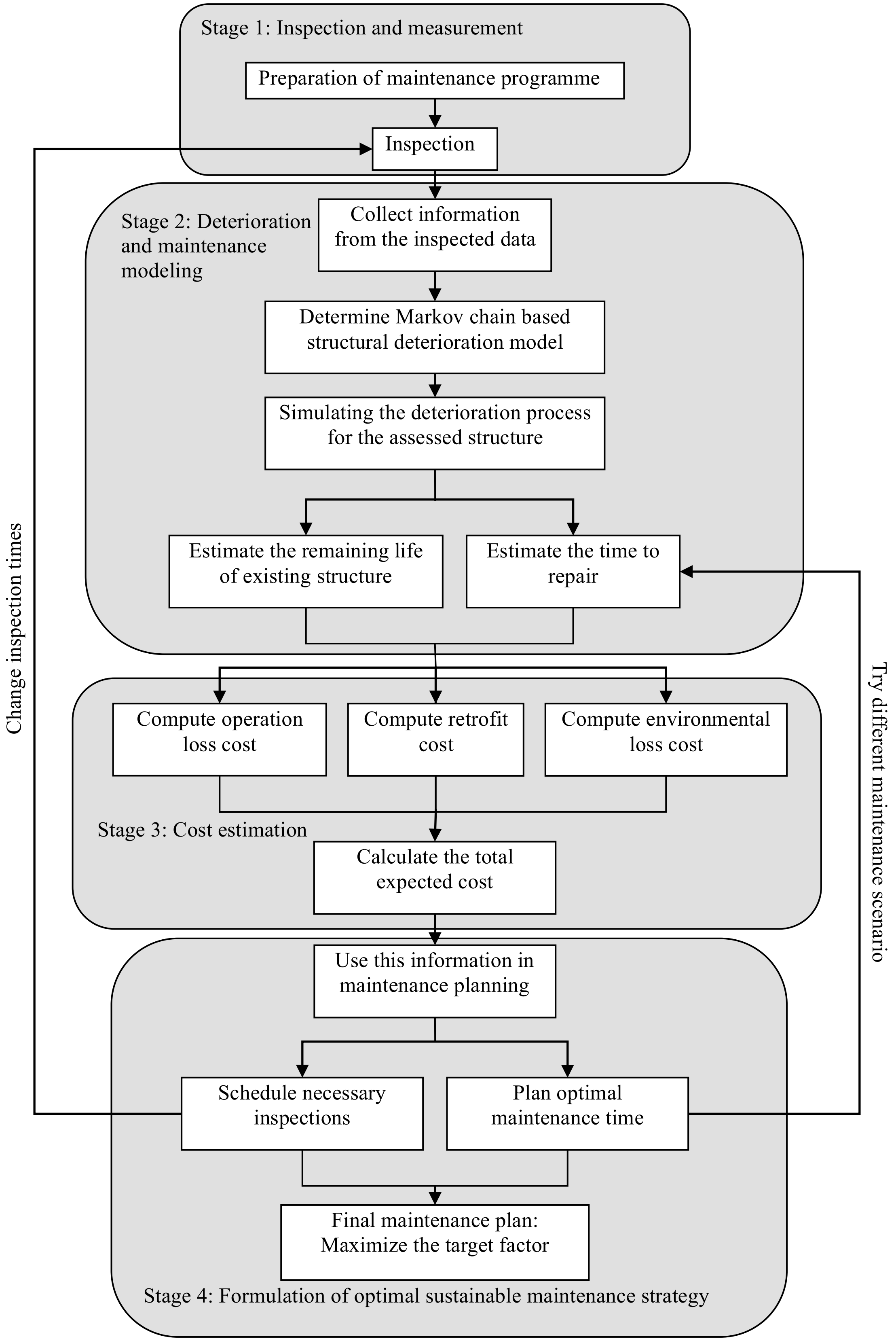


Figure 1. Flowchart for optimal sustainable maintenance planning.

The whole framework can be divided into the following four stages which include both engineering analysis and economic evaluation in the assessment:

1. Standardized inspection of current status of the infrastructures;
2. Estimate remaining service life and predict future performance of the deteriorated structures and components;
3. Analytically quantify the cost in the maintenance works including economic, environmental and societal considerations;
4. Assess the maintenance strategies and find the optimal solution based on the target factor.

Figure 1 illustrates the flow of the whole maintenance planning process. The present work aims to investigate the maintenance actions associated with port infrastructures; however, the framework can be utilized in other structural maintenance management which also needs to consider sustainable issues.

4. Inspection and measurement

The initial step in the maintenance planning is to monitor all the port infrastructure elements. In the first step of the framework, the performance of the port infrastructure elements including current health condition, initial condition and service time are necessarily identified. The information of initial and current health conditions could provide the extent of deterioration occurred in the structural elements. Following the deterioration theorem, the physical deterioration model for the structural elements can be derived based on the information of service time.

Most of the time, the inspection results are recorded as conditional ratings for the structural elements. Many technical standards and commentaries for the inspection procedures of port infrastructures have already been provided (Kong et al., 2013). The most widely accepted rating assessment is developed from the classical reliability concept. Each structural element's reliability is evaluated based on the inspected site data. Then by comparing the derived reliability with the reference value, the results can be further mapped onto a scale of certain grades. Thus, the condition of the structural elements can be simply represented by a characteristic grade.

Moreover, for convenience, the grading is usually converted to a structural health index (SHI) for guiding the maintenance management. For example, if four grades are used to evaluate the structural elements, the following equation is a typical calculation of this indicator (Zhang et al., 2016)

$$SHI = 1.0 \times G_d + 0.75 \times G_c + 0.50 \times G_b + 0.25 \times G_a \tag{1}$$

where G_d, G_c, G_b and G_a are the percentages of the structural elements having health conditions from Grade *d* ("Very good") to *a* ("Very bad"), respectively. Here, the values of coefficients multiplied with all the grades are chosen arbitrarily. It can be modified according to personal preferences or grading importance.

Depending on SHI values, the maintenance actions can be scheduled according to the health condition of the infrastructure. Once the SHI value reduces to a value lower than the required level, maintenance actions would be required to recover the structural strength. After maintenance, another cycle of deterioration will start. A typical example of this process can be illustrated in Fig. 2.

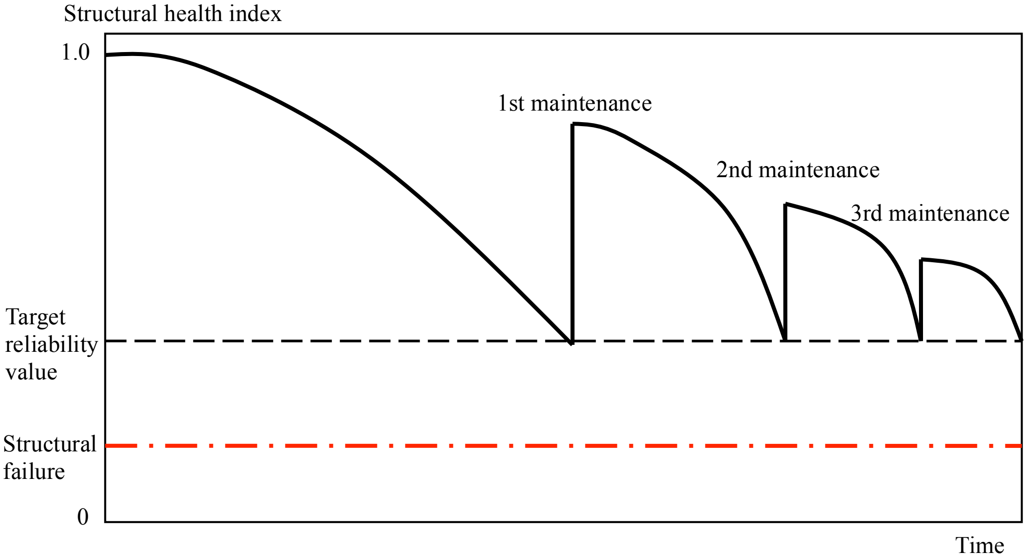


Figure 2 SHI based maintenance actions

However, the SHI based maintenance strategy is too simple which could only provide limited information. The deterioration process could not be realized by the SHI curve and thus the future performance of the structure cannot be predicted. A method that is capable to perform structural deterioration analysis is demanded in the next stage of the maintenance planning.

5. A randomized Markov chain deterioration model

The best way to determine and improve the prediction of future performance of deteriorated structure is through a simulation study. Markov chain model is proved to be an efficient and widely applied simulation approach for various engineering deteriorating structures in the literature (Saydam and Frangopol, 2015; Fang et al. 2016). In a Markov chain model, the structural deterioration process is considered as structural state changes over discrete time intervals. The transition from one state to the other is treated as random which is characterized by a probability. Such transition probabilities are assembled into one matrix, namely transition probability matrix [***P***]. Based on this transition probability matrix, the structural condition $\{S_t\}$ at time t can be developed from that at time t-1 as follows

$$\left\{S_t\right\}=\left[P\right]\left\{S_{t-1}\right\} \tag{2}$$

where S_{t-1} and S_t represents the structural condition vector at time $t-1$ and t which can be described by a vector including all the grading for structural health condition. For example, if four grades as mentioned in Eq. (1) are used to assess the structure, the condition vector should be expressed as $\left\{S_t\right\}=\left\{G_d, G_c, G_b, G_a\right\}^{\mathrm{T}}$.

Normally, port infrastructure inspection is conducted every one to five years. It is common to believe that the structure will not deteriorate too much between two consecutive inspections. For this reason, the Markov chain based deterioration model will not consider the case that structure deteriorates two grades between two consecutive inspections. Under this assumption, the transition probability matrix become a matrix having all the elements of zero except for the on-diagonal elements and the elements below them. A typical example of the transition matrix can be presented as the following

$$
\begin{array}{ccc}
\{S_t\} & [P] & \{S_{t-1}\} \\
\begin{bmatrix} G_d(t) \\ G_c(t) \\ G_b(t) \\ G_a(t) \end{bmatrix} = & \begin{bmatrix} 1-P_{dc} & 0 & 0 & 0 \\ P_{dc} & 1-P_{cb} & 0 & 0 \\ 0 & P_{cb} & 1-P_{ba} & 0 \\ 0 & 0 & P_{ba} & 1 \end{bmatrix} & \begin{bmatrix} G_d(t-1) \\ G_c(t-1) \\ G_b(t-1) \\ G_a(t-1) \end{bmatrix}
\end{array}
\tag{3}
$$

where P_{dc}, P_{cb} and P_{ba} indicate the transition probability of changes for structural conditions $G_d \rightarrow G_c$, $G_c \rightarrow G_b$ and $G_b \rightarrow G_a$, respectively.

Therefore, Eq. (3) can be used to estimate the life cycle performance of port infrastructures. For example, the initial health condition of a newly built structure can be formulated as $\{S_0\} = [1,0,0,0]^{\mathrm{T}}$. Then the health condition of the infrastructure after t time interval of operation can be predicted as

$$\{S_t\} = [P]^t \{S_0\}. \tag{4}$$

Once the current health condition $\{S_t\}$ is estimated, the maintenance management can be conducted based on the comparison of $\{S_t\}$ with a target reference level.

Unfortunately, the transition probabilities are usually unknown in real practice. The transition probability matrix has to be determined from a reverse calculation based on accumulated inspection data. Assuming there is a dataset containing several inspections $\{S_t\}_{\text{Inspection}} = \left[G_d^t, G_c^t, G_b^t, G_a^t\right]^{\mathrm{T}}$ of an existing infrastructure at different discrete times t=1,…,i, the transition probability matrix can be estimated by comparing it with the theoretical structural condition vector $\{S_t\}_{\text{Predicted}}$. This can be done by minimizing the following equation

$$\Theta = \arg\min \sum_{t=1,\ldots,i} \left[\{S_t\}_{\text{Inspection}} - \{S_t\}_{\text{Predicted}}\right]^2 = \sum_{t=1,\ldots,i} \sum_{j=a,\ldots,d} \left[G^t_{j,\text{Inspection}} - G^t_{j,\text{Predicted}}\right]^2 \tag{5}$$

where $\Theta = \{P_{dc}, P_{cb,} P_{ba}\}$ denotes the set of transition probabilities which needs to be determined. Once the transition probability matrix is confirmed, the structural condition at any given time can be calculated by using the initial state condition, e.g. $\{S_t\}_{\text{Predicted}} = [P]^t \{S_0\}$.

In the minimization process in Eq. (5), all the transition probabilities in the Markov chain model are considered to be deterministic. In fact, port infrastructural deterioration process is never homogeneous. In other words, the structural deterioration rate is time varying and can change a lot during the whole life service time of the infrastructure. The determined transition probabilities in Eq. (5) are only an averaged value for the entire observed time. When predicting the health condition of port infrastructures, the uncertainties in the deterioration process must be considered. To deal with this issue, a Markov chain model using random transition probabilities is proposed in this work. Instead of utilizing only the mean, the randomness of the transition probabilities is brought into consideration in this novel approach. That is, all the transition probabilities will be modeled as random variables. A stochastic term will be added to the mean values of transition probabilities to represent the probabilistic nature. Therefore, the transition probability matrix is refined to a random matrix containing several variables as the following

$$\begin{array}{cccc} \{S_t\} & & [P] & \{S_{t-1}\} \\ \begin{bmatrix} G_d(t) \\ G_c(t) \\ G_b(t) \\ G_a(t) \end{bmatrix} & = & \begin{bmatrix} 1-P_{dc}-\varepsilon_{dc} & 0 & 0 & 0 \\ P_{dc}+\varepsilon_{dc} & 1-P_{cb}-\varepsilon_{cb} & 0 & 0 \\ 0 & P_{cb}+\varepsilon_{cb} & 1-P_{ba}-\varepsilon_{ba} & 0 \\ 0 & 0 & P_{ba}+\varepsilon_{ba} & 1 \end{bmatrix} & \begin{bmatrix} G_d(t-1) \\ G_c(t-1) \\ G_b(t-1) \\ G_a(t-1) \end{bmatrix} \end{array} \tag{6}$$

where ε_{dc}, ε_{cb} and ε_{ba} are random terms associated with the transition probabilities. Normally, stochastic characters of these noisy terms have to be determined from inspection data. From experiences, the determined transition probabilities are usually having a variation that has a coefficient of variation around 10~20% (Zhang et al., 2016).

Therefore, the steps of developing a Markov chain model with random transition probabilities can be given as follows. First of all, for each inspected data, the transition probability matrix is estimated based on Eq. (5) in a conventional manner. Then a group of estimated transition probability matrixes can be assembled. Secondly, probabilistic analysis is applied to the estimated transition probabilities and the most appropriate statistical models are identified. Finally, with the developed random transition probabilities, Monte Carlo simulations can be conducted to simulate various possible Markov chain based deterioration processes for the inspected infrastructure. The port infrastructural performance would thus be predicted based on these simulated results.

6. Life cycle cost estimations

The deterioration model provides the necessary information for the time of performing the maintenance works. If these maintenance actions can be expressed in monetary terms then an optimal planning or decision will be the one that minimizes the life cycle cost of the investigated port infrastructure. Generally, the overall cost resulted from maintenance activities can be classified into three categories, namely, costs due to retrofitting, operating loss and environmental loss.

6.1 Cost due to retrofitting

The retrofit cost is the direct cost incurred by the maintenance works. It depends on the type and methods of repairs applied on the infrastructures. For concrete structures, the most commonly adopted maintenance strategies are cross section restoration and surface coating. Both strategies include expenses of repair materials and labour charges (Stephan et al., 2013). In cross section restoration, the concrete grouting is usually employed. The cost of this maintenance scenario can be estimated based on the volume of used concrete. This is given in the following equation

$$C_{retrofit} = c_{labour}\Delta t + c_{concrete}Ad \, , \tag{7}$$

where c_{labour} is the average labour cost per hour (e.g. US\$/hour), $c_{concrete}$ is the cost of concrete used for repair in unit of US\$/m^3, Δt is the total time of repair in hours, A (in m^2) and d (in m) are the area and thickness of restored concrete sections.

However, there are some minor differences in calculating the surface coating cost. Compared with cross section restoration, surface coating uses epoxy spray instead of mortar grouting. A slight change should be made to the above equation for calculating the material cost. This is given as below

$$C_{retrofit} = c_{labour}\Delta t + c_{coating}A_{beam} , \tag{8}$$

where $c_{coating}$ denotes the cost of surface coating per unit area (e.g. US\$/m^2) and A_{beam} represents the total area of beam surface coating. Thus, the material cost is solely depending on the repaired area. The labour cost and the time of repair have an inverse dependent relationship. For example, if more people are working in the maintenance (e.g. higher c_{labour}), the total time of retrofit can be reduced (e.g. lower Δt). The cost depends on the man power, economic budget, and the techniques of repair, among other factors. Additionally, it should be noted that the labour cost also represent the cost of transporting the repair material, removing the corroded areas and applying new paint. The direct cost includes all the expenses for conducting the maintenance works.

6.2 Cost due to operating loss

In the case of repairing the infrastructural elements, maintenance activities are implemented on the berths of the port. These require control for the ships in the harbor. Depending on many factors, such as daily arrival rate of ships, average cargo value and loading/unloading speed, different control procedures will lead to completely different port disturbance and economic loss. In this study, for the port under maintenance, it is assumed the control procedure will cause the stoppage of berth service. Therefore, there would be an operating loss to the port for not using the berth areas which undergo repair. This can be estimated on the basis of the income of berths. An equation can be formulated as

$$C_{operation} = c_{port} \frac{A}{A_{total}} \Delta t \, , \tag{9}$$

where c_{port} stands for the income of the port per unit time (e.g. US$/day), A and A_{total} denote the repaired berth area and the total area of the port, Δt denotes the total maintenance time in days. The cost is only to account for the direct operating loss of the port caused by berth stoppage. The indirect loss, such as delay of transportation, is not included in the calculation. The length of maintenance time is depending on various factors including structural types, deterioration extent, repair technology, efficiency of construction management and so on. Normally, it will not take too long in order to guarantee the flow of seaborne transport. For structures having minor damages, the maintenance time is usually less than two weeks. For severe damaged structures, the maintenance time can be longer depending on the situation.

6.3 Cost due to environmental loss

One of the main purposes of this study is to take into account of sustainability concerns in the maintenance strategies for port infrastructures. As defined by World Commission on Environment and Development (1987), sustainable development should meet the needs of the present without compromising the ability of future generations to meet their own needs (Cuellar-Franca and Azapagic, 2012; Chou and Yeh, 2015; Atmaca and Atmaca, 2016). Therefore, a key issue in sustainable development is to provide a balance between the economy and the environment. A procedure which computes the maintenance induced environmental loss is therefore included in this study.

When using concrete as retrofit materials, one has to note that concrete is one of the largest and most visible components in construction waste. For sustainable considerations, it is necessary to include waste generation in the evaluation of the total maintenance cost. However, to compute the waste generated during the whole concrete production process is very difficult, and thus, this study would only calculate the waste produced during the repair operations. An economic loss due tothe generated waste during the repairs of concrete can be calculated by

$$C_{\mathrm{waste}} = c_{waste} r_{waste} \rho_c V_c, \tag{10}$$

where c_{waste} is the cost of the waste in unit of US$/t, r_{waste} is the volume of generated waste for producing 1m^3 of concrete, ρ_c and V_c are the density and volume of used concrete in the unit of t/m^3 and m^3. Normally, the generated waste is came from the concrete spraying and grouting. The amount of concrete is calculated based on the total area of repaired concrete surface.

Another concern in the production of concrete is carbon dioxide emissions. The production of cement results in 7% of the global emission of CO_2 into the atmosphere (IPCC, 2007). The emission of CO_2 is one of the major causes of climate change which should not be ignored. Compared with other generated waste, the emission of CO_2 is much more serious. Therefore, the assessment of the total carbon dioxide emission is a crucial part in sustainable development. To compute this specific environment loss, the following equation is provided

$$C_{CO_2} = c_{CO_2}\rho_{CO_2}E_{CO_2}V_c, \tag{11}$$

where c_{CO_2} is the cost of the environmental metric (e.g. US$/t of carbon dioxide), ρ_{CO_2} is the density of carbon dioxide in the unit of t/m^3, E_{CO_2} is the amount of carbon dioxide released by producing 1m^3 of concrete and V_c is the volume of used concrete for repair in the unit of m^3. In this study, only the emission of CO_2 during the production of repair materials is considered. However, it should be noticed that CO_2 emissions can also be produced during the transportation of materials, equipment and waste. Compared with the CO_2 released during production of concrete, this amount of emissions is quite small and thus ignored in the current study.

The total environment loss include both C_{waste} and C_{CO_2}. The cost is computed based on the repair method of cross section restoration by mortar. In other words, the cost of the total environment loss is estimated in terms of the total concrete used in repairs. If other maintenance strategies, such as surface coating, are utilized, the cost regarding waste generation and CO_2 emissions can be neglected. Meanwhile, it should be realized that the rate of resulting in environment loss per unit of concrete (c_{CO_2}) is different in different locations depending on the local concrete manufacturing techniques. For example, the production of CO_2 can range from 0.65 kg to 0.92 kg per kg of cement across several countries (IEA, 2007). The environment protection technology plays a key role in the cost of environmental loss.

Therefore, the total cost of a maintenance action can be estimated as a summation of $C_{retrofit}$, $C_{operation}$, C_{waste} and C_{CO2}:

$$C = C_{retrofit} + C_{operation} + C_{\mathrm{waste}} + C_{CO_2}. \tag{12}$$

Moreover, maintenance cost of port infrastructures during the whole service life has to be subjected to a discount rate of money at the application time t. Therefore, the present value of the kth maintenance action cost at time t is estimated as

$$C_{PV,k} = \frac{C_{retrofit}}{(1+r)^t} + \frac{C_{operation}}{(1+r)^t} + \frac{C_{\mathrm{waste}}}{(1+r)^t} + \frac{C_{CO_2}}{(1+r)^t}, \tag{13}$$

where $C_{PV,k}$ is the present value of the kth maintenance action at time t, r is the discount rate of currency.

The discount rate is usually determined by the annual changing rate of producer price index (PPI) and social discount rate. Based on the model proposed by Cady (1983), the discount rate r_i for a particular year can be expressed as

$$r_i = \frac{i_{ci} - f_i}{1 + f_i}, \tag{14}$$

where f_i is the annual changing rate of PPI, i_{ci} is the social discount rate. To evaluate the total cost of a single maintenance, the discount rate has to be estimated from the economic condition of the country where the port belongs to. The time varying effects should also be considered when estimating the social discount rate and annual changing rate of PPI.

7. Decision making based on utility function

The final challenge in the port infrastructure maintenance planning development is to find out the best strategy among all the optional maintenance strategies. To achieve an optimal maintenance strategy, a consistent criterion for measuring the benefit of a maintenance program should be established. The formulation of a utility function can be employed to provide the decision maker the information of the relative value for different maintenance strategies. The maintenance strategy that has a high utility value corresponding to relatively small maintenance cost is generally preferred to those with small utility values (Dong et al., 2015). Giving the risk attitude of the decision maker and the maximum budget, a utility function associated with the maintenance cost can be formulated. The value of utility function for a given maintenance cost can be computed as (Ang and Tang, 1984)

$$u_c = \frac{1}{1 - \exp(-\lambda)} \left[1 - \exp\left(-\lambda \frac{C_{budget} - c}{C_{budget}} \right) \right], \tag{15}$$

where C_{budget} is the maximum budget that the port manager can afford, λ is the risk attitude of the decision maker (i.e. $\lambda>0$ indicates risk-averse, $\lambda=0$ indicates risk-neutral, $\lambda<0$ indicates risk-taking), and c denotes the total expected maintenance cost. The value specification of λ must be accurate and should reflect the risk behavior of humans. A more detailed procedures in finding this value can be found in Hillson and Murray-Webster (2007). The expected maintenance cost should not be larger than the maximum budget and therefore the utility function can always take values between 0 and 1. Based on Eq.(15), the optimal solution can be derived from the comparison of utility values for all the choices of maintenance plans. For example, for the same decision maker, a maintenance plan with lower cost will always yield a higher utility than that produced from a higher cost maintenance plan.

8. Case study – Tokyo port

To demonstrate the proposed framework, the port infrastructure of Tokyo is assessed for its long term maintenance planning in the following investigation. The selected infrastructure is an open-type wharf lying in the Tokyo bay. It was built in 1977 and began its service in 1979. The wharf is designed for a water depth of 12 meters with the main purpose of automobile export. The total length is about 300 meters which aims to provide service to vessel with the size up to 35000 DWT. Main components in all the berths are concrete beams and concrete slabs as shown in Fig. 3. More detailed information regarding the port infrastructure elements can be found from MLITT (2011).

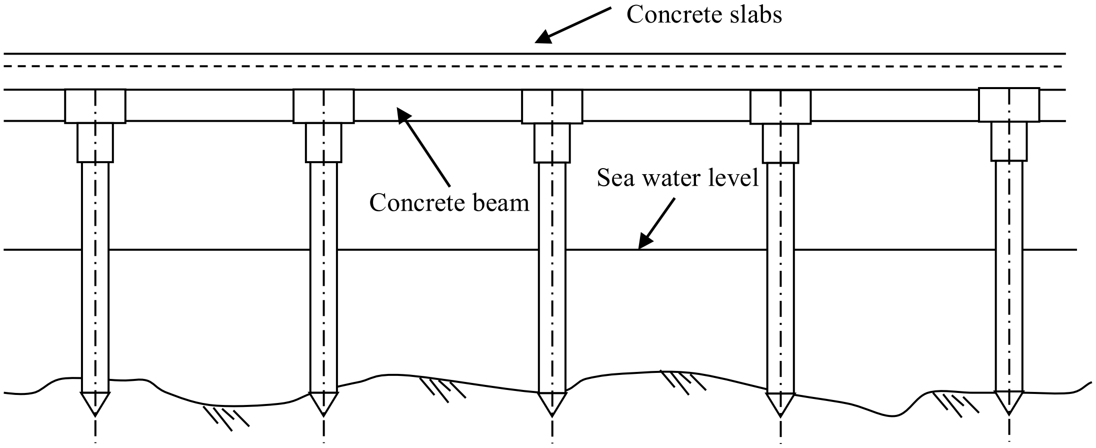


Figure 3. Structural components in a wharf

8.1 General information and inspection data

The wharf is initially designed for a service life of 50 years (until year 2029). However, its service time was later decided to be extended so as to sustain smooth port operation. Therefore, the port infrastructure management conducted several inspections on the deteriorated structures around year 2001. For slabs, the inspections are conducted in the years 1999, 2001 and 2004. For beams, the inspections are conducted in the years 1999, 2001, 2004, 2006 and 2007. The quality of each elements and the overall grading were all recorded during these inspections. Since all the structural materials are concrete, the port management has established the same guideline for structural grading. As the easiest way to inspect the port infrastructure is visual inspections, the criteria in the grading are also set accordingly. For the concrete slabs, the total cracking area is employed as a measure of the structural damages. For concrete beams, the cracking width along the reinforcement is used as an indicator of damages. Both structural elements are graded into four grades from Grade *a* ("Highly deteriorated") to Grade *d* ("No deterioration"). Thus, the initial condition of all the structural elements is graded as "*d*". If any cracks are noticed, the structure will be degraded. These are explained in Table 1.

Table 1. Basic information for deterioration grading

Grade	Criteria	Basic policy	Comments
a	Slab: Map cracking (over 50%) Spalling off of concrete cover Heavy rust stain Beam: Crack along reinforcement with width of larger than 3mm Spalling off of concrete cover Heavy rust stain	Performance of component is seriously degraded	-
b	Slab: Map cracking (less than 50%) Much rust stain Beam: Crack along reinforcement with width of less than 3mm Much rust stain	Performance of component is degraded	-
c	Slab: One directional crack or gel extraction Partially extended rust stain Beam: Vertical crack to longitudinal direction Partially extended rust stain	Performance of component is slightly degraded	Short term unavailability of the service caused by partial repair is allowed. Long term unavailability of the service caused by the countermeasures or renewal would interfere port operation.
d	Nothing observed	Performance of component is not degraded	Any deterioration is not allowed, which largely influences safety. Long term unavailability of the service caused by countermeasures or renewal would interfere port operation.

Based on these categorizations, the historical inspection data can be graded. The recorded data in this study includes the inspections for all the concrete slabs and concrete beams in the wharf. The data are recorded for each block area in the wharf respectively. Therefore, the grades are also given to each block area instead of all the structural elements. A typical inspection result of concrete slabs in the year 2001 is illustrated in Fig. 4. From the figure, it can be recognized that most parts of the wharf have been downgraded to Grade *c* except some parts experienced highly deteriorations to Grade *b* or *a*.

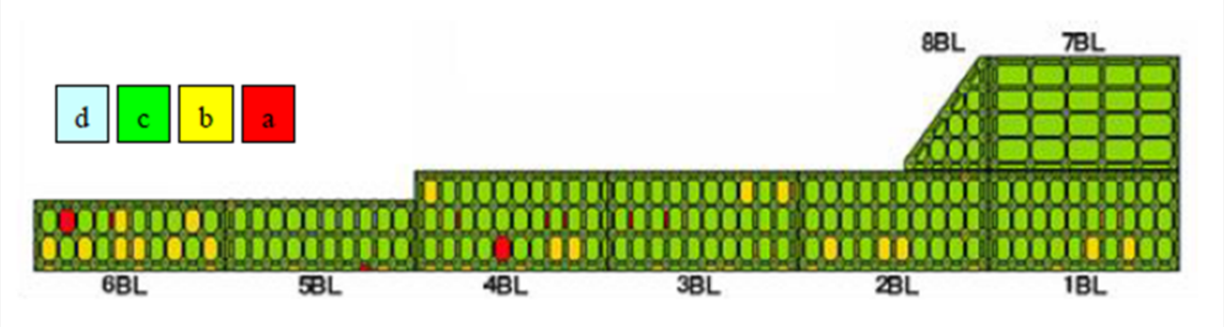


Figure 4. Inspected results of deteriorating grades for the concrete slabs in 2001

Meanwhile, the port management has also provided the maintenance limit for the concrete structural elements. As shown in Table 2, both concrete slabs and concrete beams have the same maintenance limit (Grade *c*). However, the repair methods are different between concrete slabs and concrete beams. The cross section restoration is the major repair strategy for concrete slabs while surface coating is the dominant repair method for concrete beams. The differences in the maintenance guidelines will lead to different economic estimations. This information will be further utilized in the cost estimations.

Table 2. Maintenance timing and strategy for concrete component

Component	Maintenance limit	Repair policy	Repair methods
Slab	Grade *c*	Removal of deteriorated parts Suppression of corrosion progress Improvement of load bearing capacity	Cross section restoration by mortar: concrete grouting; concrete spraying
Beam and bottom deck	Grade *c*	Suppression of corrosion factors Removal of deteriorated parts	Surface coating

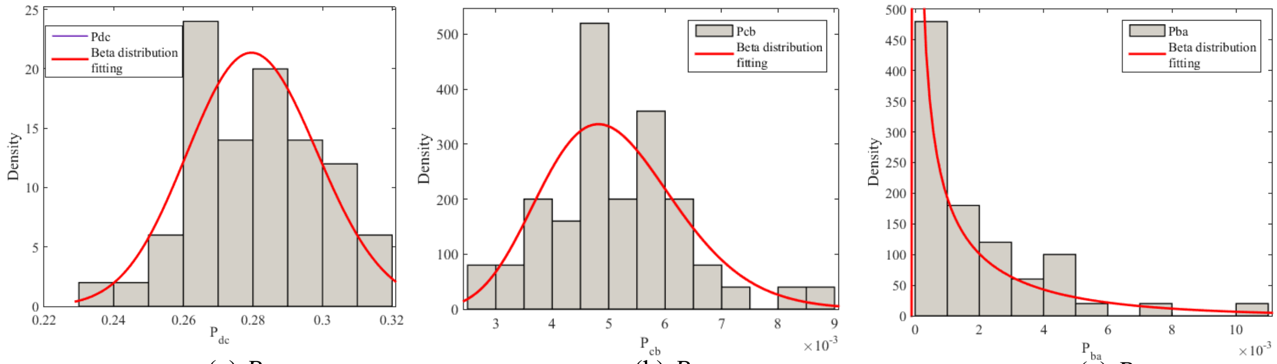
8.2 Deterioration and maintenance analysis

Following the procedure in Section 5, the inspection data is assembled to estimate the transition probabilities. The inspected data forms the observed structural condition vector $\{S_t\}_{Inspection}$. The theoretical estimate of the structural condition vector $\{S_t\}_{Prediction}$ is calculated based on Eq. (4). The transition probabilities are determined based on the minimization provided in Eq. (5). Here, the transition probability matrix in the Markov chain model represents the likelihood of structural health condition changes during one year. In other words, the transition probabilities describe the structural health condition changes between two consecutive years. Since concrete slabs and concrete beams suffer from different extent of deterioration, two separate Markov chain models are used to model their deterioration processes. The histograms of the computed transition probabilities are depicted in Figs. 5 and 6. From these figures, a large difference in the transition probabilities between different grades can be observed. The estimated transition probabilities for both slabs and beams show that P_{dc} is larger than P_{cb} and P_{cb} is larger than P_{ba}. This indicates an increase in deterioration rate of the infrastructure during its whole deterioration process. In other words, this implies that the infrastructural deterioration process is very fast at the beginning but gradually becomes slow when infrastructure is highly deteriorated. Another observation is that the variance of the transition probability increases from P_{dc} to P_{ba}. This reveals a fact that the uncertainties associated with the transition probabilities in Markov chain model tend to increase when deterioration time is increasing.

To further model the random properties of transition probabilities, Beta distribution is applied to fit the estimated values in this study. As discussed in Section 5, the values of transition probabilities are bounded by 0 and 1, therefore, Beta distribution is considered as a proper choice for fitting the transition probabilities. The probability density function of Beta distribution is given as

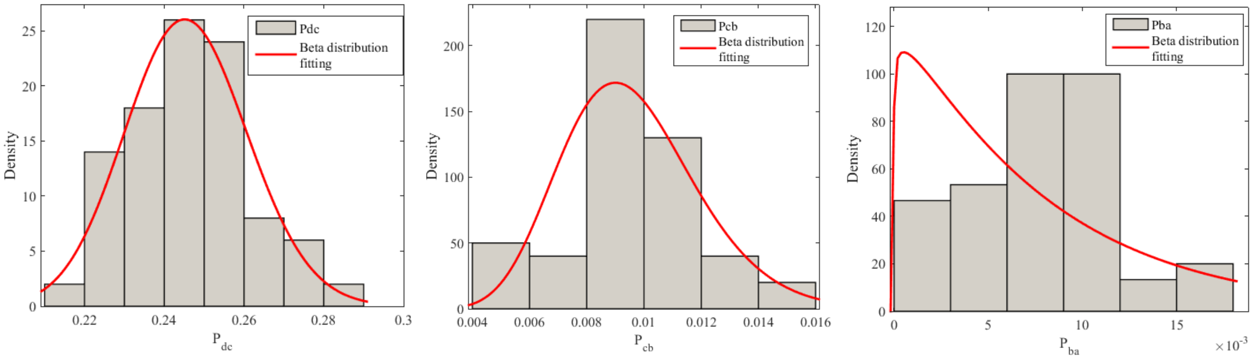
$$f\left(x \mid \alpha,\beta\right) = \frac{1}{B\left(\alpha,\beta\right)} x^{\alpha-1}\left(1-x\right)^{\beta-1} \quad for \;\; x \in \left(0,1\right) \tag{16}$$

where $B(.)$ is the beta function, α and β are the shape parameters of the Beta distribution. The fittings to the estimated transition probabilities are illustrated in Figs. 5 and 6.



(a) P_{dc} (b) P_{cb} (c) P_{ba}

Figure 5. Beta distribution fittings to the estimated transition probabilities for concrete slabs



(a) P_{dc} (b) P_{cb} (c) P_{ba}

Figure 6. Beta distribution fittings to the estimated transition probabilities for concrete beams

Therefore, by utilizing the fitted distribution models, Monte Carlo simulations can be conducted to simulate the deterioration processes for both concrete slabs and concrete beams. In order to present the structural deteriorations in a comprehensive way, the structural health index (SHI) is utilized. Equation (1) is employed herein to calculate the SHI. A number of 1000 simulations are performed to simulate a period of 30 years for both the concrete slabs and concrete beams. These simulated results are plotted in Fig. 7. As expected, all the simulated SHI values undergo a similar trend over the time. However, the SHI values drop faster in concrete beams compared to concrete slabs which imply a higher deterioration rate in concrete beams. Meanwhile, it can also be observed that the variance of simulated SHI values becomes larger when time increases. Both concrete slabs and concrete beams show the same phenomenon. The reason is because of the chain effect which could amplify the deterioration model uncertainties in the long term. Thus, the randomness of the structural long term health condition is very large. This also explains why frequent maintenance actions are needed for highly deteriorated structures.

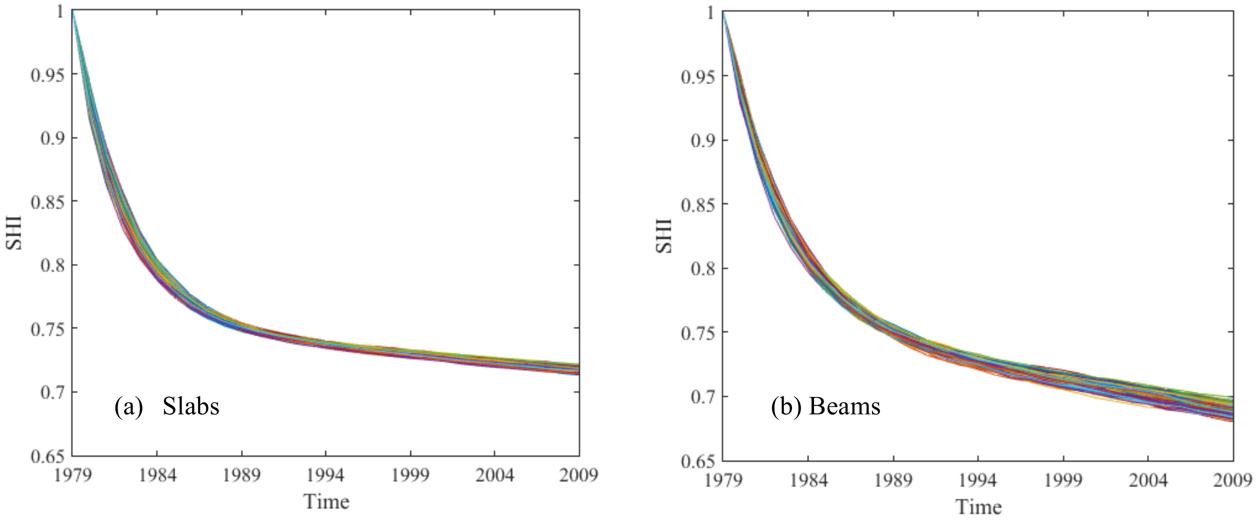


Figure 7. Simulated 1000 deterioration processes for inspected concrete slabs and beams (each line represents a simulated deterioration process)

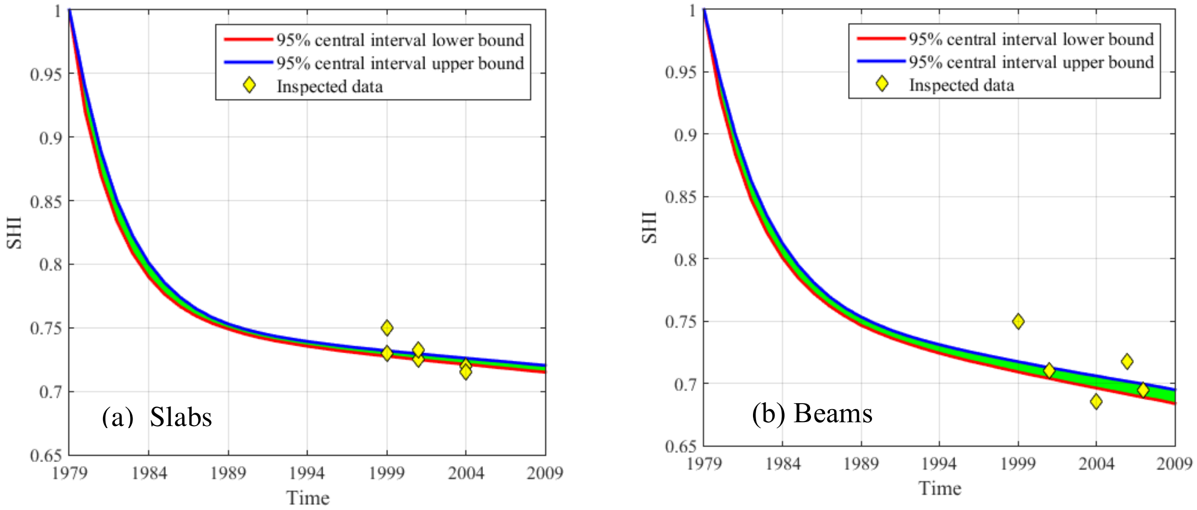


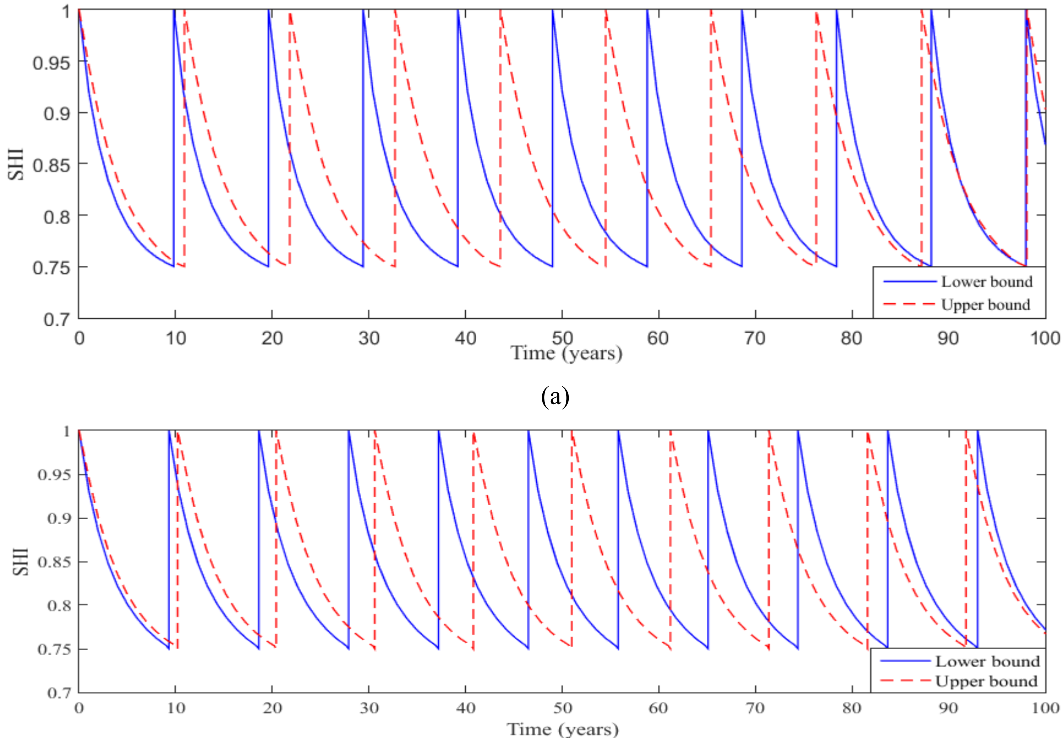
Figure 8. Comparison of simulated deteriorating SHI values with inspection data for (a) concrete slabs and (b) concrete beams (shaded area represents the central 95% interval from 1000 simulated data)

However, knowing the deterioration pattern is never enough for maintenance management. From the practical point of view, the uncertainty quantification of the deterioration process would be more meaningful. Realizing this, the central 95% interval of the simulated data in each year is utilized for reference. This creates an upper bound and a lower bound for the estimates as shown in Fig. 8. In order to show the accuracy of the proposed approach, the original inspected data for concrete slabs and concrete beams are also plotted in the figure. It can be observed that, the inspected data closely lies around the simulated data. The differences between the inspection and simulated bounds are quite minimal. This has validated the applicability of the proposed randomized Markov chain model.

The derived deterioration model can provide an estimate for maintenance actions. As required by the port, the maintenance limit of concrete slabs/concrete beams is Grade *c*. Therefore, the timing for starting the maintenance actions can be estimated from the simulations. For instance, in this case, the maintenance action should start at the time when SHI values drop to 0.75. The statistics of the estimated results are recorded in Table 3. Based on the massive simulations, the bounds for the number of years with a maintenance action can be simply evaluated. For concrete slab, it has a prediction of the cyclic maintenance time of about 9.8 years to 10.9 years which is slightly larger than concrete beams whose cyclic maintenance time is around 9.3 years to 10.2 years. This agrees well with the observation in the deterioration simulation which shows that concrete beams deteriorate faster and, therefore, demand more frequent maintenance works. A comparison between the proposed approach and the traditional Markov chain model is also provided in Table 3. The prediction of the time when SHI value drops to 0.75 is also calculated in the traditional way. That is, the values are based on Monte Carlo simulations from a standard Markov model, which does not consider any randomness associated with the transition probabilities. It can be seen from the results that the estimated time range becomes much narrower compared to the proposed approach. The standard deviation also becomes smaller indicating smaller variations associated with the results. The other statistics including skewness and kurtosis are quite close to the developed approach. Generally speaking, the predictions from the traditional Markov model are much less uncertain. Therefore, we could see the amount of uncertainties that has been ignored in the traditional Markov model is quite large. If the traditional Markov model is utilized for this study, the estimated results will not be reliable as uncertainties associated with transition probabilities are not fully captured.

Table 3 Estimated times for conducting maintenance actions

	SHI values	Predicted time range	Mean	S.D.	Skewness	Kurtosis
with random transition probabilities						
(ii) Slab Grade c	0.75	9.8 yrs ~ 10.4 yrs	9.9 yrs	0.29	0.20	0.18
(iii) Beam Grade c	0.75	9.3 yrs ~ 10.2 yrs	9.8 yrs	0.41	0.10	0.11
Without random transition probabilities						
(ii) Slab Grade c	0.75	9.9 yrs~10.2 yrs	10 yrs	0.15	0.21	0.25
(iii) Beam Grade c	0.75	9.6 yrs~ 9.9 yrs	9.8 yrs	0.23	0.14	0.13



(a)

(b)

Figure 9. History profile of port infrastructural conditions under maintenance actions for (a) concrete slabs and (b) concrete beams

Using the estimated maintenance timing, the life cycle profile of port infrastructures can be depicted. Figure 9 illustrates the life cycle profile for both the concrete slabs and concrete beams with 100-year service life. The repeated cycles of maintenance actions (structural health recovery) and deteriorations (structural health reduction) are represented by the SHI value changes. Here, both the upper bound and lower bound of the estimated maintenance timing are used in the profile. These create two paths of SHI values in the profile. The real profile should lie in between these two curves. It shows from

Fig. 9 that the upper bound and lower bound curves become very different when service time increases. For both concrete beams and slabs in the first 100 years of service time, the lower bound has one more cycle than the upper bound. This uncertainty in the number of maintenance works needed for the port infrastructure is well presented in the current model.

8.3 Cost estimations

According to the proposed method in Section 6, the estimation of the cost associated with the port infrastructure maintenance can be performed. To be realistic, this study utilized the real data collected from the Tokyo port. The average labour cost is estimated from the contractor company for a port that is similar to Tokyo (Castalia, 2012). The cost of concrete and surface coating is obtained from the concrete institutes (JCI, 2016). The average daily revenue is estimated by dividing the total annual revenue of the wharf over 365 days based on the Tokyo port annual report (TPTC, 2013). The environmental metric of CO_2 is directly obtained from the IPCC report (IPCC, 2007). For the total area of the port, slabs and beams, the information is collected from the port maintenance guidelines (MLITT, 2011). The waste generation and emission of carbon dioxide for using 1 m^3 of concrete are found from the literature (Bastidas-Arteaga and Schoefs, 2015). In calculating the discount rate, the information of social discount rate and annual changing rate of PPI in Japan are collected from the government annual report (Ministry of Foreign Affairs, 2016; Bank of Japan, 2016). According to the recent statistics (2008-2015), Japan's social discount rate is 2%~5% and annual changing rate of PPI is between 1% and 4 %. Therefore, a range of 1%~4% is a rational prediction of the discount rate *r*. Here, for the maintenance planning, a step function is adopted for the discount rate. This is given as below

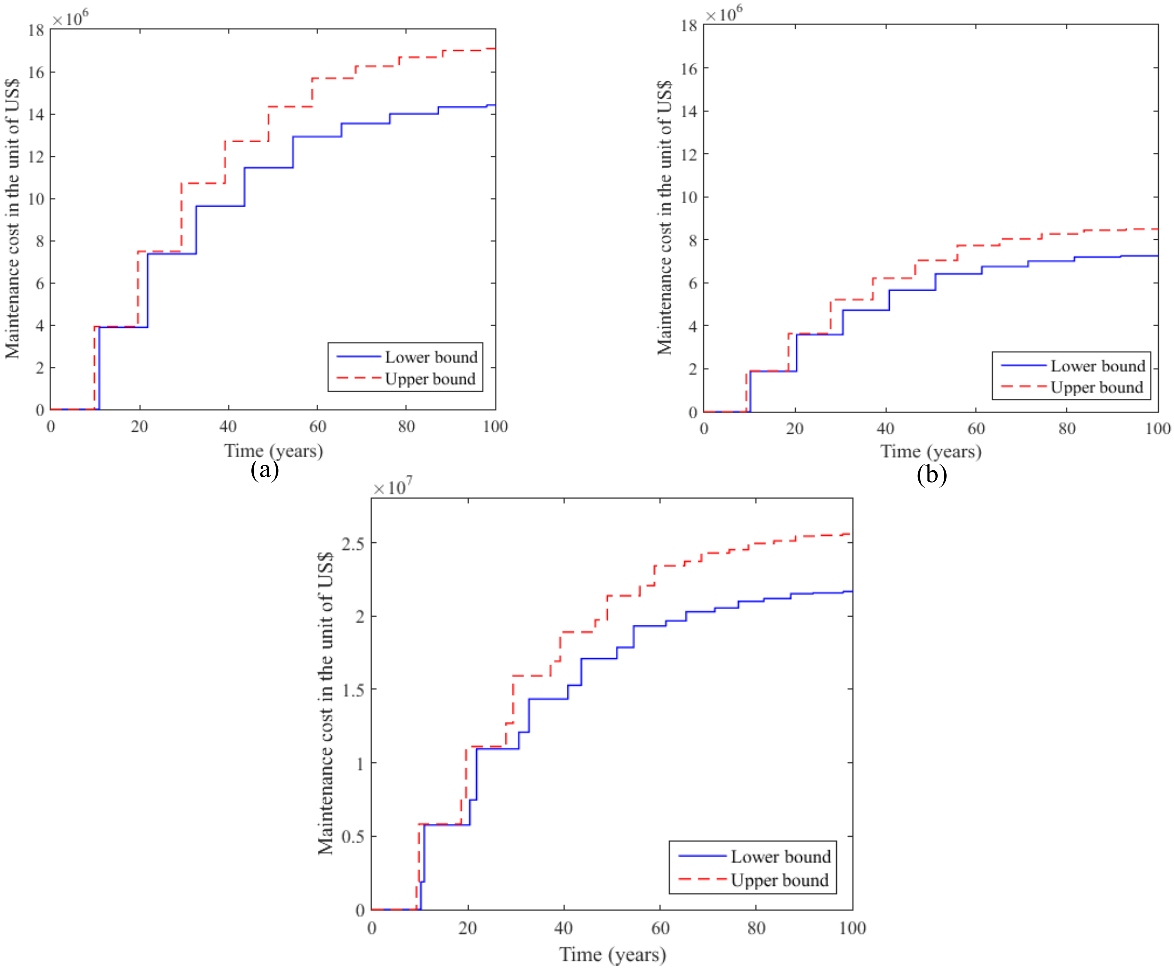
$$r_i = \begin{cases} 1\% & for\, 0-20\, years \\ 2\% & for\, 20-40\, years \\ 3\% & for\, 40-60\, years \\ 4\% & for\, 60-80\, years \end{cases}. \tag{17}$$

More detailed information is provided in Table 4.

Table 4. Parameters to compute the overall cost of port maintenance actions.

Parameter	Values
Average labour cost c_{labour} (Castalia, 2012)	135 US\$/day per person
Cost of concrete $c_{concrete}$ (JCI, 2016)	120 US\$/m^3
Cost of surface coating $c_{coating}$ (JCI, 2016)	35 US\$/m^2
Revenue of the port c_{port} (TPTC, 2013)	413700 US\$/day
Cost of the waste c_{waste} (Bastidas-Arteaga and Schoefs, 2015)	30 US\$/t
Cost of the environmental metric c_{CO2} (IPCC, 2007)	26 US\$/t
Total time of repairs Δt	15 days
Area of restored concrete sections A (MLITT, 2011)	104926 m^2
Thickness of restored concrete sections d (MLITT, 2011)	0.15 m
Area of beam surface A_{beam} (MLITT, 2011)	39347 m^2
Total area of the ports A_{total} (MLITT, 2011)	945700 m^2
Volume of generated waste r_{waste} per 1 m^3 of concrete (Bastidas-Arteaga and Schoefs, 2015)	1.3 m^3
Density of carbon dioxide ρ_{CO2}	1.977×10^{-3} t/m^3
Density of used concrete ρ_c	2.4 t/m^3
Emissions of carbon dioxide E_{CO2} to repair 1 m^3 of concrete (Bastidas-Arteaga and Schoefs, 2015)	313.6 m^3
Social discount rate i_{ci} (Ministry of Foreign Affairs, 2016)	2%~5%
Annual changing rate of PPI f_i (Bank of Japan, 2016)	1%~4%

The overall maintenance cost of concrete slabs and concrete beams are calculated based on the equations given in Section 6 and information provided in Table 4. The time for each maintenance is assumed to be 15 days. By using the deterioration model and the predicted maintenance timing, the cumulative maintenance cost is computed for a period of 100 years. The calculation also includes the lower bound and upper bound which considers the uncertainties associated with the maintenance timing. Based on Eqs. (7)-(13), the overall costs are estimated for the retrofit, operarating loss and environmental loss separately. The cumulative maintenance costs for concrete slabs, concrete beams and the total cost are plotted in Fig. 10.



(a)

(b)

(c)

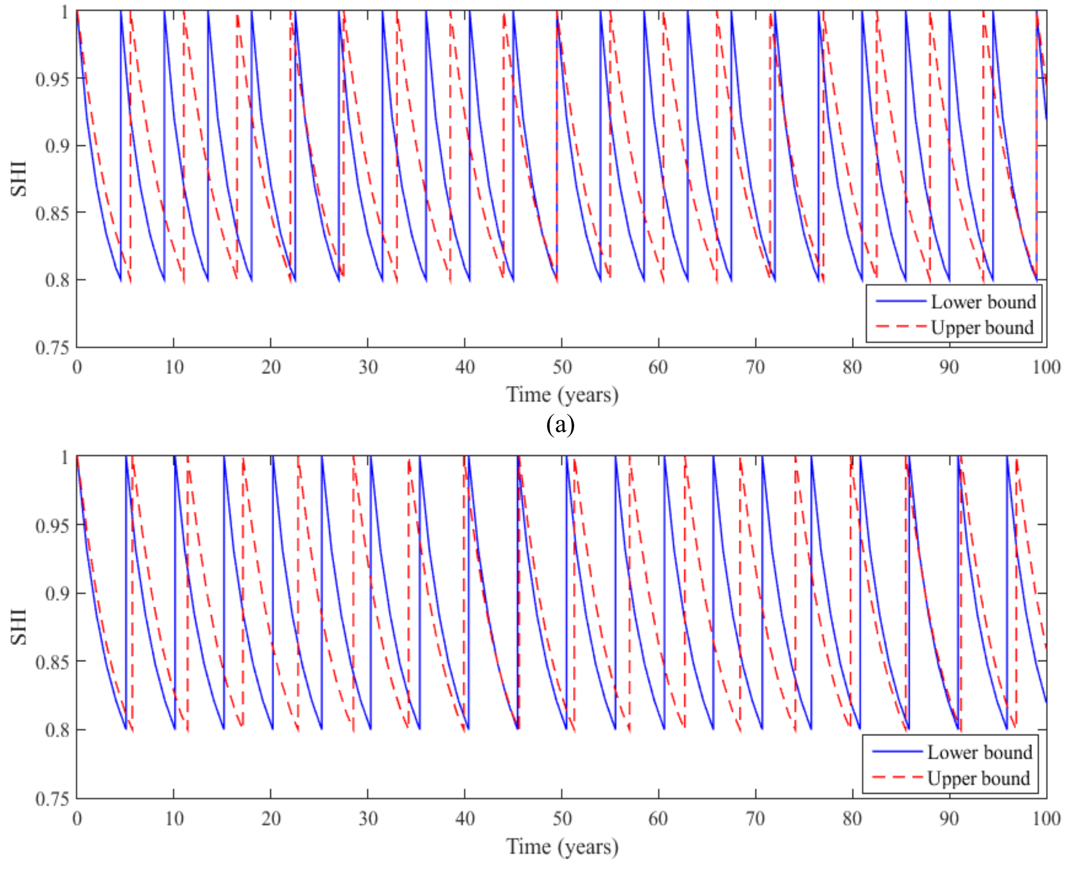
Figure 10. Profiles of cumulative maintenance cost for (a) concrete slabs; (b) concrete beams and (c) total cost of slabs and beams

As can be seen from these figures, the overall cost for concrete slabs is generally higher than concrete beams. This is mainly because more concrete used for repair in slabs compared to beams. Another minor reason is because the deterioration rate in concrete slabs is higher at the beginning deterioration years. The increase of the cumulative maintenance cost becomes slower in the long term. This is mainly because the long term cost is very sensitive to the discount rate. The differences between the upper bound and lower bound are around 2.5 million, 1.3 million and 13.1million dollars for concrete slabs, beams and total cost, respectively. Compared to the mean value, the differences between the upper bound and lower bound are quite significant. Therefore, when making the maintenance planning, the economic uncertainties resulted from the structural deteriorations should be considered. In addition to the analysis of maintenance cost, different components of the total cost are compared. The major component is the retrofit cost which takes a percentage of 51.58%, while the operating loss and environmental loss take percentages of 21.48% and 26.94%, respectively. These estimated percentage values are the same in both the upper bound and lower bound cases. The environmental loss shows its obvious significance in the total cost calculations. The influence of sustainable issues on port infrastructure maintenance is comprehensively reflected using the proposed approach.

8.4 Comparison of different maintenance strategies

The final part is to find a way in selecting the most appropriate maintenance plan among several alternatives. In this section, a comparison study is performed to discuss the way of finding the optimal maintenance strategy. To make a comparison, another maintenance strategy which requires the infrastructure at least to have a SHI value of 0.8 is proposed herein (Strategy 2). That is, maintenance actions will be conducted once an inspection of SHI value of 0.8 is noticed. This is different from the original strategy which only requires the structural SHI value to be higher than 0.75 (Strategy 1). Thus, in this work, these two alternatives are assessed and compared with a full consideration of all the factors. However, it should be pointed out that many other strategies are available in reality. The adopted strategies in this study are designed based on the minimum SHI value. In fact, this minimum SHI value should be determined for certain reasons. For example, 0.75 could indicate a minor repair is needed; 0.5 could indicate a major repair is needed. Therefore, it is not necessary to compare the maintenance strategies for all different minimum SHI values. A comparison between the strategies having the most reasonable minimum SHI values is good enough. The study conducted in this section is aiming to provide the procedures for comparing different maintenance strategies. The optimum decision has to be made based on comparisons among more alternative plans.

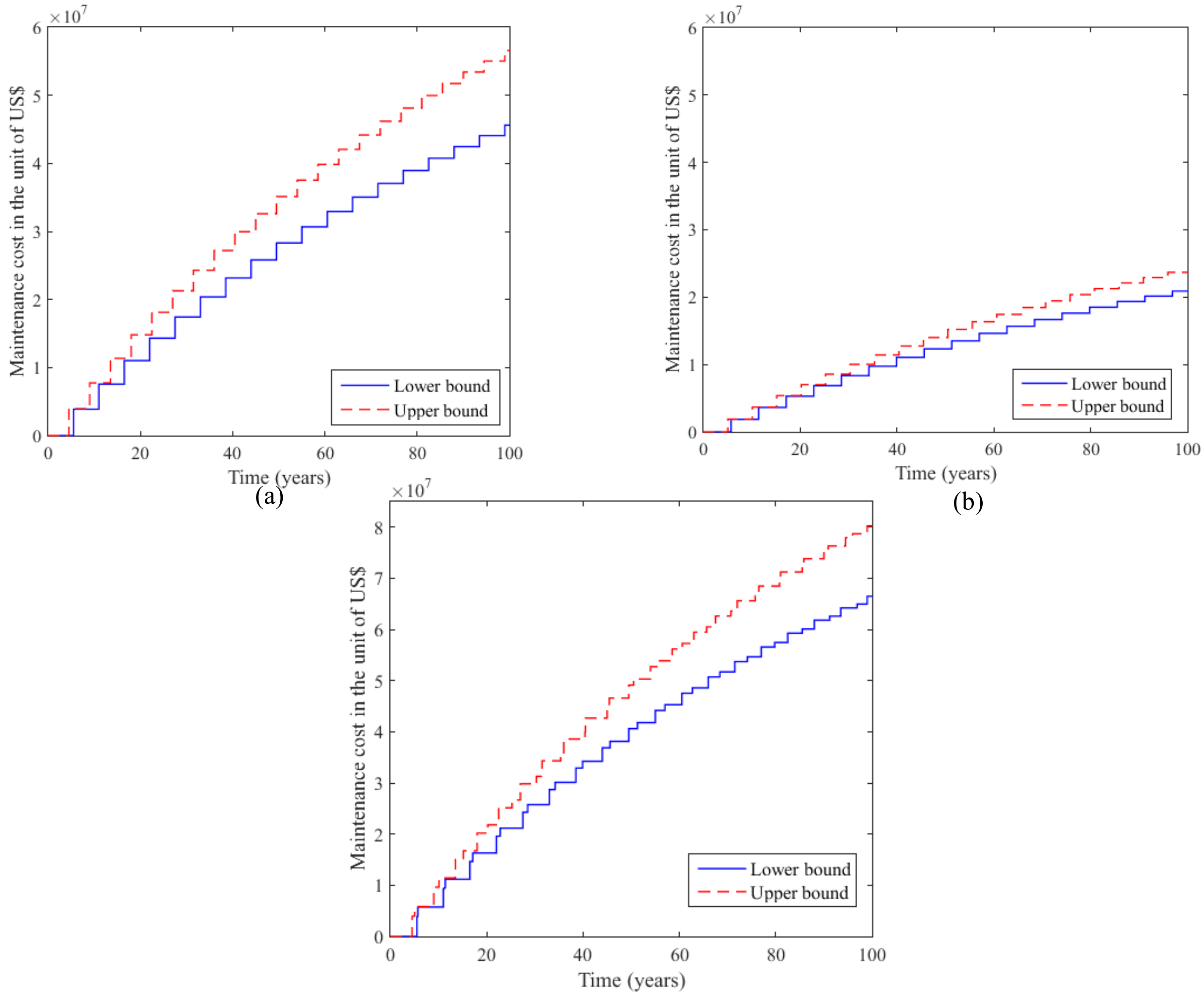
Following the same procedures, life cycle performance of port infrastructure utilizing Strategy 2 can be illustrated in Fig. 11. Based on the same procedures in the cost calculation, the cumulative maintenance cost of maintenance Strategy 2 is estimated for 100 years and plotted in Fig. 12. From the comparison between Fig. 11 and Fig. 9, Strategy 2 is more conservative than Strategy 1 as the average SHI value in Strategy 2 is higher. This is also the reason why more frequent maintenance actions are conducted in Strategy 2. Expectedly, the maintenance cost in Strategy 2 (US66 million ~ US80 million) is much higher compared to that in Strategy 1 (US21 million ~ US25 million). Figure 12 illustrates this fact in the cost estimation. However, when comparing the maintenance strategies, the overall cost is not the only factor. The reliability of port infrastructure to ensure the normal operation of port is also important. There is a need to have a balance between risk and cost.



(a)

(b)

Figure 11. History profile of port infrastructural conditions under maintenance actions (Strategy 2) for (a) concrete slabs and (b) concrete beams



(a)

(b)

(c)

Figure 12. Profiles of cumulative maintenance cost for strategy 2 (a) concrete slabs; (b) concrete beams and (c) total cost of slabs and beams

In order to have a fair comparison between Strategy 1 and Strategy 2, the total maintenance cost of the whole port infrastructure (concrete slabs and concrete beams) for a period of 100 years is used in this assessment. The concept of utility as introduced in Section 7 is utilized herein. Two risk averse attitudes (λ=3, λ=5) are considered in the maintenance plan decision making. Since Strategy 2 is more conservative than Strategy 1, a higher value of risk attitude is given to Strategy 2 (λ=5) and the lower one is given to Strategy 1 (λ=3). In order to compare these two strategies with different budgets, two cases with maximum budget of US$100,000,000 and US$1,000,000,000 are investigated. Basic information of these two strategies is summarized in Table 5. Again, in this approach, the estimated bounds from the randomized Markov chain model are considered in the decision making.

Based on Eq. (15) , the utility values for both strategies under different budget constraints are computed and plotted in Fig. 13 and Fig. 14. The utility curve for risk attitude λ=3 has a higher slope compared with another curve having risk attitude λ=5. This is because a high risk attitude person is more sensitive to the risks while low risk attitude person is more sensitive to the cost. It is also noted that the utility curves tend to be flatted when budget increases from 100 million dollars to 1 billion dollars. More detailed results are recorded in Table 5. Therefore, the most appropriate maintenance strategy can be determined based on the comparison of utility function from these two alternatives. For the case of US100 million budget, Strategy 1 has higher utility values in both the upper bound and lower bound (0.9363~0.9451) compared to Strategy 2 (0.6334~0.5121). However, when the budget changes to US1 billion dollars, Strategy 2's utility values (0.9967~0.9972) tend to be higher than Strategy 1 (0.9951~0.9965). Thus, based on the comparison, Strategy 1 is a better maintenance plan when budget is US100 million dollars whereas Strategy 2 is more preferred when budget is US1 billion dollars.

The reason is that when the monetary budget is limited, the cost becomes a dominant factor in the decision making. However, if the monetary budget is sufficient, the importance of cost is reduced and the risk becomes the dominant factor. Therefore, this maintenance planning is in fact a decision making on a tradeoff between risk and cost. For a port that plays a vital role in the regional economy, the risks of failure in the infrastructures should be the most concerned and thus Strategy 2 should be adopted (providing that budget is enough). On the other hand, if monetary budget is limited for the port maintenance, Strategy 1 should be chosen for the maintenance planning. The decision on which strategy should be utilized is depending on the given condition and manager's attitude towards the risks. Meanwhile, it should be pointed out that the comparison of these two strategies is based on the estimated bounds from the randomized deterioration model. It is not a decision judged only by a crisp value. Therefore, the determined optimized maintenance strategy takes a full consideration of uncertainties from the structural deteriorations.

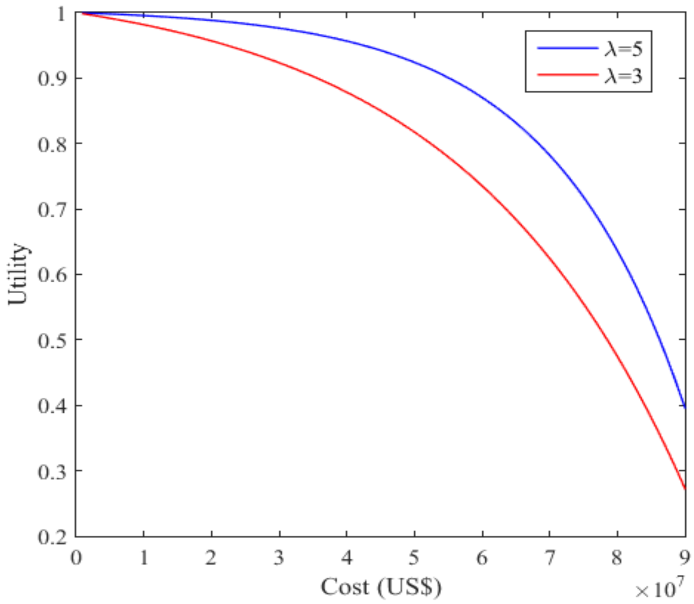


Figure 13. Utility curve for maintenance actions with budget of 100 million dollars

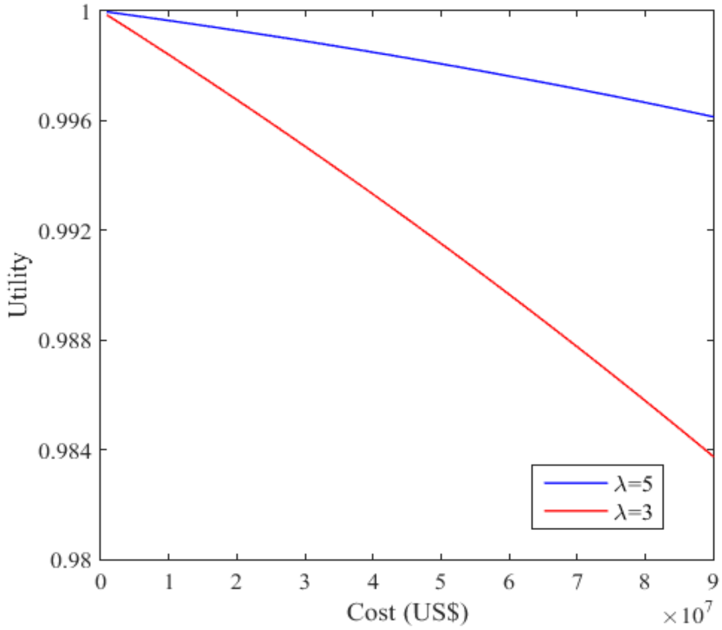


Figure 14. Utility curve for maintenance actions with budget of 1 billion dollars

Table 5. Estimated maintenance cost and utilities for two strategies

		Strategy 1	Strategy 2
Maintenance cost	Lower bound Upper bound	US$21,670,210 US$25,594,151	US$66,498,864 US$80,254,125
Risk attitude (λ)		3	5
Case 1 budget: US$100,000,000			
Utility	Lower bound Upper bound	0.9451 0.9363	0.8121 0.6334
Case 2 budget: US$1,000,000,000			
Utility	Lower bound Upper bound	0.9965 0.9951	0.9972 0.9967

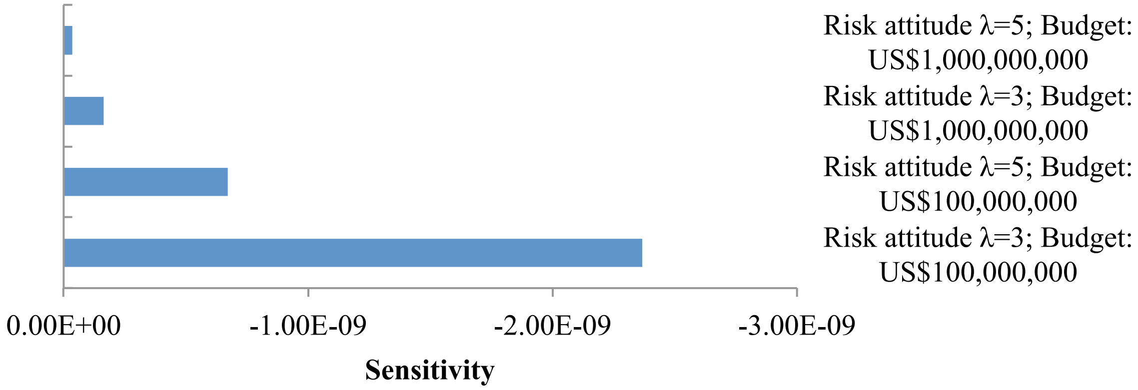


Figure 15.Sensitivities of utility values to the cost in strategy 1

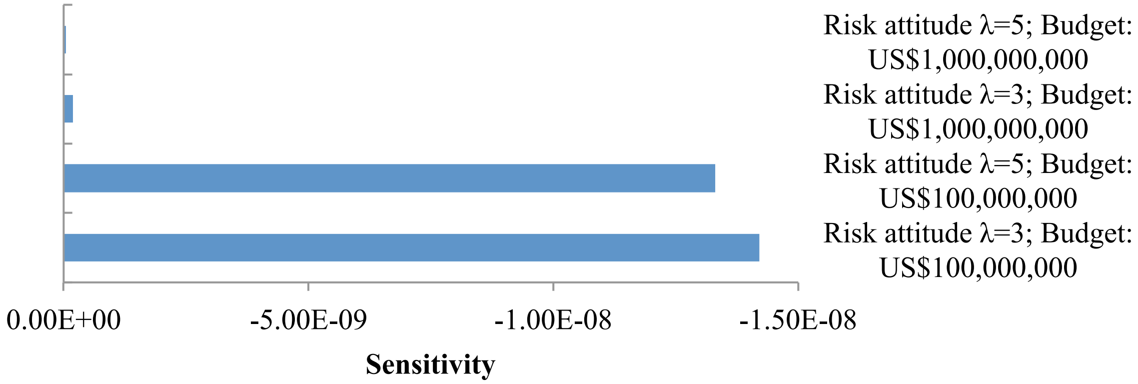


Figure 16.Sensitivities of utility values to the cost in strategy 2

A sensitivity study is also performed in this study. The sensitivities of utility function values to the mean cost in both strategies are computed and plotted in Fig. 15 and Fig. 16. It can be seen Strategy 2 are generally more sensitive than Strategy 1 for all the studied cases. This is more obvious when budget is only US$100,000,000. This means the influence of the cost uncertainty is higher in Strategy 2. These results agree well with the conclusions obtained in the above case study while the estimated utility bounds in Strategy 2 are wider than Strategy 1. The sensitivity analysis can provide an estimate of the importance of cost uncertainty to the selection of optimum strategy.

The investigation shows that the proposed approach provides comprehensive evaluations in maintenance planning. The randomized approach provides extended flexibility in the modeling and processing of deterioration uncertainties. Considering such uncertainties in the modeling of deterioration process can improve the reliability of the maintenance planning. On one hand, the room for indeterminacy in probabilistic models reduces the risks of too optimistic conclusions, which might be created from deterministic result under casual assumptions. On the other hand, the full utilization of collected inspection data to the available extent leads to more conservative predictions of structural performances compared to the deterministic approaches which can be quite bias.

While this work endeavor to develop a methodology for sustainable assessment of maintenance strategies for port infrastructures, many simplifications were made in the example analysis. The cost of environmental loss in this study only considers the loss induced by CO_2 emissions. However, we should realize that many other metrics related to environmental loss can be produced during the production of repair material. It needs more efforts to have a full consideration of all types of environmental losses, e.g., water pollution, air pollution, soil degradation. Besides, the structures analyzed in present work are only concrete structures. The cost evaluation associated with the maintenance for other materials need to be further studied. With regards to the structural maintenance, it is assumed all the maintenance actions can fully restore the structural health condition. However, in reality, not all the structural deteriorations can be recovered. Usually, there exist certain permanent deteriorations that could not be restored (as shown in Fig. 2). The current analysis did not consider this fact. Moreover, the comparison study only considers two maintenance strategies and budget constraint. More alternative maintenance plans should be considered if the port manager wants to obtain an optimum scenario. Finally, the use of current method at the design stage of a new port is not addressed in this study. Rather, the key focus is on the designing of maintenance strategies by considering the inspected structural health condition data. The developed procedures in handling the maintenance of port infrastructure serve as a pre-cursor step to a full life cycle analysis of a port. The conclusions drawn from the paper should be seen in the light of these limitations. The influence of these limitations to the results may need further investigations in the future.

9. Conclusions

In this research, a methodology for sustainable assessment and optimization of maintenance strategies for port infrastructures is developed. A Markov chain model with randomized transition probabilities is proposed and developed to model the port infrastructural deteriorations. The cost regarding sustainable issues is considered and counted in the total estimations for maintenance actions. It is found that the developed randomized Markov chain model is more flexible to quantify the uncertainties associated with structural deterioration process compared to the deterministic approach. The results show that the component of cost regarding sustainability is a significant factor in the total cost of port maintenance. The use of utility function for finding the optimal maintenance strategy is also discussed. The utility function is able to provide a reference for judging the optimum maintenance strategy among the options which risk and cost trade-offs exist. The identification of the utility value bounds can be useful when reliable maintenance scheduling is concerned in the maintenance management. In view of making critical maintenance decisions, the direct emphasis can be put on the extreme values in the estimated bounds for the SHI values. An additional feature of the proposed maintenance method is a direct reflection of various intensities of deterioration uncertainties represented by the bounds of the cost at once, whilst traditional approach could not provide. Such randomized maintenance planning approach can take into account various uncertainties associated with the deterioration process in a quantitative manner and provide a tool for rationalizing the prioritization and scheduling of the maintenances. The developed framework can be used to compare and improve the sustainability of various port infrastructure maintenance strategies. Its application to the selected case study indicates that through comparison of different risk attitudes and budget limits, it could provide more rational, economic and sustainable solutions in the maintenance planning.

Acknowledgments

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References

Ang A H-S, Tang WH. Probability Concepts in Engineering Planning and Design: Decision, Risk and Reliability, Vol. 2. John Wiley & Sons, New York; 1984.

Atmaca A, Atmaca N. Comparative life cycle energy and cost analysis of post-disaster temporary housings. Applied Energy 2016; 171: 429-443.

Bank of Japan, Price Indexes Annual. 2016. Available at https://www.boj.or.jp/en/about/index.htm/

Bastidas-Arteaga E, Schoefs F. Sustainable maintenance and repair of RC coastal structures. Proceedings of the Institution of Civil Engineers - Maritime Engineering 2015; 168(4): 162-173.

Boero J, Schoefs F, Yáñez-Godoy H, Capra B. Time-function reliability of harbour infrastructures from stochastic modelling of corrosion. European Journal of Environmental and Civil Engineering 2012; 16(10): 1187-1201.

Bommer C, Phillips M, Arenson LU. Practical recommendations for planning, constructing and maintaining infrastructure in mountain permafrost. Permafrost and Periglacial Processes 2010; 21(1): 97-104.

Boéro J, Schoefs F, Capra B, Rouxel N. Technical management of French harbour structures - Part 1: Description of built assets. Revue Paralia 2009. http://doi.org/10.5150/revue-paralia.2009.006

Cady PD. Inflation and highway economic analysis. Journal of Transportation Engineering 1983; 109(5): 631–639.

Castalia. The effect of wages on Australian port costs – castalia. port wage cost report, Australia: Castalia Advisory Group; 2012.

Chau CK, Leung TM, Ng WY. A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. Applied Energy 2015; 143: 395-413.

Chou J-S, Yeh K-C. Life cycle carbon dioxide emissions simulation and environmental cost analysis for building construction. Journal of Cleaner Production 2015; 101: 137-147.

Cuellar-Franca RM, Azapagic A. Environmental impacts of the UK residential sector: life cycle assessment of houses. Building and Environment 2012; 54: 86-99.

Dong Y, Frangopol DM, Sabatino S. Optimizing bridge network retrofit planning based on cost-benefit evaluation and multi-attribute utility associated with sustainability. Earthquake Spectra 2015; 31(4): 2255-2280.

Ee JYC, Kader ASA, Ahmad Z, Beng LK. Univariate throughput forecasting models on container terminal equipment planning. Jurnal Teknologi 2014; 69(7): 163-171.

Fang Y, Tao W, Tee KF. Time-domain multi-state markov model for engine system reliability analysis. Mechanical Engineering Journal, Japan Society of Mechanical Engineers 2016; 3(3): 16-00084.

Fettweis M, Baeye M, Francken F, Lauwaert B, Van den Eynde D, Van Lancker V, ... Michielsen T. Monitoring the effects of disposal of fine sediments from maintenance dredging on suspended particulate matter concentration in the Belgian nearshore area (southern North Sea). Marine pollution bulletin 2011; 62(2): 258-269.

Frangopol DM, Soliman M. Life-cycle of structural systems: recent achievements and future directions. Structure and Infrastructure Engineering 2016; 12(1): 1-20.

Frangopol DM, Strauss A, Kim S. Bridge reliability assessment based on monitoring. Journal of Bridge Engineering 2008; 13(3): 258-270.

Frittelli J. Harbor Maintenance Finance and Funding. In: CRS Report for Congress R43222, 2013.

Hess S, Hess M. Predictable uncertainty about terminal operations in the sea. Transport 2010; 25(2): 148-154.

Hillson D, Murray-Webster R. Understanding and Managing Risk Attitude. Gower. 2007.

IPCC. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. (S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, … H. L. Miller, Eds.) 2007. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

International Energy Agency (IEA) Tracking Industrial Energy Efficiency and CO_2 Emissions - Energy

Indicators. Paris: OECD; 2007.

Japan Concrete Institute (JCI). JCI Standards guidelines; 2016. Available at http://www.jci-net.or.jp/e/guideline/index.html

Kong D, Setunge S, Molyneaux T, Zhang G, Law D. Structural resilience of core port infrastructure in a changing climate, Enhancing the resilience of seaports to a changing climate report series, National Climate Change Adaptation Research Facility, Gold Coast; 2013.

Lam JSL, Lai K. Developing environmental sustainability by ANP-QFD approach: the case of shipping operations. Journal of Cleaner Production 2015; 105: 275-284.

Khan LR, Tee KF. Quantification and comparison of carbon emissions for flexible underground pipelines. Canadian Journal of Civil Engineering 2015; 42(10): 728-736.

Khan LR, Tee KF. Risk-cost optimization of buried pipelines using subset simulation. Journal of Infrastructure Systems, ASCE 2016; 22(2): 04016001.

McIntosh CR, Skalberg RK. A statistical approach to US harbor maintenance tax rates and replacement user fees. Maritime Economics & Logistics 2010; 12(3): 263-279.

McIntosh CR, Wilmot NA, Skalberg RK. Paying for harbor maintenance in the US: Options for moving past the Harbor Maintenance Tax. Transportation Research Part A: Policy and Practice 2015; 74: 210-221.

Ministry of Foreign Affairs. Annual evaluation report on Japan's economic cooperation; 2016. Available at https://rnavi.ndl.go.jp/politics/entry/JGOVe-eibun.php

Ministry of Land, Infrastructure, Transport and Tourism (MLITT). The Guidelines on Strategic Maintenance for Port Structures; 2011. Available at http://www.mlit.go.jp/en/index.html

Mitchell K, Wang B, Khodakarami M. Selection of dredging projects for maximizing waterway system performance. Transportation Research Record 2013; 2330: 39-46.

Ortiz O, Castells F, Sonnemann G. Sustainability in the construction industry: A review of recent developments based on LCA. Construction and Building Materials 2009; 23(1): 28-39.

Permanent International Association of Navigation Congresses (PIANC). Life cycle management of port structures: General principles. Brussels, Belgium: Permanent International Association of Navigation Congresses; 1998.

Rosquoët F, Bonnet S, Schoefs F, Khelidj A. Chloride propagation in concrete harbor. In J. Marchand, B. Bissonnette, R. Gagne, M. Jolin, & F. Paradis (Eds.), 2nd International RILEM Symposium on Advances in Concrete through Science and Engineering. Quebec, Canada: RILEM Publications; 2006.

Sarma KGS. Siltation and coastal erosion at shoreline harbours. Procedia Engineering 2015; 116, 12-19.

Saydam D, Frangopol DM. Risk-based maintenance optimization of deteriorating bridges. Journal of Structural Engineering 2015; 141(4): 04014120.

Scheffler A, Roth T, Ahlf W. Sustainable decision making under uncertainty: a case study in dredged material management. Environmental Sciences Europe 2014; 26(1): 7.

Simkins ZS, Stewart RD. Factoring a real value of cargo in port investment and funding decisions. Maritime Policy & Management 2015; 42(7): 712-728.

Sorensen JD. Framework for risk-based planning of operation and maintenance for offshore wind turbines. Wind Energy 2009; 12(5): 493-506.

Stephan A, Crawford RH. de Myttenaere K. A comprehensive assessment of the life cycle energy demand of passive houses. Applied Energy 2013; 112: 23-34.

Straub D, Faber MH. Risk based inspection planning for structural systems. Structural Safety 2005; 27(4): 335-355.

Strogen B, Bell K, Breunig H, Zilberman D. Environmental, public health, and safety assessment of fuel pipelines and other freight transportation modes. Applied Energy 2016; 171: 266-276.

Sulaiman OO, Saharuddin AH, Kader ASA. Sustainable maintenance of navigation channel: the case of Port Tanjung Pelepas (PTP) Port. Asian Social Science 2011; 7(12): 175.

Talley WK. Financing port dredging costs: Taxes versus user fees. Transportation Journal 2007; 46(3): 53-58.

Tee KF, Khan LR, Chen HP, Alani AM. Reliability based life cycle cost optimization for underground pipeline networks. Tunnelling and Underground Space Technology 2014; 43: 32-40.

Tokyo Port Terminal Corporation (TPTC). Annual report of port Tokyo; 2013. Available at http://www.tptc.co.jp/en/tabid/798/Default.aspx

Tsai CY, Chang AS. Framework for developing construction sustainability items: the example of highway design. Journal of Cleaner Production 2012; 20(1): 127-136.

Tsinker GP. Port engineering: planning, construction, maintenance, and security. John Wiley & Sons; 2004.

Walker TR, Bernier M, Blotnicky B, Golden PG, Hoffman E, Janes J, Kader A, Kovacs-Da Costa R, Pettipas S, Vermeulen S. Harbour divestiture in Canada: Implications of changing governance. Marine Policy 2015; 62: 1-8.

World Commission on Environment and Development (WCED). Our common future. Oxford: Oxford University Press; 1987.

Yang L, Li K, Pang X. Design and optimization of maintenance strategies for a long life-span port project. Materials and Structures 2013; 46(1-2): 161-172.

Zabalza Bribian I, Aranda Uson A, Scarpellini S. Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. Building and Environment 2009; 44(12): 2510-2520.

Zhang Y, Lam JSL. Estimating economic losses of industry clusters due to port disruptions. Transportation Research Part A: Policy and Practice 2016; 91: 17-33.

Zhang Y, Lam JSL. Estimating the economic losses of port disruption due to extreme wind events. Ocean & Coastal Management 2015a; 116: 300-310.

Zhang Y, Lam JSL. Reliability analysis of offshore structures within a time varying environment. Stochastic Environmental Research and Risk Assessment 2015b; 29(6): 1615-1636.

Zhang Y. Comparing the robustness of offshore structures with marine deteriorations — a fuzzy approach. Advances in Structural Engineering 2015a; 18(8): 1159-1171.

Zhang Y. On the climatic uncertainty to the environment extremes: a Singapore case and statistical approach. Polish Journal of Environmental Studies 2015b; 24: 1413-1422.

Zhang Y, Kim CW, Tee KF. Maintenance management of offshore structures using Markov process model with random transition probabilities. Structure and Infrastructure Engineering 2016, DOI: 10.1080/15732479.2016.1236393.