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Life-Cycle-Oriented Framework for Seaport Infrastructure Maintenance and Climate Change Adaptation

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Abstract Life-cycle considerations are a prerequisite for rational seaport engineering design and planning since they actually retain seaports' resilience and operational effectiveness. However, the current climate crisis poses threats to the resilience of existing seaport infrastructure, leading to functional degradation and structural failures. Life-cycle-oriented approaches have been proposed to tackle these issues since they constitute an important element for seaport rehabilitation schemes. This paper uses the case study of Evdilos Port in Ikaria Island, Greece to investigate alternative configuration scenarios for the seaport windward breakwater, damaged during a severe storm event in 2018. Multi-criteria decision aid (MCDA) analysis was performed for the examined configurations to select the optimal solution regarding the rehabilitation of the damaged section. The present research seeks to enhance seaport sustainability, particularly while implementing maintenance and rehabilitation practices via the incorporation of life-cycle-oriented design approaches.

Keywords: Life Cycle, Seaport Infrastructure, Seaport Rehabilitation, Seaport Resilience, Seaport Sustainability

1. Introduction

Seaports contribute as civil infrastructure to the economic, social and political development of a modern society by confronting ageing and degradation, as well as natural hazards (Ellingwood & Lee, 2015). Nowadays, changing climate is an additional challenge with impacts on engineering practices in terms of design, planning and decision-making (ASCE, 2015). Seaports represent long-lasting and critical infrastructure that is sensitive to climate change (Asariotis et al., 2017; Ng et al., 2018), resulting in temporary loss of functionality or, even, permanent partial or total physical damage of the structure.

In the context of supporting reliable design practices and rational maintenance and rehabilitation strategies for seaports, life-cycle-oriented design approaches have been proposed to fulfill multi-dimensional requirements including economic and environmental needs. These approaches are expected to extend the typically ad-hoc design criteria to a holistic time-variant performance evaluation during infrastructure lifetime (Biondini and Frangopol, 2018). Life-cycle approaches' development for seaport infrastructure is based on criteria that incorporate technical, socio-economic and environmental dimensions (PIANC, 2008), such as Life-Cycle Assessment (LCA) techniques.

However, proposed life-cycle approaches are mainly focused on new design rather than rehabilitating damaged seaport infrastructure. Indeed, while developing criteria for selecting the optimal rehabilitation scheme, it is important to include the presence of other existing structures, as well as the former history of the damaged structure. In the present paper, a life-cycle-oriented approach based on multi-criteria decision aid (MCDA) methods is presented towards the design and planning of a seaport's rehabilitation scheme. Therefore, Evdilos Port in Greece was considered as a case study since the seaport's windward breakwater was damaged during a severe storm event in 2018 and required rehabilitation.

2. Material and Methods

2.1. Case study

The windward breakwater of Evdilos seaport in the north coast of Ikaria island, Greece was used as a case study to implement the life-cycle-oriented approach presented herein (Fig. 1).The initial length of the windward breakwater was approximately 275 m, while in 2015 a 200 m length breakwater extension was built. However, during an extreme storm event occurred in 18 January, 2018, a large part of the extension has failed (Fig. 1).

Table 1. Alternative configurations for rehabilitating the damaged section of the windward breakwater of Evdilos seaport (Skourti et al., 2019).

Con.ID	Description
Con.1	Reconstruction of previous cross-section (Reference Design)
Con.2	Crest width increase
Con.3	Crown wall height increase
Con.4	Crest width and crown wall height increase
Con.5	Submerged breakwater construction on the foreshore

In an effort to rehabilitate the damaged section of the breakwater while enhancing seaport resilience towards the impacts of climate change, Skourti et al. (2019) examined five alternative configurations (Table 1). These five alternatives were considered in the present study to identify the optimal solution based on a MCDA analysis for seaport infrastructure rehabilitation in the context of a life-cycle approach.

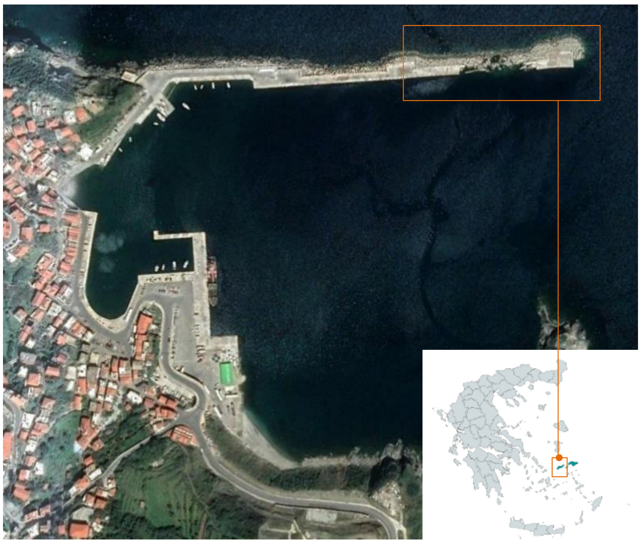

Figure 1. Evdilos port – Damaged section of the windward breakwater (Source: Google Earth).

2.2. Life-Cycle-Oriented Design Approach

Building sustainable seaport infrastructure with a life-cycle-oriented approach shall consider the four phases included in PIANC (2008), namely: a) planning and design; b) construction; c) operation and maintenance, and d) re-use and/or disposal. In this study only the first three phases were considered. In particular, for alternative rehabilitation scenarios (phase a), criteria referring to construction and operation (phases b and c, respectively) were developed.

The life-cycle-oriented approach incorporated criteria (Table 1) with a focus on environmental (LCA and physical), technical and socio-economic parameters affected during both the construction and the operation of the structure (PIANC, 2008; Tsoukala et al., 2015). It is noted that criteria of the operation phase is inherently linked to the structure's former history. Therefore, factors, such as ageing, inadequate maintenance, natural hazards and climate change impacts (e.g. overtopping and extreme storm events) were considered to consolidate and enhance criteria development.

For the MCDA analysis, estimating the weighting values of each criterion is important while trying to identify the optimal configuration scenario. Four discrete weighting approaches were applied based on existing literature. Cost is considered as the most important factor among selection criteria (PIANC, 2008). Therefore, three out of the four weighting approaches were focused on economic criteria. The approaches were: a) equal weighting (EW), where all criteria bear equal weights, b) unequal weighting (UW), where emphasis is attributed on the economic criteria of both phases, while the weights for the remaining criteria are equally distributed, c) unequal weighting (UWC) in favor of the construction phase, where emphasis is attributed on the construction economic criteria, while the weights for the remaining criteria are equally distributed, and d) unequal weighting (UWO) in favor of the operation phase, where emphasis is attributed on the operation economic criteria, while the weights for the remaining criteria are equally distributed (Table 2).Taking into account the fact that carbon footprint and waste volume derived during the breakwater lifetime (CO13* and CO14*, respectively; Table 2) remain the same for the different configurations since no alteration regarding the number of ships, as well as the ship size has been predicted, these criteria were not considered in the analysis, thus, no weighting factors were included in Table 2 for these parameters. These two criteria would be useful for analyses regarding seaport expansion or upgrade that estimate future cargo and shipping requirements (e.g. number, size and type).

Criteria of Table 2 are included in a multi-criteria analysis performed with the PROMETHEE-GAIA software (Visual PROMETHEE, 2013). With this tool, the decision-maker can prioritize the criteria and evaluate the output according to predetermined limitations. Comparison of the configurations of Table 1 was undertaken with the estimation of the *Phi* value, i.e. the net flow which is equal to the difference between the entering and leaving flow. The optimal configuration scenario corresponds to the higher *Phi* score (Eq.1):

$$Phi(a) = Phi^{+}(a) - Phi^{-}(a) \tag{1}$$

where, $Phi^{+}(a) = \frac{1}{n-1}\sum_{b\neq a}\pi(a,b)$ is the leaving flow, $Phi^{-}(a) = \frac{1}{n-1}\sum_{b\neq a}\pi(b,a)$ is the entering flow, a and b are the actions (i.e. different configuration scenarios) and π is the multi-criteria preference index.

A range of discrete values from one to five was assigned to each criterion to quantify them and estimate the *Phi* value. The value of each criterion (i.e. 1-5) represents the magnitude of the configurations' impact, ranging from very low to very high. The higher the score for each criterion, the greater the impact will be. The precise estimation of the values is out of the scope of the present work, and, consequently, scale definition was considered a suitable practice for criteria quantification.

Table 2. Life-Cycle-Oriented Design Criteria for damaged structure rehabilitation.

Phase	Category	Criterion ID	Criterion	Short description	Weighting (%)			
					EW	UW	UWC	UWO
Construction	Socio-economic	CC1	Construction cost	National regulations (e.g. the Official Greek Government Rates as stated in Greek Government Gazette - FEK 363B/19-2-2013)	7.69	15.00	15.00	6.36
	Socio-economic	CC2	Safety-Security	Construction impact on navigation/ transportation & bathing	7.69	5.50	7.08	6.36
	Technical	CC3	Constructability	Transition zones with existing structures/ Difficulties in construction	7.69	5.50	7.08	6.36
	Environmental (LCA)	CC4	Terrestrial & marine ecosystems	Ecological footprint	7.69	5.50	7.08	6.36
	Environmental (LCA)	CC5	Carbon footprint	CO_2 emissions during construction (e.g. Cejuela et al., 2020)	7.69	5.50	7.08	6.36
Operation	Socio-economic	CO6	Maintenance-Rehabilitation-Adaptation cost	Consideration of climate change scenarios, storm events, physical degradation	7.69	15.00	7.08	15.00
	Socio-economic	CO7	Indirect costs	Impact on income during upgrade activities	7.69	15.00	7.08	15.00
	Socio-economic	CO8	Safety-Security	Operation impact on navigation/ transportation & bathing	7.69	5.50	7.08	6.36
	Technical	CO9	Durability & Maintainability	Durability of materials & feasibility of maintenance	7.69	5.50	7.08	6.36
	Technical	CO10	Sustainability	Climate Adaptive Capacity	7.69	5.50	7.08	6.36
	Technical	CO11	Inspectability	Feasibility of inspections/monitoring	7.69	5.50	7.08	6.36
	Environmental	CO12	Aesthetics	Visibility/aesthetic interaction with the landscape	7.69	5.50	7.08	6.36
	Environmental (LCA)	CO13*	Carbon footprint	CO_2 emissions from shipping activities	-	-	-	-
	Environmental (LCA)	CO14*	Waste volume	Waste disposal from shipping	-	-	-	-
	Environmental (Physical)	CO15	Adjacent coastline morphology	Impact on the hydrodynamic & the sediment transportation regimes	7.69	5.50	7.08	6.36

3. Results

The main output of this analysis is presented in Tables 3 and 4. Table 3 includes the scores of criteria examined with the PROMETHEE software, while Table 4 shows the Phi values for each weighting alternative (EW, UW, UEC, UEO; Table 2). It is noted that Con.1 (Reference Design) is scored with the value 5 for all criteria of the operation phase since this configuration cannot be functional during the structure's lifetime.

The optimal configuration scenario for all weighting alternatives is the increase in crest width (Con.2, Table 1). Moreover, the ranking for the remaining configurations (Con.1, Con.3, Con.4 and Con.5) is different for the various weighting alternatives. This outcome underlines the significance of the weighting process. An indicative example of the significance of the weight estimation is the fact that for the UWC alterantive (i.e. higher weighting for the economic criteria of the construction) the configuration of Reference Design (Con.1, Table 1) has higher score than Con.4 (i.e. increase in both crest width and crown wall height). However,this solution is not expected to be functional, as mentioned above.

Table 3. Criteria scoring for the configuration scenarios.

Con. ID	Criteria												
	CC1	**CC2**	**CC3**	**CC4**	**CC5**	**CO6**	**CO7**	**CO8**	**CO9**	**CO10**	**CO11**	**CO12**	**CO15**
Con.1	1	1	1	1	1	5	5	5	5	5	5	5	5
Con.2	4	3	4	4	2	1	2	3	2	3	1	2	3
Con.3	2	3	4	2	3	3	3	1	4	3	2	4	1
Con.4	5	3	5	3	4	3	3	2	3	2	2	3	2
Con.5	3	4	2	5	5	2	1	4	2	1	4	1	4

The contents of Table 4 indicate that for all weighting alternatives Con.2., Con.3 and Con.4 (i.e. crest width increase, crown wall height increase and construction of a submerged breakwater respectively) have a positive Phi value. However, once specific characteristics of the configuration scenarios change (e.g. increase in the volume of the armour accropodes in Con. 2), the relative scores of criteria will also alter (i.e. for the above mentioned example the increase in crest width will be lower). This observation could be helpful for the decision-makers who need to adjust configurations to fulfill desired socio-economic, technical and environmental requirements. Therefore, solving a rehabilitation issue such as a damaged windward breakwater should consider multi-dimensional perspectives for optimizing the selection among various alternatives.

Table 4. Criteria and Phi scoring for the configuration scenarios.

Config. ID	Phi value			
	EW	**UW**	**UWC**	**UWO**
Con.1	-0.231	-0.260	-0.133	-0.368
Con.2	0.212	0.246	0.155	0.302
Con.3	0.096	0.069	0.128	0.043
Con.4	-0.096	-0.211	-0.168	-0.118
Con.5	0.019	0.156	0.018	0.141

4. Conclusions

The purpose of this paper is to describe a rehabilitation approach for a life-cycle-oriented design of seaport infrastructure towards enhancing sustainability and building resilience. Therefore, research activity and information are provided in the framework of implementing multi-criteria analyses to identify the optimal alternative design solution based on predetermined criteria and weights. The ultimate goal of this study is to encourage decision-makers to improve their practices in the context of a life-cycle rehabilitation basis. Finally, MCDA analysis has been proved to be a promising tool while rehabilitating infrastructure since it combines multi-dimensional parameters for an effective short-term and long-term infrastructure functionality.

Further research is needed towards the criteria selection, as well as the suitable criteria weighting. This could be achieved via the formation of questionnaires and their guided completion by seaport experts and stakeholders.

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