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Minimizing lifetime structural costs: Optimizing for production and maintenance under service life uncertainty

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Current naval shipowners are being forced to extend the service lives of their aging vessels from budgetary and political constraints. This is causing them to incur significant costs due to maintaining the structure of these older ships to keep the ships in operation. These increasing costs make it desirable to design new naval structures with their minimization in mind, as well as ensuring that such vessels are robust to changes in expected service life with respect to their total lifetime cost. However, such structures will necessarily have higher production costs, therefore, an optimization framework is presented to estimate both production and maintenance costs for a naval vessel's internal structure and develop trade-spaces between these two competing objectives in order to find designs that represent a balance of both.

1. Introduction

The costs of producing and maintaining the internal structure of a naval vessel constitute a large percentage of the lifetime costs the ship will experience. As budgetary and other political issues force governments to extend the operational life of vessels within their fleets the associated maintenance costs are becoming unexpectedly large. This is partly a result of operating these structures for years

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beyond their design horizon. These costs make it desirable to minimize the total expected lifetime costs to maintain the structure, and to ensure that these expenses are robust with respect to changes in the service life of the ship as it ages. This can be approached by considering the life of the vessel to have a probabilistic nature instead of a deterministic one within an optimization framework. However, a vessel designed to have minimal costs due to maintenance over its entire service life will consist of larger members and generally be more expensive to produce. Thus, it is important to design the internal structure of a naval vessel to strike an effective balance between these two competing aspects of costs in order to minimize the monetary impact to the shipowner over the entire lifetime of the vessel. This paper presents a framework to estimate the lifetime maintenance cost of a naval vessel's structure based on fatigue and corrosion damage while considering the service life of the ship to be probabilistic in nature. It is used in conjunction with a multi-objective evolutionary optimization algorithm in order to develop trade spaces between the cost to produce a structure and the cost to maintain it in order to determine the trade offs between these two costs under service life uncertainty.

In order to develop a framework that can estimate the cost to maintain these structures physics-based models for the time-dependent damage must be utilized. A number of studies have been published on developing models for the damage ship structures experience as they age due to corrosion and the effect this damage has on their overall strength [16–19]. Work has also been published to estimate fatigue damage over a structure's life. Work has been published that uses reliability estimates based on fatigue damage models in Refs. [4,6,23,26]. A probabilistic model for fatigue based on the S–N approach was proposed in Ref. [3] and is used in this work to track cumulative fatigue damage.

Work has been published on estimating the lifetime maintenance costs for ships. The significant of these costs in the total lifetime expenses a vessel will experience has been discussed in Refs. [2,7,21]. The lifetime maintenance cost of chemical tankers was used as part of the formulation of an optimization routine in Ref. [25] using a weight-based estimation strategy. In Refs. [10,11,14] the author's find optimal inspection strategies for fatigue details based on probabilistic estimations of structural damage. The reliability analysis used in these analyses was extended to utilize corrosion damage estimates as well in Ref. [12]. However, these formulations only examine a single fatigue detail throughout the optimization. In Ref. [24] a framework was proposed to estimate the maintenance cost of naval vessel's structure considering the fatigue and corrosion to the entire structure while utilizing a deterministic service life. There have also been initiatives to reduce the production cost of naval vessels. In Ref. [15] outlines for a program to reduce the initial costs of U.S. Navy acquisitions. In Ref. [8] a bi-level optimization scheme to minimize the cost to produce a vessel's midship section was presented. The author's of Ref. [13] formulated an optimization problem that combined both cost and structural integrity in order to reduce the initial cost of a vessel's structure while maintaining the strength of the vessel. A method for estimating the production cost of steel sections was presented in Ref. [20], and is relied on in the presented framework. In Ref. [27] multi-objective optimization was used to optimize corrugated bulkheads for both production cost and weight, showing the potential of these algorithms in structural design. However, given that maintenance cost is only a single category among multiple contributing facets of a vessel's lifetime cost it is necessary to understand the trade-offs between this and other cost categories, such as production. Current studies have focused on single-objective optimization; which does not explore these trade-spaces. Also the current body of work on maintenance optimization does not take into account the uncertainty in naval vessel's operational life; this has a significant impact on the costs to keep a ship operational as it ages.

In this work models to estimate the corrosion and fatigue damage experienced in each year of the vessel's life are used in conjunction with models for the emergency and scheduled maintenance cycles at different repair facilities in order to estimate the lifetime maintenance cost for a vessel's internal structure. This work shows the potential of this model to explore the trade-offs between different aspects of cost in early stage structural design, analyze the effects of service uncertainty on the overall cost of a vessel as well its impacts on design, and to find structural solutions that will minimize the overall structural costs for the vessel. In the subsequent sections the framework methodology is described, beginning with the structural damage model followed by the calculations used to estimate the associated maintenance costs. The optimization problem used in this work is then formulated and the algorithm is tested on a nominal mid-ship section for a DTMB-5415 naval combatant. The results of this application are discussed, as well as the impacts of changing the expected service life of the