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Design for flexibility: Evaluating the option to extend service life in preliminary structural design

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ABSTRACT

In this paper, a new type of real options analysis is used to evaluate the worth of an option to extend the service life (ESL options) of an aluminum structure from twenty to twenty-five years. It is an early application of prospect theory-based real options analysis (PB-ROA) in naval design. PB-ROA abstracts the principles of real options analysis to suit naval design applications where the assets do not generate cash flows, and therefor one cannot define value in monetary terms. Instead, the example in this paper defines the utility of a structural design based on three components: structural availability, cargo capacity, and producibility. The utility is contingent on risk factors like the time to crack initiation of a welding detail which is included using stochastic fatigue analysis. From an entire Pareto front of optimal structural designs, the options analysis exposes a partition in the design space which could be valuable in a design setting. The partitioning reveals the conditions in which certain candidate designs maximize the present value of future flexibility. Ultimately, this paper demonstrates a new approach to valuing flexibility in preliminary structural design that may generate useful insight for early stage decision makers.

1. Introduction

Traditional processes for the structural design of naval vessels rely heavily on fixed standards and minimum thresholds, such as the Guide for Building and Classing High Speed Naval Craft (American Bureau of Shipping (ABS), 2007). Such rules, while essential for safety, do not offer the designer insight into any potential benefits of exceeding the minimum thresholds, like enhancing the product's flexibility. Flexibility in this paper is defined as the ability of a design to adapt to new and changing conditions. Flexibility is an important consideration when designing for the possibility of service life extension. For instance, a design which minimizes weight may be structurally impossible to (safely) operate past its original design lifecycle. This paper demonstrates the use of a modified real options framework to guide the optimization of a high performance structure in the preliminary design stages, given the possibility of a service life extension. The case study presented in this paper is an early application of prospect theory-based real options analysis (PB-ROA) (Knight and Singer, 2014) in naval design.

Real options analysis (ROA) is a financial discipline specializing in the valuation of corporate managerial flexibility. For example, Bendall and Stent (2005) model the managerial flexibility to choose between the most valuable of three different shipping strategies as a real option. Specifically, the ship operator must decide which ports to service as well as how many ships to operate given prevailing market conditions. ROA combines stochastic models for uncertainty with dynamic strategy to more accurately value capital-intensive projects. It has been used extensively in commercial shipping, for example (Bjerksund and Ekern, 1995; Tvedt, 1997; Dikos and Thomakos, 2007; Dikos, 2008). However, previous research has shown traditional ROA's limited applicability to the naval domain because it requires a financial market and assets which generate cash flows (Knight and Singer, 2014; Page, 2011; Gregor, 2003). PB-ROA abstracts the principles of real options analysis to suit assets that do not generate cash flows.

Because many naval real options exist *in* an interdependent system, it is important to integrate their analysis with early stage design efforts where the freedom to exploit physical design change opportunities is greatest. This is true for modular systems and architectures which may offer substantial flexibility but require considerable structural modifications. Capt. N. H. Doerry (USN) notes,

> "While many [modular adaptable ship] technologies have been available for many years, and in many cases have been installed onboard ships in a ad hoc manner, a design methodology does not currently exist to establish a sound technical basis for

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determining how much of what type of modularity to install on a ship." Doerry (2012)

The authors contend that this problem is not limited to modular technologies, but also applies to general design features which enable flexibility. For instance, under the ship-as-a-truck paradigm (Doerry, 2011), the performance of the ship structure itself becomes critically important because every other system is housed by the ship structure and hence dependent on it. As Collette notes,

> "[F]or naval structures, the structural system is typically supporting an investment of weapons, sensors, machinery, and other vessel systems worth many times the value of the structure itself but effectively permanently tied to the structure." Collette (2011)

Two potential components of a ship structure's utility are availability and cargo capacity.[1] The degree of flexibility provided by a ship structure is dictated, at least in part, by the combination of its ability to carry the demanded cargo and be available, where structural availability is related to fatigue and cracking of structural members that may prevent the ship from going to sea or otherwise completing its mission, as studied by Hess (2008).

To demonstrate the principles of PB-ROA and the types of insights possible with its use, the value of a real option to extend the service life (ESL option) of a ship is investigated. The ship is a high speed military catamaran with aluminum structure, making fatigue and cracking a critical issue. In this study, the ESL option may be "purchased" by making enhancements to the structural design of the strength decks which reduce the expected number of cracks over its lifetime. The resulting increase in structural weight is considered by PB-ROA to expose partitions in the design space and the conditions under which one candidate structural design can be said to maximize flexibility (option value) over another candidate design.

Such analysis, however, takes a shift from requirements-thinking to performance-thinking, which is not a typical approach to structural design. In his doctoral dissertation, Hess (2008) develops a reliability-based, operational performance analysis framework for naval ship structures. Hess defines three new performance metrics for structures: capability, dependability, and availability. Operational capability of the structure relates to the probability of countering a threat, or performing the mission. Operational dependability is the probability that the system can complete its mission once it has successfully started. Operational availability is the probability that the system will be fully functional when needed. Such performance metrics for structures have begun to be used to examine tradeoffs from a full lifecycle perspective by Collette (2011), Rigterink et al. (2013) and Temple and Collette (2013) and others.

A critical tool for enabling the shift to performance-thinking for structures is stochastic fatigue analysis. Fatigue analysis is used to evaluate when a structural element will crack or fail under stress. Fatigue analysis is a large area of academic research. A thorough literature review on the subject is outside the scope of this paper. However, the interested reader is referred to the survey by Fricke for a summary of the field (Fricke, 2003). For this paper it suffices to explain that fracture of a structure is typically divided into three phases; the crack initiation phase, the crack propagation phase, and failure of the structure. In this case study, only the crack initiation phase will be considered – the number of stress cycles applied to a structural detail before a crack first forms. While there are many methods for determining the time to crack initiation, this case study relies on a *nominal stress* approach. Under a nominal stress analysis, the standard $S-N$ curve for a material is translated based on classes of basic joints which are cataloged in several standards and guidelines, such as the International Institute of Welding (Hobbacher, 2009), and others (Boller and Seeger, 1987).

2. Methodology

The analysis method used in this paper follows prospect theory-based real options analysis (PB-ROA), as first described in Knight and Singer (2014). It is a framework which abstracts the principles of real options analysis to suit problems in the Naval domain. Real options is commonly used in commercial applications to value managerial flexibility. An issue when using options theory for naval applications is that naval assets do not generate cash flows. PB-ROA solves this issue by measuring the value of naval assets using utility theory. The general process flow for PB-ROA, as used in this paper, is shown in Fig. 1.

After the design features (independent variables) are identified and probability distributions assigned to each of the risk factors, sets of capabilities can be defined. The capabilities for the assets are functions of both the design variables and state of the risk factors. The complexity of the design is then quantified and used to define an overall utility function for the asset. Next, the marginal of the utility function is used to adjust the probability distributions of the risk factors to reflect the decision makers' risk tolerances. This process is discussed in more detail in Section 5.1. Finally, this risk-adjusted probability measure is used to calculate the option's value, a dynamic expected utility analysis with adjusted probabilities. Performing the analysis in this way promotes a probabilistic understanding of the option's benefit to the end user, and allows for the dynamic nature of naval operations and complex decision making.

3. Structural utility and risk

The platform under consideration is a fictional military high speed aluminum catamaran. It's primary mission is as a fast intratheatre transport for troops and materiel. Conceptually, it is inspired by the Spearhead-class Joint High Speed Vessel (JHSV) (Schank et al., 2006). However, this study is purely the perspective of the authors and is not reflective of the actual JHSV program.

The service life for this vessel is assumed to be twenty years. However, decision makers intuitively understand that there is value in having the flexibility to extend the service life beyond twenty years. In the early design stages for this high-speed catamaran, we consider investing in a real option that would enable them to extend service life (ESL option) by five years, if desired. Purchasing this flexibility *may* come at the cost of structural modifications to the vessel and increases in complexity.

Designs which maximize availability (minimize cracking) will tend to be heavier, thus carrying less cargo. Designs which maximize cargo capacity will tend to be lighter (for a constant displacement), thus exhibiting more cracking. This case study examines the tradeoff between cargo capacity and expected availability for a high-speed aluminum catamaran. More importantly, we evaluate how early stage structural design decisions impact the value of the option to extend service life. The case study illustrates how PB-ROA can be used to generate insight on the conditions in which additional section modulus for the midship section of a vessel, above and beyond that required by regulatory institutions like the American Bureau of Shipping

[1] Basically, how much the ship can carry before it exceeds its design displacement or becomes unstable.