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Versatility vs. retrofittability tradeoff in design of non-transport vessels

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ABSTRACT

In this paper, we study the relationship between economic performance and flexibility for non-transport vessels. More specifically, we investigate the difference between two means of achieving flexibility: retrofittability and versatility, i.e., the ability of a vessel to satisfy diverse needs *with* or *without* change of physical form, respectively. A model is presented to study this relationship, where we first generate design alternatives with relevant, flexible properties before we subsequently evaluate the design alternatives based on their expected discounted economic lifecycle performance. The evaluation model is based on a two-level decomposition of the planning horizon to handle temporal complexity, using scenario planning and Epoch-Era analysis (EEA) for long-term strategic considerations, and Monte Carlo simulation and optimization for medium-term tactical ship deployment. The proposed model is applied to an offshore construction ship design case. Findings indicate that retrofittability can increase economic performance significantly for non-transport vessels operating in an uncertain heterogeneous context.

1. Introduction

Determination of the design specifications of a new ship is a complex strategic problem every shipowner needs to solve as part of a fleet renewal or expansion program. Due to long time horizons and a high degree of contextual uncertainty in the maritime markets (Alizadeh and Nomikos, 2009; Erikstad and Rehn, 2015), this problem is complex and strategic in nature (Christiansen et al., 2007). The ship design problem is different for transport and non-transport vessels. Non-transport vessels serve various service-related needs in the maritime industry, such as offshore construction and anchor handling. This contrasts with traditional ships designed for transportation purposes, such as oil tankers and bulk ships. The revenues for non-transport ships come from contracts with various technical requirements and durations. The ship designer thus needs to determine whether the ship should be designed only for the short-term contract specifications or to be *versatile* and have additional capabilities to handle a broader set of missions after the first contract has ended. However, adding extra equipment increases the initial investment costs. Alternatively, the ship can be optimized for the initial contract, but be *retrofittable* and prepared to be easily retrofitted later. The retrofit decisions can then be made after future uncertainty has been resolved. Following, the degree to which a ship is designed to be flexible is thus a decision to be made at the conceptual design stage, as it will significantly influence the choice of design concept. This motivates the following research question: What is the relationship between economic performance and flexibility for non-transport vessels? By economic performance, we mean aspects of investment cost, retrofit costs, and revenue potential.

In ship design, one needs to understand the operational phase of the lifecycle to evaluate and compare the performance of different design alternatives. In traditional design literature, this is often reduced to the process of requirements elicitation, or elucidation (Andrews, 2011). However, to study the link between contextual uncertainty and the ability of a system to change form, function, and operation, we need to explicitly consider temporal and contextual complexities of the operational part of the lifecycle (Rhodes and Ross, 2010). Operations research, therefore, becomes an integrated part of this extended design problem. Operations research is a well-established field, with extensive contributions for maritime transportation applications. An excellent review of transportation ship routing and scheduling is presented by Christiansen et al. (2013). However, operations research for non-transport shipping cases is less covered in the literature. A case for operational planning of offshore ships is presented by Fagerholt and Lindstad (2000), where optimal policies for supply in the Norwegian Sea are determined with the objective to reduce operational costs. Gundegjerde et al. (2015) present a case study of a *fleet size and mix*

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problem for maintenance operations at offshore wind farms using a stochastic optimization model. Christiansen et al. (2007) discuss strategic, tactical, and operational planning in the context of maritime transportation. Even though their perspective is from maritime operations research, they clearly relate strategic decisions to ship design, such as *fleet renewal* and *fleet size and mix*. They thus classify ship design as a long-term strategic decision problem.

Erikstad et al. (2011) present the ship design and deployment problem (SDDP), which is applied to the design of non-transport vessels. This problem involves the determination of the best specification for a non-transport vessel facing a set of available contracts with different start-up periods, durations, and capability requirements. The authors propose a binary integer programming model to select the optimal design and its deployment specifications. Therefore, the SDDP explicitly considers the deployment of the vessel in the operational phase of the lifecycle, with the purpose of improving the initial design specifications. Building on SDDP, Gaspar et al. (2012) discuss aspects of handling temporal complexity in design using Epoch-Era Analysis (EEA). However, SDDP, as presented by these collective authors, does not consider the possibility of changing a ship's capabilities after it is built, which we explicitly address in this paper.

The ability of a system to change form, function, or operation, generally called *changeability* (de Weck et al., 2012), is extensively covered in the systems engineering literature. Changeability is a collective term for change-related system properties such as flexibility, adaptability, versatility, and agility. Fricke and Schulz (2005) introduce the term Design for Changeability (DFC) and discuss principles enabling changeability in design. Ross, Rhodes, and Hastings (2008a, 2008b) present a design-neutral framework for defining changeability and explicitly connecting it to change-related ilities, including adaptability and flexibility. Traditional methods for evaluation of changeable design alternatives have roots in the financial derivatives literature, with real options applied to physical systems (Trigeorgis, 1996). However, traditional option pricing methods rely on various assumptions that do not necessarily hold for applications of systems design (Wang and de Neufville, 2005). To separate between traditional, well-defined real options on assets and more ill-structured real options in systems design, Wang and de Neufville (2005) introduce real options "on" and "in" projects respectively. Real options "in" projects do not treat technology as a "black box," in contrast to traditional real options "on" projects. A good reference for flexibility in engineering design, including practical applications and examples, is de Neufville and Scholtes (2011).

The literature on design of non-transport vessels under uncertainty has increasingly focused on aspects of changeability to handle operational uncertainty. Choi, Rehn, and Erikstad (2017) present a module configuration model for adaptable ship design. They use a rolling horizon optimization approach for tactical decision-making in the operational phase of the lifecycle and use that to evaluate and compare two initial main body design alternatives. They conclude that flexibility enabled by modularity can mitigate risks and increase performance. Changeability in ship design is also covered by Niese and Singer (2014), using Markov decision processes for changeability evaluation studying a case from ballast water treatment.

While most contributions on changeability in ship design provide insights into the *evaluation* of one changeable design alternative, they typically do not explicitly study *different changeable design alternatives.* That is, little or no focus is on the characterization and exploration of alternative design solutions with different types and levels of changeability built in. This especially accounts for design characteristics that enable retrofits. Versatility, or multi-functionality by design, is to some degree addressed in the literature, e.g., by Stopford (2009), who introduces *lateral cargo mobility* (LCM) measuring the number of different types of cargo a vessel can carry. Rehn et al. (2018a, 2018b) differentiate between two main aspects of changeability in systems engineering practices: quantification of changeability level for a design alternative, and valuation of a given level of changeability for a design alternative. They further present a case from offshore shipping to illustrate how different levels of changeability in design can be quantified. A more practical perspective on ship design and retrofit is presented by Ullereng (2016), who studies how offshore shipping companies can reutilize platform supply vessels (PSVs) in poor offshore markets. Ullereng focuses both on classical operational real options such as sell, layup, or scrapping, in addition to exploring retrofit options. He mentions that offshore shipping companies have discarded potential ship conversions due to too high conversion costs. This supports the research topic explored in this paper, as we investigate how retrofittability, enabling reduced conversion costs and times, can be of importance for the next generation of offshore ships.

2. Flexibility in non-transport shipping

2.1. Concepts and definitions

Changeability represents the ability of a system to change form, function, or operation (de Weck et al., 2012), and is a collective term for change-related ilities such as flexibility, adaptability, versatility, and agility. In this paper, we generally use the term flexibility, as it assumed best suitable for the targeted ship design audience. Changeability and flexibility are thus used interchangeably. We are interested in studying two nuances of flexibility, which relate to the ability to satisfy a diverse set of needs *with or without* change of form. Change of form represents a physical change of an engineering system, which can be collectively called retrofits. Change of form can result in a change of function, but change of function does not necessarily require a change of form. For example, a multi-functional offshore ship can handle different types of missions, without the need for any retrofits. This built-in multi-functionality is characterized as *versatility* (Chalupnik et al., 2013). This example illustrates the two different aspects of flexibility in design:

- **Versatility:** the ability of a system to satisfy diverse needs, *without* change of form.
- **Retrofittability:** the ability of a system to satisfy diverse needs, *by* change of form.

We define *retrofittability* as a general change-related ility involving change of form, for lack of a better word. Other, more specific ilities in the literature relating to change of form are reconfigurability, modifiability, scalability, and extensibility. de Weck et al. (2012) define these as: reconfigurability – ability to change component arrangement and links reversibly; modifiability – ability to change the current set of specified system parameters; scalability - ability to change the current level of a specified system parameter; and extensibility – ability to accommodate new features after design. Retrofittability thus represents a superset encapsulating these four change-related ilities, explicitly contrasting versatility. One relevant application of the phrase *retrofittable* in the literature is by Baker et al. (2016), who study requirements engineering for retrofittable subsea equipment.

2.2. Examples from the industry

Market changes are the driving factors for flexibility in commercial maritime systems. The needs-specifications from the industry are operationalized through tenders. For offshore shipping, the market is heterogeneous, with tenders of various length, technical requirements and at different operational areas. The shipping industry is capital intensive, coupled with an uncertain heterogeneous market, therefore is it natural to see retrofit and redesign of vessels. Table 1 provides some recent examples from retrofits in the maritime industry.

It has been demonstrated in the marine industry that several ships are prepared for retrofits at the design stage. For non-transport vessels, examples typically involve being prepared for equipment retrofits. In the classification societies, there exist class notations for flexibility such

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