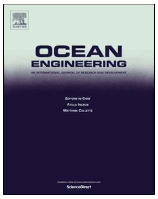
Ocean Engineering 106 (2015) 371–385

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng



Ship design evaluation subject to carbon emission policymaking using a Markov decision process framework

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ARTICLE INFO

Article history:
Received 17 November 2014
Accepted 24 June 2015
Available online 31 July 2015

Keywords:
Markov decision process
Ship design
Design metrics
Changeability

ABSTRACT

This paper outlines a novel ship design evaluation framework rooted in Markov decision analysis and derived metrics. The framework synthesizes concepts from dynamic network optimization, decision theory, and scenario analysis to holistically manage exogenous uncertainty and value ship system changeability. A Markov decision process is used to analyze development and operational paths over a ship's life cycle and to identify system characteristics consistent within high performing designs. Decision metrics then contextualize a fuller extent of design engineer and operator preferences toward tradeoffs between value creation and active ship management. The case study specifically examines future scenarios subject to carbon emission regulations and uncertainty surrounding enforcement of the Energy Efficient Design Index. Results inform decisions about when, where, and how to incorporate the changeability that maximizes expected life cycle rewards.

1. Introduction

There has been a significant overhaul in the traditional engineering design approach over the past decades to improve on shortcomings related to uncertainty and system dynamics. Traditional design methodologies have improperly externalized the fact that systems regularly experience disturbances due to technology innovations, market upheavals, and policy developments. On top of this, designers have traditionally adhered to a short-sighted belief that customer requirements were static and well understood (Jarke et al., 2010). This has led to many designs becoming technologically obsolete, economically uncompetitive, or regulatory non-compliant with time.

Changeability has been pinpointed as being critical for maintaining long-term performance and overcoming past design deficiencies (Fricke and Schulz, 2005). Improved understanding of the consequences stemming from dynamic environmental contexts and uncertainties has increasingly led to the view of a design solution as a continuous pathway instead of a stable point (Kelly, 1998). Unpredictable exogenous events prevent control of factors causing system performance variability. However, designers and system managers can attempt to manage the consequences of these events by (1) decreasing sensitivity to disturbances or (2) by enabling dynamism (i.e., increasing changeability) within the system itself (Forrester, 1961). The latter method views customer requirements as variables instead of rigid specifications and advocates for active redesign as change occurs (De Neufville, 2004).

Response mechanisms that produce value despite evolving requirements help ensure the design remains optimal over its life cycle. However, following a temporal design strategy creates both risk and opportunity with change (Ross, 2006). Emphasizing life cycle product qualities, known collectively as the – ilities, prevents chasing short-term solutions at the expense of long-term success. Attention to path dependencies and lock-in of design freedom grants system managers the capacity to “match change with change” if unanticipated or unintended conditions arise.

Change management has its origins in the machine maintenance and replacement problem (Smallwood and Sondik, 1973), and can be defined similar to the dynamic resource allocation problem (Topaloglu and Powell, 2005). Strategic planning improves system performance by (1) ensuring resources are continually re-distributed among system components and (2) hedges against uncertainty. Efficient distribution requires that design freedom is maintained within the system over the life cycle. Reachability, or access to a diverse range of design states, is often limited by cost or physical dependencies. Non-zero transaction costs borne out of architectural lock-in elevate the importance of the strategic timing and types of change options executed (Dixit and Pindyck, 1994).

Lock-in is traditionally defined as an inability to change course due to infrastructure constraints and resource thresholds that

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http://dx.doi.org/10.1016/j.oceaneng.2015.06.042
0029-8018/

decision-makers decline to exceed. Literature regarding lock-in is derived from mathematical approaches to nonlinear dynamic models, for which a key finding is “sensitive dependence on initial conditions” (Liebowitz and Margolis, 1995). Initial conditions are largely set during early stage design, and conceptual design proves to be the life cycle stage where decisions are likely to have the greatest impact on total cost. A poorly conceived artifact limits opportunity for efficient improvement during later phases of life cycle activity.

While design methodologies that attempt to manage dynamic, uncertain contexts, such as environmental policies, exist (Fet et al., 2013), the research is not mature (Andrews and Erikstad, 2015; Ross, 2006). Decision-theoretic frameworks have been introduced for a range of change options while accounting for uncertain information, risks, opportunities, and preferences. Evaluation methods such as utility theory, cost-benefit analysis, and optimization aid in selecting among alternatives, while techniques apply subjective or imprecise probabilities, intervals, possibility theory, or evidence theory to model uncertainty (Dym et al., 2005). Network theory (Silver and De Weck, 2007; Siddiqi, 2006), stock-option theory (Walton, 2002), time-dependent reliability theory (Singh et al., 2010, Frangopol et al. 2011), and game theory (Briceno and Mavris 2006; Coulter and Bras, 1997) have been applied to value and direct design change.

This research showcases a Markov decision process (MDP) methodology, along with novel metrics, that focuses on the interaction between initial conditions and life cycle operations under uncertainty and dynamism. An early stage design of a containership is presented as a case study. The study models uncertainty surrounding cargo trade economics in face of increasing environmental concerns and emission regulations. One primary objective is to understand and quantify the degree to which changeability is valued in addressing uncertain future regulations. Results presented better characterize the design and decision space with respect to lock-in and expected change strategy. The framework enables identification of “good” design characteristics in the face of internal and external life-cycle change drivers. The outcome is an expanded set of system design tradeoffs under consideration at the design stage, where management leverage is greatest and prior to significant resource commitment. Thus, the MDP framework can be used as a tool for eliciting decision making insight as it relates to operation, regulation, and technology uncertainty.

2. Methods

A Markov decision process was chosen as the model framework due to the fundamental assumption that changeability is a state-based, sequential decision-making problem. Changeability is state based due to the design need to understand the system components where proactive decision-making should be exercised. Throughout the system's life cycle, a decision-maker has multiple discrete opportunities to invest in resources that affect performance. Uncertainty, dually controlled by a decision-maker and by randomness, is modeled using probabilistic distributions. Decisions are valued using cumulative discounted sums of expected rewards. In sum, the use of a MDP represents a natural extension to design evaluation and allows for greater control of initial condition (Niese and Singer, 2013).

2.1. Design statement

When designing a containership, a design team must determine the dimensions of the vessel, identify primary powering and propulsion equipment, define the operational limits of the ship’s systems, and prescribe technologies used to deliver on the vessel's mission. The team must also understand future contexts that the ship will face including economical and regulatory external factors.

The team's objective is to maximize cumulative expected profitability of the vessel for the owner. The vessel earns revenue for transporting containers between ports. Delivery of cargo requires a capital equipment investment, variable operating expenses for ship and crew consumables, and voyage outlays for insurance and port access. The life cycle economic equation is summarized below

$$\text{Rewards} = \max\left[\sum(\text{Revenues}-\text{Capital cost}-\text{Operating cost}-\text{Voyage cost})\right] \tag{1}$$

Revenues, operating costs, and voyage costs can vary significantly from year to year and are based on design characteristics as well as economic factors beyond the control of any design team. Capital costs include initial build costs and retrofits, or switching costs, which can serve to increase revenues and/or decrease expenses.

Carbon emissions must also be accounted for via the mandatory Energy Efficient Design Index (EEDI). The International Maritime Organization (IMO) and its represented Parties agreed to regulate emissions of greenhouse gases from international shipping in 2011 (IMO, 2012). A simplified version of the formula is presented below

$$\text{EEDI} = \frac{\text{Installed power}*\text{Specific fuel consumption}*\text{Fuel carbon content}}{\text{Design speed}*\text{Capacity}} \tag{2}$$

The objective of the index is to measure a vessel's grams of carbon output per ton-mile, or rather, a ratio of emissions to transport utility. Achieved EEDI is measured against a reference value for the specific ship type and deadweight cargo capacity. The reference curve is set to decrease with time, and required EEDI in 2025 for a new-build shall be 30% lower than current required levels.

The case study presented uses an MDP as the framework to minimize total ownership costs in the face of uncertain future scenarios between various design alternatives.

2.2. Independent variables and setup

An 8000 TEU (twenty-foot equivalent unit) post-Panamax containership is expected to transit cargo across the Pacific between the Port of Los Angeles and the Port of Hong Kong. The lifespan of the vessel is set for 20 years. Minimum design speed is 18 knot and maximum design speed is 25 knot. All regulations set forth by the IMO, port states, and the classification society under which the ship is registered must be satisfied.

Other assumptions and fixed parameters are listed in their appropriate following sections.

Sensitivity analysis is beyond the scope of this paper, however, the authors acknowledge the framework presented in Tan and Hartman (2011) is a potential means to study the role a fixed parameter can play in determining an MDP solution.

2.3. Approach outline

Fig. 1 outlines the MDP framework process for which design evaluation and changeability analysis are conducted. The policy under consideration and its macro-level implication are first introduced. A brief discussion of the problem setup outlines the state, action, transition, and reward characteristics input to the MDP-based methodology. First order analysis associated with expected rewards and design drivers are presented first in order to lay the foundation for results associated with changeability analysis. Temporal understanding gained from application of change metrics marks the intent of both the case study and the greater research thrust of this paper.