Ocean Engineering 72 (2013) 365–374

Contents lists available at ScienceDirect

Ocean Engineering

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

Strategic life cycle decision-making for the management of complex Systems subject to uncertain environmental policy

Nathan D. Niese*, David J. Singer

Department of Naval Architecture and Marine Engineering, University of Michigan, Ann Arbor, MI 48109, USA

A R T I C L E I N F O

Article history:
Received 6 December 2012
Received in revised form
10 April 2013
Accepted 22 July 2013
Available online 14 August 2013

Keywords:
Markov decision
Environmental policy
Life cycle cost
Shipping and the environment

A B S T R A C T

Environmental regulations play a significant role in ship design, manufacturing, operations, and disposal. As the life cycle progresses, a ship's environmental performance can degrade if more stringent policies are implemented at a port of call or for operations on the open seas. Tightened constraints over time may increase life cycle cost due to mandated replacement and repair costs, larger insurance premiums, or less operational flexibility. Unless design and maintenance activities account for uncertainty related to the environmental policy agenda, regulation changes can present considerable economic, operational, and mission-based risks to the life cycle of a vessel.

The optimal design and maintenance strategy for time-dependent environmental compliance can be determined via the use of a sequential decision-making framework known as a Markov decision process (MDP). The purpose of the presented research is to demonstrate the application of a non-stationary MDP to the design and maintenance decisions of a ship that must consider ballast water exchange and treatment policy changes. Research efforts outline the preliminary approach, outcomes, and conclusions resulting from the use of a MDP to model life cycle decisions.

1. Introduction

Developments in environmental policymaking over the last half-century have altered how products are designed and managed. Policy changes result in new constraints which may emerge during the initial design stage or in midst of existing operations. The likelihood of these challenges increases for long-life cycled products such as ships, aircraft, and industrial plants. Thus, the dynamics of environmental policy present considerable economic, operational, and mission-based risks to the life cycle of a complex engineered product (Son and Savage, 2007; Sussman, 2000).

Sustained life cycle effectiveness in face of uncertain operating and regulatory environments requires rigorous foresight of cause-effect relationships and an understanding of a design's ability to change in response to disturbances (Fricke and Schulz, 2005; Silver and de Weck, 2007). The unique location, magnitude, timing, and uncertainty of disturbances do not adhere to a "one-response-fits-all" approach. Thus, the design strategy spectrum might range from a single, irreversible decision to an active approach that shapes the product's life cycle trajectory (Mun, 2002; Teece, 2011).

Prior research on assessing ship-related environmental policies under elements of uncertainty simplifies these elements of strategic decision-making. Methods include cost-effectiveness decision criterion (Eide et al., 2009; Hoffman et al., 2012), scenario modelling (Altman et al., 1994, Eyring et al., 2005), stochastic integer programming (Balland et al., 2013), and mixed-integer nonlinear programming (Winebrake et al., 2006), primarily pertaining to air emission policies and macro, fleet-level consequences. The focus is more on what technologies to insert to achieve emission reductions or satisfy a new regulation and less on when to invest or alter a design strategy.

An improved strategic plan can identify key drivers of performance change due to disturbance and locate responses to uncertain disturbances at their appropriate life cycle stage (De Neufville, 2004). The research presented in this paper seeks to provide a more complete structure for life cycle decision-making by extending latest efforts on the machine maintenance problem under technological development (Borgonovo et al., 2000; Kumar and Saranga, 2010; Hopp and Nair, 1994). Where previous models have considered deterioration and/or technology obsolescence in prescribing a maintenance plan, a comprehensive framework that explicitly accounts for the interplay of external influences remains incomplete (Lin, 2009; Sornette, 2006). For example, legislation and technology are often coupled in an environment with progressive policymaking, where a new regulation can serve as the impetus for technology development (Metcalfe, 1994).

The following paper models the historical evolution of ballast water legislation for ocean-going vessels, product development across the ballast water management industry, and stochastic

* Corresponding author. Tel.: +1 419 367 1547; fax: +1 734 764 9649.
E-mail address: ndniese@umich.edu (N.D. Niese).

0029-8018/$ - see front matter © 2013 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.oceaneng.2013.07.020

degradation of the equipment's internal components. Accrued capital, operating, and maintenance costs are determined. The objective is to devise a life cycle strategy that minimizes cost over a vessel's life cycle while still achieving performance requirements. Decision-making results are instructive for ship managers, ballast water system manufacturers, and policymakers, alike.

2. Background and literature review

The authors formulate a discrete, finite horizon, non-stationary Markov decision process (MDP) to determine the optimal maintenance and replacement (M&R) policy under stochastic degradation, technology development, and environmental policymaking. Of particular interest is capturing the interplay between these internal and external stochastic forces. The following section contextualizes this paper's niche and contributions by systematically introducing past work related to the performance drift problem.

2.1. Performance drift

Performance reliability is time-dependent and is defined as the probability that system performance measures are within specification limits for the lifetime of the product (Savage and Carr, 2001). The vector of performance drift is affected by the components undergoing disturbance, the rate at which disturbance occurs, and the interactions of components (Son and Savage, 2007; Styblinski, 1991).

Fig. 1 illustrates the various ways in which disturbance may appear in the design objective space. Satisfaction of all constraints is signified by the shaded region, the star represents the selected design solution, and the Pareto frontier results from the minimization of both objectives. As presented in Fig. 1, the product may drift with time due to physical deterioration of components (away from Pareto front). Technological innovation may cause a shift in the Pareto frontier toward the origin. Performance limitations due to regulations may strengthen or weaken through time. Each form of disturbance may be uncertain and leads to impact which can be described via a probability distribution. The result is that the product has now become less preferred, co-located solutions may have diverged, and action is required to move back toward the Pareto frontier (Smaling and de Weck, 2007).

In Ross and Hastings' (2006) discussion of a tradespace network, the authors define possible transition paths that result from active or passive changeability of the system. Change, in this context, is defined as a transition over time to an altered state. It is the increased understanding of a design facilitated via a tradespace network view that this research exploits to assess strategies for managing environmental policymaking.

2.2. Sequential decision-making

A primary thrust within disturbance research is to assess and improve performance reliability of a system as its condition and influencing environmental conditions change (Singh et al., 2010). Management involves a series of sequential actions on the part of system operators; throughout the system's life cycle, a decision-maker has multiple discrete opportunities to invest in resources that affect performance. Outcomes are often a complex mix of predictability and unpredictability, dually controlled by a decision-maker and by randomness.

Determining the appropriate timing and response among a set of choices can be aided by decision analysis. Fig. 2 is used to illustrate potential decision paths that result from consideration of design trade-offs and action choices for two designs, Concept A and Concept B. The figure both captures the changes due to disturbance highlighted in Fig. 1 and overlays a decision tree in the objective space. Design subscripts highlight instances in the decision path where multiple options for change exist. Inherent to each path are switching costs. Design and decision path evaluation at both the intra- and inter-levels of comparison can now answer the following questions:

- Is a transition from A' to A_1'' more preferable than the transition from A' to A_2''?
- Is the decision sequence proposed by Concept A more preferable than that of Concept B?

2.3. Markov decision processes

A Markov decision process (MDP) has proven to be an effective framework for modelling this sequential decision space. A MDP is a method to formulate and solve dynamic decision-making problems under stochastic conditions. MDPs, also commonly known as sequential dynamic programming, have been studied extensively since their introduction in the 1950s (Puterman, 1994). Common problems where MDPs are employed include route planning, goal-seeking, resource allocation, replacement, maintenance and repair, inventory, queuing, scheduling, and asset pricing (Feinberg and Schwartz, 2002).

The machine maintenance problem using Markov decision processes was one of the first applications of the sequential decision-making frameworks (Smallwood and Sondik, 1973). Optimal strategies for improving reliability, controlling failures, and

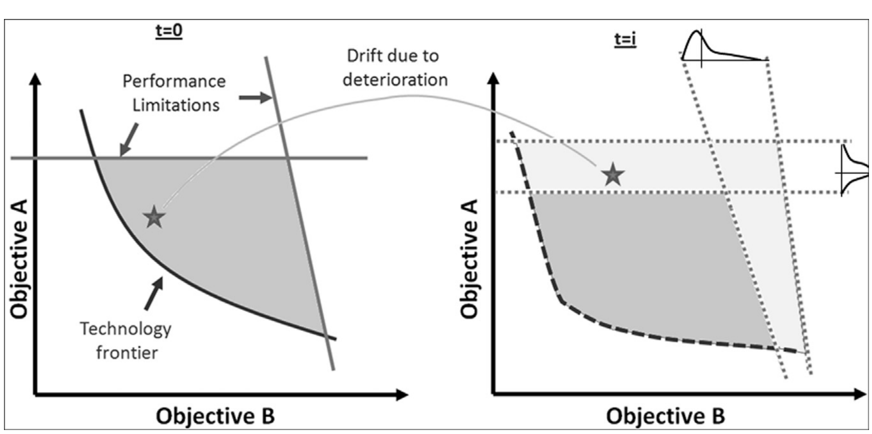

Fig. 1. Modelling impacts of disturbance in objective space.