Life Cycle Evaluation under Uncertain Environmental Policies Using a Ship-Centric Markov Decision Process Framework

by

Nathan Douglas Niese

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Naval Architecture and Marine Engineering)
in The University of Michigan

2012

Doctoral Committee:

- **Assistant Professor David J. Singer, Chair**
- **Professor Gregory A. Keoleian**
- **Professor Nickolas Vlahopoulos**
- **Assistant Professor Matthew D. Collette**

Dedication

In remembrance of my grandfather, Donald C. Niese

Acknowledgements

I have been a blessed individual since enthusiastically pledging my allegiance to “That School up North” eight years ago. My time at the University of Michigan has been defined by the special individuals who have enabled and who have shared in my journey. I leave Ann Arbor with the utmost gratitude, and my heart will forever bleed Maize and Blue.

I thank my advisor and mentor, Dr. David Singer, for his guidance and support in my development as a problem-solver and a researcher. Dr. Singer provided the freedom to creatively construct a research topic that stretched my understanding of early stage design. His technical acumen, instincts, and synthesizing ability offered a blend of thinking that helped shape my educational experience. Our times shared in and out of the office have left a lasting impression, and it is this collection of intellectual, career, and personal advice that will guide me through future challenges.

I am very grateful to the American Society of Engineering Education for the National Defense Science and Engineering Graduate (NDSEG) fellowship and the Office of Naval Research (ONR) that supported me through my years of doctoral education.

Thank you to the faculty who have served on my doctoral committee: Dr. Greg Keoleian for his encouragement to approach the problem through multiple viewpoints, Dr. Matthew Collette for his insightful questions that served as inspiration, and Dr. Nickolas Vlahopoulos for his assistance in scoping the research problem. Your time in review of my thoughts and materials, your support, and your friendship have been highly valued.

The men and women of the Advanced Naval Concepts Research (ANCR) lab have provided generous feedback during research meetings and welcomed distractions from day-to-day activities. A special thanks to Justin Gillespie for our spirited brainstorming

sessions; Brian Cuneo for providing balance to my research activities; Dr. Alex Gray for his leadership; and Anthony Daniels, Fang Dong, Josh Knight, Thomas McKenney, Doug Rigterink, Morgan Parker, and Jason Strickland. May Team Independence forever maintain its strength. Additional thanks to Bill Rosemurgy, Nick Stowe, and other Members of the SwellTime crew.

I am also grateful for support offered by colleagues and friends beyond the world of the Naval Architecture & Marine Engineering department, namely: Jason Angel, Eric Boye, Emily Chi, Tara Dailey, Ryan Dreifke, Dave Murray, Josh Palka, Alex Prosperi, Daniel Schachne, Jake Stewart, and the players and families through the Rec&Ed soccer program I have had the pleasure to know and coach.

The tremendous love offered by my family remains a tremendous source of strength in all that I do. I am indebted to my parents, Mr. Dean Niese and Mrs. Cathy Niese, for their unceasing encouragement, inspiring work ethics and tenacity, and endless sacrifices that shaped me into the man I am today. Siblings Alyssa and Justin have been sources of confidence, and I look on with great pride as they continue their own academic and career journeys.

The most lasting and significant treasure I have received at the University of Michigan is the joy brought about by my fiancée Jaye. As a diligent study buddy, a steadfast supporter, and a loving partner, you have touched this work and its author in untold ways. Thank you for the spirit and the richness that you add to the world and my life.

Table of Contents

List of Figures

List of Tables

List of Appendices

Abstract

A novel design evaluation framework is offered to improve early stage design decisions relating to environmental policy change and similar non-technical disturbances. The goal of this research is to overcome the traditional treatment of policy as a static, external constraint and to address in early stage design the potential disruptions to performance posed by regulatory policy change. While a designer's primary purpose is not to affect policy, it is the responsibility of the designer to be cognizant of how policy can change, of how to assess the implications of a policy change, and of how to deliver performance despite change. This research addresses a present need for a rigorous means to keep strategic pace with policy evolution.

Use of a Markov Decision Process (MDP) framework serves as a unifying foundation for incorporating temporal activities into early stage design considerations. The framework employs probabilistic methods via a state-based structure to holistically address policy uncertainty. Presented research enables exploration of the performance of a design solution through time in the face of environmental instabilities and identifies decisions necessary to negotiate path dependencies. The outcome of this research is an advanced framework for addressing life cycle management needs that arise due to policy change, as judged from a life cycle cost perspective.

Original metrics for evaluating decision paths provide insight into how the timing, location, and confluence of disturbances impact design decisions. Development of the metrics is driven by a desire to communicate the design-specific characteristics of a strategic response to policy change. Quantifying the amount and type of uncertainty present, changeability afforded, and life cycle changes exercised offer points of comparison among individual design solutions. The knowledge gained from path-centric measurements enables an enhanced ability to characterize design lock-in. Principles and metrics borne out of the design evaluation framework are validated through two ship design examples related to ballast water treatment and carbon emissions.

CHAPTER 1 – INTRODUCTION

All men can see these tactics where I conquer but what none can see is the strategy out of which victory is evolved.

Sun Tzu

The environmental revolution in the shipping industry marks just one of the ways in which evolving design requirements are threatening to outpace the arrival of new, affordable solutions. However, this revolution also marks an instance where ship design decisions present unique opportunities. For example, carbon emission policies pose multiple paths for implementation. Conversely, the double skin hull requirement for oil carriers is a mandatory shift with little opportunity for innovation that the whole industry must follow. Correctly determining where and when resources should be allocated can prove rewarding from both a performance and financial standpoint. Designers of the future must appreciate both these new compliance needs as well as life cycle management needs.

A deep understanding of path dependency and the temporal aspect of decisions across the life cycle has yet to fully enter the primary consciousness of ship designers. Physical reliability is one ship design discipline where such considerations are more prevalent in decision-making. Other –ilities, specifically environmental and political sustainability, have not been approached with a similar perspective. Managers have found it difficult to translate information regarding vulnerabilities from policy and architectural lock-in into actionable decisions regarding the future.

1.1 Context

1.1.1 ANCR

The University of Michigan Advanced Naval Concepts Research (ANCR) lab was founded in 2007 to establish a focused discipline concerned with decision-making for conceptual design of naval and maritime vessels. ANCR's interdisciplinary scope spans production management, operations research, systems integration, requirements analysis, and technology and policy within the context of preliminary ship design.

This dissertation focuses on the strategic management of early stage design decisions subject to future, uncertain, exogenous factors such as expected regulatory changes. Strategic measures combine design and innovation with business principles. Management is needed to assess and reassess whether a strategy "has succeeded or needs replacement by a new strategy to meet changed circumstances, new technology, new competitors, a new economic environment, or a new social, financial, or political environment" (Lamb, 1984). Exogenous factors are especially relevant in design as cross-industrial relationships become tighter and their effects more significant. Any hope of managing these stronger ties in the concept design phase, where issues can best be resolved, first requires new measurements and methods that elucidate these considerations.

This research aims to further bring decisions forward into early stage design that have historically been completed late in the design process while also showing appreciation for the irresistible force paradox. For a design to move forward, the design manager must make decisions which lock in future abilities. However, designers are not omnipotent. Knowledge of the best solution is only revealed with more time, especially in the instance of ship design where the governing environment can be harsh and volatile, stakeholders are numerous, and life cycle paths are infinite.

1.1.2 Conceptual Design Decision-Making

Conceptual design is one phase within the design process, before detailed design but following the development of requirements. During this phase, a design team specifies the high-level mapping of function to form. The physical form selected then determines the majority of the cost and schedule for the ensuing development process.

Specifying a ship, and subsequently designing to that specification, is an intricate undertaking. The design itself is complicated given that a ship is composed of dozens of systems and thousands of components. Managing the design process is complex because it involves reciprocal ties between individuals and a dynamically evolving information set. These complicated and complex natures inherent to the design are further categorized and explained as follows:

- *Ambiguous Requirements* – The client does not or cannot always specify the necessary requirements before design commences. Often, the first step of design demands validating the feasibility of the requirement set. Requirements may be modified once further information is obtained.
- *Non-linear Interdependencies* – The laws of physics governing construction and operation of a ship involve non-linear relations. For example, variables such as speed or beam size are related to engine power via a cubic function. Design requires detailed integration considerations to manage the large degree of coupling between ship systems, its operators, and the marine environment.
- *Limited resources* – An individual cannot imagine all possible solutions for a ship design. A computer cannot analyze all combinations in a reasonable amount of time. Early stage design relies on experience, which offers a foundation for success but may also over-emphasize past methods and outcomes. Low fidelity tools are utilized to support experience in a timely manner; low fidelity also may provide inconclusive results due to significant error bounds.
- *Lack of tools* – Certain requirements or preferences are not yet aptly measurable in early stage design. Life cycle characteristics are increasingly specified at the outset, but evaluation may be restricted to the use of rudimentary calculations and regressions.
- *Delegation of design responsibilities* – The Herculean task of ship design is regularly managed in sub-teams. Decisions occur at various rates, resulting in

competition for space or requirement satisfaction and potential lock-in before a sub-team has had an opportunity to fully explore the design space.

- *Many "right" solutions* – Infinite possibilities, ambiguous requirements, and low fidelity modeling are likely to lead to a range of equally valued solutions. Where one solution performs well by Metric A, another outperforms in Metric B. Convergence to a final solution requires trade-off judgments.
- *First time solutions* – Ships are often one-off or low batch designs. Many of the largest vessels sailing global waters today also carry a significant price tag. A sub-optimal design cannot be easily scrapped and replaced with a new version. Pressure is on designers to deliver a product that expertly satisfies a client's needs without the aid of prototyping.
- *Uncertainty* – Operations are functions of stochastic parameters such as weather and enemy threats. Market and regulatory environments are time dependent. Where, when, and how these factors originate is highly uncertain. Designers are consistently asked to capture the correct behavior to successfully manage these consequences, despite the lack of predictability and complete human understanding.

Andrews (2012) summarizes these characteristics as ship design's *wicked problem*, stating that both the designer and the client must work together "to reveal what is wanted and what is realistic in terms of time, cost, and risk." Without the comfort of a prototype, elucidating what is wanted and affordable is a complicated endeavor that relies on trial-and-error dialogue and generating multiple prospective solutions.

The greatest amount of uncertainty and variability is derived at a design's outset. The lack of data is especially salient for large, heterogeneous systems such as ships. Design progress improves information learning, and so diminishes uncertainty and removes opportunities for variability, a concept often illustrated via the knowledge curve (Figure 1-1).

Poor decisions during conceptual design can have significant cost implications, leaving a product manager with a tough choice between suboptimal performance or heavy change costs. As design progresses from conceptual design, through contract design and detailed design, to construction, change costs for naval ships have been noted to increase by a factor of ten at each stage (Keane and Tibbits, 1996). Careful analysis of the design space can mitigate the risk of required change. Increasing knowledge and reducing uncertainty in early stages of design can prevent untimely elimination of strong candidate regions within the design space. Analysis that provides this additional information can lead to the realization of higher-utility, more robust solutions.

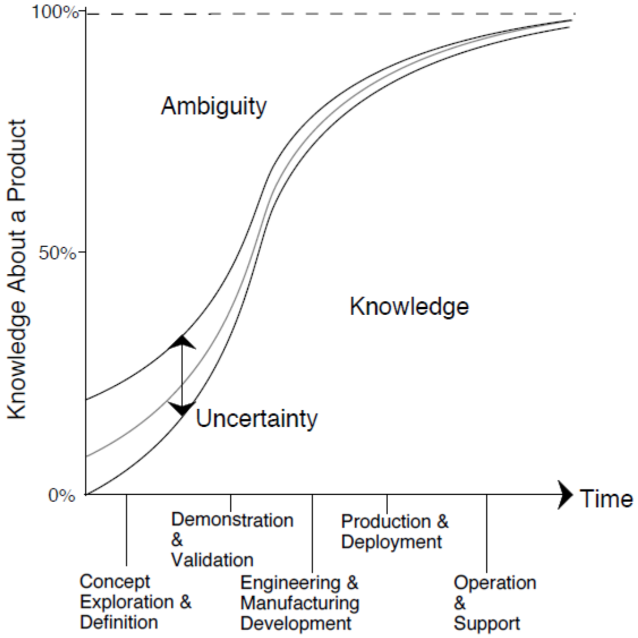


Figure 1-1: Knowledge increases and uncertainty diminishes with time (Mavris, 1998).

One pervasive dilemma within the conceptual design phase is how to incorporate dynamic life cycle considerations (Holloway et al., 1994; Pistikopoulos, 1995; Schaltegger and Burritt, 2000; Pindyck, 2007). While set-based design has proven capable of parallelizing intra- and inter-group decision-making, the same ability cannot be guaranteed for intra- and inter-life cycle time periods. Product life cycle itself is one aspect which will forever and always remain “over the wall”; end-of-life treatment follows operation which follows construction. What occurs in the future cannot be parallelized with events of today due to path dependencies. The best one can hope for in the management of life cycle concerns is to properly value the future implications of decisions today. That valuation is still lacking robust design management methods and metrics.

1.1.3 Policy Robustness

The research presented draws into focus the political realm. Doing so results in a blending of rigorous mathematical logic that is the cornerstone to engineering design and influenced, informal logic inherent to policymaking. The link and feedback between the technical and political domains is made apparent when one recognizes that both domains are concerned with cost, performance, and risk (Weigel, 2002). Technical requirements drive cost, performance, and risk. Policy decisions drive the reorganization of technical requirements if current levels of cost, performance, and risk are deemed unsuitable to other stakeholders. While both technical and political domains seek to answer the following questions, the desired answers may prove divergent:

- At what environmental cost should a product achieve its purpose?
- Can a cleaner, more equitable service be affordably provided?
- Do operations put at risk the safety and/or livelihoods of crew, other industries, and future generations?

Answers to the above questions are also dynamic with time. A ship owner may desire to trade off environmental cost, should conditions prove favorable for higher revenues as well. A government may seek to trade off strict performance margins if the basic operation of a vessel is deemed important to national security. As such, constraints and objectives that exist today may no longer exist tomorrow. This dissertation recognizes that the traditional treatment of policy as a static, external constraint is proving ever more inadequate.

Environmental policy activities are adding to or revising ship design objectives. Policy regimes enforcing a previously marginalized design constraint can significantly alter the status quo. Automobile, electronics, and appliance manufacturers that failed to design for disassembly or recyclability found their product cost structure disproportionately impacted by European “take back” laws (Atasu & van Wassenhove. 2011). U.S. Army equipments developed for the Cold War were ill-prepared to handle the dust intrinsic to Middle East operations (Konrad et al., 2005). Safety tends to become an elevated concern following a catastrophic event, and the new status quo may be marked by additional procedures (Atkeson & Maestas, 2012).

Robustness to disturbance helps ensure a product remains functional throughout its intended lifespan. In transportation systems and other large capital, long life cycle systems, the lack of accommodation for the dynamism of political-based constraints has led to premature failure of designs and/or suspension of whole industries, e.g., early retirement of coal plants due to tougher federal air pollution regulations (Walsh, 2012); cancellation of deepwater drilling projects following increased permitting requirements, more stringent drilling practices, and a moratorium on oil exploration (Mason, 2010); and boom-bust cycles associated with clean energy policy (Jenkins et al., 2012). In addition to product obsolescence, disturbances may also be caused by technological revolution, new economic competition, and transformations to form or function.

It is the coupling of these dynamic and disruptive properties that make policy considerations in design both intriguing and disconcerting. The previous two paragraphs offer examples for why overlooking the impact of policy on design in a world that is rapidly growing more connected is a risk-filled move. Poor satisfaction of new constraints and early product retirement can be a costly and time-consuming fix. However, rigorously considering policy, which is time-dependent and uncertain, cannot be achieved through traditional tools such as Analysis of Alternatives or static optimization techniques that fail to consider evolution of the design and objectives spaces.

The following research presented in this dissertation proposes a methodology for handling time-based and path-dependent characteristics. As a result, a firm link between policy and design is established. A framework that tackles both the dynamic and disruptive characteristics of policy also permits extensibility to other technical and economic domains. The aim of this research is to propose a design choice framework for assessing an emissions policy change that differs minimally from assessing a revolutionary technological innovation, a significant spike in oil prices, or a similar disturbance, for example.

Clarifying the scope of the term "policy" in this thesis is important before moving forward. The author defines *policy* as a method of action adopted by a government or organization intended to guide and determine present and future decisions. Legislation in the form of laws and regulations are the outcomes of policies and the instruments of policymakers. The spectra across which policymakers operate include free markets, education and research, market-based incentives, regulation, and direct government ownership and allocation (Cubbage et al., 1993). Policies explored in this research are drawn from the national and international levels, allowing the author to neglect options for mitigating local policy changes through route shifting and other similar actions.

1.1.4 –ilities

Design architects increasingly conduct their activities with intentional care for the dynamic life cycle properties of a system. Achieving performance for systems with long life cycles is made more difficult as the pace of disturbances accelerates and stakeholder needs evolve. Ensuring the continued delivery of high performance is complicated by the presence of uncertainties related to future design decisions, operating contexts, economic markets, and technology developments (Fricke and Schulz, 2005).

The degree to which a system's value is influenced by shifting contexts can be described by temporal properties collectively known as the –ilities. Methods that extend beyond the optimization of static needs in fixed environments and instead incorporate time-dependent system analysis are said to evaluate the –ilities class. Temporal properties are increasingly moving from non-traditional design measures to inclusion within the set of standard design criteria. For example, an emphasis by the U.S. Navy on total ownership costs has superseded traditional contract negotiations focusing only on acquisition cost projections.

Managing –ilities adds another level of uncertainty to design. Whereas satisfying a design speed requirement is a simple yes/no proposition, achieving an –ility-related constraint is a function of context and stakeholders. For example, a five percent mortgage interest rate that appeared affordable in 2008 no longer remains so today when rates are 200 basis points lower. Dynamic constraints are further characterized by conditionality. A malfunctioning scrubber can reduce the sustainability profile of a vessel; however, the program manager may find the reduced sustainability acceptable so long as the scrubber is fully operational upon entry to the next port. Thus, sustainability preferences in this case are conditional.

Further defining –ilities and operationalizing these –ilities through associated metrics are existing research needs. Scholars and practitioners acknowledge that each -ility exists along a spectrum and is non-exclusive of other –ilities. For example, two products may both be deemed sustainable by stakeholders, though one product may prove to exhibit superior sustainability properties. Similarly, a sustainable product may also be characterized as survivable and reconfigurable. As research more aptly bounds –ilities descriptions and provides rigorous methodologies usable for validating design, the unevenness with which enterprises promote the temporal abilities of their products can be expected to diminish.

The role of this dissertation is to further operationalize changeability in response to environmental policymaking. The value of matching “change with change” and the idea of latent change potential are studied from a design management perspective. The research attempts to draw a clear distinction between a design requirement that an –ility be present at the outset and the *opportunity* for that –ility to be available in the period(s) desired.

1.2 Motivation

> *The margins on regulations, environmental awareness, and life cycle cost now have more influence on the success of a ship program than at any other time in the past (Briceno and Mavris, 2006).*

1.2.1 Increasing Environmental Policymaking

The transportation sector has witnessed an evolution of environmental-related regulations and overarching policies. Despite the fact that shipping is the most efficient mode of transportation in terms of energy use, the industry's current size and growth expectations warrant improved sustainability performance. The impacts of shipping manifest themselves in the air, in the water, and on land. The last decade alone has seen international efforts to reduce carbon, sulfur oxides, nitrogen oxides, particulate matter, chlorofluorocarbons, sound, oil, invasive organisms, grey water, black water, organotins, and solid waste emissions.

Example outcomes of these efforts on the international level include:

- *Annex VI—Air Pollution to the International Convention for the Prevention of Pollution from Ships*
- *Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal*
- *International Convention for the Control and Management of Ships' Ballast Water and Sediments*
- *International Convention for the Control of Harmful Antifouling Systems on Ships*
- *Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships*.

These policy documents represent both a strengthening of old policies and the development of new policies. Hundreds of national, regional, and state programs have also been adopted. The earliest regional effects were in the waters surrounding Northern Europe, though recent advancements are set to include the coastal areas surrounding North America and the Far East.

Ideally, the evolution of a ship coordinates with the timing of policy changes. However, given the innate constraints of a complex system, evolutionary capabilities must be planned for early in the design process. Leading or lagging policy changes can present significant financial, environmental, and operational difficulties. A rigorous means to keep strategic pace with policy evolution is an open and significant research challenge.

The second underlying trend related to environmental policymaking is the manner in which policies are communicated. Adoption of the goal-based standards (GBS) framework by the governing bodies of the shipping industry, Figure 1-2, has led to a shift from prescriptive to performance requirements (ISSC, 2009). The prescriptive rule-making strategy was diagnosed as leading to ineffective constraint extremes. Rules proved to be either too lax or overly conservative. Conversely, a performance-based approach is hailed as affording greater freedom to a designer and encouraging the exploitation of a wider range of feasible designs. The new framework can offer guidance and incentive to designers that want to exceed legislative compliance. However, the transition to GBS has required sacrifices, for which the industry is dependent on research to overcome; the former prescriptive methods were simple for designers to understand, easy for managers to check, and rooted in an empirical basis (ISSC, 2009).

Figure 1-2: Goal-based standards pyramid (ISSC, 2009)

1.2.2 Increasing Ship Cost and Complexity

Ship build and operation costs have outpaced the rate of inflation over the past four decades, which has concerned navies and commercial industry alike—7+% and 2.7%, respectively (Arena, 2006). Greater expense threatens to outstrip the ability to pay for the vessels. Naval ship programs have especially been plagued by cost overruns, a percentage of which can be attributed to factors concerning shifting stakeholder needs. Shifting contexts lead to ship systems that are inadequate, incompatible, obsolete, or technologically unready. These design inconsistencies propagate across the procurement, scheduling, manufacturing, and operating phases. Poor decision-making is the result of methods and realities that preclude the observation, analysis, and synthesis of the many dimensions affecting design performance and valuation (Arena, 2006).

Cost issues are exacerbated as ship system complexity increases. The electrification of ships presents a notable example of innovation that delivers revolutionary performance but at an increased level of complexity. Greater complexity allows for more points of failure as well as failure modes that may not even be identified before they occur. A move to a more holistic design approach increases the dimensions of the performance space and accounts for a wider range of interactions between systems and with a product's surroundings (ISSC, 2009).

The addition of environmental objectives has added to the burden in both the cost and complexity dimensions. New systems are onboard ships to treat ballast water and grey water, where previously no such systems were necessary. Multiple fuels and associated equipment must be carried so that a vessel can enter ports located in sulfur emission control areas (SECAs). The cost-benefit equation has changed as (1) energy prices have increased markedly over the last decade, and (2) evolving policies require enterprises to internalize the cost of emissions. Sustainability initiatives are increasingly competitive as fuel prices increase and marginal abatement costs appear lower. Yet, overall cost inflation continues to occur as the supply of alternative measures is constrained by new policies just as demand increases.

Holistic design has also swelled the number of stakeholders and redefined the roles of existing stakeholders. As examples, ports are increasingly conscious of the impacts of point emissions on the health of local populations and charterers have indicated that their clients expect sustainability throughout the supply chain. Improving benefits on the global scale can come at the expense of ship owners and operators. A ship owner in a 2011 Moore Stephens survey notes, “There will be an inevitable cost consequence of implementing fuel efficiency measures at the request of charterers, while the benefits of such measures will not be seen in terms of operating costs.”

1.2.3 Realizing Sustainability Innovations

The concept of sustainability as a high-level objective is well understood: demonstrate stewardship of resources so that the ability of future generations to meet their own needs will not be compromised (Omer, 2008; Robert et al, 2002). Intense research has led to innovations related to optimized hull forms, the use of alternative propulsors and fuels, diesel configurations that promote efficiency, and technologies that treat sulfur dioxides and ballast water. Researchers have conducted life cycle analyses of a containership, a LNG carrier, a ferry, and a recreational charter boat (Birmingham et al., 2006), both for conceptual and completed designs. Works such as the IMO 2009 Greenhouse Gas study have identified sustainability implementations at the industry level under future scenarios.

However, methodologies that synthesize sustainability information and add to the validation of new concepts remain incomplete. Designers have demonstrated difficulty identifying practical actions at the individual ship level that will lead to significant impact. Efforts to date focus on comparative studies of two or a small set of alternatives, as opposed to wider exploration of the design space.

1.3 Scope

1.3.1 Relevant Literature

A literature review is conducted to place the unique contributions of the dissertation relative to previous academic, government, and industry efforts. More specifically, the purpose of the review is to develop an understanding of the strengths and weaknesses inherent to currently applied methodologies related to sustainability engineering under a changing policy context. Interdisciplinary, referenced literature reaches across policy, environment, and technology domains. The -ilities are addressed at the systems and subsystem levels. Literatures focusing on decision analysis and uncertainty management during conceptual design are of particular focus.

1.3.2 Research Questions

Table 1-1 summarizes the key problems addressed in this dissertation and poses questions that, once answered, should lead to an improved understanding of early stage design decisions. The following research addresses the challenges mentioned in Section 1.2 by developing a methodology rooted in the theory and methods discussed in Section 1.1. Theory is further developed in Chapters 2 through 4, while the new methodology and metrics are proposed in Chapter 5. The principal goal is to provide a structured manner for enabling design engineers to link policy change to early stage design decision-making.

Table 1-1: Problem statement and research questions

Problem	**Question**
Instability of the environment means a product solution may not be quality through time; Design must consider future product use that is uncertain and/or unforeseeable	Where must system capability for performance change lie given an uncertain life cycle environment?
Multiple sources, strengths, uncertainties, and time scales of disturbance exist	How can these sources be handled in a unified framework that considers both individual and cumulative impacts?
The rate and magnitude of environmental policies for ships are increasing, changing how good design is defined	Can understanding decision paths in response to policy change help identify design drivers of today and tomorrow?
A static viewpoint of the design artifact leads to over- or under-design, resulting in reactive change costs	How does a dynamic perspective on design enable more timely change and better management of life cycle cost?
Evaluation of optimal decision paths across alternative design concepts is limited when using only life cycle cost for comparison	What metrics can extend evaluation of decision paths beyond a discussion of life cycle cost?

1.3.3 Contributions

The research goal is to develop a design evaluation framework that strategically considers path dependencies inherent to life cycle decisions. Several high-level contributions are brought forward as a part of this work:

1. Incorporation of environmental policy into early stage design through the establishment of a unifying methodology that links disparate technical and non-technical concerns
2. Improved control of product lock-in through analysis of path dependencies within the decision space
3. Broadened understanding and quantification of the role of timely changeability.
4. Introduction of the Markov Decision Process framework to ship design
5. Development of new changeability evaluation metrics stemming from Markov Decision Process setup and analysis

1.4 Thesis Structure

The first phase of the research is to synthesize the role of policy and policy change in technical decision-making. The outcome is to provide methodological insight and a generalized structure for the case application phases.

Chapter 2, **Framing Policy: The Political Perspective**, offers a descriptive synopsis of the policymaking process, noting triggers in both the policymaking and technical arenas that incite action. Political science literature is consulted to frame policy agents, policy instruments, and the organizing structure of policy development from a social learning perspective.

Chapter 3, Framing Policy: The Technical Perspective, discusses the role of policy in crafting a design and maintaining performance through the life cycle of the product. Reliability engineering, strategic management, requirements change research, and design theory concepts are surveyed. The process by which a policy change translates into a technical change following an evaluation of available options is described in detail.

Chapter 4, Problem Formulation, details related efforts in the exploration of a design methodology that manages policy change, outlines limitations and differences in approaches, and formalizes the problem statement for this dissertation. The incompleteness of design methods for handling sustainability and changeability is documented. A thorough literature review of change management is conducted, spanning past research using networks, tradespace exploration, portfolio theory, matrix methods, game theory, and reliability-based techniques.

Chapter 5, Methods & Metrics, details the Markov decision framework that serves as a foundation to an improved understanding of design in the face of environmental policy change. A combination of traditional and novel metrics is suggested to operationalize strategic decision-making.

Chapter 6, Case Application #1: Responding to Ballast Water Policy and Technological Development, applies the proposed methodology to a historical ship-related example. Analysis produces a decision matrix, which is then utilized to reduce the decision tree and identify common life cycle paths. Sensitivity is conducted to elicit a full design strategy irrespective of the regulatory schedule. Changeability is then evaluated using the suggested metrics.

Chapter 7, Case Application #2: Design Evaluation Subject to Carbon Emission Policymaking, again applies the proposed methodology to a more open design scenario. Environmental and economic preferences of design variable values are discovered through application of the Markov framework. A detailed discussion of the value-added activity of changeability is related through use of qualitative and quantitative metrics.

Chapter 8, Conclusion, returns to the research questions identified in the introduction and discusses the performance of this dissertation across these objectives. The extensiveness with which each question is answered is assessed, with inclusions for a discussion of methodology limitations and areas for future research.

Chapter Citations

1. Andrews D. (2012). Is marine design now a mature discipline? *In proceedings of International Marine Design Conference*, Glasgow.
2. Arena, M., Blickstein, I., Younossi, O., & Grammich, C. (2006). Why has the cost of Navy ships risen?: A macroscopic examination of the trends in U.S. naval ship costs over the past several decades. *Report*. RAND Corporation.
3. Atasu, A. & Van Wassenhove, L. (2011). What's yours is mine: Getting to grips with take-back laws. *IESE Insight, 8*.
4. Atkeson, L., & Maestas, C. (2012). Catastrophe politics: How extraordinary events redefine public perceptions of government (Overview). Cambridge: Cambridge University Press.
5. Birmingham, R., Landamore, M., Wright, P., & Downie, M. (2006). Investigation of sustainable technologies for the design, construction, operation, and decommissioning of recreational craft. *In proceedings of 19th Intl HISWA Symposium*, Amsterdam.
6. Briceno, S., & Mavris D. (2006). Applications of game theory in a systems design approach to strategic engine selection. *In proceedings of 25th International Congress of the Aeronautical Sciences*, Hamburg.
7. Cubbage, F., O'Laughlin, J., & Bullock, C. (1993). *Forest Resource Policy* (Chapter 2, pp. 23-41). New York: John Wiley, Inc.
8. Elshof, L. (2009). Technology education: overcoming the General Motors Syndrome. *Pupils' Attitudes Towards Technology – 22*, Delft, Netherlands.
9. Fricke, E., & Schulz A. (2005). Design for changeability: principles to enable changes in systems throughout their entire life cycle. *Systems Engineering, 8* (4), 342–359.
10. Holloway, L., Clegg, D., Tranter I., & Cockerham, G. (1994). Incorporating environmental principles into the design process. *Material & Design, 22* (15), 259-267.
11. ISSC. (2009). Design principles and criteria. *17th International Ship and Offshore Structures Congress*, Seoul, Korea.
12. Jenkins, J., Muro, M., Nordhaus, T., Shellenberger, M., Tawney, L., & Trembath, A. Beyond boom & bust: Putting clean tech on a path to subsidy independence. *Report.* Breakthrough Institute, Brookigs Institute, & World Resources Institute.
13. Keane, R., & Tibbitts, B. (1996). A revolution in warship design: Navy-industry integrated product teams. *Journal of Ship Production, 12* (4), 254-268.
14. Konrad, M., Beebe, M., Skelton, D., & Schmidt, D. (2005). Assessment of the impact of Iraq environment on army material. *Tri-Service Corrosion Conference*, Orlando, Florida.
15. Mason, J. (2010). The economic cost of a moratorium on offshore oil and gas exploration to the Gulf region. *Report.* Louisiana State University.
16. Mavris, D., DeLaurentis, D., Bandte, O., & Hale, M. (1998). A stochastic approach to multi-disciplinary aircraft analysis and design. *In proceedings from AIAA 98-0912*.
17. Omer, A. (2008). Energy, environment and sustainable development. *Renewable and Sustainable Energy Reviews,* 12(9): 265-2300.
18. Pindyck, R. (2007). Uncertainty in environmental economics. *Environmental Economics and Policy, 1* (1), 45-65.

19. Pistikopoulos, E. (1995). Uncertainty in process design and operations. *Computers & Chemical Engineering,* 19 (1), 553-563.
20. Robert, K., Schmidt-Bleek, B., de Larderel, J., Basile, G., Jansen, J., Kuehr, R., Thomas, P., Suzuki, M., Hawken, P., & Wackernagl, M. (2002). Strategic sustainable development—selection, design, and synergies of applied tools. *Journal of Cleaner Production,* 10(3): 197-214.
21. Schaltegger, S., & Burritt, R. (2000). Contemporary environmental accounting: issues, concepts, and practice. London: Greenleaf Publishing.
22. Walsh, B. (2012). War on coal: Why polluting plants are shutting down nationwide. *Time* (March 1).
23. Weigel, A. (2002). Bringing policy into space systems conceptual design: quantitative and qualitative methods. *Dissertation*: Cambridge, MA.

CHAPTER 2 – FRAMING POLICY: THE POLITICAL PERSPECTIVE

The world is in a constant conspiracy against the brave. It's the age-old struggle: the roar of the crowd on the one side, and the voice of your conscience on the other.

-Douglas MacArthur

Three broad complex systems of importance to engineers are the natural environment, the built environment, and the policy environment. The parallels among the three systems are undeniable: resource-limited hierarchies, perceived and unperceived constraints, and varying degrees of susceptibility, thresholds, and episodic events (McGinnis and Ostrom, 2010). Perhaps *more* important to decision-makers than the three complex systems individually is the natural environment—built environment—policy environment nexus at which decision-making must operate (Figure 2-1). No environment is a permanent driver of the other two environments, and the linkages are defined by a blend of cooperating and competing forces.

Understanding the complex manner in which the three environments pervade design decisions can be vital to a product's life cycle performance and economics (Holloway et al., 1996). Traditionally, issues of technical and social domains were treated separately. Both the environment and policy may have been best described as nuisances to design processes and risks to the core business philosophy. Strategic integration and synergies were not thoroughly explored or employed (Schaltegger and Burritt, 2000).

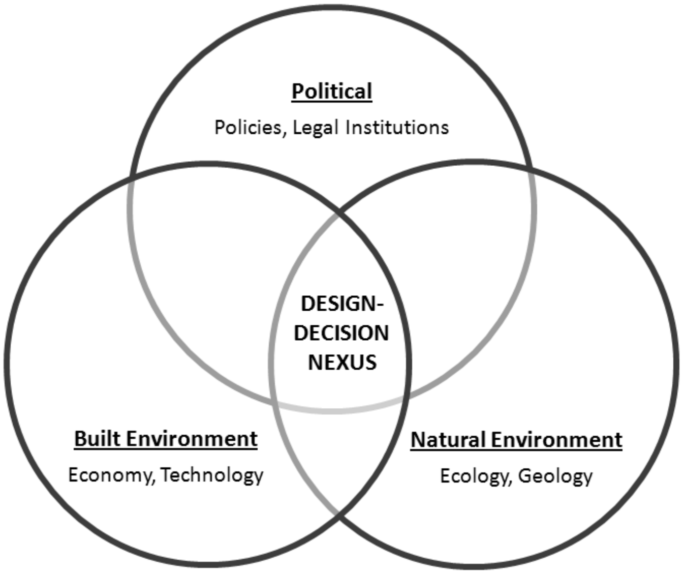


Figure 2-1: The technical design-decision nexus is at the confluence of the natural, built, and political environments

The growth of a systems approach to engineering has ushered in an era of appreciation for the socio-technical aspects of the world. Human efforts to understand and govern dynamic environmental, economic, social, and political linkages have been truly interdisciplinary (Kates et al., 2000). The need for understanding the complex interactions among domains grows ever more important as the pace, cost, and connectedness of human endeavors increase.

This dissertation employs a systems dynamics approach that recognizes the role of the policymaker as a conduit and arbitrator between the “silent” environment and decision-makers within the technical domain. This indirect communication between a technical decision-maker and the natural environment is revealed in the form of policy initiatives. The outcome of this approach is a unique ability to investigate and evaluate the strategic integration of the environment’s wishes, via policy, into the design of ship system.

Najam (2005) finds that policy reveals itself in the form of rules, principles, norms, and negotiated decision-making processes. Policymaking, the art of developing and modifying policy, is inherently a long-term and participatory process. Heclo’s (1974) often cited theory states, “Governments not only ‘power’…they also puzzle. Policymaking is a form of collective puzzlement on society's behalf…Much political interaction has constituted a process of social learning expressed through policy."

Understanding policy from the perspective of policymakers serves as a guide for decision-making in the technical domain. Of particular significance to a technical designer is that policy *changes*. Simply put, policy change comes about if actors at the bargaining table are replaced or added and in instances where external events and new knowledge alter how the values of existing actors are expressed.

The following section provides commentary on how policy changes, who changes policy, and why policy change is justified. This chapter serves as the foundation for identifying triggers that change policy and for framing design decision problems in which policy uncertainty exists. Discussion within this chapter outlines the author's growth in understanding the links between policy and design as well as revelations that served as sources of ideation. The end of the chapter offers crossover learnings that ultimately form the foundation of the proposed design methodology introduced in later chapters.

2.1 Structural Policy Components

Hall (1993) disaggregates policy into the following three central variables: overarching goals, techniques and instruments used to attain these goals, and precise settings of these instruments. For example, an overarching goal affecting the ship industry might be to internalize the cost of emissions produced. The instrument used to achieve this goal might be a market-based sulfur trading scheme, while the setting might be the number of credits allocated.

Policy goals directed at naval vessels are likely to be drawn from a different set than those aimed at other maritime vessels, though some overlap may exist. Techno-political systems, such as naval vessels, are uniquely defined by the fact that the government is the purchaser and the client. Sample policy goals are listed in Table 2-1:

Table 2-1: Example list of military and/or commercial ship-related policy goals

	Goals
Techno-political enterprises	Reduce total ownership cost
	Improve green water capabilities
	Reduce dependence on fuel supply chain in foreign waters
	Serve as test platform for advanced technologies
	Combat international piracy
Commercial enterprises	Reduce cargo transit cost
	Increase short sea shipping
	Improve safety of crew
	Eliminate port congestion
	Manage disposal of vessel at end-of-life

Strategy represents a comprehensive plan of action and is the means with which a policy is put into effect. Strategy requires decisions under circumstances that have not been encountered before in quite the same form. One way in which policymakers formulate or delegate strategic implementation of policy is through the use of instruments. Policy instruments are often categorized into four types: economic, direct expenditure, regulatory, and institutional (IISD & TERI, 2003). Definitions of each instrument type and examples are listed in Table 2-2. Instruments are most often conveyed in terms of governmental policy, though forms of each instrument can also be applied by other organizations.

Table 2-2: Structural categorization of policy instruments

Instrument	**Definition**	**Examples**
Economic	Measures directly influencing producer and consumer pricing on a product or service	Taxes, subsidies, refunds, user fees, performance incentives, tradable permits
Direct Provision	Measures channeling institutional expenditures toward behaviors the institution seeks to promote	Research and development, green procurement, investment funds, innovation prizes
Regulatory	Measures using legal means to change behaviors	Standards, bans, permits, quotas, zoning, liability
Institutional	Measures implemented to affect internal decision-making of an organization	Education, checks and balances, information disclosure

Policy settings are crafted to achieve a desired effect. For example, a subsidy can improve a product’s competitiveness and offer support to an industry of national importance. Increased demand for green procurement can lead to spillover pricing and technology effects for the rest of a nation state or industry. Information disclosure still allows free market tendencies but increases the knowledge of a consumer choosing between alternatives.

Policies may be characterized as general or specific; implicit or explicit; reactive or proactive; evolutionary or revolutionary; independent or nested; mandated or voluntary; punitive or incentive; preventative or curative (IEA, 2012). The 17th International Ship and Offshore Structures Congress (ISSC, 2009) notes that policymaking bodies in the maritime industry increasingly accept performance-based strategies over traditional prescriptive strategies. Performance-based strategies afford a wider scope of options for satisfaction. The degree to which each individual party complies with a performance-based policy directive is a function of marginal costs and benefits.

2.2 Policy Change

Hall's (1993) distinction of policy variables allowed for his identification of three policy change types. The basic, most common policy change is denoted as being of the first order. First order change involves the modification of policy instrument settings without alterations to the overall goals and policy instrument type. An example of first order change includes the incremental decrease in the number of available trading credits per annum. Incremental change over time can require increased tradeoffs on emission producers, but the change is largely predictable, sequential, and involves routine decision-making. A policy under first order change conditions at time t_1 is expected to maintain many of the same features as the policy at t_0.

Second order change affects both the instrument settings and the instrument itself, though the overarching goals remain unbothered. Dissatisfaction with the influence of current policy instruments can lead to re-evaluation. An example of second order change is a shift from command-and-control mechanisms to a market-based system that moderates carbon emissions. The goal remains to reduce emissions, but the strategy used to achieve the goal now operates using a new set of instruments and settings.

Revolutionary change that simultaneously affects a goal, its instruments, and its settings is described as third order change. Third order change occurs least regularly. The impetus for third order change may be a significant scientific discovery, a reorganization of world power, or a catastrophic disaster. Because change is likely to occur through a very different process marked by discontinuities, the radical reorganization spawned by third order change represents a "paradigm shift." Conversely, the continuous evolution of policy through first and second order change can be described as "normal policymaking," in a similar vein to how Thomas Kuhn describes *normal science* (Hall, 1993). Third order change does not simply occur when multiple first or second order changes accumulate and cross a threshold.

The environmental policy landscape has changed remarkably in the last forty years as organizations learn about environmental impacts of their processes; one might argue that all three flavors of policy change have occurred. The 'Regulatory Compliance' age of the 1970's gave way to 'Strategic Environmentalism' by the 1990's, which has since been supplanted by the 'Sustainability' era (Hoffman, 2000). Long life cycle products that have had to persevere through this upheaval have often witnessed changes to themselves in response to policy, the magnitude of which has been significant. For example, power plants have been readapted multiple times in some cases to satisfy new air emission regulations.

Responses to environmental challenges have increasingly recognized that "wicked problems" cannot be solved without a systems-thinking perspective. Command-and-control programs instituted during the environmental movement's early years neglected intrinsic natural and social cycles, proving insufficient, and at times, counterproductive (Holling and Meffe, 1996). Approaches transitioned to ones involving diverse participation in assessment, learning, and planning in hope of developing more flexible, adaptive institutions and sustainable outcomes (Gunderson et al., 1995).

Changes to policymaking approaches have shifted the onus of solving society's "wicked problems." Initiatives that might have once been dictated by governments or rule-making institutions are now the added burden of designers and operators. Designers are expected to locate creative solutions despite additional ambiguous and open-ended constraints. Higher levels of adaptivity and flexibility in the new policymaking approaches still require translating the array of policymakers' wishes into a form designers can measure and evaluate. Without tools and training, these individuals find it difficult to analyze the full range of economic, performance, environmental, and compliance merits to a design.

2.3 Policy Spectrum

Policy components exist along a continuum ranging from the technical to the sociological. Technical and sociological properties are more apparent in certain policy variables and change archetypes. Policy instruments and settings provide greater technical depth than policy goals. Third order change is more sociological than first or second order change. Hall (1993) further details:

> *The process whereby one policy paradigm comes to replace another is likely to be more sociological than scientific. That is to say, although the changing views of experts may play a role, their views are likely to be controversial, and the choice between paradigms can rarely be made on scientific grounds alone. The movement from one paradigm to another will ultimately entail a set of judgments that is more political in tone, and the outcome will depend, not only on the arguments of competing factions, but on their positional advantages within a broader institutional framework, on the ancillary resources they can command in the relevant conflicts, and on exogenous factors affecting the power of one set of actors to impose its paradigm over others.*

A 2009 policy by the U.S. Navy to commit to a Green Fleet exhibits both technical and sociological dimensions. On the scientific front, the commitment requires that 50% of the energy consumed comes from alternative sources by 2020. A fleet of vessels and aircraft powered by biodiesel is not yet without technical concerns and is not the most cost-effective energy source for U.S. Navy operations. Such a policy will spur increased research, development, and innovation. Furthermore, the Navy represents a major source of demand—the Department of Defense is the single largest consumer of energy in the world, with the Navy second to only the Air Force in terms of energy requirements—that can reset the supply-demand curve and bring about opportunities for non-governmental organizations.

Psychologically, the policy reframes the climate and energy challenge as a national security issue. Skeptics that refuse to accept climate change or doubt the environmental advantages of biodiesel as a fuel might instead be swayed by the claim that biodiesel reduces dependence on foreign oil and reduces vulnerability to the nation's energy supply lines. The U.S. Navy is committing to being an early adopter, legitimizing the alternative fuel industry and offering traction for future development.

Navy Secretary Ray Mabus served as the primary environmental champion for the Green Fleet commitment. He and his staff overcame competing factions that might have believed the Navy's budget was best used elsewhere. If scientific grounds alone had been used to craft the goal, the controversial environmental benefits of biodiesel and the significant price premium incurred would have likely submarined Mabus' initiative. By drawing upon the historical context of Theodore Roosevelt's Great White Fleet, used to project the United States' increasing military prowess at the turn of the 19th century, Mabus invoked the patriotism of decision-makers and secured a bold policy initiative.

2.4 Policy Actors

Many individuals and organizations, herein described as actors, possess an explicit and implicit role in shaping policy. An incomplete but illustrative list of actors involved in shaping policies related to trans-Pacific containership transport is recorded in Table 2-3.

.

A brief review of the table indicates that actors can be regulatory, organizational, and community stakeholders at the local, regional, national, supranational, and international levels. The environment is an omnipresent, silent actor represented by human actors. Other demographic characteristics describing actors include size of population, level of integration, self-sufficiency, stability, exclusiveness, legitimacy, etc. Actor relations may be described as stable or fickle depending on the rate at which an actor forms and disbands alliances.

Table 2-3: Sample list of stakeholders in shipping activities

Ship owner	International Maritime Organization
Ship operator	Environmental agencies
Ports	Coast Guard
Classification society	Environmental advocacy groups
Shipyard—build, repair	Crew associations, unions
Original equipment manufacturers	International trade organizations
Equipment suppliers	Research & development facilities
Financiers	Road, rail interest groups
Cargo clients	Insurance agencies

As it relates to sustainability, Hunt and Auster (1990) labels actors based on their degree of proactive environmental management. The designations are briefly outlined below:

- "The beginner" provides no protection from environmental risk.
- "The fire-fighter" provides problem-specific minimal protection.
- "The concerned citizen" provides moderate protection, demonstrating a degree of commitment to environmental management.
- "The pragmatist" provides comprehensive protection and promotes minimizing environmental impacts as an important business function.
- "The proactivist" makes maximum protection a priority item.

The psychology of an actor is made apparent through an actor’s strategy. Roome (1992) identifies strategies corresponding to each of Hunt and Auster’s respective designations: noncompliance, compliance, compliance plus, commercial and environmental excellence, and leading edge. Steger (1993) categorizes environmental strategy by both the actor’s risk profile and the actor’s perception of opportunities.

An actor is likely to employ a defensive strategy if opportunities, market-based or otherwise, are low and the environmental risk of an actor's activities is unavoidable. Indifferent strategies exist when both opportunities and risk are low. Conversely, a high level of opportunity can lead to offensive or innovative strategies. Actors adhering to offensive strategies witness little risk and perceive considerable potential. Innovative strategists seek actions that offer many opportunities despite high level of risk.

Table 2-4: Strategy differentiation based on risk-opportunity perception (Steger, 1993)

		Risk	
Opportunity		**High**	**Low**
	Many	Innovative	Offensive
	Few	Defensive	Indifferent

Not only may the strategy of a policymaker be unclear to his or her own self, a designer must interpret these signals to ascertain the risks and opportunities associated with product decisions. Matching design strategy with policy strategy enables cooperation in the face of proposed change. A defensive industry pitted against an offensive policymaking regime can result in gridlock and sub-optimal decision-making by all parties. Niese and Singer (2010) perform a simple case study to quantify the influence of a sulfur dioxide policymaking strategy on design strategy.

2.5 Policy Rationalization

Policy development concerning the environment draws upon knowledge from the natural, physical, political and social sciences. A mix of research, monitoring, and surveys is often utilized to elicit quantitative and qualitative estimates. Technical input is derived from case study models, risk assessments, cost-benefit analysis, and stakeholder preferences (Kiker et al., 2005). A life cycle assessment (LCA) can serve as a valuable tool for characterizing the environmental impacts of a process. Risk assessments involve hazard identification, transport modeling, dose-response analysis, and exposure estimates. Cost-benefit analysis (CBA) attempts to quantify the economic value of policy alternatives and often involves debates regarding option values and contributions from ecosystem services. Multi-criteria decision analysis methods such as multi-attribute utility theory (MAUT), outranking, and the analytical hierarchy process (AHP) may be employed to structure stakeholder preferences and value judgments (Dodgson et al., 2009; Figueira et al., 2004). The effectiveness of technical input is impacted by uncertainty. Furthermore, the involvement of human decision-makers leaves open the possibility that even irrefutable evidence does not ensure the optimal solution will be implemented.

Regardless of the technical or sociological underpinnings in which a policy is formulated, environmental policies all prescribe to the notion of limiting externalities (Owen, 2004; Zywicki, 1999). An externality is described as a cost or benefit that is incurred by a party that did not agree to the action serving as the source of the cost or benefit. The cost or benefit is not transmitted through prices. Hardin's (1968) influential essay on "the commons" illustrates how shared resources such as the air and oceans can be exploited in a manner that offers oversized individual benefits relative to the costs the exploiting party incurs. Environmental-related costs are also often characterized by irreversibility, invisibility, and pervasiveness in space and through time (Holdren, 1981).

Most importantly for the purpose of this dissertation's connection between policy and design is the author's argument that an actor whose transactions result in a high level of externalities is likely to be more affected by an environmental policy change than one generating fewer externalities. Conscientious design that analyzes where in the space of Figure 2-2 a proposed design falls relative to other design options will hint at the potential risk of a new or adjusted policy affecting cost and performance. Program managers typically set a maximum budget, constraining horizontal movement to the right. Policymakers and other societal organizations limit maximum impact in the vertical direction. The aim of design is to generate at least one solution that satisfies both these constraints.

A design team can further physically decompose externalities by system type to identify which sub-assemblies may most be at risk of an environmental policy change. In instances where a range of alternatives lie across the externalities-cost spectrum, policymakers have more leeway to set minimum thresholds of performance.

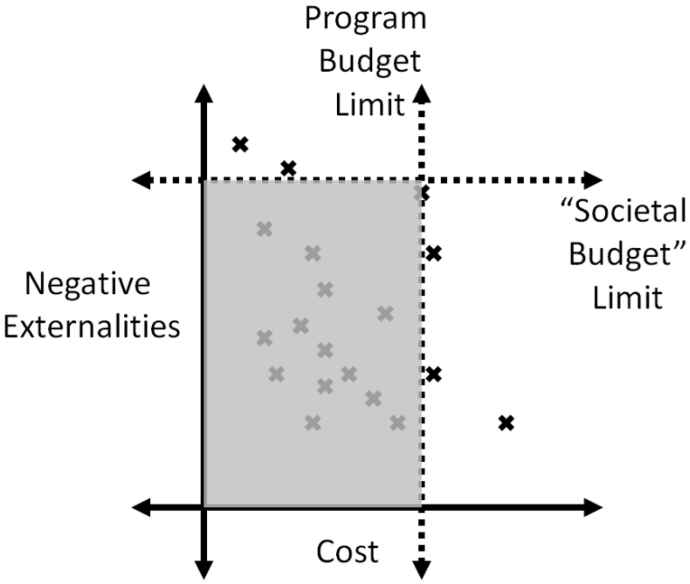


Figure 2-2: Plot of costs to society versus costs incurred internally by an organization due to use of a product; each 'x' represents a product alternative

The dual cost dimensions perceived by a policymaker can have major implications for a designer or product manager. The primary purpose of a design is to maximize utility at minimum cost. Utility is the value *internal* to the design team and the client. Environmental policy stems from *external* value. Designs that minimize negative externalities are expected to be less subjected to policy change. In most cases, product life cycle cost and negative externalities are competing objectives for designer and policymaker alike.

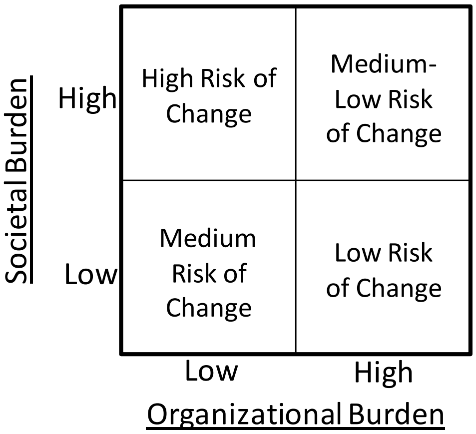
The cost equations pertinent to policy and technical actors are not equal in most cases. A policymaker seeking to judge a product or industry is likely to quantify total costs by the following equation:

$$\text{Total cost} = \text{Industry costs incurred} + (\text{Externalities} \times \text{Price per externality}) \qquad [2\text{-}1]$$

where a fair balance between internal and external costs is sought. Product managers are traditionally measured only by the first term in the equation's right-hand side. Policy-conscious design understands that measuring design decisions on both the internal and external value created aligns with the rational policy actor's perspective.

When externalities exceed society's capacity or begin to outstrip internal costs, a policymaker may seek to redistribute the burden via the use of policy instruments. Often, *Total Cost* cannot be easily reduced because internal and external costs tend to demonstrate negative correlation. Thus, policy instruments habitually "internalize an externality" in what corresponds to shifting *(1-α)*Externalities* of society's burden to industry, where *α* denotes the percentage of externalities absorbed by society.

A summary of such observations leads to the author's development of a simple 2-by-2 matrix for design decisions with environmental consequences (Figure 2-3).



*Societal burden=α*Externalities *($/Externality)*
*Organizational burden=(1-α)*Externalities*($/Externality)+Internal Costs*

Figure 2-3: Author's interpretation of policy change risk given organizational vs. societal cost ratio

A decision-maker is accepting policy risk if an alternative that exists in the upper-left quadrant is selected, especially if alternatives exist in the lower quadrants. If all alternatives exist in the lower quadrants, policymakers may be unwilling to expend political capital for relatively small environmental "wins." If all alternatives exist only in the upper-right quadrant, significant resistance is likely to be derived from producers despite large externalities seemingly warranting an interjection of new policy.

2.6 Policy Networks and Policy Formation

Predictability of a policymaker's strategy can be better understood through a network perspective. Discussion within this section sets the stage for the introduction of the Holling and Gunderson's panarchy model, which serves as a formative representation in the author's development of the method and metrics proposed later in this dissertation.

Public policymaking is a hybrid arrangement involving representation from government and non-government actors alike. Actors seated in formal positions of power are not the only actors with influence. A classic argument by Heclo (1978) states, "Looking for the few who are powerful, we tend to overlook the many whose webs of influence provoke and guide the exercise of power." Autonomy of decision-making by any one actor is limited and the set of actors involved may be in constant flux.

Relevant actors exhibit relationships of varying strengths between one another. These linkages among actors, rather than the actors themselves, have become a central analytical focus of academics. Social scientists use the term *network* to describe clusters of heterogeneous actors who are linked by political, social, or economic activities. A network can be loosely structured but is capable of engaging in collective action. While theories of neofunctionalism and intergovernmentalism attempt to describe the process by which actors integrate, analysis of policy networks seeks to describe, explain, and predict the policy outcomes that arise from the policymaking process. This type of analysis has been shown to explain "why policy outcomes reflect purely technocratic rationality or, alternatively, the overtly political agenda of key actors" (Peterson, 1995).

Designers are often one or two levels removed from policymaking decisions, and the strength of their influence can often best be described as indirect. Including designers more directly in the policy network can balance out the power of politicians, management, and scientists with biases resulting from positions of non-technical pressures. Design engineers are typically directed with the task of translating policy to compliant products, and so may best understand the technical limits with which the flow of materials and other wastes can be managed, for example.

A policy network is generally defined as “a cluster of actors, each with a set of interests, or ‘stake’ in a given…policy sector and the capacity to help determine policy success or failure” (Peterson and Bomberg, 1999). Regardless of the policy network model type used, where terminology and structure remain hotly contested and disjointed, one agreeable assumption is that networks exist to decrease uncertainty and reduce surprises (Heinz et al., 1993). Actors and their networks look to establish a position that manages the political agenda so as to mitigate policy uncertainty.

A strong hand in agenda-setting reduces uncertainty by allowing actors to frame policy discussions toward their interests. Attempts to instill an individual’s dominant set of values within a policy network arrangement lead to a tension between cooperative moves that create joint value and competitive moves that achieve individual advantage. Policy proposals that reach the negotiation phase *should* exhibit common criteria including technical feasibility, fit with the dominant values and national mood, budget workability, and political support, though practice finds one or multiple of these elements is not always realized (Kingdon, 1995).

An issue receives legitimacy and a stronger life when actors manage to get it on the agenda. A multi-stakeholder issue that never reaches the agenda cannot be introduced, negotiated, and developed into policy. Progression from the agenda to actual policymaking occurs when Political, Policy, and Problem streams converge (Kingdon, 1995). The Problem stream spurs the attention of the public, the Policy stream prompts the attention of specialists who frame issues into policy, and the Political stream stimulates partisan campaigning that leads to decision-making.

These times of potential cooperation that permit major policy change are described as *policy windows*. Diagnosing these windows in advance enable actors to prepare for and play off of impending change. For example, utility providers who built large cash balances may be able to take advantage of a limited period of time in which solar and wind subsidies are heavily subsidized. The policy window could close when global and governmental economic pressures cause an end to the range of subsidies.

A lobby attempts to influence policy by at least changing the "framing" of an issue, even when not admitted to the core policy-making arena (Dudley and Richardson, 2000). Failure to be invited to, or break through at, agenda-setting and policy development negotiations can result in roster-altering and networks seeking alternative venues. Baumgartner and Jones (1991) make the following argument for the gamesmanship of actors:

> *On the one hand, they try to control the prevailing image of the policy problem through the use of rhetoric, symbols, and policy analysis. On the other hand, they try to alter the roster of participants who are involved in the issue by seeking out the most favorable venue for consideration of their issues.*

When the framing and the venue align, a period of stability is replaced by non-incremental change. Baumgartner and Jones (1993) describe this period as "punctuated equilibrium."

The number of venues can be multiple. The inability of an environmental advocacy group to gain traction in airborne emission policy circles may lend the group to instead focus efforts on developing sustainable manufacturing practices. A well-positioned classification society might seek to squeeze out representation from competing firms. A state government agency could aim to shape policy at the international level, too. Transport policies have increasingly witnessed a debate that has shifted from "the closed world of scientific advisory bodies to the public domain" (Dudley and Richardson, 2000). Advocacy groups have proven particularly adept at offensive strategies that utilize the Internet and court systems.

2.7 Panarchy

One organizing model of the dynamic engine guiding policy formation is that of a panarchy. The panarchy concept draws on information presented in the previous sections—social learning, change, actors, and time. The idea of connected states, change potential, and decision-making capital serve as a key inspiration leading to the author's proposed model and derived metrics. A detailed explanation follows. Periodic reconnect will be made throughout the remainder of the dissertation.

Hierarchies and adaptive cycles form the basis of social-ecological systems across scales, which together form a panarchy (Holling, 2001). Holling and Gunderson invented the term "panarchy" to explain the evolving nature of complex adaptive systems nested within one another over space and time. The panarchy concept transforms the view of hierarchies as static structures to dynamic, adaptive entities. The panarchy moderates relationships among agents, institutions, and systems (Holling and Gunderson, 2002).

Simon (1962) wrote the seminal article on adaptive significance within hierarchical structures. He described *hierarchies* as "semi-autonomous levels that formed from interactions among a set of variables operating at similar speeds and shared spatial attributes," a key divergence from the traditional administrative definition of the term. According to Simon, dynamic hierarchies offer the following two significant services:

1. Conservation and stabilization of conditions for faster and smaller cycles
2. Generation and testing of innovations by experiments occurring within a level

The second function has since been summarized as an "adaptive cycle" (Holling, 1986). Future responses by systems and humans are governed by three properties inherent to adaptive cycles (Holling and Gunderson, 2002):

1. Wealth: the potential for change and the range of options possible

2. Controllability: flexibility/rigidity of internal controlling variables, as described by the degree of connectedness between these controls
3. Adaptive Capacity: system resilience and vulnerability to unpredictable shocks

Figure 2-4 illustrates the first two properties of an adaptive cycle. An excerpt from Holling (2001) describes the representation:

> *The trajectory alternates between long periods of slow accumulation and transformation of resources (from exploitation to conservation, or r to K), with shorter periods that create opportunities for innovation (from release to reorganization, or Ω to α). That potential includes accumulated ecological, economic, social, and cultural capital as well as unexpressed chance mutations and inventions. During the slow sequence from exploitation to conservation, connectedness and stability increase and capital is accumulated. The phase from Ω to α is a period of rapid reorganization during which novel recombinations can unexpectedly seed experiments that lead to innovations in the next cycle. Initially, the "front loop" of the trajectory, from r to K, becomes progressively more predictable as it develops. In contrast, the "back loop" of the adaptive cycle, from Ω to α, is inherently unpredictable and highly uncertain. At that stage, the previously accumulated mutations, inventions, external invaders, and capital can become re-assorted into novel combinations, some of which nucleate new opportunity.*

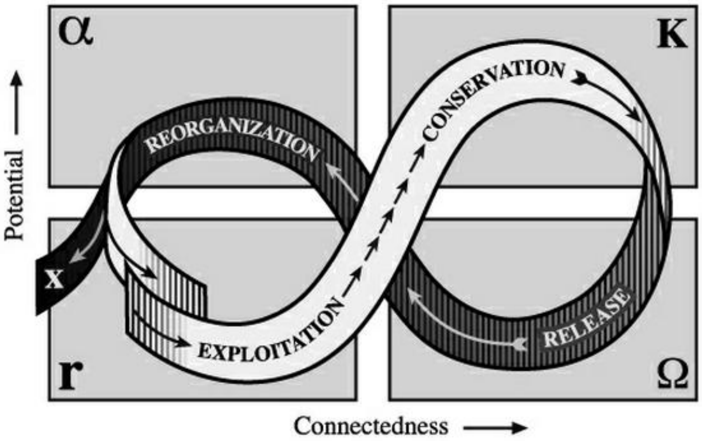


Figure 2-4: An illustrative adaptive cycle, in 2-D (Holling & Gunderson, 2002)

The third property, resilience, is illustrated via the third dimension of the adaptive cycle (Figure 2-5). Resilience expands and contracts during periods within the adaptive cycle, which results from embracing two opposite objectives—growth and stability versus variability and change. Low resilience corresponds to the first objective of an adaptive cycle: to maximize production and accumulation. The front loop is characterized by increased connections and stable development. The second objective, to maximize invention and recombination, occurs in the back loop of the adaptive cycle where resilience is highest and when controllability is low. Novel reassortments and low costs of failure are associated with this back loop. Near achievement of one objective inescapably sets the stage for its opposite, as the two objectives are in competition with one another.

The panarchy in a policymaking sense has the following correspondence:

- Exploitation, Γ: Policy formulation
- Conservation, K: Policy implementation
- Release, Ω: Policy failure
- Reorganization, α: Policy alternatives

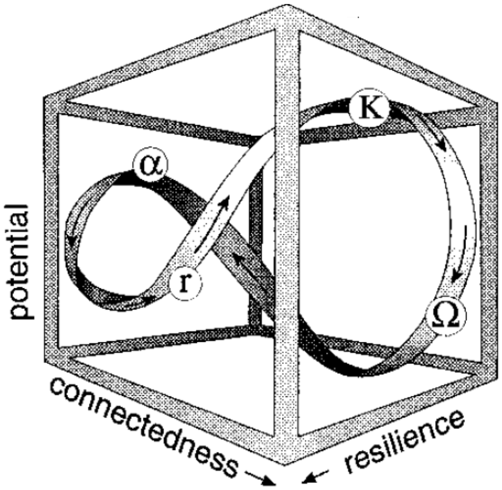


Figure 2-5: Adaptive cycle in 3-D, illustrating the resilience property (Holling & Gunderson, 2002)

Successful policy formulation leads to formalization of policies. The ruling institution can be confronted with evidence that expectations no longer hold, resulting in release. Alternative policies are proposed in reaction to this release.

Various levels of the panarchy can be seen as a nested set of adaptive cycles, as illustrated in Figure 2-6. The adaptive cycle serves as the engine that generates variability and novelty. Hierarchies are sensitive to disturbance at the α and Ω phases but stable and robust along other periods in the adaptive cycle.

Higher level systems within the panarchy correspond to slow variables, while the lowest levels are governed by fast variables. Reorganization may occur within each hierarchical level in a way that partially isolates creative experimentation and reduces the risk to the integrity of the whole structure. Productive novelty can cascade up the levels, while destructive actions cascade downward. In times of change, these “revolt” and “remember” connections are especially prevalent to policy. For example, environmental policy changes leveled on automobiles cascaded up to the entire transport sector and instigated an era of sustainable mobility. “Remember” draws on the potential stored in a larger, slower cycle to aid in renewal at a lower level. The recent reorganization of carbon policy for ships drew on past efforts related to other emission developments such as sulfur and nitrogen dioxides.

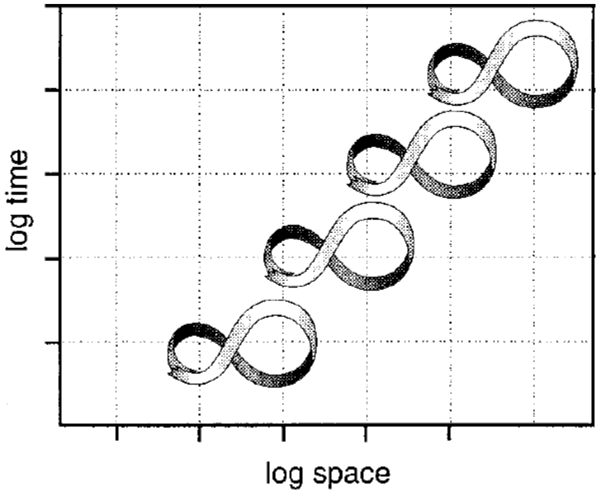


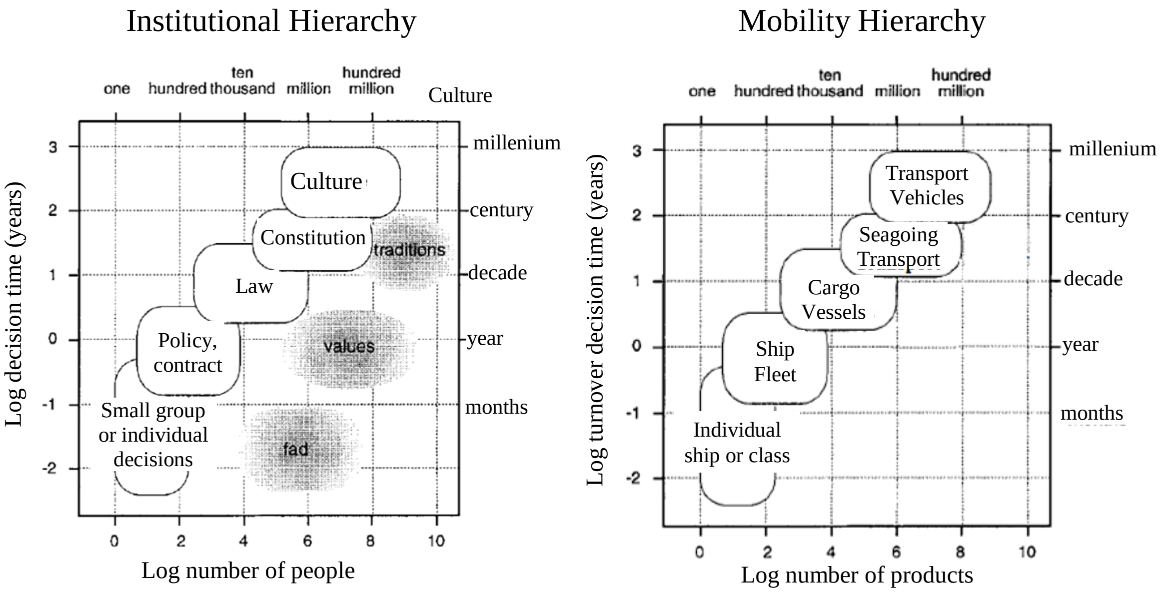
Figure 2-6: The panarchy concept of nested adaptive cycles (Holling & Gunderson, 2002)

Again ceding discussion to Holling and Gunderson, the value of the panarchy theory is summarized below:

> *The panarchy is a representation of the ways in which a healthy social-ecological system can invent and experiment, benefiting from inventions that create opportunity while it is kept safe from those that destabilize the system because of their nature or excessive exuberance. Each level is allowed to operate at its own pace, protected from above by slower, larger levels but invigorated from below by faster, smaller cycles of innovation. The whole panarchy is therefore both creative and conserving. The interactions between cycles in a panarchy combine learning with continuity.*

2.8 Relevance to Product Designers within the Technical Domain

The political panarchy is not the only collection of adaptive cycles; other panarchies are related to natural, physical, and organizational systems (Figure 2-7). Each system interprets issues uniquely, operates on its own level within its own panarchy, and adapts based on the current phase of the cycle in which it is situated. Yet, the systems are interrelated and system managers' actions and solutions must account for the dynamics of other systems. Actions within one system can facilitate developments elsewhere, such as the role of technology development as an enabler to new policymaking.


Institutional Hierarchy

Mobility Hierarchy

Figure 2-7: Similarity between institutional hierarchy (left; Holling (2001)) and strategy within mobility hierarchy, as adapted by author (right)

The phases of several systems' cycles can become coincident with one another and lead to revolutionary transformation. In other instances, an impoverished state results due to misuse or an external force that eradicates potential and diversity. Still other times a sustainable but maladaptive state can result from perverse resilience that resists disturbances, maintains excessive wealth and capital, and wields social control that smothers novelty. This last case, described as a rigidity trap, preserves the status quo despite the urge for change in other systems. For example, industry and government may favor business-as-usual due to considerable investment in existing infrastructure despite responses in nature that signal changes in behavior are required.

In addition to understanding forces of creativity and conservation within one's own panarchy, a design manager must also appreciate outside influences and their own respective dynamics. Even if only qualitative, a designer may be able to use the following information to improve design in the face of policy change:

- The stability of policy goals, instruments, and settings
- The risk profile of policy actors and the strategy a designer has been instructed to pursue
- The number of adaptive cycles the proposed life cycle of the product is intended to cross, in both time and space
- The current panarchy stage(s) in which design is occurring, with expectations for how much resilience to engineer into the design

2.9 Chapter Summary

A designer's responsibilities rarely include that of shaping policy. Traditionally, the political and technical domains have been viewed separately. The increasing influence of the policy domain on performance criteria has made such separation impractical and imprudent. Theoretical and experiential evidence has led to the notion that this traditional view does not result in policy-robust designs. Given a policy change affecting the performance of an operational product, a ship owner is faced with a decision between the losing alternatives of either noncompliance or significant expenditures. Products still in the design phase must be re-worked or accept that the final product will prove less optimal than originally anticipated. A designer who considers policymaking to be a "black box" fails to appreciate opportunities for learning and improved decision-making.

While a designer's primary purpose is not to affect policy, it is the responsibility of the designer and product manager to be cognizant of how policy can change, of how to assess the implications of a policy change, and of how to deliver performance despite change. This chapter offers an extended look into policy characteristics, and the social science of policymaking serves to offer an improved understanding on how policy changes and what policy signals a technical designer might observe.

References to political science literature in this chapter have been applied to showcase that policy is not always rational or deterministic. Information relevant to policymaking is often scarce, incomplete, or misleading. Decision-makers rarely select alternatives that expend all one's political capital, often opting for the short-term alternative that satisfies the largest number of stakeholders. Short-termism and a lack of information are likely contributors to sub-optimal solutions. Policymaking could improve if technical managers more clearly advocated for long-term systems thinking and demonstrated how uncertainty and irrationality lead to sub-optimal solutions for the policy and technical domains, alike.

Equation 2-1 illustrates that three primary time-dependent levers are at play in the effort to manage externalities and improve the environment. These include:

- Internal measures to reduce quantity of externalities produced
- Price per externality
- Burden ratio, α, of the party responsible for paying the costs of externalities

The only lever that a design engineer has great control over is the incorporation of abatement measures; market and policy factors largely govern the other two levers.

Life cycle design strategies that manage these uncertain levers, appealing to the policy landscape and risk profiles of policy actors, influence the success of a product. How a design engineer perceives policy change and develops a response is the focus of the next chapter.

Chapter Citations

1. Baumgartner, F., & Jones, B. (1991). Agenda dynamics and policy subsystems. *Journal of Politics, 53* (4), 1044–74.
2. Baumgartner, F., & Jones, B. (1993). *Agendas and instability in American politics*. Chicago: University of Chicago Press.
3. Dodgson, J., Spackman, M., Pearman, A., & Phillips, L. (2009). Multi-criteria analysis: A manual. *Report.* Department for Communities and Local Government, London, UK.
4. Dudley, G., & Richardson, J. (2000). *Why does policy change?: Lessons from British transport policy*. New York: Routledge.
5. Figueira, J., Greco, S., & Ehrgott, M. (2004). *Multi-criteria decision analysis: State of the art surveys*. Boston: Kluwer Academic.
6. Gunderson, L., & Holling, C. (2002). *Panarchy: Understanding transformations in human and natural systems*. Washington: Island Press.

7. Gunderson, L., Folke, C., & Janssen, M. (2005). Integrating ecology and society to navigate turbulence. *Ecology and Society, 10* (1), 39.
8. Haas, P. (1992). Introduction: Epistemic communities and international policy co-ordination. *International Organization, 46* (1),12-35.
9. Hall, P. (1993). Policy paradigms, social learning, and the State: the case of economic policymaking in Britain. *Comparative Politics, 25* (3), 275.
10. Hardin, G. (1968). The tragedy of the commons. *Science, 162* (3859), 1243-1248.
11. Heclo, H. (1976). Conclusion: Policy dynamics. In R. Rose, *The dynamics of public policy: a comparative analysis* (pp 237-266). London: SAGE.
12. Heclo, H. (1974). *Modern social politics in Britain and Sweden: From relief to income maintenance*. Yale University Press.
13. Heclo, H. (1978). Issue networks and the executive establishment. In A. King, *The new American political system*. Washington: American Enterprise Institute.
14. Heinze, J., Laumann, E., Nelson, R. & Salisbury, R. (1993). *The hollow core. Private interests in national policy-making.* Cambridge: Harvard University Press.
15. Hoffman, A. (2000). *Competitive environmental strategy: a guide to the changing business landscape.* Washington: Island Press.
16. Holdren, J. (1981). Energy and human environment: The generation and definition of environmental problems. In G. Goodman, L. Kristoferson, & J. Hollander, *The European transition from oil: Societal impacts and constraints on energy policy* (Chapter 5). London: Academic Press.
17. Holling, C. (2001). A new phase. *Conservation Ecology, 5* (2), 23.
18. Holling, C., & Meffe, G. (1996). On command-and-control, and the pathology of natural resource management. *Conservation Biology 10*, 328-337.
19. Holling, C. (1986). The resilience of terrestrial ecosystems: Local surprise and global change. In W. Clark and R. Munn, *Sustainable development of the biosphere* (Chapter 10, pp 292-317). Cambridge: Cambridge University Press.
20. Holloway, L., Clegg, D., Tranter I., & Cockerham, G. (1994). Incorporating environmental principles into the design process. *Material & Design, 22* (15), 259-267.
21. Hunt, C., & Auster, E. (1990), Proactive environmental management: Avoiding the toxic trap. *Sloan Management Review, 31* (2), 7-18.
22. IEA. *Understanding policies and the policy process*. United Nations Environment Programme. Retrieved 2012, from http://www.unep.org/ieacp/iea/training/manual/module5/1229.aspx
23. IISD & TERI. (2003). *A framework for energy sustainability assessment: the energy sustainability gauge*. International Institute for Sustainable Development/ The Energy and Resources Institute. Retrieved 2012, from http://www.teriin.org/
24. Jordan, G. (1982). The British policy style or the logic of negotiation?. In J. Richardson, *Policy styles in Western Europe.* London: George Allen & Unwin.
25. Kates, R. (1999). Our common journey: A transition toward sustainability. *Report.* National Academy Press.
26. Keck, M., & Sikkink, K. (1998). *Activists beyond borders*. Ithaca: Cornell University Press.

27. Kiker, G., Bridges, T., Varghese, A., Seager, T., & Linkov, I. (2005). Application of multicriteria decision analysis in environmental decision-making. *Integrated Environmental Assessment and Management*, *1* (2), 95-108.
28. Kingdon, J. (1995). *Agendas, alternatives, and public policies*. New York: HarperCollins.
29. Kuhn, T. (1962). *The structure of scientific revolutions*. Chicago: University of Chicago Press.
30. McGinnis, M., & Ostrom, E. (2011). SES framework: Initial changes and continuing challenges. *Ecology and Society*, special issue.
31. Najam, A. (2005). Policy analysis for integrated environmental policy. Presentations at the West Asia Regional Training Workshop. UNEP, Manama, Bahrain.
32. Owen, A. (2004). Environmental externalities, market distortions and the economics of renewable energy technologies. *The Energy Journal*, 25(3), 127-156.
33. Peterson, J., & Bomberg, E. (1999). *Decision-making in the European Union*. New York: Macmillan and St. Martin's Press.
34. Peterson, J. (1995). Decision-making in the European Union: towards a framework for analysis. *Journal of European Public Policy, 2* (1), 69-93.
35. Rhodes, R., & Marsh, D. (1992). New directions in the study of policy networks. *European Journal of Political Research, 21* (1), 181-205.
36. Roome, N. (1992). Developing environmental management systems. *Business Strategy and the Environment*, 1, 11-24.
37. Sabatier, P., & Jenkins-Smith, H. (1993). *Policy learning and policy change: An advocacy coalition approach*. Boulder: Westview Press.
38. Schaltegger, S., & Burritt, R. (2000). *Contemporary environmental accounting: issues, concepts, and practice*. United Kingdom: Greenleaf Publishing.
39. Simon, H. (1962). The architecture of complexity. *Proceedings of the American Philosophical Society*. *106* (6), 467-482.
40. Smith, A. (2000). Policy networks and advocacy coalitions: Explaining policy change and stability in UK industrial pollution policy. *Environment and Planning C: Government and Policy, 18* (1), 95–114.
41. Steger, U. (1993). The greening of the board room: How German companies are dealing with environmental issues. In K. Fischer & J. Schot, *Environmental Strategies for Industry (*pp.147-66). Washington, DC: Island Press.
42. Zywicki, T. (1999). Environmental externalities and political externalities: The political economy of environmental regulation and reform. *Tulane Law Review*, 73: 845-922.

CHAPTER 3 – FRAMING POLICY: THE TECHNICAL PERSPECTIVE

At times tensions emerge within disciplines when theory and practice do not coincide. The theorist is frustrated because work is not utilized, while the practitioner laments not having guidelines. But more important, extended incompatibility between theory and practice can result in decay of the discipline.

Brock et al., Public Policy Decision-Making

At the heart of this dissertation is a viewpoint that a product must be viewed in a dynamic sense, from concept through the end of the life cycle. The following section builds the case for strategic management of life cycle disturbances in early stage design, leading to the conclusion that a design evaluation framework that holistically analyzes disturbance would be of significant added value to ship designers and program managers.

The transition toward systems-thinking and greater environmental considerations is both long-term and complex due to lock-in along three dimensions (Raven et al., 2010):

1. Rigid institutional structures, both formal and informal
2. Incumbent organizational capital and institutional power, in the form of actors and social networks
3. Technological artifacts, production technologies, and physical infrastructure

The previous chapter highlighted the first two points, which are beyond the scope of the average design team. This section aims to discuss the idea of design as being more than an artifact. This research contends that focusing on design as a static artifact is akin to introducing artificial constraints on the process. Research efforts in both the set-based design and –ilities domains demonstrate that premature elimination of solutions from the design space can significantly diminish the potential value created for stakeholders (Singer, 2003; Ross, 2006).

The first half of the chapter provides a summary of how technical managers perceive design and product management. The chapter's second half offers insight into the technical process for dealing with policy change, given this perception of design. This chapter wraps up with a discussion of how policymakers can "do their job" in a manner that better aids management of design decisions by the technical community. This synthesis offers the converse of the previous chapter, which discussed how the action's of technical decision-makers can force the hands of policymakers. Here, a discussion from the technical perspective can be instructive for policy actors.

3.1 Design Requirements

A design team is primarily concerned with producing a physical entity representing a component, subassembly, or assembly. The entity achieves specific tasks and delivers capabilities that satisfy functional and design requirements set forth by stakeholders. A designer's main objectives are to dominate the requirements space and deliver maximum customer value. Requirements can be demanded of both the design vector and the performance vector. For example, a requirement may include a limit on beam size or a maximum level of accelerations in a specified sea state. All requirements must be verifiable to be effective.

Needs and preferences of a decision-maker can be prescribed through attributes and associated utility curves. Attributes can measure both explicit design requirements as well as other value-adding activities that may not be directly specified as requirements by the management team. Combinations of design variables are mapped into cost space and are transformed into aggregate attribute values to measure benefits or utility. A traditional cost-utility plot can be employed to consider the Pareto set of non-dominated design solutions.

Policy, as viewed from the design engineer's standpoint, acts as a design requirement. If the policy is explicitly expressed in the formal requirements document at the onset of design, the requirement is articulated. If the policy is revealed following design activities, the requirement can be viewed as emergent or previously unarticulated. Failure to satisfy articulated or unarticulated design requirements results in a substandard product that could represent a breach of contract.

3.2 Wider Scope of a Design Artifact

A common definition of the term artifact as "an object created by humans usually for a practical purpose and *remaining from a particular period*" [emphasis added] emphasizes the traditional thought that an artifact is something to be viewed in past tense. Adhering to this definition prevents an artifact from being perceived through a long-term temporal lens and orients the focus of the design team to describe the artifact as a static entity: its initial condition. Belief in the artifact as only the initial construct diminishes the dynamic nature of the artifact, the dynamic environment in which the artifact exists, and the dynamic agents interacting with the artifact.

A more contemporary view recognizes that an artifact is not simply the initial physical manifestation; instead, the artifact is represented by its function, its form, and its behavior, which Fenves et al., (2008) outlines as:

- *Function* is the intended purpose of a design and is expected to satisfy a customer's needs
- *Form* is the proposed solution to achieving the desired function and includes both geometry and materials
- *Behavior* is an observation of how the form implements its function and provides evidence that the artifact satisfies the design problem

Artifacts can be initially designed to satisfy a range of functions by enabling different behaviors via multiple forms. Equally important, a functional need can emerge with time, and so with it, must the form and behavior develop. This viewpoint understands that the design process does not end at construction and that the artifact is continually evolving throughout its life cycle.

A static view of the design artifact means management efforts will battle to revert to equilibrium (initial function, form, and behavior) when change within the artifact's surrounding inevitably occurs. The traditional perspective does not handle well "surprises," high magnitude change, or change that is not temporary. Acknowledgement of dynamism and uncertainty through the contemporary perspective shifts the discussion from one of maintaining equilibrium to that of actively driving toward opportunities. The contemporary perspective values *changeability* to the artifact's function, form, and behaviors.

3.3 Defining Change

Management of a system implies the ability to cause change. Change is often defined as the transition of a system to an altered state, in either form or function. A change in functional requirements can necessitate a change in form. Similarly, a change in form may cause a change in function. Interactions between form and function can lead to change propagation. Time inevitability causes change itself to both the system and the environment.

Ross et al. (2008) characterize change by its three elements: (1) the agent of change, (2) the mechanism of change, and (3) the effect of change. Flexible changes occur if the change agent is external to the system, while change agents internal to the system represent an adaptable-type change. The mechanism of change describes the path taken and implies path dependency. Change effect is the difference in states before and after a change occurs, and members of the -ilities class describe the effect to parameters given internal or external changes to the system. This dissertation is particularly intended to more deeply explore change mechanisms in response to agents generating environmental policy.

3.4 Underlying Causes Necessitating Change

Researchers identify two major cases of design failure. “Hard” failures result in the complete breakdown of a component or system’s functionality. The research presented in this dissertation is particularly concerned with “soft failures”, or performance reliability, and their impacts to ship functions. A system is still functional after a “soft” failure, but the performance measures are no longer in conformance. Performance reliability is time-dependent and is defined as the probability that system performance measures are within specification limitations for the lifetime of the product (Savage and Carr, 2001). In effect, performance reliability can be viewed as quality over time. The standard definition of reliability focuses on non-conformance due to component disturbance.

By definition, a disturbance is an irregular event outside of current activities that impacts cost and/or value. Disturbance, in the context of this research, implies the existence of both upsides and downsides to product performance as well as factors beyond simply those technological in nature. There exist significant *risks* associated with a degraded propulsion system that might underperform at sea. Conversely, higher port fees for heavy emitting ships represent a higher utilization *opportunity* for cleaner ships. Degradation is viewed as a subset of disturbance and relates to the downsides of product performance only. Jarratt, Eckert, and Clarkson (2006) refer to disturbances that cause change as *triggers*.

3.4.1 Disturbance Regimes

The disciplines in which disturbance occurs can be any combination of technological, environmental, political, or economic in nature. Examples of disturbances to transport systems such as ships include:

- *Technological*: Major re-design or overhaul, product innovation/obsolescence
- *Environment*: Natural disaster, enemy attack
- *Policymaking*: New regulation, strengthened existing regulation, zonal differentiation
- *Economic*: New competition, supply interruption, pricing differentiation/ revolution

Earl et al. (2005) identify four elements in the design process where disturbance can originate. These include (a) the Product – the artifact through its forms and functions, (b) the Process – tasks used to create the Product, (c) the Designer – the capabilities and knowledge of the team charged with defining the Product's form and functions, and (d) the User – operators with unique specifications, requirements, and market wishes. Change complexities arise from relations within and among these elements.

Disturbance is inherently both a spatial and temporal concept (White, 1985). Spatially, complex engineered systems interface with other systems, and interactions occur at both the system and subsystem levels. Disturbance due to engine knock affects different systems than the impact of wave loads on the bow structure. Despite their different locations about the ship, a new hull coating and waste heat recovery system could both mitigate a disturbance due to fuel economics.

Similarly, disturbance can occur at multiple time scales. All products fail with time, yet some deteriorate at a faster rate. Disturbance due to technological obsolescence may occur on the order of a few years for a computer but on scale of a couple decades for fuel pumps. Physical disturbance due to corrosion of the ship's hull occurs at rates dependent on paint type, paint coverage, and water salinity. Disturbance due to policy change can be on the order of a decade for emission standards or centuries for anchoring practices. Products with long life cycles are likely to experience a greater number and a greater range of disturbance causes (Savage and Carr, 2011).

Certain disturbances—summarized in Table 3-1—are within the direct control of product managers, while other risks are very much subject to the whims of economies, governments, and human interactions. Haimes (2004) classifies these disturbances as endogenous and exogenous, respectively. Eckert, Clarkson, and Zanker (2004) distinguish endogenous disturbances as *emerging* changes and exogenous disturbances as *initiated* changes. For example, the reliability of a vessel's components can be held to a high standard if maintenance and replacement schedules are adhered to regularly and operations are conducted within the outlined specifications. Failing to adhere to a schedule signifies acceptance of an endogenous risk. Conversely, a decision by the Australian government to ban all nuclear-powered vessels in its waters is an exogenous risk that is beyond the direct influence of a ship owner or ship operator.

Table 3-1: Author's categorization of risks, starred (*) if particularly important in design

Endogenous Regimes	**Exogenous Regimes**
***Reliability** - Maintenance, Repair, Overhaul	**Market** - Product Demand, Forecast, Fixed/Variable Costs
Organization - Business Philosophy, Goals, Position	***Regulatory** - Environment, Government Policies
***Safety** - Accidents, Human Error	***Obsolescence** - Competition, Mission Change
***Internal Innovation** - Research, Development	***External Innovation** - Research, Development
Marketing - Brand, Image	

Because ships do not exist in a vacuum, certain losses due to disturbance may become another person or product's gain. An energy-efficient ship can potentially obtain higher margins when fuel prices swing upward. Ships that can install a less expensive "fill-in" component might be able to delay system upgrades until a future, improved technology innovation is available for adoption. Thus, disturbance can also imply opportunity.

3.4.2 Performance Drift

Disturbance results in performance drift (Styblinski, 1991). The vector of drift is affected by the components undergoing disturbance, the rate at which disturbance occurs, and the interactions of components. Son and Savage (2005) illustrate via Figure 3-1 how degradation within components can lead to "soft" failures at the system level.

Niese and Singer (2010) demonstrate how the strength and timing of disturbance, in the form of a policy regulation, determines the suitability of a product exhibiting architectural lock-in. The potential to mis-time policy adoptions urges application of the precautionary principle: when a risk to humans or the environment is suspected, greater action is often advocated. When the future landscape is unclear, an offensive management strategy that considers a vessel's performance drift may prove most resilient or robust. Work in Niese and Singer (2010) represent preliminary efforts of this dissertation and offers insights that led to a re-formulation and re-structuring of the final research problem under investigation.

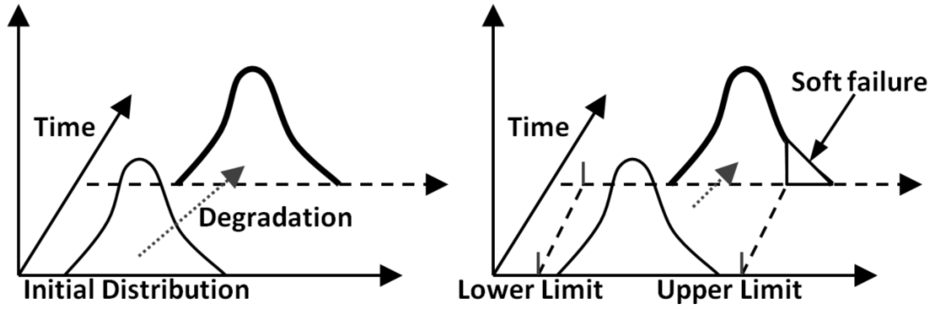


Figure 3-1: Performance drift as the result of degradation (Son & Savage, 2005)

Of particular interest to degrading components is the relationship between loading, strength, and failure. Reliability theory increasingly views the limit state as time-variant and models the function as a random variable. Structural engineering typically uses a *limit state* to identify the bounds on degradation a structure is designed to withstand. The limit state represents the condition beyond which a product is no longer safe for use, and so the term applies beyond simply the structural dimension. The “strength” of a performance variable must exceed the “load” caused by environmental variables, else the component or system will fail.

Drift rate is a function of disturbance type and magnitude. An economic disturbance that plays out over a decade is on a drift time scale that is different than a sudden, catastrophic environmental disturbance such as the 2012 tsunami off Japan’s coast. In the environmental disturbance case, drift might better be represented as a discontinuity.

3.5 Implications of Disturbance on Artifact

Both design value and expected life cycle cost are in flux throughout the artifact’s life cycle as a result of disturbance. A decision-maker may choose to “match change with change” if (1) the artifact no longer delivers the demanded level of performance, or (2) artifacts that continue to deliver the demanded level of performance may still prove suboptimal to other design variable combinations with time. Reasoning behind both avenues is explained in the next paragraphs.

Artifact evolution is a result of seeking to match the changing preferences of the client or decision-maker while managing the role of technical, economic, political, and environmental disturbances. A disturbance may only affect the performance of the system marginally, yet the disturbance can lead to a disproportionate change in perception. Coupled with human nature to always "get more" from a system, a change in perception leads to demands for higher value, higher performance products.

Figure 3-2 illustrates a scenario in which the supplied design value attempts to match the dynamic value demanded. A design may initially exceed performance in anticipation of stronger preferences. The buffer is fully consumed when requested performance is increased later in the life cycle, which requires a change action by the designer to conform to requirements. Just as demanded performance is set to increase again, a disturbance hits that severely degrades performance delivered. Again, a change action—and the corresponding expenditure—must occur. However, recovering full requested performance is either technically infeasible or economically too extravagant. Performance drift occurs as the design ages. Demanded performance is reduced toward life cycle end, at which point a change action can occur that simultaneously reduces value delivery. Figure 3-2 is constructed in an intentionally general fashion to highlight that requirement changes and design changes can occur before and after construction.

Characteristics of change are also revealed in the figure. Change can be initiated to increase value or decrease value dependent on requested needs. If not anticipated, there may be a delay between the time when a new performance level is requested and when a change action can be fully executed. The change action itself may be nearly instantaneous or more gradual. Finally, change options are often limited by technical, economic, or regulatory restrictions.

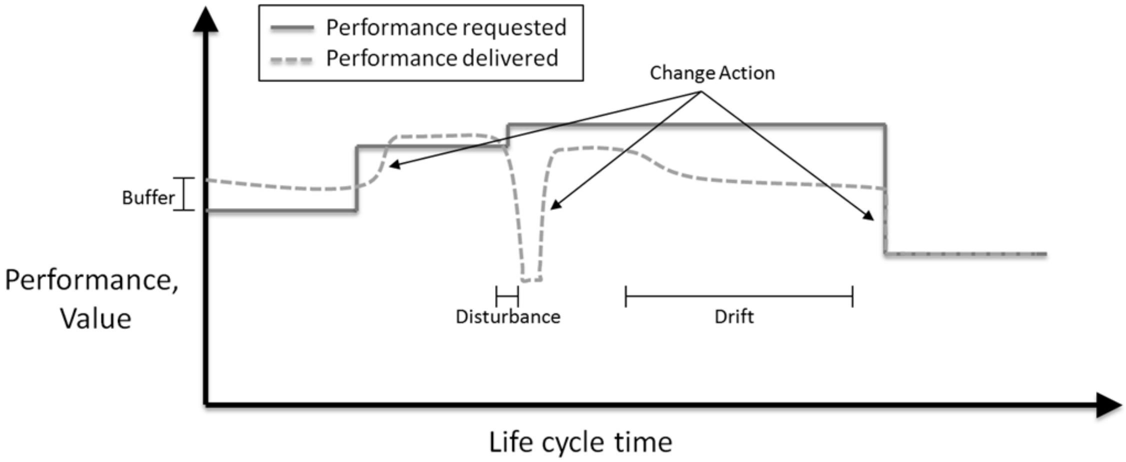


Figure 3-2: Evolving value of a system as a result of disturbances & response to disturbances

A designer's responsibility is also to ensure the selected design approaches the Pareto frontier when built and throughout the system's life span. The author uses Figure 3-3 to illustrate the various ways in which disturbance may appear in the 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 Figure 3-1, the product may drift due to physical deterioration of components (away from the Pareto front). Technological innovation may cause a shift in the Pareto frontier toward the origin. Regulatory policies, certain at time t_o, 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.

The discussion above highlights that changeability is fundamentally a state-based problem. Transitions occur in time due to disturbance and the effect is a change in state. While time-domain methods could identify that transitions occurred, only a state-based methodology can identify the evolving design vector and the change agents serving as the impetus for such transitions.

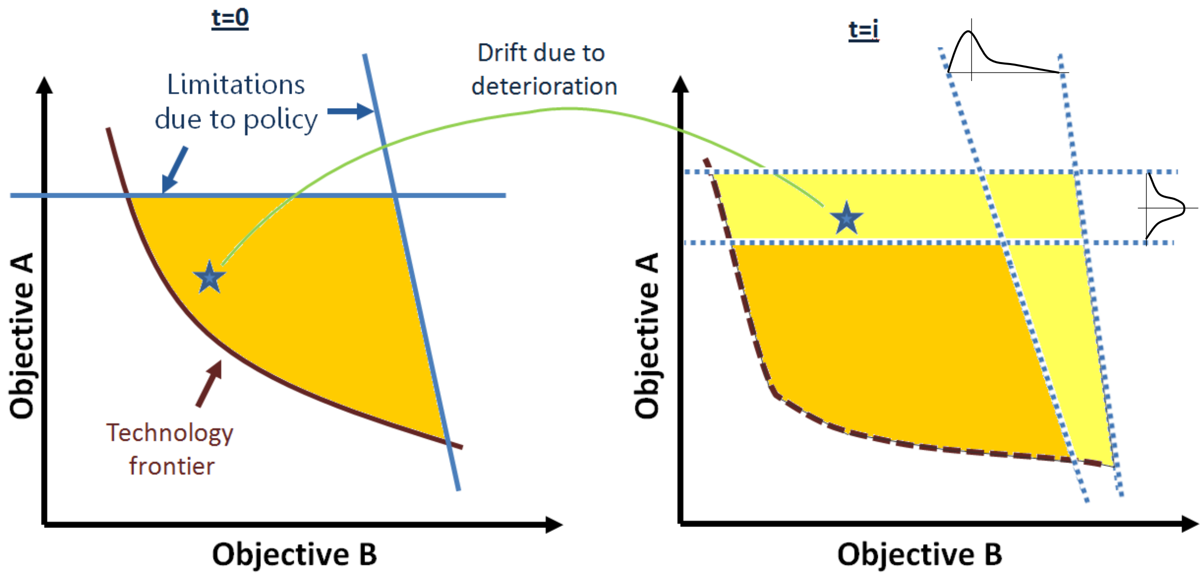


Figure 3-3: Modeling impacts of degradation in objective space

3.6 Evaluating and Managing Policy Change

The need for change is a paradoxical situation. Artifact change is to be both prevented as well as utilized to address system disturbances and evolving customer needs. Either way, a decision-maker is likely to prefer that a disturbance event does not necessitate additional allocation of cost or time toward maintenance of a design's physical characteristics and functional properties. A robust design represents one instantiation of this preference. Here, this dissertation adheres to the definition of *robustness* as continued value delivery in spite of emergent variations to product usage or changes in environmental context in which a product exists (Ullman, 2001; Taguchi & Clausing, 1990). Designs that decouple design parameters and functional requirements or that include design parameters with "flat" performance curves mitigate variation to performance (Ross, 2006).

Robustness is delivered at a cost, and the degree of robustness a designer delivers may still not inhibit impacts to performance caused by a disturbance. For example, Company X might choose to spend Y additional dollars on its product to design in a buffer against a current regulation. The product is robust to policy disturbances up to the buffer level. However, if the regulation is increased beyond the installed buffer, the product is out of conformance despite exhibiting a level of robustness.

A decision-maker should ask if the appropriate amount of robustness—too little since the system did not conform, or too much, too early because the buffer was consumed anyway—was designed-in. In the example of Company X, more robustness could have been added through additional expense. However, the decision-maker might have determined that the risk of non-conformance was low or unavoidable, that cost would only be committed when uncertainty was reduced, or that a non-conforming product is preferable to a more robust but more costly product.

A decision-maker must conduct analysis that trades robustness, or more generally, value-based changeability, with cost. The questions a design team must ask as it relates to managing disturbance include "How many resources should be allocated to achieve robustness?"; "Within what components or systems should resources be allocated?"; and "When should resources be allocated?" Carefully answering the questions from the {when, where, how much} set will determine if trades deliver appropriate value at the incurred cost level.

3.7 Managing Change: Answering the 'When' and the 'Where'

Systems dynamics methods suggest using a causal loop diagram to illustrate issues that a disturbance or series of disturbances may engender. The causal loop diagram shown in Figure 3-4 captures interactions of a system subjected to a new disturbance. A positive sign (+) signifies positive reinforcement, and reads as, "___ leads to higher ____."The opposite is true for a negative sign (-).

A disturbance reduces the potency of a system in its current state. Suboptimal performance leads a decision-maker to make adjustments that attempt to restore potency. However, patching also leads to increased life cycle costs and/or increased unavailability.

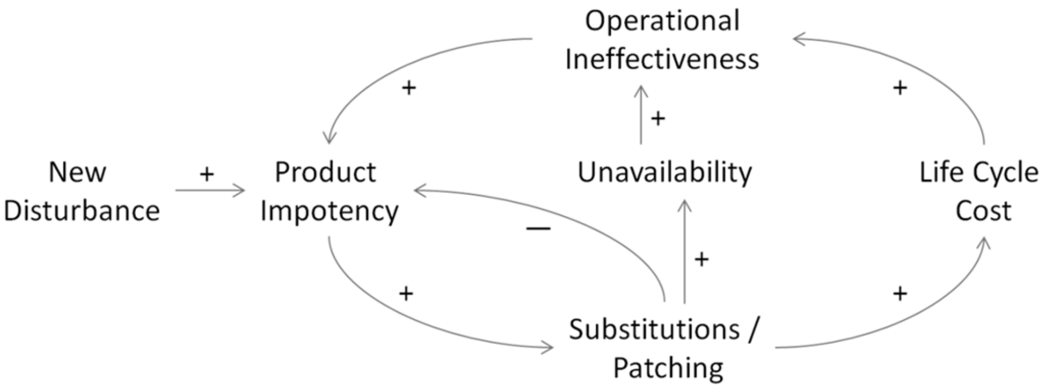


Figure 3-4: General causal loop diagram stemming from a disturbance

Because budgets are often constrained or fixed, substitution costs may draw resources from other planned activities or surplus. Greater downtime needed to complete patching also restricts operating capabilities. Fewer overall operational resources prevent the full and proper performance of the system. Thus, while a balancing loop between potency and patching addresses the immediate problem caused by a disturbance, a long-term negative reinforcement loop may be initiated.

Two means for preventing a loop that reinforces high cost and suboptimal performance include (1) severing the link between a disturbance and product potency, and (2) ensuring that patching events are built into the strategic plan. Both solutions require an understanding for how disturbance impacts system components and the system at-large.

Leech and Turner (1985) outline a generic engineering change sequence in Figure 3-5. The process can be triggered at any time in the system's life cycle when a disturbance is deemed worthy of requiring a response. Despite the fact that no physical production has occurred in the design phase, the change process can still commence because information about design decisions has formally been released.

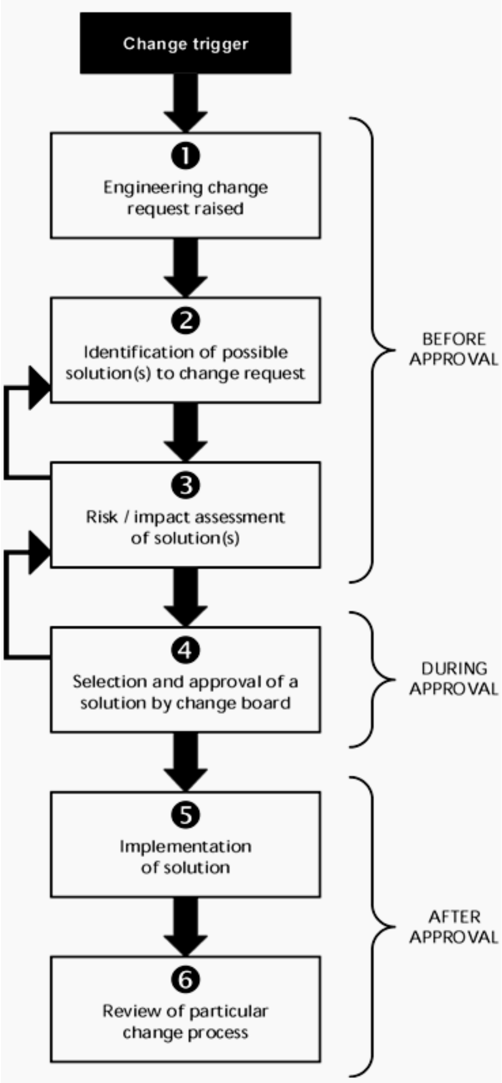


Figure 3-5: Generic engineering design change process (Leech and Turner, 1985)

Efforts to select a design vector which is effective in handling disturbance involve four general steps.

1. Develop an understanding of the disturbance set
2. Identify systems and subsystems impacted by the disturbance set
3. Identify potential preventative measures and change options that can respond to the disturbance set
4. Evaluate change options for their incorporation into the design vector

The remainder of Section 3.7 systematically explains these steps in greater detail, with the intent of laying the foundation for answering where and when resources are to be allocated to manage disturbance due to environmental policy. Next, Section 3.7.1 draws on policy knowledge offered in the previous chapter. Sections 3.7.2 and 3.7.3 outline how connections are drawn between policy disturbance and design change. The final subsection, Section 3.7.4, represents a bridge between broad theory discussed in Chapters 2 and 3 and the detailed methodological analysis, problem formulation, and strategy development offered in Chapters 4 and 5.

3.7.1 Understand the Disturbance Set

Table 3-2 provides a list of policy endeavors that act as disturbances. From the perspective of the designer, an environmental policy can be differentiated by its arena, activity focus, instrument, and specificity. Policy arenas are identifiable by tracing the sources of negative externalities. The previous chapter discussed potential policy instruments.

Table 3-2: Elements of a policy disturbance

Arena:
Air: Carbon, NOx, SOx, PM, Refrigerants, Halons Water: Grey, Black, Oil, Paint, Invasive species Land: Solid waste, Hazardous materials
Activity Focus:
Construction Operations Maintenance Disposal
Instrument:
Economic Direct Provision Regulatory Institutional
Specificity:
Component Sub-system System System of systems

The route from policy objective to technical parameters can be direct or indirect (Figure 3-6). An environmental policy directive may be communicated to a technical designer straightforwardly as a ban on the use of a material, such as the application of tin on the hull of a vessel. A policy directive may also reach a design engineer through a specification to reduce speed, thereby reducing emissions. A speed reduction can result in the desire for a smaller engine, new hull shape, and fewer fuel stores. A policy directive can also affect a designer in an economic manner, such as a desire to receive incentives for reduced environmental impact by earning Green Passport certification from a classification society (ABS, 2011). Qualifications for earning the Green Passport Inventory may include designating specific ship zones for waste treatment. While the technical domain can also impact policy and the economic domain can also influence the operations domain, for example, this research is concerned with the uni-directional impact of policy on system design (see: Figure 3-6).

Figure 3-6: Means through which policy influences technical parameters

Additional effort must be placed into diagnosing the expected magnitude, commencement, and duration of the relevant disturbance set. Many disturbances falling within the sustainability-related subclass offer some level of prediction. Unlike risks such as a catastrophic storm or an attack from an adversary, the factors involved in environmental policymaking that lead to a disturbance exhibit qualitative and quantitative trends. Trend data enable anticipation of the expected timing and period of a disturbance event. For example, ship owners could anticipate the enforcement date of Annex VI within the International Convention for the Prevention of Pollution from Ships

(MARPOL) by counting the number of signatories that had ratified the document's provisions.

The internal and external dynamics that converge to create a disturbance can be slowly building, quickly accumulating, or a combination of the two extremes. The period between initial adoption of Annex VI and the date it entered force spanned eight years. Amendments to Annex VI in 2011 relating to greenhouse gas emissions are expected to enter force in the year 2013. Gasoline prices nearly doubled in just a few month's time in 2008. These policies and other punctuated accomplishments of the environmental movement have resulted through the slow assemblage of actors, significant discoveries and events, and the ebb and flow of context variables.

Appreciation for the duration of a disturbance helps a decision-maker understand if the event is temporary or should be considered the "new normal." High gasoline prices in 2008 retreated by the end of the year, though they did not return to previous levels. Conversely, ratification of Annex VI means that the consequences of the policy disturbance are likely to be present for the foreseeable future. Duration can also contribute to the cumulative effect of a disturbance. A benign disturbance that continues uninterrupted for a half-century may match the impact caused by a strong but transitory disturbance.

3.7.2 Identify Potential System Impacts

Disturbances can impact the physical structure of systems or influence system functions. The impact of disturbance on technical parameters can be quantified in terms of cost, performance, availability, margin, and risk. Emerging properties may be positive or negative. Affected systems and functions may be mission critical or expendable, for either current activities or those expected to occur in the future. As such, correcting disturbance impacts to a system may require immediate response.

Drawing relationships between disturbance types and design impacts helps a decision-maker prioritize trade-offs that might be explored. Weigel (2002) suggests using an influence diagram to qualitatively model the relationship between a disturbance (new policy direction) and technical parameters, via architecture objectives. An artifact with few impacts resulting from a new policy direction is described as policy robust.

Use of networks, diagrams, and matrices helps determine if a system or functions are independent of disturbance, directly or indirectly. The literature distinguishes between *local* change and *interface-overlapping* change (Lindemann et al., 1998). Where a disturbance does influence technical parameters, physical and functional decomposition can be employed to determine the fidelity at which a system must be explored and the decentralization afforded to decision-making.

Propagation of a disturbance throughout the system can be identified via the use of a design structure matrix (DSM), networks, or other dependency tools. Eckert, Clarkson, and Zanker (2004) propose four general reasons why change propagates:

1. Due to oversight
2. Due to lack of knowledge
3. Due to communication breakdowns
4. Due to emergent properties

A Failure Mode and Effect Analysis (FMEA) serves as one change technique commonly conducted to identify critical characteristics (Jarratt, Eckert, and Clarkson, 2006).

3.7.3 Identify Change Options

Decision-makers have the ability to invest at various levels in the life cycle to achieve acceptable performance, including:

- *Design stage* – building a reliable system requires committing resources upfront to identify and plan for expected loads, component interactions, and modes of failure.
- *Construction* – a quality product is more likely to be a reliable product, given operations occur under stated environmental conditions. Quality often demands a premium during the manufacturing stage.

- *Operations* – costs are a function of the product's performance level and unit output. For example, the variable costs of a machine may increase as the components degrade. Similarly, environmental costs may be a linearly increasing function of carbon output.
- *Maintenance* – labor and/or the purchase of new materials are required to maintain or repair a component. Downtime can lead to loss in revenues, and switching costs are associated with replacement of a component that requires additional rework to the system.
- *Disposal* – inconsistent performance caused by disturbance lowers the resale value of a product. Use of hazardous materials to achieve performance may require costly procedures to render the materials harmless.

Cataloging engineering changes by life cycle phase allows decision-makers to reference available options. Figure 3-7 illustrates a sample categorization of change options within one life cycle phase in response to a disturbance. Change actions that are anticipated or identified in design and executed as necessary can be described as deliberate. Action options that are unforeseen can be described as emergent. Recall from Section 3.3 that flexible and adaptable changes are a function of whether the change agent is external or internal to the system, respectively (Ross et al., 2008). Research identifies three general directions of change options: operational, growth, or abandonment (Mikaelian, 2008).

Change options may not always be feasible or the implementation of certain technologies precludes the implementation of other technologies. Instances often exist where transition from one state to another is made impossible due to technical or non-technical limitations. Similarly, state changes may only be possible during specific life cycle phases and change windows, given the current design vector and stakeholder requirements. Human elements to the decision-making process, including the perceived undesirability of an option's behavior, can especially restrict transitions.

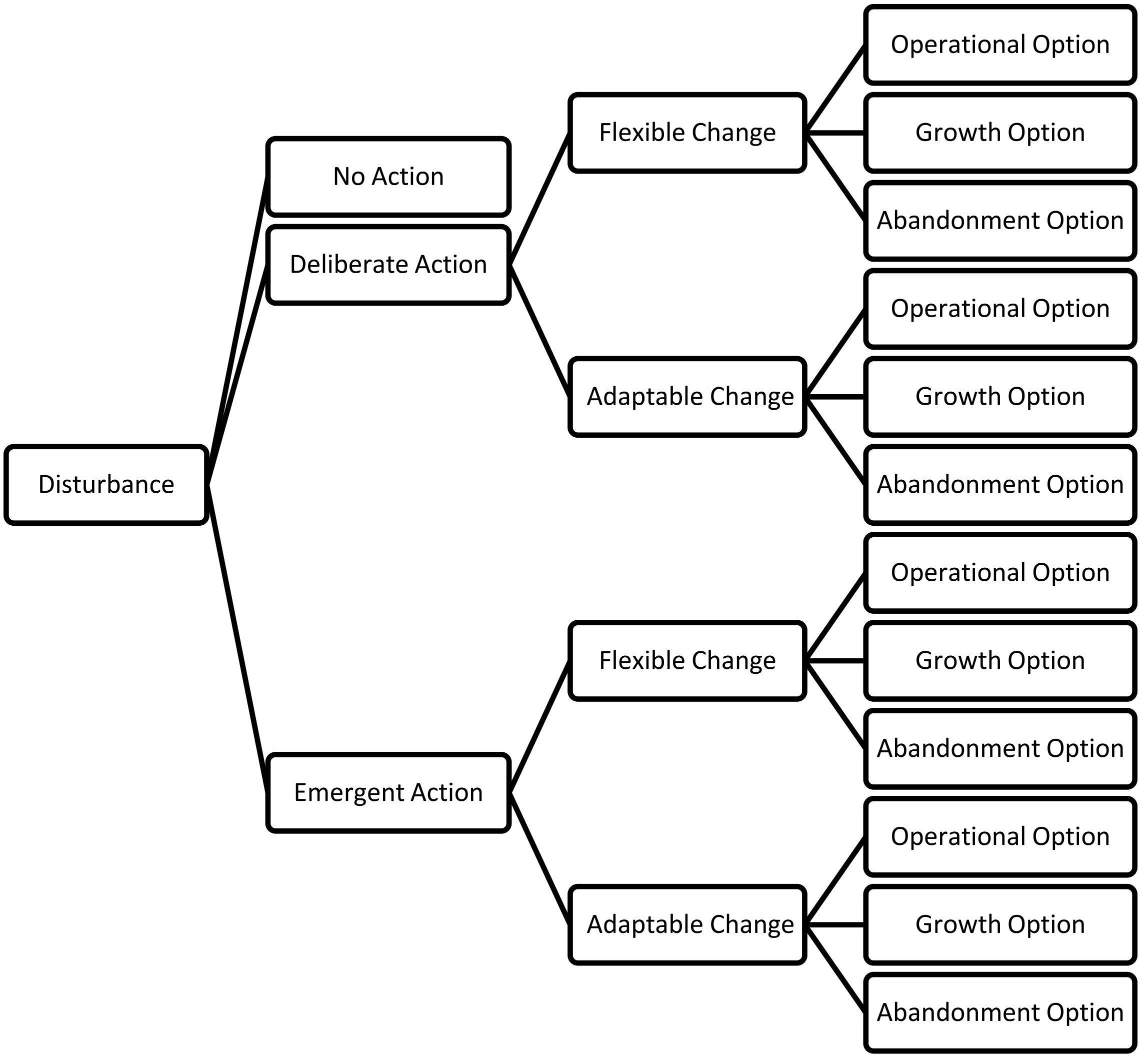


Figure 3-7: General decision tree of change options

3.7.4 Evaluate Change Options

Cost of a change action increases with time due to design lock-in. Investment trade-offs can be readily apparent and linear or particularly surprising and nonlinear. Classically, late stage design changes are to be avoided due to the Rule of Ten (Figure 3-8). A change action that must be sourced from outside the current set of an artifact's forms and behaviors necessitates a *switching cost*. Expenditure, singular or recurring, related to maintaining the ability for change is commonly known as *carrying cost*.

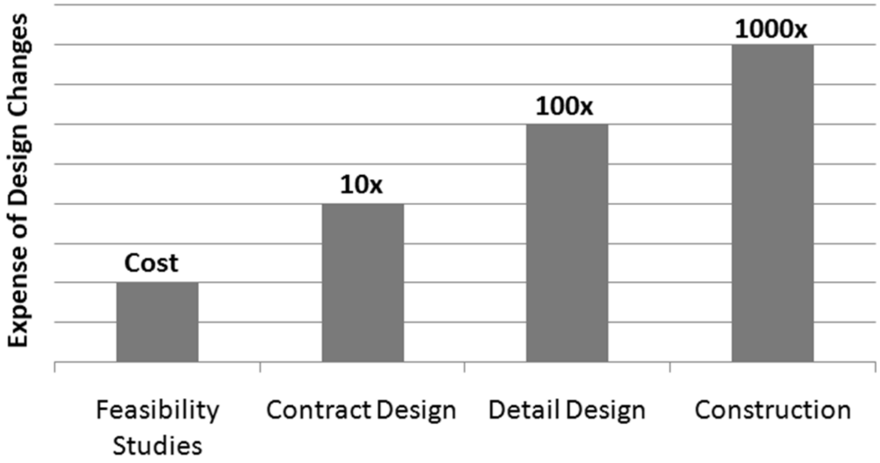


Figure 3-8: Expense of design changes during different design phases of naval ships (Adapted from Keane & Tibbitts, 1996)

Understanding that change options are not mutually exclusive is also important. Much work has been placed into developing marginal abatement cost curves to identify sustainability-related endeavors at the fleet level (Buhaug, 2009). A detailed example of global activities related to greenhouse gases is offered in Figure 3-9.

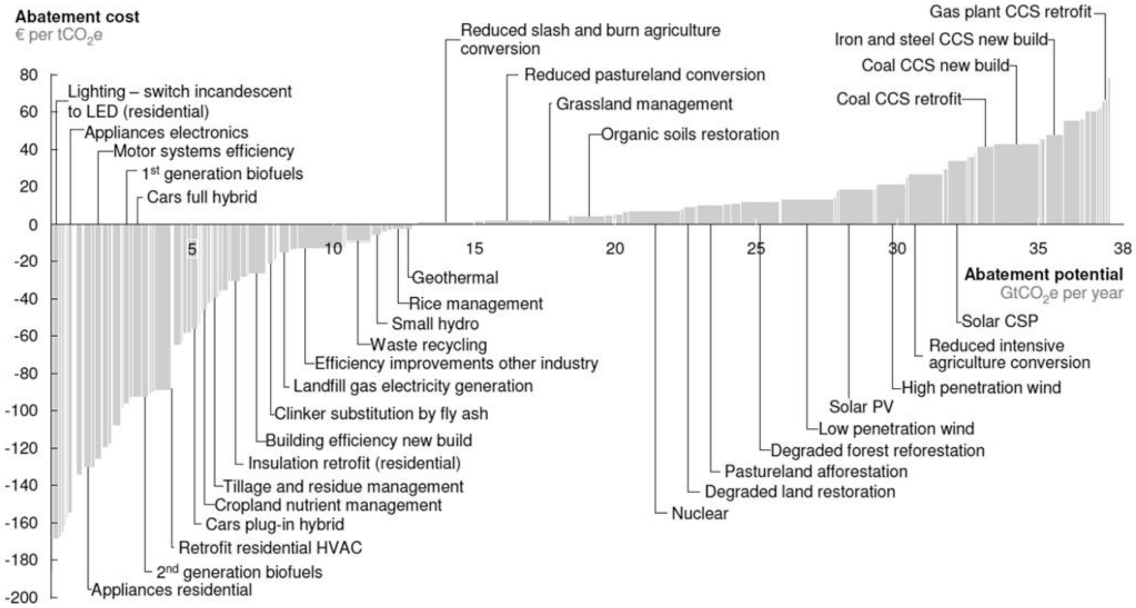


Figure 3-9: Global GHG abatement cost curve beyond business-as-usual—2030 (McKinsey & Co., 2007)

Decision analysis is often suggested for navigating the many choices that lead to cumulative performance and life cycle cost. One parameter which cannot be traded is time. Time proceeds forward continuously, and many decisions in the past serve as the irreversible foundation upon which future decisions exist. In a resource-limited environment, for example, heavy expenditures in the design and construction phases may limit the ability to employ funds for operations, maintenance, or disposal. This dissertation focuses on managing path dependencies in a manner that enables state reachability and future decision opportunities.

Because changes may be performed for multiple reasons, developing a strategy for their timely implementation is important. Fricke et al. (2000) list five strategies for improved change management:

1. Prevention—minimizing the need for change, especially at later phases of the life cycle where changes require more resources
2. Front-loading—controlling the risk of future changes through early detection and application of the precautionary principle
3. Effectiveness—managing the elimination of uneconomic changes by rejecting change requests requiring efforts that outweigh the benefits
4. Efficiency—optimizing use of resources, especially cost and time to fulfill functional needs given the context in which the artifact exists
5. Learning—performing changes for the sake of learning about product development for the next time; requires employing a strategy with a perspective on multiple product life cycles

Fricke et al. (2000) suggest use of a strategy mix is more important than application of a single strategy. Balance must be drawn between the Rule of Ten and the ability to adjust to disturbance environments. Strategies must also balance risk and opportunities that spring forth due to varying adoption rate responses of competitors.

3.8 Relevance to Policymakers

The above summary of how the technical community perceives and reacts to policy change generates a “wish-list” for how those involved in policymaking conduct their efforts. The preferences of an engineering team with respect to policy include:

- Early and clear communication—an unknown policy direction increases the dimensions of uncertainty associated with development of large complex systems. Figure 3-10 illustrates a sample regulatory schedule that may play forward during the expected life span of a product. Policy A is known before the product is built, while Policy B and Policy C are unknown until after construction. Important dates of notice from both the standpoint of a policymaker and product manager include the timing of policy proposal, ratification, enforcement initiation, and enforcement expiration.
- Reachable goals—policy targets may be set high, but also must be achievable before the given date of enforcement. Too drastic a response time can result in bottlenecks for switchover resources, inadequate testing periods, or outsized research, development, and implementation costs.
- Even enforcement—regulations should be without loopholes that unduly select winners and losers within an industry. Evenness must also occur across comparable sectors so as not to significantly impact competition, e.g., growth of trucking industry as a result of unbalanced regulation in shipping industry (Garcia-Menendex & Feo-Valero, 2009).
- Flexible application—multiple avenues for satisfying the same policy enable organizations to develop catered solutions given the strengths and weaknesses of their portfolios.
- Policy stability—policies that lean heavily to one side of the aisle, and are thus prone to be scaled back when the power structure changes, do not result in consistent development. Strategic engineering of products requires a long-term view where the volatility of exogenous factors is minimized.

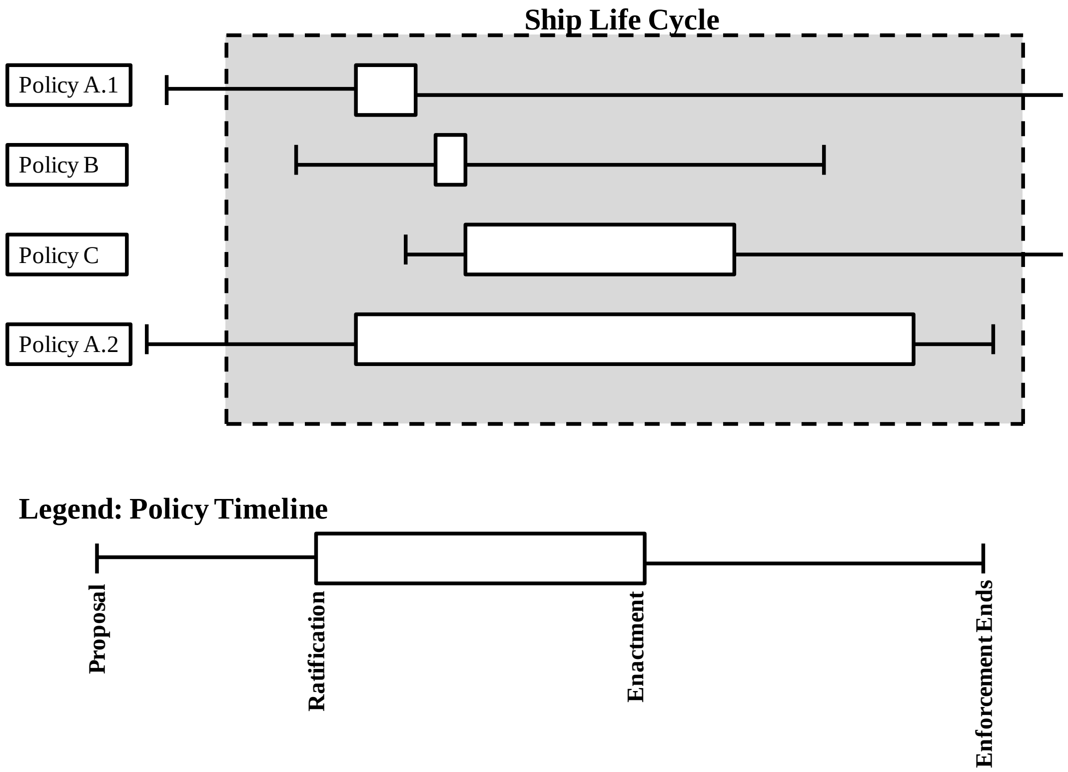


Figure 3-10: Sample regulatory schedule relative to product life cycle

Policymakers who utilize decision tools such as influence diagrams can discover the range of impacts to a technical system. Weigel (2002) suggests that policy directions causing the least number of impacts could be vigorously pursued without fear of losing technical robustness. Policy directions that cause a significant number of impacts must be pursued carefully, cognizant of potential impacts of a policy direction change.

3.9 Chapter Summary

Numerous disturbance regimes exist, each with the potential for altering the design artifact to the point that change may be desired. Environmental policy is increasingly becoming a disturbance regime of note. The traditional artifact viewpoint is unable or unwilling to address the role of environmental policy change, and so accepts lock-in. A widened scope of the artifact more fully values changeability and the rest of the –ilities class.

Change capacity must be strategically built-in or otherwise available to handle disturbance. Relief from disturbance means answering when, where, and how much change should occur. Managing the decisions associated with this set of questions becomes all the more important due to temporal dimensions that can inhibit change or enable opportunity.

The past two chapters first interpret policy change from the policy and technical perspectives and then lay the foundation for translating uncertain policy change to design action. The concept of product drift and corresponding implications firmly plants policy change as a time and state dependent issue for design engineers. This dissertation seeks to understand how the path dependency of decisions stemming from disturbance contributes to lock-in at both the design and use stages of the life cycle. Understanding disturbance-induced lock-in can help designers understand key system drivers of life cycle performance and life cycle cost. Future chapters explain various past interpretations, explain issues with current state-of-the-art change management strategies, and offer the author's solution for improving design under environmental policy change.

Chapter Citations

1. ABS. (2011). Guide for the class notation: Green Passport. *Report.* American Bureau of Shipping.
2. Briceno, S., & Mavris, D. (2006). Applications of game theory in a systems design approach to strategic engine selection. *Proceedings of 25th International Congress of the Aeronautical Sciences*, Hamburg.
3. Buhaug, Ø., Corbett, J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D., Lee, D., Lindstad, H., Markowska, A., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Winebrake, J., Wu, W., & Yoshida, K. (2009). Second IMO GHG Study 2009. *Report.* London: International Maritime Organization.
4. Clarkson, P., Simons, C., & Eckert, C. (2004). Predicting change propagation in complex design. *Journal of Mechanical Design, 126* (5), 788-797.
5. Eckert, C., Clarkson, P., & Zanker, W. (2004). "Change and customization in complex engineering domains. *Research in Engineering Design*, *15* (1).
6. Fenves, S., Foufou, S., Bock, C., & Sriram, R. (2008). CPM2: A Core model for product data. *Journal of Computing and Information Science, 8* (1), 014502-014508.
7. Fricke E., Gebhard, B., Negele, H., & Igenbergs, E. (2000). Coping with changes: Causes, findings and strategies. *Systems Engineering*, *3*, 169-79.

8. Fricke, E., & Schulz, A. (2005). Design for changeability (DfC): Principles to enable changes in systems throughout their entire life cycle. *Systems Engineering, 8* (4), 342-359.
9. Frangopol, D., Kallen, M., & Noortwijk, J. (2004). Probabilistic models for life cycle performance of deteriorating structures: Review and future directions. *Progress in Structural Engineering and Materials, 6* (3), 197-212.
10. Garcia-Menendez, L., & Feo-Valero, M. (2009). European common transport policy and short-sea shipping: empirical evidence based on modal choice models. *Transport Reviews, 29* (2): 239-259.
11. Haimes, Y. (2004), *Risk modeling, assessment and management.* New Jersey: John Wiley and Sons, Inc.
12. Holloway, L., Clegg, D. Tranter, I., & Cockerham, G. (1994). Incorporating environmental principles into the design process. *Material & Design, 22* (15), 259-267.
13. Hopp, W., & Nair, S. (1991). Timing replacement decisions under discontinuous technological change. *Naval Research Logistics, 38* (2), 203-220.
14. Jarratt T., C. Eckert, and P. Clarkson. (2004). Development of a product model to support engineering change management. *In proceedings of TMCE 2004 1*, 331-342. Lusanne.
15. Jarratt T., Eckert, C., & Clarkson, P. (2006). Pitfalls of engineering change: Change practice during complex product design. In H. Maraghy & W. Maraghy, *Advances in Design* (pp. 413-424)**.** London: Springer.
16. Leech, D., & Turner, B. (1985). *Engineering design for profit.* Chichester: Ellis Horwood Ltd.
17. Liebowitz, S., & Margolis, S. (1995). Path dependence, lock-in, and history. *Journal of Law, Economics and Organization, 11* (1), 205-26.
18. Lindemann, U., Kleedorfer, R., & Gerst, M. (1998). The development department and engineering change management. In E. Frankenberger, P. Badke-Schaub, & H. Birkhofer, *Designers: The Key to Successful Product Development* (pp. 169-182). London: Springer.
19. Mavris, D., Baker, A., & Schrage, D. (1997). IPPD through robust design simulation for an affordable short haul civil tiltrotor. *In proceedings of American Helicopter Society 53rd Annual Forum.* Virginia Beach.
20. Mikaelian, T., Hastings, D., Rhodes, D., & Nightingale, D. (2007). Model-based estimation of flexibility and optionability in an integrated real options framework. *In proceedings of 3rd Annual IEEE Systems Conference*. Vancouver.
21. Mikaelian,T., Rhodes, D., Nightingale, D., & Hastings, D. (2008). Managing uncertainty in socio-technical enterprises using a real options framework. *In proceedings of 6th Conference on Systems Engineering Research*. Redondo Beach.
22. Niese, N., & Singer, D. (2010). Future environmental policy decision-making for preliminary ship design using Markov Decision Processes. *In proceedings of the 11th International Symposium on Practical Design of Ships and Other Floating Structures.* Rio de Janeiro.
23. Niese, N., & Singer, D. (2011). Life cycle decision-making under uncertain environmental policy using nonstationary Markov Decision Processes. *In proceedings of ICCAS*. Trieste.

24. Noortwijk. J. (2004). Probabilistic models for life cycle performance of deteriorating structures: review and future directions. *Progress in Structural Engineering and Materials*, *6* (3).
25. Pindyck, R. (2007). Uncertainty in environmental economics. *Environmental Economics and Policy, 1* (1), 45-65.
26. Pistikopoulos, E. (1995). Uncertainty in process design and operations. *Computers & Chemical Engineering, 19* (1), 553-563.
27. Raven, R., Bosch, S., & Weterings, R. (2010). Transitions and strategic niche management: towards a competence kit for practioners. *International Journal of Technology Management, 51* (1), 57-74.
28. Rosenfield, D. (1976). Markovian deterioration with uncertain information. *Operations Research, 24* (1), 141-155.
29. Ross, S. (1971). Control under Markovian deterioration. *Management Science*, *17* (9), 587-596.
30. Ross, A. (2006). Managing unarticulated value: changeability in multi-attribute tradespace exploration. *Dissertation*: Cambridge, MA.
31. Ross, A., & Hastings, D. (2006) Assessing changeability in aerospace systems architecting and design using dynamic multi-attribute tradespace exploration. *In proceedings of AIAA Space*. San Jose.
32. Ross, A., Rhodes, D., & Hastings, D. (2008). Defining changeability: reconciling flexibility, adaptability, scalability, modifiability, and robustness for maintaining system life cycle value. *Journal of Systems Engineering*, *11* (3), 246-262.
33. Savage, G., & Carr, S. (2001). Interrelating quality and reliability in engineering systems. *Quality Engineering*, *14* (1), 137- 152.
34. Schaltegger, S., & Burritt R. (2000). *Contemporary environmental accounting: issues, concepts, and practice.* London: Greenleaf Publishing.
35. Shapiro, C. (1989). The theory of business strategy. *RAND Journal of Economics, 20* (1), 125–137.;
36. Simon, H. (1969). *Sciences of the Artificial*. Cambridge: MIT Press.
37. Smaling, R., & de Weck, O. (2007). Assessing risks and opportunities of technology infusion in system design. *Systems Engineering*, *10* (1), 1-25.
38. Son, Y., & G. Savage. (2005). Set theoretic formulation of performance reliability of multiple response time-variant systems due to degradations in system components. *Quality and Reliability Engineering International*, *23* (2), 171-188.
39. Styblinski, M. (1991). Formulation of the drift reliability optimization problem. *Microelectronics Reliability, 31* (1), 159-171.
40. Taguchi, G., & Clausing, D. (1990). Robust quality. *Harvard Business Review* (Jan.-Feb.): 65-75.
41. Ullman, D. (2001). Robust decision-making for engineering design. *Journal of Engineering Design*, *12* (1): 3-13.
42. Van Noortwijk, J. (2007). A survey of the application of gamma processes in maintenance. *Reliability Engineering and System Safety, 94*, 2-21.
43. Weigel, A. (2002). Bringing policy into space systems conceptual design: quantitative and qualitative methods. *Dissertation*: Cambridge, MA.

44. White, P., & Pickett, S. (1985). Natural disturbance and patch dynamics: An introduction. *The ecology of natural disturbance and patch dynamics*. New York: Academic Press.
45. Wright, I. (1997). A review of research into engineering change management: Implications for product design. *Design Studies, 18***,** 33-42.

CHAPTER 4 – PROBLEM FORMULATION

In war as in life, it is often necessary when some cherished scheme has failed, to take up the best alternative open, and if so, it is folly not to work for it with all your might.

Winston Churchill

The last chapter exhibited that researchers and practitioners recognize the need to implement changeability upfront in the design architecture. The goal is to manage uncertain risks that arise while being able to pursue opportunities that present themselves. The solutions and expected learnings are far from obvious. The dynamic design problem continues to offer opportunities for further research. Fricke and Shultz (2005) and Ross (2011) contend approaches, methods, and tools remain insufficient for deep analysis and portrayal of –ility issues in design decisions.

There is an important role for economic analysis in determining the strategy—and adjusting the strategy as conditions and value perceptions change—that satisfies policy initiatives. Any analysis will be subject to a highly uncertain economic, technology, and policy future.

The following chapter aims to formulate the problem through a description of the state-of-the-practice and identification of current limitations. Both the description and identification of limitations are broken into two parts: a discussion of sustainability practices in the shipping industry and a discourse on change management methodologies.

The literature review culminates in a focused problem statement for the remainder of this dissertation.

4. 1 Background

Literature related to preliminary design, sustainable engineering, and decision analysis involve a broad collection of topics and issues. Only resources relevant to the dynamic design problem subject to policy change are considered here. The following background section introduces concepts and past research to develop an understanding of the state-of-the-practice. Literature is sourced from that of the design of buildings, automobiles, space systems, and other large systems comparable to ship design.

4.1.1 Sustainability in Shipping

4.1.1.1 State of the Industry

The greater pace at which industrial activity occurs, and a deeper understanding of the impact of these activities on the environment, has increased concerns of sustainability. Few industries have remained untouched, and advancing sustainable low-carbon transport has been identified by policymakers, system architects, product managers, suppliers, and buyers alike. The transportation sector accounts for approximately a quarter of total energy consumed globally (Buhaug et al., 2009). Furthermore, the sector is expected to grow significantly over the next many decades. Business-as-usual practices predict an increase of 2% in energy use per year until 2030 and carbon emission growth of 80% over 2002 levels in worldwide transportation (IPCC, 2007).

While shipping is generally the most efficient form of transportation in terms of energy use, the magnitude of the industry activity requires that the shipping community increasingly seek measures to limit environmental impact. International shipping is estimated to have contributed 2.7% of all global emissions in 2007 (Buhaug et al., 2009). In the absence of additional policies, estimates show ship emissions may grow by 150-250% by 2050 as compared to 2007 figures. Overall average annual growth in tonne-miles has exceeded 4% since 1986 (Buhaug et al., 2009).

Several high profile studies to date have investigated the impact of a policy change on the global shipping front. Two of the most notable studies include the International Maritime Organization's Second GHG Study 2009 and U.S. Environmental Protection Agency's Regulatory Impact Analysis Report from 2009. As both the sources and the study titles suggest, the aim of both reports was for governing bodies to explore regulatory options and assess the implications of a policy initiative. The research assessed various scenarios to understand the expected future emissions of the industry, quantify cargo transport demand, and determine the effects of variable technology uptake rates on environmental quality. The effect of the reports was to:

- Provide a state-of-the-industry report on emissions inventory, reduction achievements, and climate impact
- Estimate the potential of technical and operational measures to reduce emissions
- Develop marginal cost abatement curves (Figure 4-1)
- Advocate for the advantages and disadvantages of a specific policy option
- Project total cost and benefit implications of a policy initiative

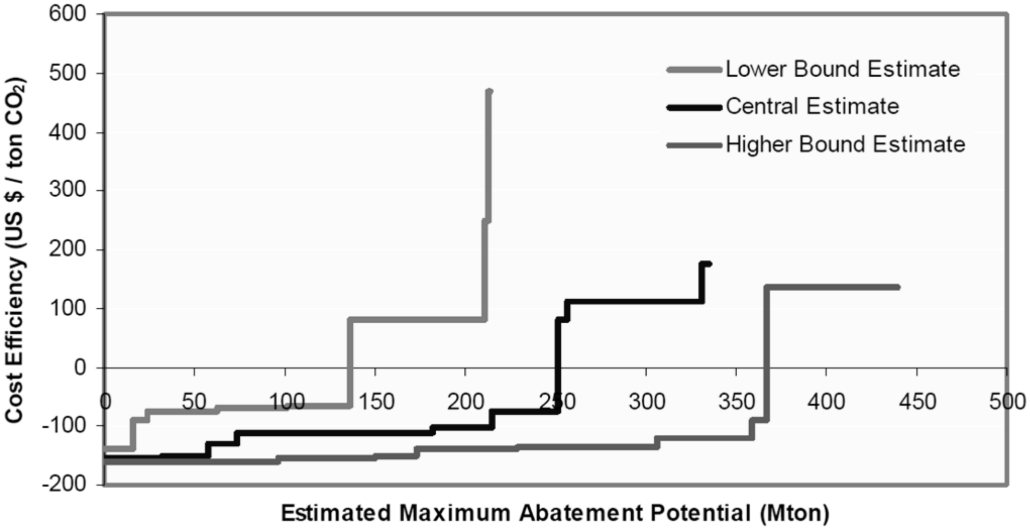


Figure 4-1: Marginal CO_2 abatement cost curve in year 2020 at fuel price of \$500 per ton (IMO, 2009)

Lee at al. (2009) depicts the connection between ship activities and policy relevance (Figure 4-2). Ship decision-makers are likely to focus on performance and economic factors directly within their set of responsibilities, such as fuel savings. Emitters rarely witness the full and direct impact of their activities. Policymakers take notice when activities cause impacts and reveal themselves in the form of damages to social welfare.

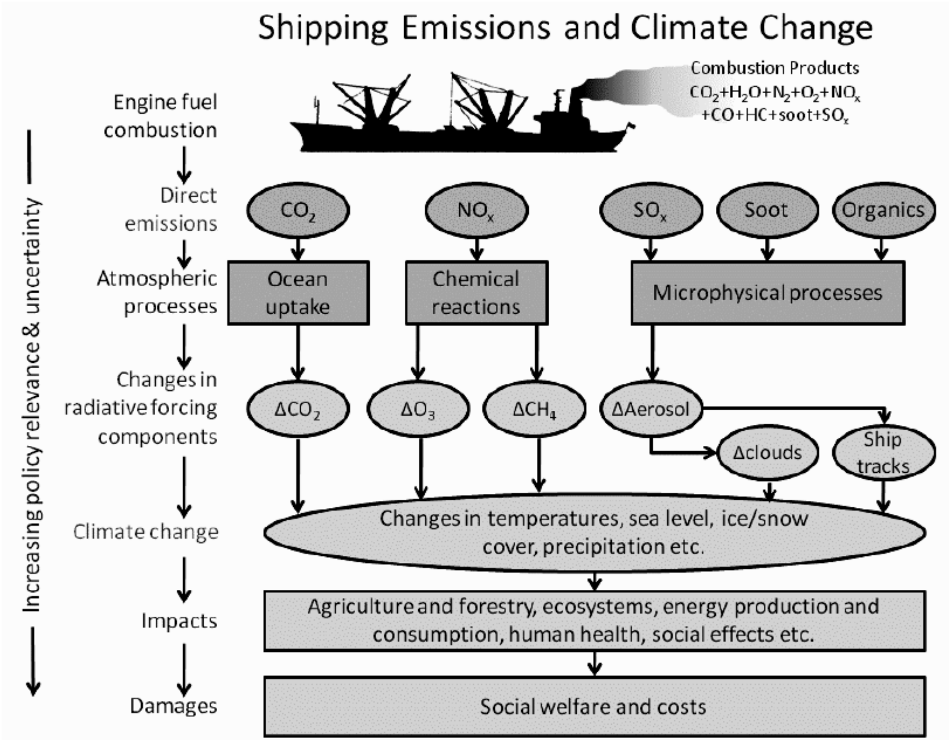


Figure 4-2: Schematic diagram on impact of ship emissions (in Buhaug et al., 2009, adapted from Lee et al., 2009)

Recent highest profile environmental regulations in shipping pertain to the management of sulfur oxides, nitrogen oxides, carbon dioxide, and invasive organisms. Figure 4-3 illustrates regulatory measures limiting the emissions of SO_x and NO_x from marine propulsion and powering systems over the next couple decades as set forth by the International Maritime Organization. Tier II NO_x standards entered force in 2011 and Tier III standards are expected to apply worldwide in 2016. Figure 4-4 illustrates that the standard containership design today is five percent below the index standard for carbon emissions (known as EEDI). Garbage, oil, sewage, organotins, and clorofluorocarbons have witnessed regulation in the past.

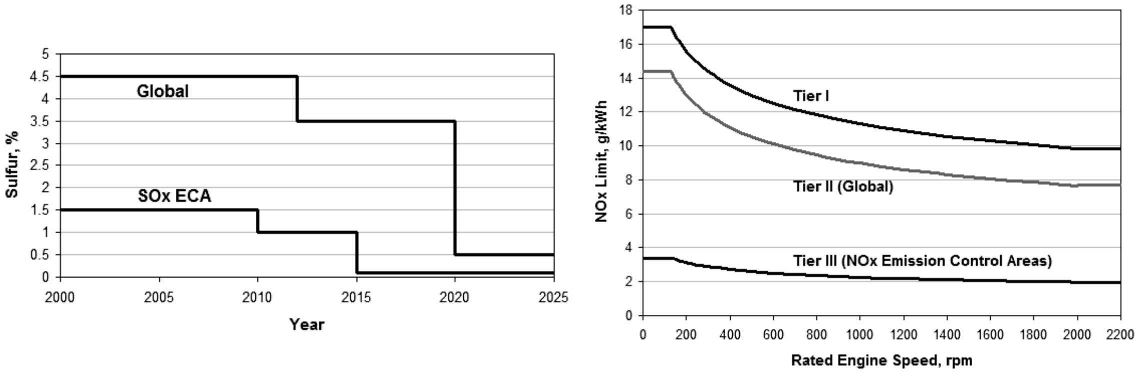
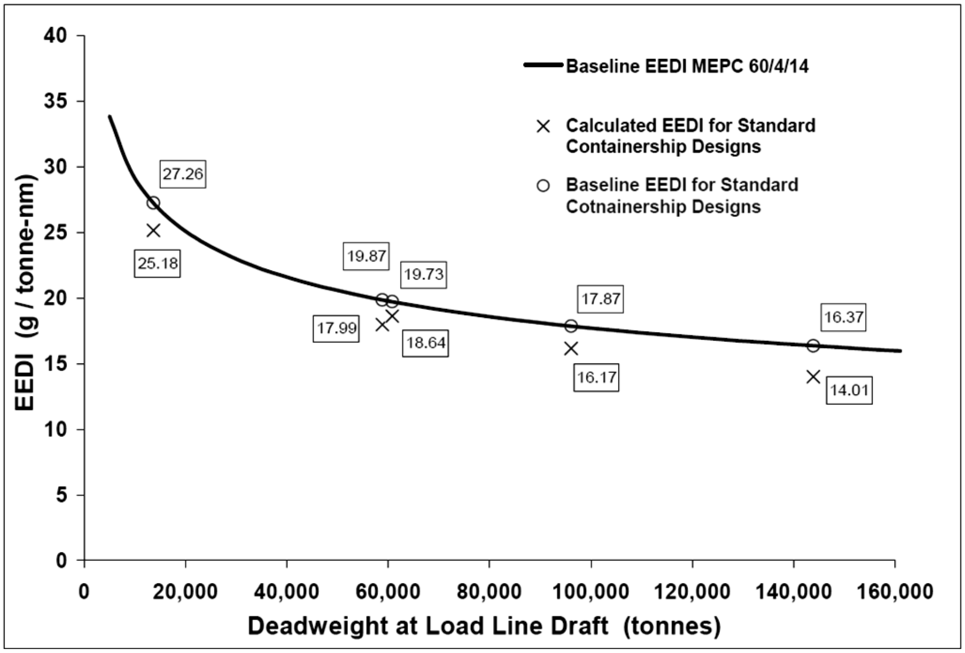


Figure 4-3: Sulfur and nitrogen oxide IMO regulatory schedule (IMO, 2009)



**EEDI=Energy Efficiency Design Index*

Figure 4-4: Environmental regulations affecting ship emissions (Ozaki et al., 2010)

Of particular note is the existence of more stringent requirements in Emission Control Areas (ECAs). A Party to MARPOL Annex VI can propose additional limits to SOx, NOx, and particulate matter (PM) in areas deemed environmentally sensitive. To date, the Baltic Sea and North Sea have been designated ECAs, with the North American coastline and Caribbean soon to join the list. In addition, the state of California, for example, mandated its own legislation even before the North American ECA was approved. Location-specific environmental requirements point out that policymaking can occur at state, regional, national, and international government levels.

4.1.1.2 Life Cycle Analysis, Design, and Costing

Environmental criteria now firmly fit within the scope of desired life cycle functionality (Frei and Zust, 1997). The life cycle of a product, often conveniently summarized as cradle-to-grave or cradle-to-cradle, includes the design, production, use, maintenance, and disposal phases (Figure 4-5).

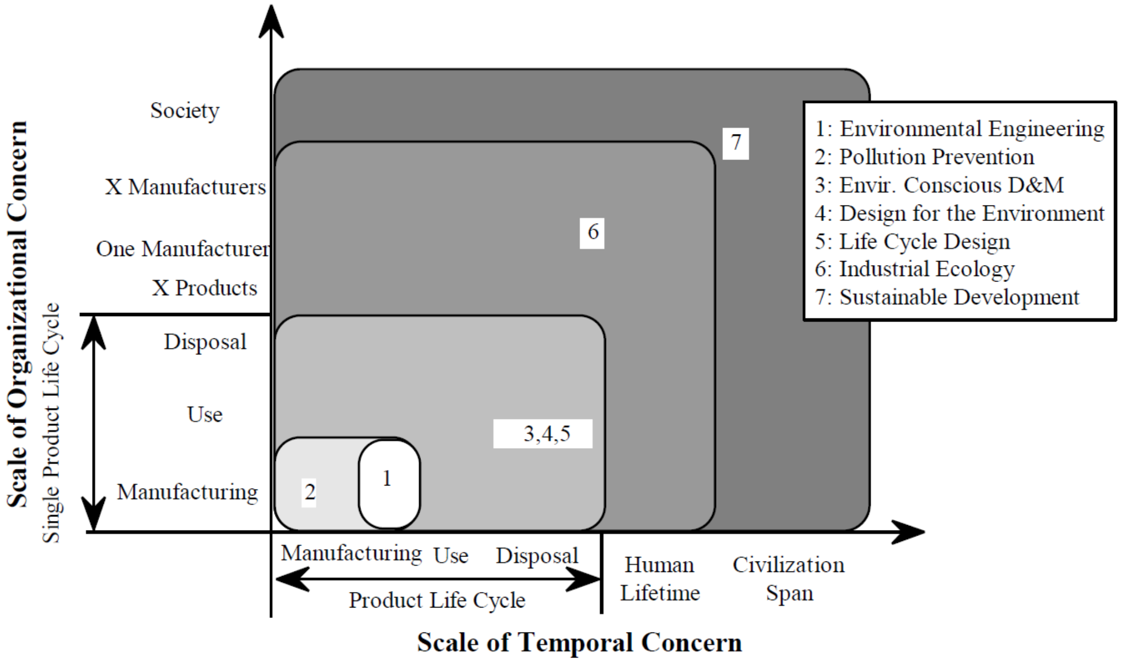


Figure 4-5: Categorization of life cycle design process (Bras, 1997)

Designs responsive to policy constraints and opportunities push the envelope by perceiving the factors governing a design’s environmental performance. These factors may be many and wide ranging, reaching across physical, economic, and regulatory spheres of influence. For example, the IMO representation, below, illustrates the extensive interdisciplinary inputs needed to inventory ship carbon emissions (Figure 4-6).

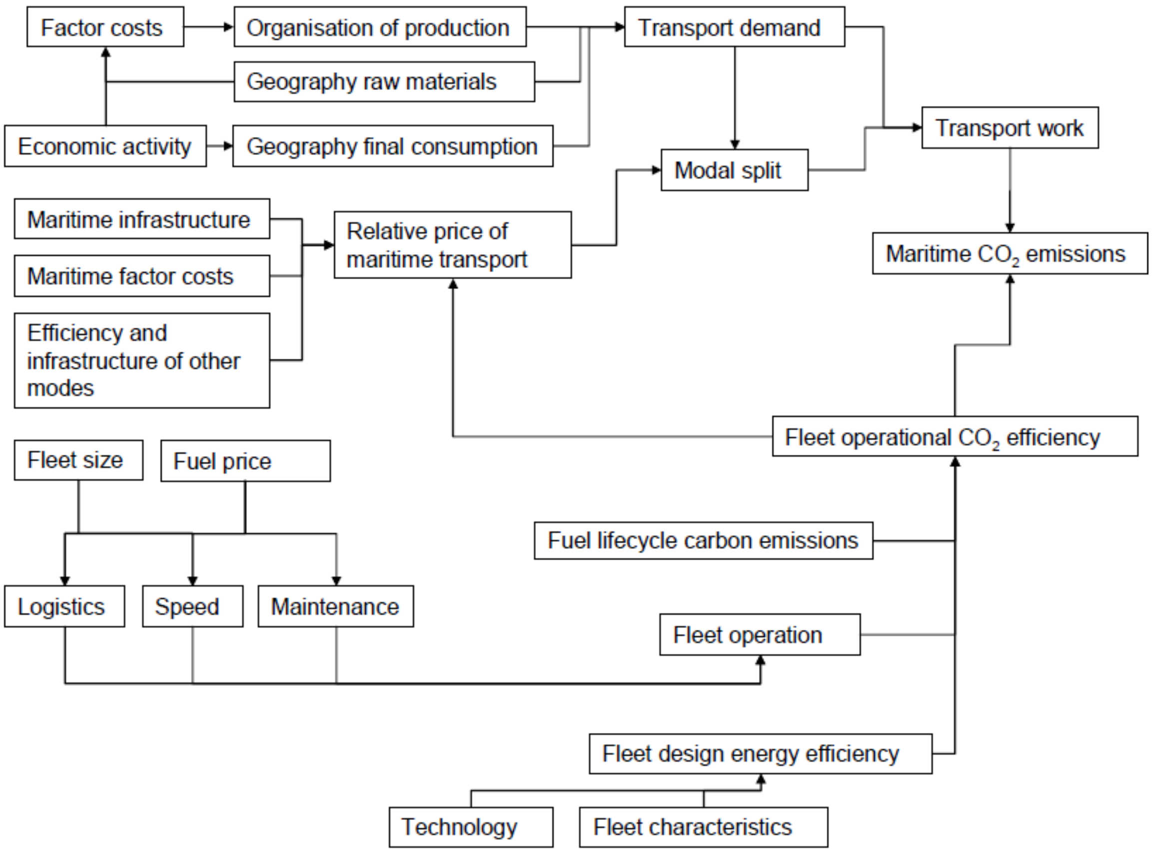


Figure 4-6: Factors determining maritime emissions (IMO, 2009)

Life cycle analysis

Life cycle analysis (LCA) has proven a common, comprehensive technique for assessing environmental impact. Process-based LCA adheres to ISO 14000 environmental management standards and is the most widely applied, though other LCA variations include the economic input-output model (EIO-LCA) and ecologically-based framework (Eco-LCA). Using any of these methodologies provides data on emissions, impacts, and resource consumption by a product or process.

Cooper and Fava (2006) note than LCA is often conducted to support business strategy, as an input into product or process design, for labeling or product declarations, and for educational purposes. Past research efforts in environmental shipping have trended toward approaches and case studies that provide insights for product and process design post-completion of concept design (Kameyama et al., 2004; Ellingsen, 2002). Still, high levels of operational uncertainty and limited resources to evaluate hundreds of thousands of ship components prevent a full LCA investigation of ship emissions and other environmental impacts.

The focus of this dissertation is to offer strategy development support so that environmental performance can be evaluated in early stage design before concepts have been completed and a majority of decisions locked. Traditionally, LCA is used to assist in understanding policy risk, but assessing environmental performance is not the end goal. Here, concept design affords a focused application of LCA due to ship environmental impacts following the 80-20 Pareto principle. A majority of impacts are caused by primary propulsion systems and are related to principal dimensions and general operations.

Life cycle design

The basic premise of the Design for Environment (DFE) approach is to inject concerns about environmental impacts into the design process, thereby avoiding environmental issues later in the life cycle. Preliminary design activities can dictate up to 70% of the total economic life cycle cost of a product according to many estimates; thus, many argue it is also reasonable to assume that a large proportion of the environmental cost might also be locked-in at the design stage (Holloway et al., 1994).

Environmentally conscious designs (ECD) adhere to the following tenets while maintaining commercial profitability, reliability, and manufacturing (Gupta, 1995; Holloway et al., 1994):

- Minimize emissions
- Minimize energy utilization
- Reduce the amount of materials used in products and include materials that have less environmental impact or more value at end-of-life
- Maximize use of materials that are recyclable or reusable
- Design for disassembly

As such, the most important environmental factors guiding DFE processes include material inputs; energy requirements; atmospheric, waterborne, and solid waste emissions; and recovered and reused materials. Material inputs and outputs are the medium through which environmental policy is connected to design. Externalities derived from material outputs draw policy into the product domain, and policy mediates the product by directly or indirectly managing material inputs (see: Chapter 2).

Speed, principal dimensions, and propulsion systems are known to have an important influence on energy requirements. Figure 4-7 list major options in design and operations that can improve energy efficiency. Design and operations are intimately intertwined, and combined energy initiatives are believed to be capable of reducing carbon dioxide emissions by 25-75%.

In addition to reduced emission levels, energy-related initiatives can also be financially beneficial. The U.S. Navy recognizes the impact that reduced fuel consumption has on both the environment and operations cost, using its Incentivized Energy Conservation program (i-ENCON) to incentivize the fleet and share best energy management practices.

DESIGN (New ships)	**Saving (%) of CO_2/tonne-mile**	**Combined**	**Combined**
Concept, speed & capability	2-50^{+}	10-50%$^{+}$	25-75%$^{+}$
Hull and superstructure	2-20		
Power and propulsion systems	5-15		
Low-carbon fuels	5-15*		
Renewable energy	1-10		
Exhaust gas CO_2 reduction	0		
OPERATION (All ships)			
Fleet management, logistics & incentives	5-50^{+}	10-50%$^{+}$	
Voyage optimization	1-10		
Energy management	1-10		

Figure 4-7: Primary options for improving energy efficiency (IMO, 2009)

In response to bustling activity on the regulatory front, design firms, engine companies, and classification societies have performed studies outlining available design options and configuring concept designs. The key purpose of endeavors such as the Green Ship of the Future, a study supported by the Danish Maritime Fund, has been to promote emission reductions through the addition of energy-saving and emission-reducing technologies to an *existing* vessel design. The effects of technology combinations are explored to achieve emission reduction targets. Specific examples of technologies include:

- Water-in-fuel technologies
- Exhaust gas recirculation
- Waste heat recovery
- Scrubber and filter systems
- Advanced propellers and rudder
- Air lubrication system
- Derated, dual-fuel engine
- Shore supply energy
- Slow steaming
- Advanced hull coatings
- Ballast treatment systems
- Waste treatment systems
- Kite-assisted propulsion
- Water-cooled reefer cargo
- Jacket water heated fresh water generator

Insights such as using a large derated engine to improve specific fuel consumption, at the expense of higher capital costs, are also revealed in studies such as that conducted by MAN Diesel.

Nevertheless, past ECD methodologies adhere to the traditional design artifact perspective and thus do not investigate the decision analysis space across the life cycle. The outcome of these efforts is to offer a collection of technologies that satisfy a performance benchmark or budget limit, without attention to temporal and spatial components of the portfolio selected. Dynamism throughout the life cycle remains an open research area.

Life cycle costing

Economic analysis plays a significant role in reaching environmental goals in a least-cost strategy. ECD methodologies have grown to employ life cycle cost (LCC) assessment to estimate expenses arising from design, production, operation, maintenance, and disposal. Life cycle costing is primarily used by the military, construction industry, and public sectors (Woodward, 1997). Fabrycky and Blanchard (1991) suggest three methods for estimating costs: (a) by engineering procedures, (b) by analogy and (c) by parametric methods. For a system such as a ship, over 50% of life cycle costs can be accrued during the operations phase. Because LCC is a forecast of the future, typical efforts include probabilistic techniques and utility assignment to convey uncertainty and risk (Kishk and Al-Hajj, 1999).

Life cycle costing may include externalities that are anticipated to be internalized in the decision-relevant future (Halog and Manik, 2011). Quantification of externalities such as ecological services and societal health risk in a manner that can be expressed in economic units remains an ongoing debate. Calculations can be extremely complex, dependent on economic models, and as data intensive as comprehensive LCA. Life cycle assessments currently do not account for environmental impact in a way that is readily used in life cycle cost-benefit analysis.

Life cycle cost, or more broadly the total ownership cost, is considered the single best metric for measuring the value of resource commitment in the defense industry (NATO, 2009). Knowledge of life cycle cost can be used for the following purposes: evaluation of alternatives and risk; affordability assessment; budget management; development of future expenditure profiles; evaluation of cost reduction opportunities; and streamlining of business processes. As such, this dissertation finds life cycle costing to be a central component of design decision-making under an uncertain policy future.

4.1.1.3 Environmental Decision-Making

Numerous methodologies for handling environmentally conscious product design have been developed, with the goal of managing environmental impact over the life cycle. Quality Function Deployment (QFD) has been readily employed as a methodology for considering environmental criteria while remaining cognizant of customer preferences (Cristofari et al., 1996; Zhang et al., 1999; Mehta and Wang, 2001). LCA techniques are often used to relate environmental impact and identify hotspots. A map of several eco-design tools illustrates the common use of QFD and LCA (Figure 4-8).

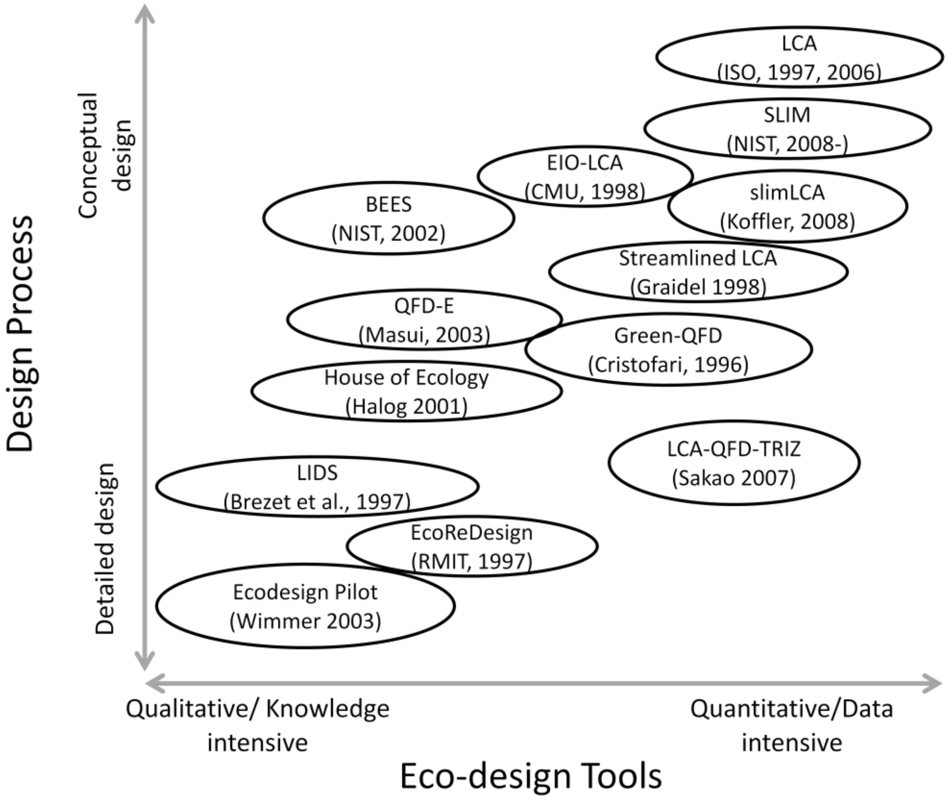


Figure 4-8: Map of current design tools and application to design process (Ramani et al., 2010)

Methods also capture the uncertainty of design embodiments. Bovea and Wang (2003) apply the QFD methodology, incorporating a fuzzy approach to evaluate customer preferences and to determine an environmental index metric that identifies product areas where environmental improvement is desired. Monte Carlo simulation and Bayesian methods have also grown in popularity as tools for analyzing uncertainty of data (Shipworth, 2002).

Multi-criteria decision-making (MCDM), multi-objective decision-making (MODM), and decision-making under uncertainty are all valuable processes for balancing uncertain environmental concerns with other uncertain design criteria, such as cost. For example, Kuo et al. (2006) employ the Analytical Hierarchy Process (AHP) method and fuzzy multi-attribute decision-making to both assemble a structure of environmental design indices and select a design alternative. Li et al. (2008) use fuzzy graph theory, AHP, and a clustering algorithm to determine that the modular design of an alternator is recommended as a way to achieve end-of-life objectives. Thurston and Srinivasan (2003) use a constrained optimization formulation to determine the optimal energy portfolio mix for a region. Wang, Zmeureanu, and Rivard (2005) use multi-objective genetic algorithms to optimize the design characteristics of a building.

4.1.1.4 Limitations in Sustainable Design Efforts

The previously mentioned efforts of sustainable design in the shipping community maintain one or several of the following characteristics:

- A global fleet perspective
- Modification of a previously designed ship
- Limited comparison of disparate concept designs
- A traditional viewpoint of the design artifact

These observations expose the limited applicability of current research to holistic design. Conclusions regarding efforts to date are summarized below.

The fleet-wide perspective does not readily offer decision-making help for a designer conducting early stage ship design.

The outcomes of global shipping studies and similar fleet level reports are of great value to policymakers and of limited value to technical decision-makers. Policymakers can utilize the analysis as justification for or against a proposed policy option. Ship owners, operators, and designers improve their understanding of shipping's role in the sustainability debate, the expected options for reducing environmental burden, and the approximate size of impacts. The research has widely communicated the benefits of specific technologies, though design drivers have yet to be clearly revealed and quantified in terms relevant to a decision-maker. The reports do not widely *differentiate* how a ship of a specific type, size, and route is expected to be constructed and operate. Furthermore, no advice is provided on how to trade-off initiatives that are not mutually exclusive.

While global fleet studies suffer from issues of aggregation, in-depth case studies suffer from a constrained design space.

Published case studies regularly posit that existing designs require only minimum modifications to achieve sustainable performance. Kemp (2000) determines that the most common responses to regulation are incremental innovations in the form of end-of-pipe solutions and non-innovative substitutions. In fact, arguments in complex system communities state that green design requires a paradigm shift and a "clean sheet." Future design does not need to simply be an extension of the past. Without surveying the full design space, innovative responses are not expected or possible. Greater discussion is warranted between lower-risk, end-of-pipe solutions and higher-risk but potentially more satisfying design solutions.

Ship sustainability research does not differentiate between environmental impacts committed and environmental impacts incurred.

A vessel is not committed to a specific environmental profile unless sub-systems or components are entirely unchangeable. Execution of a design only locks-in the production-related impacts; thereafter, impacts are a function of how the vessel is operated. As an extreme example, is an energy-inefficient vessel that never leaves port environmentally conscious? Here, impacts are only incurred if the ship consumes fuel while sailing. An alternative example is a "clean" vessel which is not maintained properly or tuned for the ship's operational profile, thus becoming "dirty." These examples highlight that use impacts are dynamic and a function of operating decisions. Current sustainability research does not actively explore trades between decisions regarding design variables and operations. A view of sustainability as a constraint rather than an active trade in the design process constrains the design space prematurely.

The reports do not offer advice on when to best adopt technical and operational initiatives.

Consider the objective posed by Green Ship for the Future: achieve a 30%, 90%, and 90% reduction in CO_2, NO_x, and SO_x emissions, respectively. Current regulations do not require such a decrease, though the targets are not too far off expectations of containership designs in 2020. The recommendation of the report is to construct a vessel equipped with numerous low-energy and emission-reducing technologies well before the future enforcement date. All suggested equipment improvements are deemed technically feasible today.

So why do vessels leaving the shipyard today not resemble the proposed design? The answer lies in both the objectives and assumptions of the study. Despite recognition of the important role economic analysis serves in determining strategy for achieving the goals of the military and commercial owners and operators, design decisions are not readily packaged in a multi-criteria decision-making context. The study fails to consider that a ship manager may prefer to exercise an option as the enforcement date approaches or when differentiation is identified as value-adding. There is an inherent failure to appreciate that the design artifact can change through retrofits, latent switch-overs, and modular system exchanges as environmental and economic conditions present themselves.

Furthermore, previous studies fail to discuss, evaluate, and plan for the implications of a policy *change* during a vessel's life cycle on a ship designer's strategy. New shipping regulations for sulfur context are still thirty times less stringent than long-haul trucks in the United States. Innovative solutions still undiscovered may transform the industry. Additional information and acceptance of the threat of climate change may spawn further regulations. A value proposition of cost-competitiveness may no longer satisfy sustainability-oriented supply chain partners. An assumption that the current policy plan will remain unchanged may prove irresponsible given the active use of policy instruments over the last decade.

4.1.2 Engineering Systems Analysis

While design is often perceived and communicated in technical terms, decision analysis and optimization are two underlying frameworks for realizing the set of design variables desired by a decision-maker (Cooksey & Mavris, 2011). The purpose of environmental or policy analysis in conceptual design is to (1) determine if the investment is a go or no-go decision, and (2) identify and capture high impact performance enhancements despite low fidelity and high uncertainty of a model. Components of a decision model include the stakeholder perspective, objective function, time horizon, definition of failure or success, cost and utility values, uncertainty level, and the decision variables themselves. Specific methods for deriving and modeling several of these components are discussed in the next sub-sections.

4.1.2.1 Objectives

Three primary economic concerns are typical to decision-makers involved in system design: cost, risk, or a combination of cost and risk. The former two concerns often result in minimization objectives, while the latter involves a balance among the two minimizing objectives. A cost-averse decision-maker will not be willing to pay a premium for risk reduction. Risk, in this context, is a broad term meant to describe the {probability of occurrence, degree of consequence} set pertaining to a policy change, a technical failure, or similar complication. A risk-averse decision-maker may be willing to incur significant cost to reduce potential impact. Risk increases with importance as more human lives are concerned and the magnitude of potential loss increases.

4.1.2.2 Uncertainty

Risk is derived from uncertainty of the future. Consideration of the future requires definition of the physical, natural, market, policy, technological, and operational environments (Walton, 2002). Uncertainty in the physical and natural environment relates to interactions between system components and themselves or interactions with hazards outside the system boundary. At the systems level, uncertainty is associated with the proper integration of sub-systems. Market uncertainty is derived from a lack of knowledge of competitor moves, financing conditions, supplier and client relationships, and a willingness to pay for product or service. Technology uncertainty pertains to component reliability, development and obsolescence schedules, technology diffusion, and future innovations. Operational uncertainty includes the element of human interfacing. Policy uncertainty, the primary focus of this dissertation, considers new, strengthened, or abandoned regulations and goals set forth in private or public sphere at any array of spatial levels. Uncertainties also compound on one another. For example, if a perceived market is unaddressed through current options following a policy change, the industry may be ripe for a technological innovation.

Uncertainty is also characterized by varying levels of depth. Donald Rumsfeld, former Secretary of Defense, delivered a now infamous statement regarding uncertainty depth:

> *[T]here are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns – there are things we do not know we don't know.*

Known unknowns may be categorized by their lack of stakeholder expertise, lack of definition, or as statistically quantified phenomena. Known unknowns can more readily be modeled via probability and utility functions. Decision trees and influence diagrams illustrate options available to a decision-maker and the respective uncertainty associated with each option. The amount of uncertainty is likely to increase for events that take place further in the future.

4.1.2.3 Architectural Lock-in

The design phase lacks knowledge of future events but stands as the place for cost- and performance-impacting decisions. The design paradox lies in the fact that decisions must be made to gain knowledge about a particular design, yet those decisions result in a loss of design freedom. Design knowledge is low and design freedom highest during the conceptual design phase, yet upwards of 70% of costs may be committed at this stage. Mavris et al. (1997) illustrate cost and freedom lock-in across the life cycle via Figure 4-9.

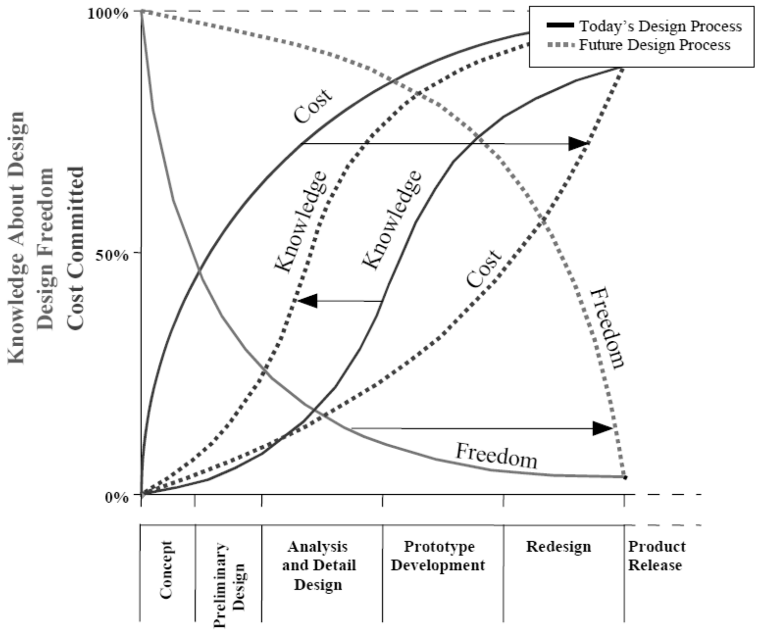


Figure 4-9: Decision lock-in via knowledge-freedom-cost relationships (Mavris, Baker, & Schrage, 1997)

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 early stage design proves to be the life cycle stage where decisions are likely to have the greatest impact on total cost. A poorly conceived artifact serves little opportunity for efficient improvement during later phases of life cycle activity.

The objective of a strategic framework is to analyze the uncertain, future, time-dependent phenomena of a product’s service life and to communicate the effects of decisions as early as possible in the design process. Strategic plans can choose to utilize modular architectures (extend design freedom), reduce foreseeable “surprises” (reshape cost curve), and offer rapid learning of the design space while still in early stages of development (shift knowledge forward).

This dissertation seeks to continue efforts that shift knowledge forward by exploring decisions related to lock-in. Understanding where lock-in occurs and the degree of changeability in the face of lock-in is the primary objective; offering means to reduce lock-in is a secondary objective.

4.1.2.4 Valuation Methods

The time-value of money is also to be considered in cost calculations. Discounted cash flow analysis (DCF) is one method to remove time from explicit consideration of dynamic decisions. The technique calculates an equivalent present value for all monetary costs and rewards of expected future events. The discounting theory assumes a decision-maker values a good more highly in the present than the same good at a future point in time. The premium with which the decision-maker values the present option determines the discount rate.

Net Present Value (NPV) analysis employs a constant discount rate to calculate the costs and rewards of future monetary streams. The equation for exponential discounting is presented below:

$$NPV = \sum_{t=0}^{N} \frac{Rewards_t - Costs_t}{(1 + Discount\ Rate)^t} \qquad [4\text{-}1]$$

where costs and rewards are calculated for period *t* up to the total number of periods *N* comprising the study. NPV is sensitive to even small changes in the discount rate selected, and a higher discount rate signifies more importance is given to the near-present. A nominal discount rate may be used to account for projected inflation, deflation, and interest rates in future values. The American Society for Testing and Materials (ASTM 1983) allows for the reflection of different inflation rates for specific cost and benefit categories.

Two primary shortfalls have been noted in net present value techniques.

1. *Reliance on a subjective discount rate*. Future cash flows are contingent, and factors such as interest rate and market risk that are inherent to a discount rate can fluctuate. Dixit (1994) reports that managers often select a discount rate that offers the most favorable picture of their preferred solution. Manipulating the answer only gives an illusion of objectivity and constrains the design space prematurely.
2. *Failure to account for flexibility*. NPV analysis may undervalue long-term projects since managers often have the ability to influence future actions once a decision is made. New information or unexpected outcomes may lead to the determination that a response action is desired.

Use of Monte Carlo analysis and decision tree analysis (DTA) in conjunction with NPV can soften the inflexibility claim. Monte Carlo analysis also accounts for uncertainty by exploring many possible pathways for uncertain variables. Monte Carlo simulations discover the behavior of a stochastic system by conducting a large number of random trials. The expected valuation is then simply the average discounted sum of the results. DTA constructs a series of future decisions that may be executed and attaches probability estimates to uncertain events. De Neufville (2004) states that decision tree analysis is valuable when important variables do not have a price history. Probability estimates within the decision tree become more subjective with higher levels of uncertainty in both exogenous and endogenous events.

Real options analysis, an alternative to DCF, explicitly values flexibility during investment projects. The approach uses option pricing theory borne out of the finance world to value non-financial, or real, options. An option is typically described as the ability, but not the obligation, to exercise an action that takes advantage of a future opportunity. The logic behind the method is that a manager is wise to wait for more information before executing a decision under large levels of uncertainty. Real option tools assess value in projects with uncertain future cash flows derived from the ability to expand, abandon, or re-tool an investment. The theory uses a different discount rate due to the increased level of perceived risk for an option. Real options analysis is especially suitable where extensive data on the price and standard deviation of an asset exists. Again, Monte Carlo analysis is useful when an option is simultaneously dependent on the price of several assets or variables.

To date, most research effort in the field has been expended on valuing the option itself, leaving actual decision-making to another method. An integrated framework that enables exploration of the design space using real options remains an open research need, attempting to answer questions of (a) what type of flexibility, if any, is desirable, (b) where flexibility should be implemented, (c) when to implement, and (d) how to value the non-market factors.

4.1.2.5 Historical accuracy of valuation

The complexity involved in predicting the consequences of a policy results in two camps of individuals: those who believe costs are over-estimated and those who believe costs are under-estimated. Overvalue claims stem from the fact that policy adoption spurs technological innovation and renders existing cost models obsolete. Historical reviews of the 1974 U.S. proposal to limit exposure to vinyl chloride and the 1990 sulfur dioxide mandate reveal that costs were wildly overestimated (Hodges, 1997). Financial ruin, factory shutdown, and a loss of global competitiveness have not occurred despite passionate claims of what would result if the regulations passed. Reliance on industry predictions, where arguments against environmental policy can be strategically useful, introduces bias into the policy debate.

Conversely, those who believe policy costs are underestimated tend to trace economic linkages. Concern of higher costs can discourage investment or result in job losses. Regulations can require increased product oversight, which can distract managers from perceiving other industry trends while tending to a disturbance. New organizational processes can result in schedule delays, which both destroy margins and impact a firm's image. Long-run social costs are discovered to exceed direct compliance expenses by 30-50% (in Weimer, 2008; via Hazilla and Kopp, 1990, and Jorgenson and Wilcoxen, 1990).

4.1.2.6 Optimization

Optimal decisions can be easily drawn when all information is available. The classic formulation for life cycle benefits is commonly written as

$$B(\boldsymbol{D}) = \int_0^T b(t, \boldsymbol{D})\gamma(t)dt \qquad [4\text{-}2]$$

with the total benefits accrued *B*, life cycle time *T*, single period benefit *b*, single period time *t*, decision set **D**, and discount rate γ. A decision-maker would then select a set of decisions that maximizes life cycle benefits. Nishijima et al. (2004) provide inclusions for multiple decision-makers, of which some are in the future, to directly account for the inter-generational and intra-generational principles inherent to sustainable decision-making.

However, rarely is deterministic life cycle analysis realistic. Traditional decision analysis under uncertainty considers the decision that maximizes expected value to be the optimal one. Expected returns are calculated by summing the product of payoffs in each state and the probability of the state occurring. The sum of the weighted payoffs across *S* number of states is typically represented by the following equation:

$$\text{Expected Payoff(Decision } i) = \sum_{j=1}^{S} \text{Pr(State } j) * \text{Payoff(Decision } i \text{ in State } j) \qquad [4\text{-}3]$$

Under conditions of ‘deep uncertainty,’ conservative methods such as info-gap theory and robust optimization are suggested. Knightian uncertainty, colloquially defined as deep uncertainty, is often described when stakeholders cannot agree upon the action-consequence set, prior probabilities, and/or value functions necessary to modeling. Info-gap theory selects decisions that are most satisficing or require the least uncertainty for a target outcome to be achievable. The decision rule is a function of whether the decision-maker elects to optimize for robustness or opportuneness. Info-gap decision theory is considered *local* in that a starting estimate must be provided upon which sensitivity is then conducted. The universe is considered fixed during info-gap analysis, and so the theory is still not robust to unexpected events.

Robust optimization also often adheres to the non-probabilistic max-min model, though it prescribes a global approach that incorporates the total uncertainty region. Robust decision-making (RDM) characterizes an uncertain decision problem with multiple views of the future and aims to reduce variance even if at the slight expense of deviating from the expected optimum. RDM foregoes first describing uncertainty (the predict-then-act approach) in favor of a vulnerability-and-response framework. The framework distinguishes uncertainty in the context of a decision, not alternative options.

Other formulations of decision-making optimization under uncertainty include minimizing the maximum regret, the Laplace criterion, and Hurcwicz criterion. These methods are also often employed when probabilistic methods are unavailable.

Given the varying degrees of uncertainty, a decision-maker should be careful to draw conclusions stemming from optimization and know that one is inherently accepting a bias when attempting to find an optimal solution in a dynamic world.

4.1.2.7 Considering the Future

Developing a strategy to navigate an uncertain future is no simple task. Forecasting, backcasting, and foresighting are all approaches that can be used in one form or another to aid in decision-making. The objective of each approach is to reveal important information about conditions beyond the control of a manager but which may impact the future value of a product or process. The information can be utilized to acquire an advantageous position or prevent loss and missed opportunities. Any portrayal of the future is derived from elements rooted in analogy, theory, reason, speculation, expert opinion, or past performance (Loveridge, 2009). Each futures studies approach has its advantages and shortfalls.

The traditional technique of choice by modelers is forecasting. Forecasting predicts future events and conditions based on an extrapolation of knowledge of the present state. Data availability is a prime reason for employing a forecast. Researchers generally specify four categories of forecasting: qualitative methods, time series methods, causal methods, and simulation. Causal methods may prove to be the most informative due to their physics-based approach, but the actual underlying mechanisms are often arcane or too time-consuming to derive. Estimating the accuracy of the forecast is of equal value to a decision-maker as the details of the forecast itself. Uncertainty in the model, inputs, and unknowns cumulatively impact forecast accuracy.

Backcasting is the converse of forecasting, as its name implies. A specific future goal point is identified, and the method walks backwards from this state to the present conditions, if possible. The approach signals the feasibility of the goal point as well as the necessary, possibly transformative, actions that must occur to achieve it. Backcasting is particularly useful when deploying cost-effectiveness analysis. Cost-effectiveness analysis can be used to sort available options and devise a blueprint for achieving the backcasted target.

While forecasting is generally viewed as a passive attempt to predict the future, foresighting can be described as more active, decision-shaping, and strategically minded (Figure 4-10). This dissertation prescribes to the foresighting viewpoint so that active management can occur, and the methodology introduced in the next chapter is structured to help with strategy-making under uncertainty.

Foresighting includes qualitative and quantitative means for monitoring indicators of evolving trends (Coates, 1985). Scenarios—rich, internally consistent narratives built around carefully constructed plots of the future—are often considered a tool of foresighting. Robust analysis relies on scenarios to discover vulnerabilities. The role of scenarios is to assess possible consequences of actions, to anticipate events before they occur, to consider the present implications of possible future trends, and to envision desired aspects of future societies. Scenarios are characterized by their breadth, level of aggregation, degree of quantification, time length explored, function, and representation. Detailed analysis of individual decisions is generally not conducted and still requires the use of probabilities to ultimately translate learning into information useful to a decision-maker. Thus, foresight and scenarios are only two components of planning, serving to prepare the landscape for decisions concerning the future.

Foresight	Forecasting
• Basic points, needs, research questions are still open and looked for as part of the foresight process	• Basic points, topics and research questions have to be clarified in advance
• More qualitative than quantitative	• More quantitative than qualitative
• Looks for ‘information’ about the future for priority-setting	• Questions what the future in the selected area might look like
• Brings people together for discussions about the future and for networking, makes use of the distributed intelligence	• More result-oriented can also be performed by individual people or in single studies (depends on methodology)
• Criteria for assessments and preparation for decisions	• Not necessarily assessments, different options and choices or the preparation for decisions
• Communication about the future as an objective	• Describes future options, results more important than the communication aspects
• Long-, medium-, and short-term orientation with implications for today	• Long-, medium-, and short-term orientation as well as the path into the future are the major points
• Finds out if there is consensus on themes	• No information about consensus necessary
• ‘Experts’ and other participants, very dependent on opinions	• Mainly ‘experts’ and/or strict methodologies, less dependent on opinions

Figure 4-10: Comparison and contrast of foresight vs. forecast (Cuhls, 2003)

Forecasting tends to focus on trend analysis, while scenario planning often purposely allows for emerging issue analysis. The environmental policy initiatives affecting the ship industry and at the heart of this thesis are examples of emerging issues. Trend analysis identifies an important fact in the present, regresses its historical development, and then casts the rate of development ahead into the future. Time series methods readily employ data documenting cyclic variations and trends to extrapolate into the future. Yet, fitted data is known to represent correlation and not necessarily causation. A trend can also be interrupted, and this interference may be described as an emerging issue. Trend analysis investigates the history of development of a product, process, or social norm, while emerging issues analysis focuses on its surfacing and thus cannot be represented through historical facts. Futurists who build scenarios tend to be most on the lookout for emerging issues.

Linking environmental policy to design decisions requires a blend of forecasting and foresighting techniques. A strategic decision-maker actively plans for emerging issues but applies quantitative metrics in his or her actions. This dissertation relies on foresighting to understand the potential for policy change and for identifying cost-reward implications to design, for policymaking is not always gradual. Nevertheless, a quantitative, results-oriented focus is then applied to discover action sequences for managing these implications. A decision-maker cannot overlook the power of forecasting to orient decisions today and to chart a path into the future.

4.1.2.8 Responding to uncertainty

Strategic planning involves the creation of a vision for a process or product, within the broader context of a company's goals, and the allocation of resources deemed necessary to achieve this vision. The use of the term *strategy* conveys an active set of responses. When uncertainty does reveal itself, or when a decision-maker elects to buffer against uncertainty through additional action, the response mix can be distilled into a number of general categories (Table 4-1). A decision-maker who fails to consider the ability to act potentially increases program risk and fails to capitalize on opportunities that may present themselves.

The actions contain both spatial and temporal elements. Each action may also require a non-insignificant time to complete as well as fail in execution with a non-zero probability.

Table 4-1: Set of common actions and example intended outcomes of each response

Response	Sample Outcome
Repair	An under-performing pump is fixed
Replace	A failed sensor is removed; a functioning version of the same sensor is installed
Relocate	A ship is designated for a new route
Reconfigure	The deck of an aircraft carrier is transformed to aid in a humanitarian missions
Upgrade	An obsolescent weapons software package is re-tooled, improving performance
Expand	An additional auxiliary generator is installed to satisfy increasing energy demand
Contract	The number of crew members onboard is reduced 10%
Delay	A planned underwater drilling is postponed until energy prices rebound
Terminate	A vessel is mothballed during an economic recession
Extend	A nuclear power plant on a submarine is refueled

4.1.2.9 Opportunity Windows

Rogers (1962) popularized the concept of a diffusion curve in his theory on adoption rate of technologies (Figure 4-11). The generally accepted definition of diffusion is the process by which an innovation is communicated through channels over time among members of a social system. Communication can occur in the oral form or through actions such as consumerism. Diffusion theory is derived from disciplines in anthropology, sociology, education, communications, marketing, economics, geography, and medicine (Grubler, 1990). In the case of this research, an innovation may be construed as a technology perceived as new and available for adoption. Numerous environmental technologies that have been available for decades, though limited in maturity, could still be viewed as novel given the context change caused by a shift in the policy landscape.

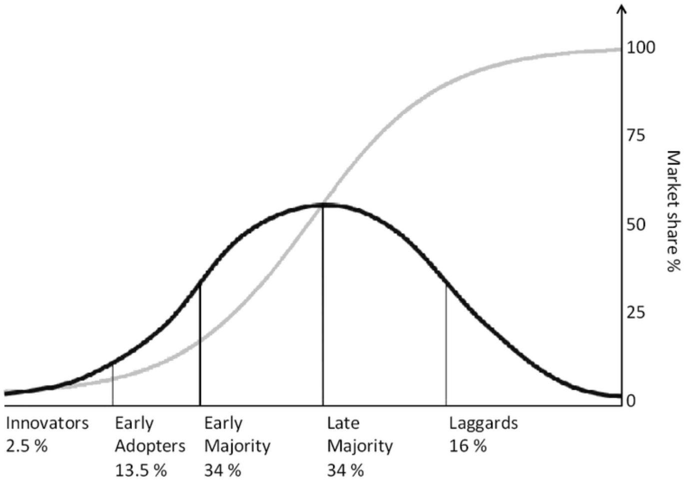


Figure 4-11: Standard diffusion of innovations curve; dark curve represents probability density function, light curve the cumulative distribution function (Rogers, 1962)

The diffusion curve relates to social systems or products in free markets. Policy in the form of a regulatory limit can re-shape the curve. If natural diffusion has not been given ample time, an authoritative decision may force the majority and laggards into adoption much sooner and the predicted logistic curve is no longer applicable. Innovators and early adopters, by adopting newly mandated "best practices" prior to regulatory enforcement, may be capable of taking advantage of market opportunities if they exist, are identified, and are balanced against potential risks. Figure 4-12 highlights the difference between natural and artificial diffusion resulting from policy enforcement. The length of time, magnitude of rewards, and number of players who can take advantage of an opportunity are altered due to policy transformation.

The window of opportunity for capturing a market advantage diminishes as novelty wears off and further innovation occurs. For complex systems where several components possess their own diffusion curves, "best practices" can continually evolve. For example, the Leadership in Energy and Environmental Design (LEED) rating system developed by the U.S. Green Building Council awards credits for inclusion of building characteristics that are present in the top 25% of the general building market. Each new building that is LEED certified sets the "best practices" bar higher, challenging the industry to push the envelope on the state-of-the-art in environmental design. For the ship industry, diffusion of ideas or technologies may cascade from ocean-going trans-Pacific vessels to coastal ships in Europe or from bulk carriers to high speed ferries. Collective diffusion is never in equilibrium, and the next innovation often develops during the saturation phase of the previous innovation.

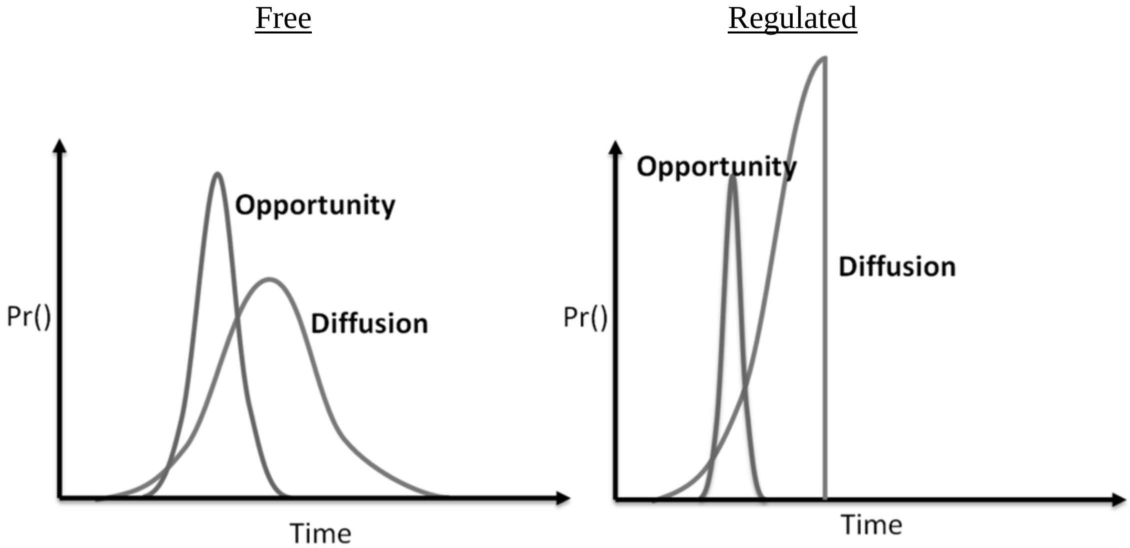


Figure 4-12: Overlay of diffusion curve with opportunity curve for free market environment (left) and regulated environment (right)

Diffusion of an emerging technology also has implications for the cost of products. The increase in efficiency and decrease in cost is described by the experience curve. Increasing demand results in knock-on effects of labor efficiency, equipment utilization, standardization, and specialization. These effects can reduce the cost of manufacturing, and cost savings may be passed on to customers. Increased experience is also likely to improve technical performance and reliability. Higher quality and technical parameters lead to additional sales, repeat customers, and greater market share. The result of the experience curve is a positive feedback mechanism if learnings are implemented properly.

4.1.3 State of the Art: Change Management

Including provisions that manage a dynamic, uncertain context is not a new research thrust; however, the research space is also far from mature. Several methods have been suggested to model change options, all of which include some provision for uncertainty, valuation, and other analysis tools highlighted in the previous section. The following section provides a literature review of proposed change management techniques, addressing limitations with certain approaches where relevant.

4.1.3.1 Networks

The use of networks and matrix linkage techniques present static representations of the system while demonstrating feasible transition paths. Potential change options are a function of the current configuration of the artifact.

Silver and De Weck (2007) propose the use of a Time-Expanded Decision Network (TDN) to study switching costs and optimize system selections. Point designs are first identified and transitions from one system configuration to another are drawn where technically feasible, forming a static network of nodes and arcs. Switching costs, or the expenses required to re-configure the originally selected system, are estimated and attached to directed arcs in the network. Concurrent consideration of design and operational changeability is not considered.

The element of time is introduced to form a dynamic decision network problem. The time-expanded static network involves a duplication of the original network for every time period under investigation. In addition to switching cost, traversal time can also be quantified. Each point design is split into a chance node and decision node to appropriately account for transversal time and to decouple operations from transitions. Chance nodes exist to model the network under a variety of probabilistic demand scenarios. Full representation of a TDN is provided in Figure 4-13. An optimization model is constructed and run under these demand scenarios to identify best point designs and transition sequences. The aim of Silver and de Weck's (2007) research is to determine where switching costs are incurred and the sensitivity of system selection to various switching costs.

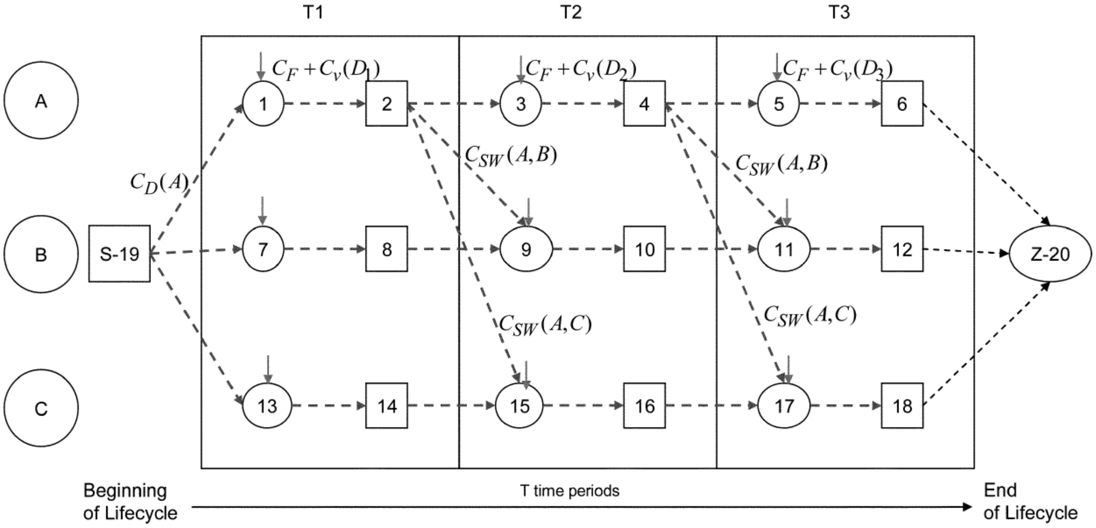


Figure 4-13: Time-expanded decision network representation with chance and decision nodes (Silver and de Weck, 2007)

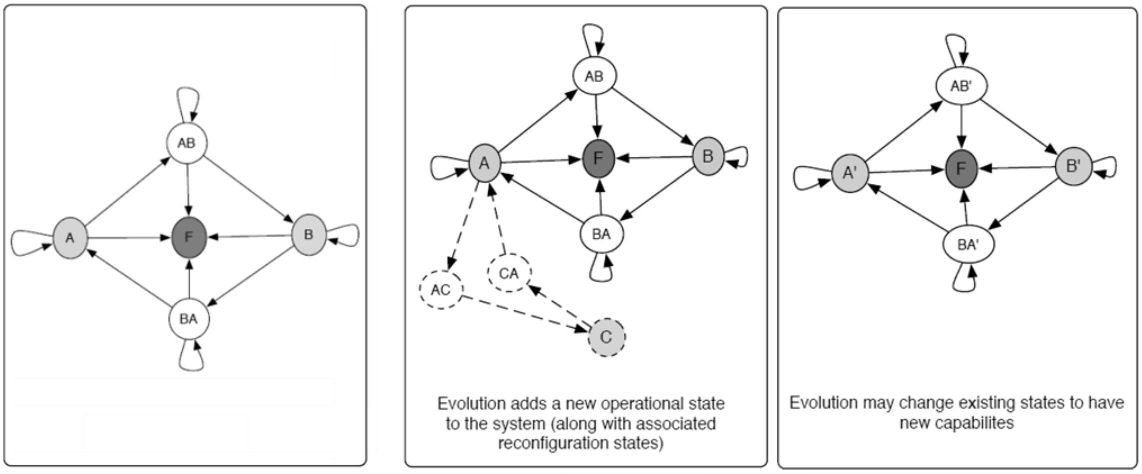
Silver and de Weck's use of TDNs do not aim to account for three aspects important to gaining an understanding of the effects of policy change on a design:

1. TDNs are not constructed to represent important non-physical or abstract states such as performance level, product availability, compliance status, etc.
2. TDNs are not constructed to account for new or broken state-to-state linkages that may occur as the network is traversed. Similarly, all transitions are modeled as deterministic.
3. The decision-maker does not readily relate what actions are necessary to change states. For example, the research does not distinguish between modifications to rocket booster, launch pad, or external fuel tank. Understanding action drivers is manual and piecemeal.

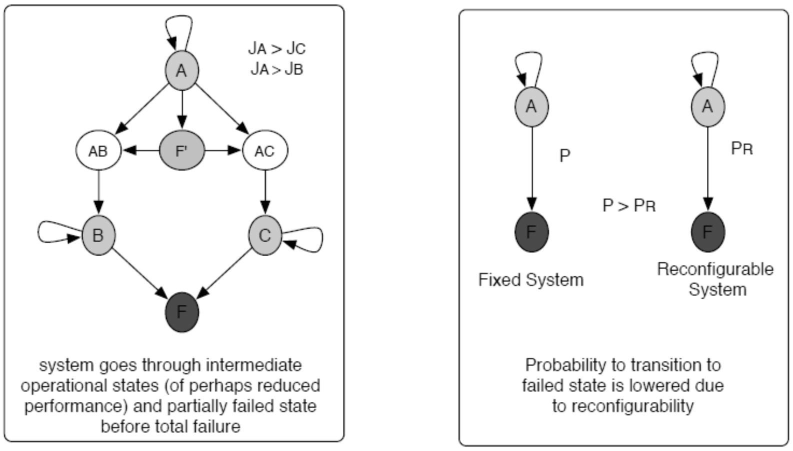
Siddiqi (2006) explores the concept of reconfigurability, a sub-concept within the changeability space. Reconfigurability is defined as the capacity for low-cost, dual-direction changes in order to adapt to new conditions. As opposed to the role of evolvability at the system architecture level, reconfigurability tends to represent a single instantiation of a design artifact with modified subsystems. The capacity to be reconfigurable is often associated with detailed upfront attention to process and layout as well as higher levels of complexity.

Siddiqi’s (2006) research suggests employing a Markov chain failure model plus network control theory to handle reconfigurable systems. A Markov process is a probabilistic model that includes state and state transitions, where in this case, the state nodes represent either operational or reconfigurable representations of a system. Figure 4-14 outlines three forms of reconfigurability (multi-ability, evolvability, and survivability) and their implications for Markov modeling. States with a single letter represent operational states, two-letter states are those representing reconfigurations, and state *F* represents the failure state. States do not contain explicit details of the design characteristics. Optimization of design states are conducted using physics-based models and task-based information. Control theory is then applied to distinguish between on-line and off-line reconfigurations. Siddiqi quantifies change capacity in a Planetary Surface Vehicle, determining the optimal configurations of the vehicle according to three known task needs. The author does not investigate and present the changes required to achieve reconfigurability.

Qualitative conclusions regarding provisions to lower switching costs are related by Siddiqi (2006) as well as Silver and de Weck (2007). Embedding extra margins, inclusion of interfaces for expansion, and standardization are proposed as possible solutions for reducing changeability.



(a) Multi-Ability (b) Evolution



(c) Survivability

Figure 4-14: Network representation of multi-ability, evolvability, and survivability (Siddiqi, 2006)

4.1.3.2 Tradespace Analysis

Ross (2006) proposes an approach known as Dynamic Multi-Attribute Tradespace Exploration (dynamic MATE) and includes dynamism through the use of Epoch-Era Analysis. The *tradespace* is often represented as a two dimensional plot of cost and utility that is parameterized from attributes and design variables. *Epochs* are described as time periods where the context (physical and environmental) and the value expectations are fixed. Additionally, an epoch is characterized by static constraints, transitions between design concepts, and utility functions. An *Era* is the compilation of multiple epochs. Context changes can trigger the start of a new epoch, upon which stakeholder value expectations may change. A decision-maker may determine that a system change is necessary to sustain value. The Epoch-Era formulation is described by Ross:

> *[Figure 4-15] illustrates the temporal evolution of a system as needs and contexts change. A system exists in Context 1 in Epoch 1 and has performance exceeding expectations. Expectations are represented by a band capturing the range from minimally acceptable to the highest of expectations. In Epoch 2, the context changes to Context 2 and the system when entering this context finds its performance is degraded. Yet, expectations are still met with the same system, so the system is relatively robust to the change in context. A change in expectation is shown in Epoch 3, with the context remaining the same as the second epoch; now the still unchanged system exhibits value robustness since it maintains value delivery in spite of changes in expectations. In Epoch 4, the system shows versatility by continuing to satisfy expectations despite the introduction of a new metric of need. Notice that even though the system no longer exceeds all expectations, it still does exceed the minimally acceptable level and thus is still successful. Finally, in Epoch 5, a change in context and a boost in expectations are too much for the system as-is; in this case the system must change in order to remain successful.*

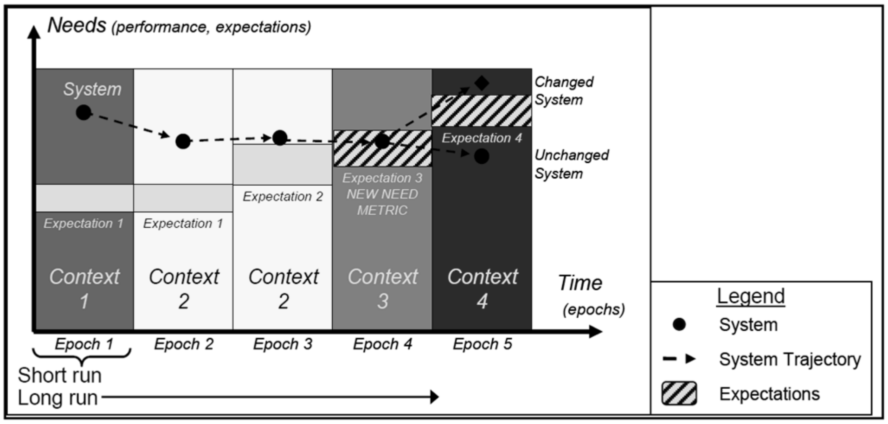


Figure 4-15: Epoch-era representation of system performance (Ross, 2006)

A series of epochs are bundled together to create a plausible era scenario, and the storyboard serves as the dynamic impetus for change. Ross and Hastings (2006) define a tradespace network as both a static tradespace representation as well as possible transition paths that result from changeability of the system. An accessibility matrix is utilized to identify the effect of transition rules in each epoch. The best path is selected according to the strategy specified by the decision-maker, such as maximum utility or minimum cost. Thresholds on switching cost and change time are included to constrain available options according to stakeholder preferences.

Insights are gained into how robust a design is to preference changes of a decision-maker and the need for flexibility to satisfy a decision-makers evolving objectives. Value robustness and changeability are measured using a Pareto Trace number and Filtered Outdegree metrics, respectively. The dynamic MATE setup is only exploratory and does not seek to optimize. Ross (2006) acknowledges path dependencies can preclude accessibility to the best overall state if an era-long perspective is not held, but does not attempt to illustrate or quantify such lock-in.

Detailed economic analysis is not conducted. A focus is placed on understanding utility change (pg 233, Ross, 2006), and design costs are not altered in the portrayal of the cost-utility tradespace with the existence of “path-enabling variables” (pg 165, Ross, 2006). Additionally, no formal method for understanding the design characteristics of systems on the Pareto front is employed. Manual inspection of the particular properties is suggested.

Depth of economic analysis in tradespace exploration is conducted by Nilchiani (2005). The author calculates the extra benefits received versus the extra cost of added flexibility as compared to a baseline design. The decision to add flexibility must balance how much to invest in de-coupling functional elements during design versus waiting to adapt later in the life cycle (Ethiraj and Levinthal, 2004). For example, de Weck and Suh (2006) estimate a 30% premium on the capital cost of developing a flexible car platform versus a rigid model. Nevertheless, the addition of flexibility to the system upfront can serve to reduce the switching cost of decisions that attempt to manage reliability during use. A component with a short lifespan or subject to technological obsolescence, such as consumer electronics, represents an opportunity for the larger system to install "plug and play" design flexibility.

Research by Weigel (2002) uses tradespace analysis to study the political sustainability of a government program given a new policy or evolving budget constraints. Cost estimating relationships are derived and implemented in a tradespace formulation to quantitatively derive the cost and risk impacts posed by a new policy on various concept designs. Sensitivity techniques are applied to diagnose the robustness of system architectures to downward budget pressure. Real Options are explored as a means to accommodate policy instabilities and value design for policy change.

4.1.3.3 Capital Asset Pricing Model

Where Real options analysis focuses on the upside of uncertainty, the application of portfolio theory has been utilized in instances where understanding downside risk is important in conceptual design. Walton (2002) considers the degree of risk aversion of a decision-maker to construct a portfolio of high-utility space systems. Optimization techniques employing semi-variance and full uncertainty analysis locate the efficient frontier. Walton argues that such research provides strategies that account for non-intuitive aspects of tradespace uncertainty such as systems covariance and diversification. However, Walton leaves open-ended a multi-period analysis that would allow one to understand how to adjust a portfolio as uncertainty changes.

4.1.3.4 Design Structure Matrices (DSM)

Also known as a dependency structure matrix, the design structure matrix (DSM) provides a compact representation of a complex system and interfaces between system elements. Interactions may be component-based, team-based, activity-based, or parameter-based (Browning, 2001). The taxonomy of interactions shown can include spatial, energy, informational, and material associations. Smaling (2005) proposed use of a ΔDSM, a model of only changes to a system's structural representation, to quantify the impact of technology insertion.

A DSM within a Change Propagation Model (CPM) created by the Engineering Design Centre predicts the likelihood of a change propagating from one area to another by counting the number of linkages. Giffin et al. (2009) then employs network clustering to describe the concentration of change requests among components. Metrics for flexibility and optionability are outlined using a Disjunctive Normal Form formula within a logical, coupled DSM model (Mikaelian, 2009). Mikaelian argues a classic DSM cannot represent flexibility and options, tradespace networks generally only refer to aggregate flexibility, and state-based models currently fail to distinguish option types.

4.1.3.5 Reliability-Based Design

Singh et al. (2010) propose a simulation-based design methodology that minimizes life cycle cost of a multi-response system subjected to time-dependent reliability concerns. System cumulative probability of failure is measured using a composite limit state and niching genetic algorithm with lazy learning metamodeling. Production, inspection, and expected variable costs are a function of quality and reliability constraints. In this instance, quality is defined as the probability of conformance to initial design specifications, while reliability is quantified as the probability the system performs its intended function successfully for a specified interval of time. Figure 4-16 illustrates the cumulative probability of failure through time for three design cases. An interesting result is that a restriction on reliability at life cycle end with no constraint on initial quality (Case 3) results in minimal life cycle cost as compared to an instance where quality is constrained.

Similarly, Frangopol et al. (2011) employ a comprehensive time-dependent reliability and monitoring framework to assess the life cycle performance of ship structures. Uncertainty is modeled through stochastic loading phenomena, and application of structural health monitoring techniques reduces uncertainty and improves fatigue performance prediction. Maintenance actions are suggested when the performance index nears a minimum acceptable threshold (Figure 4-17). An optimal inspection schedule that minimizes both damage detection delay and inspection cost is determined.

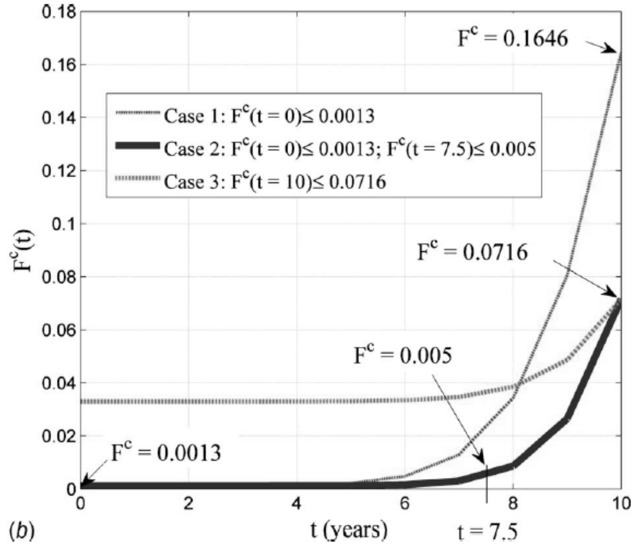


Figure 4-16: Cumulative probability of failure plot through time given various quality and reliability constraints (Singh et al., 2010)

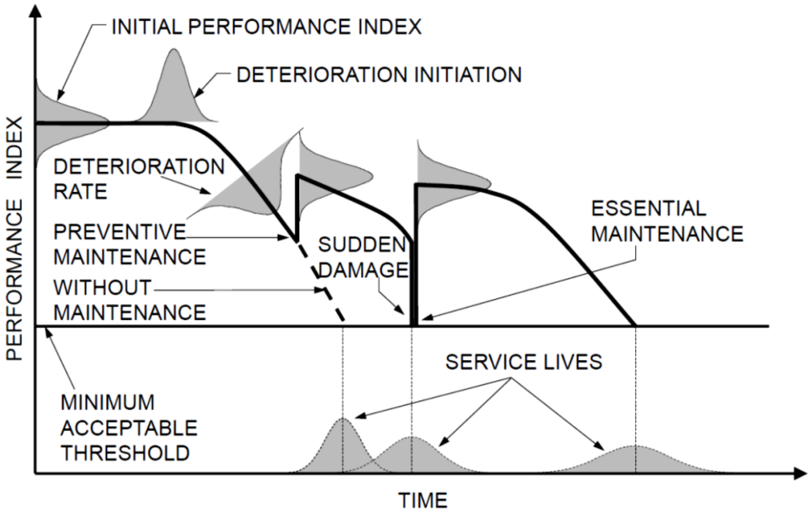


Figure 4-17: Profile of reliability index through time (Frangopol et al., 2011)

4.1.3.6 Game Theory

Notional concepts of project salience and distributive techno-political benefits are considered in a game theoretic formulation by Broniatowksi (2008). Political sustainability of a government program is explored by evaluating the competitive and cooperative actions between Congress and NASA. The author qualitatively illustrates the need to balance new technology with the use of legacy components to structure a strategic program development cycle that accounts for future funding uncertainty.

Briceno and Mavris (2006) encourage the use of game theoretic elements for an engine company positioning their product line in response to the emergence of new engine requirements. The authors explain how a game-based design approach can allow decision-makers to strategically position their core engine design in the presence of competitive uncertainty, with the intent of using a product family to take advantage of emerging markets. The method simulates the emergence of a new requirement, and competing firms—the players—assess potential moves to provide an engine architecture that captures market share and matches client preferences (Figure 4-18). Through this methodology, the influence of present and future market competition on the decision-making process can be quantified and evaluated.

A related approach, though without game theoretic components, is proposed by Coulter and Bras (1997). The authors suggest using a multi-iteration, robust strategy to satisfy forthcoming legislation regarding the recyclability of a fleet of vehicles (Figure 4-19). A decision-maker would use the approach to determine the pace and rigor with which a design would achieve environmental improvements. Several other authors explore changeability in the context of product evolution, learning opportunities, and incremental innovation (Martin and Ishii, 2002; Maier and Fadel, 2001; Simpson, 1998; Sanderson, 1991).

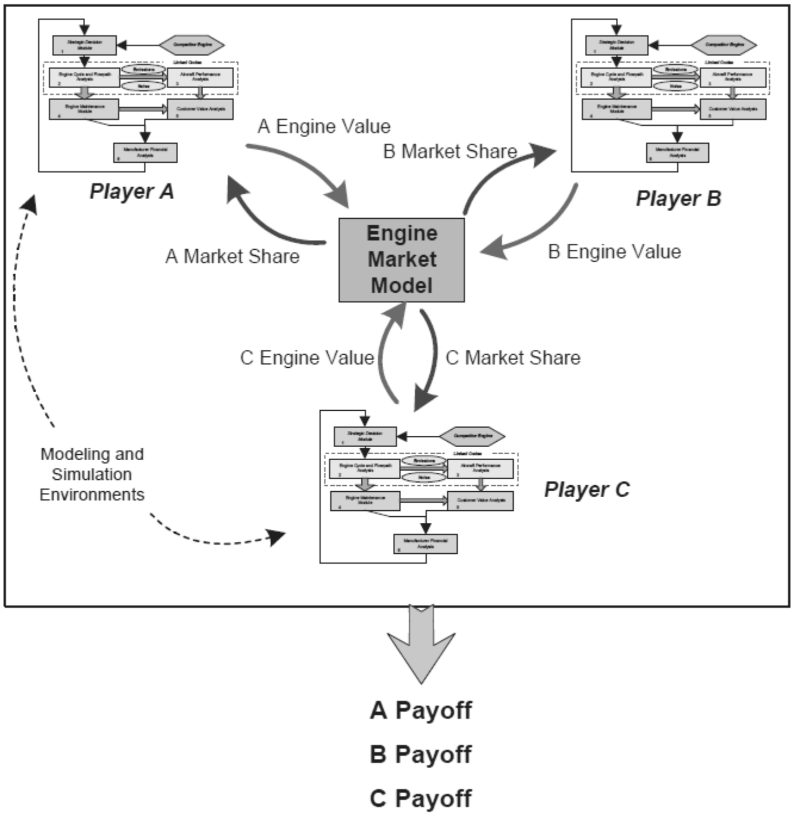


Figure 4-18: Game-based engine design given competitive uncertainty (Briceno & Mavris, 2006)

This research in this dissertation does not consider the ship as one in a line of products or as a member of a multi-cycle product family. Iterations in total ship designs are unlikely for two reasons:

1. A fleet manager is unlikely to desire a set of ships with dissimilar equipment, which is known to increase maintenance inventory and crew training costs
2. Ship life cycles are not insignificant in time and new deliveries are on a schedule of years or months, not hours or weeks; a set of iterations is likely to span a time period that exceeds evolving regulatory limits

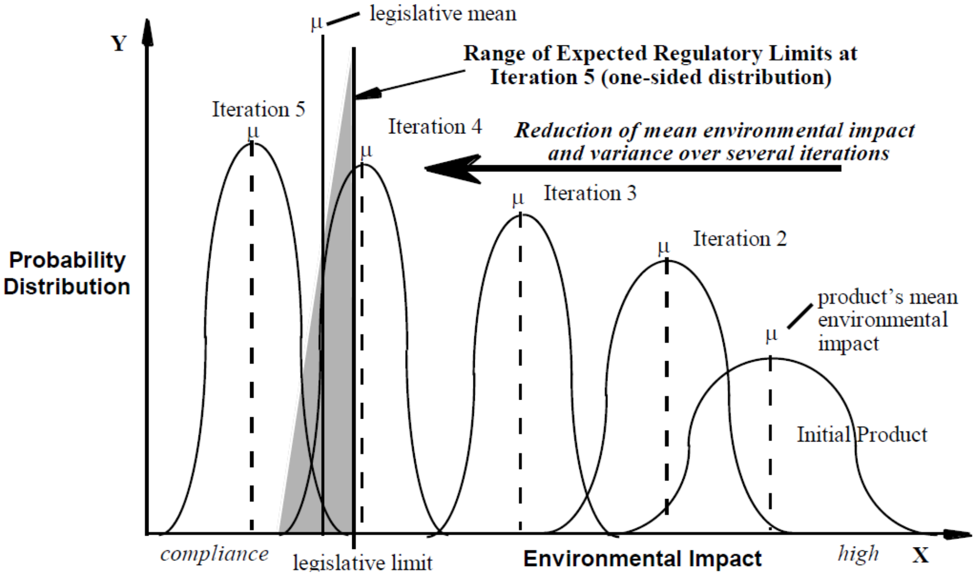


Figure 4-19: Adjustment of environmental impact over product iterations (Coulter & Bras, 1997)

This dissertation does not seek to study how designers influence politics, the economy, or other decision-makers in the shipping industry. Research explores the one-way influence of external factors on the design process. Literature stemming from diffusion of innovations and competitive market advantage is instead employed to capture the self-interested nature of a decision-maker and probabilistically quantify payoff opportunities.

4.1.3.7 Limitations in Change Management

Excellent research has been conducted to rigorously define the primary elements of change management and to incorporate dynamic design concerns. To date, no ship applications and no focus on sustainability has been conducted. The following conclusions relate several gaps in current change management research that prevent ready application to sustainable design.

<u>*Lack of focus on communicating design drivers*</u>

The various methods tend to provide outputs at two ends of the decision analysis spectrum: optimized point solutions and full tradespace exploration. In the former instance, the solution is provided in terms of design variables, which are of direct use by decision-makers. However, these methods—for example, Siddiqi's network research and reliability-based techniques—tend to employ optimization to derive a point solution.

Point-based solutions are known to constrain the design space prematurely and fail to capture the richness of information offered by the wider design space. Conversely, methods that stop with construction of the tradespace do not map learnings back to the design space where managers can readily conduct decisions. Current efforts bridge this gap through qualitative insights and count statistics. This dissertation argues that better handling of life cycle concerns requires elevating the importance of the decision space.

Quantitative-driven synthesis in a form that is packaged for set-based design decisions is a still an elusive end goal. Set-based design (Singer, 2003; Ward et al., 1995) calls for communicating design variables through a more-is-better or less-is-better approach. Understanding and relating both the hierarchy of design variables and the pool of actionable decisions can ensure that the design space is converged in an intelligent manner. Change actions are also categorized as flexible or adaptable through current methods, but no differentiation according to the response types listed in Table 4-1 is conducted. Determining if desired actions include responses other than to "expand," which continue the trend in ship design of added complexity, would aid designers in the search for affordable, sustainable solutions that integrate well with the existing system architecture.

Lack of non-stationary transition linkages

A method that explicitly considers dynamic change must recognize that transition linkages can break or build. A deterministic state-transition mapping applies a static threat and opportunity assessment to a dynamic landscape. Changeability can grow and shrink with time due to technology innovation or a regulatory ban, for example. Transitions are also probabilistic due to internal and external uncertainties, and uncertainty is located in both the environmental context as well as the actions of a decision-maker. A repair may be unsuccessful. Technology readiness may be delayed. A policy schedule may accelerate with the election of a new official. Coinciding change with lay-up schedules and budget cycles is also a necessary addition to complexity.

Moving from stationary to non-stationary transition arcs is not a terribly difficult endeavor; however, the consequences also do not afford “analysis-as-usual.” A non-stationary setup prevents a closed-form or steady state solution from being developed. A set of metrics should ensure not only that the ability to change exists, but also that sufficient changeability exists at the moment when and where changeability is desired. Existing metrics such as Filtered Outdegree do not actively value the importance of the {when, where} elements to change.

Lack of economic measures that differentiate alternatives according to path dependence

Just as sustainability practices do not differentiate impacts committed versus impacts incurred, change research does not consider the temporal dimensions of cost. Past change management research does not consider systems with routine operating expenses. Space systems, the primary application thrust to date, are typically characterized by high capital expenditures that far outweigh variable operating costs. Thus, cost commitment and cost incurred are approximately one-in-the-same curve, where the only distinguishing feature between the two is how the investment is financed.

A decision-maker cannot take an abstract scope on path dependence when operating expenditures are the same order of magnitude as investment costs. Not all cost paths are equal. Uncertainty is not linear through time. When costs are incurred is important, not simply from a net present value perspective but also from a risk perspective, due to higher levels of uncertainty deeper into the future. Decisions are potentially stronger the later cost is committed and incurred due to the added value of information. A decision possesses a degree of irreversibility in that a decision both requires expense to initiate and requires expense to revert. Appreciation for cost lock-in and path dependence expands the lens with which decisions are selected on economic merits.

4.2 Problem Statement

The pressure to deliver greater value despite emergent policies emphasizing life cycle costs and environmental concerns poses a challenge for ship designers. Often, environmental- and energy-related measures constitute a significant portion of total outlays necessary to construct, operate, maintain, and dispose of a vessel. Sustainability, and the full range of –ilities class pertinent to ships, is increasingly defined in a comparative context where “best practices” continually evolve. Evolution is driven by efforts within the ship industry and across the transportation sector. “Best practice” designs are well-positioned to capture policy-enabled opportunities and mitigate policy-driven risks.

Military and commercial managers are without the necessary methods to handle their ship systems in a changing environmental policy climate. Past research on sustainability packages results at the aggregate level or via a small group of alternatives; these approaches suffer from high levels of abstraction or insufficient design space exploration to such a degree that decision-making ability is limited. Efforts defining the relationship between policy uncertainty and dynamic, technical design decisions are also of limited quantitative development.

A growing body of literature has focused on representing complex systems so that changeability can be measured. Much analysis answers the questions: “Is a design changeable?” and “How does one recognize the need for change?” Current methods demonstrate less concern for developing an understanding of the time- and path-dependent factors inherent to the ability to change. Economic value is related through a single metric, life cycle cost, limiting the depth of information required for intelligent decision-making.

The purpose of this dissertation is to employ a state-based structure to determine how a single ship artifact is expected to respond to policy change, with emphasis on strategic, timely actions. Cost metrics are used as the impetus for decisions, and uncertain policy-related disturbances are modeled probabilistically. Actions pertain to capital investments, operating measures, and maintenance activities. A Markov Decision Process is proposed as the general decision-making framework due to its ability to handle uncertainty, manage non-stationary context evolution, and differentiate decision-maker responses.

4.3 Chapter Summary

A review of sustainable design and change management approaches details recent advances to both design theory and application. However, recent efforts have not fully addressed the temporal intricacies relating design decisions and external disturbances. Limitations of varying degree among current methods include:

- Inability to draw individual decisions from aggregate sustainability studies
- Constrained design space due to incremental policy outlook
- Failure to incorporate active trading of design sustainability
- Incomplete communication of change-dependent design drivers
- Lack of uncertainty in transition linkages enabling change
- Insufficient measurement of design lock-in and path dependencies

This author claims that a state-based disturbance formulation begins to overcome limitations to current approaches detailed in this chapter. The explicit capture of path dependencies and policy events serves to advance the state-of-the-art in both sustainable design and change management. Furthermore, sustainable design is strengthened by including temporal aspects in the decision structure. Change management literature is strengthened by driving at an issue yet to be fully tackled: directly linking pathways within the external environment to the path sequences of strategic design decisions. The proposed approach offered in the next chapters draws upon a more holistic vantage point, yet builds from the trend of using life cycle cost as a primary valuation metric.

Chapter Citations

1. Bovea, M., & Wang, B. (2003). Identifying environmental improvement options by combining life cycle assessment and fuzzy set theory. *International Journal of Production Research, 41*, 593–609.
2. Bras, B. (1997). Incorporating environmental issues in product design and realization. *Industry and Environment,* special issue, *20*, (1-2).
3. Briceno, S., & Mavris, D. (2006). Applications of game theory in a systems design approach to strategic engine selection. *In proceedings of 25th International Congress of the Aeronautical Sciences*. Hamburg.
4. Broniatowski, D. (2006). Political sustainability in the vision for space exploration: Articulating the policy-technology feedback cycle. *Thesis:* Cambridge, MA.

5. Browning, T. (2001). Applying the design structure matrix to system decomposition and integration problems: A review and new directions. *IEEE Transactions on Engineering Management, 48* (3), 292-306.
6. Buhaug, Ø., Corbett, J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D., Lee, D., Lindstad, H., Markowska, A., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Winebrake, J., Wu, W., & Yoshida, K. (2009). Second IMO GHG Study 2009. *Report.* London: International Maritime Organization.
7. Coates, J. (1985). Foresight in federal government policymaking. *Futures Research Quarterly Summer*, 29–53.
8. Cooksey, K., & Mavris, D. (2011). Game theory as a means of modeling system of systems viability and feasibility. *In proceedings of IEEE Aerospace Conference*.
9. Cooper, J., & Fava, J. (2006). Life cycle assessment practitioner survey: Summary of results. *Journal of Industrial Ecology, 10* (4), 12-14.
10. Coulter, S., & Bras, B. (1997). Reducing environmental impact through systematic product evolution. *International Journal of Environmentally Conscious Design & Manufacturing, 6* (2), 1-10.
11. Cristofari, M., Deshmukh, A. & Wang, B. (1996). Green quality function deployment. *In proceedings of 4th International Conference on Environmentally Conscious Design and Manufacturing*, 297- 304. Cleveland.
12. Cuhls, K. (2003). From forecasting to foresight process: New participative foresight activities in Germany. *Journal of Forecasting, 22*, 93-111.
13. De Neufville, R. (2004). Uncertainty management for engineering systems planning and design. *Monograph*. Massachusetts Institute of Technology.
14. De Weck, O. & Suh, E. (2006). Flexible product platforms: Framework and case study. *In proceedings of International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. Philadelphia.
15. Ellingsen, H., Fet, A., & Aanondsen, S. (2002). Tool for environmental ship design. *Norwegian University of Science and Technology*.
16. Environmental Protection Agency. (2009). Regulatory impact analysis: Control of emissions of air pollution from Category 3 marine diesel engines. *Report*. EPA-420-R-09-019.
17. Ethiraj S., & Levinthal, D. (2004). Modularity and innovation in complex systems. *Management Science, 50* (2), 159-73.
18. Fabrycky, W., & Blanchard, B. (1991). Life cycle cost and economic analysis. Englewood Cliffs: Prentice Hall.
19. Frangopol, D., Bocchini, P., Decò, A., Kim, S., Kwon, K., Okasha, N., & Saydam D. (2011). Integrated life-cycle framework for maintenance, monitoring, and reliability of naval ship Structures. *In proceedings of International Conference on Fast Sea Transportation.* Honolulu.
20. Frei, M., & Züst, R. (1997). The eco-effective product design: the systematic inclusion of environmental aspects in defining requirements. In F. Krause and G. Seliger, *Life Cycle Networks* (pp. 163-173). London: Chapman & Hall.
21. Fricke, E., & Schulz, A. (2005). Design for changeability: principles to enable changes in systems throughout their entire life cycle. *Systems Engineering, 8* (4), 342–359.

22. Giffin M., de Weck, O., Bounova, G., Keller, R., Eckert, C., & Clarkson, P. (2009). Change propagation analysis in complex technical systems. *Journal of Mechanical Design*, *131* (8), 081010.
23. Grubler, A. (1990). *The rise and fall of infrastructures: dynamics of evolution and technological change in transport*. New York: Physica-Verlag.
24. Gupta, M. (1995). Environmental management and its impact on the operations function. *International Journal of Operations and Production Management, 15* (8), 34-51.
25. Halog, A., & Manik, Y. (2011). Advancing integrated systems modeling framework for life cycle sustainability assessment. *Sustainability*, *3*, 469-499.
26. Hazilla, M., & Kopp, R. (1990). Social cost of environmental quality regulations: A general equilibrium analysis. *Journal of Political Economy, 98* **(**4), 853- 73.
27. Hodges, H. (1997). Falling prices: Cost of complying with environmental regulations almost always less than advertised. *Report*. Economic Policy Institute Technical.
28. Holloway, L., Clegg, D., Tranter, I., & Cockerham G. (1994). Incorporating environmental principles into the design process. *Material & Design*, *22* (15), 259-267.
29. IPCC. (2007). Climate Change 2007: The physical science basis contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. *Report*. New York: Cambridge University Press.
30. Jorgenson, D., & Wilcoxen, P. (1990). Environmental regulation and U.S. economic growth. *RAND Journal of Economics, 21***, (**2).
31. Kameyama, M., Hiraoka, K., Sakurai, A., Naruse, T., & Tauchi, H. (2005). Development of LCA software for ships and LCI analysis based on actual shipbuilding and operation. *In proceedings of 6th Intl. Conf. on Ecobalance*. Japan.
32. Kemp, R. (2000). Technology and environmental policy—Innovation effects of past policies and suggestions for improvement. *In proceedings of OECD proceedings Innovation and the Environment,* 35-61. Paris
33. Kishk, M., & Al-Hajj, A. (1999). An integrated framework for life cycle costing in buildings. *In proceedings of COBRA 1999,* (2), 92-101. Salford.
34. Kuo, T., Chang, S., & Huang, S. (2006). Environmentally conscious design by using fuzzy multi-attribute decision-making. *International Journal of Advanced Manufacturing Technology, 29,* 209–215.
35. Lee, D., Eyring, V., Hilaire, J., Lauer, A., Lim, L., Ponater, M., & Rodriguez, R. (2009). Radiative forcing from shipping emissions: spatial and zonal mean responses. *Manuscript*.
36. Lipson, H. (2006). Evolutionary systems design: Recognizing changes in security and survivability risks. *Technical Report CMU/SEI-2006-TN-027*. Carnegie Mellon Software Engineering Institute.
37. Loveridge, D. (2009). *Foresight: The art and science of anticipating the future*. New York: Routledge.

38. Lubin, D., & Esty, D. (2010). The sustainability imperative. *Harvard Business Review, 88* (5), 43-50.
39. Maier, J., & Fadel, G. (2009). Affordance-based design methods for innovative design, redesign, and reverse engineering. *Research in Engineering Design, 20* (4), 225-239.
40. Martin, M., & Ishii, K. (2002). Design for variety: Developing standardized and modularized product platform architectures. *Research in Engineering Design, 13* (4), 213-235.
41. Mehta, C., & Wang B. (2001). Green quality function deployment III: A methodology for developing environmentally conscious products. *Journal of Design and Manufacturing Automation, 1*, 1–16.
42. Mikaelian, T. (2009). An integrated real options framework for model-based identification and valuation of options under uncertainty. *Dissertation:* Cambridge.
43. NATO. (2009). Code of practice for life cycle costing. *RTO Publication SAS-069.*
44. Nilchiani, R. (2005). Measuring the value of space systems flexibility: A comprehensive six-element framework. *Dissertation:* Cambridge.
45. Nishijima, K., Straub, D., & Faber, M. (2006). Sustainable decision for life cycle based design and maintenance. *International Journal of Risk Assessment and Management*.
46. Ozaki, Y., Larkin, J., Tikka, K., & Michel, K. (2010). An evaluation of the Energy Efficiency Design Index (EEDI) baseline for tankers, containerships, and LNG carriers. *In proceedings of SNAME & Marine Board Symposium*.
47. Pruzan-Jorgensen, P., & Farrag, A. (2010). Sustainability trends in the container shipping industry: A future trends research summary. *Report*. BSR.
48. Ramani, K., Bernstein, W., Ramanujan, D., Zhao, F., Sutherland, J., Handwerker, C., Choi, J., Kim, H., & Thurston, D. (2010). Integrated sustainable life cycle design: A review. *Journal of Mechanical Design, 132* (9), 091004.
49. Rogers, E. (1962). *Diffusion of Innovations*. New York: Glencoe.
50. Ross, A. (2006). Managing unarticulated value: Changeability in multi-attribute tradespace exploration. *Dissertation*: Cambridge.
51. Ross, A., & Hastings, D. (2006). Assessing changeability in aerospace systems architecting and design using dynamic multi-attribute tradespace exploration. *In proceedings of AIAA Space*. San Jose.
52. Ross, A., Rhodes, D., & Hastings, D. (2008). Defining changeability: Reconciling flexibility, adaptability, scalability, modifiability, and robustness for maintaining system life cycle value. *Journal of Systems Engineering, 11* (3), 246-262.
53. Ross, A., & Hastings, D. (2005). The tradespace exploration paradigm. *In proceedings of INCOSE International Symposium*. Rochester.
54. Ross, A., & Rhodes, D. (2011). Anatomy of a change option: mechanisms and enablers. *Report*.
55. Sanderson, S. (1991). Cost models for evaluating virtual design strategies in multicycle product families. *Journal of Engineering Technology and Management, 8* (3), 339-358.

56. Shipworth, D. (2002). A stochastic framework for embodied greenhouse gas emissions modelling of construction materials. *Building Research & Information, 30* (1), 16-24.
57. Simpson, T. (1998). A concept exploration method for product family design. *Dissertation*: Atlanta.
58. Singh, A., Mourelatos, Z., & Li, J. (2010). Design for life cycle cost using time-dependent reliability. *Journal of Mechanical Design*, *132* (9), 0910081-09100811.
59. Singer, D. (2003). A hybrid agent approach for set-based conceptual ship design through the use of a fuzzy logic agent to facilitate communications and negotiation. *Dissertation*: Ann Arbor.
60. Smaling, R., & de Weck, O. (2007). Assessing risks and opportunities of technology infusion in system design. *Systems Engineering, 10* (1), 1-25.
61. Thurston, D. & Srinivasan, S. (2003). Constrained optimization for green engineering decision-making. Special issue of *Environmental Science and Technology, 37* (23), 5389-5397.
62. Walton, M. (2002). Managing uncertainty in space systems conceptual design using portfolio theory. *Dissertation*: Cambridge.
63. Wang, W., Zmeureanu, R., & Rivard, H. (2005). Applying multi-objective genetic algorithms in green building design optimization. *Building and Environment, 40* (11), 1512-1525.
64. Ward, A., Liker, J., Cristiano, J., & Sobek, D. (1995). The second Toyota paradox: How delaying decisions can make better cars faster. *Sloan Management Review, 36* (2) 43-61.
65. Weigel, A. (2002). Bringing policy into space systems conceptual design: Quantitative and qualitative methods. *Dissertation*: Cambridge.
66. Weimer, D. (2008). *Cost-benefit analysis and public policy*. New York: John Wiley & Sons.
67. Zhang, Y., Wang, H., & Zhang, C. (1999). Green QFD-II: A life cycle approach for environmentally conscious manufacturing by integrating LCA and LCC into QFD matrices. *International Journal of Production Research, 37* (5), 1075-1091.

CHAPTER 5 – METHODS & METRICS

A pint of sweat, saves a gallon of blood.
George S. Patton

Some conclusions of the previous chapters bear repeating. Difficulty linking policy to design decisions derives from an uncertain, emergent future; a traditionally static design perspective; limited resources at the early stages of design; and analysis approaches that insufficiently value the sequential nature of life cycle decision-making. A detailed review of policy and design theory posits the concepts of the state-based panarchy model, performance drift, and inter-generational optimization as foundational to a modern approach to strategic design. The author collects these disparate concepts to form a unique perspective to the problem at hand.

What is presented in the following chapter is a holistic, scalable methodology for incorporating environmental policy decisions into life cycle design. New representations and metrics are suggested to complement traditional metrics associated with life cycle cost. The approach is novel from the following standpoints:

- The first inclusion of Markov Decision Processes in early stage ship design, and the most extensive deployment of Markov Decision Processes in any known engineering design methodology
- Incorporation of both internal design features and exogenous details into the Markov Decision Process structure
- Rapid assessment of design alternatives from an action sequencing perspective
- Inclusion of the product manager's change capital in addition to the change capital of the product itself in design evaluation

The chapter is divided into three sections. Section 5.1 outlines the methodology, which details the Markov Decision Process structure, similar applications, and structural extensions to include sensitivity and simulation. Section 5.2 proposes the use of state and action representations to assist in the characterization of design change potential. Finally, Section 5.3 offers a set of metrics that accounts for the decision-maker’s preferences for well-defined courses of action, early receipt of rewards, and freedom to perform design alterations as deemed necessary.

5.1 Methodology

Given the understanding of techno-political interactions summarized in Chapters 2 and 3 and the limitations with current approaches outlined in Chapter 4, a Markov Decision Process is chosen as the framework for modeling decision-making. The benefits of such a framework include a state-based representation of the system that handles uncertainty, the ability to differentiate actions, and the ability to handle non-stationary developments. A Markov framework has the ability to incorporate expert belief, probabilistic inference, prior knowledge and numeric information—all of which exist in the management of large scale environmental problems.

Optimization, simulation, and sensitivity techniques are employed. Decisions are first optimized in a recursive fashion and are based on expected transitions and rewards. Then, simulations are conducted to model the range of results that might be witnessed given the employed strategy. Thus, the method moves backward and forward through the product life cycle to value a manager’s decision-making. Sensitivity is then employed to determine the uncertainty bounds for which the discovered policy remains optimal.

The goal of dynamic programming + sensitivity analysis + simulation is explicit: to understand the underlying life cycle product decisions and drivers across design concepts and uncertain policy futures. This is achieved by strengthening the decision-making relationship between policy and design.

5.1.1 Markov Decision Processes

Various mathematical structures for assessing policies under elements of uncertainty currently exist. A Markov Decision Process (MDP) is a method to model and solve dynamic decision-making problems under stochastic conditions. The basic structural representation includes nodes and conditional arcs (Figure 5-1). MDPs, also commonly known as sequential dynamic programming, have been studied extensively since their introduction in the 1950's (Puterman, 1994).

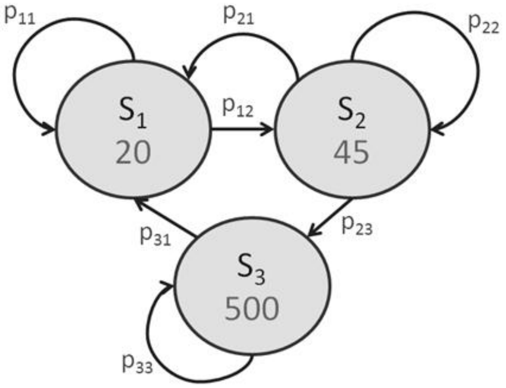


Figure 5-1: A standard sample Markov decision process

A common explanatory application of an MDP is that of robot navigation. The purpose of the MDP is to determine which direction to move at any location the robot may find itself. Robot movements are imperfect, as a decision to move forward may result in accidental movement laterally instead. Each incremental movement represents a state change, and the resulting state is marked by a transition probability. The robot is rewarded at each decision point, or *epoch*, until reaching either the goal state or running across a hazard.

5.1.2 Structure

The sequential decision-making structure of MDPs accounts for both the outcomes of current decisions and future decision opportunities. Discrete, finite-time MDPs are the most basic application of the technique. A classic unconstrained, fully observable MDP can be defined as a 4-tuple ‹S, A, T, R›, where:

- S ={s} is a set of finite states in which an agent can exist

- A ={a} is a finite set of actions an agent can execute
- T(*s'*|*s,a)* = the transition probability that an agent moves to state *s'* if it executes action *a* in state *s*
- R(*s,a*) = real-valued reward when the agent executes action *a* in state *s*

Figure 5-2 illustrates the relationship between MDP components. At each state, a reward is earned. An action is taken before time increments, and the state transitions to a new (or possibly the same) state given uncertain change in the action prescribed and exogenous factors.

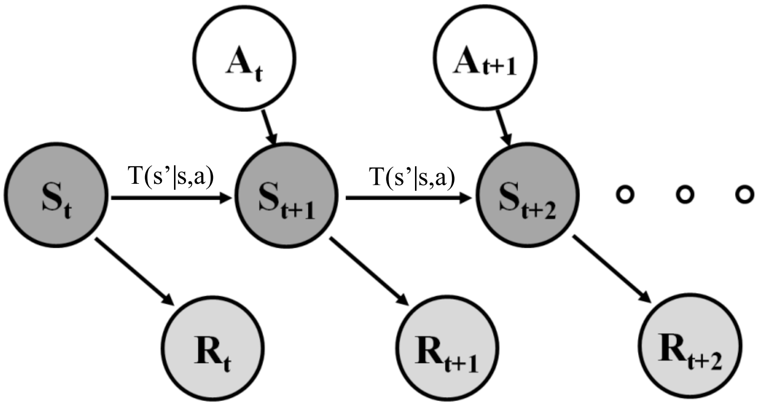


Figure 5-2: Process for how state, action, transitions, and rewards interact within MDP framework

MDP theory assumes that both T(*s'*|*s,a)* and *R*(*s,a*) are measureable for any action *a* at any state *s*. At each time step in a discrete, finite, fully observable MDP, the agent both observes the current state of the system and selects an action that impacts its immediate reward and the probabilities of future states.

The structure of problem is sub-divided into states, whereby each state adheres to the memoryless *Markovian* property. Given the current state, an optimal policy is independent of the policy decisions in previous states. In situations where the policy does not depend on time, the MDP is defined as *stationary*. Figure 5-1 is one representation of a stationary MDP. A stationary policy is always Markovian, by definition (Puterman, 1994).

The output, a decision matrix, provides the optimal actions given each state-time combination. An example decision matrix is provided in Table 5-1. Optimal actions within the same state differ from epoch to epoch due to a non-stationary transitions and/or rewards. An associated matrix details the expected reward-to-go given each state and epoch.

Table 5-1: Sample non-stationary decision matrix

	State 1	State 2	…	State n
Epoch 1	Action A	Action A	.	Action A
Epoch 2	Action B	Action C	.	Action C
Epoch 3	Action C	Action A	.	Action A
…	.	.	.	.
Epoch m	Action D	Action B	…	Action A

5.1.3 Value Iteration

The objective of an MDP is to identify a *policy*, **π**, that maximizes the cumulative, long-term reward from an agent's actions. The policy is a mapping from states to action, **π:** *S* → *A***.** Decision-making performance is often measured by a utility, or *value function*, summarizing long-term expected rewards. The standard MDP value function, *V*, depends on the policy and current state, *s*, and is expressed as follows:

$$V^{\pi}(s) = \mathrm{E}\{r_{t+1} + \gamma r_{t+2} + \gamma^2 r_{t+3} + \dots | s_t = s, \pi\} \qquad [5\text{-}1]$$

$$V^{\pi}(s) = \mathrm{E}\{r_{t+1} + \gamma V^{\pi} s_{t+1} | s_t = s, \pi\} \qquad [5\text{-}2]$$

$$V^{\pi}(s) = \sum_{a \in A_s} \Pi(s,a) \sum_{s' \in S} T(s'|s,a)\left[r(s'|s,a) + \gamma V^{\pi}(s')\right] \qquad [5\text{-}3]$$

where Π(s,a) represents that probability with which policy π chooses to take action $a \in A_s$, r(s,a) represents the probability of receiving a reward given current state *s* and action *a*, and $\gamma \in [0,1]$ denotes the discount factor. The time horizon, or number of epochs in the process, may be finite or infinite. When the process operates over an unbounded number of periods, infinite-horizon discounted performance criteria is required.

Equation [5-3] is a Bellman equation (1957), used by many dynamic programming methods to recursively estimate the value function. The optimal value function gives the state value under an optimal policy, and is expressed below:

$$V^*(s) = \max_{\pi} V^{\pi}(s) = \max_{a \in A_s} \sum_{s' \in S} T(s'|s,a)\left[r(s'|s,a) + \gamma V^*(s')\right] \qquad [5\text{-}4]$$

The optimal policy can be extracted by finding the argument of the optimal value function. Equations [5-3] and [5-4] must also account for time when the problem is finite in horizon. In this instance, the optimal policy may be non-stationary.

All MDP classes apply similar logic rooted in the use of value functions to determine a policy, though the problem's structure can vary. A system can be built as a single agent, a single agent with a factored set of sub-states, or a collection of many agents. Continuous time, imprecise rewards or transitions, fuzzy states, non-observability, and macro courses of action (behaviors) further generalize the problem. Solutions may employ optimal, approximately optimal, or heuristic approaches.

5.1.4 Applications

MDPs have become an important research arena with a rich theory and diverse applications, particularly in engineering and business disciplines. MDP applications are common in operations research, telecommunications, and computer science. Historical examples include problems related to route planning, goal-seeking, resource allocation, replacement, maintenance and repair, inventory, queuing, scheduling, and asset pricing (Feinberg and Shwartz, 2002).

A research discipline receiving little Markovian application is the early stage design process itself. Yet, as the research intends to demonstrate, thinking about design decisions in the state—action—event—reward framework is both logical and helpful for removing uncertainty in life cycle decision-making.

5.1.5 Sensitivity

Standard approaches to solving sequential decision problems assume that the parameters of the models are known. However, often the rewards, transition probabilities, and discount factor rely on forecasts and therefore may be uncertain estimates.

The literature distinguishes between sensitivity and solutions that account for imprecise parameters (Tan & Hartman, 2011). In the latter case, parameter point estimates are replaced by closed intervals. The imprecise parameter MDP formulation discovers a series of optimal policies that exist for some realization of the bounded parameter set (White & El-Deib, 1986). The number of policies which exhibit partial optimality across the bounds can become intractable in the worst case scenario. Typically, imprecision is resolved into a single implementable policy using max-min techniques. Perturbed dynamic programming using regret-minimizing approaches is often considered for MDPs where the reward functions may change arbitrarily, while robust dynamic programming techniques are advocated for imprecise transition functions (Wallace, 2000; Hopp, 1988).

Conversely, sensitivity continues to use the parameter point estimate and the resulting single, optimal policy. Parameter bounds are determined for which the stated policy remains optimal, i.e. is insensitive. In essence, sensitivity and imprecision techniques are marked by key distinctions in the order of operations, which are summarized in Table 5-2.

Table 5-2: Difference between imprecise parameters and parameter sensitivity

	Estimate	**No. Optimal Policies**	**Objective**
Sensitivity	Point	One	Determine maximum parameter range such that policy remains optimal
Imprecision	Closed Interval	One to Infinite	Determine set of all optimal decisions at each state

As noted in a previous chapter, max-min policies can be overly conservative and can fail to capture critical opportunities. The design under environmental policymaking uncertainty problem necessitates openness to opportune decision-making. Thus, this dissertation applies sensitivity techniques in its continued development of the problem. Detailed development of a strategic sensitivity analysis formulation is presented below.

Sensitivity analysis is applied to judge the stability of a solution using an estimated parameter. The classic approach to answering how an optimal solution changes with parameter deviations is to solve the problem for different values of the uncertain parameter(s) in question. This process can be time consuming and is difficult to address systematically if the number of uncertain parameters is large. Instead, Tan and Hartman (2011) suggest exploiting the Bellman equations directly to significantly reduce computation time. Here, they express rewards as affine functions of uncertain parameters, and the method is related to that of shadow price calculations common in linear programming.

The reward, $\tilde{r}^{a_s}$, associated with an action *a* at state *s* is expressed as

$$\tilde{r}^{a_s} = \lambda_0^{a_s} + \boldsymbol{\lambda}^{a_s}\boldsymbol{x} + \boldsymbol{\Delta}^{a_s}\boldsymbol{\rho} \qquad [5\text{-}5]$$

where $\lambda_0^{a_s}$ is a known constant, $\boldsymbol{x}$ represents a vector of estimated parameter values, $\boldsymbol{\lambda}^{a_s}$ denotes the respective known coefficients, $\boldsymbol{\rho}$ represents a vector of the corresponding estimation error, and $\boldsymbol{\Delta}^{a_s}$ details the corresponding error coefficient.

A relationship between the range of error values and the current optimal solution is expressed through the value function. A state value expression with uncertain parameters is expressed as

$$\mathrm{V}^{\pi}(s,\boldsymbol{\rho}) \;= \mathrm{r}(\mathrm{s},\pi) + \boldsymbol{\Delta}(\mathrm{s},\pi)\boldsymbol{\rho} + \gamma\sum_{\mathrm{s}'\in\mathrm{S}}\mathrm{T}(\mathrm{s}'|\mathrm{s},\pi)\mathrm{V}^{\pi}(\mathrm{s}',\boldsymbol{\rho}) \qquad [5\text{-}6]$$

and depends on the value functions of other states. The full set of state value functions can be expressed in matrix form $\mathbf{V}^{\pi}(\boldsymbol{\rho}) = (\mathrm{V}^{\pi}_{\mathrm{s}=1}(\boldsymbol{\rho}), \mathrm{V}^{\pi}_{\mathrm{s}=2}(\boldsymbol{\rho}), \ldots \mathrm{V}^{\pi}_{\mathrm{s}=|\mathrm{S}|}(\boldsymbol{\rho}))^{\top}$, and as the reformulated equation

$$\mathbf{V}^{\pi}(\boldsymbol{\rho}) = \mathbf{V}^{\pi}(\boldsymbol{\rho} = \mathbf{0}) + (\boldsymbol{I} - \gamma \boldsymbol{T}(\pi))^{-1}\boldsymbol{\Delta}(\pi)\boldsymbol{\rho} \qquad [5\text{-}7]$$

Here, $\mathbf{I}$ denotes the identity matrix, $\mathbf{V}^{\pi}(\boldsymbol{\rho} = \mathbf{0})$ represents the value function matrix without uncertain parameters prescribed in Equation [5-3], and $(\boldsymbol{I} - \gamma \boldsymbol{T}(\pi))^{-1}\boldsymbol{\Delta}(\pi)$ represents the marginal change.

Tan and Hartman (2011) outlines $\mathrm{c}(\pi^*, \mathrm{s}, \mathrm{a})$ and $\mathbf{b}(\pi^*, \mathrm{s}, \mathrm{a})$ as the marginal decrease in the estimated reward and the marginal change in the estimation error that results from a single perturbation of the action at *s*, respectively. The terms are defined below:

$$\mathrm{c}(\pi^*, \mathrm{s}, \mathrm{a_s}) = \mathrm{r}(\pi^*, \mathrm{s}) - \mathrm{r}(\mathrm{s}, \mathrm{a_s}) + \gamma[\boldsymbol{T}(\pi^*, \mathrm{s}) - \boldsymbol{T}(s, \mathrm{a_s})]\big(\boldsymbol{I} - \gamma \boldsymbol{T}(\pi^*)\big)^{-1}\boldsymbol{r}(\pi^*) \qquad [5\text{-}8]$$

and

$$\mathbf{b}(\pi^*, \mathrm{s}, \mathrm{a_s}) = \boldsymbol{\Delta}(\pi^*, \mathrm{s}) - \boldsymbol{\Delta}(\mathrm{s}, \mathrm{a_s}) + \gamma[\boldsymbol{T}(\pi^*, \mathrm{s}) - \boldsymbol{T}(s, \mathrm{a_s})]\big(\boldsymbol{I} - \gamma \boldsymbol{T}(\pi^*)\big)^{-1}\boldsymbol{\Delta}(\pi^*) \qquad [5\text{-}9]$$

Further define the set of $\rho_{s=i} \in \left[\rho_{s=i}^{lower}, \rho_{s=i}^{upper}\right]$ values as the error range in which π^* remains the optimal policy. This set is related to the marginal change terms related in the above equations through the following relation:

$$\rho_{s=i}^{lower} = \min(\infty, \max_{\mathrm{b}(\pi^*,\mathrm{i},\mathrm{a_s})>0 \; for\ all\ s, \mathrm{a_s})} (\frac{-\mathrm{c}(\pi^*, \mathrm{i}, \mathrm{a_s})}{\mathrm{b}(\pi^*, \mathrm{i}, \mathrm{a_s})})) \qquad [5\text{-}10]$$

and

$$\rho_{s=i}^{upper} = \max(-\infty, \min_{\mathrm{b}(\pi^*,\mathrm{i},\mathrm{a_s})<0 \; for\ all\ s, \mathrm{a_s}} (\frac{-\mathrm{c}(\pi^*, \mathrm{i}, \mathrm{a_s})}{\mathrm{b}(\pi^*, \mathrm{i}, \mathrm{a_s})})) \qquad [5\text{-}11]$$

Each $\rho_{s=i}$ set outlines the single-parameter sensitivity of an optimal policy.

Often, a decision-maker is interested in understanding sensitivity when multiple parameters are uncertain. Such an instance is addressed through a tolerance approach. The tolerance level, τ, for each (s,a_s) pair is expressed as

$$\tau(s, a_s) = \frac{c(\pi^*, i, a_s)}{\sum_{i=1}^{N} |b(\pi^*, i, a_s)|} \qquad [5\text{-}12]$$

and the maximum allowable tolerance τ^* is the minimum of all tolerances across all (s,a_s) pairs. Tan and Hartman (2011) further develop the stationary tolerance approach for the non-stationary rewards problem.

This dissertation has adapted the sensitivity method presented above to more appropriately address the early stage design problem. Differences between the design problem discussed here and the lot-sizing problem discussed by Tan and Hartman (2011) include the former's inclusions of a non-stationary, finite horizon and state infeasibility through time. Not only is the sensitivity value at each state important to a decision-maker, but so, too, is how the sensitivity trends with time and if the high probability states of entry exhibit high tolerance. Nevertheless, this research strategically models the state structure so that calculation procedures for $\tau(s, a_s, t)$ remain unchanged.

5.1.6 Simulation

This dissertation's intent is to arm a decision-maker with value-added information in the selection of a design or in the communication of favorable design characteristics. The standard output of an MDP does not readily outline which states are actually reached and the likelihood a state sequence is achieved. As such, simulations using both the transition matrix and decision matrix must be conducted. Whereas the MDP is back-solved using dynamic programming, a series of simulations are played forward. The result is that simulations can track state-to-state transitions, accumulated cost, policymaking timelines, and technology availability. A benefit of this tracking ability is clearer identification of the states deserving greater focus; the decision matrix can quickly become too large for a decision to assess if the state size of interest is not restricted. Simulation also affords decision-makers insight into *why* changeability is hindered instead of remaining satisfied with knowing *how much* and *when* change is built into the system's structure.

The decision-maker in the early stage design problem is uniquely capable of choosing the starting state for this problem. The start state sets the course for future decisions and reward accumulation. In many other MDP applications, the information from all states is equally weighted because the starting location is unknown. This structural benefit of the design problem raises the question how one might select the best state, given he or she now knows not just the expected cumulative reward but also the policy accompanying each starting state. Both the *desirability* of the decisions themselves and the *reachability* of future states stemming from a policy must be considered.

The standard output of an MDP can provide answers to whether or not changeability is valued, if expected value sufficiently meets the desired project goal, and/or the degree to which the optimal policy is stationary for each state through time despite non-stationary parameters. Simulations supplement the richness of design information by exploiting the decision matrix to answer the following questions:

- Impact of uncertainty on cumulative costs:
    - How likely is Design Concept A to achieve a minimum target of X dollars as compared to alternative design concepts?
    - How many unique state sequences exist within each unique action sequence?
- Role of changeability in decisions:
    - Is the optimal policy active or passive in nature?
    - Is the ability to change exercised, non-existent, or latent?
    - When and within which design element is changeability valued?
- Path dependence:
    - How does following a certain action sequence lock-in future outcomes?
    - Are switching costs significant relative to other costs and rewards?
    - Are there absorbing states, and are these states desirable to enter?

  - Does the trajectory of cost accumulation differ significantly from one design concept to another?
- Relative independence to environmental factors:
  - Does one starting design concept perform more favorably under certain simulated occurrences but less favorably under a different simulation sequence compared to an alternative concept?
  - What techno-political factors have implications for design, and how do these implications manifest themselves?

Simulations more fully exploit the wealth of knowledge offered by an MDP approach than simply relaying the expected state values and optimal decision matrix. Structural and environmental dependencies constrain product performance, uncertainty adds risk to decisions, and flexibility increases the ability to aptly respond to a changing environment. The degree to which a design is impacted by each of these factors can be studied in depth via simulation and ultimately used in the formulation of a global utility function.

By no means is simulation a novel concept; however, traditional MDP applications do not perform simulation in search of these answers. This dissertation values the insight that can be derived from simulations based on the decision matrix.

5.2 Representation

MDP, sensitivity, and simulation provide information on the cumulative rewards, state sequences, and action sequences related to a decision-maker's governance. Communicating this wealth of information in a form suitable for rapid decision-making is no easy task. This section first identifies standard methods of representation before offering a unique series of plots that take advantage of the state-action structure to communicate state feasibility and action optimality through time.

First and second order reward results often communicate expected life cycle rewards, variance, and distribution type. De Neufville and Scholtes (2011) note that a target curve is a convenient manner for representing the distribution of possible values associated with a design and for describing the probability that realized performance will fall below a specified target. The results of a simulation are collected, sorted in ascending order, and plotted within the satisfaction probability versus target NPV space (Figure 5-3). Target curves are specifically useful for highlighting the probability of breaking even, the value-at-risk, and asymmetry in the distribution. Difference curves, upside-downside curves, and regret plots use the ideas of NPV gain and satisfaction probability to compare simulated values of alternate designs.

These forms of representing value and risk do not communicate a number of other important economic information elements that factor into a decision-maker's assessment. For example, initial capital investment, payback period, agreement with budget limitations, and returns consistency are not illustrated. Target curves are illustrative for a final snapshot of cumulative economic performance, though not the nature of the pathway that leads to the NPV calculation. Other means must be used to capture the initial conditions and full range of temporal elements of interest to a product manager.

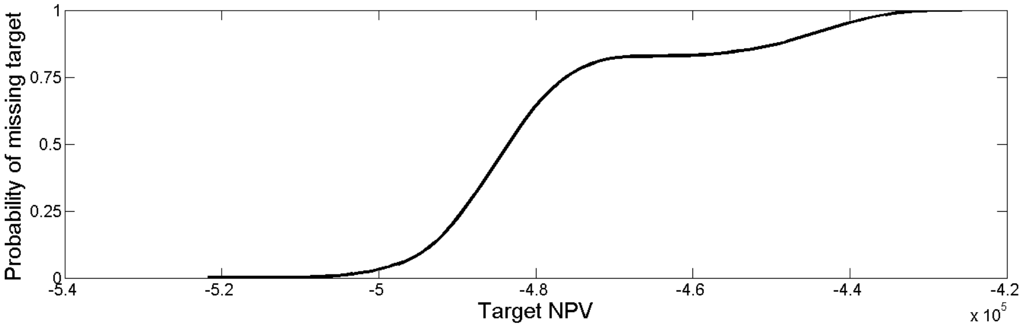


Figure 5-3: A sample target curve displays the simulated distribution of potential life cycle rewards

This dissertation identifies several unique means in which the MDP framework enables additional degrees of representation. These illustrations include: state and action entry plots as well as hotspot analysis, each of which is explained in the next several subsections. The goal of each plot is to rapidly communicate the availability of states and the optimality of actions, which together form the basis for identifying design drivers, systems desiring change, and designs constrained from responding to policy change. An outgrowth of these representations is a set of metrics that expands the understanding of what a decision-maker constitutes as an appropriate and timely degree of change. The illustrations represent a unique contribution of this dissertation.

5.2.1 State Entry Plot

A state entry plot marks which states or state groupings are accessible through time given any available starting state and corresponding optimal policy (Figure 5-4 & Figure 5-5). Shading can be used for one of two purposes, as relevant to a decision-maker: (1) to denote average probability of state accessibility if exogenous factors limit reachability, or (2) to describe the frequency with which the state is accessible across a range of scenarios with changing rewards or transitions. In all cases, hatching is used to denote states that are inaccessible with 100% certainty.

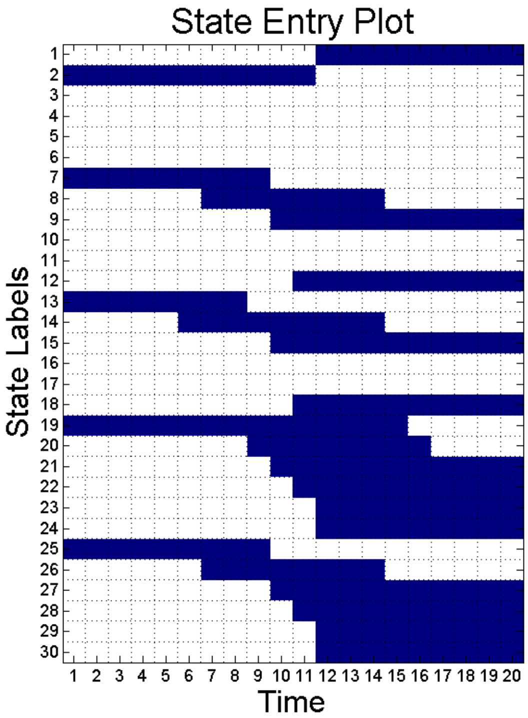


Figure 5-4: Example state entry plot; highlights non-zero probability of accessing a state

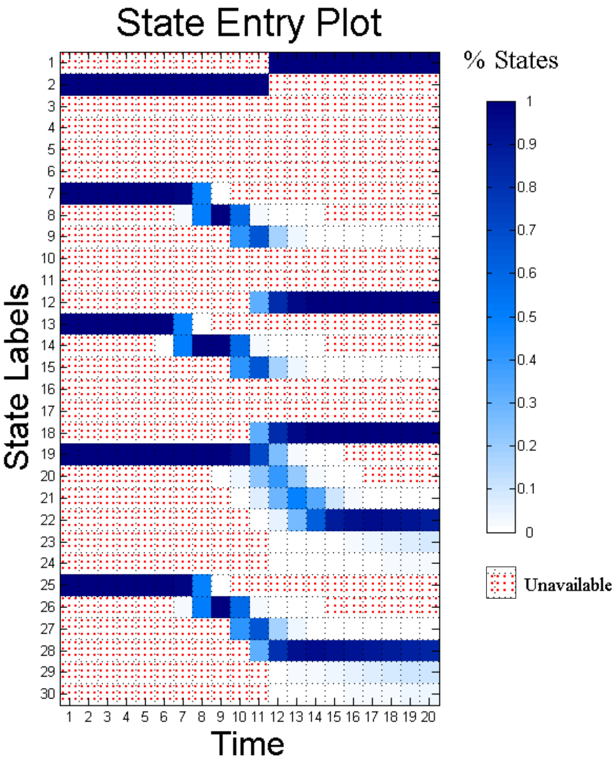


Figure 5-5: Example state entry representation; denotes probability of accessing a specific state

The plot enables a decision-maker to witness the exact states accessible and trends in time. The information contained in the plots can be summarized to (a) determine the number of states per epoch with non-zero probability of entry, and (b) determine the expected number of accessible states per epoch. By definition, (a) ≥ (b) for all time.

5.2.2 Action Entry Pool

The full decision matrix that serves as a standard MDP output provides information for states that are both reachable and unreachable. Analysis using a state entry plot can eliminate extraneous information and summarize the frequency with which an action is prescribed by accessible states. This charting of frequency per epoch is denoted as the Action Entry Pool (Figure 5-6). Removal of extraneous information rapidly arms a decision-maker, who is limited by time, resources, and processing power in early stage design, with key life cycle takeaways.

Action options at each time may be classified into one of three markings: unavailable for selection, available but unselected, or available and selected. Here, a zero frequency decision due to action unavailability is marked by hatching. Zero frequency white markings denote sub-optimal or dominated action options. The degree of colored shading highlights the sum of reachable states whose optimal policy calls for each specific action.

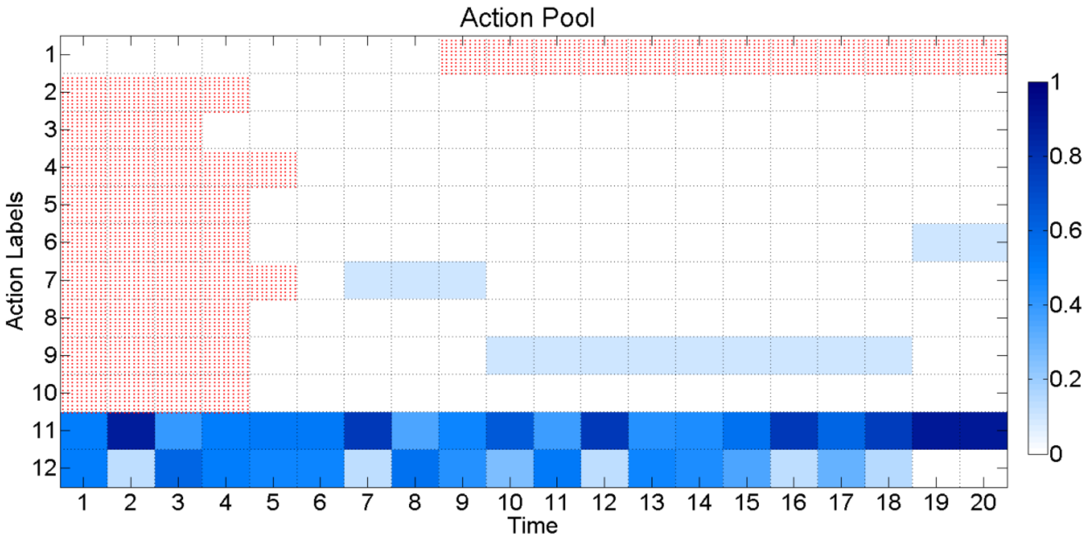


Figure 5-6: Example representation of action popularity as called for by accessible states

Again, the information presented in the plots can be summarized (a) to describe the number of available actions given the set of reachable states, (b) to relay the number of actions per epoch that are dominated regardless of state, and (c) to share the average number of times an action is executed over the full horizon.

5.2.3 Optimal State and Action Sequencing

Both the state and action entry plots describe trends in transitions and decisions irrespective of the starting state. A decision-maker in the context of this dissertation must specify the start state, representing the initial construct of a design concept. Careful selection of the start state can lock-in a course of action that leads to a high total expected reward. Determining the optimal initial state can be based on expected value information output from MDP analysis in combination with multi-attribute utility techniques that assess other measures of design performance.

Compiling simulation information that employs the MDP-derived decision matrix, in contrast to relying on the decision matrix directly, captures the effect of action unavailability. For example, if the decision matrix calls for Action X, but the action is not available due to a technological development delay, the next best decision, Action Y, may be executed. Simulations act as a physical realization of this added layer of uncertainty, even as the underlying reward matrix involved in constructing the decision matrix already accounts for probabilistic and/or imprecise parameters.

Figure 5-7 and Figure 5-8 illustrate the simulated states and actions entered, as well as their probabilities, starting from the optimally determined start state and as drawn from the decision matrix. The figures clearly display the role of uncertainty in state movements and actions executed. For example, a decision-maker may need to plan for four possibly optimal actions at Epoch 9 (Figure 5-8) and recognize that the selected design may fall in any one of five states in Epoch 12 (Figure 5-7).

Summary takeaways from Figure 5-7 & Figure 5-8 include (a) the number of unique, possible states accessed per epoch, (b) the number of unique, non-dominated actions per epoch, (c) the percent time the design exists in a current state, and (d) the percent time an action is executed across the full horizon.

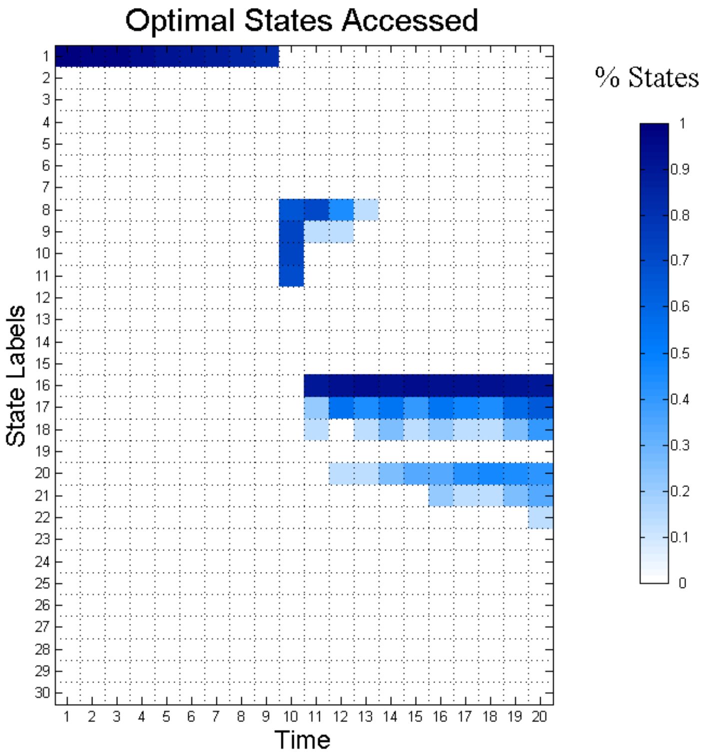


Figure 5-7: Probability plot of states accessed by following policy from optimal initial design

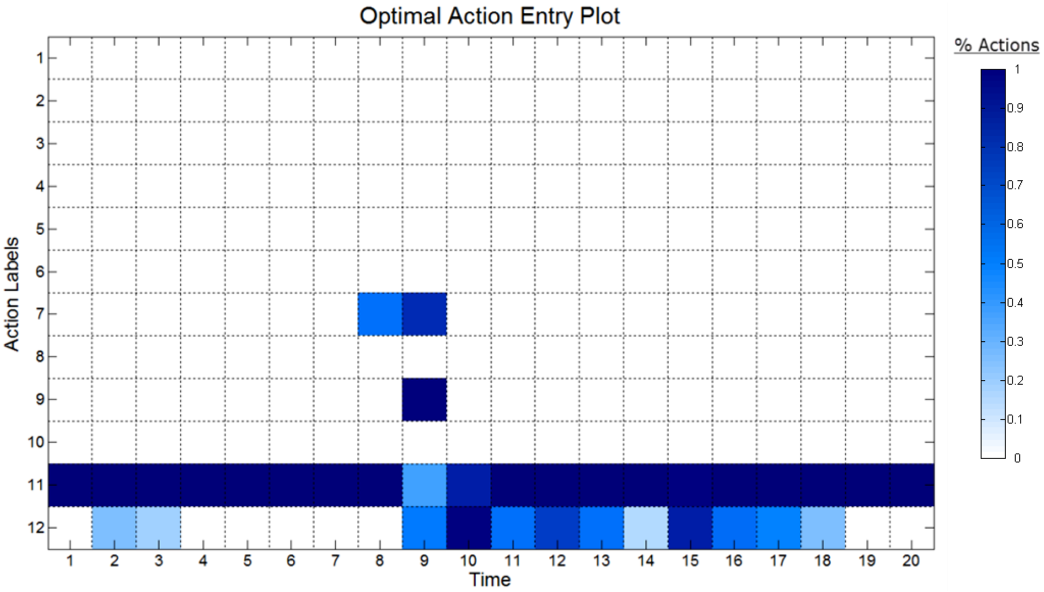


Figure 5-8: Probability plot of actions executed by following policy from optimal initial design

From a planning perspective, a decision-maker is also interested in learning the number of unique action sequences that may be deemed optimal under any manifestation of possible state transitions. Figure 5-9 plots the number of unique action sequences and denotes the actions selected per epoch for each sequence. A decision-maker is likely to prefer few optimal sequences so that planning can continue with greater certainty. The most commonly executed optimal sequence is also preferably the one with the highest simulated average reward (greater than unweighted mean of unique action sequences) and the fewest actions required (least management required).

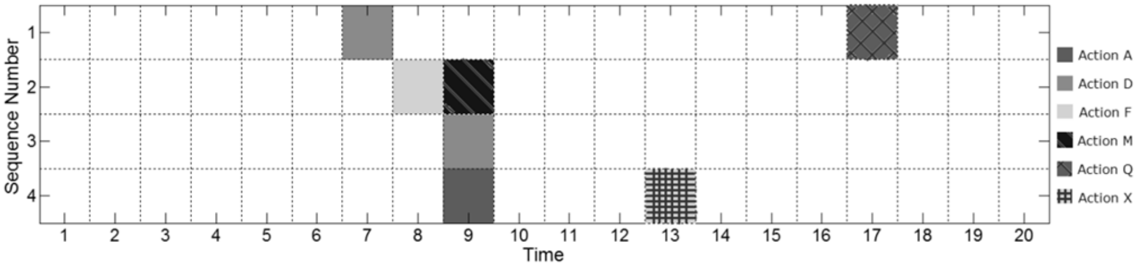


Figure 5-9: Example representation of unique action sequences and associated decisions across time

Despite potentially thousands of future pathways, the MDP + simulation formulation can distill decisions to a much smaller set of optimal actions and state sequences.

5.2.4 Cross-Design Analysis and Hotspot Identification

Oftentimes, design space exploration requires generating a multitude of concepts noted by differences in their primary characteristics. Selecting one best concept is difficult in early stage design, though the top range of concepts can be assessed for shared features and behaviors.

Traditional analysis seeks to identify design characteristics common among various high scoring configurations. The MDP framework extends such analysis to another dimension by eliciting shared action sequences. A decision-maker can employ hotspot illustration techniques to determine if actions are common across “good” designs, and can construct taxonomy for concepts defined by not just their design characteristics but also by their optimal policies. A 3D plot of time versus action type versus action frequency can provide insight into the role of changeability in strong candidate concepts.

5.3 Metrics

A recent proposal request by the Office of Naval Research highlights the lack of evaluation capability surrounding design decisions, noting “it is often difficult to measure the impact of design decisions, as there are no standard definitions, metrics, and measurements that define, let alone calculate, the return on investment of any design decision that impacts multiple aspects of the Navy enterprise” (ONR BAA 11-022, 2011). The author proposes several metrics to aid in design evaluation.

Particularly weakly measured are the management and planning preferences of a decision-maker. Most metrics focus on the product itself, without considering a broader view of the resources required to sustain and manage the product. Several of the following metrics are devised to improve appreciation for this component of design decisions.

5.3.1 Time-weighted Cost Incurred

Figure 5-10 illustrates the cumulative, discounted life cycle cost curves of two unique designs. In instances where NPV is approximately equal for two proposed projects, the author claims a manager would prefer the design option that delays expenses (Design B). Delay is especially valued in the face of uncertainty; the lack of knowledge can lead to a design trajectory that proves suboptimal with time or that can only be modified through additional expense.

A decision-maker can apply the same logic when rewards exist. Earlier achievement of an organization’s financial goals may allow a decision-maker to use the added leeway to extend his/her position. Consider two alternatives: Design C achieves its expected net present value of $1M in Year 5 and then stagnates, while Design D achieves its expected net present value of $1M in Year 10. Given that variance is the same in both instances, which would a decision-maker prefer? The answer is likely Design C because the design could be retired at Year 5 and still achieves the expected estimate of Design D.

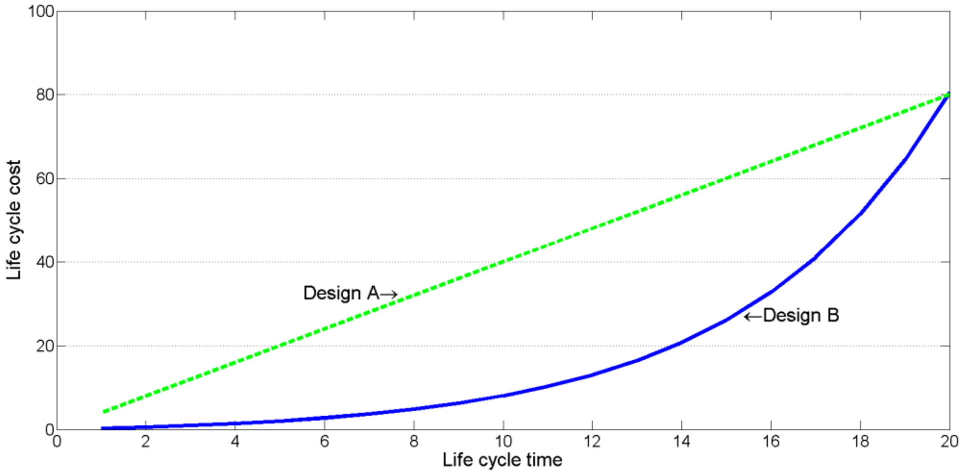


Figure 5-10: Path dependent illustration of discounted, product life cycle cost

Utilizing this characterization of cost preference, the proposed metric, time-weighted cost incurred, is defined:

$$\overline{C_t} = \int_0^T \frac{Cost\ Incurred}{t_i - t_o} dt \qquad [5\text{-}13]$$

where *cost incurred* is defined as the cumulative cost up to time t_i. The parallel also exists for time-weighted reward calculations. Time-weighted cost incurred is communicated in dollars or a similar economic functional unit. A lower time-weighted cost value is preferred.

The metric accounts for life cycle cost path dependence and captures the value associated with delaying incurred cost. Path dependence is inherent when considering cumulative cost. A plot of life cycle cost (magnitude) versus time-weighted cost incurred (vector) serves to rapidly compare the cost characteristics of a design, and the decision-maker’s dual objectives should be to minimize both metrics.

5.3.2 Context Premium

The MDP framework offers an understanding of the impact of a decision on future reward potential. Uncertainty—in rewards, in state transitions, and in action availability—is implicitly accounted for in the standard outputs of a MDP. The result is that multiple action sequences per starting state exist, despite no change to the transition or reward matrices. Multiple action sequences derive from two primary sources:

1. *State transitions are uncertain.* Uncertain transitions lead to a possible set of next states and their accompanying state-specific actions. Entering a unique state can lead to a set of actions wholly different from the set of actions that may have resulted if the previous action led to a different state. If all state-to-state transitions are deterministic and/or an optimal decision is common to all reachable states, a single unique action sequence can be found. Interactions with Nature rarely allow for this level of certainty.
2. *Action unavailability is uncertain.* The next-in-line best action must be selected when the optimal action cannot be executed. Exogenous factors such as delayed technology development can lead to divergent action sequences.

Simulations afford *explicit* understanding of the context for which actions can, and should, be taken. Finite horizon action sequences can be tracked through simulation, and information such as the probability of following a specific sequence, the number of unique non-zero probability sequences, and the average number of unique actions exercised each period is revealed.

Only one curve represents the ideal in terms of lowest cumulative cost. The “best” intra-design curve is the one in which uncertainty plays the least role in determining the effect of actions on the desired outcome. A decision-maker can then inspect the action sequence to gain insight into why specific actions did or did not lead to the ideal state path.

Figure 5-11 illustrates a sample scenario. The expected cost curve is produced by the MDP. Simulations are performed using the MDP decision matrix, leading to two unique action sequences. The action sequences result in unique mean cost paths and final life cycle cost outcomes. The best curve from a final cost standpoint is Sequence 1. Sequence 2 arises because the action that enabled Sequence 1 was sub-optimal at time $t=10$ in some percentage of the simulations given the state in which the design existed at that epoch.

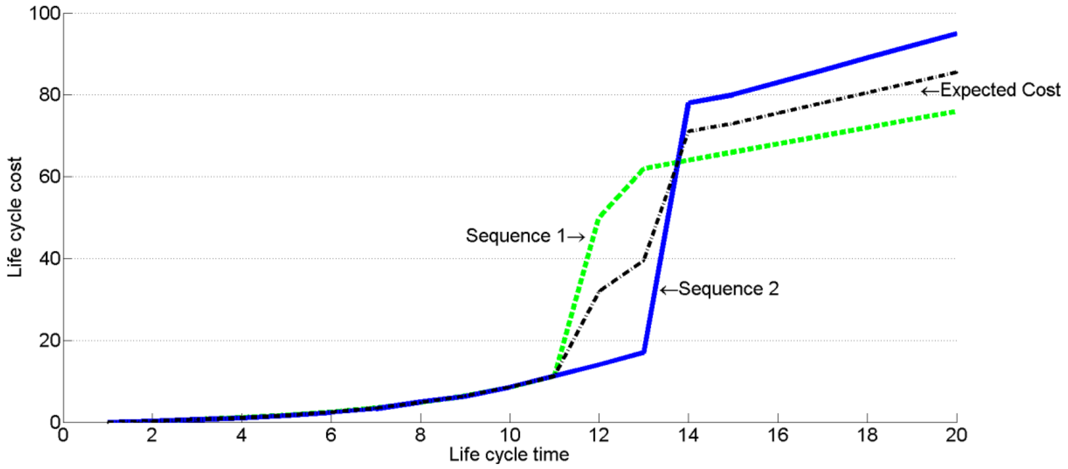


Figure 5-11: Effect of action unavailability on optimal decision sequence

The state-based MDP framework enables a deeper appreciation for the role of uncertainty. Transition uncertainty and action unavailability add a premium, noted as the difference between the best cost sequence and the expected sequence. Using this characterization of premium, this dissertation defines the metric as follows:

$$Context\ Premium = \frac{Expected\ Cost - Best\ Cost}{Best\ Cost} \qquad [5\text{-}14]$$

A design concept's context premium is ideally minimized. Designers should seek to actively manage the underlying reason for the premium, if possible. For example, working alongside an equipment manufacturer to ensure a product receives timely certification can remove exogenous pressures on cost decisions.

5.3.3 Temporal Outdegree

This dissertation recognizes the value of a metric for changeability. Dynamic rewards and transition probabilities lead to new ideal states with time. Changeability is also important if predictions of future rewards and transition probabilities prove incorrect.

Ross and Hastings (2006) define filtered outdegree as the number of potential transition paths available to a design and filtered by an acceptable change cost. Filtered outdegree is a measure of changeability. The metric is an outgrowth of graph theory, whereby a design is treated as a node and the outdegree is defined as arcs with tail endpoints adjacent to the state node.

Where an outdegree metric best suits the needs of a designer using an MDP framework is in the ability to trace changeability over time. Temporal outdegree is defined as the outdegree curve plotted against life cycle time. In the case of Figure 5-12, outdegree is presented as a percentage, where

$$Outdegree\ Percentage = \frac{\#\ unique\ states\ connected\ by\ a\ transition\ path}{Total\ \#\ of\ states\ per\ period} \qquad [5\text{-}14]$$

The concept of outdegree as a measure of changeability is attributed to Ross (2006); plotting outdegree through time and differentiating reachability by technology, market, and policy limits constitute unique contributions of this dissertation.

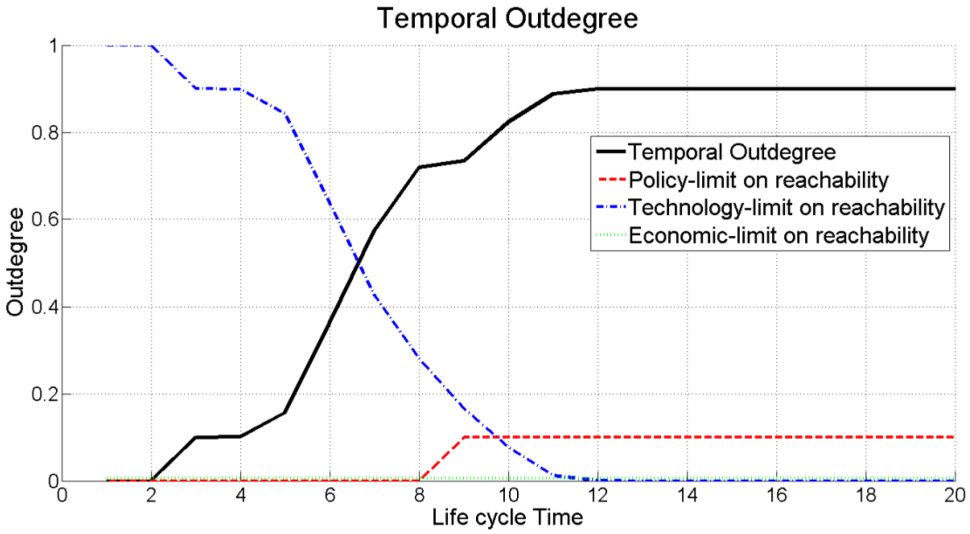


Figure 5-12: Sample plot of temporal outdegree and associated limits to state change

Mapping outdegree through time affords improved understanding of whether or not changeability drives path dependency. An inability to change can result in lock-in to a particular reward path or limit the number of actions necessary to escape a suboptimal pathway. Similar to the manner in which a monopolized industry leads to higher overall prices for products, so too, may cost increase due to a limited ability to change.

States which are not reachable through a transition arc are categorized by their limiting factor; a specific state-to-state arc may not exist due to political, economic, or technological infeasibility. Understanding the limits to changeability can help a decision-maker direct mitigation efforts toward the most inhibiting endogenous and exogenous factors.

5.3.4 Clarity-Changeability Ratio

Recall what is learned from dynamic programming and simulation with respect to action sequencing and changeability. Simulations demonstrate the certainty with which a specific action sequence can be planned in advance. Unique courses of action revealed through simulation represent an *actualization* of the decision matrix. Outdegree measurements highlight a product's changeability. Temporal outdegree relates the underlying *potential* within the system configuration. Together, actualization and potential are key metrics for a decision-maker hoping to manage product effectiveness.

The panarchy model introduced in Chapter 2 emphasizes the dynamic interactions of actualization and potential and serves as the source of inspiration for the following metric. Preferably, planning clarity (actualization) and changeability (potential) are both high. High planning clarity is revealed in the form of few unique action sequences. High changeability is noted through a high outdegree score. As a ratio of clarity to changeability, a low fraction signals the ideal: planning robustness and a latent potential for a product to adjust in any number of ways to a dynamic environment.

$$Clarity\text{:}\,Changeability\ @\ t_i = \frac{\#\ Unique\ simulated\ action\ sequences\ @\ t_i}{Outdegree\ @\ t_i} \qquad [5\text{-}15]$$

Policy clarity and product changeability may be at odds with one another. A greater ability to change may make a product more sensitive to small environmental developments, leading to a lower ability to plan for future needs.

5.3.5 Management Level

A decision-maker is likely to be interested in the effort demanded to achieve the optimal policy. This dissertation proposes the terms *horizon activity level* (HAL) and *mean epoch attention level* ($\overline{EAL}$) to describe the scale of active management, and defines the metrics as:

$$HAL = \frac{\sum_{i=1}^{N} \Pr\left(Action\ other\ than\ 'Do\ Nothing' @\ t_i\right)}{Total\ Number\ of\ Epochs\ in\ Horizon} \qquad [5\text{-}16]$$

$$\overline{EAL} = \frac{\sum_{i=1}^{N} Unique\ Actions\ other\ than\ 'Do\ Nothing' @\ t_i}{Total\ Number\ of\ Epochs\ in\ Horizon} \qquad [5\text{-}17]$$

As their names suggest, HAL is a measurement across the entire life cycle and $\overline{EAL}$ is a measurement focusing on the time scale of one period. Both life cycle action-conscious metrics are unique contributions of this research.

In words, HAL is the average number of actions dictated by the optimal policy per product life cycle. If the optimal policy for nearly the entire horizon is to “do nothing,” then the product may be described as passively robust. A large number of actions across the horizon, where “large” is determined by the decision-maker, demonstrates that flexibility is valued in response to dynamic environmental factors.

$\overline{EAL}$ denotes the amount of disagreement among the unique action sequences by measuring the average number of actions per epoch that may be deemed optimal given probabilistic conditions. The magnitude of the $\overline{EAL}$ value suggests the extent to which a manager must pay particular attention to “which way the winds are blowing.” The larger the $\overline{EAL}$ value, the more conditional the manager’s plan is to state transitions.

Together, HAL and $\overline{EAL}$ describe the expected role of a manager during the product’s life cycle. A simple 2x2 matrix is presented in Table 5-3. High values for both HAL and $\overline{EAL}$ require an attentive manager prepared to execute an active life cycle plan. Low

$\overline{EAL}$ values signal that low monitoring of state transitions is required once the plan is set forth. Low HAL values indicate that the optimal life cycle policy is relatively passive.

Table 5-3: Categorization of management activity & attention levels across horizon and within epochs

	$\overline{\boldsymbol{EAL}}$	
HAL	High – High	Low – High
	Low – High	Low – Low

A decision-maker is left to determine the degree of active and attentive management desired. At times, the decision-making team may be indifferent to required management level and focus only on rewards. HAL and $\overline{EAL}$ measurements become instructive when the product team must balance rewards with effort or cost spillover to other areas of the enterprise.

5.4 Chapter Summary

The proposed evaluation framework and metrics provide two key riches for understanding design decision-making. First, the framework identifies the preferred course of action for a design over time. Approaching design in this manner exhibits a holistic appreciation for both the physical design as well as the life cycle decisions required to support the design. The classic design approach prescribes to the viewpoint that a system exists within a well-defined context where goals and requirements are fixed. Rarely is this the case for modern complex systems. An evaluation framework, such as the one proposed in this dissertation, should afford a temporal perspective on design and should accept that a system is subjected to a variety of dynamic environments.

Figure 5-13, showcases the added capability of this approach. Simulations are now directly built-in to the design process. Just as the external context is dynamic, so, too, is a system capable of change. The cost and performance implications of operating in a dynamic environment can now be more fully appreciated and assessed.

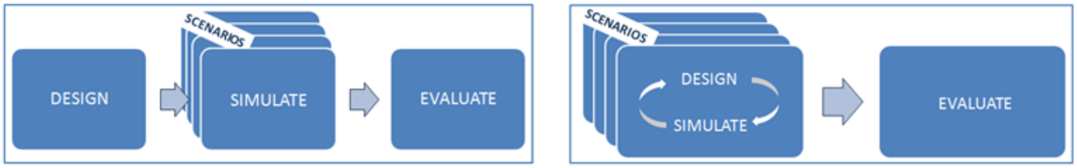


Figure 5-13: Traditional (left) versus temporal (right) evaluation environment

Structurally, simulation using the MDP decision matrix results in a reduced-order action tree, pictured in Figure 5-14 and explained as follows. Prior to state-action calculations performed within the MDP structure, the number of available decisions is exponential with the number of action options and the length of the horizon. Constructing an action pool diagram via assessment of the MDP decision matrix output significantly reduces a decision-maker's focus to only those actions deemed optimal by accessible states. The final reduction that is enabled through simulation is to review decision pathways emanating solely from the initial states with the highest earning potential.

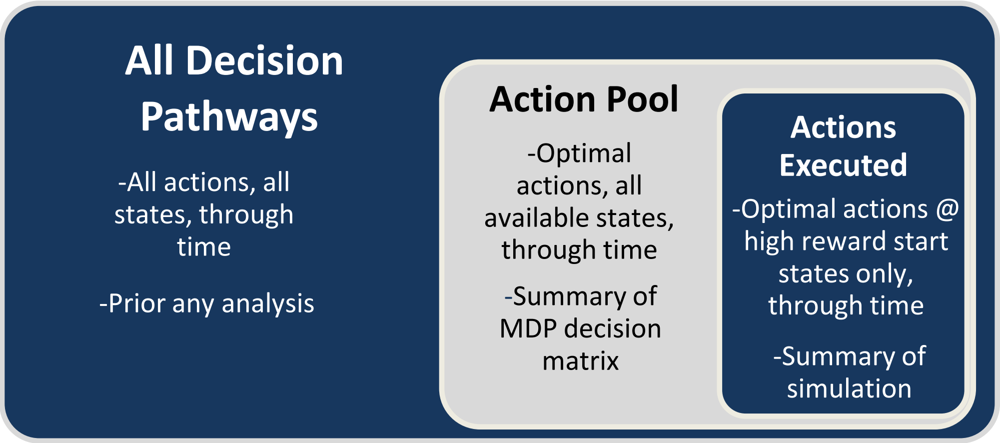


Figure 5-14: The MDP framework enables systematic reduction of action sequence information to only that most relevant to a decision-maker

The second fundamental understanding gained through use of a dynamic, state-based framework is how limitations due to path-dependence and external contexts guide decision-making. Capturing the strength of interactions can identify key indicators and trends, as well as lead to proactive management of cause-and-effect relationships. Design teams can then develop life cycle strategies that exploit regulatory, technological, and environmental interactions more completely. Knowing where, when, and why costs accumulate is critical to ensuring a complex system that appears affordable during early stage design is actually realized as such.

There exists a strong interplay between a design and its external context, both in terms of system cost and utility. Designers cannot be too quick to judge a ‘bad’ versus a ‘good’ design without determining if performance merits result from positives or merely a lack of negatives. A design may be deemed ‘good’ simply because it is the only option given a severely limiting external context. A design may be deemed ‘poor’ early in the system’s life cycle, yet a future ‘best’ state may only be accessible via this path. Comprehensive design is inclusive of both the concept and its expected path through future uncertainty. The proposed framework and metrics outline an improved picture about what makes a strong design over the long run as well as the costs needed to fund the investment over the life cycle. While decision-makers are certainly limited in their predictive ability, failing to view complex systems design in a continuous and anticipatory manner is equally, if not more, dangerous.

Chapter Citations

1. Bellman, R. (1957). *Dynamic programming.* Princeton: Princeton University Press.
2. De Neufville, R., & Scholtes, S. (2011). *Flexibility in engineering design.* Cambridge: MIT Press.
3. Feinberg, E., & Shwartz, A. (2002). *Handbook of Markov Decision Processes: Methods and applications.* Norwell: Kluwer Academic Publishers.
4. Hopp, W. (1988). Sensitivity analysis in discrete dynamic programming. *Journal of Optimization Theory Applications, 56,* 257-269.
5. ONR. (2011). ONR BAA 11-022 Assessing total ownership cost. *Report*. Office of Naval Research.
6. Puterman, M. (1994). *Markov Decision Processes – Discrete stochastic dynamic programming*. New York: John Wiley.
7. Ross, A., & Hastings, D. (2006). Assessing changeability in aerospace systems architecting and design using dynamic multi-attribute tradespace exploration. *In proceedings of AIAA Space*. San Jose.
8. Tan, C. & Hartman, C. (2011). Sensitivity analysis in Markov Decision Processes with uncertain reward parameters. *Journal of Applied Probability, 48*, 954-967.
9. Wallace, S. (2000). Decision-making under uncertainty: Is sensitivity analysis of any use? *Operations Research, 48*, 20-25.
10. White, C., & El-Deib, H. (1986). Parameter imprecision in finite state, finite action dynamic programs. *Operations Research, 34*, 120-129.

CHAPTER 6 – CASE STUDY #1: RESPONDING TO BALLAST WATER POLICY AND TECHNOLOGICAL DEVELOPMENT

Leadership is a potent combination of strategy and character. But if you must be without one, be without the strategy.

-Norman Schwarzkoph

Past chapters have demonstrated that environmental policy change presents a real and potentially significant constraint to ship designers tasked with achieving life cycle compliance, performance, and affordability. Lock-in can be minimized by determining how best practices will evolve and then how a design can be positioned to capture policy-enabled opportunities and to mitigate policy-driven risks. Efforts to develop a design + design strategy, and measure it against alternative design concepts and their strategies, remain incomplete; limitations and existing needs are detailed in Chapter 4.

This chapter serves to validate the methodology introduced in Chapter 5. The study formulates a discrete time, non-stationary Markov Decision Process 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. A key purpose of this chapter is to illustrate how policy change is incorporated into the MDP framework. The presented results and first application of the changeability metrics proposed in Chapter 5 lead to discussions of design strategy under uncertainty and the sensitivity of product decisions to policy timing.

This case study models the evolution of ballast water legislation, product development across the ballast water management industry, and stochastic degradation of the equipment's internal components. Accrued capital, operating, and maintenance costs are determined. The decision-maker's objective is to devise a ballast water management strategy that minimizes cost over a vessel's life cycle while still achieving performance requirements. The outcome is a life cycle strategy that outlines the expected total investment cost. The decision-making results are instructive for ship managers, ballast water system manufacturers, and policymakers, alike.

Specific objectives for the study from a research standpoint include:

- To firmly anchor Markov modeling of changeability by using past efforts in M&R research as a launching point
- To apply the metrics of the previous chapter to gain insight into their value as decision-making resources
- To demonstrate the strong tie between policy and technology through the use of a historical example

The case study represents a basic design case in order to feature several aspects of the MDP framework, including formation of the decision matrix, sensitivity analysis, and several of the derived changeability metrics. All design characteristics with the exception of the ballast system are assumed fixed. Thus, any design portfolio decision relates to a single, discrete asset among a pool of known investment options.

Early work in this chapter has been presented at the 2011 International Conference on Computer Applications in Shipbuilding (ICCAS) in Trieste, Italy (Niese &Singer, 2011).

6.1 Case Study Background

The following section offers a broad introduction to ballast water management design and policy problem as well as the structural roots from which the problem is constructed as an MDP. Section 6.1.1 provides a cursory overview of current developments in ballast water management. The author believes understanding the technical and political underpinnings of the ballast water system are an important foundation for detailing insights gained by the MDP methodology. Ideation of both the case study and the fundamental arrangement of the policy problem as solvable via a state-based perspective are drawn from past M&R literature, the basis of which is explained in Section 6.1.2

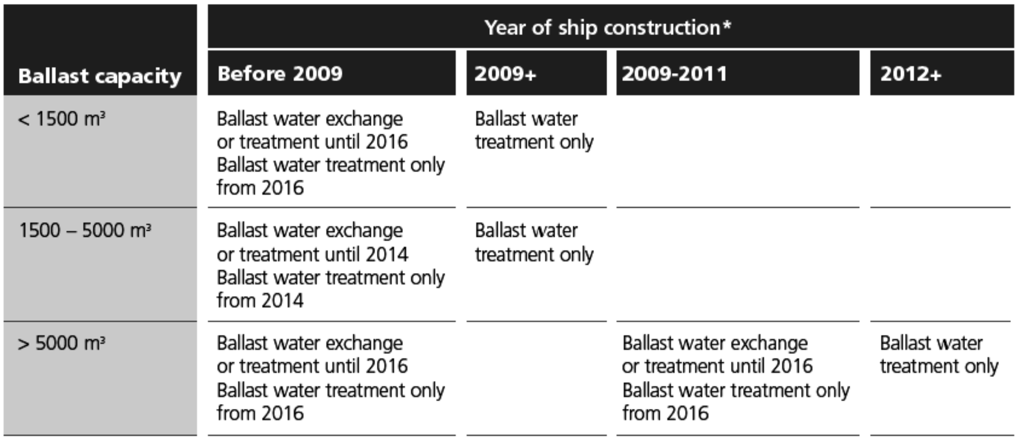
Ballast water system management is selected as the focus of this case study for several prominent reasons. First, a ship's ballast water system can largely be viewed as self-contained. Relatively minor interactions between the ballast water system and other ship systems result in a small, focused application of the MDP framework. Second, recent ballast water policymaking efforts demonstrate the relevance of such a study to ship managers. Interest by ship managers, technology innovators, classification societies, and other related actors has generated studies and summaries of developments in the ballast water arena. These reports and observations provide the wealth of resources used to formulate the transition and reward matrices, as well as mark a baseline with which the model can be judged. Finally, the structure of the ballast water problem represents a bridge between past efforts in the M&R problem and this dissertation's goal of early stage design evaluation with temporal considerations.

6.1.1 Ballast Water Management

Ballast is the fluid a ship takes aboard from the surrounding water to assist with stability as cargo is transported and as reserves such as fuel diminish. Ballast water can contain a diverse array of organisms including bacteria, viruses, and the larval stages of marine life. Transport inside the hull of ships and subsequent disposal in foreign waters can introduce organisms to habitats in which they are non-native. Non-native species that survive and become established can threaten the ecological and economic health of a region through disturbance of the existing food chain. Thus, commercial, government, recreational, and environmental organizations have a stake in the prevention of organism transplants resulting from ballast water practices.

The International Maritime Organization (IMO) implemented the 2004 International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM Convention) to regulate ballast water discharges. The Convention stipulates the use of ballast water treatment systems in place of traditional ballast water exchange. Other policies have been adopted at the regional and state level to further mitigate the risk of introducing non-native species. For example, the State of California and the Great Lakes/Saint Lawrence Seaway both include stricter provisions due to the ecological sensitivity of the coastal waters (Coastal Ecosystems Protection Act of 2006 and National Invasive Species Act of 1996/Clean Water Act, respectively).

Figure 6-1 lists the schedule agreed upon at the BWM Convention for enforcement of ballast water practices on ocean-going vessels. Until 2009, empty-refill or flow-through ballast water exchange was allowed for both existing and newly constructed vessels. By 2016 at the latest, loading and discharging untreated ballast water will be eliminated.



Ballast capacity	Year of ship construction*			
	Before 2009	**2009+**	**2009-2011**	**2012+**
< 1500 m^3	Ballast water exchange or treatment until 2016 Ballast water treatment only from 2016	Ballast water treatment only		
1500 – 5000 m^3	Ballast water exchange or treatment until 2014 Ballast water treatment only from 2014	Ballast water treatment only		
> 5000 m^3	Ballast water exchange or treatment until 2016 Ballast water treatment only from 2016		Ballast water exchange or treatment until 2016 Ballast water treatment only from 2016	Ballast water treatment only

Figure 6-1: IMO Ballast water regulatory schedule (Lloyds Register, 2010)

The technical limitations of a specific system's ability to comply with emerging regulations are a factor in the case study. Primary technical factors for installation of a treatment system include flow capacity, footprint, and cost. Systems are modular in design and can accommodate flows in excess of 5000 m^3/hr. Technologies are derived from municipal and land-based industrial applications. Two process technologies are generally used for treatment: solid-liquid separation and disinfection (Figure 6-2). Often, a combination of processes is employed. Criteria a technology should exhibit include biological efficacy, environmental acceptability of chemicals used, safe handling by crew, and cost-effectiveness.

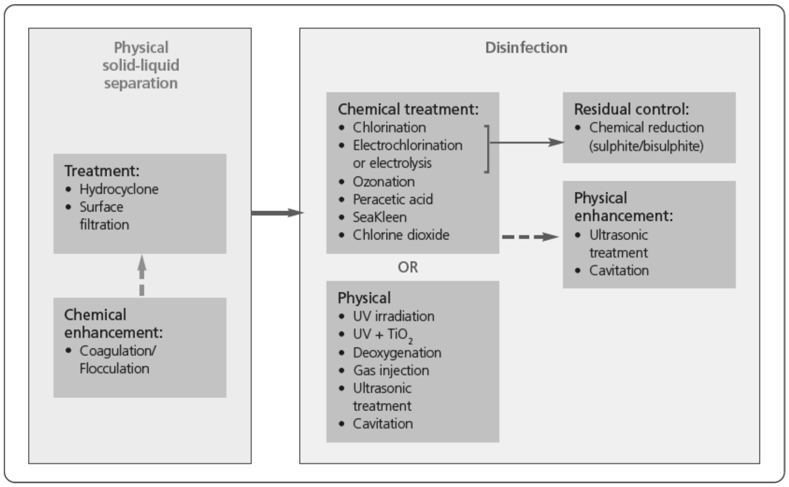
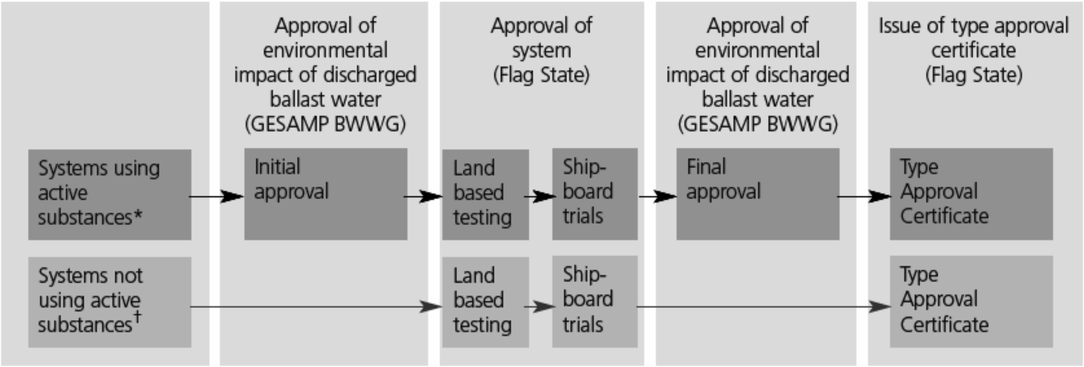


Figure 6-2: Generic ballast water treatment process options (Lloyds Register, 2010)

All proposed technologies are subject to a still-evolving approval process (Figure 6-3). The staged approval process includes basic approval, Flag State approval via land and shipboard testing, and final approval. Current testing methods prevent evaluation with a high level of statistical sensitivity (Swackhamer & Meyer, 2011). Expectations are that the development and implementation of treatment technologies will accelerate as procedures and standard conditions are better defined.



* Includes chemical disinfectants, e.g. chlorine, ClO_2, ozone
† Includes techniques not employing chemicals, e.g. deoxygenation, ultrasound

Figure 6-3: Approval sequence for ballast water treatment technologies (Lloyds Register, 2010)

The approval process presents an especially relevant uncertainty considered in this case study.

6.1.2 Machine Maintenance

The machine maintenance problem was one of the first applications of the sequential decision-making frameworks (Smallwood and Sondik, 1973). Earliest formulations sought to identify when to maintain or replace a product with its new equivalent in order to maximize total profit. Capital costs are typically treated as sunk costs. Time and path dependencies inherent to the machine maintenance problem have led to notable structural results that continue to provide insight into maintenance decisions today (Ross, 1971; Rosenfield, 1976).

Optimal maintenance strategies for improving reliability, controlling failures, and reducing maintenance costs have steadily increased over the last half-century (Wang, 2001). Literature first explored the machine maintenance problem in terms of deterioration, the contributions of which are provided in summaries by Frangopol et al. (2004) and van Noortwijk (2007), among others. Efforts then expanded to consider technological obsolescence (Hopp and Nair, 1994; Hartman and Rogers, 2004), demand economics (Silver and de Weck, 2007), and environmental performance (Spitzley et al., 2005; Kim et al., 2006).

However, the larger design construct remains unchanged in the above applications. Replacement actions consist of replacing Red Version 1 with Red Version 2, as opposed to replacing Red with Blue or determining if Red Version 1 should have been implemented in the first place, for example. Focus on a single, built product versus open design space fails to enable comparative studies that analyze merits and pitfalls of a strategy beyond minimized life cycle cost. Given that replaced equipment may be a part of a larger system, interactions between other subsystems and their respective maintenance actions can also be explored more fully. These efforts demonstrate there is a strong basis for extending the M&R problem one step forward in the process: into design, or the $t=0$ M&R stage, where the decision space is more open.

Injection of environmental concerns in the machine maintenance problem has also been limited to date, with most emphasis on life cycle cost not including enviro-techno-political costs. For example, Singh et al. (2010) designed for life cycle cost using time-dependent reliability, but opted not to consider time-dependent exogenous measures such as environmental regulations or uncertain fuel costs. Sloan (2011) considered environmental performance in the equipment replacement problem but did not address the underlying policymaking space that dictates such performance.

Abstractly, design artifact responsiveness to environmental policymaking is not wholly different from deterioration modeling in the machine maintenance problem. Both issues are concerned with performance reliability and are able to measure performance via life cycle cost. The two key differences include (a) that environmental policymaking is an exogenous disturbance, and (b) that responses to environmental policy can be more varied than the {maintain, replace, do nothing} action set typically deployed to handle physical deterioration. Linking policy change and design decisions requires that the state structure within the M&R problem accommodate the statuses of both the machine and the exogenous disturbance regime. A wider set of policy directions and corresponding change options means that machine maintenance under uncertain policy is more a machine *strategic positioning* problem. Both the modified structural basis of the M&R problem and decision strategy are on display in the research presented in this chapter.

6.2 Design Variables

The following section details problem setup of a case study involving ballast water management on ships, rooted in historical context, for which an MDP is featured. The objective, variables, and decision criteria are outlined. Design variables model elements introduced in Section 6.1, including system efficacy, policymaking approval processes, and M&R state space construction, in a manner that helps validate use of the methodology proposed in Chapter 5.

6.2.1 Objective Function

Consider a single-component machine that operates continuously. The machine deteriorates over time, operating until failure or until a decision is made to remove the machine from service. The decision-maker is faced with a choice of whether to keep the existing piece of equipment or to find an alternative that may demonstrate improved performance in term of cost, revenue, and/or environmental burden, for example. Any decision is further complicated by the fact that new technology or a change in regulations may occur stochastically in time.

The objective remains the same despite the uncertain future: to maximize profits for the life cycle of the machine. In the case of a ballast water system, where no revenue is earned, the objective is simply to minimize cost. The life cycle economic equation is summarized below:

$$\text{Cost}=\min(\text{Capital Cost} + \text{Install Cost} + \text{Operating Cost} + \text{Maintenance Cost}) \qquad [6\text{-}1]$$

Disturbances due to deterioration, technology development, and policymaking impact the economic profile of a machine. These disturbances may be compounding or cancelling. Increasing machine deterioration leads to a decrease in profits and an increase in maintenance cost. Life cycle decisions are also impacted by external factors, namely, technology and regulations. For example, an increase in operating expenditures may result from additional regulations and their associated compliance costs. Technology and policymaking evolve over time, and at each epoch, there exists potential that a new technology option has become available or that a regulation has been introduced.

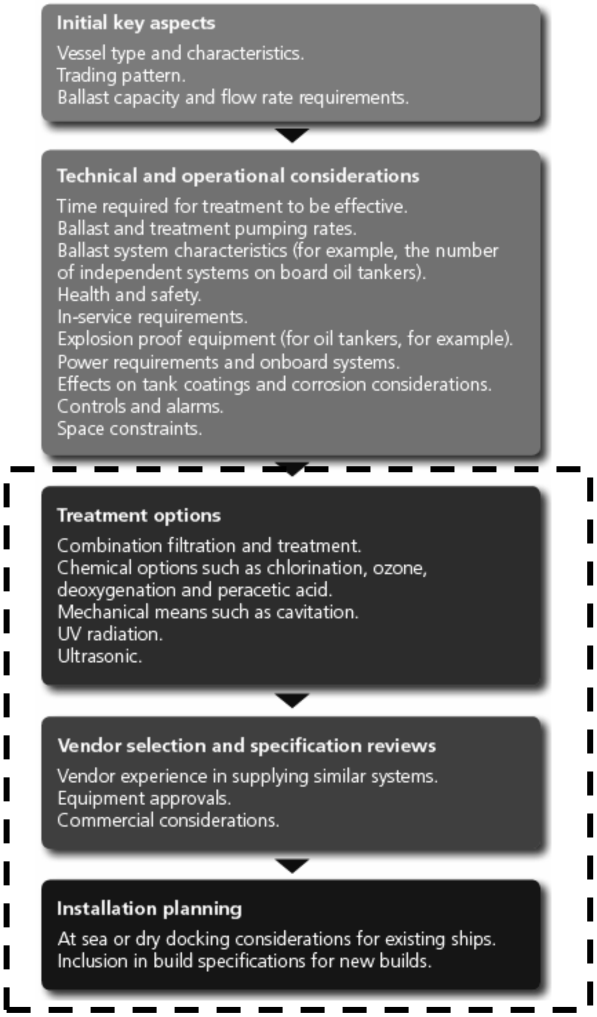
6.2.2 Independent Variables & Setup

A 150,000 DWT containership with 30,000 MT ballast water capacity is used. The vessel sails between two ports, one in California and the other in China. Depending on market conditions and seasonality, round-trip transit times vary between 28-40 days. Total capacity for an installed ballast water treatment system must exceed 10,000 m^3/hr.

Figure 6-4 illustrates the steps to selecting a ballast water system. The system boundary is noted by the dashed box. Decisions will consider the treatment type, approval status, and implementation venue. The case study fixes the initial key aspects and technical and operational considerations.

A 20-year time horizon, representing the life of a ship, is employed, commencing in the year 2000 and before the BWM Convention occurred in 2004. A reflective view enables this case study to validate results against historical events and reduces uncertainty involved in generating transition and reward values.

The scenario considers ten historical systems, with System A representing the standard pump system for ballast water exchange and Systems B-J representing commercial ballast water treatment systems. Performance, capital costs, operating expenditures, and availability and approval status details are elicited from reports by Lloyd’s Register (2010, 2007) and the California State Lands Commission (2010).


Initial key aspects
Vessel type and characteristics.
Trading pattern.
Ballast capacity and flow rate requirements.

Technical and operational considerations
Time required for treatment to be effective.
Ballast and treatment pumping rates.
Ballast system characteristics (for example, the number of independent systems on board oil tankers).
Health and safety.
In-service requirements.
Explosion proof equipment (for oil tankers, for example).
Power requirements and onboard systems.
Effects on tank coatings and corrosion considerations.
Controls and alarms.
Space constraints.

Treatment options
Combination filtration and treatment.
Chemical options such as chlorination, ozone, deoxygenation and peracetic acid.
Mechanical means such as cavitation.
UV radiation.
Ultrasonic.

Vendor selection and specification reviews
Vendor experience in supplying similar systems.
Equipment approvals.
Commercial considerations.

Installation planning
At sea or dry docking considerations for existing ships.
Inclusion in build specifications for new builds.

Figure 6-4: Selection process of a ballast water treatment system (Lloyds Register, 2010)

6.2.3 Actions

Decisions—do nothing, provide maintenance, or replace machine—occur at regular inspection intervals. The effect of each action is summarized below:

- ‘No Action’—The unaffected machine continues to deteriorate; denoted ‘DN’
- ‘Maintain’—The machine is restored to a less deteriorated state, based on maintenance efficiency; denoted ‘M’
- ‘Replace’—The machine is substituted by a new machine, possibly containing improved performance or marked by lower operating costs; denoted ‘R + system identifier’

Then, let the action vector at decision epoch, *i*, be denoted as $\mathbf{A_i}$={DN_i, M_i, RA_i, RB_i, RC_i, RD_i, RE_i, RF_i, RG_i, RH_i, RI_i, RJ_i}.

6.2.4 States

The state is represented by the ballast system installed, as well as the approval status and deterioration level of the system. A non-stationary structure is considered for the problem due to changing technology and regulations over time. The state must also track epochs due to this non-stationary structure, leading to the following full state description: *epoch_system_status_deterioration*.

Six status levels per system exist: unavailable, commercially available, basic approval, final approval—low, final approval—medium, and final approval—high. The low, medium, and high final approval designations correspond to IMO, State of New York, and State of California ballast water regulations, respectively. The State of New York is roughly a factor of 10x and the State of California approximately 100x the strength of the ballast water regulations currently under consideration by the IMO.

The case study mirrors the events since the 2004 Ballast Water Convention, in which dozens of companies selected to develop ballast water treatment systems. Commercial availability of the systems varied, and once efficacy testing was in place, the systems were certified with a performance rating. Historical research demonstrates that basic approval was generally granted when testing came online, and final approval was granted 6-24 months following basic approval.

The deterioration state, *x*, is represented as a percentage of total deterioration and is discretized into *m* intervals, allowing the state to be modeled by the lower-bound of the interval $x \in \{0,1/m,2/m...(m-1)/m,1\}$. Maintenance actions repair the deteriorated state by a maintenance efficiency, *d*, and result in a next deterioration state of *max*{0, x-d}.

6.2.5 Transitions

Machine degradation is often modeled via a Gamma distribution (van Noortwijk, 2007). The exponential distribution, a special case of the Gamma distribution, presented below, is used in this case study.

$$f_j(x)=\lambda(j)e^{\lambda(j)x} \qquad [6\text{-}2]$$

At any decision point, deterioration transitions are independent, identical, and follow an exponential distribution with parameter λ. The parameter λ is a function of the system's treatment method, *j*, as ballast water treatment systems using filtration, electrochlorination, cavitation, radiation, de-oxygenation, and/or ozone-generation degrade uniquely. The system-specific reliability parameter is thus represented as follows:

$$\lambda(j)=a(j)*e^{-b(j)}+c(j) \qquad [6\text{-}3]$$

State transitions are also caused by changes to the environment. The following regulatory stages are considered in the scenario:

- A ballast water convention is held, outlining the strength of proposed legislation and the expected date of enforcement, pending ratification
- Labs and procedures dedicated to testing ballast water treatment efficacy are made available
- Legislation is ratified
- Legislation enters force

The status of a commercial treatment system, *k*, is dependent on the regulatory profile for ballast water treatment. For example, due to lack of demand before a convention is held, commercial availability of a treatment system is highly unlikely. Similarly, final approval must be preceded by basic approval, which is dependent on both commercial availability of the product and the availability of procedures and laboratories to test the product. Availability potential increases following a convention, testing procedures, and/or ratification.

Here, research, development, and launch timelines are derived from historical data. Actual past events serve as the mean year of commercial availability, and the author incorporates normal probability distributions about the mean to model uncertainty. Table 6-1 details the expected years following a convention before a system is commercially available. Realistically, external competitive forces shape when a firm is most likely to launch its treatment system.

Table 6-1: Maximum achievable performance, availability

System	Maximum Performance	Expected Availability (yrs after Convention)
A	Exchange	-
B	Treatment-High	3
C	Treatment-High	2
D	Treatment-Low	7
E	Treatment-Low	3
F	Treatment-Medium	5
G	Treatment-High	7
H	Treatment-High	5
I	Treatment-Medium	4
J	Treatment-High	3

External regulatory factors and approval status also determine the ability of a firm's product to satisfy the performance needs of a client. For example, ballast systems employing physical treatments have been noted for their inability to satisfy stringent standards under consideration in California. Table 6-1 outlines treatment efficacy potential for each system. Five systems (B, C, G, H, J) are not constrained by regulatory strength. Systems B, C, and J also hold a second advantage of early-to-market capability.

In summary, the total transition probability is denoted $T_i(x',j',k'|x,j,k,a)$. Each case-study scenario considers 1.1 million unique state-to-state transition combinations. Not all states are reachable or actions actionable if the external environment has precluded certain transitions, examples of which include: deterioration status cannot improve when action 'DN' is performed; action 'RA' cannot be instituted if the regulatory environment requires ballast water treatment; and ‘RC’ is not actionable if System C is not yet commercially available.

6.2.6 Rewards

Several resources provide insight into the capital expenditures, installation costs, and annual maintenance and operating expenses. Table 6-2 summarizes data sampled from Lloyd’s Register 2007 and 2010 reports, a California State Lands Commission 2009 study, and work by Rigby and Taylor (2001).

Table 6-2: System-specific reward information

System	Capex ($/2000m^3/hr)	Install ($/2000m^3/hr)	O&M ($/m^3/hr)
A	50/50	0/0	0.06
B	800/820	40/55	0.08
C	950/1200	5/15	0.07
D	950/1500	50/65	0.06
E	690/670	60/60	0.13
F	800/450	80/100	0.32
G	500/975	65/125	0.013
H	1600/1600	5/15	0.06
I	559/600	100/150	0.03
J	1800/1200	25/40	0.01

Legend: # / # in Capex column corresponds to costs before/after Basic Approval
 # / # in Install column corresponds to costs newbuild/retrofit

Capital Expenses

Capital cost is listed for both before and after a system is granted Basic Approval. Trend data for capital costs demonstrate marked increases following approval, signifying, perhaps, that technology validation has warranted a price increase, that firms offer their products at heavy discounts for early adopters, or that supply-demand economics allow for such an increase. Note that capital cost is not directly a function of performance (Table 6-1 & Table 6-2).

Recall discussion in Section 4.1.2.9 regarding opportunity windows. Evidence drawn from this case study aided the author in clearly articulating the role of opportunity within a disturbed environment.

Installation Costs

A system that is installed on a new build or as a retrofit is also an important distinction. Depending on system type and treatment, installation costs vary from 1-25% of the capital equipment cost. The study assumes that sufficient space exists within the ship to install the necessary equipment for any system type and treatment.

Operation & Maintenance Costs

Similarly, operation and maintenance (O&M) cost is a function of treatment method. Systems employing ultraviolet require periodic replacement of lamps, for example, and many treatments require replenishment of chemical additives or filter replacement. Studies have listed maintenance costs as a function of use, not time.

Equipment operates less efficiently as deterioration occurs, often increasing operating costs. Thi et al. (2010) suggest using an increasing convex function for operating cost, below:

$$\theta(x)=\theta_0+g_\theta x e^{\lambda(j)x} \qquad [6\text{-}4]$$

The full O&M cost is described as follows:

$$\text{O\&M Cost}=\text{Annual trips(i)}*\text{Required Ballast}*\theta(x) \qquad [6\text{-}5]$$

Operating cost fluctuates per year due to the fact that the number of annual trans-Pacific trips varies throughout the vessel’s life cycle.

6.2.7 Decision Criteria

The MDP framework finds a policy that minimizes the expected discounted cost over a finite horizon, denoted $V^\pi(s)$. The notation $V^\pi(s)$ is equivalent to $V_1(s)$, as the value at the first decision epoch includes the cumulative discounted value over all decision epochs. Let $V_i(s)$ denote the minimum expected discounted cost to-go, i.e. from decision period, *i*, to the final decision epoch, *N*. Then,

$$V_i(s)=\min\{DN_i(s), M_i(s), RA_i(s), RB_i(s), \dots RJ_i(s)\} \qquad [6\text{-}6]$$

No salvage revenue is obtained or cost is incurred at product retirement. The value for decision period *N+1* is thus $V_{N+1}(s)=0$ for all states.

The value of each action may be denoted as:

$$DN_i(x,j,k)=-r_{i,DN}(x,j,k)+\gamma\ \Sigma\ T_i(x',j,k'|x,j,k,DN)\ V_{i+1}(x',j,k') \qquad [6\text{-}7]$$

$$M_i(x,j,k)=-r_{i,M}(x,j,k)+\gamma\ \Sigma\ T_i(x',j,k'|x,j,k,M)\ V_{i+1}(x',j,k') \qquad [6\text{-}8]$$

$$RA_i(x,j,k)=-r_{i,RA}(x,j,k)+\gamma\ \Sigma\ T_i(x',j,k'|x,A,k,RA)\ V_{i+1}(x',j,k') \qquad [6\text{-}9]$$

6.3 Results

Conducting sequential optimization using the design variables described above within the MDP framework delivers a M&R strategy under uncertain policy development. The resulting decision and expected value matrices are inadequate for communicating to the design engineer the relevant life cycle features of the optimal strategy. Additional analysis and application of certain metrics introduced in Chapter 5 offer a greater level of information richness, including:

- Temporal outdegree – conveys limits to state changeability through time
- Sensitivity analysis – describes robustness of strategy to policy strength, policy timing and capital costs of treatment system
- Context premium – describes the role of uncertainty in executing the optimal strategy
- Time-weighted cost incurred – incorporates greater appreciation of the cost vector
- Management level – details the active role required by a decision-maker to plan and execute strategy

The results of the case study are presented in the following formats: the standard decision matrix, threshold-limited action tree, and as decision path simulations. The unique presentation formats enable comprehensive analysis of resulting state-action sequences.

The results also prove informative from a problem development standpoint, including:

- The importance of efficient design state structure. Many variables that change with time can be added to the state matrix, but not all variables are relevant for determining the action plan. Efficient problem setup requires differentiating between variables involved in functions separate from decision-making, variables indirectly affecting actions via incorporation into transition and reward matrices, and those elements which must be made explicit in the state matrix to allow a designer to understand the implications to the optimal policy of entering a specific state.
- The difficulty representing results given a large state size and non-stationary structure. The author witnessed a lack of metrics and forms of design-assisting representation in past research efforts that clearly communicate the optimal policy and its associated characteristics.
- The ease with which dynamic programming using computer assistance can be conducted, despite involving a large state matrix. Thousands of value functions can be calculated in a matter of seconds.

6.3.1 Standard Output: Decision Matrix

The primary output from an MDP is the set of actions corresponding to each state through time. A sample segment of the full decision matrix, Figure 6-5, illustrates decision patterns given a currently installed system, new system availability, and deterioration. The optimal policies for different legislation sequences (convention date, testing availability, ratification, in-force date) are produced. Because the case study is non-stationary, state-action combinations can also change with time.

The results of the sample decision matrix match intuition: standard ballast water exchange pumps (System A) should be maintained as necessary over the first years of the life cycle, followed by installation of a new treatment system once the in-force date occurs. Analysis of the sample legislative sequence governing the decision matrix in Figure 6-5 shows that Systems G, F, and I are possible preferred treatment systems to consider as transitions from System A.

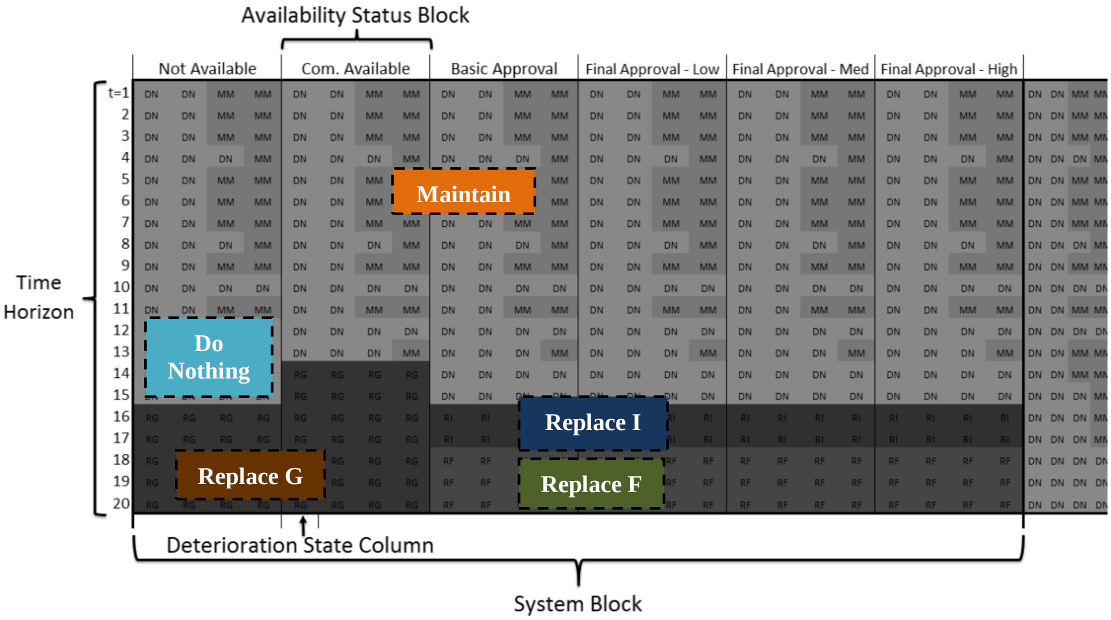


Figure 6-5: Sample decision matrix segment (Niese & Singer, 2011)

The decision matrix, as it stands, is only marginally useful to a design manager. First, the information contained within a decision matrix can become unmanageable in instances where the state matrix is large. Figure 6-5 represents approximately 1/10th of the total decision matrix. All told, the optimal policy consists of 4800 (state, action) pairs across the full horizon.

Second, a primary take-away expected by a design manager is a distilled vision of the sequence of actions to be selected, foregoing all interest in states that are unreachable or suboptimal. For example, System F is determined unreachable by deduction of Figure 6-5, because by Year 18, Systems G or I will already have been installed and the current state will no longer be located in the segment of the decision matrix provided above. A decision-maker should not be expected to deduce unreachability or be led to believe a ‘Replace with System F’ action forms a part of the M&R strategy. An added step in analysis should differentiate between an optimal, reachable action and an optimal but unreachable action.

Finally, the decision matrix does not give added insight into backup actions should technology development of the preferred system be hindered and certain actions prove unavailable. The optimal policy is conditional upon availability of actions and state entry, which themselves are probabilistic in this study. Thus, the host of suboptimal but potentially exercised actions should also be clearly articulated.

Several issues identified here are otherwise addressed in later sub-sections by the author using metrics and representations offered in Chapter 5. First, the second standard output of an MDP, expected cost, is detailed.

6.3.2 Life Cycle Costs

Recall that the objective of the decision-maker is to discover a strategy that minimizes expected cumulative life cycle cost. Expected life cycle costs are comparable across regulatory strengths and across legislation sequences. The most expensive scenario is a ‘Treatment-High’ early life cycle enforcement date, corresponding to an expected life cycle cost of $3.9M. The least expensive regulated scenario is a ‘Treatment-Low’ late life cycle enforcement date, yielding a $2.1M cost. In this latter scenario, the owner/operator may elect to retire the vessel early so as to forego installation required by legislation. The author estimates the cost of a 150,000 DWT containership is $100M. Thus, the $2.1-3.9M range is largely consistent with findings by Lloyd’s Register that ballast water legislation amounts to an additional 2-3% of total build cost.

6.3.3 Decision Tree

One method for more appropriately identifying action sequence results is to construct a threshold-limited decision tree, illustrated in Figure 6-6. The decision tree is threshold-limited in that only actions called for by multiple, or likely, reachable states are shown. The example tree demonstrates that systems G or I are preferred actions resulting from reachable states and given all probabilistic external factors.

The benefits of such an approach are two-fold. By following all non-zero probability transitions through time, one can note the states accessed and unique actions prescribed.

Knowing which (state, action) pairs are accessible may allow one to significantly reduce the size and scope of the decision matrix. Secondly, a review of the number of unique sequences determines how many decisions a design manager might be asked to make over the life cycle and how many options might be considered at each decision step. This second point is better summarized through management level calculations in Section 6.4.4.

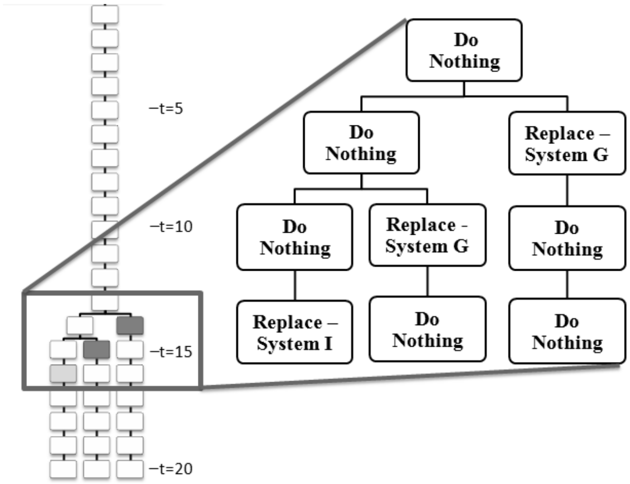


Figure 6-6: Sample threshold-limited decision tree

Again, drawbacks to the decision tree are presented. The tree says nothing about the likelihood of following one sequence over another. Second, determining an appropriate threshold involves a value judgment on the part of the design manager, and the tree itself can grow to an unworkable size for analysis. Even a non-stationary state matrix with two threshold-exceeding actions per epoch across the 2-year horizon can result in combinations of 1M+ unique pathways. The issue with representing potential unavailability of the preferred action also remains unresolved.

6.3.4 Simulated Decision Pathways

Simulations prove to be a complementary solution to the decision tree, capable of managing the explosion of results and for dealing with action unavailability. To perform one round of simulation, randomly select a series of non-zero probability state-to-state transitions, one per time, and then execute the appropriate actions. Conducting rounds of simulations can draw the highest frequency action sequences to the forefront. Should a preferred action prove unavailable during a simulation, the next best action can be selected; the MDP structure is such that the reward impact of every action is calculated, leaving an ordered ranking of actions per state, per time step.

An author-defined *decision path* is one method for communicating the results of the simulation. The decision path rapidly summarizes the epoch-specific action types and frequencies exercised in simulations. Optimal actions within the available action set are displayed, unlike what is presented in the non-differentiated decision matrix. The decision path plot is also much more compact than the threshold-limited decision tree.

Figure 6-7 showcases a sample decision path as called for by the decision matrix under the simulated conditions. In 80% of one scenario's runs, System G is available by Year 14 and should be installed at the time that corresponds to the year prior to granting of Basic Approval. In approximately 20% of the runs, likely due to the unavailability of System G at Year 14, System I at Year 16 is the optimal solution within the available action set. A distinguishing feature related to decision timing is that the significant price break on capital expense for System G encourages adoption before Basic Approval is granted, while the price break for System I does not outweigh the benefits of waiting until legislation enters force.

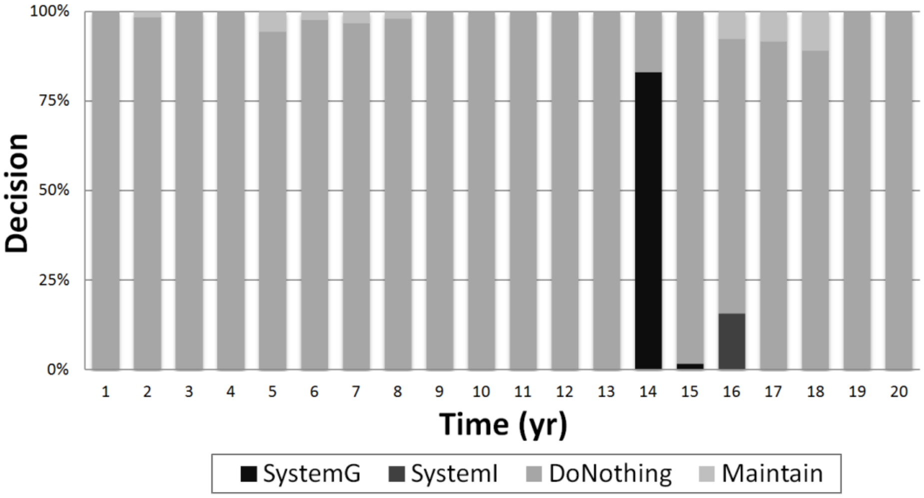


Figure 6-7: Sample decision path output (Niese & Singer, 2011)

Per regulatory scenario, 10000 simulations of treatment equipment's commercial availability and annual trans-Pacific trips are conducted.

While the number of simulations is just a fraction of the total *state* sequences, the simulations can be expected to capture all but rare *action* sequences. Estimating the timing and type of an actionable decision can serve a design manager well in terms of planning, scheduling, budgeting, and strategy-making. Diagnosing and minimizing the effect of rare, but potentially extreme, sequences is an open problem that can be addressed using robust and risk-constrained techniques.

6.3.4.1 Sensitivity: Legislative Sequence

The following two decision paths illustrate how the preferred system to install can be affected by the legislative sequence of events. The mandated regulatory level is that of 'Low,' or equal to the proposed standards set forth by the IMO Ballast Water Management Convention of 2004. Optimal systems to install depend on the relative timing of legislation proposal, testing availability, ratification, and entering force (herein denoted by respective implementation sequence, ex. 01-04-04-09).

When the time between legislation proposal and the legislation entering force is short, one of multiple systems, at widely varying capital costs, may be chosen. High-cost optimal selections result from the fact that few treatment options are available at the required in-force date. Figure 6-8 illustrates an instance where Systems B, E, and I are potentially optimal treatment options.

Such a result confirms a first-to-market advantage for equipment suppliers, but also illustrates to a design manager that little opportunity for strategy exists. Because policy implementation and technology development occur simultaneously, no early adopter benefits are present. All decisions can thus be viewed from a compliance lens. Had an early adopter advantage existed, the decision path results might see a system installed across different years.

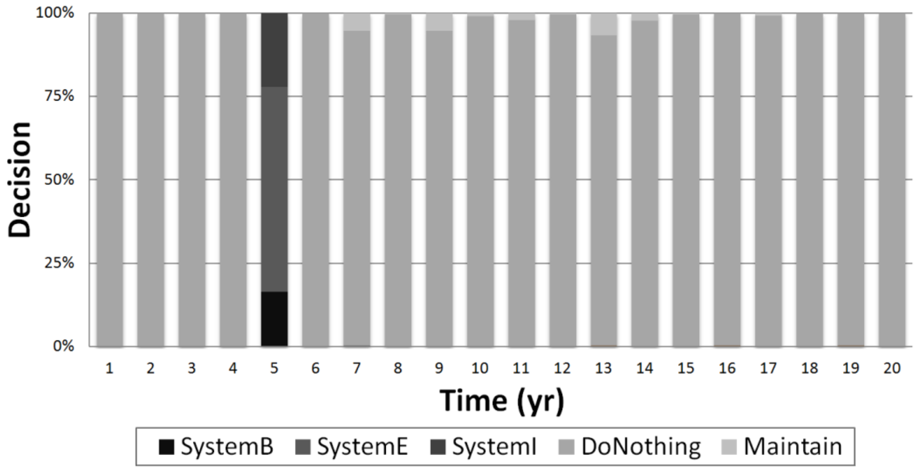


Figure 6-8: Decision path for 01-03-02-05 sequence, regulatory treatment level 'Low' (Niese & Singer, 2011)

Figure 6-9, below, illustrates the scenario where the ballast water treatment market has matured and Final Approval has been granted to a number of treatment options. The preferred option (System I) and decision path is nearly constant across all runs. System I stands as a near-unanimous system install of choice, and the replacement decision is robust to stochastic operating factors. Again, the strategy drawn from this instantiation of policy development is one of pure compliance.

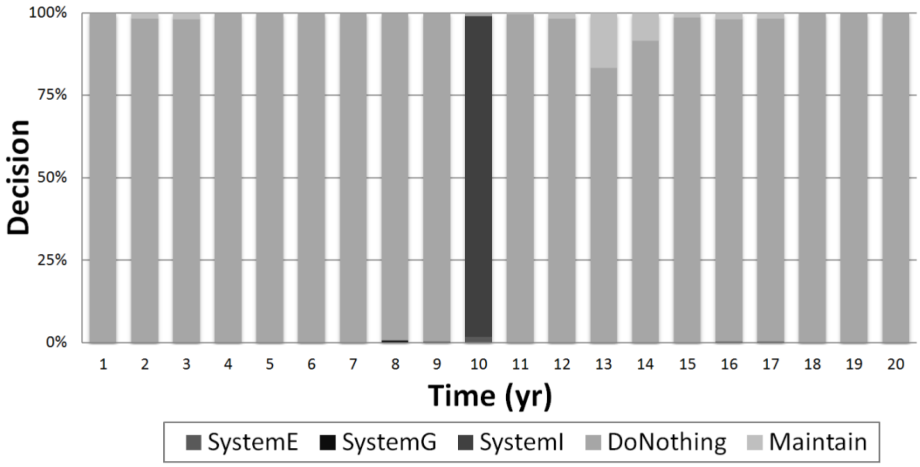


Figure 6-9: Decision path for 04-08-06-10 sequence, regulatory treatment level 'Low' (Niese & Singer, 2011)

6.3.4.2 Sensitivity: Regulatory Level

The following two decision paths illustrate how the preferred system and installation timing are affected by regulatory strength. Figure 6-10 details the decision path for the 'Medium' regulation, while Figure 6-11 showcases the 'High' regulation level, both for a 04-14-16-17 sequence.

System I, strongly preferred at 'Medium' strength, does not satisfy the 'High' scenario and is unavailable to the decision-maker. In the former scenario, the late-life timing of testing availability and small price break for being an early adopter call for System I to be installed when legislation is set to enter force. However, in the latter scenario, the substantial price break for early adoption of System G encourages a decision-maker to install when Basic Approval testing comes online. In 20% of the simulated runs where System G is not yet commercially available in Year 14, a decision-maker waits until Year 17 to install the more affordable System B.

It is also worth noting how the regulatory strength, for the same legislation sequence, affects cost. The expected cost difference between the scenarios portrayed by Figure 6-10 and Figure 6-11, for example, amounts to $400k, or roughly 12%. In other scenarios, such as that illustrated by Figure 6-9, the cost difference is negligible.

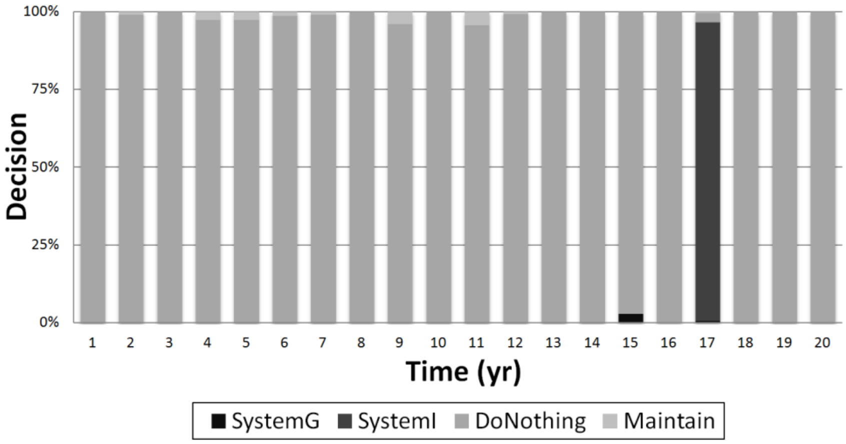


Figure 6-10: Decision path for 04-14-16-17 sequence, regulatory treatment level 'Medium' (Niese & Singer, 2011)

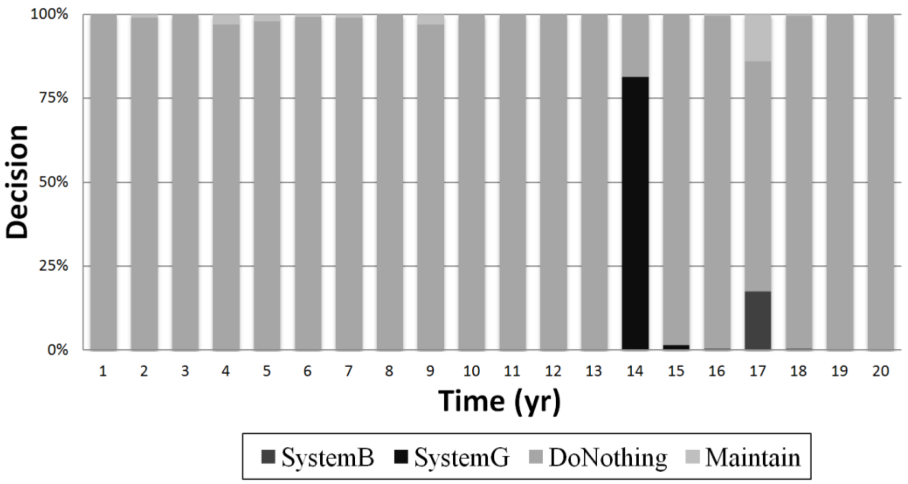


Figure 6-11: Decision path for 04-14-16-17 sequence, regulatory treatment level 'High' (Niese & Singer, 2011)

6.3.5 Strategy Summary

Ultimately, the legislation specific optimal policies tend to produce a succinct overall *strategy*, summarized in Table 6-3. Legislation sequences that call for mid-life cycle decisions are separable based on the time span between testing availability and a regulation entering force. A short span, defined as less than a three year difference, calls for decision-makers to take advantage of the early adoption discount. A large span finds it preferable to wait until legislation enters force to act. Execution of the early life cycle strategy involves greater uncertainty due to dependence on external technology development.

Table 6-3: Strategy under uncertain legislation sequence

		Legislation Strength		
		'Low'	**'Med'**	**'High'**
Timing of Policy Enactment	**Early Life cycle**	B, E, I	B, I, J	B, J
	Mid, Late Life cycle—Early Testing	I	I	B
	Mid, Late Life cycle—Late Testing	G	G	G
	End Life cycle	F	F	B

Knowing the strategy and its sensitivity to policy sequence and policy strength arms a decision-maker with the link between alternative futures and alternative actions. Strategies taking advantage of opportunity windows convey offensive tendencies. Early detection and response might correspond to a strategy description Fricke et al. (2000)

describes as front-loading. Conversely, a wait-and-see approach favors a strategy of simple compliance. A methodology for strategy identification represents a major contribution of this dissertation.

6.4 Characterizing Strategy & Changeability

A decision-maker is likely to want to evaluate the merits and downfalls of a strategy beyond satisfying a strict expected net present value cost objective. From a holistic and learning perspective, understanding the underlying principles governing a strategy may be far more important than the tactical decisions called for by the strategy. One may want to answer what characteristics define a compliance strategy versus alternative strategies beyond simply timing of a decision, for example. This dissertation argues that characteristic differentiation of a strategy pertains to uncertainty levels, degrees of changeability, and management involvement.

Strategy evaluation leads to additional questions, including:

- In legislative sequence situations where tactical decisions are more mixed, how variable are the per-sequence life cycle costs?
- Is the mixed decision-making due to internal operating requirements or techno-political factors?
- How limited is the ability to change?
- What degree of active management is required to execute the optimal action sequence?

The proposed metrics of Chapter 5 are systematically introduced to answer just such remaining questions. First, Table 6-4 lists the summary details and statistics from the simulations of a 05-10-10-12 policy schedule, ‘Low’ policy strength scenario. Figure 6-12 illustrates the expected cumulative cost as well as the mean cost paths for each of the unique action sequences.

The combination of economic, technical, and political dynamics involved in the model lead to four unique action sequence realizations. The summary table conveys a strong likelihood of performing replacement action ‘RI.’ The globally optimal replacement action is ‘RG,’ but a decision-maker is prevented from executing this action in all simulations due to uncertain state transitions and/or action unavailability. The sequences are unique with respect to the replacement action specified as well as the timing in which the replacement action occurs.

Table 6-4: Notable statistics for Scenario 05-10-10-12

# Simulations	10,000
Expected life cycle cost	\$2.45M
St. dev. life cycle cost	\$0.15M
Minimum life cycle cost	\$2.12
Maximum life cycle cost	\$3.11
# Unique action sequences	4
Action sequence Likelihood	0.18% [Replace w/ System G @ t=9] 2.24% [Replace w/ System G @ t=10] 17.4% [Replace w/ System G @ t=11] 80.2% [Replace w/ System I @ t=12]

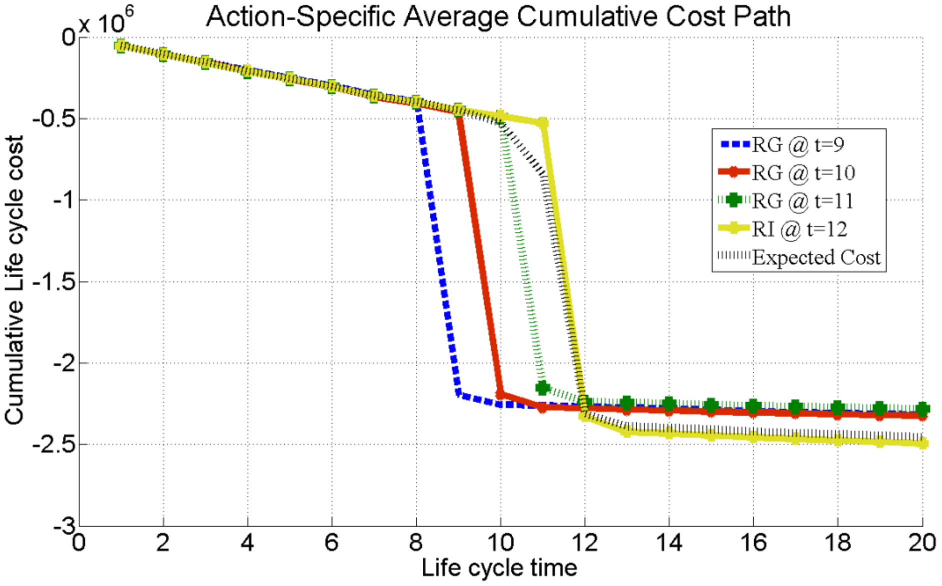


Figure 6-12: Mean cost paths for unique action sequences under 05-05-05-12 scenario following optimal decision-making

6.4.1 Temporal Outdegree

Figure 6-13 illustrates the state entry plot for the same scenario. The state entry plot illustrates the likelihood with which exact states are available through time. States marked with hatching are 100% unavailable given ballast water regulations, technology development, and transition rules.

The state entry plot rapidly illustrates how few technology systems are available for much of the horizon studied. About a decade in, much of the technology set exhibits some likelihood of reaching commercial availability and regulatory approval. The lack of commercial availability certainty for some systems by Year 12, however, denotes a potential techno-political limitation to changeability.

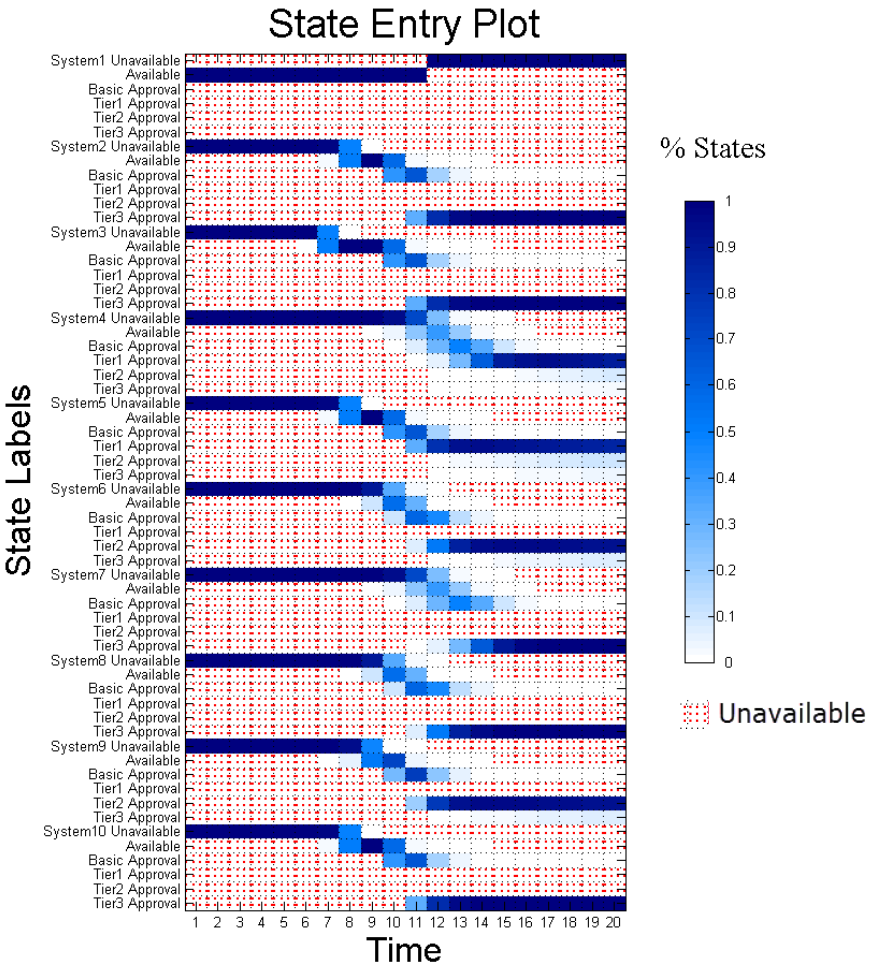


Figure 6-13: State entry plot illustrating probability of a state being accessible through time

The techno-political role on system reachability through time is made further evident via the temporal outdegree plot, Figure 6-14. Exploring the technical, political, and economic limits differentiates the constraints to reachability. The critical year for changeability is

Year 12, as it is at this time that all vessels without ballast water treatment systems are no longer in compliance with international regulations. The figure demonstrates that reachability is not limited due to economic filters. Political limitations eliminate the lowest cost replacement solution, System A, in Year 12, but otherwise play no continued role. Conversely, technology limits to reachability play a prevalent role early but improve with time as additional systems achieve commercial development stage.

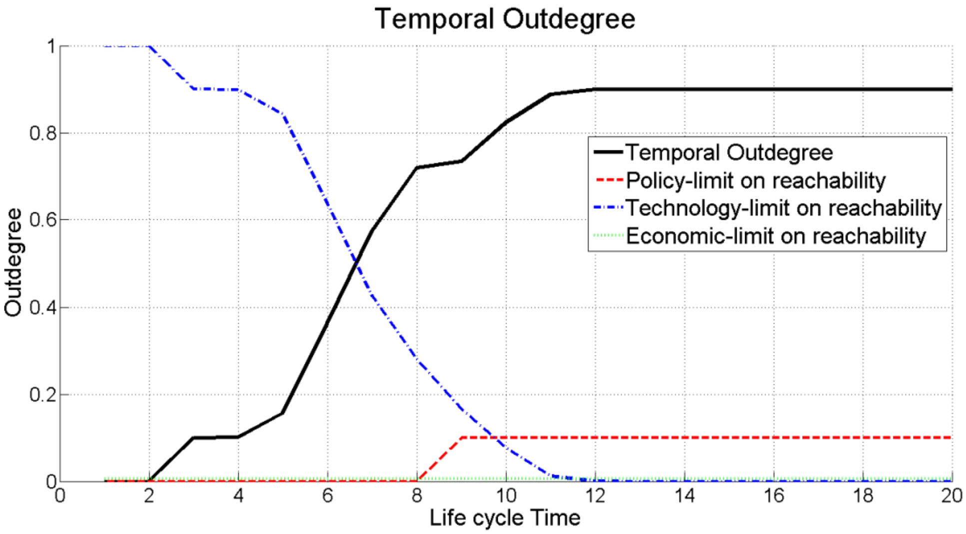


Figure 6-14: Temporal outdegree and limits to system reachability, scenario 05-05-05-12

Trends in outdegree with time highlight the role of changeability limitations in the execution of a strategy. On average across simulations, only 50% and 82% of the ballast water technology set is reachable in Year 9 and Year 12, respectively. Any exogenous limits to performing action 'RG' at Year 9 are technological in nature.

6.4.2 Context Premium

Unique action sequences are borne out of uncertain transitions, state reachability, and action availability. The impact of uncertainty on the action sequence executed is summarized via two metrics: context premium and management level. This subsection addresses context premium, which measures the role of uncertainty on expected life cycle cost.

A low versus high context premium measurement may offer important design insights. A variety of potential action sequences with nearly equal expected life cycle costs may be of little issue when attempting to strongly reduce uncertainty or constructing a budget. Here, the corresponding low context premium indicates cost insensitivity of strategy execution to uncertainty. However, action sequences that dictate wholly unique cumulative cost profiles are potentially a more significant concern. Here, a decision-maker has strong incentive to manage both change *and* uncertainty in (state, action) pairs.

Figure 6-12, above, illustrates the difference between the best cost path and the expected cost path for the policy scenario under investigation. The divergence in paths is appreciable beginning in Year 9.

The presented scenario results in a context premium of 7.5%, stemming from a combination of commercial unavailability of the full complement of ballast water treatment systems and policy factors affecting purchase prices. Given the regulatory schedule of the above scenario, System G is selected in approximately 20% of the simulated runs. System unavailability leads a decision-maker to select System I the remainder of the simulations, incurring a cost premium over the preferred System G.

The optimal policy is to capture the early adopter price offered for System G by waiting until the option becomes commercially available but before it receives Basic Approval. However, the regulation for all vessels to treat ballast water onboard is put in force before all technology options are commercially available. System G is expected to enter the market later than other treatments. Thus, a decision-maker’s policy is more uncertain as the pace of the regulatory schedule from convention to enactment quickens.

Technologies that are faster-to-market understandably can capture greater market share when the regulation enters force quickly. Quick regulation entry constrains change options and can amount to artificially choosing winners and losers with less regard for the economic concerns of ship managers. Conversely, delaying a regulatory schedule may come at the expense of continued externalities the policy is intended to mitigate. Policymakers must trade off the premium ship managers incur due to policy-driven uncertainty with the responsibility to care for society.

6.4.3 Management Level

Horizon activity level and mean epoch attention level are metrics used to measure the role of uncertainty in management involvement. The two measurements are discussed below for the scenario under consideration in Section 6.4.

Horizon Activity Level

Each unique action sequence commits to only one action other than ‘do nothing’ across the full 20 year horizon. The scenario is set up such that a single replacement action is needed to cost-effectively provide desired functionality and compliance. The result is a horizon activity level of 0.05, for which a product manager can determine if such life cycle decision-making involvement is acceptable for the ballast water system. In this case, any less management involvement would require (a) installation of a ballast water treatment system during ship construction, or (b) an ability to receive a compliance waver and to continue using ballast water exchange.

Epoch Attention Level

As discussed previously, the product manager must remain attentive to political, market, and technological developments to determine which treatment option is best to install. The decision-making component within the four unique action sequences is simply to determine which epoch to initiate the replacement action (see: Table 6-4, Figure 6-12). The result is an $\overline{EAL}$ value of 0.2. Figure 6-15 illustrates activity level over time, demonstrating the time and degree of attentiveness required. Here, attentiveness starts in Year 9 and spans until Year 12. The decision-maker need only be attentive to exogenous factors surrounding the single ballast technology at each epoch that has a non-zero probability of being more optimal than a ‘Do Nothing’ action.

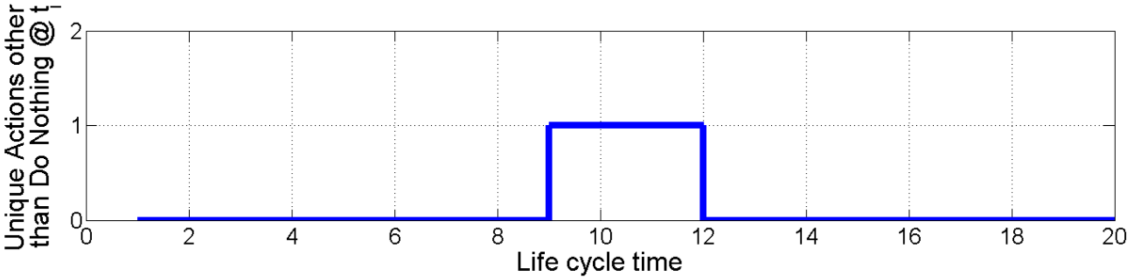


Figure 6-15: Number unique actions other than ‘Do Nothing’ @ t_i in Scenario 05-10-10-12

6.4.4 Time-weighted Cost Incurred

A time-weighted cost incurred metric values the temporal aspect of the action sequence. The metric can be used for both intra- and inter-design evaluation. Intra-design evaluation of time-weighted committed cost distinguishes among the consequences of unique action sequences; inter-design evaluation uses expected time-weighted cost calculations to compare across design concepts. The case study above considered only one design concept, and thus the following conclusions of time-weighted committed cost draw from an intra-design evaluation.

Time-weighted committed cost values identify which action sequence is the preferred cost vector. Conversely, life cycle cost communicates the sequence which is most preferred from a cost magnitude standpoint. Together, the two metrics can communicate an expanded view of the full cost picture. Plotting each sequence in the magnitude-vector space generates Figure 6-16. The sizes of the bubbles represent the execution frequency of a unique action sequence.

The plot illustrates characteristics of the relationship between cost vector, cost magnitude, action types, and action timing. Both the cost vector and magnitude are a function of time due to the inclusion of a discount factor. Here, the shaded ellipse highlights cost vector and magnitude improvement that is gained by delaying action ‘RG’ from Year 9 to Year 10 to Year 11. However, executing a strategy dependent on the environment—in this case, technology development in response to a new ballast water policy—is not as simple as delaying an investment. The action sequence containing ‘RG’ at Year 11 is often suboptimal due to how uncertain nature of transition, rewards, and action availability materialize. In fact, action ‘RG’, regardless of timing, is not always a component of the optimal action sequence. Both action type and timing may not be globally optimal across all simulated transitions, resulting in a (cost vector, cost magnitude) pair that is specific to each action sequence.

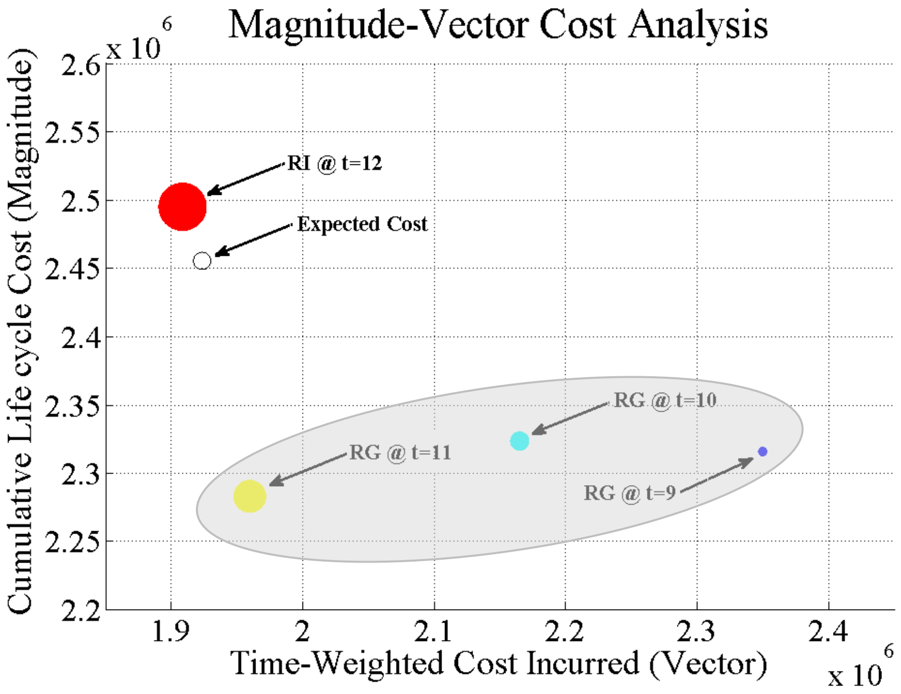


Figure 6-16: Life cycle cost vs. time-weighted cost incurred for one scenario, intra-design

The existence of a sequence containing action ‘RI’ at Year 12 reveals information about the relation between cost vector and cost magnitude as well as the underlying strategy at play. First, recall that the primary strategy for the presented legislative sequence is to take advantage of the capital cost price discount offered for System G. The price discount is temporary, and so the optimal decision is to capture the discount immediately upon its availability. Yet, the fact that the sequence containing ‘RI’ is a non-dominated solution in the magnitude-vector space finds that the primary strategy gives way under specific environment conditions. This newly-activated strategy calls for delaying investment until legislation enters force; activation may stem from entering a different state than the primary strategy expected or because of different manifestations of technology development, for example. The result is a strategy that deals with the inevitability of a higher expected life cycle cost by delaying expense, which so happens to improve time-weighted cost incurred relative to the ‘RG’ sequences.

One interpretation of this finding is that the higher cumulative cost expected by installing System I is not as poor an alternative as might be initially believed. Consider that uncertainty resolves itself with time. One can expect that the MDP model is updated during the life cycle if it is found that transitions and rewards are different than originally configured. These updates may find that having remained in a state due to action unavailability or having entered a less ideal state due to uncertainty now leads to the best expected life cycle value after more time has passed. For example, a policy that is revoked in Year 11 means that the System I replacement action is no longer warranted; conversely, a System G replacement action that occurs in Year 9 cannot be readily undone. Uncertainty in policy development could prove that the inability to execute the globally preferred action sequence turns into a positive. Overall, this discussion shows an appreciation for the fact that, despite best efforts to properly model transitions and rewards at the start of the horizon, the optimal policy can change.

6.5 Discussion

The metrics developed offer qualitative and quantitative information to both policy-making and design. To aid the following discussion, the author presents a comparison of regulatory policy strength. Figure 6-17 plots 40 scenarios of unique legislative sequences in the life cycle cost versus time-weighted cost incurred space, for which the only difference between (a) and (b) is the mandated level of ballast water treatment efficacy. California’s ballast standards are 100x more stringent than that of the IMO. The shaded ovals call particular attention to differences in the two plots. For comparable legislative sequences, a stronger policy increases both cost magnitude and cost vector in many scenarios.

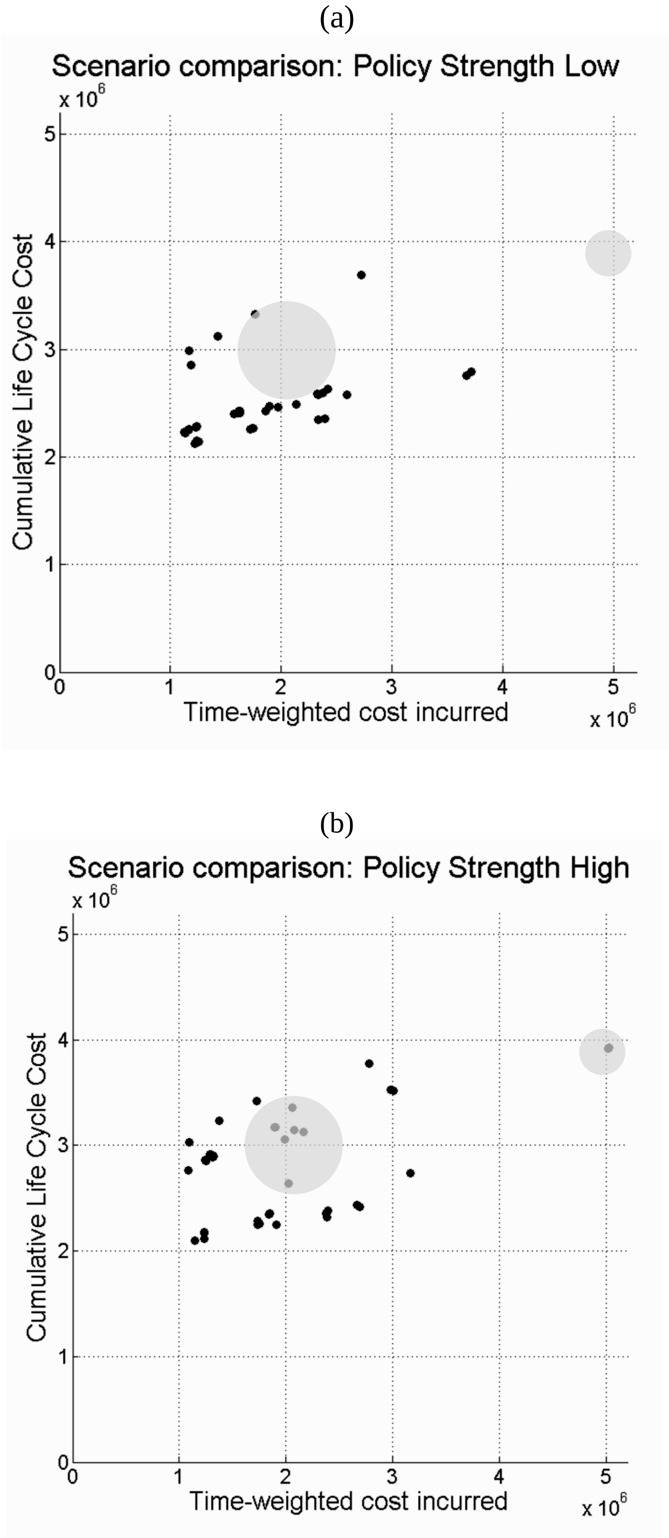


Figure 6-17: Comparison of policy strength (a) IMO standards (b) California standards scenarios

A policy that enters under a 01-06-06-14 policy schedule results in up to a 29% increase in life cycle cost and 33% for time-weighted cost incurred. Higher expected costs are due both to limitations on technology choice as well as strategy adjustments that call for different timing of a treatment system investment. For other policy schedules, increased stringency contributes to an increase of only 0.01% and 0.1%, respectively. Thus, the negligible added burden demonstrates that policy strength is not the only reason behind increased cost differences.

On the policy front, Figure 6-17 and earlier results within this research demonstrate a ship manager's affordability objectives are at odds with both early timing and stricter treatment standards. While policymakers have determined that a regulation is necessary to re-balance which stakeholders absorb the pollution costs, the shipping industry is financially incentivized to delay enforcement and installation of treatment technology due to both discounting and a lack of technology-ready systems. Knowing which metrics designers consider important can serve as guides for how policymakers draft regulations. Thoughtful timing, incentives, and advanced technology development can limit the magnitude and vector of the cost burden to ship managers while still improving an industry's environmental footprint.

On the design front, such scenarios identify the scope for which design must occur. The above results highlight the importance of the relevance paradox: long-term consequences to affordability can be rooted in paradigms outside the design engineering space. A number of the "known unknowns" and "unknown unknowns" are political, economic, and mission-based. Figure 6-17 and analysis of context premium and temporal outdegree metrics find that only 10-25% of ballast system life cycle cost is attributable to the operational environment. The remaining 75-90% is attributable to policy and technology schedules as well as strategic product pricing. Premiums due to uncertainty are as high as 80% of total expected cost for a policy implemented early in a vessel's life cycle but are negligible for a late life cycle mandate. Regulatory constraints contribute the remainder, which in many instances, are the largest contributors to life cycle cost. Traditional scenario planning that allocates resources for only operational needs, such as fuel cost and man-hours, has the potential to significantly underestimate the impact of an investment decision.

The results offer a decision path for owners/operators and convey intuitive strategies for owners, equipment manufacturers, and policymakers, alike. On the owner/operator side, the non-stationary MDP framework more completely evaluates a range of scenarios that assess total ownership cost (TOC). A clearer understanding of the regulatory landscape allows for more strategic life cycle planning and coordination with other expected maintenance and dry-docking cycles. The information conveyed could also be used in conjunction with tools, such as an Analytical Hierarchy Process ballast water system design approach proposed by Parsons (2003), to identify the degree to which life cycle cost influences design choices.

Equipment manufacturers may choose to utilize the MDP framework to improve understanding of how the policy landscape impacts decision-making of potential clients. The results above demonstrate the trade-offs between sale price and early adoption discounts, the timing of commercial availability, and system performance.

Policymakers may elect to use the improved understanding of TOC to assist cost-benefit ratio evaluations and to assess the burden ballast water management policies place on the shipping industry. An understanding of life cycle costs and implementation timelines can lead to discussions about early compliance incentives and speedier uptake rates. For example, tax rebates, lower insurance costs, and subsidies targeted at age-specific vessels may be used to encourage more rapid technology adoption prior to legislation entering force.

Perhaps, most importantly, is that sharing information among the three stakeholders is the only way to arrive at a strong solution. The presented results required estimated expected prices from equipment manufacturers, expected legislation sequences and regulatory strengths from policymakers, and estimated size and performance needs from the owner/operator.

6.6 Chapter Summary

This dissertation proposes an extension to the Markov maintenance and replacement framework to include policymaking effects as an initial step in capturing external economic and political realities. The state model accounts for characteristics of both the system and environment. Historical information related to ballast water management on ships is used to study a range of regulatory and market scenarios.

The traditional focus of a design engineer is, naturally, on the design space; results in this chapter showcase the additional information a designer can gather by exploring the decision space. The decision path is offered as a complement to the system's design itself. Following a design through its life cycle helps elicit susceptibility to disturbance, measures taken to avoid or respond to disturbance, and the buildup of design lock-in that results from decisions. The underlying methodology enables development of a life cycle strategy, enriching design decision-making.

Research presented in this chapter represents the first application of novel change strategy metrics and the use of state-action-time representations to facilitate strategy communication. These metrics are applied to enrich understanding of the governing components of the optimal strategy, beyond simply achieving minimum life cycle cost. Particular attention is given to the roles of changeability, uncertainty, and degree of active strategic maneuvers that underline response to policy change.

Chapter Citations

1. Goldstein, T., Ladany, S., & Merhrez, A. (1988). A discounted machine-replacement model with an expected future technological breakthrough. *Naval Research Logistics, 35* (2).
2. Hopp, W. & Nair, S. (1991). Timing replacement decisions under discontinuous technological change. *Naval Research Logistics, 38* (2).
3. Gunningham, N., Grabosky, P., & Sinclair, D. (1998). *Smart Regulation: Designing Environmental Policy*. Oxford: Oxford University Press.
4. Frangopol, D., Kallen, M., & Van Noortwijk, J. (2004). Probabilistic models for life-cycle performance of deteriorating structures: review and future directions. *Progress in Structural Engineering and Materials, 6* (3).

5. Frangopol, D., & Liu, M. (2007). Maintenance and management of civil infrastructure based on condition, safety, optimization, and life-cycle cost. *Structure & Infrastructure Engineering: Maintenance, Management, Life-cycle Design and Performance, 3* (1).
6. Hartman, J., & Rogers, J. (2006). Dynamic programming approaches for equipment replacement problems with continuous and discontinuous technological change. *Journal of Management Mathematics, 17* (2), 143-158.
7. Hopp, W., & Nair, S. (1994). Maintenance and replacement policies under technological obsolescence. *Reliability Engineering and System Safety, 94*.
8. Kim, H., Keoleian, G., & Horie, Y. (2006). Optimal household refrigerator replacement policy for life cycle energy, greenhouse gas emissions, and cost. *Energy Policy, 34* (15), 2310-2323.
9. Parsons, M. (2003). Considerations in the design of the primary treatment for ballast systems. *Marine Technology*.
10. Rigby, G., & Taylor, A. (2001). Progress in the management and treatment of ship's ballast water to minimize the risks of translocating harmful nonindigenous aquatic organisms. *Marine Environmental Engineering, 6*.
11. Silver, M., & de Weck, O. (2007). Time-expanded decision networks: A framework for designing evolvable complex systems. *Systems Engineering, 10* (2), 167-188.
12. Singh, A., Mourelatos, Z., & Li, J. (2010). Design for life cycle cost using time-dependent reliability. *Journal of Mechanical Design, 132* (9), 0910081-09100811.
13. Sloan, T. (2011). Green renewal: Incorporating environmental factors in equipment replacement decisions under technological change. *Journal of Cleaner Production, 19*, 173-186.
14. Smallwood, R., & Sondik, E. (1973). The optimal control of partially observable Markov decision processes over a finite horizon. *Operations Research*.
15. Spitzley, D., Grande, D., Keoleian, G., & Kim, H. (2005). Life cycle optimization of ownership costs and emissions reduction in US vehicle retirement decisions. *Transportation Research Part D: Transport and Environment, 10* (2), 161-175.
16. Swackhamer, D., & Meyer, J. (2011). EPA-SAB-11-009 Efficacy of ballast water treatment systems: a report by the EPA Science Board. *Report*. Environmental Protection Agency.
17. LR. (2010). Ballast water treatment technology. *Report*. Lloyd's Register.
18. LR. (2007). Ballast water treatment technology. *Report*. Lloyd's Register.
19. CSLC. (2010). Assessment of the efficacy, availability, and environmental impacts of ballast water treatment systems for use in California waters. *Report.* California State Lands Commission.
20. Thi, P., Yueng, T., & Castanier, B. (2010). Optimal maintenance and replacement decisions under technological change. *In proceedings of the European Safety and Reliability, 40* (1).
21. Van Noortwijk, J. (2007). A survey of the application of gamma processes in maintenance. *Reliability Engineering and System Safety, 91* (1).
22. Wang, H. (2002). A survey of maintenance policies of deteriorating systems. *European Journal of Operations Research, 139,* 469-489.

CHAPTER 7 – CASE STUDY #2: DESIGN EVALUATION SUBJECT TO CARBON EMISSION POLICYMAKING

Neither a wise nor a brave man lies down on the tracks of history to wait for the train of the future to run over him.

Dwight D. Eisenhower

The first case study completed in this dissertation is limited in its scope for two primary reasons. First, the study does not consider decisions at the vessel's design stage. In other words, despite the fact that the previous strategy considers the full 20-year life cycle of a vessel and its ballast water system, the initial design conditions are fixed. Fortunately, initial conditions—the starting design components and configuration—are not fixed if the MDP framework is applied in the conceptual design process. Thoughtful evaluation at the design stage might have reduced the size and scope of a ballast water treatment system retrofit or eliminated the need entirely. A strategy at the design phase that considered the role ballast water policies could have on a vessel's performance and economics might have reduced needed investment cost during the use phase.

As explained in Chapter 3, the ability to contain cost is highest in the conceptual design phase. A greater number of cost-effective tradeoff options exist when fewer decisions have been locked-in. When decisions compound on one another, physical and psychological irreversibility set in. Establishing a course of action that can accept an uncertain future might prevent such irreversibility from leading to a sub-optimal product. The need to overcome the strong role of inheritance, or infrastructural constraints in both the physical sense and in expectations, is lessened at the design stage. Nevertheless, life cycle requirements and characteristics are also most uncertain in conceptual design, and so a delicate balance exists.

Second, the previous study demonstrates limited strategic insight gained from a single policy, single system setup. The study only included actions that were discrete and binary in nature, decisions the author describes as “what” choices. The result is that effects were viewed in a linear sense, when, in fact, real-world design decisions for complex systems are known to be portfolio allocation problems. A setup of actions that span multiple systems, address both continuous and discrete variables, and exist within a hierarchy of levels begin to answer the “how much” question. It is the combination of “what” and “how much” choices that is integral to satisfying open-ended, performance-based policy requirements. As an uncertain future plays forward, one can expect the components of the portfolio to change. Changes to portfolio components can engender nonlinear properties and behaviors at the highest system level that are unpredictable or non-existent at the sub-system level.

To this end, the case study developed in the second phase of this dissertation applies a strategic framework now aimed at the design evaluation of multiple ship systems. The key question the research intends to answer is “which design concept appropriately handles disturbance and performance drift in the most cost-effective manner?” The objectives of the research in this chapter are multi-fold:

- Conduct economic analysis that explicitly considers design’s ability to passively and actively change over its life cycle
- Understand and quantify the degree to which changeability is valued in addressing uncertain future regulations
- Identify “good” design characteristics as well as the internal and external drivers of change during the use phase of a product’s life cycle

The chapter follows a form similar to the previous, with both progression of the chapter’s sections and application of the methodology (Figure 7-1) described below.

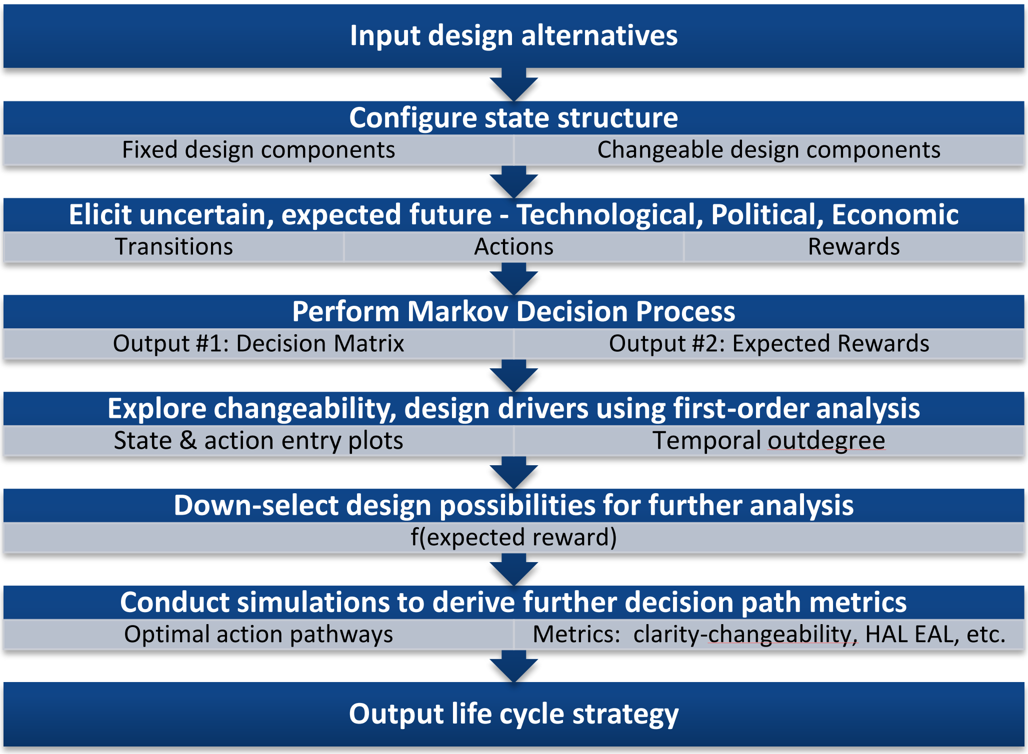


Figure 7-1: Procedure for this chapter's application of MDP-based methodology to early stage design

The policy under consideration and its macro-level implication are first introduced. A detailed discussion of the problem setup outlines the state, action, transition, and reward characteristics input to the MDP-based methodology. Initially presented results focus on first-order analysis associated with expected rewards and design drivers in order to lay the foundation for results associated with changeability analysis. It is this temporal understanding gained from application of change metrics that marks the intent of both the case study and the greater research thrust of this dissertation.

7.1 Overview – EEDI Carbon Policy

The International Maritime Organization (IMO) and its represented Parties agreed to regulate emissions of greenhouse gases from international shipping in 2011. An amendment to MARPOL Annex VI: *Regulations for the prevention of air pollution from ships*, outlines a new mandatory design metric known as the Energy Efficiency Design Index (EEDI). The details of the index formula are located in MEPC.1/Circ.681, Interim

Guidelines on the Method of the Calculation of the Energy Efficiency Design Index for New Ships (IMO, 2012).

A simplified version of the formula is presented below:

$$EEDI = \frac{Installed\ Power * SFC * Fuel\ Carbon\ Content}{Design\ Speed * Capacity} \qquad [7\text{-}1]$$

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.

An understanding of the Guidelines is important to understanding the assumptions of the calculations. The formula measures emissions from both main and auxiliary engines. The main engine’s 75% Specified Maximum Continuous Rating (SMCR) and corresponding specific fuel consumption (SFC) are used in the calculation. Corrections for use of waste heat recovery and other energy efficient measures are included. EEDI is not currently available for vessels outfitted with diesel-electric propulsion, turbine propulsion, or hybrid propulsion systems. Speed is measured in knots. For containerships, the Capacity term is measured as 70% of the maximum cargo deadweight. Of particular note is that EEDI is an instrument for *design*, not operations. As such, actual emissions from two ships that attain the same EEDI value may prove widely variable.

Retrofits, maintenance, and operational changes can improve ship energy efficiency, and thereby, the attained EEDI value. Addition of technological measures can mitigate the need to burn petroleum based products. A well-maintained paint coating prevents fouling on the hull that can significantly increase resistance. Slow-steaming, an economically-motivated move which saved the shipping company Maersk $300 million in fuel costs across its fleet in 2009, also improves vessel energy efficiency by reducing power requirements (Jorgensen, 2010). The drive to lower EEDI is expected to result in design speeds for large containerships closer to 24 knots than recent newbuilds in the 25-26 knot range (MAN Diesel & Turbo, 2011). The IMO affirmed in its 2009 study that such measures can improve efficiency between 25-75% by 2050 (Buhaug et al., 2009). Nevertheless, no silver bullet exists; tradeoffs among affordability, sustainability, and reliability do remain. For example, operating off-design can threaten structural integrity, increase consumption of lubricant, or decrease efficiency of heat recovery systems (Devanney, 2010).

The specifics of an EEDI policy have remained uncertain for thirteen years, from the time IMO was commissioned to reduce greenhouse gas emissions to when the Guidelines were ratified in 2011. In that time, the European Union threatened unilateral action that would have integrated regulating vessel emissions into its existing trading scheme. Pressure to enact a policy resulted in arguably both a too complex and a too simple regulation at the same time. Complexly, the EEDI formula includes a multitude of correction factors, some of which appear to run counterintuitive to sustainability principles. For example, EEDI favors smaller, under-powered, single screw vessels for transit despite the known efficiency benefits of large vessels and those fit with twin screws (Devanney, 2010). Simplistically, the expressed formula assumes a vessel will always operate at the same percentage of its installed power despite prevailing market conditions, and thus, that emissions are linearly related to installed power. The environmental effect of EEDI is limited because it does not incentivize operational measures such as weather routing or offer design incentives for technological measures such as dual fuel capabilities.

7.2 Objective Function

Consider a team tasked with conducting early stage ship design. The 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 understand the future context in which the ship will be utilized as well as external factors that may influence the design’s ability to operate economically and in compliance. Modifications to the design or operations over time may be planned to improve performance.

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:

$$Rewards=max[\sum (Revenues - Capital\ Cost - Operating\ Cost - Voyage\ Cost)] \quad [7\text{-}2]$$

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.

7.3 SWOT Analysis

Managers can identify strengths, weaknesses, opportunities, and threats (herein called SWOT) to better understand if design objectives are attainable. Here, SWOT analysis is used to appreciate how the regulation of EEDI can alter containership operations and finances (Table 7-1).

Table 7-1: Qualitative impact analysis of EEDI regulation enforcement

A ship with a low attained EEDI	*Strengths:* • low emissions per ton transported option • protection from future carbon regulation • no added route limitations • advanced design and technology *Weaknesses*: • constrained design • higher initial investment • complexity *Opportunities*: • brand differentiation if early adopter • favorable pricing or utilization contracts • fuel flexibility and energy independence • reduced liability *Threats*: • added financing restrictions • training and infrastructure needs • uncompetitive when efficiency does not pay • underpowered if policy repealed or delayed • tightened or fully consumed design margins

7.4 Independent Variables & Setup

An 8,000 TEU Post-Panamax containership is expected to transit cargo across the Pacific between the Port of Los Angeles to the Port of Hong Kong. The lifespan of the vessel is set for 20 years. Minimum design speed is 18 knots and maximum design speed is 25 knots. All regulations set forth by the IMO, port states, and the classification society under which the ship is registered must be satisfied.

7.4.1 Concept Design Core and Shell versus Concept Design Bundles

The case study developed differentiates between design *core and shell* and design *bundle*. The core and shell of a design is comprised of unchangeable, or nearly unchangeable, characteristics such as the principal dimensions of a vessel or the prime mover installed. Outside of the occasion in which increasing parallel midbody via jumbo-izing can increase revenue projections, most designs do not call for overhauls to a ship's envelope or major structural and primary propulsion equipment due to cost and technical issues.

Bundles, on the other hand, consist of ship systems or sub-systems deemed changeable. Technologies such as flow devices, hull coatings, and emission traps constitute systems that can be added, subtracted, upgraded, or otherwise retrofit. Additionally, operational changes such as an adjustment to speed affect core ship equipment or services and so are also included in the definition of a design bundle.

The distinction is illustrated in Figure 7-2, and the combination of both the design bundle and the core and shell will herein be described as a design concept.

Figure 7-2: The design core & shell and the design bundle together form the design concept

The following EEDI study identifies 800+ core and shell designs that satisfy design requirements due to the combinatorial nature of core and shell components. The core and shell is composed of principal characteristics and the low-speed diesel engine installed. Table 7-2 lists principal dimension permutations and Table 7-3 lists possible engine selections. All core and shell designs provide for a single propulsor with diameter that is 72% of draft.

Of particular note is that Configuration #2 has become the standard newbuild envelope for 8,000 TEU containerships over the last decade. Common prime movers for a Post-Panamax containership with design speed of 25 knots are the 10-12 cylinder options.

Bundle options under consideration are categorized as add-on technologies, fuel type, operating speed and engine rating features. The add-on technologies set includes {kite, flow device, air hull lubrication system}. Fuel type can be one of the set {IFO 380, LS 380, MDO, LNG, IFO/LNG dual fuel}. The speed set is comprised of {18 knots, 20 knots, 22 knots, 24 knots, 25 knots}. Note that no option for mothballing, or a zero knot speed condition, is considered; actual practices might opt to layup a vessel in particularly difficult economic climates. The engine can be rated for the maximum speed achievable within the set or 80% of maximum engine power available, described as the set {max speed rated, fully derated}. The derived specific fuel consumption curve is a function of the engine's rating and operating speed, with allowances for age and expected transit conditions.

Table 7-2: Configuration Set for Core and Shell Design Concepts

	LOA (m)	LWL (m)	B (m)	D (m)	T (m)
Configuration 1	352	337	40.4	17.6	12.1
Configuration 2	323	308	42.8	22.8	13.1
Configuration 3	333	318	42.8	25.4	12.8
Configuration 4	333	318	45.6	20.2	12.0
Configuration 5	295	280	45.6	22.8	14.0
Configuration 6	338	323	45.6	22.8	11.9
Configuration 7	310	295	45.6	25.4	13.3
Configuration 8	317	302	48.2	20.2	12.2
Configuration 9	289	274	48.2	22.8	13.8
Configuration 10	275	260	48.2	25.4	14.8
Configuration 11	253	237	50.8	22.8	15.5
Configuration 12	275	260	50.8	22.8	14.0
Configuration 13	305	290	50.8	25.4	12.5

Table 7-3: Engine Set for Core and Shell Design Concepts

Engine Name	RPM	Cylinders									
		5	6	7	8	9	10	11	12	13	14
MAN B&W S90ME-C8	78		☑	☑	☑	☑					
MAN B&W S90ME-C9	84	☑	☑	☑	☑	☑	☑	☑	☑		☑
MAN B&W K80ME-C9	104		☑	☑	☑	☑	☑	☑	☑		
MAN B&W K98ME-C7	104		☑	☑	☑	☑	☑	☑	☑		☑
MAN B&W K98ME-7	97		☑	☑	☑	☑	☑	☑	☑		☑
Warstila RT-flex 82T	76		☑	☑	☑	☑					
Warstila RT-flex 82T+	84		☑	☑	☑	☑					
Warstila RT-flex 84T	76	☑	☑	☑	☑	☑					
Warstila RT-flex 96C	127		☑	☑	☑	☑	☑	☑	☑	☑	☑
Warstila X62	97	☑	☑	☑	☑						
Warstila X62+	103	☑	☑	☑	☑						
Warstila X72	84	☑	☑	☑	☑						
Warstila X72+	89	☑	☑	☑	☑						

7.4.2 Actions

Decisions—do nothing, adjust engine rating, add or remove technology, switch fuel composition, and change speed—are assumed to occur once per year. The effect of each action is summarized below:

- ‘No Action’ — the vessel design bundle remains unchanged and operations repeat from the previous epoch. Labeled ‘NA’.
- ‘Adjust Engine Rating’ — the prime mover is tuned for a different engine power-propeller rpm combination. Labeled ‘R’.
- ‘Add/Remove technology’ — an energy-efficient technology is retrofit to the vessel. Only one technology may be added per epoch. Labeled ‘T’.
- ‘Alter Fuel Mix’ — a fuel type different from the previous epoch is used for main ship power. Labeled ‘F’.
- ‘Change speed’ — a speed that is different from the previous epoch, but within the speed set, is selected. Labeled ‘S’.

Then, let the action vector at epoch, *i*, be denoted as $\mathbf{A_i}$=$\{NA_i$, $R_0T_0S_0F_{1\_i}$, $R_0T_0S_0F_{2\_i}$, … $R_wT_xS_yF_{z\_i}$,$\}$, where subscripts *w, x, y, z* denote action combinations from individual action sets. In total, a maximum of 792 actions are available, dependent on current state, physical limitations, and external regulatory conditions.

7.4.3 States

The full state representation is the collection of design bundle characteristics, operating considerations, and influential external conditions. State setup also includes provisions for which flexibility is installed but remains latent, due to the relationship between a design’s reward profile and incorporation of any real options. Finally, state descriptions account for time, as transitions are non-stationary.

A sample state designation includes the following: time, engine rating, add-on technologies included, fuel type used, operating speed, and market conditions for charter rate, fuel prices, and environmental footprint premium.

state=epoch_Rating_Techs_Speed_Fuel_FreightMarket_FuelMarket_EnvPemium [7-3]

Combinations of these properties results in 3500+ unique states per epoch.

7.4.4 Transitions

State changes are a combination of action-dependent and action-independent transitions probabilities. Bayesian conditionality and the law of total probability are utilized to construct the full transition matrices.

Action dependent transitions among state components pertain to the assemblage of the design bundle. Speed transitions are deterministic, while energy technologies, engine ratings, and dual fuel mix transitions are configured with small allowances for component failure. Examples of action dependent transition sub-matrices are outlined below. Row labels represent current states and columns correspond to next states. The tables are filled with transition probabilities whose rows add to unity.

Table 7-4: Transition Example 1 – Speed sub-matrix, execute ‘No Action’

	18kts	20kts	22kts	24kts	25kts
18kts	1	0	0	0	0
20kts	0	1	0	0	0
22kts	0	0	1	0	0
24kts	0	0	0	1	0
25kts	0	0	0	0	1

Table 7-5: Transition Example 2 — Fuel sub-matrix, execute ‘Use LNG fuel’

	IFO	LS	MDO	LNG	Dual Fuel
IFO	0	0	0	1	0
LS	0	0	0	1	0
MDO	0	0	0	1	0
LNG	0	0	0	1	0
Dual Fuel	0	0	0	1	0

Legend: *IFO=intermediate fuel oil, 380 Centistokes*
LS=low sulfur fuel oil, 380 Centistokes
MDO=marine diesel oil
LNG=liquefied natural gas
Dual Fuel=combination of IFO and LNG

Table 7-6: Transition Example 3 — Technology sub-matrix, execute ‘Add Kite’

	No Techs	Kite	Flow	Air	K+F	K+A	F+A	K+F+A
No Techs	q_1	p_1	0	0	0	0	0	0
Kite	q_1	p_1	0	0	0	0	0	0
Flow	q_1q_2	p_1q_2	q_1p_2	0	p_1p_2	0	0	0
Air	q_1q_3	p_1q_3	0	q_1p_3	0	p_1p_3	0	0
K+F	q_1q_2	p_1q_2	q_1p_2	0	p_1p_2	0	0	0
K+A	q_1q_3	p_1q_3	0	q_1p_3	0	p_1p_3	0	0
F+A	$q_1q_2q_3$	$p_1q_2q_3$	$q_1p_2q_3$	$q_1q_2p_3$	$p_1p_2q_3$	$p_1q_2p_3$	$q_1p_2\ p_3$	$p_1p_2p_3$
K+F+A	$q_1q_2q_3$	$p_1q_2q_3$	$q_1p_2q_3$	$q_1q_2p_3$	$p_1p_2q_3$	$p_1q_2p_3$	$q_1p_2p_3$	$p_1p_2p_3$

Legend: p_1=*operational kite* ; $q_1=1-p_1$
p_2=*operational flow device kite install* ; $q_2=1-p_2$
p_3=*operational air lubrication system* ; $q_3=1-p_3$

Transitions among state components representing the environmental and external market conditions are action independent. Three probabilistic external conditions exist in the study, related to charter rates, fuel pricing, and environmental surtaxes, respectively. Transitions occur between high and low expert-drawn curves per each condition. The curves implicitly capture market cycling, and the addition of probabilistic transitions is used to capture varying magnitude and rate trends. Stationary sub-matrix transition tables are provided below for illustration.

Table 7-7: Transition probabilities of environmental sub-states

Charter Rate		
	High	Low
High	0.6	0.4
Low	0.3	0.7

Fuel Price		
	High	Low
High	0.65	0.35
Low	0.3	0.7

Environment Surtax		
	High	Low
High	0.98	0.02
Low	0.1	0.9

7.4.5 Rewards

Several resources provide insight into the capital expenditures, installation costs, and annual maintenance and operating expenses. Primary information sources include Maritime Economics, *Significant Ships*, UNCTAD’s 2011 *Review of Maritime Transport*, a 2011 life cycle cost analysis of Car Ferry LNG by Glosten, a 2008 LNG report prepared by MARINTEK, a 2011 article on bunker fuel demand by Mazraati, and Parsons’ NA&ME 470 design class worksheets. An annual interest rate of 3% is used.

7.4.5.1 Capital Costs

Hull, machinery, and equipment are estimated using simple regression models. An outfit and hull engineering capital cost model is based on vessel characteristics, such as length and block coefficient, and shipyard variables, such as labor rate, profit rate, and steel cost. The propulsion machinery model is a function of installed power, engine type, and power-to-propulsor arrangement. Multiplier factors for including design options, such as the installation of flex fuel capabilities, are included for design bundles where appropriate.

Concepts generated from core and shell designs listed in Table 7-2 and Table 7-3 range in cost from \$87M to \$138M. Principal and interest payments are spread across the life of the vessel using a simple decreasing function and constant loan rate.

7.4.5.2 Operating Revenues

Revenues are derived from successfully transporting cargo from its origin to its destination. Freight rate is often communicated in terms of \$/TEU for containership vessels. Figure 7-3 notes volatility in routes emanating from Asia due to sensitivity of consumer good exports to recession and growth cycles. Total revenues are a function of cargo utilization rate and are limited by TEU capacity.

Utilization rate has increasingly become dependent on environmental footprint. Classification societies offer certificates for outstanding performance, which can include a direct or indirect monetary incentive. Furthermore, fleet owners have successfully used green certification to market their efficient vessels to clients whose consumers value sustainable shipping. As such, a vessel's energy efficiency serves as a harbinger of demand for its transport service.

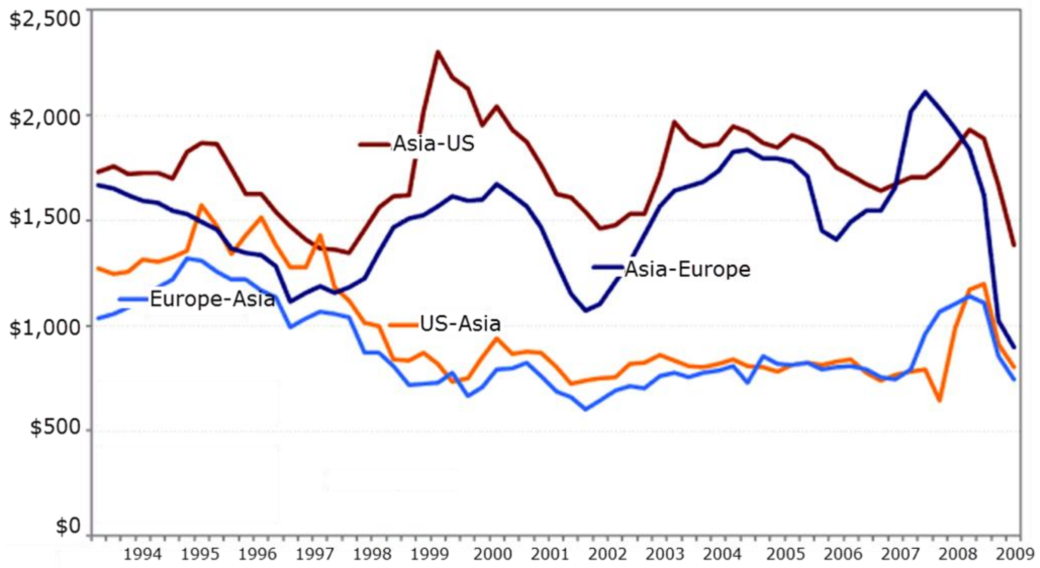


Figure 7-3: Historical freight rates by route (Rodrigue et al., 2009 from UNCTAD 2004)

A simple function for utilization is described as follows:

$$utilization(t) = f(ship\ age, simliar\ ship\ fleet, market, EEDI) \qquad [7\text{-}4]$$

7.4.5.3 Operating Costs

Voyage expenses are the aggregation of fuel, manning, stores, insurance, maintenance, and cargo handling costs. Ship design governs the number of crew members and stores required onboard, amount of fuel consumed, magnitude of canal and pilotage dues, and rate at which maintenance might be requested. Generalized functions are listed in the table below:

Table 7-8: Variable inputs composing high-level voyage cost categories

Cost Type	**Inputs**
Fuel cost	f(fuel type, $/ton, engine type & loading, voyage days, ship age)
Port fee	f(TEU handling rate, pilotage dues, annual embarkations/ disembarkations, capacity utilization, EEDI)
Manning, Stores	f(ship age, crew size)
Maintenance	f(ship age, engine loading, onboard technologies)
Insurance	f(ship age, onboard technologies, EEDI)

Odense Steel Shipyard's Green Ship of the Future concept study (2009) relates the typical main engine load profile for a post-panamax containership operating at 25 knots (Figure 7-4). The distribution of the profile is adjusted for concepts in the case study with powering capabilities less than the traditional 25 knots.

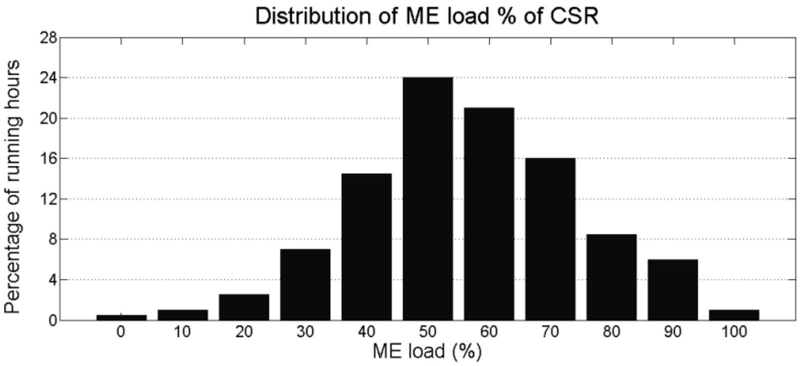


Figure 7-4: Main engine load profile for a post-panamax containership (Nielsen, 2009)

Just as utilization rate has become dependent on energy efficiency, so too, have insurance and port rates. Third party insurance has long assumed coverage of pollution, the scope of which has recently grown to include vessel emissions. Cargo surtaxes have been added by ports to vessels with below-standard efficiency, as ports are also attempting to reduce their environmental footprint. Similarly, some ports have started to offer favorable handling rates for best-performing vessels. This case study accounts for rate differentiation by including EEDI within the set of function arguments used to determine insurance and port fee values.

Many projections for future fuel costs exist (Outlook for Marine Bunkers and Fuel Oil to 2030, a 2011 report by IHS CERA, a 2010 report by European Community of Shipowners' Associations, a 2009 U.S. EPA report). Prices over the last several years have exhibited significant volatility, captured in Figure 7-5. A rapid price increase over the last decade has caused ship owners to elevate fuel efficiency concerns. An additional surge in demand for low sulfur fuels, and a price point to match, is expected in 2020 when the global maximum sulfur content of marine bunker fuels drops to 0.5%. Flex fuel technology appeal has increased with both a better understanding of LNG as a fuel alternative and the growth of sulfur emission control areas (SECA) around the world.

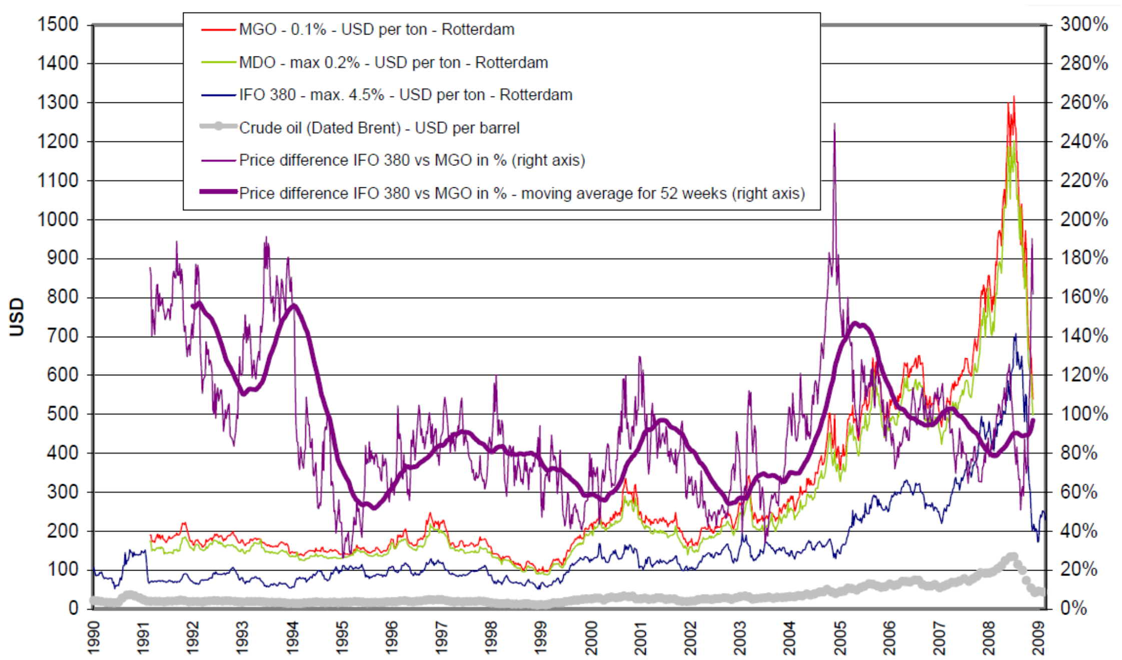


Figure 7-5: Price evolution by fuel type (Notteboom, Delhaye, & Vanherle, 2010)

Significant changes to the economics of ship operations mean that future designs cannot be expected to iterate off past designs. Optimal design characteristics and configurations may be located in radically new locations within the design space.

7.5 Decision Criteria

The MDP framework finds a policy, denoted $V^{\pi}(s)$, that minimizes the expected discounted cost over a finite horizon. $V^{\pi}(s)$ is equivalent to $V_{t=1}(s)$, as the value at the first decision epoch includes the full discounted value over all decision epochs.

Let $V_i(s)$ denote the minimum expected discounted cost from decision period, *i*, to the final decision epoch, *N*. Then,

$$V_i(s) = \max\{NA(s)_i, \mathrm{R_0T_0S_0F_1}(s)_i, \mathrm{R_0T_0S_0F_2}(s)_i, \dots, \mathrm{R_wT_xS_yF_z}(s)_i\} \qquad [7\text{-}5]$$

The output of MDP calculations is a decision matrix, providing for a set of actions and expected rewards for any state, at any time. Of particular importance in the case study is identifying the appropriate starting state itself, where the state represents the design and operating characteristics that are expected to be the output from the conceptual design process.

In instances where the start state is fully deterministic, the best start state can be identified as the one with the largest expected reward. However, the full state representation often includes stochastic components which prevent simply selecting for the state with the maximum reward, e.g., freight rates and fuel costs. The time between conceptual design and the product's use phase is non-zero, and so the probabilistic components of the start state representation cannot be guaranteed. In one stochastic environment, Design X may prove most desirable. Conversely, if a different stochastic environment exists upon build completion, Design Y may be warranted. Careful reasoning of the selected start state is critical to effective use of the MDP framework for design decisions.

7.6 Assumptions

Other notable simplifying assumptions are sub-categorized below:

7.6.1 Design Features

All configurations are installed with a waste heat recovery system
Deadweight is a constant 96,000MT
Auxiliary power required for refrigerated containers (reefers) is 6000 kW
Auxiliary fuel is MDO and design specific fuel consumption of auxiliary engine is 185 g/kWh
Specific fuel consumption curve is a function of designed engine rating
Dual fuel systems can be optioned at build or retrofitted during use phase
Add-on technologies are not mutually exclusive
Operational availability of add-on technologies is limited to less than 100%

7.6.2 Operating Features

280 days-at-sea per annum
Round-trip voyage is 12,700 nautical miles

7.6.3 Design-Build-Operating Costs

Build cost derived via regression employing principal dimensions and powering inputs
Engine cost estimated on basis of $/kW installed, adjusted for fuel capabilities
Standard operating costs derived from Maritime Economics (Stopford, 2009)
Installation cost at build less than installation cost at overhaul
Discount rate is a constant 4%
Inflation rate is a constant 3%

7.6.4 External Factors

Charter rates and fuel rates are probabilistic through time, fluctuating between high and low expert-drawn projections.
Cost premium on environmental performance is probabilistic through time, fluctuating between high and low projections.
EEDI reference line changes are deterministic and consistent with timeline set forth in Chapter 4 of MARPOL Annex VI.
Operating decisions, voyage expenses, and utilization remain constant per epoch. One epoch is equivalent to one year.

7.7 Results

The following results are explored as follows:

1. Values and figures detailing expected rewards output from MDP
2. Figures identifying drivers of the initial design construct
3. Measurement of relation between design changeability and expected rewards
4. Metrics based on action sequencing and state entry

Insights gathered from the results are expected to improve early stage design evaluation and more clearly link design and operation decisions to underlying change forces.

7.7.1 First Order Analysis

7.7.1.1 Expected Rewards

Simple MDP analysis outlines the first order results in the form of each state's expected rewards. As outlined in the above section, some states represent the same physical design and are simply differentiated by external market and political conditions. The author herein describes the external conditions as set forth in Table 7-9, noting each condition in the study is a combination of freight, fuel, and environmental market factors. Because the study setup included high and low expert-drawn curves for each market factor, eight combinations are presented.

Table 7-9: Environmental Condition, Name and Description

Condition No.	**Description**	**Symbol**
1	Freight rate high + fuel rate high + env. surtax high	$\mathbf{R}_H\_\mathbf{F}_H\_\mathbf{E}_H$
2	Freight rate high + fuel rate high + env. surtax low	$\mathbf{R}_H\_\mathbf{F}_H\_\mathbf{E}_L$
3	Freight rate high + fuel rate low + env. surtax low	$\mathbf{R}_H\_\mathbf{F}_L\_\mathbf{E}_L$
4	Freight rate high + fuel rate low + env. surtax high	$\mathbf{R}_H\_\mathbf{F}_L\_\mathbf{E}_H$
5	Freight rate low + fuel rate high + env. surtax high	$\mathbf{R}_L\_\mathbf{F}_H\_\mathbf{E}_H$
6	Freight rate low + fuel rate high + env. surtax low	$\mathbf{R}_L\_\mathbf{F}_H\_\mathbf{E}_L$
7	Freight rate low + fuel rate low + env. surtax low	$\mathbf{R}_L\_\mathbf{F}_L\_\mathbf{E}_L$
8	Freight rate low + fuel rate low + env. surtax high	$\mathbf{R}_L\_\mathbf{F}_L\_\mathbf{E}_H$

The author defines starting condition as the environmental factor combination in effect at the end of ship construction and the commencement of ship operations. High-level design evaluation must occur per starting condition because the environmental factors themselves are in the future and thus uncertain when MDP calculations are conducted. Resolving the reward trades among various starting conditions then involves dialogue with decision-makers and additional post-analysis and utility judgment.

Figure 7-6 illustrates a sample output of expected rewards, given Starting Condition 1. The x-axis represents nominal variables corresponding to 827 core and shell designs under review. Up to a total of 880 bundle options exist per core and shell design, each with its own expected reward value.

Of particular note is the range of values across core and shells as well as the spread among bundles within the same core and shell. Of the 800+ core and shell design distributions explored, in excess of 30% result in an expected loss. The relative locations of the expected values of core and shell distributions are indicative of the influence initial design characteristics and external starting conditions have on the cost performance of the whole core and shell concept. The differing bundle-specific rewards within individual core and shell distributions indicate uniqueness of relationship among changeable design components, unchangeable design components, and the environment. The difference between the highest earning bundle within a core and shell and the lowest earning counterpart exceeds \$10M in several cases.

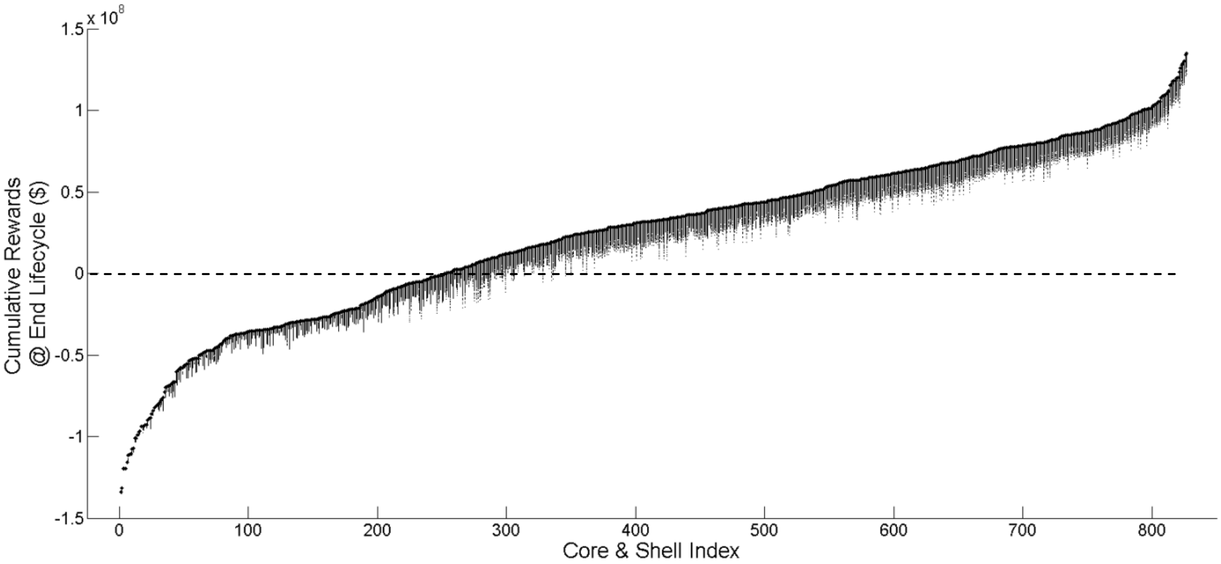


Figure 7-6: Scatter plot of cumulative reward at life cycle end for all design bundles, categorized by core & shell

The design concepts with the highest expected cumulative reward are easily identified via their markers. Unique core and shell combinations in the 98th percentile of starting condition $\mathbf{R}_H\_\mathbf{F}_H\_\mathbf{E}_H$ are presented below in

Table 7-10. Configuration 11 appears as a dominant solution for high reward designs.

Table 7-10: Top core and shell designs, according to expected rewards

Core & Shell Designs –98th percentile		
Config. 11 @ 21,660 kW	**Config. 11** @ 36,890 kW	**Config. 11** @ 25,270 kW
Config. 11 @ 21,660 kW	**Config. 11** @ 28,880 kW	**Config. 11** @ 18,620 kW
Config. 11 @ 25,200 kW	**Config. 11** @ 18,050 kW	**Config. 11** @ 28,880 kW
Config. 11 @ 29,050 kW	**Config. 11** @ 29,400 kW	**Config. 11** @ 37,800 kW
Config. 11 @ 18,050 kW	**Config. 11** @ 31,620 kW	**Config. 5** @ 18,050 kW
Config. 11 @ 21,000 kW	**Config. 11** @ 33,250 kW	

Highest core and shell rank containing each of the configurations is presented in Table 7-11. Configuration 11 is a clear favorite. The greatest expected rewards any other configuration is expected to earn is less than 82% of the highest expected reward earned via a design containing Configuration 11.

Table 7-11: Relative rank of best concept containing each configuration

Principal Dimensions	Best Placement (out of 827 design concepts)	Percentage of Max
Configuration 1	67th	0.66
Configuration 2	70th	0.65
Configuration 3	123rd	0.58
Configuration 4	232nd	0.45
Configuration 5	17th	0.82
Configuration 6	275th	0.40
Configuration 7	80th	0.64
Configuration 8	219th	0.46
Configuration 9	38th	0.74
Configuration 10	23rd	0.78
Configuration 11	1st	1.00
Configuration 12	48th	0.70
Configuration 13	263rd	0.42

7.7.1.2 Unchangeable Design Drivers

The goal of design evaluation is not to simply select the single candidate solution with the highest expected reward. In fact, with set-based design (SBD) practices increasingly advocated, there is growing evidence that point design analysis contributes to greater re-design, higher life cycle cost, and sub-optimal performance. SBD does not require the selection of good design concepts as much as it requires that poor design concepts are removed. One outgrowth of the paradigm shift in design thinking and practices is greater interest in discovering the underlying design drivers and complex relationships among design agent preferences.

Expected cumulative life cycle rewards represent a clear, standard metric for identifying the main effects of selecting a particular design parameter value. Figure 7-7 through Figure 7-11 illustrate that expected reward values are indeed predicated on the values of certain design variables more strongly than others. Note that the results plotted in the figures are based on only thirteen sample ship dimensions.

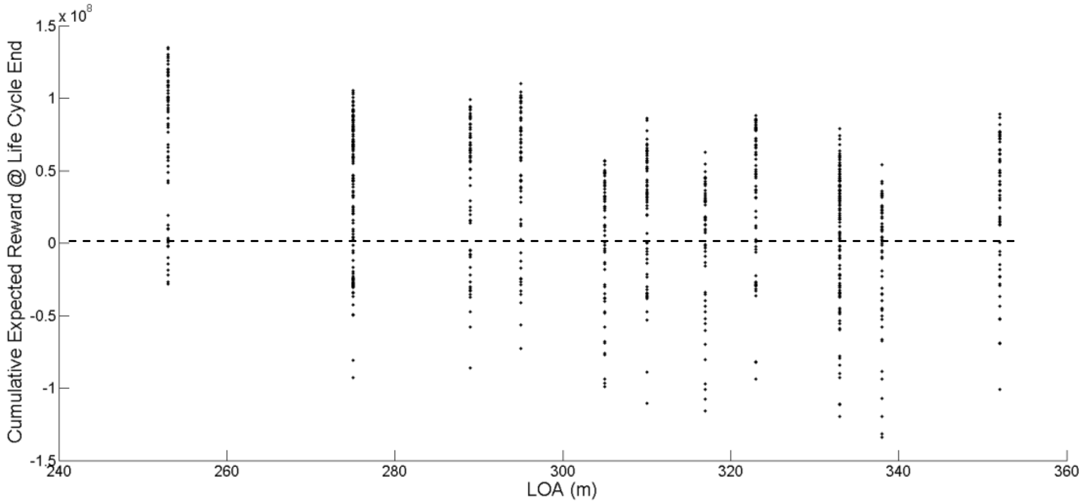


Figure 7-7: Expected reward dependency on overall vessel length

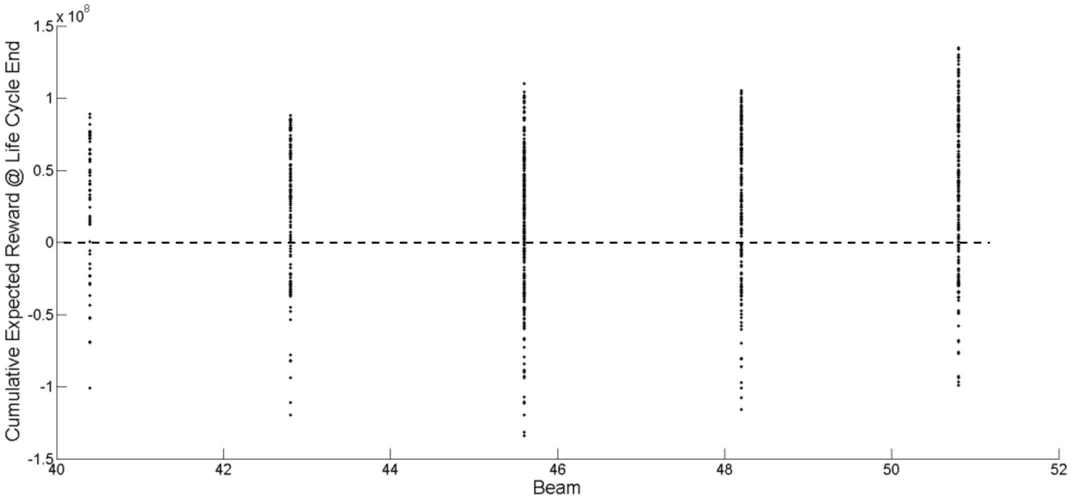


Figure 7-8: Expected reward dependency on vessel's beam

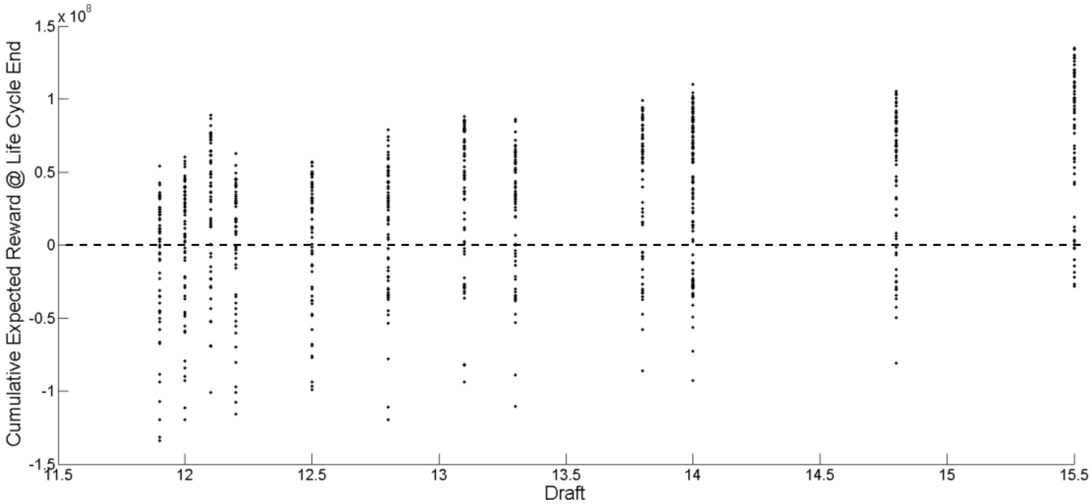


Figure 7-9: Expected reward dependency on vessel's draft

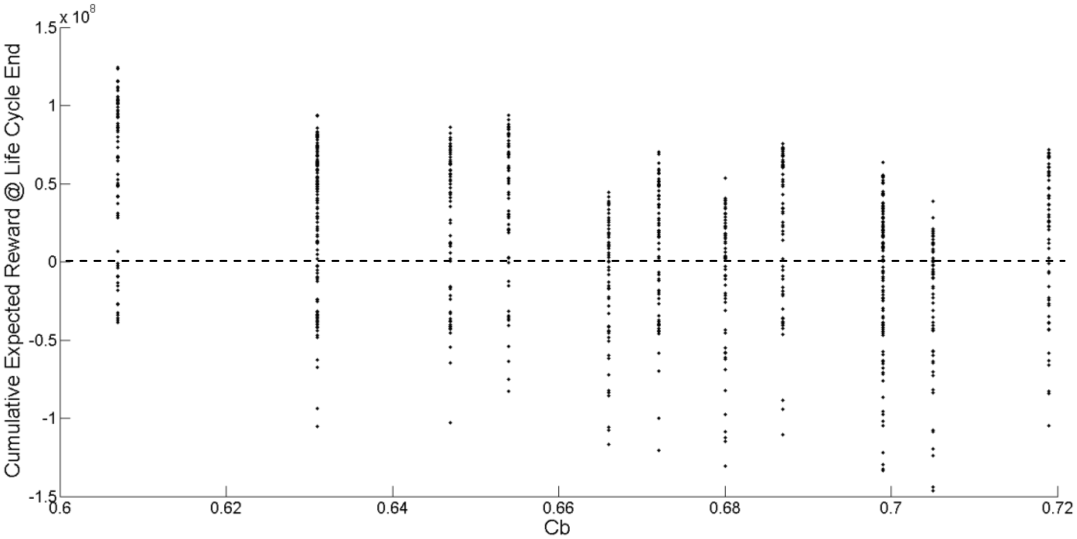


Figure 7-10: Expected reward dependency on vessel's block coefficient

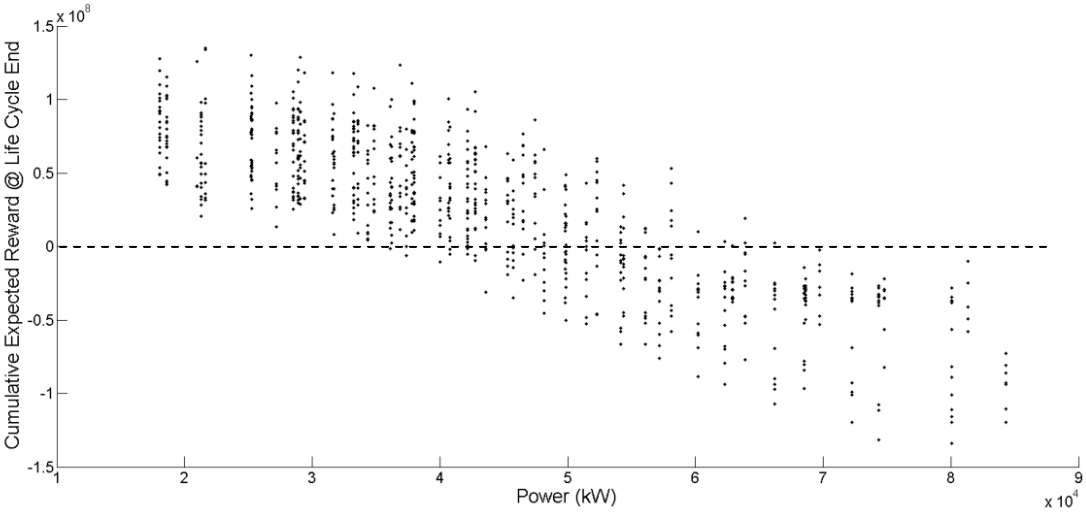


Figure 7-11: Expected reward dependency on vessel's installed power

Possible design configurations within this particular study are not constrained by physical parameters at ports, for example. This theoretical case study purposely applies an expanded view to investigate if infrastructure is constraining the earning potential of ship managers. An actual design project must contend with infrastructure limitations inherent to many ports and marine passageways, such as beam and draft restrictions.

The summarized results, Table 7-12, are then compared to recent post-Panamax containership designs (Configuration 2 in Table 7-2). In general, designs under an uncertain market future due to policy change exhibit the following more-is-better or less-is-better tendencies relative to the modern design:

Table 7-12: Comparison of results to common design types

	Modern Configuration (Table 7-2)	**Tendency**
LOA	323m	Shorter
Beam	42.8m	Wider
Draft	13.1m	Deeper
Cb	0.687	Streamlined
Power	60,000 kW	Less powered

7.7.1.3 Changeable Design Drivers

The MDP framework provides an opportunity to further elicit significant drivers to good design, identifying bundle characteristics common among various high scoring configurations. Figure 7-12 through Figure 7-15 illustrate the frequency with which design bundle components appear in the 98th percentile of core and shell concepts.

If common to the top percentile is a particular collection of energy technologies, one can determine that fuel efficiency is highly valued. Similarly, high frequency of a specific speed or fuel type offers the decision-maker insight into preference for a design characteristic. Conversely, if, for example, multiple operating speeds exist in the top percentile, a decision-maker can interpret that speed is negotiable as the design process progresses.

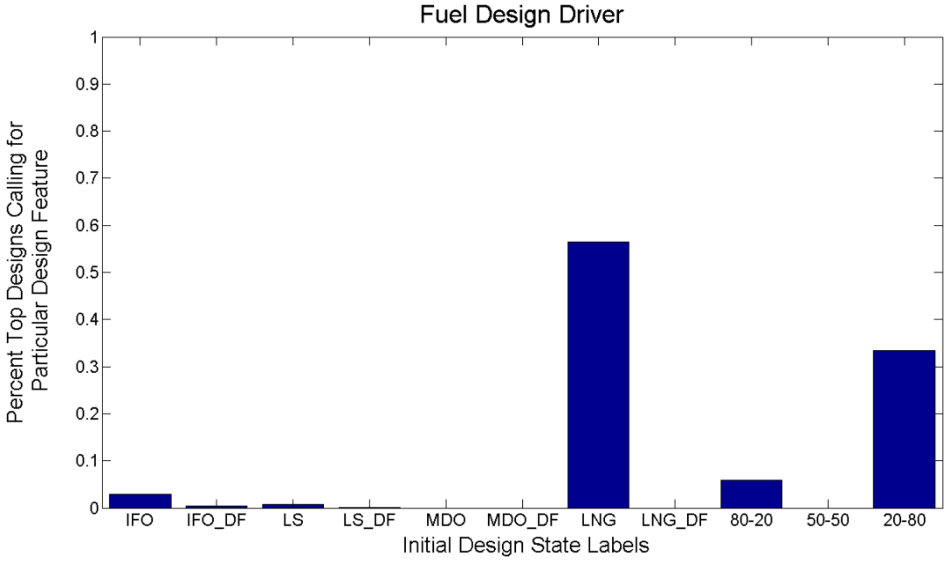


Figure 7-12: Distribution of initial fuel configurations for top design concept candidates

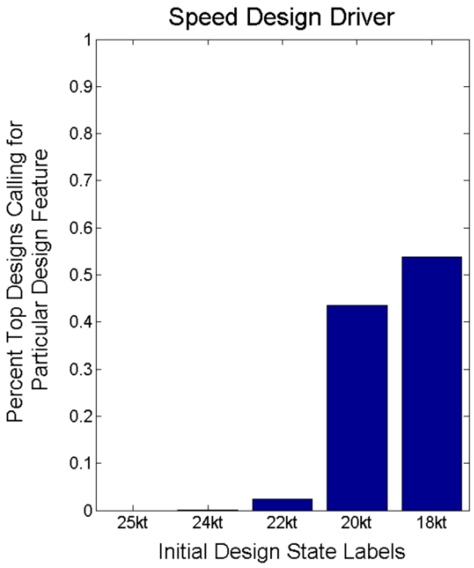


Figure 7-13: Distribution of initial operating speed configurations for top design concept candidates

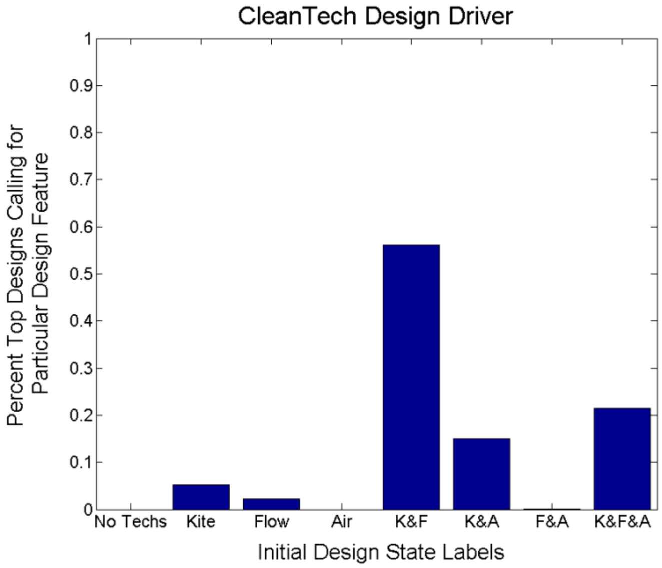


Figure 7-14: Distribution of initial clean technology configurations for top design concept candidates

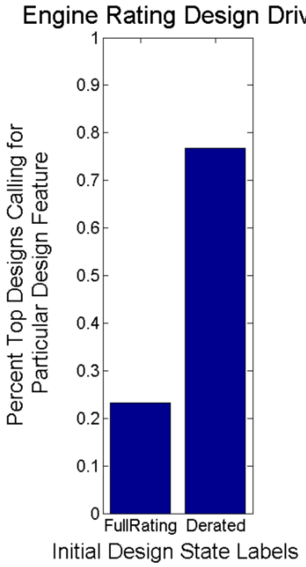


Figure 7-15: Distribution of initial engine rating configurations for top design concept candidates

A number of conclusions, as well as additional questions, are brought forth.

- Figure 7-12 illustrates that LNG or a varying degree of dual fuel capability is favored at construction. Where a traditional fuel oil is selected, the dual fuel real option is not regularly included. Temporal analysis is required to determine if future fuel changes occur despite forgoing the option for dual fuel capabilities at the concept's outset.
- Preference for the lower end of the allowable speed range is suggested by Figure 7-13. No designs are initially set to operate at the traditional post-Panamax design speed of 25 knots. This interesting result may arise from a combination of engine selection satisfying EEDI legislation and expected high fuel costs originating from Starting Condition 1.
- Clean technologies are value-added according to Figure 7-14. The kite is desired by nearly all top designs. The flow device and an air lubrication system are called for in approximately 80% and 40% of initial design constructs, respectively.
- Figure 7-15 illustrates that fully derated engines are strongly preferred. Excess engine capacity requires higher initial investment, but the cost appears to be offset by lower specific fuel consumption. Derating also positively impacts attained EEDI. Furthermore, latent capacity enables future additional power in the event

that the ratio between freight rate and fuel price turns more favorable and re-adaption of the engine is desired.

Multiple methodologies could have been used if expected value analysis was the end-goal. However, follow-on questions—does speed ever return to 25 knots?; when might a flow device be added?—borne out of the above conclusions cannot be answered via a static, expected rewards perspective only. Fortunately, the state-based MDP framework enables instructive temporal analysis that adds depth to first-order conclusions. The additional metrics and representations introduced in Chapter 5 are next derived to improve understanding on a design concept's ability and need to change given an uncertain future environment. This life cycle appreciation for a product is then mapped back to the t=0 initial design point to complement standard expected NPV analysis.

7.7.2 Changeability

Each design concept is part locked-in and part changeable, represented by the core and shell and the bundle, respectively. A poorly selected core and shell cannot be overcome through strategic product management following the ship's construction. Properly selecting a core and shell is a traditional focus of many design tools and methods. Yet, a focus only on the core and shell misses opportunities to identify additional design drivers whose importance ebbs and flows with time.

Far less traditional is a focus on the bundle's ability to influence the earning potential of a specific design proposal. The MDP decision matrix of each core and shell identifies the changeability preferences of the concept through time. Identifying similarities and differences among action pools can inform a decision-maker as to why one core and shell concept may achieve higher or lower returns in an epoch over that of another core and shell concept. Disparate concepts exhibiting similar behaviors speak to the advantage of possessing a specific design feature. Concepts exhibiting unique behaviors in response to the same external environment highlight that the value proposition of available bundles is design-specific.

The following section uses the changeability metrics presented in Chapter 5 to add timely design information to a decision-maker’s purview. The order of introduction includes a discussion and sampling of (a) temporal outdegree diagrams, (b) state entry plots, and (c) action pool illustrations. Representations for two core and shell designs are featured.

7.7.2.1 Temporal Outdegree

A proposed design is uniquely limited by physical, economic, and regulatory considerations. Examples include demands that a ship float upright while carrying sufficient cargo at contracted design speed, that construction costs meet a budget, and that suitable floodable length and transverse stability exist for safety purposes, respectively. Naturally, these constraints can change during the vessel’s use phase, whether by internal or external agents. Limits that did not exist before may be added, while earlier requirements may be lifted or amended. As such, the options for change also contract and expand with time.

Physical feasibility changes with time due to technological innovation, while policy and budget feasibility fluctuate given the evolution of complex decision-making regimes. Given the setup constraints in this case study, a ship capable of achieving 20 knots at full engine loading is limited technologically from entering a state that represents a 25 knot option, for example. The study also places a $10M switching cost on any change action, conceding that such an economic limit might in fact sacrifice long-term reward opportunities. The purpose of an economic limit is to acknowledge that ship owners are also constrained by annual budgets, cash flow limitations, and perceptions of risk. Finally, product change is limited in the regulatory dimension. Reductions to the EEDI reference line over time prevent access to states that were once reachable.

Temporal outdegree is a metric proposed to trace changeability over time. Outdegree is defined as the number of transition arcs emanating from a state, normalized over the total number of states. Figure 7-16 illustrates sample core and shell plots of temporal outdegree. Life cycle time is presented on the x-axis, while the y-axis represents the normalized outdegree value. Because the relationship between outdegree and reachability constraints can be described by the equation,

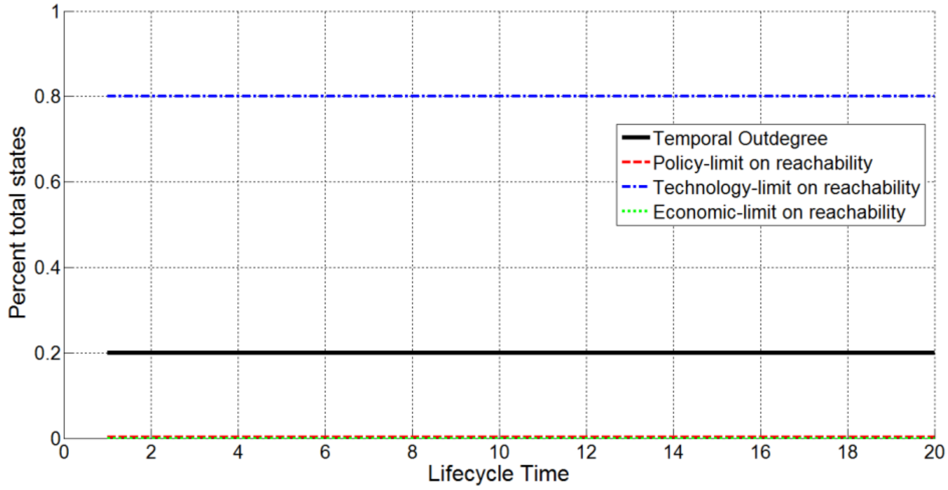
$$\text{Temporal Outdegree} = 1 - (\text{Technology} + \text{Economic} + \text{Political Limitations}) \qquad [7\text{-}6]$$

outdegree decreases as state limitations increase.

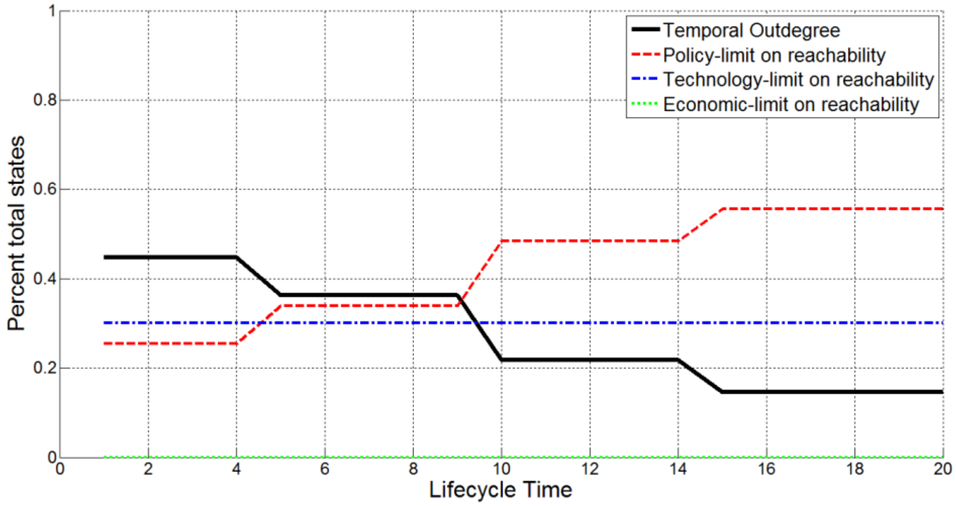
The top example, nicknamed *Tortoise*, illustrates that technological constraints on state transitions remain constant through time and pose the only limit to changeability. State changeability is independent of EEDI policies and switching costs. Conversely, the lower example, *Hare*, does exhibit limitations due to policy efforts. Limitations increase in stages through time, corresponding to planned strengthening of the EEDI reference line. The result is an equal and opposite value change to outdegree.

Plotting outdegree demonstrates that *Tortoise* maintains a higher potential for change at the end of the life cycle despite half the initial change capacity as *Hare*. Comparison of temporal outdegree values among core and shell concepts outline relative levels of reachability as well as where differences in limitations lie within the techno-politico-economic space.

A highly constrained core and shell concept, represented by a low temporal outdegree score, may possess a low expected reward relative to an unconstrained design. In such an instance, added changeability may be a valued contributor to performance. If the difference between expected rewards of the constrained and unconstrained designs is not a statistically significant margin in comparison to the unconstrained design, a decision-maker can interpret that a portfolio of change options represents little upside value. The preferred change option may prove reachable in both the unconstrained and constrained cases, or no change is actually the preferred option.



(a) Tortoise



(b) Hare

Figure 7-16: Sample temporal outdegree plots for core & shell designs, outlining design changeability

Concluding if changeability is valued can be determined by measuring the relationship between outdegree and expected reward. Figure 7-17 plots time-weighted temporal outdegree (TWTO) versus the greatest expected reward within each core and shell concept. Time-weighted outdegree is used as the metric to (a) value higher the change options that exist early in a product's life cycle and (b) produce a point value from a dynamic measurement. Simple analysis demonstrates that rewards generally increase with increasing TWTO and then flatten after meeting a threshold degree of changeability. In other words, a design with greater ability to change in the technology, speed, and/or fuel type dimensions produces higher expected rewards than a design with its change options constrained.

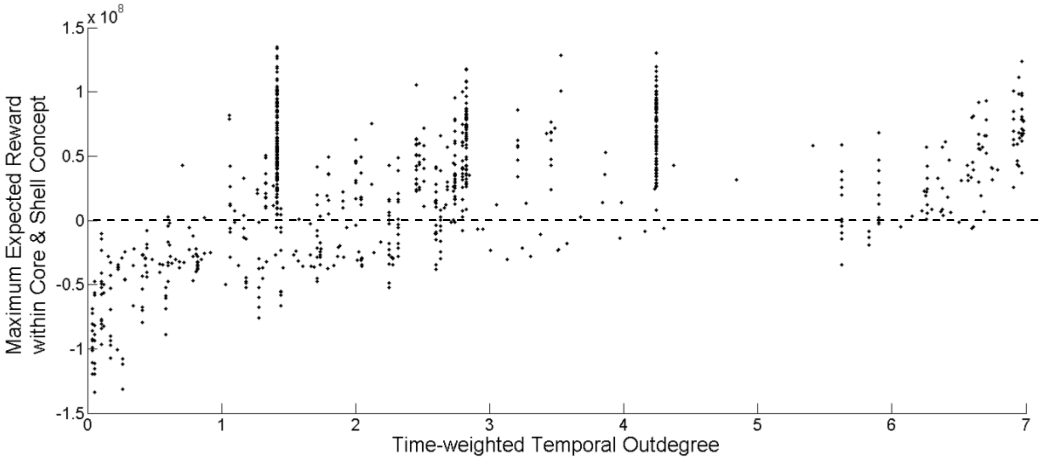


Figure 7-17: Expected reward vs. time-weighted outdegree, illustrating role of changeability in expected reward

Changeability may not result in consistently larger expected rewards for a variety of reasons. A lack of positive correlation between outdegree and rewards can highlight presence of the wrong type, wrong location, wrong timing, and poor systems integration of changeability. These revelations are further detailed below:

- Too much changeability for the sake of changeability simply increases capital expenses
- Changeability can be located in the wrong components, failing to capitalize on emerging needs
- Changes intended to capture the full benefits or to mitigate risk are time-sensitive; changeability too early might require holding costs and change too late can incur penalties or opportunity cost losses
- As a result of increasing changeability in one component or system, other unchangeable characteristics of the product may perform quite poorly

Expected rewards and changeability are positively correlated when the degree of change is properly bounded and change is available at the necessary location and time.

7.7.2.2 State Change & Action Potential

State entry and action pool plots illustrate the availability of specific design concepts and associated actions in time. Exploration of state availability and action optimality deepens the knowledge driving costs, benefits, and change options.

Representation of state entry and action pool plots remain the same as in previous chapters. Each plot represents availability of bundle options specific to one core and shell design. States and actions filled by hatching denote unavailability of all bundles possessing a particular design characteristic due to physical, political, and economic constraints. The remaining states are shaded to mark the percentage of available bundles. Actions are also colored in various shades to denote the percentage of available bundles calling for each feasible design decision. The state entry and action pool representations are further sub-divided into the four primary design features—fuel type, primary operating speed, clean technologies onboard, and engine rating—to both simplify the display of information and to readily communicate key takeaways.

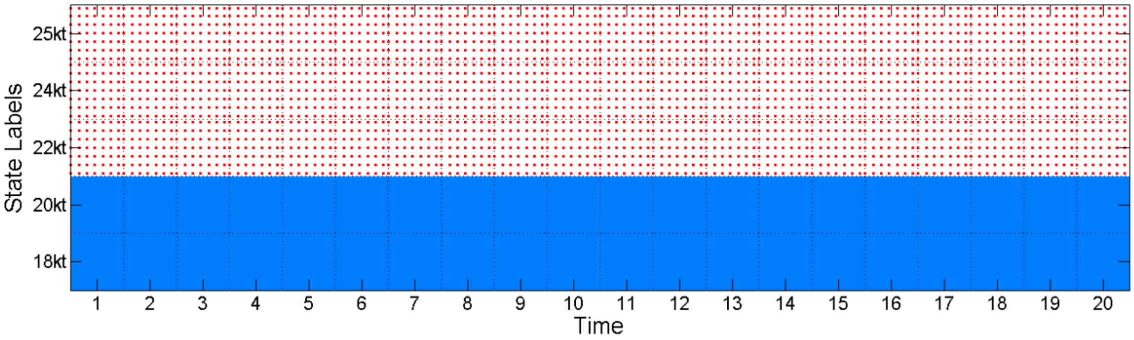
The sampled state entry plots, action pool representations, and temporal outdegree diagrams in Figure 7-16 and Figure 7-18 through Figure 7-29 draw attention to stark differences among both changeability and change optimality particular to core and shell designs. Readily apparent is the fact that some core and shell combinations are heavily hatched, signifying a substantial degree of lock-in. Other core and shell designs offer significant opportunity for change. In conjunction with its corresponding temporal outdegree diagram, a state entry pool identifies the extent of state accessibility within a core and shell design. The two diagrams together answer the {how many, which, and why} set of questions important to understanding state accessibility and unavailability.

Figure 7-18 through Figure 7-19 showcase the state entry plots of two core and shell sets for comparative purposes. The primary features of the sampled core and shell sets are outlined in Table 7-13, and are defined as C&S-A and C&S-B hereafter.

Table 7-13: Core and shell designs featured in discussion below

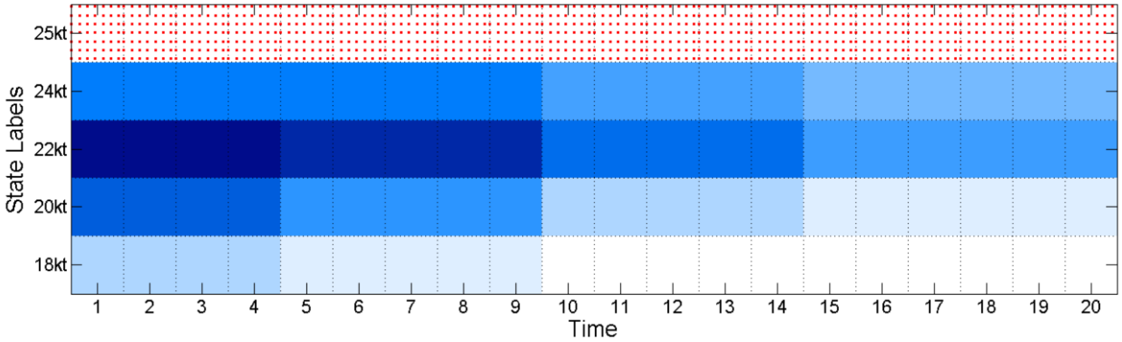
Sample Name	Primary Features
C&S-A	Configuration 1 @ 31,620 kW
C&S-B	Configuration 2 @ 54,360 kW

The first two figures highlight accessibility related to speed. Figure 7-18 details that states are limited to a maximum operating speed of 20 knots for C&S-A. Speed availability reaches 24 knots for C&S-B, in Figure 7-19, but the number of states available at this speed decreases over the horizon due to environmental factors.



Legend: Shading denotes % state availability, on continuum from dark (100%) to light (0%)
Hatched states are 100% unavailable

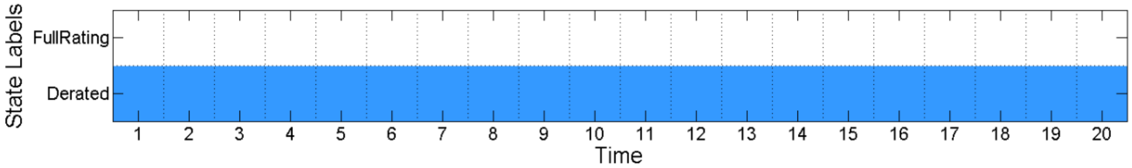
Figure 7-18: Speed state entry subplot for C&S-A



Legend: Shading denotes % state availability, on continuum from dark (100%) to light (0%)
Hatched states are 100% unavailable

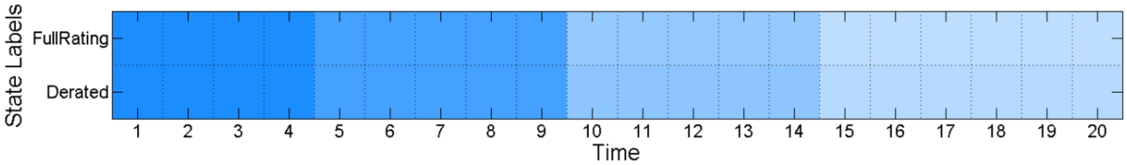
Figure 7-19: Speed state entry subplot for C&S-B

A similar trend is noticed for the state entry subplots detailing the availability of life cycle states featuring a particular engine rating. Figure 7-20 illustrates constancy in availability through time and much reduced availability of a fully rated C&S-A engine. Figure 7-21 represents decreasing availability with time, coinciding with the planned EEDI schedule. While both fully rated and derated options are largely available at the design's onset, a much reduced state space exists at life cycle end.



Legend: Shading denotes % state availability, on continuum from dark (100%) to light (0%)
Hatched states are 100% unavailable

Figure 7-20: Rating state entry subplot for C&S-A



Legend: Shading denotes % state availability, on continuum from dark (100%) to light (0%)
Hatched states are 100% unavailable

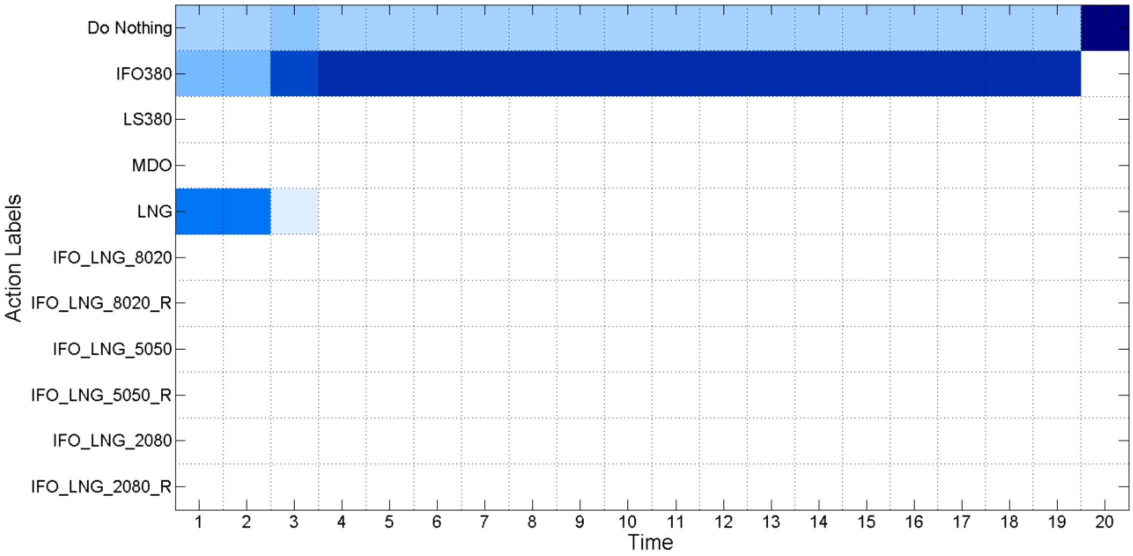
Figure 7-21: Rating state entry subplot for C&S-B

Other points of note are drawn from similarities and differences in action pool diagrams. At time t=20, the optimal action within both core and shells is almost universally 'Do Nothing,' while a mix of state-dependent action combinations occur at *t=10*. Whereas one action is a potential decision for C&S-B, no such action is optimal for any available state within C&S-A. Similarly, other actions are emphasized more strongly within C&S-A. Overall, a unique distribution of actions in terms of frequency and epoch occurrence is found to exist.

Furthermore, action availability may be constant through time, fleeting, or emergent at rates unique to each core and shell. Optimality and availability are inextricably linked; an action must be available to be found optimal. Wider availability of actions results in a greater opportunity for the non-zero action pool to possess a fuller range of actions.

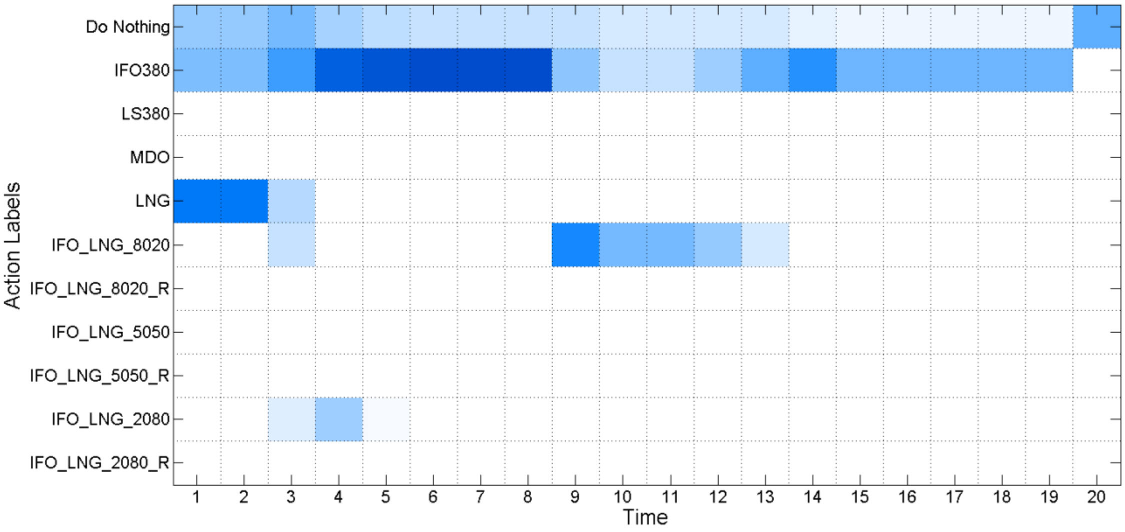
Despite the same quantity of action availability, two core and shell designs may opt to exercise this opportunity uniquely. Thus, a wider non-zero optimal set is not a direct consequence of availability.

Figure 7-22 reveals that {Do Nothing, Switch to IFO 380, and Switch to LNG fuel} comprise the optimal actions given all available states in C&S-A. A switch to LNG fuel is only optimal early in the horizon, giving way to the decision to use IFO 380 fuel later in the life cycle. CS-B yields a larger action pool set, as illustrated in Figure 7-23. Several available states value a switch to dual fuel usage in the early to middle life cycle of the vessel.



Legend: Shading denotes % reachable states calling for action, on continuum from dark (100%) to light (0%); Hatching denotes unavailable actions

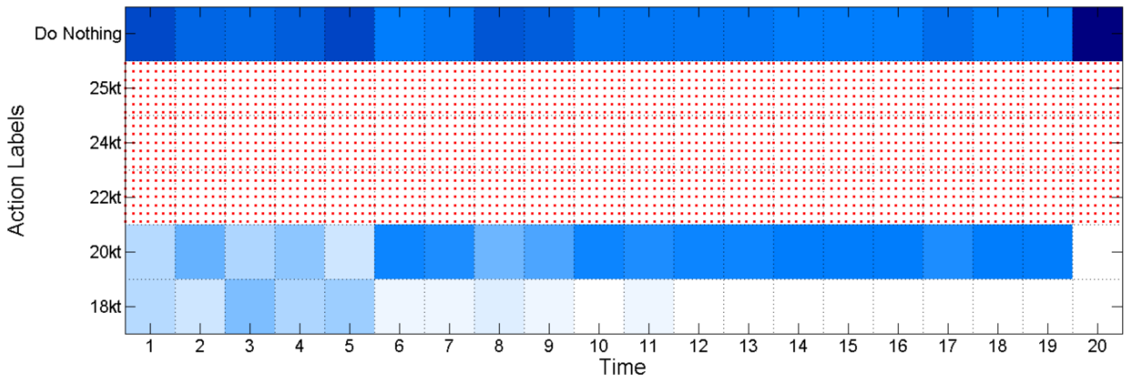
Figure 7-22: Fuel action pool subplot for C&S-A



Legend: Shading denotes % reachable states calling for action, on continuum from dark (100%) to light (0%); Hatching denotes unavailable actions

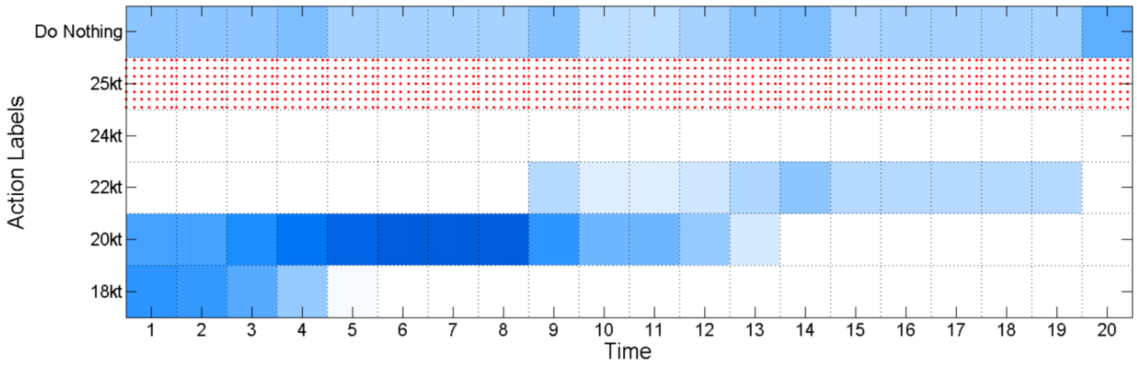
Figure 7-23: Fuel action pool subplot for C&S-B

Change actions related to speed are also a function of the core and shell. Figure 7-24 illustrates a desire by the decision-makers of C&S-A to ‘Do Nothing’ or to switch to a speed of 20 knots with near equal frequency. Early in the life cycle of the vessel, a change in operations to a speed of 18 knots is also potentially desirable given the current state. Operating speed for C&S-B is highly state-dependent. Figure 7-25 exhibits that several speed ranges are optimal in non-zero proportion for all time.



Legend: Shading denotes % reachable states calling for action, on continuum from dark (100%) to light (0%); Hatching denotes unavailable actions

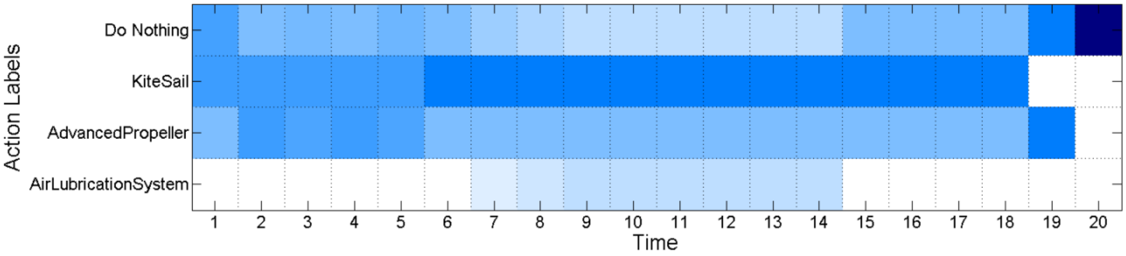
Figure 7-24: Speed action pool subplot for C&S-A



Legend: Shading denotes % reachable states calling for action, on continuum from dark (100%) to light (0%); Hatching denotes unavailable actions

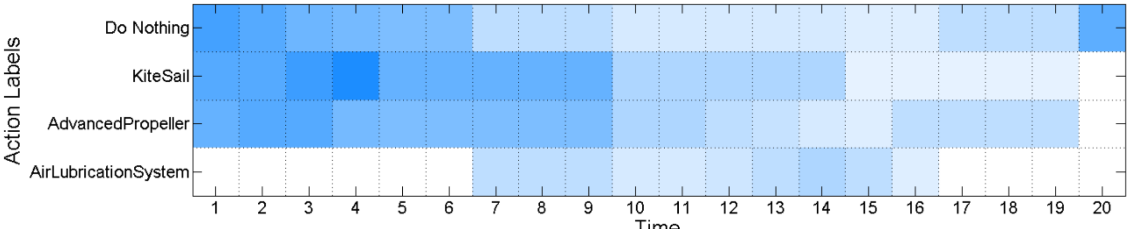
Figure 7-25: Speed action pool subplot for C&S-B

C&S-A and C&S-B demonstrate similar action preferences for changes related to the use of clean technology (Figure 7-26 and Figure 7-27). A desirability to include clean technology is valued by both core and shell designs. Overhaul to include an air lubrication system is called for in the mid-life cycle of both designs. Nevertheless, specific systems are emphasized to a greater degree at different epochs due to innate differences in each core and shell.



Legend: Shading denotes % reachable states calling for action, on continuum from dark (100%) to light (0%); Hatching denotes unavailable actions

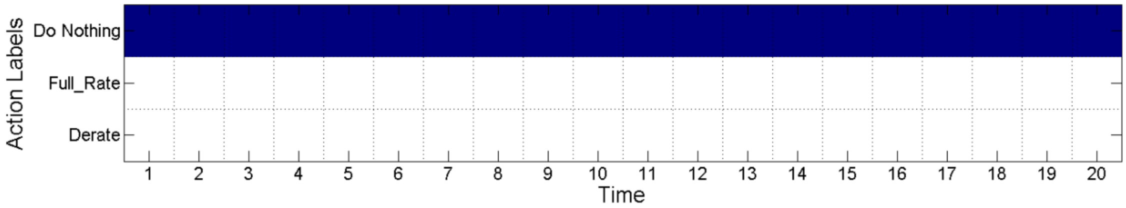
Figure 7-26: Technology action pool subplot for C&S-A



Legend: Shading denotes % reachable states calling for action, on continuum from dark (100%) to light (0%); Hatching denotes unavailable actions

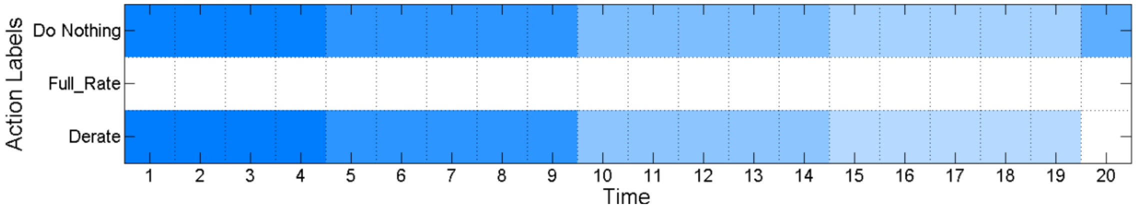
Figure 7-27: Technology action pool subplot for C&S-B

Lastly, Figure 7-28 and Figure 7-29 compare the subplot action pools related to engine rating. C&S-A demonstrates a clear preference to ‘Do Nothing’ with the prime mover’s tuning over the full decision-making horizon. Correlation to the EEDI schedule is again witnessed in the rating plot associated with C&S-B. One may recall that both full and derated engine options are available for C&S-B. Thus, by process of elimination, ‘Derate’ actions relate to states with fully rated engine and ‘Do Nothing’ actions relate to the derated engine states. The long-term preference for C&S-B is to operate with a derated engine. This preference realization will be made further explicit following simulation.



Legend: Shading denotes % reachable states calling for action, on continuum from dark (100%) to light (0%); Hatching denotes unavailable actions

Figure 7-28: Rating action pool subplot for C&S-A



Legend: Shading denotes % reachable states calling for action, on continuum from dark (100%) to light (0%); Hatching denotes unavailable actions

Figure 7-29: Rating action pool subplot for C&S-B

In summary, state entry and action pool diagrams provide rapid identification of preferred design form, function, and behavior over the life cycle. Similar as to how a police precinct can use hotspot analysis to focus patrols on locales of high crime incidence, so too, can decision-makers focus their design efforts on candidate design groups with particular characteristics. Identifying state and action clusters through hotspot analysis can shift efforts from eliciting top combinations of physical and operational factors (analysis of alternatives) to configuring the assets in a manner that maximizes system-level rewards and utility (optimization).

7.7.3 Simulation

Simulation uses the transition, reward, and decision matrices of the MDP setup and results. Sampling potential manifestations of events and actions leads to a fuller image of what *actual* rewards may be obtained and the decision pathways followed. The simulations start at $t=0$, sample feasible state paths using the MDP decision matrix for guidance, and collect rewards as earned.

The full core and shell's action pool says nothing of the specific action sequence designated by top design bundle candidates. In fact, certain decisions within the action pool are unlikely to ever be executed if the initial design bundle is correctly selected. A significant percentage of the action pool may include information from other states that are executing sub-optimal policies.

The policy for a concept which initially begins shipping operations using a sub-optimal fuel mix is likely to call for an adjustment to fuel type at an early epoch. Such an action may then cause the remainder of the policy to fall in line with the globally optimal sequence. The author describes this occurrence as merging with the *absorbing path*. Studying top-tier design bundles from the outset leads to rapid identification of the absorbing path; the optimal action sequence of the top bundle itself comprises the absorbing path. Multiple absorbing action paths may be identified if top bundle candidates exhibit unique policies, in which case optimal sequences are viewed as local.

The next several sub-sections expound upon learnings that are generated from identification of the absorbing action path(s). First, optimal state and action sequencing representations are used to contextualize the results of simulation. The proposed metrics of Chapter 5 are then applied in order to deepen knowledge of the implications of design decisions. These metrics include cost premium, clarity-changeability ratio, horizon activity level, and epoch attention level. Individual and collective conclusions pertinent to both the case study and the overall discussion of design changeability are shared.

7.7.3.1 Optimal State and Action Sequencing

The purpose of determining the states accessed and actions executed is (a) to determine the non-dominated state and action solution set through time, (b) to assess the percent of time a design exists in each state, and (c) to identify the percent of time fuel, speed, technology, and engine rating actions are expected to occur.

Purposeful application of simulation techniques prevents the problem from becoming unwieldy. A decision-maker would be also wise to first down-select further analysis to core and shell combinations with high expected reward potential. The following discussion again focuses only on C&S-A and C&S-B. Initial design states scoring within the 98th percentile of each core and shell enter simulation. A total of 1000 runs for each initial design state are used to simulate the optimal action sequences within the full core and shell. The process for selecting where to conduct simulations is summarized via Figure 7-30.

Figure 7-30: Suggested method for limiting simulation needs

Information from the set of simulations is compiled into probability plots of states accessed and actions executed. The plots mark a subset of the state entry and action pool diagrams offered in the previous section. A general outline of the presented figures is first offered in Table 7-14.

Table 7-14: Index of state entry and action pool diagrams by core and shell + design bundle set

	States Accessed				Actions Executed			
	Fuel	**Speed**	**Techs**	**Engine**	**Fuel**	**Speed**	**Techs**	**Engine**
C&S-A	Figure 7-31	Figure 7-32	Figure 7-33	Figure 7-34	Figure 7-35	Figure 7-36	Figure 7-37	Figure 7-38
C&S-B	Figure 7-39	Figure 7-40	Figure 7-41	Figure 7-42	Figure 7-43	Figure 7-44	Figure 7-45	Figure 7-46

Sample observations include the following:

- C&S-A findings
    - One absorbing path is identified. A single absorbing path results only when the number of states accessed per epoch is equal to one. The absorbing path includes the {IFO 380, 20 knots, Kite+Flow+Air Lubrication Device, Derated Engine} set.

  - Initial physical differences in top design candidates converge to the absorbing path by Year 8, marked by the first year in which the quantity and types of state accessed no longer differ from the previous year.
  - No change is executed to C&S-A once the absorbing path is reached. Changes to fuel, speed, and onboard technologies occur early in the vessel's life cycle.
- C&S-B findings
  - A single absorbing path is also reached in Year 8.
  - Fuel fluctuates between IFO 380, LNG, and dual fuel capabilities. Speed steadily increases with time, all clean technologies are implemented, and the engine is derated.
  - A speed change to 22 knots and fuel changes both from dual fuel to IFO 380 and back again to IFO 380 are recommended by the optimal policy after the absorbing path has been reached.

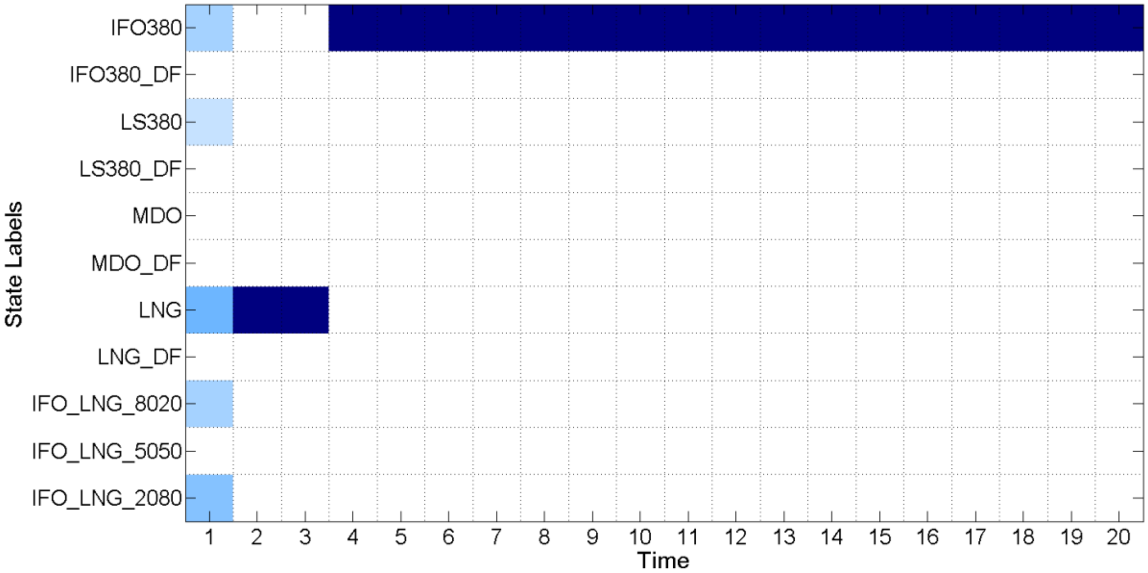


Figure 7-31: Optimal fuel states accessed given best initial design bundle within C&S-A

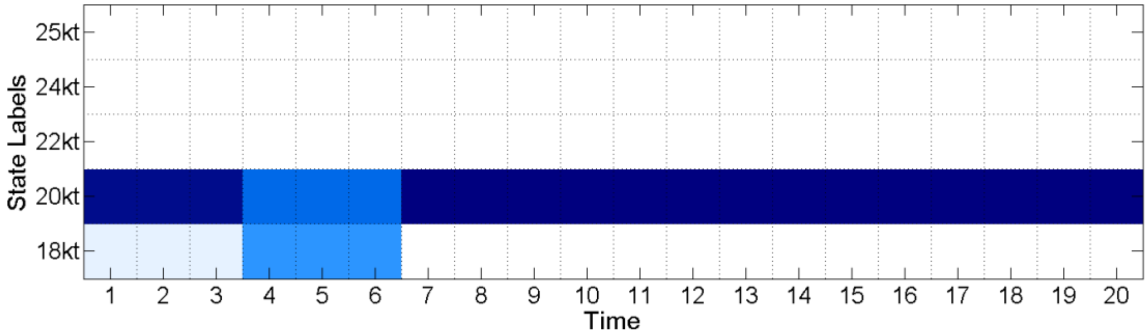


Figure 7-32: Optimal speed states accessed given best initial design bundle within C&S-A

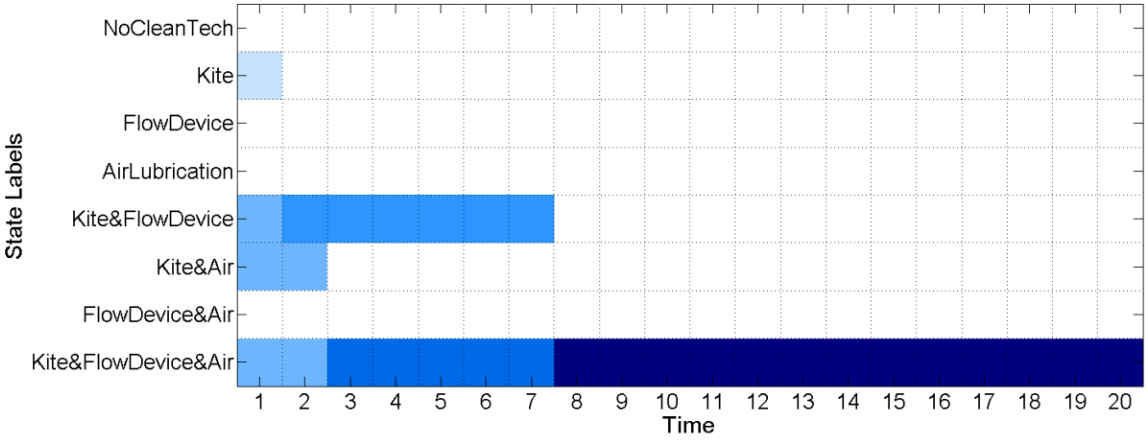


Figure 7-33: Optimal technology states accessed given best initial design bundle within C&S-A

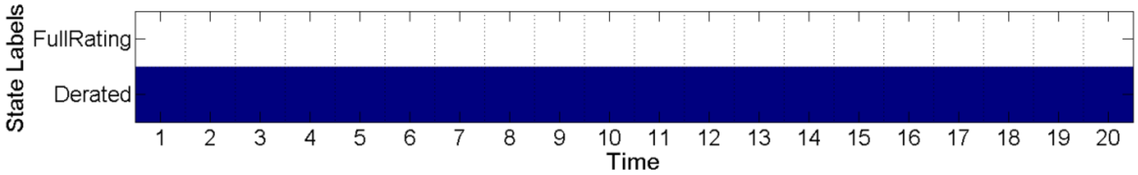


Figure 7-34: Optimal engine rating states accessed given best initial design bundle within C&S-A

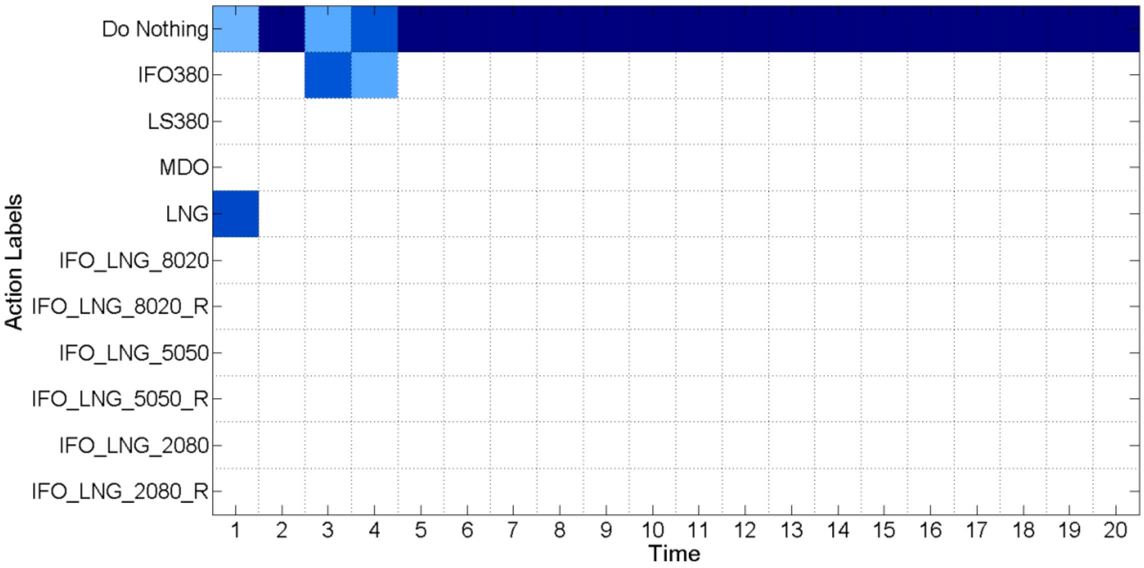


Figure 7-35: Optimal fuel actions executed given best initial bundle within C&S-A

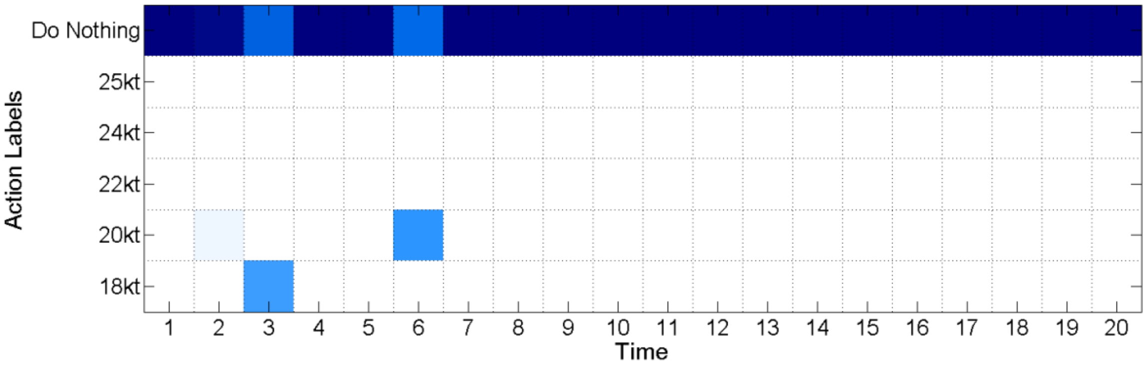


Figure 7-36: Optimal speed actions executed given best initial bundle within C&S-A

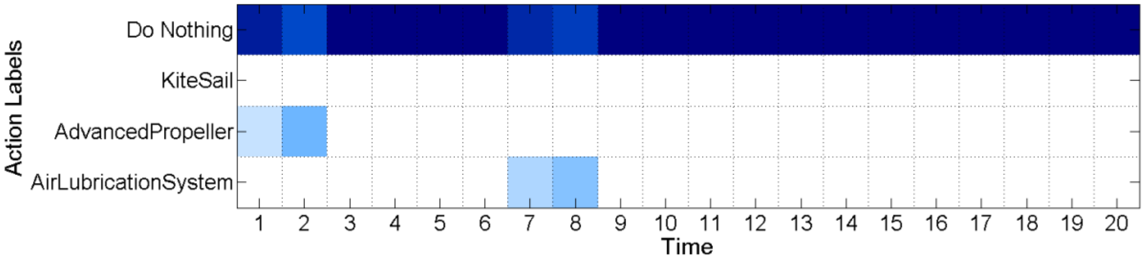


Figure 7-37: Optimal technology actions executed given best initial bundle within C&S-A

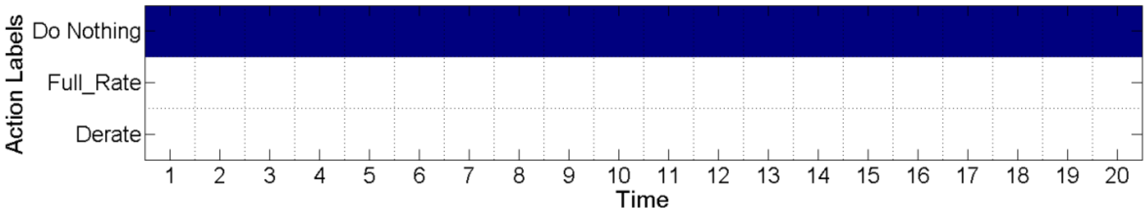


Figure 7-38: Optimal engine rating actions executed given best initial bundle within C&S-A

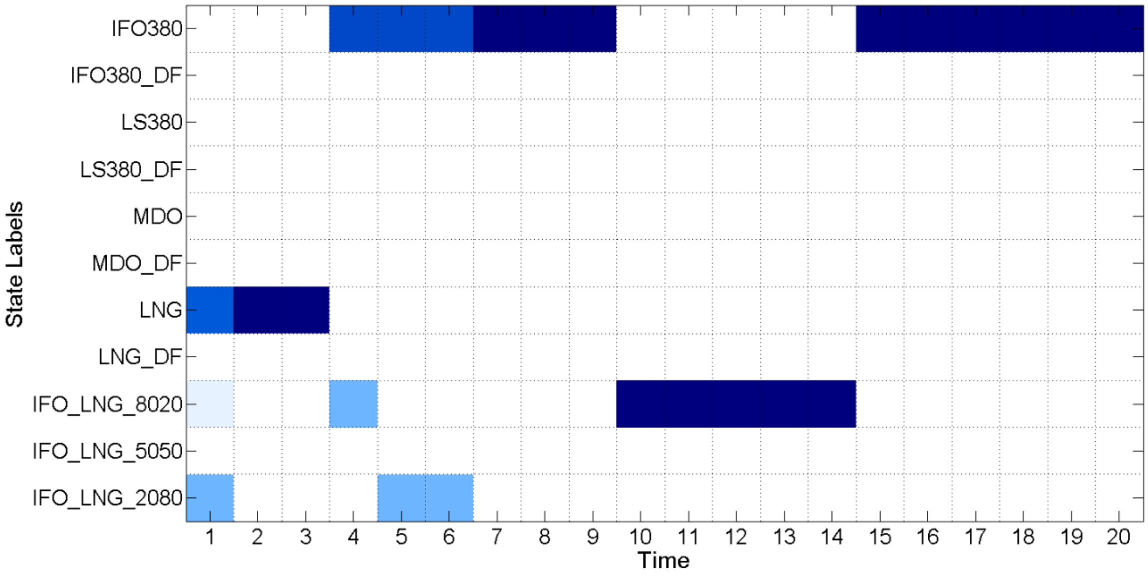


Figure 7-39: Optimal fuel states accessed given best initial design bundle within C&S-B

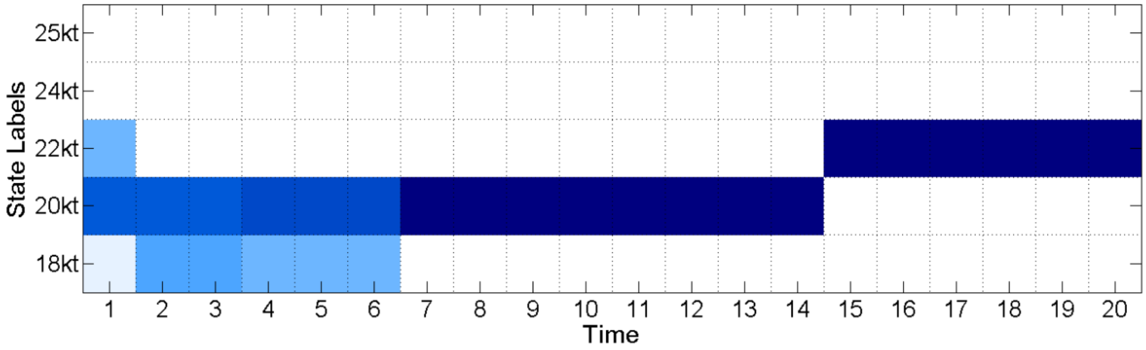


Figure 7-40: Optimal speed states accessed given best initial design bundle within C&S-B

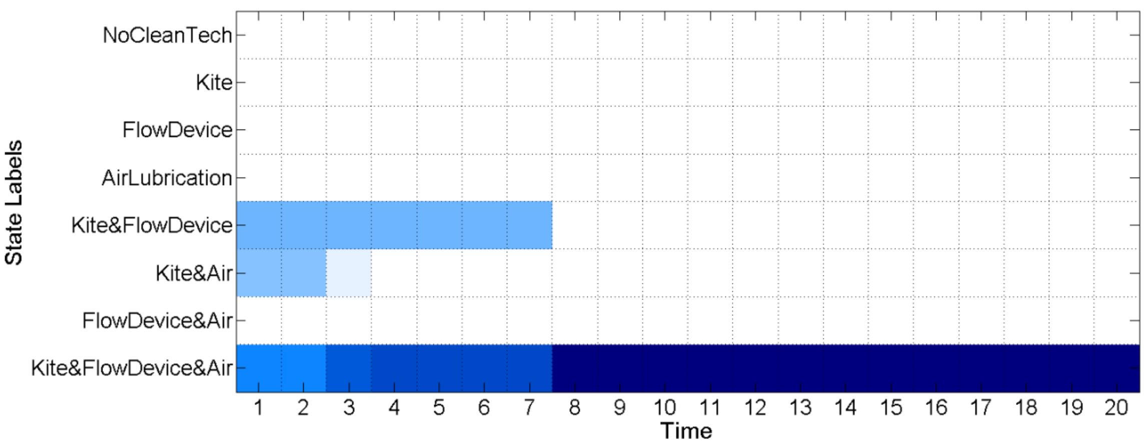


Figure 7-41: Optimal technology states accessed given best initial design bundle within C&S-B

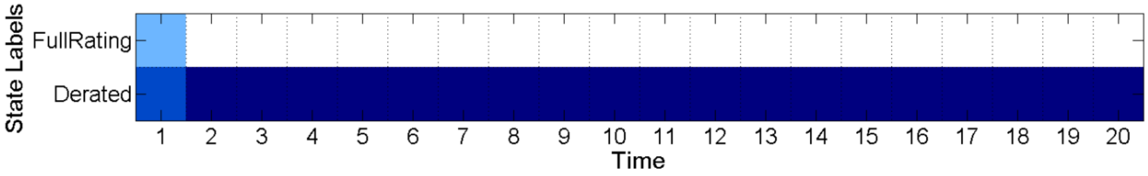


Figure 7-42: Optimal engine rating states accessed given best initial design bundle within C&S-B

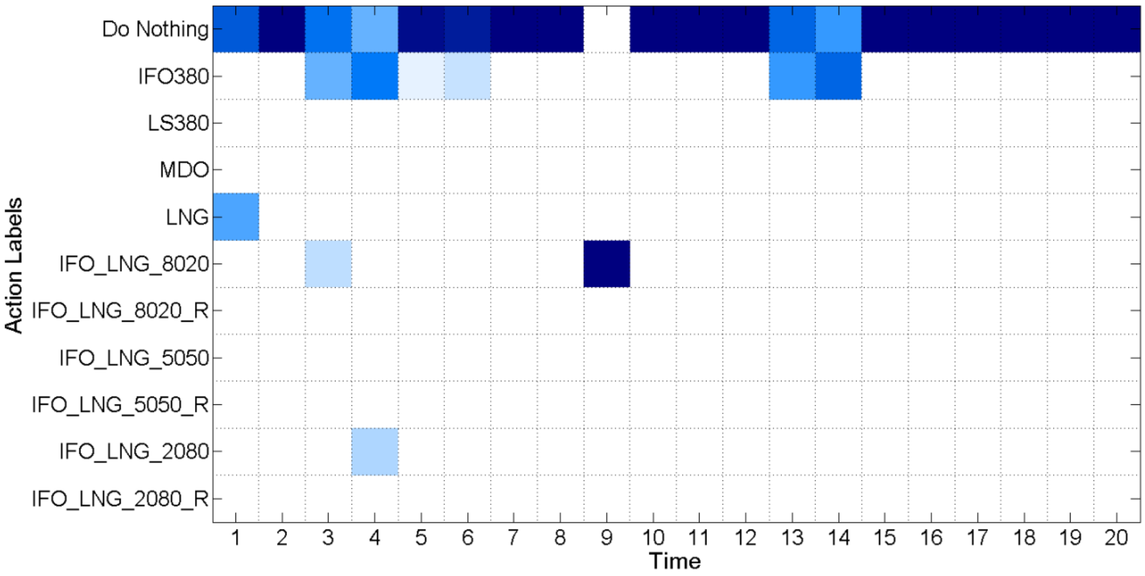


Figure 7-43: Optimal fuel actions executed given best initial design bundle within C&S-B

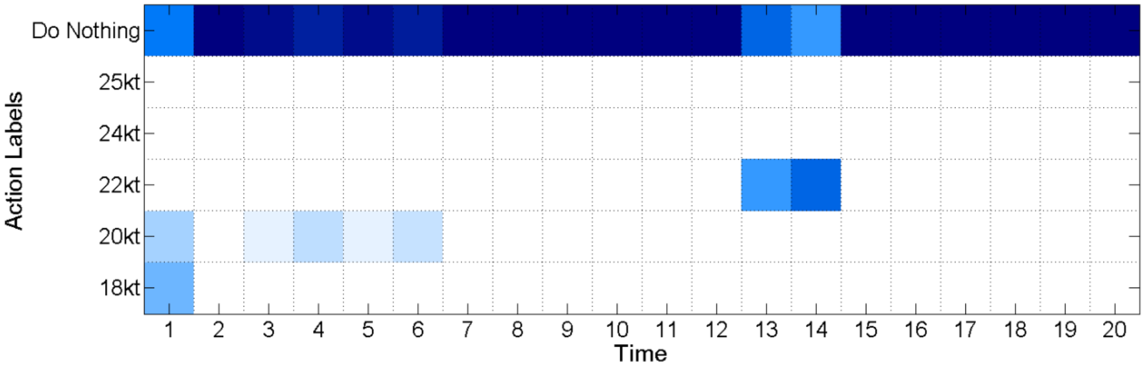


Figure 7-44: Optimal speed actions executed given best initial design bundle within C&S-B

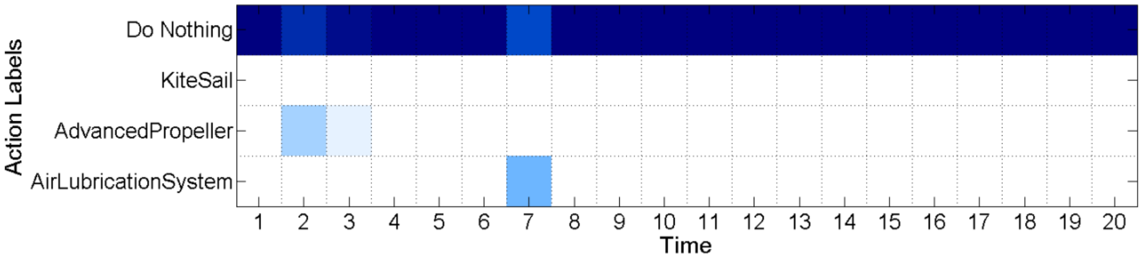


Figure 7-45: Optimal technology actions executed given best initial design bundle within C&S-B

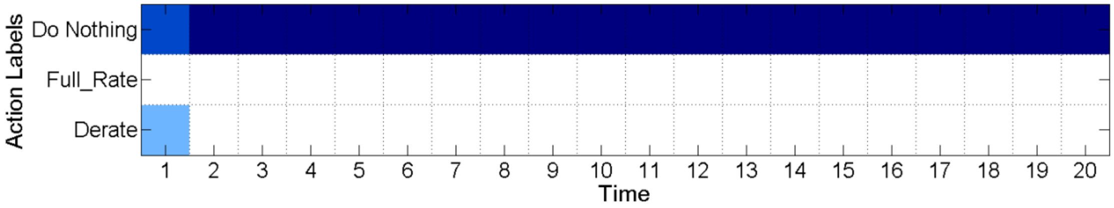


Figure 7-46: Optimal rating actions executed given best initial design bundle within C&S-B

A benefit of the simulation is the ability to identify *when* change actions are expected. Given the configuration of system components when the disturbance occurs, responses may be unique to each design concept. For example, different failure rates among technologies or vulnerabilities to new regulation might uniquely affect the change sequence of concepts. Ship owners are also likely to prefer design changes that coincide with the standard overhaul schedule versus a series of changes that optimally occurs off-cycle.

A late life cycle decision is more uncertain, yet also affords more time for knowledge capture. A decision-maker can elect to forego a late life cycle design change with more confidence if the individual knows such a decision will not largely impact the total reward picture and provided that cumulative rewards to date are in line with operational and economic goals originally sought.

Early life cycle actions are likely to signal an attempt to reach a global or local absorbing path. A decision-maker can be clued to question if early change actions should be foreseeable and correctable at the design stage. Detailed exploration of the causes for such action, and corresponding modifications to the initial design concept, may eliminate the need for early stage change.

Conversely, optimal decision paths that include late life cycle changes likely signal disturbance events. The initial design may very well be robust to all but uncertain, long-term events and/or subject to natural performance decay with time.

7.7.3.2 Changeability Metrics

A simple count of the number of uniquely optimal decisions, at life cycle end or at another particular epoch in time, determines *how many* action choices are suggested. Too many choices at one epoch or cumulatively may prove undesirable to a decision-maker seeking to contain potential design changes. A contained set of alternatives may position decision-makers with greater opportunity to minimize the additional risks resulting from design modifications, e.g., acquisition, testing and verification, scheduling, and budgeting. Certainly, too few choices prevent an appropriate level of responsiveness when disturbances occur.

Figure 7-47 and Figure 7-48 outline the unique action sequencing called for in C&S-A and C&S-B, respectively. A total of five unique actions and four unique sequences are non-dominated solutions for C&S-A given the probabilistic expectation of the future detailed in the problem setup. A total of seven unique actions and twelve unique action sequences are discovered for C&S-B. Only two actions are common to both optimal action pools, one of which is the basic ‘Do Nothing’ action. Changeability associated with engine rating is not exercised by the decision-maker in the case of C&S-A, but technology additions, speed changes, and fuel switches are utilized in both design cases.

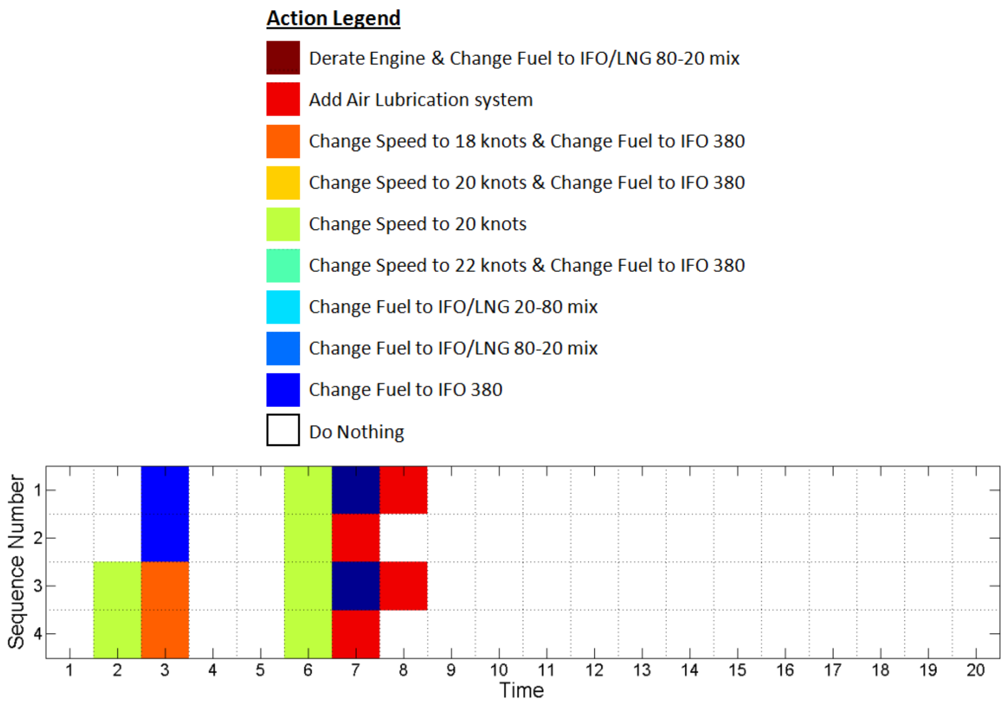


Figure 7-47: Unique sequences by action type and timing for C&S-A, initial design construct D

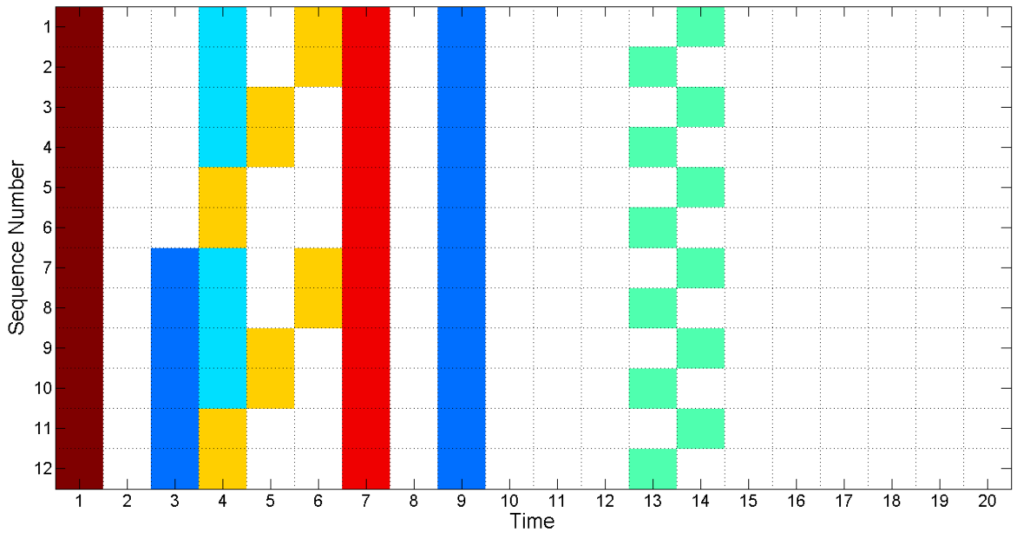


Figure 7-48: Unique sequences by action type and timing for C&S-B, initial design construct H

Unique action sequencing, as its name implies, results from either distinctive actions or distinctive timing of a planned action. For example, Sequences 1 & 2 in Figure 7-47 differ by one year when an action is to be executed, while the remainder of the sequence is the same in terms of timing and specific actions called. Sequences 2 & 3 differ both in action type executed at Years 2 & 3 as well as in timing of a technology addition executed in either Year 7 or 8. A decision-maker may prefer to manage uncertainty related to action type more closely than action timing, or vise versa, given particular capabilities of the vessel, its operators, and supporting institutions.

The desire by a decision-maker to achieve both planning clarity and the ability to change is measured in the form of the clarity-changeability ratio. Recall previous discussion of temporal outdegree, which now can be coupled with the above simulation information regarding optimal action sequencing. The interplay between policy actualization and potential is modeled in Figure 7-49, below.

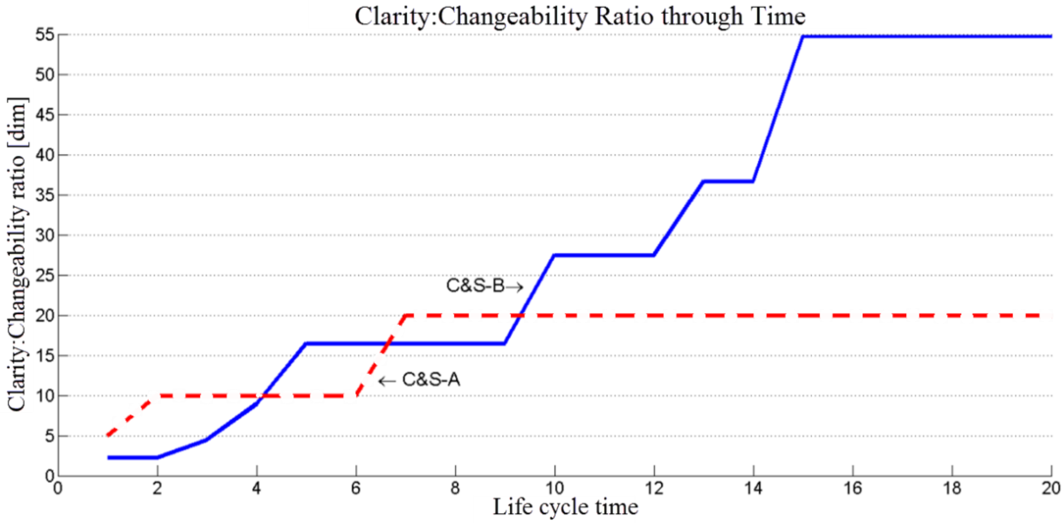


Figure 7-49: Comparison of clarity-changeability ratio through time

Recall that a low ratio is preferred: planning robustness and a latent potential for a product to adjust in any number of ways to a dynamic environment. Neither C&S-A nor C&S-B is dominant across the entire horizon. C&S-B is marked by high initial changeability and little policy directive to act during the first several years of the product's life cycle. However, decreasing changeability resulting from EEDI environmental policy initiatives, together with probabilistic disturbances affecting cost and revenue, ultimately lead to a rapidly increasing clarity-changeability ratio through time. The ratio for C&S-A over C&S-B is favorable for much of the life cycle despite low changeability reflected by its temporal outdegree valuation. C&S-A benefits from greater policy robustness to disturbances developing late in the life cycle.

Heavier life cycle change expectations for C&S-B are further reflected in HAL and $\overline{EAL}$ metrics. Horizon activity level and mean epoch attention level values are presented in Table 7-15 for both the initial design constructs whose optimal action sequencing is modeled in Figure 7-47 and Figure 7-48 as well as the average for all initial design constructs falling in the 98th percentile of C&S-A and C&S-B.

Table 7-15: Differences in management level metrics for two same core & shell designs

Management Level	**C&S-A**	**C&S-B**
HAL, initial design construct D & H, respectively	3.55	5.98
HAL, 98th percentile average	2.92	4.62
$\overline{\boldsymbol{EAL}}$, initial design construct D & H, respectively	0.30	0.50
$\overline{\boldsymbol{EAL}}$, 98th percentile average	0.22	0.38

Given that HAL, $\overline{EAL}$, and the clarity-changeability ratio performance might all be described as "better" for C&S-A than C&S-B, it is no surprise that the expected value of C&S-A is also more favorable ($86.7M vs. $-6.42M). Initial experimentation finds that expected value and changeability metrics are not always correlated.

What is surprising is that temporal outdegree diagram appears to favor C&S-B (C&S-A=*Tortoise*, C&S-B=*Hare* in Figure 7-16). This finding serves to re-emphasize that changeability is only as valuable as the type of change, place of change, and timing of change available to a decision-maker. Little can be done to improve an improperly selected core and shell design. Design, operating and environmental decisions or events can engender lock-in in product features that need changed while continuing to allow change in other product features that do not need change.

7.8 Discussion

The following section is divided into two subsections. The first provides general insights as it pertains to containership design. The second, and more important from a research standpoint, offers insights for the framework itself after having applied the MDP methodology and its metrics to the early stage analysis of a containership design.

7.8.1 Containership Design Insights

Containership designs and operations have changed markedly in the last decade, some features and factors which include:

- Efficiency macro-trend calls for ships of increasing size and cargo capacity
- Slow-steaming and super slow-steaming of oceanic vessels when fuel rates experience an uptick
- Specialized pricing contracts and at ports for high performing vessels, including favorable rates for flexible cargo spaces and environmental footprint
- Environmental regulations moderating air and water emissions; regulations are inconsistent from waterway to waterway, nation to nation, and even port to port
- New technologies capable of improving engine performance, reducing energy use, monitoring ship systems, and electronically controlling ship functions

The research conducted in Chapter 7 finds that new design features are encouraged in response to current and future trend policy and market projections. There exists both some match between the “best” design concepts identified in the case study and latest ship builds as well as some disagreement in dimensions and technologies applied.

The case study, as well as most traditional early stage design activities, involved low fidelity cost estimation and performance modeling. While these efforts reveal broad trends and can provide general insights, the resulting valuations remain uncertain. The study is most valuable from the comparative analysis standpoint of (a) guiding the selection of a few promising alternatives for more detailed design, (b) discovering potential change needs and the underlying drivers behind the selection of certain design features, and (c) drawing insights regarding correlation between type, timing, and location of change with expected rewards.

The broad array of concepts explored reveals that expected values among alternative designs cover a range of nearly $300M. Performance is strongly driven by the core and shell design itself; for example, high powering requirements caused by poor shaping of a ship's dimensions lead to poor overall valuations.

Disparate high-performing core and shells advocate for unique assemblies of bundle features to maximize positional advantage. One design may call for a smaller engine and operating speed to minimize fuel cost risk, while another advocates use of energy efficient technologies and high operating speeds to maximize revenue. Trade-offs exist within both the initial design construct and future change opportunities. The distribution of initial bundles within a core and shell involves a $10M range itself, which evolves out of both design lock-in and switching costs leading to the absorbing path.

7.8.2 Methodological Insights

Research in this chapter involved the rapid analysis of hundreds of design concepts from the advanced artifact life cycle perspective. The framework developed affords a range of reporting levels for results, including the full core and shell, filtered core and shell, filtered design concept, and individual design concept levels. Each level provided added insights, detailed in the following list:

- Broad core and shell – reporting diagnoses macro-level trends of design characteristics in relation to expected rewards and temporal outdegree.
- Filtered core and shell – investigation reveals initial design states associated with top scoring core and shells.
- Filtered bundle + core and shell – analysis results in representations of state entry and action pools plots, as well as second order economic statistics resulting from simulation. Probability differences between optimal state sequencing and state entry plots highlight that highest likelihood actions across all available states are not always the actions exercised.

- Individual design concept – querying a point design provides design-specific action sequence understanding and identifies causal relationships. This layer of depth possesses the ability to reveal latent design changeability responses.

The dynamic state model offers a probabilistic trajectory of major life cycle decisions. The method developed informs both the initial design vector and the overarching strategy for negotiating environmental policy change as the design proceeds dynamically through its life cycle. There exists a range of activity, especially as it relates to the timing of a change, even among design concepts in the top percentile. Despite the existence of an absorbing path, a design concept trends toward the path in a manner particular to the initial state and given the realization of external events.

Analysis also demonstrates that a traditional artifact viewpoint underestimates expected rewards. A failure to appreciate the need for change would have resulted in higher expected cost lock-in despite accessibility to improved cost pathways. Changeable concepts prevented from changing are unduly affected unless all designs are insensitive to the external environment. Enabling change to occur leads to more equivalent analysis among alternatives and a proper valuation of intermediate and end life cycle preferences.

The case study revealed a number of challenges associated with implementing the MDP framework, and more generally, for managing temporal aspects of design. These include:

- *Future starting condition* – The outputs of a MDP decision matrix are expected rewards and actions for each state. Choosing the "best" design might appear as simple as selecting the state at $t=0$ with the greatest expected reward. However, the time lag between the design process and construction of the design is non-zero, and the state is a function of a constantly changing external environment. Two states with the same physical characteristics but different environmental conditions may be marked by wildly different expected values due to state-specific rewards and transition probabilities. An initial state will always be uncertain to some level.

- *Down-selection sensitivity* – A decision-maker must be sensitive to the stability of a solution when down-selecting for simulation and eventual detailed design. Representing paths and communicating average measurements for design core and shells are a function of the percentile with which they are reported. Some design core and shells demonstrate wide variability of expected rewards and action sequences, while others exhibit much less. There are diminishing returns to including too many poorly scoring designs in the cutoff; over-populated state entry and action pool representations can serve to over-emphasize globally sub-optimal trends. Too few concepts included in the cutoff fails to appreciate that rewards are both expected values and uncertain.
- *State space explosion* – Intelligent problem setup is important for managing memory requirements and reducing necessary calculations. The size of the problem can be reduced through proper scoping and awareness of independent variables. The addition of unnecessary state variables only serves to exponentially increase the number of possible pathways despite no difference in the action sequence. The problem can be partitioned into multiple sub-MDPs when important variables are independent of one another.
- *Difficulty expressing action sensitivity* – A large state space is also harder to manage from a sensitivity standpoint. The large number of states and actions increases the likelihood that tolerances are quite small, and the multitude of change needs throughout the life cycle prevent a focused study of only a select number of epochs. Tan and Hartman's method (2011) remains applicable, yet could use further thought as to how to represent this added dimension of information.
- *Need for a global utility function* – The study demonstrated that changeability, management, and expected rewards are not positively correlated in all instances. A decision-maker may need to perform decision space trades to find a design that satisfies a threshold level of performance in each category. A utility function is one suggestion for enabling a decision-maker to specify one's preferences for life cycle change performance.

7.9 Chapter Summary

The research presented in this chapter expressly transitioned the M&R problem forward into early stage design. Application of the proposed framework elicits expected tactical decisions through the artifact's life cycle that reveal a broader strategic response to policy change. A critical benefit to using a state-based framework is the ability to identify limitations and lock-in resulting from design decisions. An engineer that can understand the design vector through time gains a wider appreciation for design selections; research within this chapter presents specific design knowledge that result from employing a dynamic perspective. Metrics communicate the degree to which changeability is restricted and how uncertain path dependencies result in specific life cycle decisions.

Chapter Citations

1. Abadie, O., Moehler, W., Ledesme, D., & Stoppard, M. (2011). The next bunker fuel. *Report*. IHS CERA.
2. Asariotis, R., Benamara, H., Finkenbrink, H., Hoffman, J., Lavelle J., Misovicova, M., Valentine, V., & Youssef, F. (2011). Review of Maritime Transport 2011. *Report.* UNCTAD.
3. Buhaug, Ø., Corbett, J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D., Lee, D., Lindstad, H., Markowska, A., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Winebrake, J., Wu, W., & Yoshida, K. (2009). Second IMO GHG Study 2009. *Report.* London: International Maritime Organization.
4. Devanney, J. (2010). EEDI, a case study in indirect regulation of CO2 pollution. *Report*. Center for Tankship Excellence.
5. Environmental Protection Agency. (2009). Regulatory impact analysis: Control of emissions of air pollution from Category 3 marine diesel engines. *Report*. EPA-420-R-09-019.
6. IMO. (2012). Annex 8—Resolution MEPC.212(63): 2012 guidelines on the method of calculation of the attained energy efficiency design index for new ships. *Report*. International Maritime Organization.
7. Jorgensen, R. (2010). Slow steaming: The full story. Report. A.P. Moller-Maersk Group.
8. Madsen, R. (2011). 144-car ferry LNG fuel conversion feasibility study: Life cycle cost analysis. *Report*. Glosten Associates.
9. MAN Diesel & Turbo. (2011). Propulsion of 8000-10000 teu container vessel. *Report*. MAN Diesel & Turbo.
10. Mazraati, M. (2011). Challenges and prospects of international marine bunker fuels demand. OPEC Energy Review, *35* (1).
11. Nielsen, B. (2009). 8500 teu container ship: Green ship of the future concept study. *Report*. Odense Steel Shipyard Ltd.

12. Notteboom, T., Delhaye, E., & Vanherle, K. (2010). Analysis of the consequences of low sulphur fuel requirements. Report. European Community Shipowners' Associations.
13. Rodrigue, J. Comtois, C., & Slack, B. (2009). *The geography of transport systems.* New York: Routledge.
14. Stopford, M. (2009). *Maritime Economics*. London: Routledge.
15. Tan, C. & Hartman, C. (2011). Sensitivity analysis in Markov Decision Processes with uncertain reward parameters. *Journal of Applied Probability, 48*, 954-967.

CHAPTER 8 – CONCLUSION

He who cannot change the very fabric of his thought will never be able to change reality, and will never, therefore, make any progress.

-*Anwar Sadat*

The following chapter contextualizes the contributions of the presented research (Section 8.1) in relation to the original problem statement, discusses areas of caution when implementing the MDP-based framework and metrics (Section 8.2), and offers direction for future work (Section 8.3).

8.1 Review of Problem Statement

Recall the research questions identified in Chapter 1, and again presented below. How each problem and question is uniquely addressed by the research in this dissertation comprises the remainder of this section.

Table 8-1: Repeat of problem statement & research questions identified in Section 1.3.2

Problem	**Question**
Instability of the environment means a product solution may not be quality through time; Design must consider future product use that is uncertain and/or unforeseeable	Where must system capability for performance change lie given an uncertain life cycle environment?
Multiple sources, strengths, uncertainties, and time scales of disturbance exist	How can these sources be handled in a unified framework that considers both individual and cumulative impacts?
The rate and magnitude of environmental policies for ships are increasing, changing how an individual defines a good design	Can understanding decision paths in response to policy change help identify design drivers of today and tomorrow?

A static viewpoint of the design artifact leads to over- or under-design, resulting in reactive change costs	How does a dynamic perspective on design enable more timely change and better management of life cycle cost?
Evaluation of optimal decision paths across alternative design concepts is limited when using only life cycle cost for comparison	What metrics can extend evaluation of decision paths beyond a discussion of life cycle cost?

The nuances of this dissertation's achievements are conveyed in answering the set of research questions. These contributions are made explicit in Section 8.1.2.

8.1.1 Addressing the Research Questions

Problem #1: *Instability of the environment means a product solution may not be quality (achieve desired value) through time; Design must consider future product use that is uncertain and/or unforeseeable.*

Question #1*: Where must system capability for performance change lie given an uncertain life cycle environment?*

Use of the non-stationary state-based framework in this dissertation enables rapid identification of a solution's deterioration in quality. Quality is both an absolute and a relative term: quality is absolute in that the product should comply with future policies as they are enacted, and quality is relative in that the product should continue to accumulate rewards in excess of those achievable by a different design solution. Performance change is thus valued where future compliance issues and/or poor reward accumulation is identified.

Quality first, and minimally, implies conformance in the context of this thesis. Research in this dissertation emphasizes the identification of design state unavailability resulting from the implementation of new environmental policies. State entry plots offer a means for understanding which design states are expected to be impacted through time by policy change and its associated effects (Figure 8-1). Matching the components of policy change to design states adds perspective to where in the system that conformance and performance reliability are likely to be challenged.

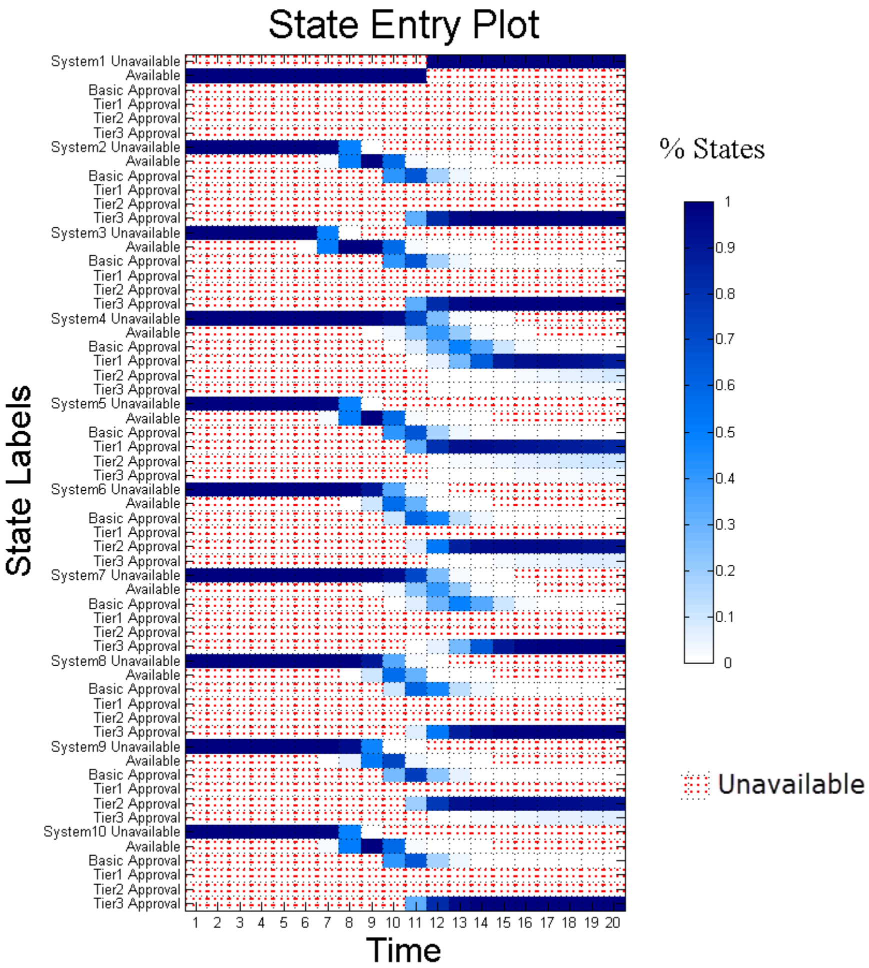


Figure 8-1: State entry plot illustrating probability of a state being accessible through time

The state entry plot illustrates that some states prove unavailable with time due to disturbance. Availability of a design state is a probabilistic function of expected disturbance rates, strengths, and interactions. Maintaining quality through time necessitates avoiding disturbance-impacted, or trap, states. Stable design configurations are robust to disturbance, while others are more susceptible to entering a trap state.

Avoiding states susceptible to disturbance may sometimes only be overcome by a decision-maker actively causing state change. The MDP attaches decision information to each state, which is identified by evaluating the second component of quality, optimality, through the use of a state-specific reward matrix. Standard dynamic programming functions provide a method for valuing how reward accumulation changes with time and for identifying if higher quality states exist.

States that desire performance change are revealed by identifying state actions that include any action other than ‘Do Nothing.’ Recall the decision matrix presented in Section 6.3.1, again presented as Figure 8-2. The MDP framework determines where and when system states desire change given environment and system uncertainty.

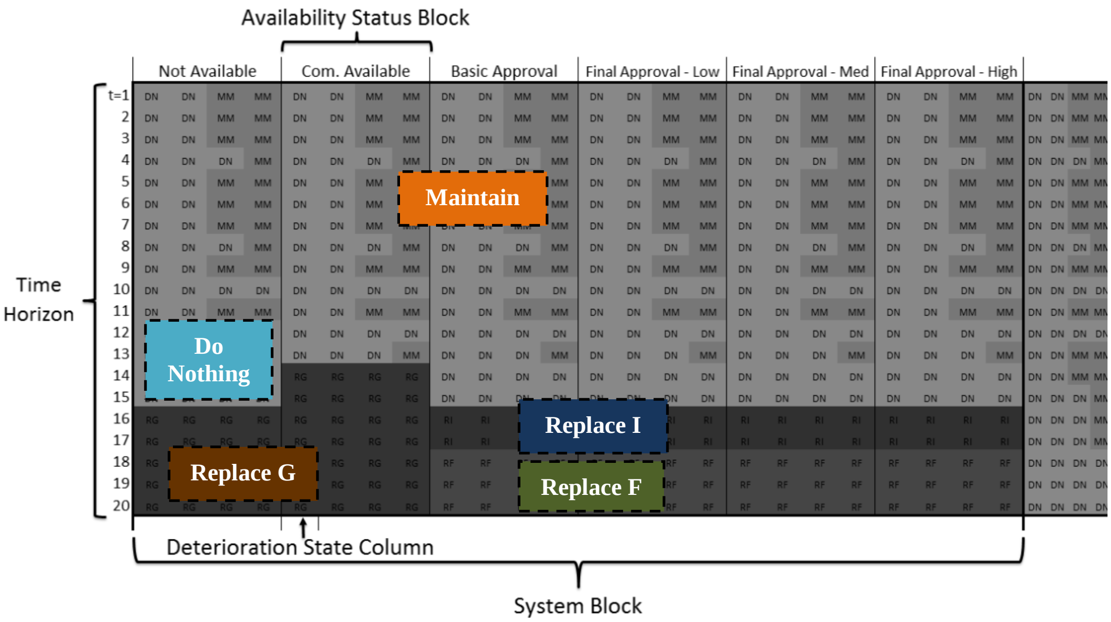


Figure 8-2: Sample decision matrix segment (Niese & Singer, 2011)

Together, state conformance mapping and sequential decision analysis demonstrate appreciation for two dimensions of quality under uncertain life cycle conditions. State change preferences are a function of both changeability and switching costs. Each design concept can respond differently to the same disturbance due to design-specific rewards and change characteristics. Markov Decision Processes enable a designer to determine that System X may elect to install Technology 1 and System Y prefers Technology 2, for example. System Z may require change as well, but the optimal response instead lies in changing from Speed 4 to Speed 3.

***Problem #2:** Multiple sources, strengths, uncertainties, and time scales of disturbance exist.*

***Question #2:** How are these sources to be handled in a unified framework that considers both individual and cumulative impacts?*

The state-based framework developed accommodates both design characteristics and disturbance characteristics. Attached to each state are transition probabilities and rewards particular to each epoch in the horizon (Figure 8-3). These sets of probabilities, rewards, and epochs form a common currency for describing individual disturbances. The implications of the collective disturbances at each epoch are summarized by incomes and outlays related to both the system itself and decisions maneuvering the system through its life cycle.

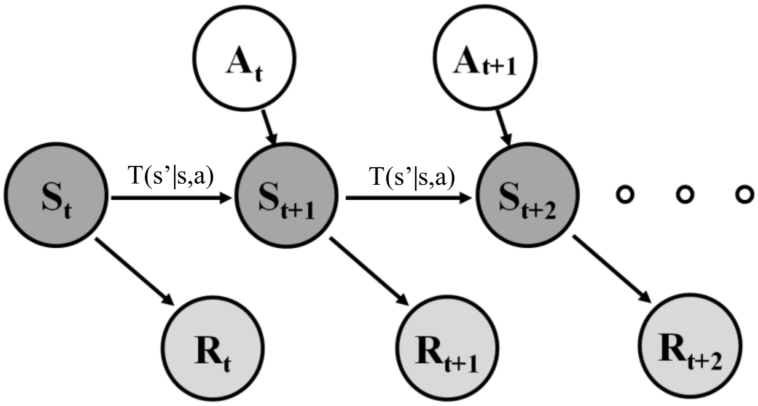


Figure 8-3: Process for how state, action, transitions, and rewards interact within MDP framework

Integrating the multitude of potential disturbances is achieved through application of the laws of Bayesian conditionality and total probability. Disturbances occurring at the same epoch are readily overlaid one another, where relevant dependencies among multiple disturbances or between a disturbance and design characteristics can be modeled. The framework developed is readily scalable in its current form, as well as capable of taking advantage of state independencies to speed calculations.

Problem #3: *A static viewpoint of the design artifact leads to over- or under-design*

Question #3: *How does a dynamic perspective on design enable more timely change and better management of life cycle cost?*

The research in this dissertation develops an evaluation framework that includes a temporal perspective on design and accepts that a system is subjected to a variety of dynamic environments. Uncertain environmental dynamics are directly built-in to the design process, coupled with a system capability to change (Figure 8-4). Whereas the traditional form of evaluation first designs and then simulates, a time-based evaluation performs design and simulation concurrently. Just as the external context is dynamic, so, too, is a system capable of change. Thus, the framework evaluates both the design and the associated life cycle decisions that enable active response to the simulated conditions.

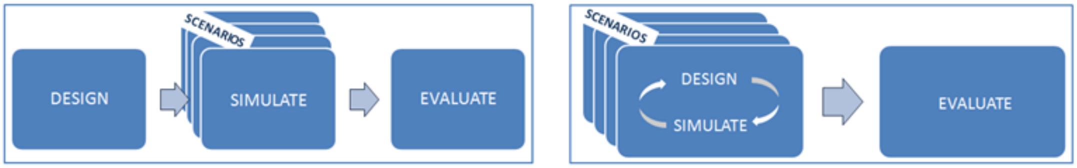


Figure 8-4: Traditional (left) versus temporal (right) evaluation environment

An under-examined component of life cycle management is identifying *when* to optimally initiate change to a design. The developed method values matching supply of capabilities with demand for capabilities. Too early of supply results in added holding costs and resource commitment that constrains future decisions. Too late of supply incurs risk of penalties and selection among a limited set of alternatives possessing high switching costs. A dynamic perspective values that design is not an all-or-nothing proposal; a designer's choices are not simply between the installation of disturbance-robust capabilities in the initial design or no such capabilities for the entire life cycle.

The fact that the optimal action sequences derived in the case studies of Chapters 6 and 7 (see: Sections 6.4 and 7.7.4.1) entail active product change from the initial design state establishes that the static perspective of design is inadequate. Figure 8-5 again illustrates potential instantiations of an initial design over its life cycle when adhering to optimal decision-making. The penalty for failing to act is a greater expected commitment of resources by life cycle end.

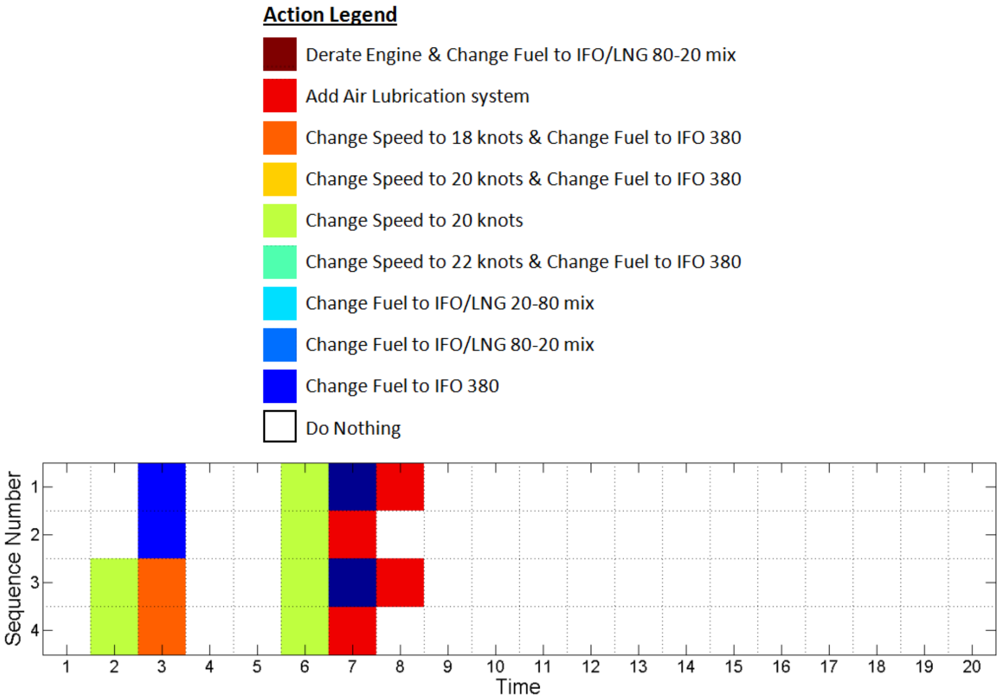


Figure 8-5: Unique sequences by action type and timing for C&S-A, initial design construct D

This re-conceptualization of the design problem as inclusive of both the product and life cycle decisions elevates the role of changeability. A static perspective resists disturbance and associated change, leading to over-design or under-appreciation of the value change affords. Acceptance of changeability as a potentially positive force more holistically addresses the design artifact as the dynamic entity it is.

Problem #4: *The rate and magnitude of environmental policies for ships are increasing, changing how an individual defines a good design.*

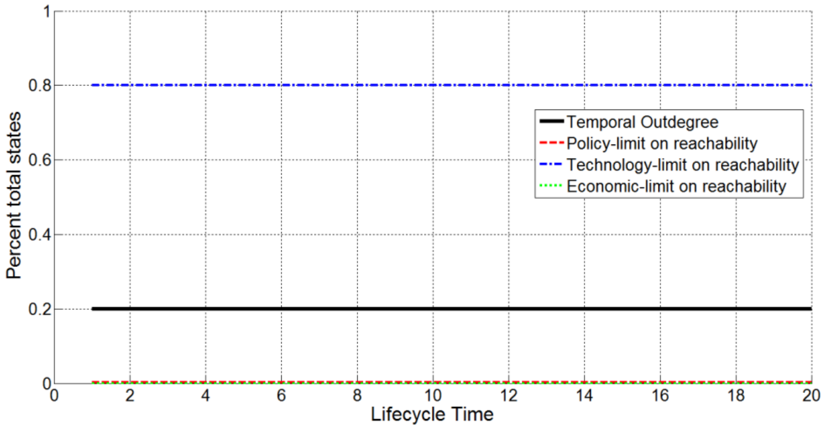
Question #4: *Can understanding decision paths in response to policy change help identify design drivers of today and tomorrow?*

Design is the act of decision-making, thus assessing a design on its physical characteristics alone fails to appreciate the decisions that may be necessary over the life cycle in the face of new policy. Evaluating how a design candidate passively and actively can respond to policy change serves to enrich design learning and add conviction to design choices. Life cycle decision options and opportunities are a function of the design due to lock-in, and design performance through time is a function of the decisions made to sustain it. This paired judgment of the design construct and its associated decision path is ultimately necessary to define “good” design over a product life cycle.

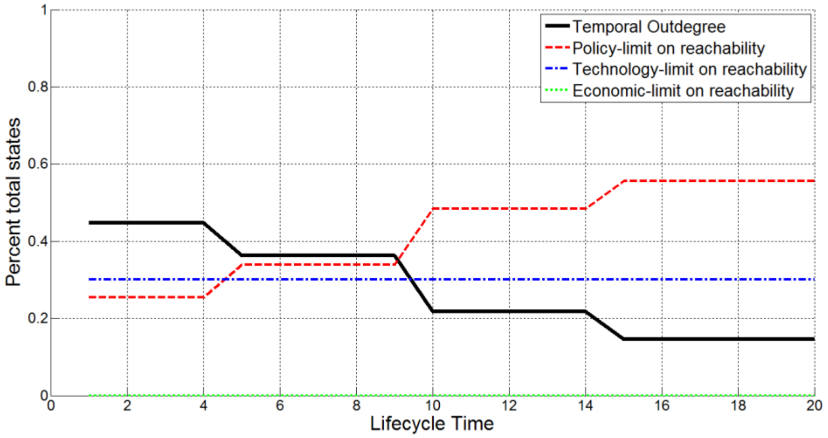
This research develops a method for the joint valuation of both design concepts and their decision pathways as well as defines metrics for describing the characteristics of each pairing. The decision space clues a design team into how much the ability to change is exercised, the positioning necessary to capitalize on policy change, and the design states to avoid when disturbance approaches.

The MDP framework informs the designer of both driving design characteristics and driving environmental factors limiting a design’s ability to satisfy its life cycle objectives. Plots in Section 7.7.1.2 and Section 7.7.1.3 identify initial design characteristics in concepts expected to achieve the greatest cumulative rewards. Research in this dissertation partitions design drivers features by changeability, defining the design core and shell as non-changeable design features and the design bundle as the collection of changeable design features. Discovery of initial design drivers proves critical to enabling future decisions due to the state dependencies governing switching costs and potential decision options.

Temporal outdegree plots reveal driving environmental factors. Recall discussion of the design concepts *Tortoise* and *Hare* in Section 7.7.2.1. Temporal outdegree and associated limitations to change are again plotted in Figure 8-6. Here, changeability of *Tortoise* is not restricted by existing or emergent environmental policy initiatives. Conversely, the initially greater degree of state changeability within *Hare* is diminished with time due to the policymaking.



(a) Tortoise



(b) Hare

Figure 8-6: Sample temporal outdegree plots for core & shell designs, outlining design changeability

The method also facilitates exploration into how different manifestations of policy contribute to multiple strategies for the same design. One manner for realizing how strategies are revealed is through interpretation of optimal decision paths (Figure 8-7).

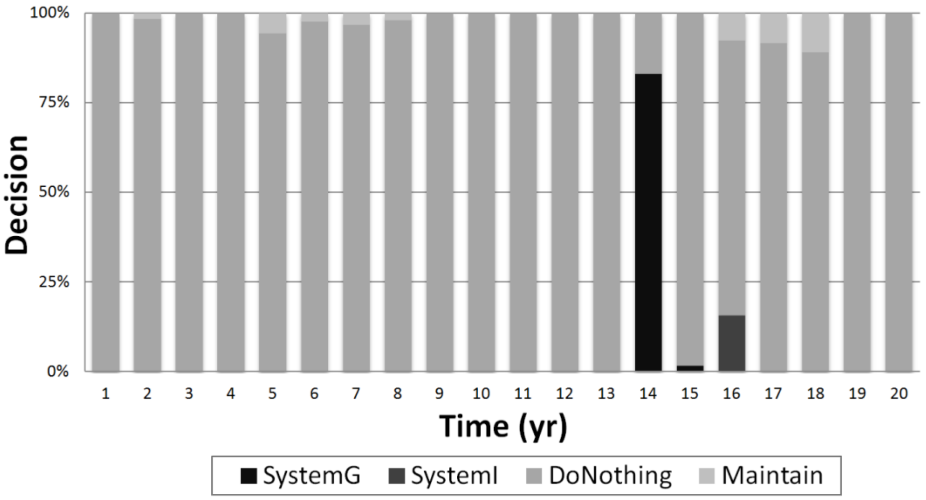


Figure 8-7: Sample decision path output (Niese & Singer, 2011)

The multitude of strategic responses to ballast water policy, found in Section 6.3.5, stem from variations of policy strength and timing influencing the relationship between technology development and shipboard installation of treatment systems. The framework enables the abstraction of decision paths to the strategy level, with the aim to better establish which system, decision-making, and environmental attributes must exist for a specific strategy to activate.

A strong design can fall short without a matching life cycle strategy, just as a strategy is not a winning one for all instantiations of design and environmental contexts. A strong candidate design can underperform if decisions related to its use and positioning within the environment cause it to enter an unsuitable state or follow a path where lock-in proves detrimental. Conversely, no amount of optimal decision-making can overcome the drawbacks of selecting poor design configurations; strategic changes to a poor design candidate may still prove expensive, extensive, and/or time-consuming. Poor cost performance can derive from low rewards due to state sub-optimality or high change costs associated with decisions that enable transition from state to state. Identifying these low reward states and decisions helps designers trace the implications of policy to design.

***Problem #5:** Evaluation of optimal decision paths across alternative design concepts is limited if only metric of comparison is life cycle cost.*

***Question #5:** What metrics can extend evaluation of decision paths beyond a discussion of life cycle cost?*

Development of original metrics is driven by a desire to holistically compare the decision paths of alternative designs when expected life cycle cost is non-differentiating. Beyond expected life cycle cost obtained, relevant information to a designer might include:

- How life cycle rewards are obtained
- When life cycle rewards are obtained
- How much decision-making capital is expended to achieve life cycle rewards

The metrics in this dissertation aim to characterize what an optimal change strategy entails, what resources of the managing team are required to support the strategy, and what elements in the strategy remain unresolved. The knowledge gained from path-centric measurements enables an enhanced ability to describe design lock-in, thus influencing early stage design.

Several original metrics contribute to a more holistic characterization of resource commitment. The approach developed seeks to balance (a) committing resources to position a product in a manner that mitigates disturbance, with (b) delaying resource commitment until uncertainty is more fully resolved and the benefits of design features alleviating the effects of disturbance can be realized. *Time-weighted cost incurred* captures the inherent trade-off between delaying resource commitment and seizing opportunities that emerge before disturbance occurs. *Context premium* represents a metric used to quantify the level of expected resources committed due to uncertainty.

Other metrics are used to quantify the decision-making resources demanded by the product team. Metrics are developed under the premise that management values a strategy that is clear, largely independent, and responsive to unplanned conditions. Insensitivity to state transition probabilities in the development of an optimal action sequence demonstrates clarity. A large number of actions involved in the execution of a change strategy could signal an over-managed system given future uncertainty and speaks to the role of stakeholders and infrastructure required in support of the product. The ability to initiate change is evidence of responsiveness. Metrics defined as *clarity-changeability ratio, horizon activity level,* and *epoch attentiveness level* quantify levels of strategy clarity, active management involvement, and system rigidity.

The additional dimensions through which preferences are perceived and measured is in line with the concepts of change potential and decision-making capital outlined by a discussion of the panarchy model in Section 2.7.

8.1.2 Synthesis of Unique Contributions

The primary product of this dissertation is the development of a design evaluation framework that strategically considers path dependencies inherent to life cycle decisions. The framework facilitates improved understanding of design decisions in the context of life cycle performance by linking policy advancements and product change. Structured analysis of path dependencies informs designers of the following:

- How a disturbance such as environmental policy changes performance
- Where the ability to change should be located to best respond to disturbance
- When the ability to change should be made available to best respond to disturbance
- How a focus on strategic life cycle decisions incorporates a design view from a management context to improve the characterization of “good design”.

Section 8.1.1 served to describe this knowledge capture more completely.

In addition to introduction of the Markov Decision Process framework as a method for assessing a design and its life cycle jointly, several other high-level achievements are brought forward as a part of this work, include:

- Chapter 2: Principles for entry of policy theory into design decision-making
- Chapter 3: Clarification of the design artifact subject to a life cycle perspective

- Chapter 4: Recognition of the current limitations in design focusing on the –ilities class
- Chapter 5: Metrics for analyzing changeability, planning uncertainty, and management preferences in the context of design.

Chapters 6 and 7 submit two original case studies to validate the theory and evaluation method and metrics developed in this dissertation.

8.2 Cautions

8.2.1 Modeling Fidelity

Decision-makers in conceptual design value the rapid ability to compare alternatives. Yet, a ship is a combination of hundreds of thousands of components and dozens of systems. Detailing all the components and operating procedures that are potentially changeable is an exhaustive task that could prevent timely analysis of alternatives. Estimating all variable relationships and future permutations of global economics, policymaking, and technology development is a herculean effort that is not rooted in nature's laws of physics. At some point, accuracy must be sacrificed.

The appropriate level of fidelity should carefully consider, and then match, the degree of uncertainty. Models are often judged by their weakest assumptions, of which there are many in the early stage design of long-life span, highly integrated products. Parametric relationship building and package bundling can be used to abstract variables of less consequence to the conceptual design problem of interest in this dissertation, e.g., structural requirements or sea-keeping performance. Unfortunately, low fidelity models may not capture product and environmental behaviors that could prove critical to specifying one action over the other or may overlook opportunities for strategic decisions.

Fortunately, certain rules of thumb exist that could aid implementation and suggest areas for purposeful inclusion of greater fidelity. Variables or components that typically dictate a significant portion of ship activities highlight sources of large direct and/or indirect costs. An exploration of historical change actions initiated by similar ships can offer similar guidance. This dissertation attempts to showcase that an engineer may also be capable of drawing new design knowledge from the decision space when low fidelity in the design space represents an obstacle.

8.2.2 Resources

As implied above, resources required in concept design include time, expertise, and computing software and hardware. This remains true for incorporation of the MDP framework for environmental policy in early stage design. Construction, maintenance, and operational expertise are highly valued in the development of states, action availability, and both transition probability and reward generation. Policy and risk expertise sheds light on the role environmental factors may play in moderating ship functions. Investment in software expertise can translate domain-specific expertise to a form that enables rapid evaluation and iteration of the model. Experts must value the temporal aspects of the design artifact else sabotage takeaways; the problem can be sufficiently restricted and the solution pre-defined through a biased establishment of rewards and transition probabilities.

Many tools and databases have been developed to aid early stage design as well as to quickly construct exploratory market and policy scenarios. Project-specific requirements, deadlines, and constraints are then integrated into these physics-based and environmental models. Regardless, computational resources are a function of the size of the modeled design space as well as how efficiently the decision matrix can be generated and simulation trials conducted. The number of possible decision paths is an exponential function of the number of states, actions, and horizon length. Thus, efforts to intelligently construct the state space can prevent an explosion of computation time.

8.2.3 Decision-making Scope

A third implementation caution involves defining the boundary of the decision-maker. Who are the stakeholders? Which stakeholders influence decisions and which stakeholders perform decision-making responsibilities? Are decisions made by an individual, a coalition of members with equal power, or a distributed team of varying influence? Do the individuals performing the actions differ from decision-makers? Are their priorities aligned? Answering these questions provides the foundation for which localized intricacies are understood and adequately valued within a joint decision-making framework.

Defining the optimal decision becomes more complex as the boundary spans space and time. For example, the cargo group may need to reconcile decisions with its cohort responsible for the propulsive needs of the ship. One team's rewards may result from another team's costs. Unbalanced localized rewards can contribute to characterizing global rewards insufficiently.

Individuals also carry different degrees of influence at various phases in a ship's life cycle. Institutional legacies within the U.S. Navy have engendered a penchant for competition between acquisition and maintenance divisions. An acquisition team's horizon for rewards accumulation may last only a handful of years, but its influence stretches across the full life cycle. Similarly, a filibuster-proof majority in Congress can open a policy or budget window that reorganizes decision-makers' conceptualization of rewards. Nishijima, Straub, and Faber (2007) conclude that decisions with potential implication for future decision-makers shall abide by the principle of equity of agents over time: compromise within the present generation is inclusive of an intergenerational perspective.

This nature of joint decision-making and distributive consequences requires careful modeling of decision logic, rewards, and the discount factor. Issues of equity, negotiation, psychology, and gamesmanship must be incorporated.

8.2.4 Markov Property Validity

A related structural issue is that of the Markov property's limiting nature. As previously stated, a process is Markovian if the decision-maker's actions are memoryless and if the conditional probability distribution of future states of the process depends only upon the present state. Transition functions are independent of (a) the time that has passed to arrive at a state, (b) the time the system has remained in the current state, (c) the sequence the system has taken to arrive at the current state, and (d) the decision sequence to be taken thereafter. The Markov constraint represents a dramatic simplification in defining the stochastic process and evaluating the state probabilities that simplifies computational effort (Boyd, 1998).

However, the assumption can also prove restrictive for certain real-world systems and render modeling results invalid. Many design issues are well-posed within a Markov model, but systems analysts must be cognizant of consistency issues between the model and actual characteristics. For example, decision-makers may possess a finite degree of decision-making capital. This instance is perhaps best exemplified in politics, where legislators only have so many “cards to play” within a period of time. Similarly, too many demands on one system or one design group can negatively impact development timelines, response rates, or risk tolerance.

Creative construction of the state matrix and action pool can account for certain issues where the Markov property might otherwise be tested. For example, issues such as matching replacement actions with planned overhaul schedules can be coordinated through strategic activation of action availability. Deteriorated policymaking, environmental, and economic states can be modeled in the same discretized manner as a deteriorated physical system. Semi-Markov modeling techniques can account for transitions dependent on the time the system has been in a particular state by employing a “local clock” conceptualization of time. Nevertheless, these creative solutions may come at the expense of evaluation speed.

8.3 Future Work

An improved understanding of both the policy link to the technical domain and the connection between the design artifact and the decision pathway offer great opportunities for additional research. This author believes a valuable direction for future work consists of studying the design-policy problem using a multi-agent or decentralized framework.

Incorporating multi-agent interactions acknowledges that the designer and the product do not exist in a vacuum. In fact, interaction with other agents could help an agent achieve its goals. This extension may allow for greater appreciation of the following realities:

- Acquisition and O&M teams often have different overall objectives and constraints, traditionally generating competition between the teams. Competition in this case can prove destructive. A joint reward, multi-agent model could facilitate cooperation between the teams, with an overall goal on life cycle cost. Load balancing among acquisition and O&M teams, as well as among ship systems design teams, can also be explored. Defined as a multi-agent problem *within the product*.
- A ship is typically a part of a larger fleet, where the fleet manager hopes to efficiently minimize product variation and decision rewards can be maximized through economies of scale. Agents act mostly independently except for specified periods, such as policy responses, where coordinated interactions can prove globally optimal. Defined as a multi-agent problem *within the fleet*.
- This dissertation focuses on the uni-directional affects of the policy domain on the technical domain. However, Chapter 2 also highlighted how decisions in the technical community can spur or mitigate decisions in the policy domain. For example, strategic implementation of sustainable measures can prevent the need for policymakers to deliver overly burdensome regulations. Defined as multi-agent problem *across domains*.

Markov games represent a possible framework for reasoning about multi-agent systems in these contexts. Markov games are an extension of game theory to MDP-like environments. A decision policy, π, is now stochastic in nature. Given the lack of non-dominated policy, the risk appetite of decision-makers can more fully be modeled.

A secondary allowance within a multi-agent framework is an opportunity to model different horizons for each agent. For example, a policymaker's horizon tends to be much shorter, e.g., one election cycle, than the ship design engineer's horizon. Individual design teams and a ship-specific versus fleet perspective also consist of varying horizons.

Chapter Citations

1. Boyd, M. (1998). An introduction to Markov modeling: concepts and uses. *In proceedings of Reliability and Maintainability Symposium*, Anaheim.

Appendix A:

Parameters for Chapter 6—Case Study #1: Responding to ballast water policy and technological development, including

- Discount Factor
- Compliance Penalty
- Deterioration
- System Status
- Operations

Discount Factor

Constant	Value	Notes
r	0.04	where $\lambda=1/(1+r)$

Compliance

Penalty= -$20M

Deterioration

Exponential Distribution: $\nu \lambda e^{\lambda x}$

Constants

$\nu=0.12$

Parameters

[Min, Max] values, function of system

Sub-State Name	Mean (λ^{-1})
0% Deteriorated	[0.150 , 0.166]
33% Deteriorated	[0.118 , 0.131]
66% Deteriorated	[0.100 , 0.114]
100% Deteriorated	[0.092 , 0.103]

Transition Matrix

[Min, Max] values, function of system

Sub-State Name	0% Deteriorated
0% Deteriorated	[0.87 , 0.89]
33% Deteriorated	[0.00 , 0.00]
66% Deteriorated	[0.00 , 0.00]
100% Deteriorated	[0.00 , 0.00]

Sub-State Name	33% Deteriorated
0% Deteriorated	[0.097 , 0.12]
33% Deteriorated	[0.92 , 0.94]
66% Deteriorated	[0.00 , 0.00]
100% Deteriorated	[0.00 , 0.00]

Sub-State Name	66% Deteriorated
0% Deteriorated	[0.011 , 0.016]
33% Deteriorated	[0.056 , 0.072]
66% Deteriorated	[0.95 , 0.96]
100% Deteriorated	[0.00 , 0.00]

Sub-State Name	100% Deteriorated
0% Deteriorated	[0.001 , 0.002]
33% Deteriorated	[0.003 , 0.006]
66% Deteriorated	[0.037 , 0.050]
100% Deteriorated	[1.00 , 1.00]

System Status

Parameters: Unavailable → Commercially Available

Normal Distribution

Without Ratification

System Name	Mean, $\mu_{without\_ratification}$ * (Years after Convention)	Deviation, σ
A	0	0.00
B	3	0.50
C	2	0.40
D	7	1.00
E	3	0.50
F	5	0.75
G	7	1.00
H	5	0.75
I	4	0.60
J	3	0.50

**Years following Convention*

With Ratification

Multiplier, η: 0.95

$\mu_{with\_ratification} = \eta * \mu_{without\_ratification}$

Parameters: Commercially Available → Basic Approval

Normal Distribution

Mean, $\mu_{basic\_approval}$: 0.1
Deviation, $\sigma_{basic\_approval}$: 0.5

Parameters: Basic Approval → Final Approval

Binomial Distribution

Success, p: 0.75
Failure, q: 0.25

Operations

Annual Number Trips

Uniform Distribution: [9,13]

Parameters: Operating Cost

Exponential Function: $\theta(x)=\theta_0+g_\theta x e^{\lambda(j)x}$

	Value, Range	Notes
g_θ	0.01	Constant
X	{1,2,3,4}	Correspond to deterioration sub-states {0%, 33%, 66%, 100%}
λ	[0.72 , 0.78]	Function of system installed

Appendix B:

Parameters for Chapter 7—Case Study #2: Design Evaluation Subject to Carbon Emission Policymaking, including

- Concept configuration required power
- EEDI fuel factors
- Energy-reducing technology impacts
- Revenues and fixed + variable cost

Powering

Required Power @ Engine RPM

- Function of propeller diameter and engine + corresponding rpm selected
- Prior to inclusion of waste heat recovery system, and other energy-reducing technology add-ons

Configuration 1		
	Min	**Max**
25 kt	63.0 MW	-
24 kt	53.2 MW	-
22 kt	36.2 MW	-
20 kt	25.4 MW	-
18 kt	17.2 MW	19.1 MW

Configuration 2		
	Min	**Max**
25 kt	61.0 MW	-
24 kt	51.2 MW	-
22 kt	35.0 MW	-
20 kt	24.4 MW	27.0 MW
18 kt	17.1 MW	18.9 MW

Configuration 3		
	Min	**Max**
25 kt	63.1 MW	-
24 kt	52.5 MW	-
22 kt	36.1 MW	-
20 kt	24.9 MW	27.6 MW
18 kt	17.4 MW	19.3 MW

Configuration 4		
	Min	**Max**
25 kt	-	-
24 kt	57.4 MW	-
22 kt	38.1 MW	-
20 kt	26.2 MW	-
18 kt	17.7 MW	19.7 MW

Configuration 5		
	Min	**Max**
25 kt	61.4 MW	-
24 kt	50.8 MW	56.2 MW
22 kt	34.9 MW	38.7 MW
20 kt	24.2 MW	26.8 MW
18 kt	16.9 MW	18.7 MW

Configuration 6		
	Min	**Max**
25 kt	-	-
24 kt	58.2 MW	-
22 kt	39.0 MW	-
20 kt	26.5 MW	-
18 kt	18.0 MW	20.0 MW

Configuration 7		
	Min	**Max**
25 kt	62.9 MW	-
24 kt	52.6 MW	-
22 kt	35.5 MW	39.4 MW
20 kt	24.6 MW	27.2 MW
18 kt	17.3 MW	19.2 MW

Configuration 8		
	Min	**Max**
25 kt	-	-
24 kt	58.3 MW	-
22 kt	37.8 MW	-
20 kt	25.8 MW	28.5 MW
18 kt	18.0 MW	19.9 MW

Configuration 9		
	Min	**Max**
25 kt	63.8 MW	-
24 kt	53.2 MW	-
22 kt	35.4 MW	39.2 MW
20 kt	24.6 MW	27.3 MW
18 kt	17.1 MW	19.0 MW

Configuration 10		
	Min	**Max**
25 kt	63.5 MW	-
24 kt	51.5 MW	57.0 MW
22 kt	35.1 MW	38.9 MW
20 kt	24.4 MW	27.1 MW
18 kt	16.9 MW	18.8 MW

Configuration 11		
	Min	**Max**
25 kt	66.0 MW	73.1 MW
24 kt	52.8 MW	58.5 MW
22 kt	35.4 MW	39.3 MW
20 kt	24.0 MW	26.6 MW
18 kt	16.5 MW	18.3 MW

Configuration 12		
	Min	**Max**
25 kt	64.7 MW	-
24 kt	52.9 MW	58.6 MW
22 kt	35.7 MW	39.5 MW
20 kt	24.6 MW	27.2 MW
18 kt	17.0 MW	18.9 MW

Configuration 13		
	Min	**Max**
25 kt	69.4 MW	-
24 kt	57.7 MW	-
22 kt	37.2 MW	-
20 kt	24.9 MW	-
18 kt	16.8 MW	18.6 MW

Power derived from sources other than main engine

- WHR system provides maximum 6% of power requirements, linearly decreasing as function of % power required for speed/engine power available

Fuel Name	Max Power Reduction
Kite*	10%
Flow Device	6%
Air Lubrication	8%

*Non-inclusive of availability factor (0.7)

EEDI Carbon Factor

Fuel Name	EEDI Carbon Factor
IFO 380	3.114
LS 380	3.151
MDO	3.206
LNG	2.750
IFO 380—LNG 80/20	3.042
IFO 380—LNG 50/50	2.932
IFO 380—LNG 20/80	2.823

Revenues, Fixed Costs, Variable Costs

Capital Cost

Vessel Configuration	Base Cost*
Configuration 1	$87.9 M
Configuration 2	$88.3 M
Configuration 3	$93.8 M
Configuration 4	$94.8 M
Configuration 5	$83.1 M
Configuration 6	$98.8 M
Configuration 7	$91.4 M
Configuration 8	$94.3 M
Configuration 9	$86.6 M
Configuration 10	$83.3 M
Configuration 11	$76.9 M
Configuration 12	$85.7 M
Configuration 13	$99.3 M

*Defined as hull + outfitting – engine – add-on power technologies

Engine Cost: $375/kW installed

Action Cost	Newbuild		Retrofit	
	Min	Max	Min	Max
Add Kite	$1.5M	$1.5M	$1.5M	$1.5M
Add Flow device	$0.4M	$0.4M	$0.5M	$0.5M
Add Air lubrication system	$5.5M	$5.5M	$5.8M	$5.8M
Add Fuel tank cleaning	$0.02M	$0.05M	$0.02M	$0.05M
Add Re-rating	$0.4M	$0.8M	$0.4M	$0.8M
Add Secondary fuel tanks	$3.5M	$4.5M	$4.0M	$5.0M
Add Speed tuning	$0.10M	$0.16M	$0.10M	$0.16M

Fuel Rate

Initial reference IFO 380 price: $700/MT
Initial reference LNG price: $600/MT

Initial premium for LS 380: $20/TEU. Increases to $400/TEU premium to LS 380 relative to IFO 380 at Year 5 due to wider expected adoption of Emission Control Area designations and decreasing sulfur emission limits

Rate increase and spread between high/low prices for residual and distillate fuels loosely based on *Assessment of IMO Mandated Energy Efficient Measures for International Shipping* (Bazari & Longva, 2011)

Generalized ratio of price growth IFO:MDO:LNG is 1:1.5:2

Freight Revenue

Initial all-inclusive head-haul rate, High: $1400/TEU +/- max $300/TEU
Initial all-inclusive rate head-haul, Low: $900/TEU +/- max $200/TEU

Back-haul rate is 50%, of head-haul rate, constant

Utilization

Initial head-haul + satisfy EEDI newbuild requirement: 90% head-haul
Initial head-haul + fail to satisfy EEDI newbuild requirement: 85% head-haul
Back-haul: 50% of head-haul utilization

Insurance

[Standard Hull/Machinery (Stopford, 2009)
+ Max 4.5% increase with vessel age (Stopford, 2009)
+ Max 3% increase dependent on technologies employed]

+ [Standard Property/Indemnity Insurance (Stopford, 2009)
+ Max 4% increase with vessel age (Stopford, 2009)
+ 50% increase if EEDI of current configuration fails to satisfy newbuild requirement]

Maintenance

[Standard Maintenance (Stopford, 2009)
+ Max 11% increase with vessel age (Stopford, 2009)
+ Max 5.5% increase for technologies employed
+/- Max 12% (LNG), Min -4% (MDO) increase for fuel type utilized]

Port Fees

[Standard User/TEU fee (Stopford, 2009)
+/- Max 5% increase or decrease in pilotage cost for vessel, using vessel beam as proxy
+/- Max 50% increase or decrease due to EEDI performance relative to newbuild requirement]

Other

40% tax rate on all revenues